A STUDY OF METHODS USED IN

MEASUREMENT AND ANALYSIS SEDIMENT LOADS IN STREAMS

REPORT NO. 8

MEASUREMENT OF THE SEDIMENT DISCHARGE OF STREAMS

MARCH 1948

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Planned and conducted jointly by
an Interdepartmental Committee
representing the following agencies

Office of Indian Affairs, Bureau of Reclamation

Tennessee Valley Authority, Corps of Engineers

Geological Survey, Department of Agriculture

and Iowa Institute of Hydraulic Research

The functions of this committee
were transferred to
the Subcommittee on Sedimentation
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SYNOPSIS

The purpose of this report is to clarify the principles of sediment transportation and to summarize the practices most commonly used in carrying out fluvial sediment investigations. The report deals with the necessity for studying sediment load problems and presents a history of early sediment measurements. Types of sediment transportation are described and an explanation based on the turbulence concept is given for the vertical distribution of suspended sediment. The general principles involved in suspended sediment measurements are treated as well as the practical aspects of selecting sampling points and of determining the frequency of sampling. The principal types of suspended sediment samplers are described, their advantages and disadvantages are discussed, and details are given regarding sampler designs which were developed after a thorough study of existing sampling equipment. Descriptions are also given of methods used in the measurement of material moving on or near the beds of streams and of the equipment used to obtain samples of the bed material.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

MEASUREMENT OF THE SEDIMENT DISCHARGE OF STREAMS

I. INTRODUCTION

1. The sedimentation problem -Many hydraulic engineering works have been built on sediment-bearing streams in the past without due consideration being given to the effects of sedimentation on the life and utility of the projects. Unforeseen difficulties in operating and maintaining these engineering works have developed due to the presence of the sediment, and the economic life for many of them has been much shorter than anticipated. As time goes on, more and more projects are expected to experience sedimentation problems because of the time lag which occurs before these problems become evident and because of the increased development of streams heavily laden with sediment. Difficulties already encountered have caused engineers to consider rivers not only as streams of water but also as streams of sediment.

The water discharge in the principal rivers of the world has been measured for many years and adequate data are generally available to permit satisfactory analysis of the hydrologic and hydraulic characteristics required for river development. Collection of corresponding information regarding the quantity and character of sediment discharge has been neglected. Only a few isolated sediment measurements were made prior to about 1925, and the importance of securing systematic records of sediment loads in streams commensurate with the parallel records of water discharge has been seriously considered only within the past few years.

In view of the increasing demand for reliable data on the sediment characteristics of streams, it becomes increasingly important that instruments and methods be developed which will facilitate collection of accurate field data. With its many ramifications into the fields of water power development, water supply, navigation, flood control and soil conservation, the sediment problem makes its impact in one way or another upon the majority of humanity and thus warrants a thorough study by the engineering profession.

2. Federal cooperative study of fluvial sediment problems--Recognizing the desirability of perfecting methods of measuring the quantity and of determining the character of sediment loads in streams, several agencies of the United States Government organized an Interdepartmental Committee in 1939 to make a thorough study of all problems encountered in collecting sediment data and to standardize accepted methods and equipment. The agencies of the Federal Government which have actively participated in this endeavor are; Corps of Engineers, Department of the Army; Soil Conservation Service of the Department of Agriculture; Geological Survey, Bureau of Reclamation, and Office of Indian Affairs of the Interior Department; and the Tennessee Valley Authority. The studies were carried on with the cooperation of the Iowa Institute of Hydraulic Research at the Hydraulics Laboratory, State University of Iowa, Iowa City, Iowa.

At a meeting of the Interdepartmental Committee in April 1946 it was agreed to transfer the activities and functions of the Committee to the recently established Subcommittee on Sedimentation, of the Federal Inter-Agency River Basin Committee. Interested Federal agencies have been invited to designate representatives to attend and participate fully in the work of the Subcommittee The Subcommittee on Sedimentation, as of June 1946, was composed of representatives of the following agencies:

Agriculture: Soil Conservation Service, Forest Service

Interior: Bureau of Reclamation, Geological Survey, Office of Land Utilization

Federal Power Commission

Department of the Army: Corps of Engineers

Department of Commerce: Coast and Geodetic Survey

Tennessee Valley Authority

The Federal Inter-Agency Subcommittee on Sedimentation formally took over the activities and the unfinished program of the Interdepartmental Committee in June 1946.

The scope of the general project, "A Study of Methods Used in Measurement and Analysis of Sediment Loads in Streams," of which the present report is a part, is indicated by the following titles and brief abstracts of other reports in this series.

Report No. 1--"Field Practice and Equipment Used in Sampling Suspended Sediment," is a detailed review of the equipment and methods used in suspended sediment sampling from the earliest investigation to the present, with discussions of the advantages and disadvantages of the various methods and instruments. The requirements of a sampler which would meet all field conditions satisfactorily are set forth.

Report No. 2-- Equipment used for Sampling Bed-Load and Bed Material," deals with bed-load and bed material in a manner similar to that in which Report No. 1 covers suspended load.

Report No. 3--"Analytical Study of Methods of Sampling Suspended Sediment," covers an investigation of the accuracy of various methods of sampling suspended sediment in a vertical section of a stream based on the latest developments in the application of the turbulence theory to sediment transportation.

Report No. 4--"Methods of Analyzing Sediment Samples," describes many methods developed for determining the size of small particles in sediment analyses. Detailed instructions are given for many of the common methods in use for determining the particle size and the total concentration of sediment in samples as developed by agencies doing extensive work in these fields.

Report No. 5--"Laboratory Investigations of Suspended Sediment Samplers," describes investigations of the effects of various intake conditions on the accuracy of sediment samples and the filling characteristics of slow filling samplers under various conditions.

Report No. 6--"The Design of Improved Types of Suspended Sediment Samplers," describes the development of various types of integrating samplers suitable for taking vertically integrated samples in flowing streams and others for taking integrated samples at a fixed point. Details of the best forms developed are given.

Report No. 7--"A Study of New Methods for Size Analysis of Suspended Sediment Samples," gives an account of a study to develop methods of size analysis more suitable to the conditions usually met in suspended sediment studies. It describes a simple form of apparatus developed and gives detailed procedure for its use.

Report No. 9--"Density of Sediments Deposited in Reservoirs," presents data on the apparent density of sediment deposited in existing reservoirs. The results are summarized and certain conclusions of value in engineering studies are given.

The purpose of the present report is to provide a resume of the data in the previous reports considered useful to engineers directly concerned with sediment investigations. It is intended also to serve as a guide to field personnel in selecting equipment and procedures to carry out a sediment program. An attempt is made to clarify the fundamental principles of sediment transportation and to indicate practical methods of obtaining reliable sediment load data.

3. Personnel--The following representatives of the cooperating agencies collaborated in various phases of the general project from which

the material for this report was derived: Cleveland R. Horne, Jr., Morgan D. Dubrow, and Martin E. Nelson, Corps of Engineers; Vernon J. Palmer, Soil Conservation Service; Victor A. Koelzer and Paul C. Benedict, Geological Survey; Philip M. Noble, Donald E. Rhinehart, and John W. Stanley, Bureau of Reclamation; Frank W. Parker, Office of Indian Affairs; and Clarence A. Boyll, Tennessee Valley Authority. During the period in which the material for this report was compiled, the project was under the general direction of Professor E. W. Lane of the Iowa Institute of Hydraulic Research. Participating in various phases of the work were personnel of the Iowa City offices of two government agencies, the Geological Survey and the Corps of Engineers.

II. GENERAL ASPECTS OF SEDIMENT DISCHARGE MEASUREMENTS

4. Definition of terms--The nomenclature used in the field of fluvial sediment has not yet been standardized and, consequently, some terms are used indiscriminately and often with ambiguous or variant meanings. Sometimes the word "silt" is used to designate the composite load of solids carried by streams and in other instances the term denotes only particles of a given size range within the composite load. In recent literature there has been a growing tendency to use the term "sediment" when referring to the mineral solids load as a whole transported by flowing water. This usage has been accepted generally by geologists and conforms with the definition given in the New Standard Dictionary, "Fragmental material, transported by, suspended in, or deposited by water or air, or accumulated in beds by other natural agents; any detrital accumulation such as loess." In this report, the term "sediment" is used to denote the composite loads of fragmental material transported by, suspended in or deposited by a flowing stream, without regard to the size of the individual particle or groups of particles.

In literature on geology and soil mechanics the term "silt" is usually restricted to the meaning, "a fragmental material composed of relatively fine particles." The graphical scales adopted to indicate various ranges of particle size place silt between clay and sand. It is in accordance with this meaning that the term "silt" is used in this report.

A great deal of confusion has been introduced into sediment literature by the use of the terms fine and coarse sediments. A person working in a region where fine sediments prevail might classify a certain sediment coarse, while another who is working in a region of coarser sediments might place this same material in the category of fine sediment. It is not always practicable to define sharply the distinction between fine and coarse sediments. Various authorities have found it convenient and practical to place the boundary somewhere between 0.050 mm. and 0.074 mm., the latter being approximately the 200-mesh sieve size. In order to clarify the use of terms in this report the fine and coarse sediments will be divided at about 1/16 mm. (0.0625 mm.), or the No. 230 mesh sieve size.

The following definitions have been adopted for certain other terms which are used frequently throughout these reports:

Suspended sediment--Sediment which remains in suspension in flowing water for a considerable period of time without contact with the stream bed.

Saltation load--Sediment which moves in a series of low arcs ending at the stream bed.

Bed-load--Sediment which moves in almost continuous contact with the stream bed, being rolled or pushed along the bottom by the force of the water.

Water sediment--Water and sediment mixture existing in or obtained from a stream or other body of water.

Sediment concentration--The weight of solids in a water-sediment mixture expressed either as the weight of dry solids per unit volume of the sample or as the ratio of the weight of dry solids to the weight of the sample.

Sediment discharge--Weight of sediment transported per unit of time.

Sediment hydrograph--Diagram showing the variation of sediment concentration or sediment discharge for selected intervals of time plotted in chronological order.

Vertical--Path taken by a sampler in moving from the water surface to the stream bed.

Point sample--Sample of water-sediment mixture taken at a single point either with an instantaneous or a point-integrating sampler.

Point-integration--Method of sampling to obtain the mean concentration of sediment at a point.

Depth-integration--Method of sampling to obtain a representative increment of sample from every portion of a vertical.

5. History of sediment measurements--The records of ancient civilizations in China, Mesopotamia, and Egypt indicate that man, since the earliest times, has experienced difficulties due to sediment carried by natural streams. However, the manner in which fluvial sediment is transported and deposited, a knowledge of which would aid in avoiding or overcoming many of these difficulties, has been investigated only in comparatively recent years. The first investigations were made in Italy in the latter part of the seventeenth century. The fundamentals of the sediment problem were investigated scientifically in France in the eighteenth century, but, so far as can be determined, it was not until the early part of the nineteenth century that quantitative observations of sediment carried by natural streams were made. The first sediment load measurements of record were made by Grosse and Subuors in the Rhone River in 1808 and 1809. Other early measurements were made by Blohm in the Elbe River at Hamburg, Germany, from 1837 to 1854 and by Baumgarten in the Garonne River France, from 1839 to 1846. Except for a reference to surface samples taken by Baumgarten, the records do not indicate what methods or equipment were used in making these measurements. The earliest measurements of sediment load in this country were made in the Mississippi River by Captain Talcott in 1838. Extensive observations were made in the Lower Mississippi by Forshey in connection with the studies

of Hymphreys and Abbott in 1851 and 1852. Sediment samples were taken in the South Pass near the mouth of the Mississippi from 1877 to 1898. Measurements were made also at several stations along the lower, middle, and upper Mississippi and in the Missouri River from 1879 to 1881. Extensive sediment observations were made on the Missouri River and its tributaries in 1929 and 1930 and on the Mississippi in 1930 and 1931.

The development of irrigation along the rivers of the southwestern part of this country met with considerable difficulty due to the heavy loads of sediment carried by these streams. In order to find a solution to this problem, sediment measurements were started in many of these rivers in the latter part of the nineteenth century. Samples were first collected in the Rio Grande in 1889 and 1890 and have been taken more or less continuously since 1897. Observations have been made continually on the lower Colorado since 1909.

While the interest in sediment information and the practice of making observations of sediment loads was advancing in this country, contemporary interest in the sediment problem was developing all over the world. Sediment investigations of record, together with such data as are available on the methods and equipment used, are listed chronologically in Table 1 of Report No. 1 in this series. The foregoing history deals only with observations of suspended sediment loads. Measurements of the heavier material moving on or near the stream bottom apparently were made first by Davis in 1898 in connection with studies for the Nicaraguan Canal. Twenty years later Kurtzman made measurements in the Tirol rivers. This type of work has been developed extensively in Europe since 1930, but very little has been done in America. Details of the development of bed-load investigations are given in Report No. 2.

6. Types of sediment transportation--Students of sediment transportation and related problems have classified the movement of particles in flowing streams into three types:

> a. Rolling or sliding along the bottom, the particles being in contact with the bed practically all the time.
>
> b. Bouncing along the bottom as the particles are carried forward by the stream. The initial impetus which launches a particle into the current may be due to the striking of one particle by another, the rolling of one particle up over another, or the flowing of water over the curved surface of a particle thus producing a negative pressure.
>
> c. Moving without contact with the bed, the particles being suspended by vertical components of the currents in turbulent water, while being carried forward by horizontal components of these currents.

The existence of these three forms of motion has been recognized for many years. As early as 1848 Mr. Baumgarten (2)* distinguished three methods by which solid particles are moved in streams.

> a. A discontinuous rolling motion along the bed of the stream which takes place when the velocity of the current is limited or the materials large.
>
> b. With greater velocities or smaller particles, a discontinuous suspension in the lower laminae of the current.
>
> c. Movement in continuous suspension when the particles are carried throughout the entire length considered.

These three general types of movement have also been described by McMath (9) as follows:

> a. Some of the traveling material never loses contact with the bottom.
>
> b. Material which, though heavy and in grains of notable size, is detached for a time by some energetic impulse and de-

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*Numbers refer to references in the bibliography.

scribes a longer or shorter free path, moving in or with the surrounding water.

c. Material which, once mingled with the water, remains in continuous suspension until it reaches the sea.

An excellent description of how these movements take place is given by G. F. Deacon (3) based on the movements of sand in connection with studies for the design of the Manchester ship canal.

"The observations were made in a long flat-bottomed trough with glass sides, by means of which the behaviour of the sand could be accurately observed. The sand was from the estuary of the Mersey, the quantities moved were weighed, and the surface velocities of the water were carefully measured. When water flowed with a steadily increasing velocity over a surface of such sand, fine pieces of broken shell were first moved; and the surface velocity required to produce such movements was considerably less than one foot per second. At such velocities, however, the sand proper was perfectly stable, and however long the flow continued it remained undisturbed; but the fine pieces of shells at the surface of the sand moved in spasmodic leaps, accumulating wherever the velocity was somewhat less.

"The first movement of sand began at a surface velocity of 1.3 foot per second. This movement was confined to the smaller isolated grains and if the same velocity was maintained, the grains so moved ranged themselves in the parallel bands perpendicular to the direction of the current, each band taking the form of the well known sand ripples of the seashore or sand-bottomed stream, with its flat slope upwards, and its steep slope downwards in the direction of the current. At this velocity the profile of each sand ripple had a very slow motion of translation, caused by sand particles running up the flatter slope and toppling over the crest. The steep downward slope was therefore being constantly advanced at the expense of the denudation of the less steep upward slope. At a surface velocity of 1.5 foot per second, the sand ripples were very perfect, and travelled with the stream at a velocity of about the 1/2160 part of the surface velocity of the water. At a surface velocity of 1.75, the ratio was reduced to about 1/1050, and at a surface velocity of 2 feet to 1/480. A critical velocity was reached when the surface of the water moved at 2.125 feet per second, when the sand ripples became very irregular, indicating greatly increased unsteadiness of motion of the water. Up to this point the whole amount of scour was represented by the volume of the sand-waves multiplied by an exceedingly low velocity, always less than the 1/480 part of the surface velocity of the water. At about this critical velocity of 2.1 feet per second, the particles rolled by the water up the flat slope, instead of toppling over the steep slope, were occasionally carried by the water direct to the next crest; and as the velocity of the water was gradually increased, an increasing bombardment of each crest from the crest behind it took place. At about 2.5 feet per second, another critical velocity was reached, and many of the little projectiles cleared the top of the first, or even of the second crest ahead of that from which they were fired. At surface velocities of 2.6 to 2.8 feet per second, the sand ripples became more and more ghostlike, until, at 2.9 feet per second, they were wholly merged in particles of sand rushing along with the water in suspension. After this the scour was of totally different character; the sand and water became mixed, and a constant process of lifting, carrying, and depositing of individual particles ensued, the sand being stirred to a depth and lifted to a height dependent upon the velocity."

Another description of the method by which material is moved in streams is that given by Gilbert (5) as follows:

"Streams of water carry forward debris in various ways. The simplest is that in which the particles are slidden or rolled. Sliding rarely takes place except where the bed of the channel is smooth. Pure rolling, in which the particle is continuously in contact with the bed, is also of small relative importance. If the bed is uneven, the particle usually does not retain continuous contact but makes leaps, and the process is then called saltation. With swifter current leaps are extended, and if a particle thus freed from the bed be caught by an ascending portion of a swirling current its excursion may be indefinitely prolonged. Thus borne it is said to be suspended, and the process by which it is transported is called suspension. There is no sharp line between saltation and suspension, but the distinction is nevertheless important, for it serves to delimit two methods of hydraulic transportation which follow different laws. In suspension the efficient factor is the upward component of motion in parts of the complex current. In other transportation, including saltation, rolling, and sliding, the efficient factor is in motion parallel with the bed and close to it."

Bagnold (1) has demonstrated that the movement of sand in air, similar to the saltation movement observed by Gilbert, consists in a series of long, low flights, propelled by the horizontal components of the velocity of the wind, after the particles have been launched into the wind stream. The initial upward movement of a particle may be due to rolling over the edge of another, to the impact of another particle at the end of its flight, or to a rebound of the particle itself upon striking an inclined surface in the bed.

7. Analysis of the vertical distribution of suspended sediment--A great many theories have been proposed concerning the suspension of sediment in flowing water but only within the past decade has a plausible analysis of this phenomenon been developed. It is now generally recognized that the suspension of sediment in a stream is directly related to the turbulence of the flowing water as explained by Lane and Kalinske (7). The analytical basis for this concept has been presented in engineering literature, but the rational analysis will be discussed in this report, as it is believed that an understanding of the turbulence concept will provide an effective aid in planning and carrying out a satisfactory sediment measurement program.

In turbulent flow the direction of the current at a given point changes rapidly and haphazardly. Although the flow at the point has a general forward motion, in a short space of time small areas of the flow or eddies fluctuate also in horizontal and vertical directions. These fluctuations are irregular and haphazard and do not follow any definite sequence. The velocity of the water also changes, fluctuating about a mean value in a manner similar to the direction of flow. Fig. 1 illustrates how the velocity was found to fluctuate at three points in a vertical in the Mississippi River (6) as determined with a current meter.

Sediment carried in suspension is acted on in the vertical direction by momentary currents which move upward or downward in a stream vertical. In order that the water level in the stream remain unchanged, the quantity of upward and downward flow must be equal. It follows that if the upward and downward currents were the only forces affecting the vertical movement of sediment, complete mixing would soon take place and the concentration of sediment would become uniform throughout the depth. However the force of gravity tends to make all particles of greater specific gravity than that of water settle steadily downward. Under the combined action of vertical currents and settling velocity, a particle caught in a current moving upward at a rate greater than the settling velocity of the

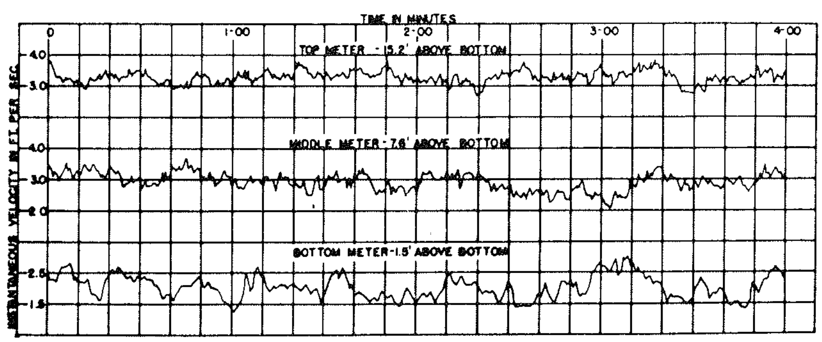


Fig. 1--Observed fluctuations of velocity in the Mississippi River near Muscatine, Iowa. Total depth 19 ft.

particle should be transported upward, but if it is suspended in water moving downward or moving upward at a rate less than its settling velocity, the particle should move downward. It might seem that the downward currents would take down as much sediment as the upward ones carry up, with the result that all the material finally would settle to the bottom. However, as settling takes place the sediment concentration increases toward the bottom, and the upward currents travel from a region of higher concentration to one of lower concentration, while for the downward currents the opposite prevails. As the amounts of water moving upward and downward are equal and the sediment concentration in the rising currents is potentially greater than in the downward currents, more sediment must be transported upward than downward by the rising and falling currents. The settling action superimposed on the fluctuating upward and downward currents tends to produce a balanced suspension in which the rate of increase in sediment concentration toward the bottom depends upon the degree of turbulence in the stream and the settling velocity of the suspended particles.

