A Study of Methods Used in

MEASUREMENT AND ANALYSIS OF SEDIMENT LOADS IN STREAMS

A Cooperative Project
Sponsored by the
Subcommittee on Sedimentation
Inter-Agency Committee on Water Resources
and Under the Executive Direction of a Technical Committee

Participating Agencies

Army Corps of Engineers ** Geological Survey
Soil Conservation Service ** Bureau of Reclamation
Agricultural Research Service ** Coast and Geodetic Survey
Tennessee Valley Authority ** Federal Power Commission
Bureau of Public Roads ** Department of Labor
Forest Service ** Bureau of Mines
Public Health Service

REPORT NO. 14

DETERMINATION OF FLUVIAL SEDIMENT DISCHARGE

Prepared for Publication by the Project Staff of Cooperating Agencies
at St. Anthony Falls Hydraulic Laboratory
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PREFACE

This report supersedes Report No. 8, "Measurement of the Sediment Discharge of Streams", which was published in 1948 as one of the series of reports on "A Study of Methods Used in Measurement and Analysis of Sediment Loads in Streams". In the ensuing years new sediment sampling equipment has been developed and sampling procedures and techniques have been improved. This report presents the new equipment and procedures together with some of the material which appeared in Report No. 8.

Acknowledgment is given to the late E. W. Lane for the enthusiastic support and valuable guidance which he gave the Inter-Departmental Project during its early years when it was under his general direction at the Iowa Institute of Hydraulic Research.

This report was prepared under the sponsorship of the Subcommittee on Sedimentation of the Inter-Agency Committee on Water Resources and under the executive direction of the Technical Committee. The report was prepared by Frederick S. Witzigman and reviewed by Byrnon C. Colby. Many helpful suggestions and constructive criticisms were received from Martin E. Nelson and from members of the Technical Committee, who are P. C. Benedict, Geological Survey; D. C. Bondurant, Army Corps of Engineers; W. M. Borland, Bureau of Reclamation; H. G. Heinemann, Agricultural Research Service; M. D. Hoover, Forest Service; E. H. Lesesne, Tennessee Valley Authority; E. M. Thorp, Soil Conservation Service.

In recent years the following men have worked on various phases of the Inter-Agency Sedimentation Project: T. F. Beckers, R. P. Christensen, B. C. Colby, Project Engineer, H. A. Jongedyk, J. A. Skinner, H. H. Stevens, Jr., and F. S. Witzigman.

SYNOPSIS

This report reviews the equipment, practices, and some of the basic concepts commonly associated with fluvial sediment investigations. Information that is useful to engineers who are directly concerned with measurement of sediment discharge has been taken from previous reports and new information has been added. The necessity for studying sediment problems that are encountered in hydraulic engineering projects is discussed and a brief history of early sediment measurements is given.

The fundamental concepts of sediment transport are described, and the vertical distribution of suspended sediment is explained on the basis of the turbulence theory. The general principles of sediment discharge measurements are discussed as well as the practical aspects of selecting sampling points and of determining the frequency of sampling. Methods of computing sediment discharge are explained.

The advantages of the equipment developed as a part of the Project activities are discussed and details of the depth-integrating, point-integrating, single-stage, and pumping type samplers are presented. Equipment for collection of samples of bed material in place and available equipment for measuring bed-load discharge are described.

So-called automatic suspended-sediment samplers for improving the sample coverage through frequent sampling of flashy or ephemeral streams are discussed. They include single-stage samplers, which are extensively used, and pumping samplers, which are in the field test stage. Research to develop better automatic sediment sampling equipment is described.

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I. INTRODUCTION

1. Purpose and scope--This report was prepared for the benefit of those who engage in, or supervise, sediment investigations. Sediment sampling equipment and procedures are described so that personnel can select appropriate samplers and sampling methods for specific sediment sampling programs. Some fundamentals of sediment transportation are explained as a basis for understanding the principles involved, also the report includes research that is currently in progress.

Some aspects of the computation of sediment discharge are discussed briefly to show the need for certain types of samples and sediment information. The discussion is not intended as a guide to those who compute sediment discharge, but as an indication of the sampling program that is needed as a basis for the computation of sediment discharge.

Because the applicable material is so extensive and space here is limited, a brief summary is included of the most important parts of publications that treat certain phases of the subject. References to the more complete publications are given for those who may wish to pursue a subject further.

2. The sediment problem--In the past, many hydraulic engineering works have been built on sediment-bearing streams without adequate consideration of the effects of sedimentation on the life and utility of the projects. The presence of sediment caused unforseen difficulties in operating and maintaining these engineering works, and shortened the economic life for many of them. As time goes on, more and more projects will experience sedimentation problems because of the time lag which occurs before these problems become evident and because of the increased development of streams that are heavily laden with sediment. Difficulties already encountered have caused engineers to consider rivers as streams of sediment as well as streams of water.