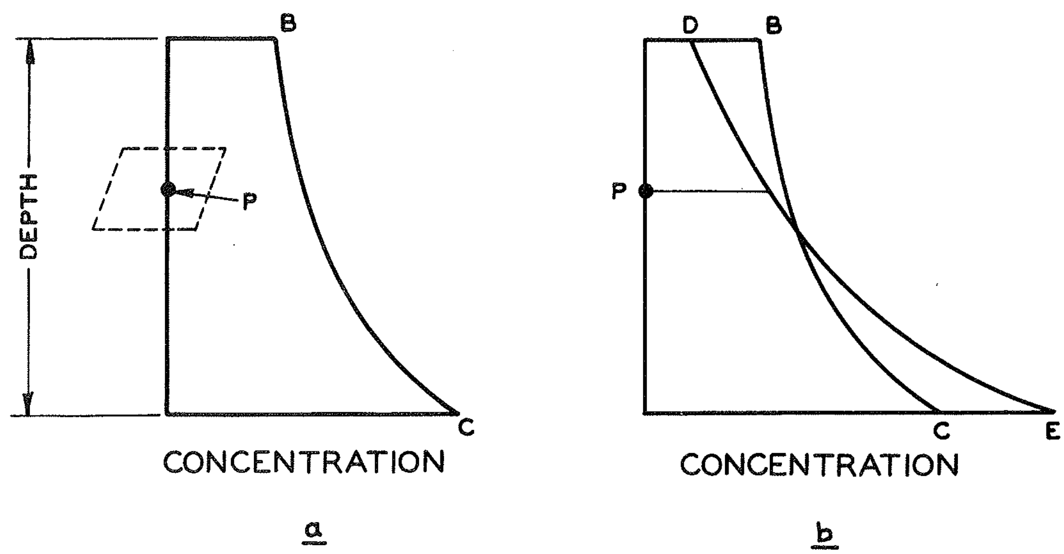


Fig. 2--Typical vertical sediment distributions

The diagram shown in Fig. 2a can be used to illustrate the condition of equilibrium of the sediment load distribution in a stream vertical. Assume that the distribution of sediment concentration in the vertical is represented by the curve BC, and consider a section of a horizontal plane at P having an area A. Turbulent currents pass through this area, some having upward and some downward components. Those which pass upward carry sediment from a lower level where the concentration is greater than at P as shown by the curve BC. Those which move downward carry water from a higher level where the sediment concentration is less than at P. As the same amount of water passes upward and downward through this area, the product of the vertical currents and the sediment concentration, that is the amount of sediment transported through the area by the vertical currents must be greater in the upward direction. When equilibrium exists the amount of material which settles through this area due to the force of gravity equals the excess of that carried upward over that carried downward by the vertical currents.

The settling velocity of sediment particles is a function of their specific weights; consequently, coarse particles will tend to settle faster through area A than the fine particles. Since the action of the water is not greatly affected by the presence of the sediment, the water motion across area A will not be appreciably different for sediments of different sizes. Therefore, equilibrium can be attained only if the vertical distribution of sediment varies, the concentration increasing more rapidly toward the bottom for coarse than for fine sediment. The distribution of sediment might be represented as shown in Fig. 2b, for fine sediment curve BC and for coarse sediment curve DE.

The settling rate of solid particles increases with size, but not uniformly. The settling rate for particles smaller than about 1/16 mm. in size varies approximately as the square of the diameter, while for extremely large particle sizes the settling rate varies approximately as the square root of the diameter. Particles of intermediate size have settling velocities which vary at rates intermediate between the square and square root ratios. The 1/16 mm. size is considered the approximate division point between sediments classed as silts and those classed as sands. The clay particles (which are finer than silts) and the silt particles are ordinarily found fairly uniformly distributed in a stream, but sand particles are usually more concentrated near the bottom than near the surface.

Typical distribution curves for various sizes of sediment in the

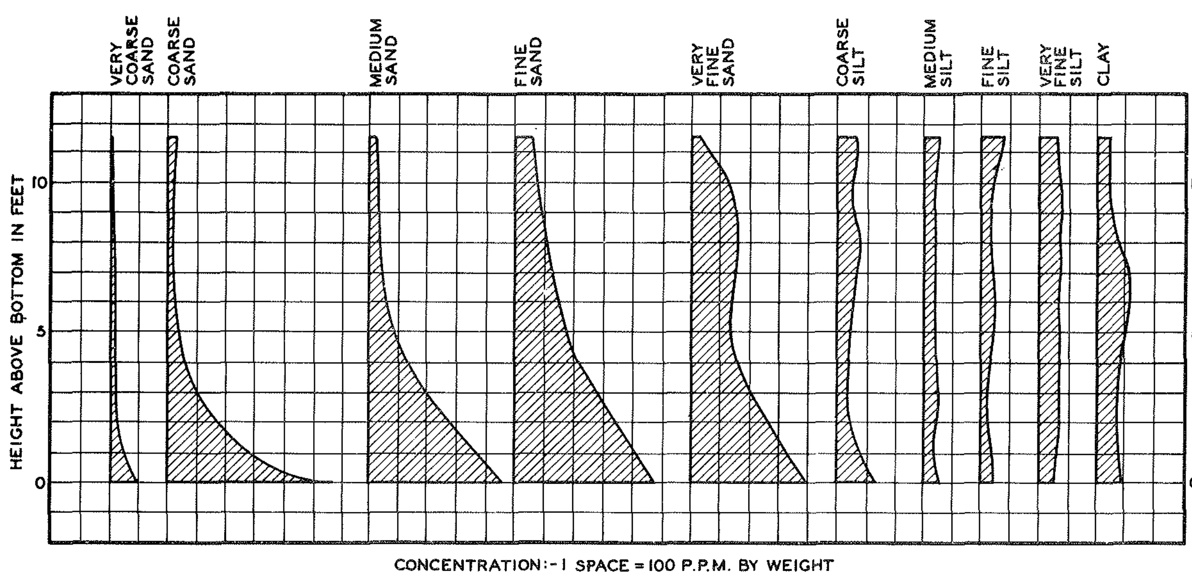


Fig. 3--Distribution of sediment in the Missouri River at Kansas City

Missouri River at Kansas City are shown in Fig. 3. In this analysis, in which the division point between the silt and the sand sizes was 1/16 mm., the silt and clay sizes were distributed nearly uniformly from the surface to the bottom of the stream, but the sand sizes were found in much greater concentrations near the bottom. In general the ratio of bottom to surface concentration increased with the size of the sand particles.

8. <u>Methods of making sediment measurements</u>--A single device has

not yet been developed which is adapted to measuring the sediment carried in a stream under all conditions of movement. Instruments designed to obtain samples of water with the true load of suspended sediment are called "suspended load samplers" or "suspended sediment samplers." This type of sampler, however, is not suitable for measuring the saltation load or that which rolls or slides along the stream bed. In these types of motion the material moves with a velocity somewhat different from the stream velocity and, therefore, cannot be correctly estimated from the amount which is trapped in a unit volume of water. Moreover, it is very difficult to measure the velocity of the water near the bottom where this type of movement takes place. The amount of sediment moving per unit time by rolling, sliding, and saltation can be determined by trapping the quantity moving in small portions of the width of the stream and combining these observations with the width over which the motion occurs to obtain the total amount moved. Samplers designed for this work are commonly called "bed-load samplers," as they measure the quantity of sediment carried near the bed.

Many suspended sediment samplers will trap some of the saltation load if placed so near the bottom that the intake is in the region of saltation load movement, and if the screens used in the construction of bed-load samplers are very fine, they may trap some of the suspended load. The errors resulting from an overlapping of the sampling zones are usually regarded as being so small that they can be neglected. An accurate determination of the sediment carried by a stream would require measurement of both suspended load and bed-load. Usually, however, the nature of the problem is such that it is considered necessary to measure only the suspended load. It is sometimes possible to construct a drop, over which both bed and suspended loads pass, where both can be sampled at the same time by passing a suitable sampler through the overflowing nappe. To obtain an accurate measurement of the total load carried by the stream, time must be allowed for the pool above the drop to be filled and sediment storage in it to cease.

III. MEASUREMENT OF SUSPENDED SEDIMENT DISCHARGE

9. General conditions--Measurements of suspended sediment are usually made to determine the amount of sediment carried in the entire cross section of the stream, or to determine both the sediment load and the particle size distribution in the entire cross section or at some particular point or points in the stream. Measurement of the total suspended sediment load (not including bed-load) has been and will probably continue to be the predominant phase of sediment exploration but greater emphasis will, no doubt, be placed upon studies of particle size and their distribution than heretofore. The development of the turbulence theory of suspended sediment transportation has shown that this type of information is necessary for the solution of practically all sediment problems which arise in connection with engineering projects.

The discussion which follows will be confined largely to methods of determining total suspended sediment load because of the probable predominance of this phase of sediment work in the future. However, it will apply also to other phases of sediment investigation, because the determination of particle size distribution in a stream is usually made from samples obtained in the same manner as those used for the measurement of total suspended sediment load. A discussion of the methods used to determine the total suspended sediment load of a stream will, therefore, cover the great majority of problems in field work connected with sediment observations.

If the sediment carried in suspension were uniformly distributed throughout a stream cross section, it would be a comparatively simple procedure to determine the total suspended sediment load. A single sample taken at any point would then indicate the sediment concentration or the weight of sediment per unit volume of water. The sediment discharge would be the product of the sediment concentration and the water discharge. Unfortunately, however, the concentration of fluvial sediment varies more or less throughout any cross section of a stream. To obtain an accurate measurement of sediment discharge, therefore, these variations must be taken into account. It is not sufficient to obtain the average of the concentrations at the various points in the cross section, but the velocity of the water at each point must also be considered because the rate of sediment transportation is directly proportional to the water velocity.

Sediment concentrations are ordinarily determined in the laboratory from samples of the water-sediment mixture obtained with a suspended sediment sampler. The corresponding water velocity and discharge are usually determined from current meter measurement. The product of sediment concentration and velocity equals the sediment discharge per unit area at the point or vertical measured in the stream. Each determination is considered representative of the sediment discharge in a segment of the stream cross section, the size of which depends upon the uniformity of sediment concentration and velocity. The mean sediment concentration of the cross section is obtained from the individual determinations weighted according to the area each represents. When depth-integrated samples are taken at sampling verticals representing areas of equal water discharge, the product of the stream discharge and the mean sediment concentration determined from the combined samples is considered representative of the sediment discharge for the entire cross section of the stream.

10. <u>Determination of water discharge from velocity distribution in streams</u>--The water velocity in a stream varies from point to point in any cross section. It is usually higher near the center of the stream than at the banks, and it is also higher near the surface than at the bottom. The maximum velocity usually occurs just below the surface along the thalweg of the stream. The velocity distribution in a cross section of a relatively straight natural stream is represented in Fig. 4a. The magnitudes of the velocities at various points normal to the cross section A B C D E F are indicated by arrows. For example, the length of arrow CG represents the velocity at the surface of the water at point C. The mean velocity of the stream at the section would be the arithmetic mean of the velocities at all points in the section, or the average distance between the plane passing through A B C D E F and the irregular surface passing through the points of the arrows which might be projected from all points in the cross section. The solid made up of the velocity arrows for all points in the cross section, as described by the four lines joining A and D in Fig. 4a, can be considered to represent the discharge of the stream. The volume of this solid of water divided by the area of cross section A B C D E F would determine the mean velocity.

To observe the velocity at every point in a cross section is of course impractical. Observations are made at a number of systematically located points and it is assumed that the velocity varies between observed points according to some reasonable rule. Usually a number of verticals in the cross section are selected and the velocity is measured at one or more points in each vertical. From extensive investigations it has been learned that the mean velocity in a stream vertical can

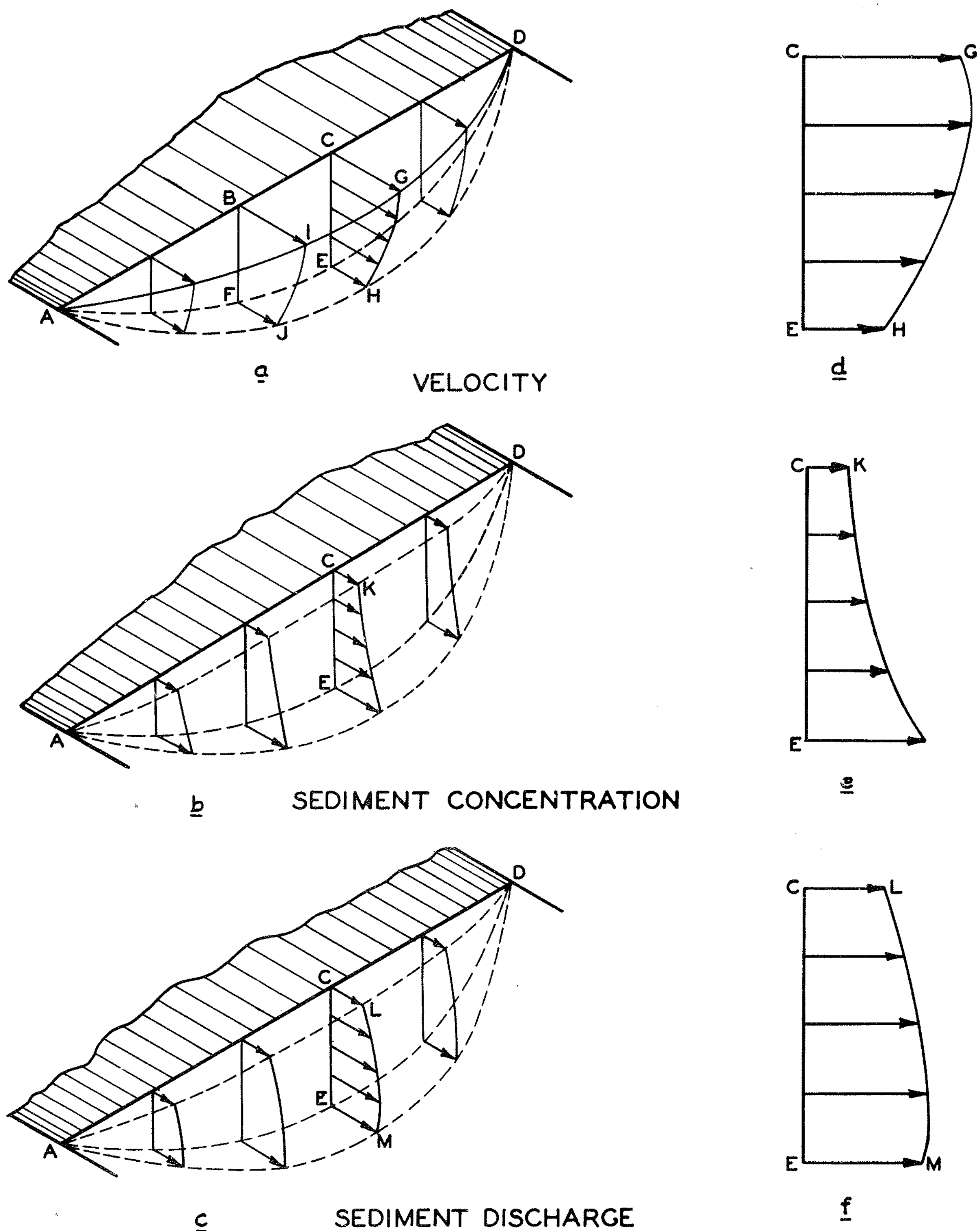


FIG. 4 - VELOCITY, SEDIMENT CONCENTRATION, AND SEDIMENT DISCHARGE IN FLOWING STREAMS.

usually be determined with an ample degree of accuracy from measurements at one or only a few properly selected points in the vertical. It is customary to assume that the velocity between adjacent verticals is equal to the average of the velocities observed at the two verticals. For example, the velocity at every point in the area between the verticals BF and CE (Fig. 4a) is assumed to be equal to the average of those measured in the two verticals. The discharge for the section between the verticals BF and CE is obtained by multiplying the area B C E F by the mean velocity for the section, and a summation of all these products in the cross section is equal to the total water discharge of the stream.

11. Determination of sediment discharge--The suspended sediment concentration in a flowing stream usually varies from the surface to the bottom, and in some instances from side to side. The sediment distribution might be represented as shown in Fig. 4b where the lengths of the arrows represent the sediment concentrations at points in the cross section used to show velocities in Fig. 4a. Fig. 4d represents the velocity distribution at vertical CE, and Fig. 4e the distribution of sediment concentration in that vertical. The sediment discharge values in the vertical CE shown in Fig. 4f are obtained by multiplying the velocity values in d by the corresponding concentration values in e. In considering the units used in the velocity and concentration curves one should keep in mind that velocity may be represented as volume per unit time per unit area, that concentration may be expressed as weight of sediment per unit volume, and that the product of the two equals weight of sediment per unit of time per unit of area.

The total sediment discharge, or the weight of suspended sediment passing the cross section per unit time, is represented by the volume of the solid in Fig. 4c in the same way that the water discharge is represented in Fig. 4a. It is assumed that the average sediment discharge per unit area between two verticals is equal to the mean of the discharges observed at the intervals. The product of this average and the area between the verticals gives the total sediment discharge for this area. For practical reasons the sediment concentration cannot be observed at every point in a vertical, and the number of verticals tested must be limited.

12. Observed vertical distribution of suspended sediment--For many years it has been known that the concentration of sediment tends to increase from the surface to the bottom of a stream. This characteristic of the concentration gradient has been verified by practically all known sediment observations. Comparisons of the mean ratios of sediment concentrations found at mid-depth and bottom to that at the surface for the sets of observations on which data are available are summarized in Fig.5. The measurements were made in a large number of rivers of the United States and other countries. Detailed information regarding these measurements is given in Table 3 of Report No. 1. In nearly all comparisons the concentrations at the mid-depth and at the bottom were greater than at the surface. The bottom concentration ratios were always greater than the mid-depth ratios. The chart also indicates that 50 percent of the mid-depth samples and 77 percent of the bottom samples exceeded the corresponding surface concentrations more than 10 percent, and that 30 percent of the mid-depth and 56 percent of the bottom samples exceeded corresponding surface concentrations more than 20 percent. Each value shown in Fig.5 is the mean of a number of observations at a single station, the

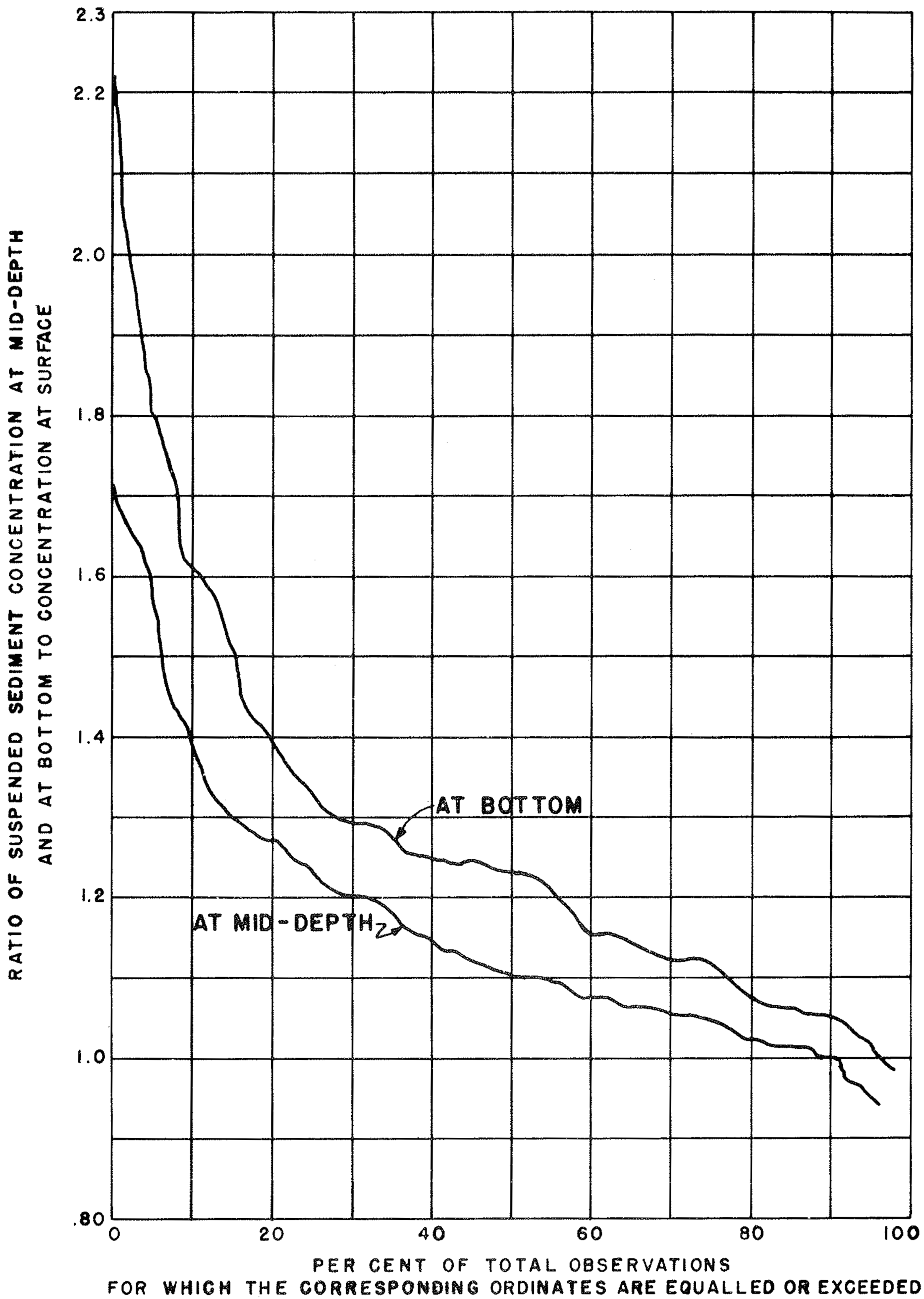


FIG. 5 — OBSERVED VERTICAL DISTRIBUTION
OF SUSPENDED SEDIMENT

observations at some stations numbering over 1000. Therefore, in preparing Fig. 5 equal weight was given not to each observation but to the average value for each sampling station.

13. Selection of sampling points in a vertical--The wide range covered in the ratios of sediment concentration in Fig. 5 emphasizes the difficulty of selecting sampling points which will take cognizance of all the possible variations in the vertical distribution of suspended sediment. Engineers have recognized the difficulty of determining the distribution of sediment and have devised many methods of solving this problem. Variations in the vertical distribution of suspended sediment have been accounted for in the following ways:

a. By taking samples at enough points to establish the vertical distribution with the required degree of accuracy.

b. By applying correction factors, based on previous observations, to samples taken at definite locations.

c. By taking samples which integrate the concentration throughout the depth.

Sampling methods used in sediment investigations in the past have indicated decided variations in accuracy. Sometimes the procedure was based on a thorough consideration of the principles involved, while in other instances the sampling points were selected in a more or less arbitrary manner, generally for the purpose of simplifying the rules to insure uniformity of sampling practice. Empirical methods were sometimes used in choosing sampling points and coefficients based on results of more exact sampling procedures were applied to the data. Semi-rational methods, based on an analysis of the principles involved in sampling fluvial sediment and combined with simplifying assumptions, have also been used.

The following are some of the more common methods which have been used to obtain the sediment concentration in a vertical:

a. A single sample taken at the surface.

b. A single sample taken at 0.6 depth.

c. Two samples, one taken at the surface, and the other at the bottom, weighted equally.

d. Three samples, taken at surface, mid-depth, and bottom, weighted equally.

e. Three samples, taken at surface, mid-depth, and bottom, with the mid-depth sample given twice the weight of the others.

The accuracy of these methods can be expected to increase with the number of samples. Taking samples at the surface, the simplest method, is well suited to unskilled observers, but, because coefficients applicable to surface samples cannot be depended on, this method is the least accurate. It is especially undesirable for size analysis since the larger particles are usually not found at the surface of the stream.

Sampling at 0.6 depth has been used in some streams in Texas, India, and Turkestan with apparent satisfactory results, but for other streams this method might yield inaccurate test data. This method would also be unreliable for size analysis. Sampling at two points in a vertical, surface and bottom, has doubtful accuracy although it is preferred to the method of sampling only at the surface. If the surface and bottom samples have the same volume, a single analysis can be made of the samples combined.

The second of the three-point methods is preferable. The mean of the upper half of the discharge will be represented by the average of the surface and mid-depth values, and the mean of the lower half by the average of the mid-depth and bottom. Thus in determining the mean for the whole stream the mid-depth value is given a double weight relative to the bottom and surface. A composite sample made up of two samples from mid-depth and one each from the surface and bottom, all of equal volume, can be used for both concentration and size analyses. The methods involving three samples are more accurate than the surface and bottom method, and they are sufficiently simple to be handled by unskilled observers.

A number of more complex sampling methods such as the Straub, Luby, depth-integration, andprecise methods have been developed for determining the average sediment concentration in a vertical. In general, these methods are based upon detailed analyses of the factors which influence the movement of sediment loads in streams.

The Straub method, which was developed during investigations of sediment transportation in the Missouri River system (10), is based on the assumptions that the vertical distribution of velocity follows an exponential law, and that the sediment concentration increases from the surface to the bottom according to a linear relationship. These assumptions closely approximated the observed conditions in the Missouri River, and it is probable that most streams of moderate slope do not depart widely from them. The following relationship was derived for sediment concentration in the Missouri River,

$$S = \frac{3}{8} S_{0.8d} + \frac{5}{8} S_{0.2d}$$

where S, the mean concentration in a vertical, was found by adding 3/8 of the concentration determined from a sample taken at 0.8 depth to 5/8 of that determined from a sample at 0.2 depth. Requiring only two samples, this method is quite simple and, as will be shown in Section 14, it appears to give accurate results over a considerable range of conditions. This sampling method may not be satisfactory, however, if sediment size analyses are required.

The Luby method was originated in sediment studies in the Upper Mississippi River valley. Basically, this method consists in obtaining samples from areas of equal water discharge. To obtain samples representing equal portions of the water discharge the area under the vertical velocity curve is divided into equal parts and the sampling points are located at the centroids of these areas. If the samples are equal in volume they can be combined and the composite used to determine both the mean sediment concentration and particle size composition in the vertical. A detailed description of this method is given on pages 68-72 in Report No. 1.

The depth-integration method of sampling suspended sediment in streams is based on the premise that the sampler fills at a rate proportional to the velocity of the approaching flow, and that by traversing the depth of a stream at a uniform speed the sampler will receive at every point in the vertical a small instantaneous specimen of the water-sediment mixture, the volume of which will be proportional to the instantaneous velocity. Only the slow-filling type of sampler is suitable for depth-integration. The sampler is lowered to the bottom of the stream at a uniform rate and raised again to the surface at another but not necessarily equal rate, sampling continuously during both periods of transit, or it may be designed to sample one way only. However, if the sampler is opened at the bottom of the stream and the vertical is integrated on the ascending trip only, the air pressure in the container at the time of opening must be balanced with the hydrostatic pressure surrounding the sampler. The depth-integration method of sampling requires only one sample from each vertical and gives a fairly reliable average of the size distribution of the particles in the stream.

The precise method requires velocity and sediment concentration determinations at several points in each vertical. Concentration and vertical velocity curves are drawn from these data, as shown in Fig. 4, and the mean sediment concentration is determined as described in the discussion of that figure. This method is more laborious than would ordinarily be justified for routine sediment investigations. However, it does provide a means for determining accurately the suspended sediment load and for making a complete analysis of the vertical distribution of particle size.

14. Accuracy of the various methods of point sampling in a vertical--In general, the accuracy of point sampling is a function of the number of sampling points and varies inversely with the coarseness of the sediment. Reasonably accurate results will be obtained with any method described in the preceding paragraphs if the suspended material is exclusively within the silt range. However, the magnitude of error increases with increasing particle sizes. The errors inherent in the simpler methods can be readily visualized in Fig. 6. Parts a and b show sediment distribution curves typical of fine and coarse sediments respectively. To simplify the illustration, it may be assumed that the velocity is uniform from surface to bottom and that the area inclosed by each curve is a measure of the mean concentration of sediment in the vertical.

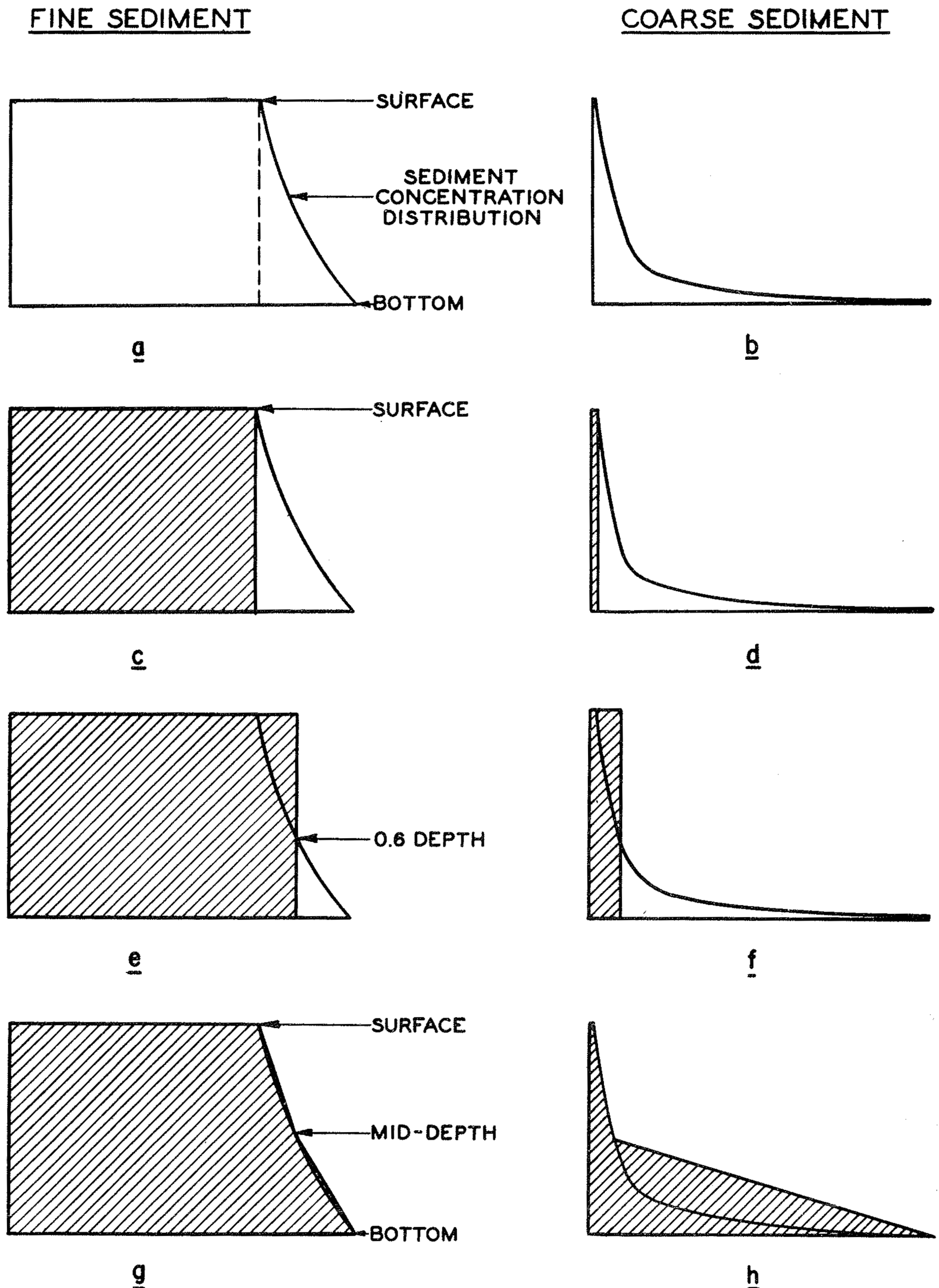


FIG. 6 - ERRORS IN VARIOUS SAMPLING METHODS

The concentrations which would be indicated by one sample taken at the surface are shown by the crosshatched areas in c and d. A comparison of these areas with the inclosed areas in a and b will show that the concentrations obtained by the surface method are less than the true mean concentrations for both fine and coarse sediments, and that the error is much larger for coarse sediments. The crosshatched areas in e and f represent the concentration obtained from a single sample taken at 0.6 depth. The results are better for both fine and coarse material than those obtained from the surface sample. From g and h it will be seen that samples taken at the surface, mid-depth, and bottom with mid-depth weighted twice, indicate concentrations which are too high and that the error increased as the particle size increases.

Point sampling methods have not been compared in a sufficient number of tests to establish their relative accuracy under natural stream conditions. Because of the wide differences found in stream conditions a great deal of study will be necessary before the merits of respective sampling methods can be ascertained.

The errors in mean sediment concentration for a vertical, indicated by various point sampling methods, are summarized in Table 1. It was assumed that the sediment was distributed vertically in accordance with the turbulence concept and that the sample taken at any point had a sediment concentration equal to the average at that point. Errors inherent in sampling methods were computed for various stream velocities, particle sizes, and channel roughness. Data in Table 1 show that no single method is accurate for all conditions, although several were found to be fairly reliable for most average velocity and sediment distributions and for