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 sediment load (the material itself) and sediment discharge (the rate of transport of the sediment load) has been neglected. Only a few isolated sediment measurements were made throughout the world prior to about 1925, and the importance of obtaining systematic records of sediment transport commensurate with the parallel records of water discharge has been seriously considered only within the past few decades. The increasing demand for reliable data on the sediment characteristics of streams requires the development of instruments and methods that facilitate collection of accurate field data. With its many ramifications into the fields of water power development, water supply, navigation, flood control, loss of reservoir storage capacity, irrigation, land damage, 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.

3. Federal cooperative study of fluvial sediment problems--Several agencies of the United States Government recognized the desirability of improving methods for measuring the quantity and determining the character of sediment that is transported in streams. They organized an Interdepartmental Committee in 1939 to standardize methods and equipment and to study problems encountered in collecting sediment data. The agencies were: Corps of Engineers of the Department of the Army; Flood Control Coordinating Committee of the Department of Agriculture; Geological Survey, Bureau of Reclamation, and Office of Indian Affairs of the Department of Interior; and the Tennessee Valley Authority. The Iowa Institute of Hydraulic Research cooperated in the study which was carried on at the Hydraulic Laboratory, State University of Iowa, Iowa City, Iowa. The project was under the general supervision of the late Professor E. W. Lane of the Iowa Institute of Hydraulic Research from 1939 to June 1942. From July 1942 to July 1945, the project activities were supervised by M. E. Nelson, Army Corps of Engineers, and L. C. Crawford, Geological Survey; and the research work was conducted by personnel of both agencies.

In April 1946, the Interdepartmental Committee transferred its activities and functions to the Subcommittee on Sedimentation of the Federal Inter-Agency River Basin Committee. The Inter-Agency Committee was composed of representatives of the Department of the Army, Department of the Interior, Department of Agriculture, Department of Commerce, Tennessee Valley Authority, and Federal Power Commission, and had as one of its objectives the coordination of the hydrologic activities of these Federal Departments through the assistance of its subcommittees. The Subcommittee on Sedimentation formally took over the activities and unfinished program of the Interdepartmental Committee in June 1946. The agencies currently represented on the Subcommittee on Sedimentation are indicated on the title page of this report. In June 1948 the project moved from the Iowa Institute of Hydraulic Research to the St. Anthony Falls Hydraulic Laboratory of the University of Minnesota in Minneapolis, Minnesota. In 1955 the name of the parent committee was changed to the current designation, Inter-Agency Committee on Water Resources. From 1946 to 1955 project activities were under the general supervision of M. E. Nelson, Army Corps of Engineers, and P. C. Benedict, Geological Survey. The research work was conducted by personnel of both agencies. Since 1956 Mr. Nelson has been a consultant to the project and Mr. Benedict has been on the Technical Committee.

The Subcommittee reorganized the project in 1956 as the Inter-Agency Sedimentation Project and adopted a Guidance Memorandum outlining project objectives, organization, and program. The basic objective of the project is the solution of problems within the field of sedimentology that are of common concern to the agencies represented on the Subcommittee. The paramount problem is measurement and evaluation of quantity and characteristics of sediment that is transported by streams.

A Technical Committee whose membership is made up of representatives from Federal agencies actively concerned with sediment problems provides technical direction for the project. The operating staff carries out the development, testing, and calibration of instruments; preparation of technical reports; and other operational phases of the project. The agencies actively cooperating in the investigation and currently represented on the Technical Committee are: Army Corps of Engineers, Geological Survey, Bureau of Reclamation, Agricultural Research Service, Soil Conservation Service, Public Health Service, Forest Service, and Tennessee Valley Authority.

Results of the cooperative studies are incorporated in a series of technical reports listed on pages 148 to 151.

4. Usage of terms--In the field of fluvial sediment, some terms have been used indiscriminately and often with ambiguous or variant meanings.

The usage of terms in this report is as follows:

BED or STREAMBED--The bottom of a water course.

BED LOAD--Sediment that moves by saltation, rolling, or sliding on or near the streambed.

BED-LOAD DISCHARGE--The quantity of bed load passing any cross section of a stream in a unit of time.

BED-LOAD DISCHARGE SAMPLER--A device to measure the discharge of bed-load over part or all of the stream width.

BED MATERIAL--The sediment mixture of which the streambed is composed.

BED-MATERIAL DISCHARGE or COARSE-SEDIMENT DISCHARGE--That part of the sediment discharge of a stream which is composed of particle sizes present in appreciable quantities in the shifting portions of a streambed.

BED-MATERIAL SAMPLER--A device for taking a sample of the sediment of which the streambed is composed.

CLAY--Sediment particles smaller than 0.004 mm in size.

COMPOSITE SAMPLE--A single sample formed by combining all the individual samples that pertain to a single sampling unit.