TABLE 1

ACCURACY OF POINT SAMPLING METHODS

Mean velocity in vertical ft./sec.	Sampling method*	Percentage error for various relative roughness conditions: Relative roughness $n/D^{1/6} = 0.010$, Particle size, mm. 0.010	0.025	0.05	0.115	0.35	Relative roughness $n/D^{1/6} = 0.020$, Particle size, mm. 0.010	0.025	0.05	0.115	0.35	Relative roughness $n/D^{1/6} = 0.030$, Particle size, mm. 0.010	0.025	0.05	0.115	0.35
0.5	Surface	-12	-58	- 98	----	----	- 5.6	-32	-83	-100	----	- 3.9	-21	-64	- 99	----
	0.6 depth	+ 2.9	+10	- 61	----	----	+ 1.7	+10	+12	- 91	----	+ 1.2	+ 8.1	+21	- 68	----
	0, 0.5, 0.9 D	0.0	+ 4.5	+ 41	----	----	+ 0.2	+ 3.8	+27	----	----	+ 0.1	+ 2.3	+18	+130	----
	0, 0.5, 0.95 D	+ 0.5	+ 8.3	+ 52	----	----	----	----	----	----	----	+ 0.2	+ 3.5	+28	+260	----
	0, 0.5, 0.98 D	+ 0.8	+11	+ 81	----	----	----	----	----	----	----	+ 0.3	+ 4.2	+34	+370	----
	0, 0.5, 1.0 D	+ 0.9	+14	+150	----	----	+ 0.7	+ 7.8	+60	----	----	+ 0.4	+ 5.3	+40	+480	----
	0, 0.5 (2), 0.9 D	+ 0.2	+ 2.5	+ 14	----	----	+ 0.2	+ 2.8	+ 6.0	----	----	+ 0.1	+ 2.1	+14	+ 94	----
	0, 0.5 (2), 0.95D	+ 0.4	+ 5.0	+ 49	----	----	----	----	----	----	----	+ 0.2	+ 3.1	+20	+180	----
	0, 0.5 (2), 0.98D	+ 0.6	+ 5.8	+ 74	----	----	----	----	----	----	----	+ 0.3	+ 3.6	+24	+250	----
	0, 0.5 (2), 1.0 D	+ 0.7	+ 9.0	+ 95	----	----	+ 0.6	+ 6.5	+38	----	----	+ 0.3	+ 4.2	+27	+340	----
	Straub	- 1.3	- 6.2	- 18	----	----	- 0.5	- 1.7	- 3.5	- 47	----	- 0.3	- 0.2	+ 1.7	+ 5.0	----
	Luby - 3 point	- 0.1	- 1.0	- 22	----	----	- 0.2	- 0.8	- 7.0	- 70	----	- 0.3	- 0.6	- 3.2	- 48	----
	Luby - 5 point	- 0.1	- 0.7	- 10	----	----	- 0.1	- 0.5	- 3.5	- 44	----	- 0.3	- 0.4	- 1.5	- 25	----
	Luby - 10 point	- 0.1	- 0.5	- 3.5	----	----	- 0.1	- 0.4	- 1.5	- 20	----	- 0.2	- 0.3	- 0.8	- 12	----
1.0	Surface	- 6.0	-33	- 84	-100	----	- 2.9	-17	-54	- 99	----	- 2.1	-11	-38	- 93	----
	0.6 depth	+ 1.5	+ 7.6	+ 1.6	- 93	----	+ 0.8	+ 5.1	+15	- 40	----	+ 0.4	+ 3.8	+14	+ 5.0	----
	0, 0.5, 0.9 D	0.0	+ 0.9	+ 15	+ 44	----	+ 0.1	+ 1.1	+ 7.5	+ 71	----	- 0.1	+ 0.7	+ 6.6	+ 64	----
	0, 0.5, 0.95 D	+ 0.2	+ 2.5	+ 29	+190	----	----	----	----	----	----	- 0.1	+ 1.0	+ 9	+100	----
	0, 0.5, 0.98 D	+ 0.2	+ 3.5	+ 39	+330	----	----	----	----	----	----	0.0	+ 1.3	+11	+120	----
	0, 0.5, 1.0 D	+ 0.4	+ 4.2	+ 46	+480	----	+ 0.3	+ 3.0	+19	+230	----	0.0	+ 1.5	+13	+150	----
	0, 0.5 (2), 0.9 D	+ 0.1	+ 1.0	+ 4.9	+ 10	----	+ 0.2	+ 1.0	+ 6.0	+ 40	----	0.0	+ 1.1	+ 5.7	+ 40	----
	0, 0.5 (2), 0.95D	+ 0.2	+ 2.3	+ 15	+120	----	----	----	----	+ 90	----	0.0	+ 1.1	+ 7.7	+ 67	----
	0, 0.5 (2), 0.98D	+ 0.2	+ 1.7	+ 23	+220	----	----	----	----	+130	----	0.0	+ 1.2	+ 9.1	+ 88	----
	0, 0.5 (2), 1.0 D	+ 0.3	+ 3.4	+ 28	+340	----	+ 0.3	+ 2.8	+15	+160	----	0.0	+ 1.2	+10	+100	----
	Straub	- 0.6	- 3.5	- 11	- 59	----	- 0.2	- 0.8	- 2.9	- 0.7	----	- 0.3	- 0.5	0.0	+ 10	----
	Luby - 3 point	- 0.1	- 0.4	- 5.2	- 60	----	- 0.1	- 0.4	- 2.1	- 30	----	- 0.3	- 0.3	- 1.0	- 14	----
	Luby - 5 point	- 0.1	- 0.3	- 2.7	- 35	----	- 0.1	- 0.3	- 1.2	- 16	----	- 0.3	- 0.3	- 0.6	- 6.8	----
	Luby - 10 point	0.0	- 0.2	- 1.5	- 12	----	- 0.1	- 0.2	- 0.7	- 7.3	----	- 0.2	- 0.3	- 0.5	- 2.4	----
2	Surface	- 3.1	-18	- 56	- 99	----	- 1.5	- 7.4	-31	- 87	----	- 1.2	- 5.7	-21	- 69	-100
	0.6 depth	+ 0.7	+ 4.2	+ 10	- 49	----	+ 0.4	+ 2.8	+ 9.4	+ 6.4	----	+ 0.1	+ 1.8	+ 7.8	+ 22	- 77
	0, 0.5, 0.9 D	0.0	+ 0.2	+ 4.4	+ 44	----	+ 0.1	+ 0.8	+ 3.0	+ 29	----	0.0	+ 0.1	+ 2.4	+ 34	+170
	0, 0.5, 0.95 D	0.0	+ 0.6	+ 9.3	+ 99	----	----	----	----	+ 49	----	0.0	+ 0.1	+ 3.6	+ 33	+370
	0, 0.5, 0.98 D	+ 0.1	+ 1.0	+ 11	+140	----	----	----	----	+ 63	----	0.0	+ 0.2	+ 4.3	+ 40	+560
	0, 0.5, 1.0 D	+ 0.2	+ 1.5	+ 14	+180	----	+ 0.1	+ 1.1	+ 6.5	+ 72	----	0.0	+ 0.3	+ 4.7	+ 46	+760
	0, 0.5 (2), 0.9 D	0.0	+ 0.1	+ 1.9	+ 15	----	+ 0.1	+ 0.8	+ 2.3	+ 17	----	0.0	+ 0.1	+ 2.4	+ 17	+ 84
	0, 0.5 (2), 0.95D	+ 0.1	+ 0.6	+ 5.3	+ 58	----	----	----	----	+ 32	----	0.0	+ 0.2	+ 3.3	+ 26	+230
	0, 0.5 (2), 0.98D	+ 0.1	+ 0.8	+ 7.2	+ 92	----	----	----	----	+ 41	----	0.0	+ 0.2	+ 3.8	+ 31	+350
	0, 0.5 (2), 1.0 D	+ 0.2	+ 1.2	+ 8.7	+120	----	+ 0.1	+ 1.0	+ 5.5	+ 48	----	0.0	+ 0.3	+ 4.2	+ 33	+490
	Straub	- 0.4	- 2.0	- 6.6	- 22	----	- 0.1	- 0.5	- 1.8	- 3.6	----	- 0.3	- 0.5	- 0.3	+ 2.7	- 13
	Luby - 3 point	- 0.1	- 0.1	- 1.2	- 22	----	- 0.1	- 0.3	- 0.7	- 8.5	----	- 0.3	- 0.3	- 0.5	- 3.5	- 61
	Luby - 5 point	0.0	- 0.1	- 0.6	- 10	----	- 0.1	- 0.2	- 0.5	- 4.3	----	- 0.2	- 0.2	- 0.4	- 1.9	- 37
	Luby - 10 point	0.0	- 0.1	- 0.5	- 2.8	----	0.0	- 0.2	- 0.3	- 2.4	----	- 0.2	- 0.2	- 0.3	- 1.0	- 18
3	Surface	- 2.1	-12	- 41	- 95	----	- 1.0	- 5.0	-22	- 71	-100	- 0.8	- 4.0	-14	- 53	-100
	0.6 depth	+ 0.5	+ 2.8	+ 8.9	- 18	----	+ 0.2	+ 1.9	+ 6.7	+ 15	- 82	0.0	+ 1.0	+ 5.1	+ 19	- 38
	0, 0.5, 0.9 D	0.0	+ 0.1	+ 1.5	+ 29	----	+ 0.1	+ 0.7	+ 1.4	+ 16	+ 93	- 0.1	+ 0.1	+ 1.2	+ 12	+120
	0, 0.5, 0.95 D	0.0	+ 0.4	+ 4.1	+ 58	----	----	----	----	+ 25	----	- 0.1	+ 0.1	+ 1.9	+ 18	+210
	0, 0.5, 0.98 D	0.0	+ 0.6	+ 6.4	+ 80	----	----	----	----	+ 31	----	- 0.1	+ 0.1	+ 2.2	+ 20	+290
	0, 0.5, 1.0 D	+ 0.1	+ 0.7	+ 7.3	+ 94	----	+ 0.1	+ 0.8	+ 4.0	+ 37	+510	- 0.1	+ 0.1	+ 2.6	+ 22	+360
	0, 0.5 (2), 0.9 D	0.0	+ 0.1	+ 0.7	+ 10	----	+ 0.1	+ 0.7	+ 1.1	+ 9.8	+ 44	- 0.1	0.0	+ 1.3	+ 10	+ 68
	0, 0.5 (2), 0.95D	0.0	+ 0.3	+ 2.7	+ 31	----	----	----	----	+ 17	----	- 0.1	0.0	+ 1.8	+ 14	+150
	0, 0.5 (2), 0.98D	+ 0.1	+ 0.5	+ 4.0	+ 47	----	----	----	----	+ 23	----	- 0.1	0.0	+ 2.1	+ 16	+200
	0, 0.5 (2), 1.0 D	+ 0.1	+ 0.6	+ 4.9	+ 58	----	+ 0.1	+ 0.2	+ 3.1	+ 28	+360	- 0.1	0.0	+ 2.3	+ 18	+250
	Straub	- 0.3	- 1.4	- 4.7	- 14	----	- 0.1	- 0.4	- 1.2	- 3.6	- 32	- 0.3	- 0.5	- 0.5	- 0.6	+ 10
	Luby - 3 point	0.0	- 0.1	- 0.5	- 11	----	- 0.1	- 0.2	- 0.5	- 3.8	- 58	- 0.2	- 0.2	- 0.4	- 1.8	- 31
	Luby - 5 point	0.0	- 0.1	- 0.3	- 4.7	----	0.0	- 0.2	- 0.3	- 2.4	- 35	- 0.2	- 0.2	- 0.3	- 1.0	- 17
	Luby - 10 point	0.0	- 0.1	- 0.3	- 2.1	----	0.0	- 0.2	- 0.2	- 1.3	- 17	- 0.2	- 0.2	- 0.3	- 0.6	- 7.4
4	Surface	- 1.6	- 9.0	- 32	- 88	----	- 0.8	- 4.5	-16	- 58	-100	- 0.7	- 3.1	-11	- 42	- 98
	0.6 depth	+ 0.4	+ 2.2	+ 7.4	- 3.3	----	+ 0.1	+ 1.3	+ 5.2	+ 16	- 62	0.0	+ 0.7	+ 3.9	+ 16	- 11
	0, 0.5, 0.9 D	0.0	0.0	+ 0.7	+ 18	----	0.0	----	+ 0.9	+ 11	+ 82	- 0.1	0.0	+ 0.8	+ 7.7	+ 86
	0, 0.5, 0.95 D	0.0	+ 0.2	+ 2.5	+ 35	----	----	----	----	+ 16	----	- 0.1	0.0	+ 1.4	+ 11	+140
	0, 0.5, 0.98 D	0.0	+ 0.3	+ 3.5	+ 48	----	----	----	----	+ 19	----	- 0.1	0.0	+ 1.5	+ 14	+185
	0, 0.5, 1.0 D	0.0	+ 0.4	+ 4.2	+ 56	----	0.0	----	+ 2.8	+ 22	+330	- 0.1	0.0	+ 1.8	+ 15	+220
	0, 0.5 (2), 0.9 D	0.0	0.0	+ 0.4	+ 6.4	----	0.0	----	+ 0.9	+ 7	+ 41	- 0.1	- 0.1	+ 1.0	+ 6.6	+ 53
	0, 0.5 (2), 0.95D	0.0	+ 0.1	+ 1.8	+ 20	----	----	----	----	+ 12	----	- 0.1	- 0.1	+ 1.3	+ 9.2	+ 97
	0, 0.5 (2), 0.98D	0.0	+ 0.3	+ 2.5	+ 28	----	----	----	----	+ 14	----	- 0.1	- 0.1	+ 1.5	+ 11	+130
	0, 0.5 (2), 1.0 D	0.0	+ 0.4	+ 3.2	+ 35	----	0.0	----	+ 2.2	+ 16	+230	- 0.1	- 0.1	+ 1.4	+ 12	+150
	Straub	- 0.2	- 1.0	- 3.9	- 12	----	0.0	- 0.3	- 0.9	- 3.2	- 15	- 0.3	- 0.4	- 0.5	+ 0.1	+ 12
	Luby - 3 point	0.0	- 0.1	- 0.3	- 6.5	----	0.0	- 0.2	- 0.4	- 2.1	- 38	- 0.2	- 0.2	- 0.3	- 1.0	- 19
	Luby - 5 point	0.0	0.0	- 0.2	- 2.8	----	0.0	- 0.1	- 0.2	- 1.5	- 23	- 0.2	- 0.1	- 0.3	- 0.6	- 10
	Luby - 10 point	0.0	0.0	- 0.2	- 1.3	----	0.0	- 0.1	- 0.2	- 0.5	- 8.4	- 0.2	- 0.1	- 0.2	- 0.4	- 3.0
6	Surface	- 1.0	- 6.1	- 22	- 73	-100	- 0.3	- 3.0	-11	- 44	- 98	- 0.5	- 2.2	- 7.4	- 30	- 88
	0.6 depth	+ 0.3	+ 1.5	+ 5.3	+ 7.9	- 86	+ 0.1	+ 0.8	+ 3.6	+ 13	- 23	0.0	+ 0.4	+ 2.5	+ 11	+ 14
	0, 0.5, 0.9 D	0.0	0.0	+ 0.3	+ 9.5	+ 51	0.0	----	+ 0.6	+ 5.0	+ 61	- 0.1	0.0	+ 0.4	+ 4.4	+ 50
	0, 0.5, 0.95 D	0.0	+ 0.1	+ 1.0	+ 16	+160	----	----	----	+ 8.4	+110	- 0.1	0.0	+ 0.7	+ 6.2	+ 78.
	0, 0.5, 0.98 D	0.0	+ 0.2	+ 1.7	+ 24	+270	----	----	----	+ 11	+150	- 0.1	0.0	+ 1.0	+ 7.3	+100
	0, 0.5, 1.0 D	0.0	+ 0.3	+ 2.1	+ 29	+380	0.0	----	+ 2.0	+ 12	+180	- 0.1	0.0	+ 1.2	+ 8.2	+110
	0, 0.5 (2), 0.9 D	0.0	0.0	+ 0.1	+ 3.3	+ 12	0.0	----	+ 0.6	+ 3.9	+ 32	- 0.1	- 0.1	+ 0.2	+ 4.1	+ 34
	0, 0.5 (2), 0.95D	0.0	0.0	+ 0.8	+ 11	+ 97	----	----	----	+ 6.4	+ 71	- 0.1	- 0.1	+ 0.5	+ 5.4	+ 54
	0, 0.5 (2), 0.98D	0.0	+ 0.2	+ 1.4	+ 15	+180	----	----	----	+ 7.9	+ 98	- 0.1	- 0.1	+ 0.7	+ 6.2	+ 64
	0, 0.5 (2), 1.0 D	0.0	+ 0.3	+ 1.7	+ 20	+260	0.0	----	+ 1.4	+ 9.1	+120	- 0.1	- 0.1	+ 0.8	+ 6.8	+ 75
	Straub	- 0.1	- 0.7	- 2.6	- 9.3	- 47	0.0	- 0.3	- 0.7	- 2.3	- 3.1	- 0.2	- 0.4	- 0.4	- 0.1	+ 8.6
	Luby - 3 point	0.0	0.0	- 0.2	- 3.2	- 49	0.0	- 0.1	- 0.3	- 1.0	- 20	- 0.2	- 0.1	- 0.3	- 0.5	- 9.4
	Luby - 5 point	0.0	0.0	- 0.1	- 1.5	- 26	0.0	- 0.1	- 0.2	- 0.7	- 12	- 0.2	- 0.1	- 0.2	- 0.3	- 3.7
	Luby - 10 point	0.0	0.0	- 0.1	- 0.8	- 10	0.0	- 0.1	- 0.1	- 0.4	- 3.8	- 0.1	- 0.1	- 0.2	- 0.2	- 1.6
10	Surface	- 0.6	- 3.5	- 14	- 52	-100	- 0.3	- 1.9	- 6.9	- 28	- 87	- 0.3	- 1.3	- 4.6	- 19	- 69
	0.6 depth	+ 0.1	+ 0.8	+ 3.5	+ 10	- 48	0.0	+ 0.4	+ 2.1	+ 8.6	+ 7.3	0.0	+ 0.2	+ 1.4	+ 7.0	+ 21
	0, 0.5, 0.9 D	0.0	0.0	+ 0.1	+ 3.3	+ 44	0.0	----	+ 0.2	+ 2.0	+ 29	- 0.1	0.0	+ 0.2	+ 1.9	+ 24
	0, 0.5, 0.95 D	0.0	0.0	+ 0.5	+ 7.1	+100	----	----	----	+ 3.7	+ 49	- 0.1	0.0	+ 0.3	+ 3.1	+ 33
	0, 0.5, 0.98 D	0.0	+ 0.1	+ 0.9	+ 9.8	+140	----	----	----	+ 4.6	+ 63	- 0.1	0.0	+ 0.4	+ 3.7	+ 40
	0, 0.5, 1.0 D	0.0	+ 0.2	+ 1.0	+ 12	+180	0.0	----	+ 0.3	+ 5.4	+ 72	- 0.1	0.0	+ 0.5	+ 4.3	+ 46
	0, 0.5 (2), 0.9 D	0.0	0.0	0.0	+ 1.4	+ 15	0.0	----	+ 0.2	+ 2.0	+ 17	- 0.1	- 0.1	+ 0.2	+ 2.1	+ 17
	0, 0.5 (2), 0.95D	0.0	0.0	+ 0.4	+ 4.6	+ 53	----	----	----	+ 3.2	----	- 0.1	- 0.1	+ 0.4	+ 2.8	+ 25
	0, 0.5 (2), 0.98D	0.0	+ 0.1	+ 0.7	+ 6.1	+ 92	----	----	----	+ 3.7	----	- 0.1	- 0.1	+ 0.4	+ 3.1	+ 31
	0, 0.5 (2), 1.0 D	0.0	+ 0.2	+ 0.8	+ 7.6	+120	0.0	----	+ 0.7	+ 4.3	+ 48	- 0.1	- 0.1	+ 0.5	+ 3.7	+ 33
	Straub	- 0.1	- 0.4	- 1.7	- 6.2	- 22	0.0	- 0.2	- 0.5	- 1.8	- 3.6	- 0.1	- 0.3	- 0.3	- 0.3	+ 2.7
	Luby - 3 point	0.0	0.0	- 0.1	- 1.3	- 22	0.0	- 0.1	- 0.2	- 0.5	- 8.5	- 0.1	- 0.1	- 0.2	- 0.3	- 3.5
	Luby - 5 point	0.0	0.0	- 0.1	- 0.7	- 10	0.0	- 0.1	- 0.1	- 0.4	- 4.8	- 0.1	- 0.1	- 0.2	- 0.2	- 1.6
	Luby - 10 point	0.0	0.0	- 0.1	- 0.5	- 4.0	0.0	- 0.1	- 0.1	- 0.2	- 2.6	- 0.1	- 0.1	- 0.2	- 0.1	- 1.0
15	Surface	- 0.4	- 2.5	- 10	- 38	- 95	- 0.2	- 1.2	- 4.6	- 20	- 71	- 0.2	- 0.9	- 3.2	- 13	- 52
	0.6 depth	+ 0.1	+ 0.6	+ 2.4	+ 8.4	- 17	0.0	+ 0.2	+ 1.4	+ 6.2	+ 13	0.0	+ 0.1	+ 0.9	+ 4.6	+ 19
	0, 0.5, 0.9 D	0.0	0.0	+ 0.1	+ 1.1	+ 29	0.0	----	+ 0.2	+ 1.0	+ 16	- 0.1	0.0	+ 0.1	+ 1.2	+ 12
	0, 0.5, 0.95 D	0.0	0.0	+ 0.3	+ 3.3	+ 58	----	----	----	+ 2.2	+ 25	- 0.1	0.0	+ 0.1	+ 1.8	+ 17
	0, 0.5, 0.98 D	0.0	+ 0.1	+ 0.6	+ 4.9	+ 80	----	----	----	+ 2.8	+ 31	- 0.1	0.0	+ 0.1	+ 2.0	+ 20
	0, 0.5, 1.0 D	0.0	+ 0.1	+ 0.6	+ 6.1	+ 94	0.0	----	+ 0.8	+ 3.3	+ 37	- 0.1	0.0	+ 0.2	+ 2.4	+ 22
	0, 0.5 (2), 0.9 D	0.0	0.0	0.0	+ 0.6	+ 10	0.0	----	+ 0.2	+ 1.1	+ 9.8	- 0.1	- 0.1	+ 0.1	+ 1.2	+ 10
	0, 0.5 (2), 0.95D	0.0	0.0	+ 0.2	+ 2.3	+ 31	----	----	----	+ 1.9	----	- 0.1	- 0.1	+ 0.2	+ 1.7	+ 14
	0, 0.5 (2), 0.98D	0.0	+ 0.1	+ 0.5	+ 3.5	+ 47	----	----	----	+ 2.2	----	- 0.1	- 0.1	+ 0.2	+ 1.9	+ 16
	0, 0.5 (2), 1.0 D	0.0	+ 0.1	+ 0.5	+ 4.2	+ 58	0.0	----	+ 0.5	+ 2.3	+ 25	- 0.1	- 0.1	+ 0.2	+ 2.1	+ 18
	Straub	0.0	- 0.2	- 1.1	- 4.6	- 14	0.0	- 0.1	- 0.3	- 1.2	- 3.8	- 0.1	- 0.3	- 0.3	- 0.4	+ 0.3
	Luby - 3 point	0.0	0.0	- 0.1	- 0.6	- 11	0.0	- 0.1	- 0.1	- 0.3	- 4.0	- 0.1	- 0.1	- 0.2	- 0.4	- 1.8
	Luby - 5 point	0.0	0.0	0.0	- 0.5	- 4.7	0.0	- 0.1	- 0.1	- 0.3	- 2.4	- 0.1	- 0.1	- 0.1	- 0.2	- 1.2
	Luby - 10 point	0.0	0.0	0.0	- 0.4	- 2.1	0.0	- 0.1	- 0.1	- 0.2	- 1.5	- 0.1	- 0.1	- 0.1	- 0.1	- 0.6

*Nomenclature: D refers to depth of stream; (2) means that the concentration of the 0.5 depth sample is given double weight.

ordinary stream conditions. Even in the more accurate methods the errors exceed 50 percent for some large sizes and low velocities.

A study was made to determine the practicability of applying coefficients to the results obtained with the various sampling methods to correct excessive errors which occur under certain conditions as shown in Table 1. To use a coefficient when it varied rapidly with small changes in stream and sediment conditions would be unsatisfactory. For such stream conditions it would be advisable to use a point sampling method for which the value of the coefficient remained fairly constant and preferably close to unity. The coefficient was found to approach unity even for the least accurate methods when sampling conditions were favorable, and the coefficient was rarely out of the range of 0.9 to 2.0 for the more accurate methods regardless of sampling conditions. The coefficient applicable to the mean sediment concentration in the vertical determined from a sample taken from a single point is discussed on pages 69 - 72 of Report No. 3. The analysis showed that the best points to collect single samples were between the 0.6 and 0.8 depths; for the larger sizes of sediment a sampling point near the 0.8 depth would be best. If consideration is given to the use of coefficients, one should keep in mind that the vertical velocity and sediment distributions on which they are based must be analogous to those of the stream being studied.

15. Transverse distribution of sediment in a stream--Except below important tributaries and in streams with irregular cross sections, the sediment concentration is ordinarily fairly uniformly distributed in the transverse direction. Water entering from a tributary tends to stay on its side of the stream for a considerable distance downstream. If the

sediment content of the main and tributary streams differ appreciably, the sediment concentration across the stream may not become uniform for a long distance below the junction.

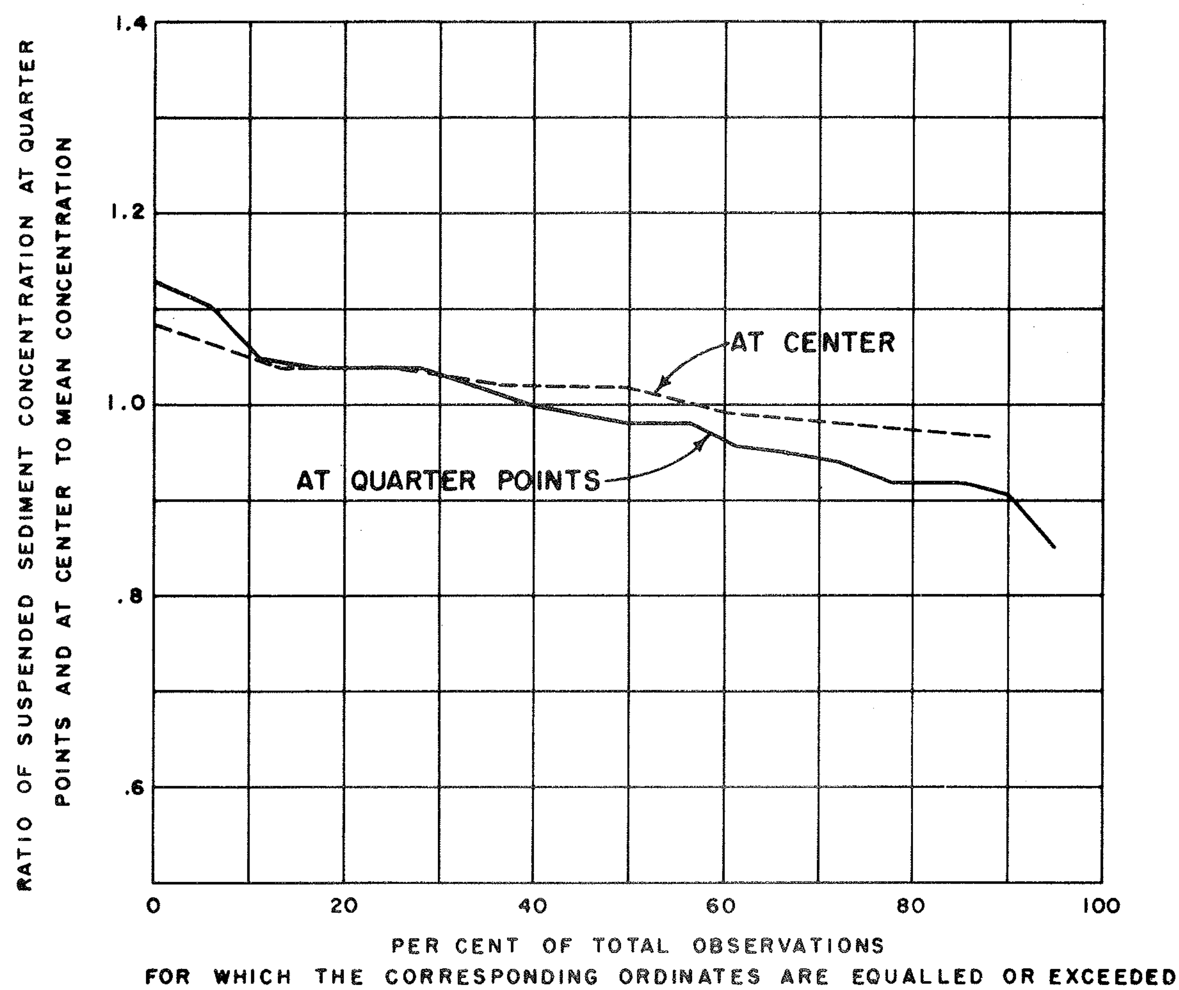


Fig. 7--Observed transverse distribution of suspended sediment

The available data on transverse sediment distribution given in Table 2 of Report No. 1 have been arranged in Fig. 7 to show the observed frequency of deviations of concentration from the mean for the cross-section. A comparison of this diagram with Fig. 5 indicates that ordinarily the transverse variation of suspended sediment concentration is considerably less than the vertical variation. Under these conditions the location of sampling points across a stream is not as important as the location of points in the vertical. However, under conditions of varying depth throughout the section, it is possible that the variation of sediment concentration is greater from one side of the stream to the other than at different points in a given vertical section.

16. Methods used in locating vertical sampling stations-Determination of the number and locations of verticals to be sampled should be governed by the degree of accuracy desired in the investigation, the size and shape of cross section, the ratio of the sediment load being carried at the time of sampling to the total load during the period under consideration, and other characteristics of the stream. The size of the stream and the accuracy desired are probably of greatest importance. Although the field technique used in any sediment investigation will naturally be dependent upon the relative importance of these factors, the basic criterion for a rational sampling technique is that the verticals should be located or their mean concentrations weighted with respect to the transverse distribution of stream discharge. That is, either the verticals should represent equal parts of the total water discharge, or the value of mean concentration observed in each vertical should be weighted in proportion to the percentage of water discharge which it represents.

The methods which have commonly been used to locate the transverse position of verticals in sediment measurements are as follows:

a. Single vertical at midstream.

b. Single vertical at thalweg or point of greatest depth.

c. Verticals at 1/4, 1/2, and 3/4 width.

d. Verticals at 1/6, 1/2, and 5/6 width.

e. Four or more verticals equally spaced across the stream.

f. Verticals at centroids of sections of equal discharge.

Obviously, the simplest practice is the selection of a single vertical at midstream or at the point of greatest depth. Of these methods the latter is preferred because the greatest percentage of discharge generally occurs in the deepest part of the stream. However, a single vertical should be used only in very small streams or in certain types of routine sampling.

Three verticals located at the 1/4-, 1/2-, and 3/4-point in a stream cross section are frequently used. This method provides more information concerning the distribution of sediment and a more accurate representation of sediment discharge than the single vertical method. The three-vertical method is popular, no doubt, because of its convenience and practicability in field use.

A few investigators have located the sampling verticals at 1/6, 1/2, and 5/6 of the stream width. This method has a rational justification when used in wide streams of uniform depth and uniform velocity distribution. Under these conditions the verticals bisect three sections of equal discharge. However, such conditions of stream flow are unusual; in most streams the mid-point of equal discharge would occur approximately at the quarter-points or even closer together.

In important investigations it has been common practice to select a relatively large number of verticals at equal intervals across the stream. This method will give a good indication of the distribution of sediment across the stream, but it is exact only when the mean concentration for each vertical is weighted with respect to the stream discharge in the section represented by the vertical.

The selection of verticals so that each represents an equal portion of stream discharge is another rational practice. However, this method is usually only approximated in the field. The sections of equal water discharge are determined by visual inspection, substantiated, in some instances, by previous stream gagings, and the verticals are located at the centroids of these sections. The accuracy of this method depends to a large extent upon the judgement and care used by the observer in dividing the stream cross section.

In small streams and in larger streams where long-period,routine investigations are being made,the method of selecting verticals so that all of them represent equal quantities of discharge, can be simplified somewhat. If only one vertical is to be sampled, it should be located so as to represent the greatest portion of the stream discharge. If two or more verticals are used, the cross section is divided into areas of equal discharge with the vertical for each area located not at its center but at the point dividing it again into two smaller areas of equal discharge. When the number of verticals becomes large relative to the width of the stream, each area can be sampled at its exact middle without appreciable error.

17. Selection of verticals across the stream representing equal discharges--A relatively simple graphical method devised by Mr. E.W. Lane for locating sampling points which represent equal proportions of the total discharge is illustrated by Figs. 8 and 9. The discharge distribu-

tion in a river cross section for varying stages is shown in Fig. 8, as a cumulative percentage of the total discharge. In the development of this

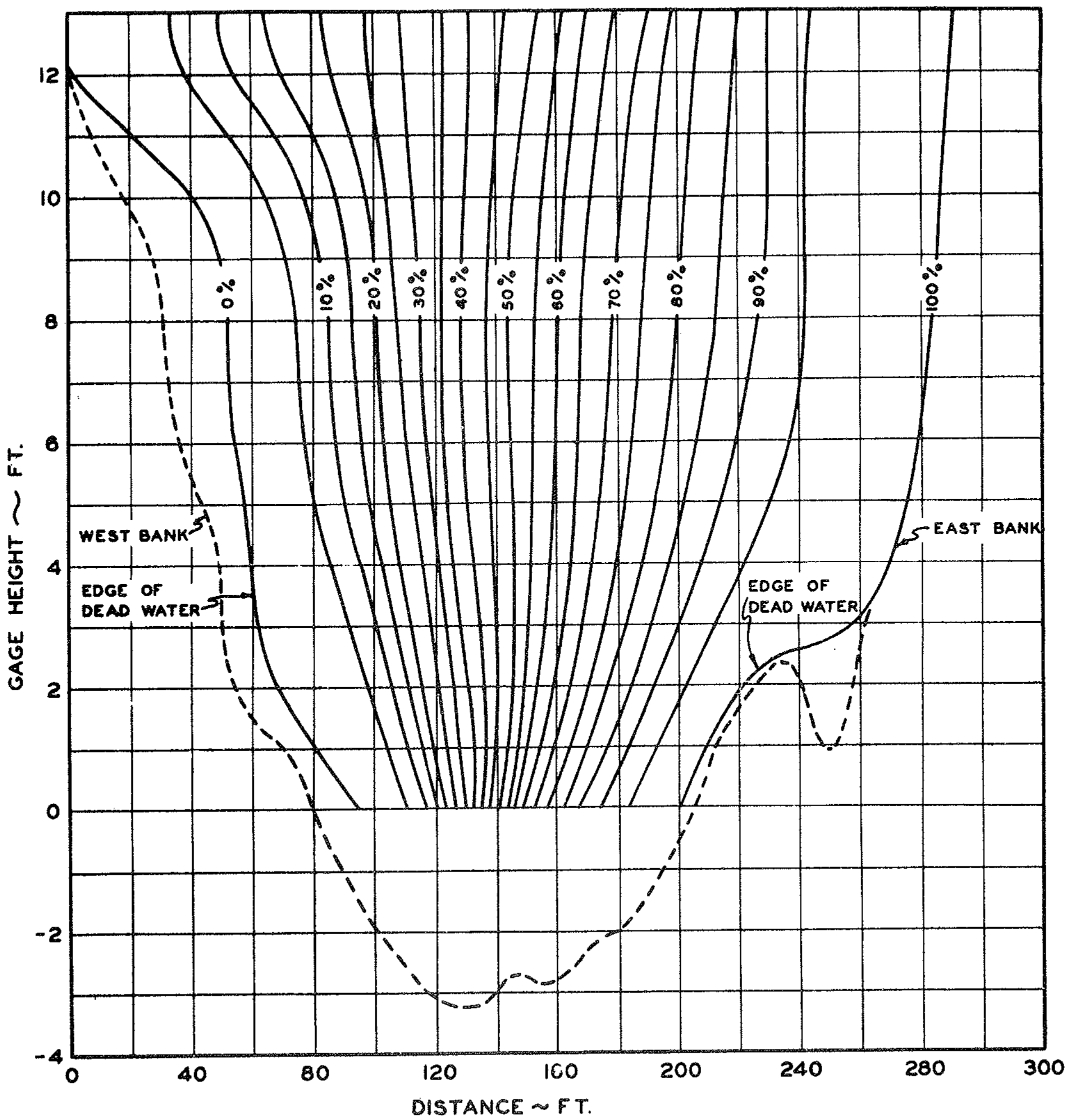
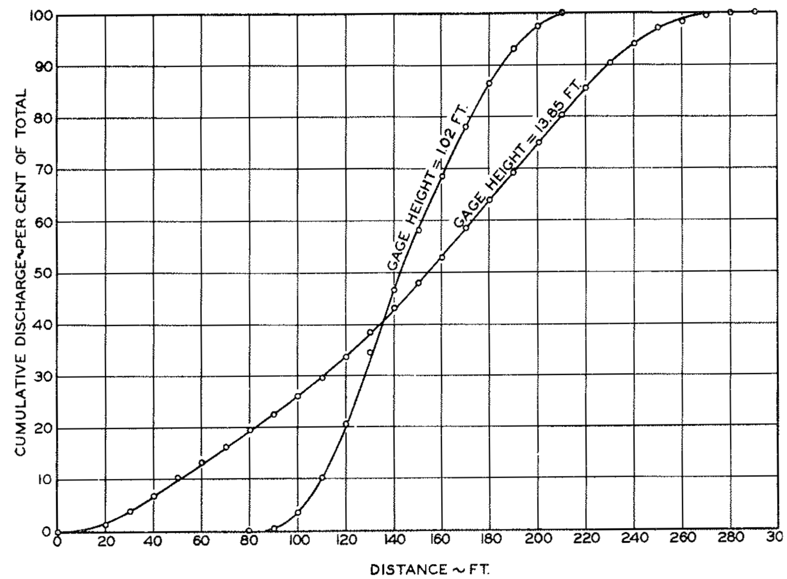
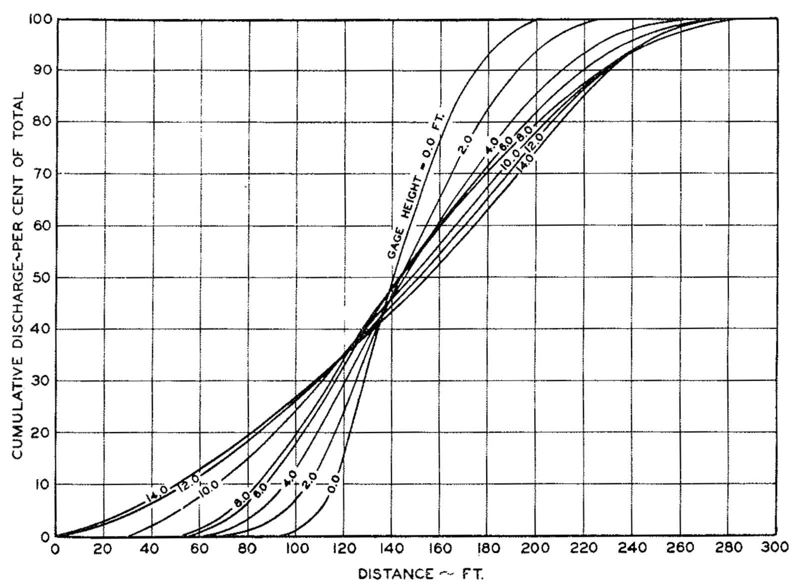


Fig. 8--Discharge distribution in cross section of Iowa River at Iowa City

graph, the distances to points of equal fractions of discharge, that is, 5, 10, 15 percent, etc., were determined for different stages from distribution of flow diagrams such as those illustrated in Fig. 9a. This



a. INDIVIDUAL MEASUREMENTS OF DISCHARGE



b. DISCHARGE VARIATION WITH GAGE HEIGHT

FIG. 9 - DISCHARGE DISTRIBUTION IN CROSS SECTION OF IOWA RIVER AT IOWA CITY

process was repeated for a sufficient number of discharge measurements to cover the desired range in stage, and smooth curves or contours were drawn to represent various percentages of discharge for all stages.

In Fig. 9b the percentages of discharge are plotted as ordinates and the distance to points of observation as abscissas for various stages of the river. The location of verticals to be sampled can be determined from the information given in Table 2 and Fig. 9b. For example, Table 2 shows that six sampling points should be located where the cumulative mean dis-

TABLE 2

LOCATIONS OF VERTICALS FOR SECTIONS OF EQUAL DISCHARGE

No. of sampling points	Cumulative discharge - percent of total													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
2	25	75												
4	12	38	62	88										
6	8	25	42	58	75	92								
8	6	19	31	44	56	69	81	94						
10	5	15	25	35	45	55	65	75	85	95				
12	4	12	21	29	38	46	54	62	71	79	88	96		
14	4	11	18	25	32	39	46	54	61	68	75	82	89	96

charges are 8, 25, 42, 58, 75, and 92 percent of the total. Fig 9b shows that for a gage height of 4.0 feet the six samples should be located 92, 114, 134, 157, 180, and 215 feet from the reference station. This method can be applied to gaging stations where sediment and water discharge measurements are made regularly. With the final graph the sampling points can be readily located for any observed river stage. If major changes in the river cross section take place, it may be necessary to revise the graph, but minor channel changes will have an inappreciable effect on the accuracy of this procedure.

The sampling points can be spaced transversely and vertically at the same time to represent sections of equal discharge. If the samples are taken by the depth-integration method or if the sampling points are located in the vertical by the equal-discharge method and the same number of equal volume samples are taken in each vertical, all the samples in the cross section may be combined for analysis. The composite sample will be representative not only of the average sediment concentration but also of the average size distribution of the sediment load.

18. Methods of computing suspended sediment concentration--Several different methods have been used to compute the concentration of sediment in a water-sediment mixture. In early studies the concentration was determined by measuring the volume of solids, but this method is seldom used today because the variations in particle size, shape, and composition make volumetric measurements very unreliable. The weight of solids is now generally used in the determination of sediment concentration, expressed either as dry solids weight per unit volume of sample or as the ratio of dry solids weight to sample weight. It is believed that the best results will be obtained when concentration is expressed as a ratio of the weight of dry solids to water-sediment sample. This ratio can be expressed either as a percent or in parts per million. The weight ratio expressed in one of these units can be readily transferred to the other by the relationship 1 percent equals 10,000 p.p.m.

The weight ratio method of expressing sediment concentration which has the advantage of being non-dimensional, is in general use in this country and in foreign countries as well. Non-dimensional ratios are also commonly used in sanitary and water-works practice.

There are three variations of the weight ratio method of determining sediment concentrations:

(1) weight of dry solids divided by the weight of the entire water-sediment sample,

(2) weight of dry solids divided by the weight of water in the water-sediment sample,

(3) weight of dry solids divided by the weight of pure water equal in volume to that of the sample.

Although the first method is generally used, situations may arise where the calculations would be expedited by the second or third method; particularly the third since it permits the volume of the water-sediment mixture to be measured in the field and thus eliminates errors which would be introduced by evaporation before the sample is analysed. The graphs shown in Fig. 10 may be used to convert the results obtained by the second and third methods to the basis of total sample weight. As shown in the upper graph, differences between the first method and the other two are negligible at 1,000 p.p.m. and even at 10,000 p.p.m. they do not exceed 1 percent.

19. Frequency of sampling--The purpose for which a sediment investigation is conducted, the budget available for the program, and characteristics of the stream and its sediment load will to a large extent determine the schedule and frequency of sampling. Some sediment investigations are conducted to develop long-term records of the sediment discharge of streams while other investigations of a research nature are conducted primarily to compile data and information regarding the sediment characteristics of streams in general. A long-term sediment measurement program will require less frequent sampling than a more intensive

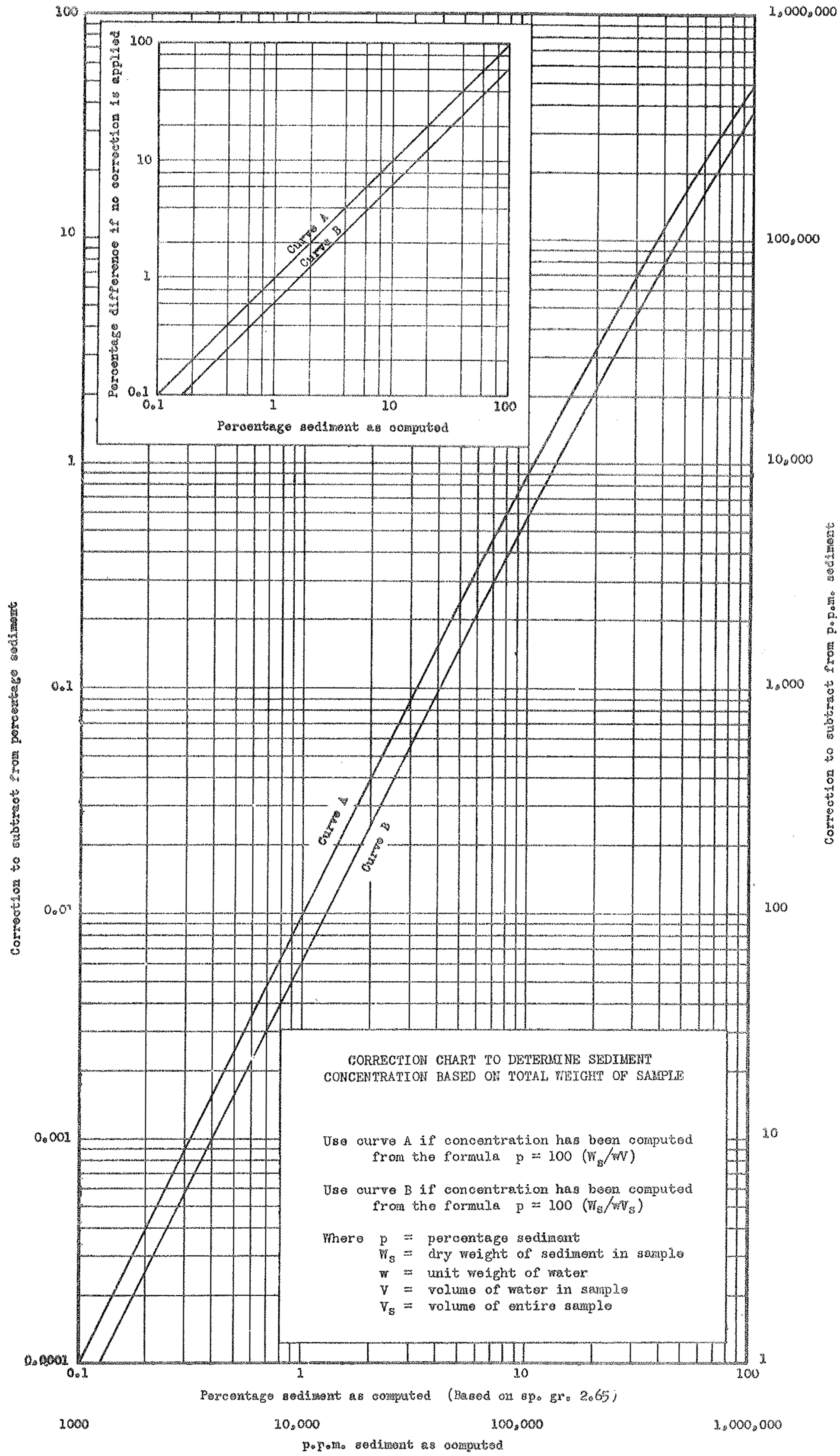

100
10
1
0.1
0.01
0.001
0.0001
1,000,000
100,000
10,000
1,000
100
10
1
Correction to subtract from percentage sediment
Correction to subtract from p.p.m. sediment
Percentage difference if no correction is applied
100
10
1
0.1
0.1
1
10
100
Percentage sediment as computed
Curve A
Curve B
Curve A
Curve B
0.1
1
10
100
Percentage sediment as computed (Based on sp. gr. 2.65)
1000
10,000
100,000
1,000,000
p.p.m. sediment as computed
CORRECTION CHART TO DETERMINE SEDIMENT
CONCENTRATION BASED ON TOTAL WEIGHT OF SAMPLE
Use curve A if concentration has been computed from the formula p = 100 (W_s/wV)
Use curve B if concentration has been computed from the formula p = 100 (W_s/wV_s)
Where p = percentage sediment
W_s = dry weight of sediment in sample
w = unit weight of water
V = volume of water in sample
V_s = volume of entire sample

FIG. 10

research project, particularly after the stream has been under observation for a sufficient length of time to determine the characteristics of its sediment load and water discharge. The cost of a sampling program is one of the most important factors, often the controlling one, in determining the frequency of sampling. The most desirable sampling frequency from other standpoints often involves expenditures in excess of the available funds.

Fluctuations of water discharge and sediment concentration are the most important stream characteristics to be considered in determining the optimum frequency of sampling. The fluctuation of water discharge of a stream and the variation of sediment concentration are to a large extent influenced by the same factors, mainly the climatic, hydrologic, and topographic features of the drainage area. The amount, distribution and intensity of precipitation, the degree of variation of temperature, the size, shape, and topography of the drainage area, and its soil, geology and vegetal cover are factors which affect the quantity of sediment production. Heavy, intense precipitation usually produces an increase in stream flow and sediment concentration. Drainage basins of friable soil with little vegetal cover produce high sediment concentrations during floods and, therefore, large variations of concentration between normal and flood flows.

During flood periods both the stream discharge and the sediment concentration change very rapidly on small streams and, therefore, frequent sampling is required. For example, in Coon Creek (8) in Wisconsin, with a drainage area of 77 square miles, it was found that 90 percent of the total sediment load for 15 months was discharged within a period of 10 days, or 2.2 percent of the time. A similar condition was found in West Tarkio Creek, Missouri. On the basis of data given in report No. 1, it may be stated that the above examples are probably typical of most small streams. In most of the streams investigated, over 10 percent of the sediment load passed in less than 0.2 percent of the time.

On large as well as on small streams the greater part of the total water discharge occurs during flood periods although flood conditions occupy a relatively small part of the total time. In general the greater part of the annual sediment load is also carried during the flood periods. The sediment discharge in the Missouri River at Kansas City varies about as the 2.16 power of the discharge and in the lower Colorado near Yuma, Arizona, as the 1.86 power. These typical examples indicate the importance of frequent observations during floods, even in large rivers. It has been found that both the water discharge and the sediment concentration changes more rapidly on a rising than on a falling stage. Therefore, samples should be taken more frequently on the rising side of the hydrograph than after the crest is passed.

In a sediment investigation conducted solely to determine the total sediment discharge of a stream, sampling could be timed so as to represent equal amounts of sediment discharge in somewhat the same way that sampling verticals are spaced across a stream to represent equal water discharges as described in Section 17. Where the variation in sediment concentration with stage has been determined approximately, the frequency of sampling can be prescribed as a function of stage. For example, if on the average the sediment discharge at a 10-foot stage is twice as great as that at a 7-foot stage, samples should be taken twice as often at the higher stage. It may be desirable to take measurements during low water somewhat more frequently than this schedule would indicate, at least until the variation of concentration with respect to stage is well established.

20. Determination of long period sediment discharge of streams--The engineer is frequently confronted with the problem of determining the total sediment discharge of a stream on which only a limited number of sediment observations, or none at all, have been made. Where there are neither sediment observations nor continuous records of stream discharge, the best approach is to find data from sediment discharge measurements or rates of reservoir filling on streams with conditions as nearly like those of the stream in question as possible. This method does not provide a conclusive solution and should be used only in lieu of a better alternative.

A record of stream discharge of considerable duration together with some sediment observations will enhance the estimate of sediment discharge to a marked degree. All available sediment samples should be correlated with corresponding water discharge or stage, and the most plausible relationship applied to the record of stream discharge or stage to derive a sediment discharge hydrograph for the period. Although this method leaves much to be desired, there is often no satisfactory alternative. The sediment-water discharge relation may vary to some extent with the seasons in which case the correlation factor should be adjusted accordingly. If the estimate is for an interval extending over several years, the work could be expedited by preparing a flow-duration curve. From this curve and the relationship between sediment concentration and water discharge a duration curve of sediment discharge is constructed which provides the information necessary to compute the total sediment discharge for the period.

The accuracy of the duration curve method described above will depend on the relationship between the observed sediment discharge and the water discharge. If the observed points plot nearly on a single curve the results can be assumed to be reasonably accurate. If the points scatter badly or are few in number,so that a good average curve cannot be determined, the probable accuracy is indicated by the degree of uncertainty in the location of the average line. These statements apply only to the estimate of the total sediment discharge over a long period of time. If a long record of water discharge is not available to establish an accurate flow-duration curve, this method should not be used. Since it has been shown that the relation between sediment discharge and water discharge is less variable for coarse than for fine sediments, this method will probably give more accurate results on rivers carrying coarse sediments than on those where the sediment is mostly fine.

Data on the turbidity of a stream can sometimes be obtained from records of city water-supply plants adjacent to the stream. If some sediment measurements have been made on the stream under study, an approximate relation between turbidity and concentration can be worked out to determine the sediment discharge of the stream. If no sediment measurements are available, the turbidity records may be compared with those of adjacent streams on which sediment measurements have been made. The estimate of sediment discharge obtained from these data will probably be undependable but may suffice in an emergency.

With adequate sediment and water discharge data available, accurate hydrographs of sediment concentration and water discharge can be determined. The product of the concentration and discharge ordinates of these curves plotted in the same manner will show the variation of sediment discharge with respect to time. An accurate estimate of the total sediment transported can then be determined by computing the area under the curve of the sediment discharge hydrograph.

21. Miscellaneous notes on sampling procedure--The budget available for a sediment program will to a large extent determine the scope of the project, the procedure, and the permissible sampling frequency. Accuracy and refinement in sediment discharge data usually can be obtained only at considerable expense. However, the importance of obtaining at least some basic data on the stream under consideration should be emphasized. Although the results obtained from these data may be considerably in error, they will generally be better than those based entirely on data for other streams. That the sediment concentration may vary widely from one stream to another is evident from the following comparison. The Casconade River at Rich Fountain, Missouri, carries an average sediment load of about 0.0076 percent while the Rio Grande at San Marcial carries about 1.42 percent, or 200 times as much. Thus, without local data, it is possible to make an error of several hundred percent in estimating the sediment load of a stream. The error may be significantly reduced with only a few field measurements and the improved accuracy will usually justify the cost of sampling.

Stream flow data must be obtained for any detailed suspended sediment study. If no gaging station is maintained at the desired point on the stream one should be established. While it is possible to obtain water discharge and sediment discharge measurements at the same time, as a practical matter it is better to have an established rating curve and vertical velocity curve for the station. Furthermore, it is impossible to make a reliable estimate for the long-term sediment discharge of a stream without accurate stream flow data.

Apparently, the most popular method of obtaining instantaneous or point-integrated samples consists in locating the sampling points in the vertical at the surface, mid-depth, and bottom. However, this method is not recommended. In the absence of a detailed study such as that undertaken by Dr. Straub for the Missouri River, the Luby method of sampling at points of equal discharge is recommended. If a representative sample of the size distribution as well as the concentration is desired, at least five points in each vertical should be sampled. A sixth sample near the bottom of the stream may be necessary for size analysis purposes if an appreciable amount of material larger than 1/16 mm. is present.

Although the verticals can be located at the quarter points across the stream and good results obtained when the sediment concentration is weighted with respect to the water discharge,the verticals can be located to better advantage at points of equal discharge by the method described in Section 17. The number of verticals to be used is a matter of judgment and depends on such factors as the width of the stream and stream bed conditions.

A great deal of work is involved in obtaining sediment discharge measurements. The cost in time and effort entailed in sampling, analyzing, and computing the average concentration and especially the average grading of sediment by point sampling methods in many instances cannot be justified. On the other hand, within their prescribed limits of depth and velocity the improved depth-integrating samplers developed in this project will obtain in a single sample for each vertical a representative or average value for both concentration and size grading. Thus the amount of work required for a sediment discharge measurement is greatly reduced in both the field and laboratory.

IV. CHARACTERISTICS OF SUSPENDED SEDIMENT SAMPLERS

22. Types of suspended sediment samplers--Considerable thought and ingenuity have been expended in the development of instruments for sampling fluvial sediment. More than 65 versions of so-called suspended sediment samplers are described in Report No. 1. Although these samplers were developed independently by various investigators, many of them are similar both in design and manner of operation. They can be classified by the following six general types:

- a. Vertical pipe.
- b. Instantaneous vertical.
- c. Instantaneous horizontal.
- d. Bottle.
- e. Integrating.
- f. Pumping.

A sampler with a vertical cylinder or pipe for the sample container, not designed to obtain an instantaneous sample, is classified as a vertical pipe sampler. As the sampler is lowered to the desired depth, the water-sediment mixture flows upward through the sample container, and when the lowering is stopped, valves at either end of the pipe close of their own weight and the sample is trapped. While the simplicity of design has been the reason for extensive use of this type in the past, many adverse sampling characteristics have practically eliminated it from current use.

Besides the obvious difference in the sampling period of an instantaneous vertical sampler and an ordinary vertical pipe sampler, the instantaneous sampler obtains a specimen from a smaller part of the vertical after the sampler is lowered to the sampling point. A messenger weight dropped down the suspension line releases the sample cylinder which falls or is forced down by a spring to a flat plate. Instantaneous vertical samplers are designed to minimize the disturbance of flow in the sampling zone.

An instantaneous horizontal trap sampler consists of a horizontal cylinder equipped with end valves which can be closed suddenly to trap a sample at any desired time and depth. Water is allowed to pass through the horizontal cylinder as the sampler is lowered to the desired depth. The horizontal trap sampler is widely used in present investigations. The principal advantages of this type of sampler are the relative simplicity of design and operation, the ability to sample close to the stream bed, and the wide range of adaptability to shallow and deep streams of all velocities.

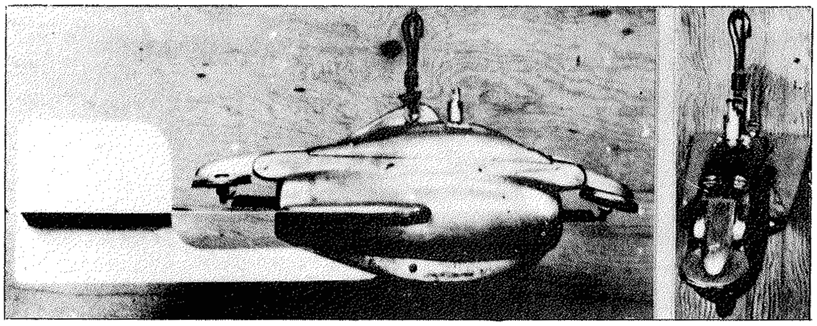
The most readily improvised sampling device for sediment investigations consists of an ordinary milk bottle, fruit jar, or other standard container with the necessary provisions for lowering to the sampling point. The bottle type sampler is provided with an entrance varying in size from about 1/4 in. in diameter up to the full opening of the container. Air within the bottle, displaced by the incoming sample, escapes through the intake opening and thus produces a bubbling action at the entrance. Because of the time required to fill the sampler and because of the air bubbles which escape through the intake, bottle samplers are often referred to as slow-filling or bubbling samplers.

The container of an integrating sampler is filled slowly and continuously over a period of time ranging from about 10 to 60 sec. An important feature of most of the integrating samplers, distinguishing them from the ordinary bottle samplers, is that the intake and air exhaust tubes are separated. Thus the escaping air causes no disturbance to the inflow as the sampler is filled. The intake tube or orifice is pointed into the current so as to eliminate change in direction of the flow.

In the operation of a pumping sampler, the water-sediment sample is sucked in through a pipe or hose, the intake of which is placed at the desired sampling point. By directing the intake of the suction hose into the current and regulating the intake velocity, the operator can obtain an undisturbed sample representative of the sediment concentration at the sampling point.

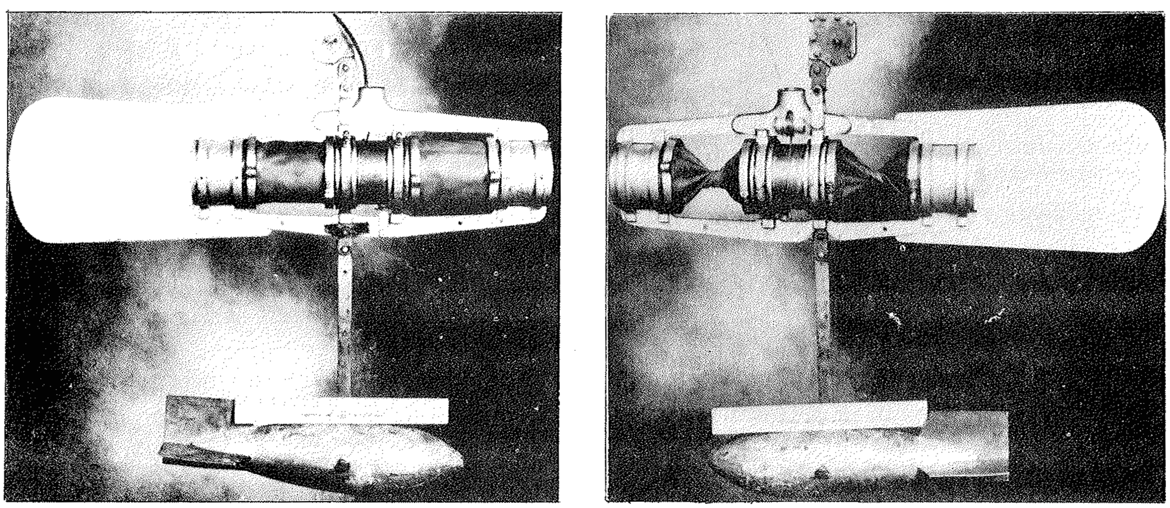
Suspended sediment samplers can be classified as to their mode of operation into instantaneous and integrating samplers. Many samplers do not actually qualify for either classification because their design, sampling action, or method of operation eliminate them from the categories of true instantaneous or integrating samplers. As the name implies, the instantaneous sampler is designed to trap a specimen of the water-sediment mixture passing the sampling point at a desired instant. On the other hand, the integrating sampler takes the sample over an extended period so as to obtain either a specimen at a point in which the momentary fluctuations in sediment concentration are averaged or a specimen in a vertical in which the concentration at different depths are averaged. Integrated samples are obtained with either a point-integrating sampler or a depth-integrating sampler.

Sampler development on this project has been confined to the integrating types. As all of the functions of the instantaneous type cannot be performed by an integrating sampler, two instantaneous horizontal samplers currently used are presented. The Tennessee Valley Authority sampler, shown in Fig. 11, has a horizontal cylinder incased in a streamlined weight. Flap valves, hinged to the weight above the ends of the cylinder, are held open by a simple catch mechanism, and they are released by a pull on an auxiliary line to trap the sample. A spring extending through the cylinder, supplies the force to hold the valves closed. While the sampler has sufficient weight for ordinary conditions in shallow streams, additional weights may be used if desired.



Side View Front View

Fig. 11--T.V.A. Sampler



Sample chamber open Sample chamber closed

Fig. 12--Tait-Binkley Sampler

The Tait-Binkley sampler, shown in Fig. 12, consists of three metal tubes of equal diameter mounted coaxially a short distance apart in a horizontal metal frame. The middle tube mounted on bearings for free rotation about its axis is connected to the two rigidly mounted end cylinders by sections of rubber tubing. To trap a sample the middle section is rotated by a pull on an auxiliary line wound around the section. The resulting twist in the rubber connecting sections seals the ends of the sample container and the sample is trapped.

23. Some adverse features of sampling procedure--The flow lines at the intake of a sampler must be undisturbed during the sampling period in order to obtain a representative sample. Many of the existing samplers as designed cause disturbances in the flow characteristics at the point of intake throughout the sampling period, and in others both the design of the sampler and the method of operation are such that the flow characteristics at the point of intake are severely disturbed at the beginning of the sampling operation. These adverse features of sampling procedure are discussed in the following paragraphs.

Conditions at the mouth of a sampler may be represented by the flow pattern of the water-sediment suspension approaching and entering the sampler. Any distortion of this flow pattern, due to changes in velocity or disturbances set up by the sampler itself, will tend to segregate the sediment from the water. This tendency is due to the difference in density of the sediment and the water; the sediment having the greater density and inertia responds less rapidly than the water to forces tending to change its motion. In the operation of a sediment sampler the flow pattern is often disturbed in such a way that the velocity in the mouth of the sampler, and for some distance upstream, is less than the natural stream velocity. This condition is represented by the sample filament diverging in cross-sectional area and decreasing in velocity as it approaches the mouth of the sampler as shown in Fig. 13. The sediment from

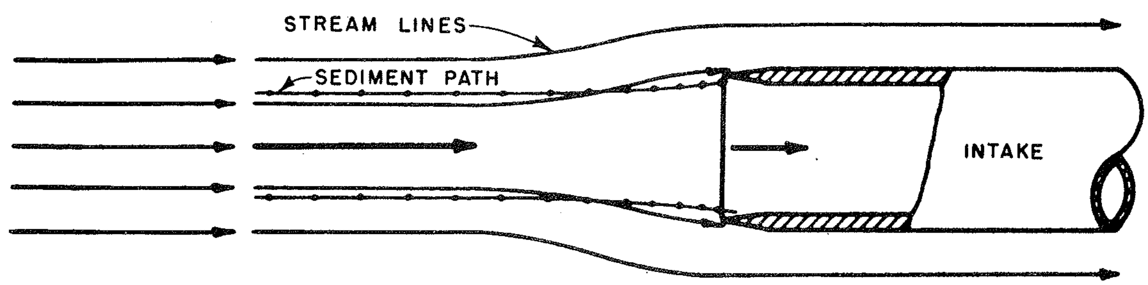


Fig. 13--Flow pattern at mouth of sampler intake, sampling rate below normal.

just outside the border of the sample filament, diverging less rapidly than the water, enters the mouth of the sampler as an excess. For the converse condition, in which the velocity at the mouth of the sampler is greater than the natural stream velocity,the sediment in the sample filament tends to converge to a lesser degree than the water, resulting in a sample too low in sediment concentration.

Experiments described in Report No. 5 show that errors resulting from sampling rates below normal are considerably larger in magnitude than errors resulting from comparable deviations in sampling rates above normal. These experiments indicated also that as the size of sediment increased above 0.06 mm. the magnitude of the errors in sediment concentration increased rapidly. With a sampling ratio, intake velocity to stream velocity, of 0.25 the error in sediment concentration was 8 percent excess for sediments of 0.06 mm. diameter and 100 percent excess for sediments of 0.45 mm. diameter. It is important, therefore, to design the sampler so as to obtain proper entrance conditions especially when the sampler is to be used in streams carrying relatively coarse sediments.

Any slow-filling sediment sampler with a fixed volume container will have an uneven rate of filling on being subjected to a pronounced pressure differential between the sampling point and the air in the container. When the sampler is opened below the water surface, there occurs an inrush of the water-sediment mixture, called initial inrush, which is volumetrically a function of the depth of submergence. Both pressure differential and filling rate are quickly reduced as the air in the sampler is compressed, after which period the filling operation becomes the normal action involving displacement of air. The initial inrush period was found

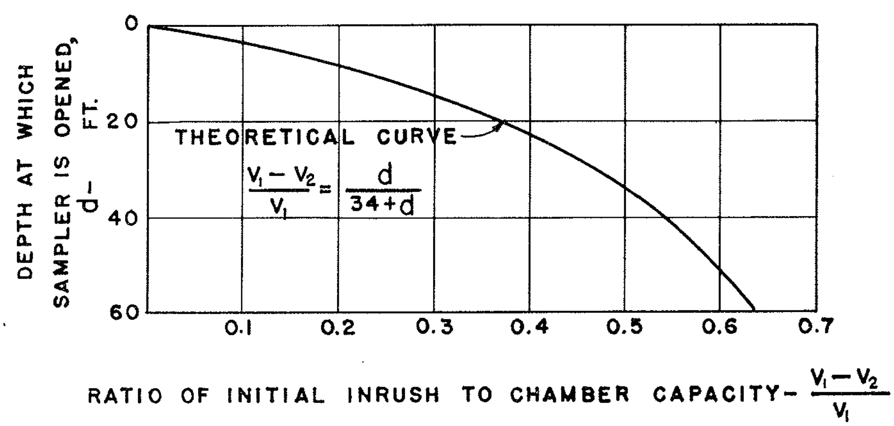


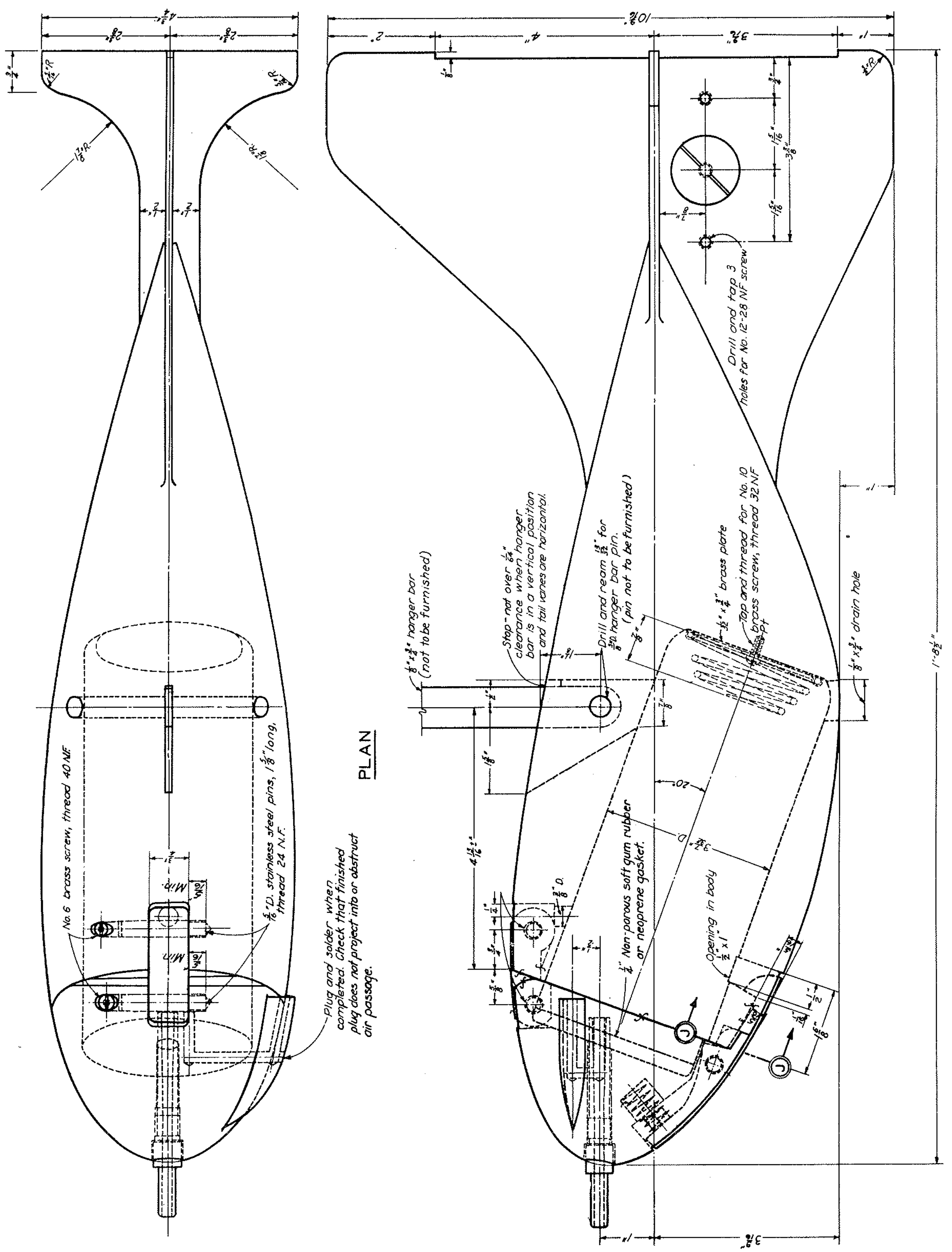
Fig. 14--Initial inrush for slow-filling samplers

to be less than 1 sec. in experiments described in Report No. 5. In still water tests on five different designs the observed initial inrush deviated less than 1 percent from the theoretical curve shown in Fig. 14. For samplers with fixed volume containers, the initial inrush can be eliminated if the design provides a means of pressure balance between the air in the container and the hydrostatic pressure surrounding the sampler. However, none of the earlier designs provided for this pressure balance. A pressure differential between the sampling point and the container can cause sampling errors in the following ways:

> a. The excessive sampling rate during the initial inrush period will tend to segregate sediment from the water resulting in a sample too low in concentration.
>
> b. With the opportunity for a relatively large portion of the sample container to be filled in less than 1 sec., the sample will not represent the mean sediment concentration at the sampling point.
>
> c. When the sample is collected only on the upward trip in the depth-integration method, too large a portion of the total sample will represent the concentration near the bottom.

In the procedure of taking point-integrated samples the open container is sometimes lowered rapidly to the desired sampling point in the belief that the sampler will not fill sufficiently in the short lowering time to cause appreciable error. However, laboratory experiments have indicated that the initial inrush attains its full effect substantially as fast as the sampler can be lowered in the stream. Consequently, this procedure should be used only if the sampler is designed to equalize automatically the hydrostatic pressure.

24. Improved designs of integrating samplers--A thorough study of existing samplers and their sampling action was made by representatives of the agencies cooperating on this project, and on the basis of findings in this study improved forms of integrating samplers have been developed. The point-integrating type of sampler would cover the greatest range of field conditions in the routine determination of sediment discharge in streams. However, the initial cost of this type of sampler was estimated to be considerably greater than the simpler depth-integrating sampler. Therefore, it was concluded that experimental models of both types of samplers should be developed with a view to providing practical and ef-



SUSPENDED SEDIMENT SAMPLER US D-43

FIG. 15

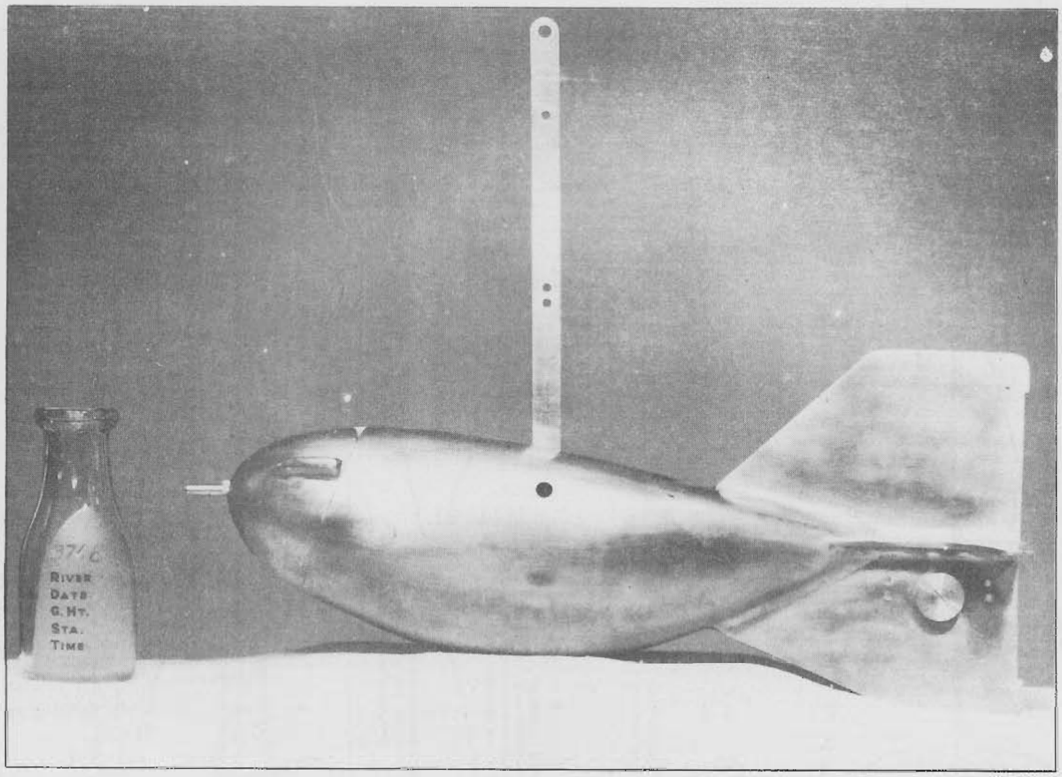


Fig. 16--U.S. depth-integrating suspended sediment sampler, D-43 (50 lb.)

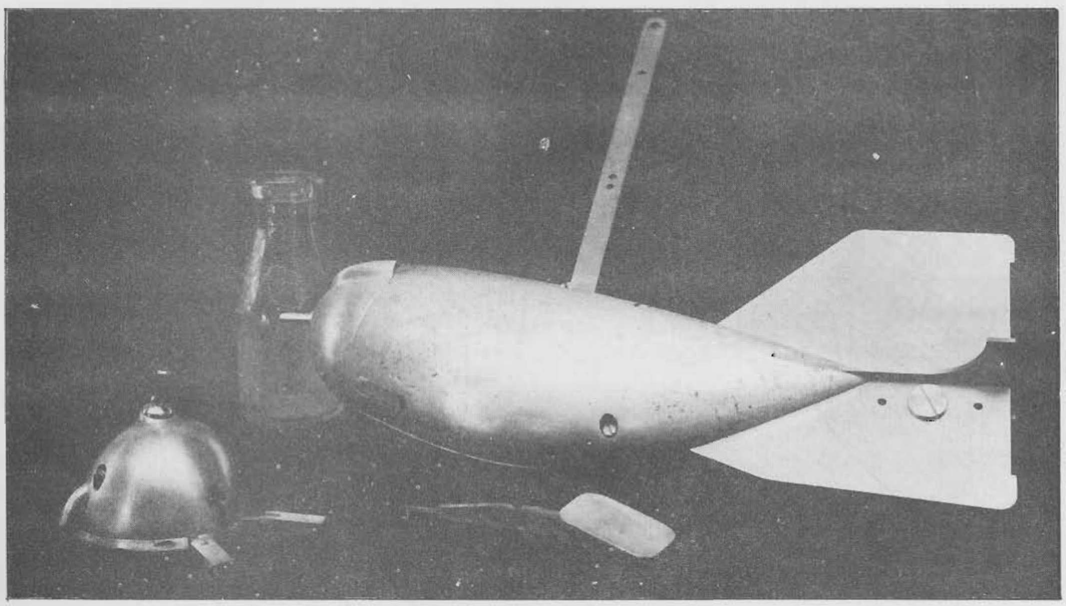


Fig. 17--U.S. depth-integrating suspended sediment sampler, D-43 with auxiliary head

ficient equipment for as wide a range of field conditions as possible. The present designs of the depth-integrators developed by representatives of the agencies cooperating on this project are designated U. S. Sediment Sampler D-43 and D-47, while that of the point-integrator is designated U. S. Sediment Sampler P-46.

The simpler of two D-43 samplers is shown in Figs. 15 and 16. It consists of a cast bronze streamlined body with integral horizontal and vertical tailvanes. The forward section or head is hinged to provide access to the sample container, a pint milk bottle which is inserted into a cylindrical recess. When the head is latched to the body of the sampler, a sponge rubber gasket on the inner surface of the head seals the sample container except for two tubes which connect the container with the outside medium. One of these tubes projects upstream in the form of an intake nozzle which is made removable so that different sizes can be used to regulate the rate of filling. With an outlet in the projection on the side of the head, the second tube provides a release for the displaced air. The sample container is supported in an inclined position in the body of the sampler in order to eliminate the tendency to spill when it is nearly full. The D-43 sampler weighs about 50 pounds and can be suspended from a standard current meter hanger bar.

By means of a slight taper in the intake tube and trial locations for the exhaust tube agreement was obtained between the intake velocity and the stream velocity at point of intake as shown in Figs. 18 and 19. Thus the sample filament should be free from the segregating effects of curved streamlines. As the sample is collected on both the descending and ascending trips, the maximum sampling depth is approximately 17 feet.

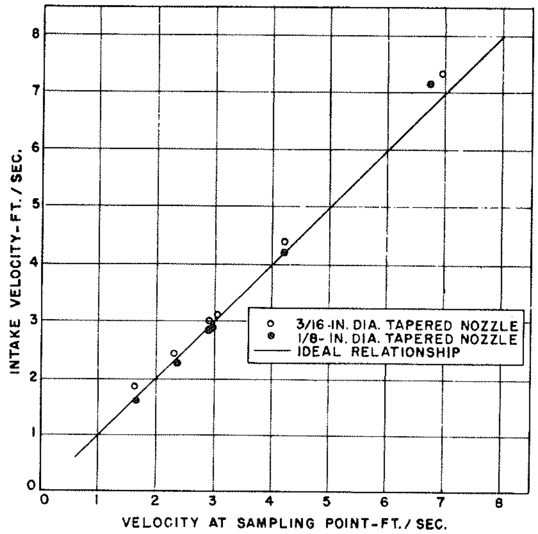


Fig. 18--Intake characteristics of the D-43 sampler (laboratory tests)

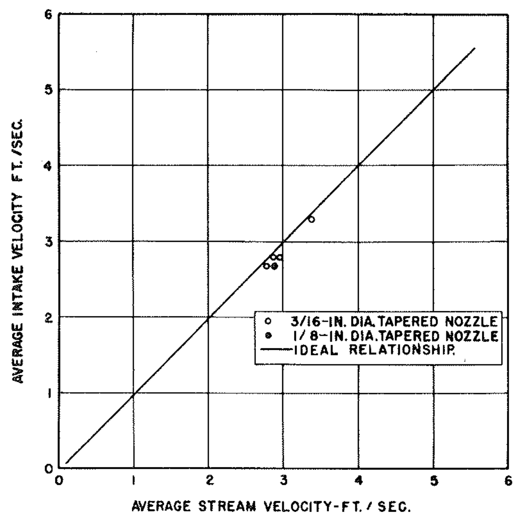


Fig. 19--Intake characteristics of the D-43 sampler (field tests)

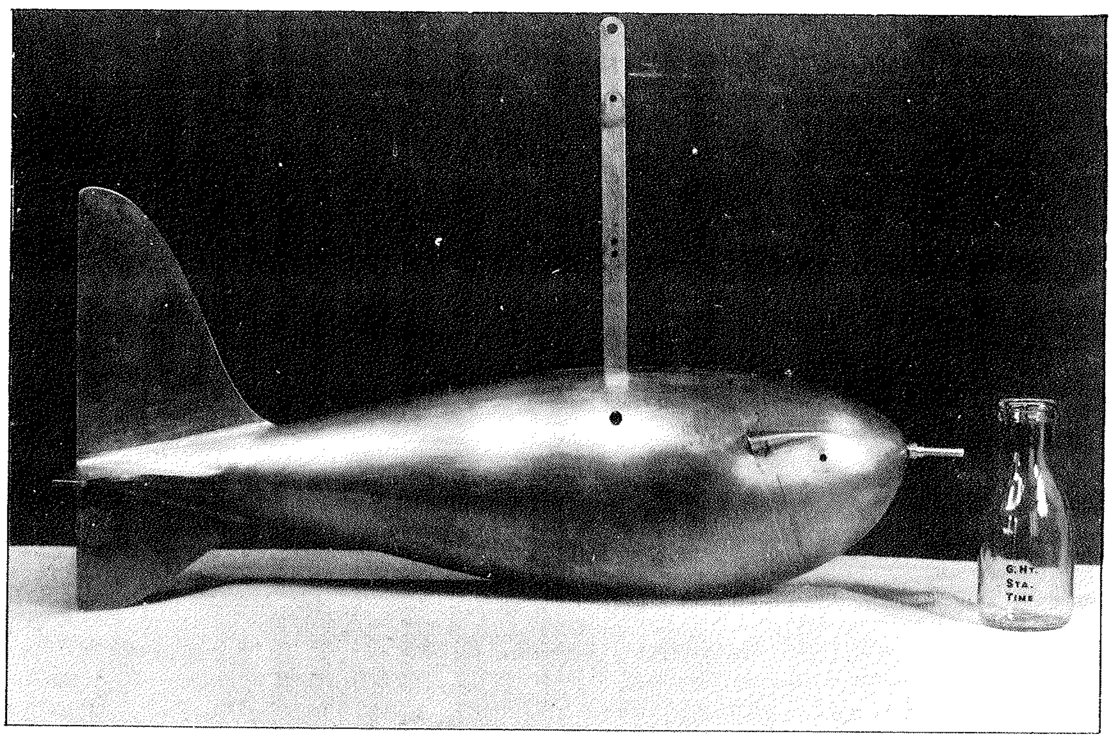


Fig. 20--U.S. point-integrating suspended sediment sampler, P-46

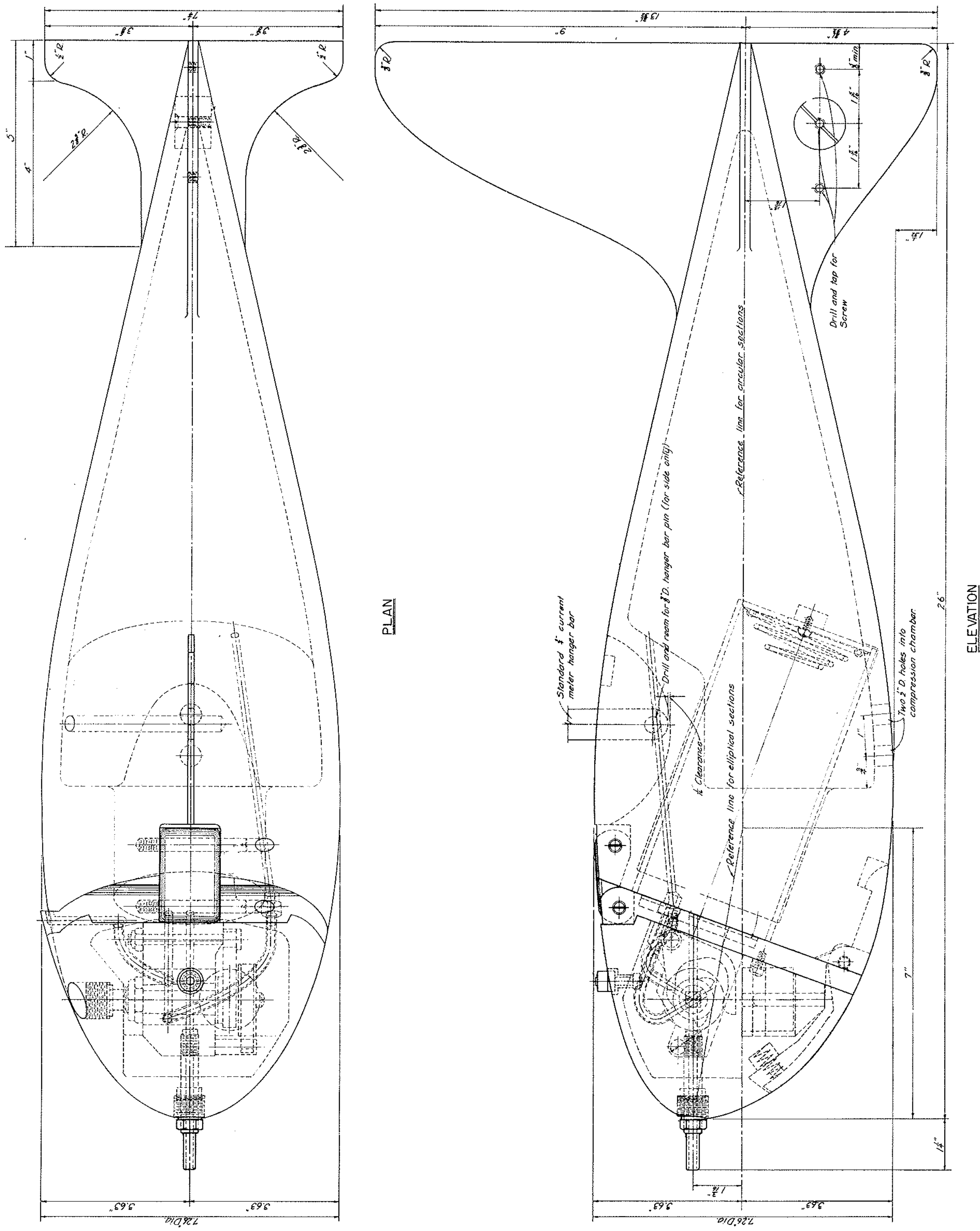
Limitations on the lowering rate and maximum sampling depth, depending on nozzle size and velocity distribution in the vertical, are discussed in Report No. 6.

The D-43 sampler with an auxiliary head is shown in Fig. 17. It differs from the simpler design in that the filling period can be terminated at the end of the downward trip. Upon contact with the stream bed a trigger, consisting of a flat plate below the body of the sampler, closes the intake and air exhaust passages. As the sampler fills on the downward trip only, its maximum sampling depth is about 34 feet.

The present point-integrating sampler is designed to accumulate a water-sediment sample which is representative of the mean sediment concentration at any selected point, and it is constructed so that the air pressure in the container and the external hydrostatic head are equalized at all depths. The inrush, which ordinarily occurs when the intake and air exhaust are opened below the surface of the stream, is thereby eliminated. Pressure equalization between the air in the container and the outside medium is achieved by the use of the diving bell principle.

The body of the U. S. point-integrating sampler consists essentially of a streamlined cast bronze shell, an inner recess to hold the sample container, an air chamber having a volume about five times that of the sample container, and a tapered rotary valve with an electro-mechanical operating mechanism. The air chamber and the sample container are interconnected by means of tubing and a passage through the rotary valve. When the intake and air exhaust tubes, which are also controlled by this valve, are closed prior to lowering the sampler into a stream, the pressure equalizing passage is open. As the sampler is submerged, water enters the air chamber through a permanent opening in the bottom of the shell, thereby compressing the air in the air chamber and in the sample container. The valve is driven by a flat clock spring and is controlled by an escapement for three positions: (1) intake and air exhaust closed, equalizing passage open; (2) intake and air exhaust open, equalizing passage closed; (3) all passages closed. A solenoid, energized by two or more 6-volt lantern batteries, is used to trip the escapement which in turn allows the valve to revolve from one position to the next. From the batteries, located on the operating rig, the current flows through a two-conductor current meter cable to the solenoid. The point-integrating sampler of the most recent design, designated U. S. P-46, weighs about 100 pounds unsubmerged. Details of this sampler are shown in Figs. 20 and 21.

The P-46 sampler is primarily a point-integrator but can be used also as a depth-integrator. With the valve in the open position a sample can be integrated from the surface to the bottom and return, or the valve can be closed at the bottom so that the sample is taken only on the downward trip. The sampler may also be lowered to the stream bed with the valve in the equalizing position, then opened, and the sample taken on the ascending trip only, or the sampler may be used to integrate any portion of a sampling vertical. Thus in extremely deep streams the vertical may be sampled either by the point method or by successively integrating portions of the vertical. As a point sampler this instrument can be used also in sampling density flows in reservoirs. By whatever method the sampler is operated the pressure in the container and outside hydrostatic pressure are automatically balanced and the effect of initial inrush



SUSPENDED SEDIMENT SAMPLER US P-46

FIG. 21

is eliminated.

The D-47 depth-integrating sampler differs from the P-46 sampler in that the valve is designed to move only once. Like the P-46 it has an air pressure equalization chamber, the form and size shown in Fig. 20, and a weight of about 100 pounds. Designed for greater depths and velocities than the D-43 samplers, the D-47 can be used to sample on the downward trip only by closing the valve at the stream bed, or on the upward trip only by opening the valve at the stream bed.

25. Summary on sediment samplers--The advantages of having a sampler that would meet the requirements of all possible stream conditions can be readily appreciated. As the attainment of such a design seemed impossible the following requirements related in particular to integrating types were kept in mind during the sampler development discussed in preceding paragraphs. This list will also serve to indicate weaknesses of some of the present unsatisfactory types.

a. The velocity within the cutting circle of the intake should be equal to the stream velocity.

b. The intake should be pointed into the approaching flow and should protrude upstream from the zone of disturbance caused by the presence of the sampler.

c. The sampler should fill smoothly without sudden inrush or gulping.

d. The sample collected at a point should not be contaminated by water or sediment accumulated prior or subsequent to sampling.

e. The volume of the sample should be sufficient to satisfy the laboratory requirements for the determination of concentration and size analysis.

f. The sampler should be adaptable for use in streams of any depth and for sampling at any desired depth.

g. The sampler should be streamlined and of sufficient weight to avoid excessive drag.

h. The sampler should be of simple design and yet sufficiently rugged to minimize the need for repairs in the field.

i. The sample container should be removable and suitable for transportation to the laboratory without loss of any of the contents.

j. The sample container should be transparent so that the degree of settlement can be observed.

k. The cost of the sampler should be as low as possible consistent with good design and performance.

As no design has been evolved thus far which has been satisfactory for taking both instantaneous and integrated samples, the engineer should consider the limitations of each type. The principal disadvantage of an instantaneous sampler lies in the number of samples that must be taken for a determination of the mean concentration in a vertical or the mean concentration at a point when the concentration fluctuates widely. Another disadvantage lies in the necessity of transferring the sample to another container, inasmuch as none of the present types has a detachable sample container. Also there is the possibility that sediment will deposit in the container of a horizontal trap sampler while the water-sediment mixture is allowed to pass through the container prior to the taking of an instantaneous sample. Integrating samplers are limited in their operation to relatively slow filling rates. Accordingly, the present types of integrating samplers cannot be used for the determination of the instantaneous concentration at a point in a stream.

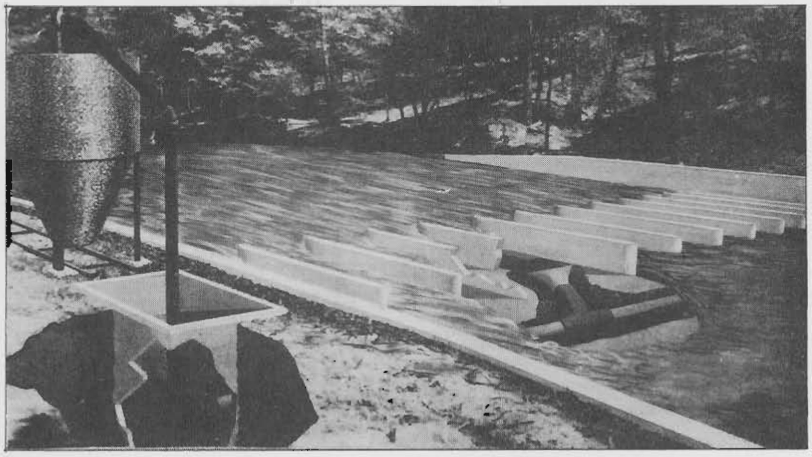
The most important application of the instantaneous sampler is in the investigation of sediment load pulsations. However, such investigations are ordinarily made only in specialized phases of research work and, therefore, constitute a minor part of the suspended sediment field. The principal reason for obtaining suspended sediment samples is to determine the mean sediment concentration at a point or in a vertical. It is thought that the integrating samplers developed in this cooperative study will be found more effective for this purpose than other samplers in the majority of conditions encountered. It is recognized, however, that until direct comparisons of the best forms of the various types of samplers are made under a wide range of conditions, conclusive proof of the superiority of one type over another will be lacking.

V. MEASUREMENTS OF BED-LOAD MOVEMENT AND BED-MATERIAL

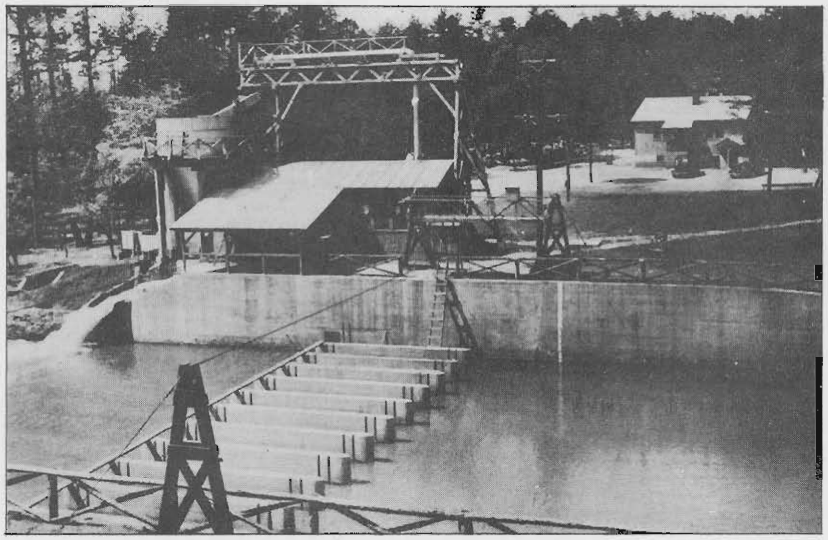
26. The measurement of bed-load movement--Fluvial sediment investigations are usually confined to measurement and analysis of the suspended sediment load; as a rule the rate of bed-load movement is not measured. In the absence of such measurements any estimate of bed-load movement must of necessity be based on some less direct method. The emphasis placed on measurement of the suspended sediment load appears to be justified because the medium of transfer of this part of the total sediment load constitutes the major portion of the depth of the stream, whereas the zone of bed-load movement is usually relatively thin. However, the amount of sediment transported as bed-load may be a significant part of the total sediment load due to the higher concentrations in the bed-load zone.

The rate of bed-load movement in streams has been determined from samples obtained by means of bed-load samplers, by traps with fixed slots located in the stream bed, or indirectly from measurements of deposits in a downstream reservoir. Samples taken from a reservoir deposit will have material from both the suspended sediment load and the bed-load, but that part of the deposit which traveled as bed-load can be estimated from the proportion of particles which are larger than the maximum size found in suspension in the flowing stream. From the rate at which the reservoir deposit builds up, the rate of bed-load movement can be computed.

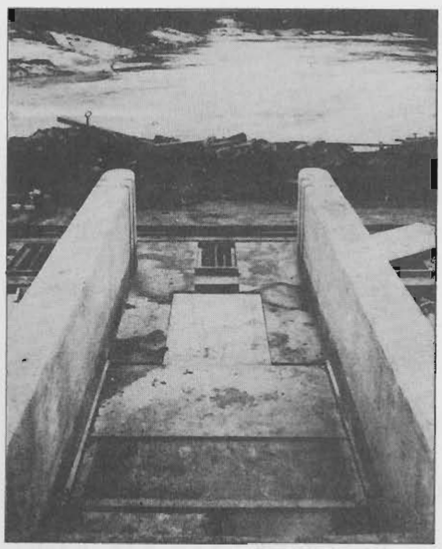
Making use of the fixed-slot method, the Soil Conservation Service has constructed at Greenville, South Carolina, an elaborate apparatus to measure the rate of bed-load transportation in the Enoree River. Views



a. Artist's conception of apparatus.



b. View of actual apparatus.



c. Door to slot in closed position

Fig. 22--Bed-load collecting apparatus used by the Soil Conservation Service Experiment Station, Enoree River, Greenville, South Carolina.

of the measuring apparatus are shown in Fig. 22. The entire width of the river bed for a length of about 100 ft. is paved with concrete. Near the lower end of this pavement the river is divided into 14 sub-channels, 5 ft. wide. Bed-load material drops into the sub-channel slots through sliding doors and is pumped through a pipe beneath the floor to a hopper on the bank. In the hopper the bed-load settles and the waste water flows over a spillway crest. This apparatus has been used by the Soil Conservation Service to obtain continuous records of bed-load movement (4).

27. Bed-load samplers--In the available literature on bed-load samplers descriptions were found of twenty-one different designs, all of which have been developed since 1898. Bed-load samplers can be classified according to their design or principle of operation into three types: basket, pan, and pressure-difference. The rate of bed-load movement is determined from the amount trapped per unit time in a sampler located at one or more points across the stream bed.

The first and probably the most commonly used type of sampler consists of a basket or box which is generally made of mesh material. In most designs of this type the upstream end has a permanent opening through which the water-sediment mixture passes. In these designs the mesh material should pass the suspended sediment load but retain the bed-load. Considerable difficulty has been experienced with the basket type sampler because of the tendency toward a forward motion as the sampler settles into the slower moving water near the bed. Because of this forward motion the sampler might remove some material from the stream bed. On the other hand, the presence of the sampler causes an increased resistance to flow and a lowering of the velocity upstream from the sam-

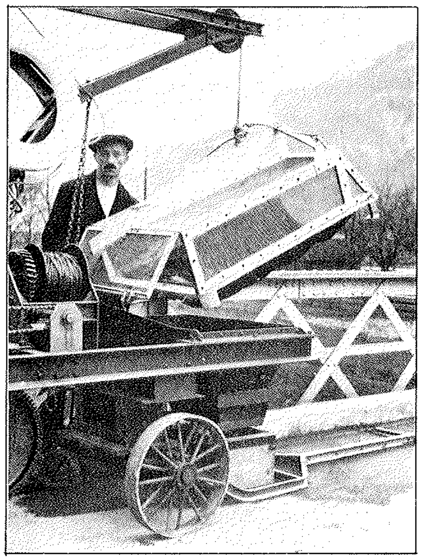


Fig. 23--Sampler used by the Swiss Federal Authority.

pler. The decreased intake velocity causes some of the bed-load movement to stop before the material reaches the sampler. The basket sampler made by the Swiss Federal Authority for Water Utilization, shown in Fig. 23, is probably the most extensively developed of any sampler of this type. It consists of a prismatic steel frame, 70 by 30 by 100 cm., inclosed on the top and three sides with screen and on the bottom with loosely interwoven rings of metal which are similar to the mail formerly used as defensive armor. The sampler is lowered in a tilted position to avoid digging of the bed at

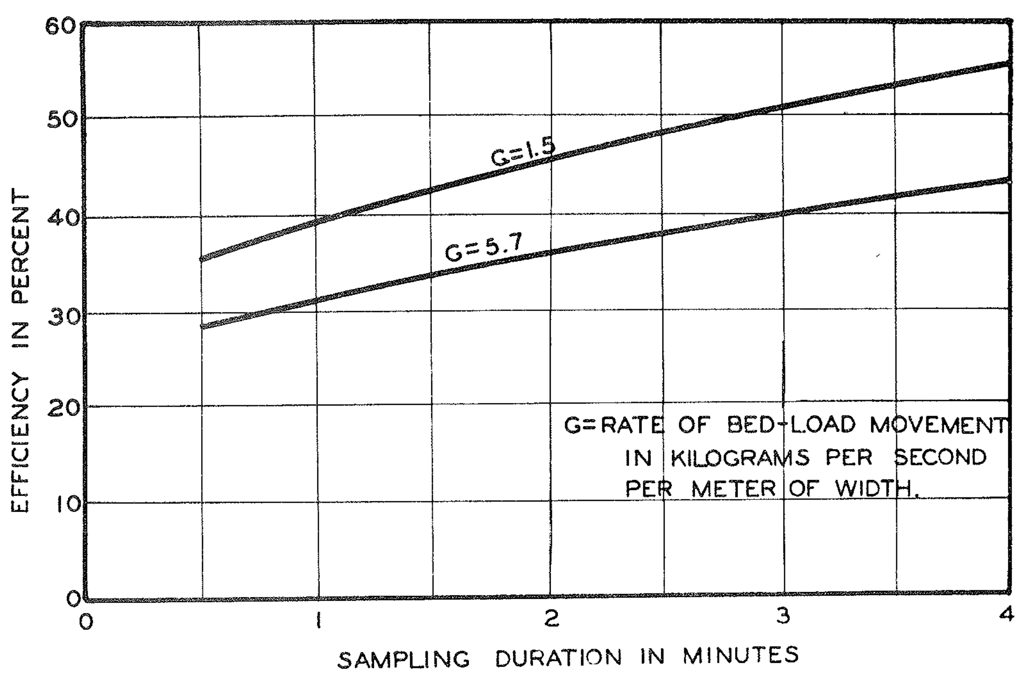


Fig. 24--Efficiency of Swiss sampler as a function of sampling duration and rate of bed-load movement.

the sampler entrance, and it rests on the stream bed with the ring mesh conforming to the shape of the bed. After the sampler is raised it is emptied through a hinged flap on the downstream side. The efficiency of this sampler as determined by the Swiss Federal Authority was found to vary with the rate of bed-load movement and the sampling duration as shown in Fig. 24.

Pan type samplers, which have been used most extensively in Russia, are usually wedge-shaped in longitudinal section, and they are located on the stream bed with the point of the wedge cutting the current. Fig. 25

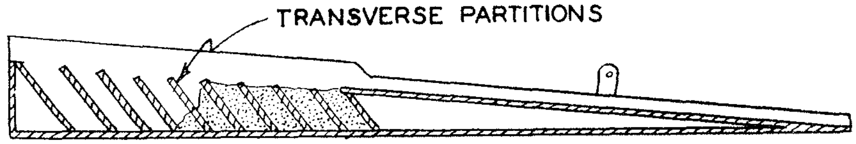


Fig. 25--Polyakov sampler.

shows a Russian design known as the Polyakov sampler. In this sampler the downstream end of the pan is divided by transverse strips of metal. The bed-load moves along the top of the pan and it is trapped in the transverse slots. Since pan type samplers also cause obstructions to stream flow, their efficiency should be determined. The Polyakov sampler was calibrated in a flume in which the true rate of bed-load movement was determined from the amount trapped at the end of the flume. The efficiency of the Polyakov sampler was found to be 46 percent in tests made by G. I. Shamov, who concluded that the low efficiency was due mainly to the inclined surface leading to the entrance. Mounds of material formed on the inclined surface, and although some material rolled over the mounds into the sampler, other grains rolled in a transverse direction away from the stream carries such great quantities of organic material that a screen tends to plug up during the sampling period, separation must be based on the principle of local velocity reduction.

The box or basket type sampler is the only one adaptable for use in mountainous streams carrying coarse gravel material. It is the smallest type for given entrance conditions, therefore, the least cumbersome, but it has the disadvantage of creating considerable back pressure which causes the slow-moving bottom layers to be deflected around the sampler but only retards the quick-flowing upper layers. Therefore, fine material creeping along the bottom (low rate of transportation) is deflected, while the same size material moving by saltation (high rate of transportation) is more readily trapped.

The pan type samplers seem to be best suited for bases which have comparatively smooth sand beds and on which a slow rate of bed-load movement occurs with all the movement concentrated in the bottom layer. For sandy beds the pressure-difference type of sampler seems to be the most satisfactory, especially when the entrance section is small and the frame flexible enough to ensure a snug fit against irregularities of the bed.

The final selection of the type most applicable to the particular conditions in a given stream can be based only on a thorough calibration test duplicating all conditions of the river as closely as possible. This calibration is necessary because the efficiency of a given sampler may change considerably with the grain size, rate of transportation, etc. It must therefore be emphasized that the calibration of the trap is almost as important as the measurements themselves, regardless of the type of sampler that is used. Only carefully performed bed-load measurements can be expected to furnish reliable results.

29. Bed-material samplers--Material of the stream bed may be composed of deposits of sediment which have been carried in suspension or along the stream bed or it may even consist of a residual. Bed-material samplers, which are used to obtain samplers of this material, have been grouped into three classes: drag bucket, vertical pipe or cylinder, and grab bucket

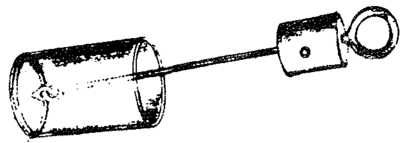


Fig. 28--Simplified Rock Island Sampler.

The drag bucket, which is the most common of the three types, consists of a weighted bucket or cylinder with a cutting edge. While being dragged along the stream bed, the bucket cuts a layer of material usually 1/2 to 2 in. in thickness. The sampler may have a weighted central stem as shown in Fig. 28. The weight is used to keep the stem at a more or less constant distance from the stream bed so that the sampled depth will be fairly constant. After the sample is collected in a drag bucket, some of the finer material may be lost in transit to the water surface because of exposure to the current.

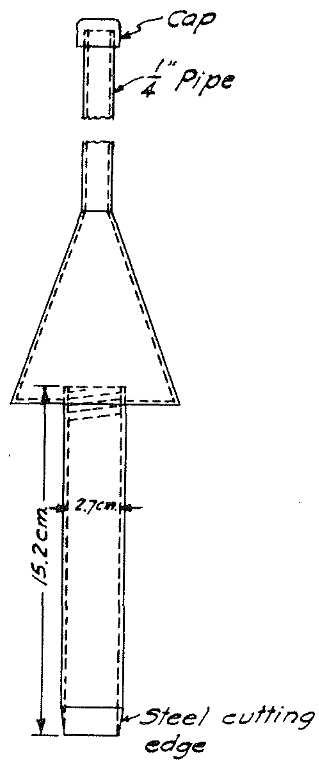


Fig. 29--Pipe sampler used in Imperial Valley Canals.

In the classification of vertical pipe samplers are pipe, cylinder, and cone-shaped containers which are forced or settle of their own weight into the stream bed. Sampled material may be held in the container by check valves or by a partial vacuum. The vacuum principle is used in the operation of the vertical pipe sampler shown in Fig. 29. After the sampler has been forced into the stream bed to a depth equal to the length of the lower pipe, the handle (ending in the cone section) is filled with water and capped, thus forming a partial vacuum when the sampler pipe is withdrawn. A vertical pipe sampler which must be forced into the stream bed is obviously less adaptable to deep than to shallow streams.

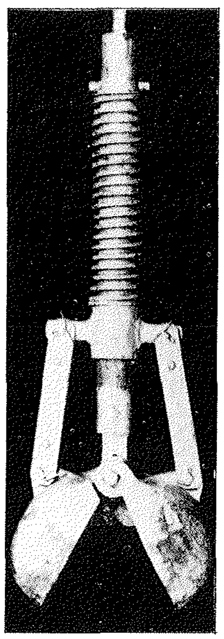


Fig. 30--Ross Grab Bucket.

The grab bucket type is similar to but smaller than the clamshell bucket used in earthwork operations. The cupped jaws of the grab bucket, on reaching the stream bed, may be closed either by a pull on an auxiliary line or by an automatic spring arrangement. A disadvantage in the operation of this type consists in the possibility of large particles becoming caught in the jaws with the result that some of the fine material might escape. The automatic spring arrangement is used in the sampler shown in Fig. 30.

30. Future research--The developmental phase of the cooperative study has been confined to the field of suspended sediment; it has not included the measurement of bed-load or bed material, or the development of new types of instruments for such measurements. This does not necessarily mean that bed-load problems have been considered unimportant. Instead, the problems related to the measurement of suspended load appeared

to be more urgent because of the preponderance of studies in that field. It is recognized that in some localities the quantity of sediment transported in streams as bed-load and the related engineering problems outweigh those of suspended sediment. Where sediment of any kind plays an important part in the development or regulation of a stream, the role of bed-load movement should be given consideration. It is apparent, therefore, that the complete solution of the various phases of the fluvial sediment problem demands further investigation of the characteristics of bed-load, and it is probable that improvements are necessary in the techniques and equipment used in making quantitative measurements of the rates of transportation.

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