CONTACT LOAD--Sediment particles that roll or slide along in almost continuous contact with the streambed.

DENSITY of water-sediment mixture--The bulk density which is the mass per unit volume including both water and sediment.

DEPTH-INTEGRATED SAMPLE--A water-sediment mixture that is accumulated continuously in a sampler that moves vertically at an approximately constant transit rate between the surface and a point a few inches above the bed of a stream, and that admits the mixture at a velocity about equal to the instantaneous stream velocity at each point in the vertical. Because the sampler intake is a few inches above the sampler bottom, there is an unsampled zone a few inches deep just above the bed of the stream.

DEPTH INTEGRATION--A method of sampling to obtain a representative sample of the water-sediment discharge from every part of a stream vertical, except in a small unsampled zone near the streambed.

DISCHARGE-WEIGHTED CONCENTRATION--The dry weight of sediment in a unit volume of stream discharge, or the ratio of the discharge of dry weight of sediment to the discharge by weight of water sediment mixture. (See Section 7).

FINE-MATERIAL LOAD or WASH LOAD--That part of the total sediment load that is composed of particle sizes not present in appreciable quantities in the bed sediment. (Normally the fine-material load is finer than 0.062 mm).

MEAN PARTICLE DIMENSION--The particle dimension for which half the sediment by weight is coarser and half is finer.

POINT-INTEGRATED SAMPLE--A water-sediment mixture that is accumulated continuously in a sampler that is held at a relatively fixed point in a stream and that admits the mixture at a velocity about equal to the instantaneous stream velocity at the point.

POINT-INTEGRATION--A method of sampling to obtain a sample that represents the mean concentration of sediment in the stream discharge passing a point in a stream during the sampling time.

SALTATION LOAD--The sediment bounced along the streambed by the impact of the flow or of other moving particles.

SAMPLING VERTICAL or simply VERTICAL--An approximately vertical path from water surface to streambed along which samples are taken to define sediment concentration or distribution.

SAND--Sediment particles between 0.062 and 2 mm in size.

SEDIMENT, actually FLUVIAL SEDIMENT--Fragmentary material that originates from weathering of rocks and is transported by, suspended in, or deposited from water.

SEDIMENT CONCENTRATION--The quantity of sediment relative to the quantity of transporting or suspending fluid, or fluid-sediment mixture.

SEDIMENT DISCHARGE--The quantity of sediment that is carried past any cross section of a stream in a unit of time. The discharge may be limited to certain sizes of sediment or to discharge through a specific part of the cross section.

SEDIMENT LOAD or simply LOAD--The sediment that is being moved by a stream. (Load refers to the material itself and not to the quantity being moved.)

SEDIMENT YIELD--The total sediment outflow from a watershed or a drainage area at a point of reference and in a specified period of time. This is equal to the sediment discharge from the drainage area.

SILT--Sediment particles between sand and clay in size (0.004 to 0.062 mm).

SPATIAL CONCENTRATION--The dry weight of sediment per unit volume of water-sediment mixture in place, or the ratio of the dry weight of sediment to the total weight of water-sediment mixture in a sample or unit volume, of the mixture. (See Section 7).

SPECIFIC WEIGHT of sediment--The dry weight per unit volume of sediment in place. It can be computed from the wet bulk density if the specific gravity of the sediment is known.

STANDARD DEVIATION--A statistical measure which in sediment analysis is obtained from the formula $1/2\ (D_{84}/D_{50} + D_{50}/D_{16})$ in which D_{16}, D_{50}, and D_{84} denote sizes of material for which 16, 50, and 84 percent by weight respectively, are finer in a given sample.

STREAM DISCHARGE--The quantity of natural water passing through a cross section of a stream in a unit of time. (The natural water contains both dissolved solids and sediment.)

SUSPENDED-SEDIMENT DISCHARGE--The quantity of suspended-sediment passing through a stream cross section in a unit of time.

SUSPENDED-SEDIMENT SAMPLER--A sampler that collects a representative sample of the water with its suspended-sediment load.

SUSPENDED SEDIMENT or SUSPENDED LOAD--Sediment that is supported by the upward components of turbulent currents and that stays in suspension for appreciable lengths of time.

TOTAL SEDIMENT DISCHARGE--The total sediment discharge of a stream. In this report it is the suspended-sediment discharge plus the bed-load discharge.

TOTAL SEDIMENT LOAD or TOTAL LOAD--The total sediment in transport in a stream. In this report, the total sediment is the sediment moving as suspended load plus that moving as bed load.

UNSAMPLED ZONE--Most suspended-sediment samplers cannot sample within three or four inches of the streambed, and this three or four inches at the bottom of the sampling vertical is called the unsampled zone in contrast to the sampled zone above it. (See Appendix Section 49).

5. History of sediment measurements--Many historical details of sediment observations are related in Report 1 [36]*. Only a few of the more basic comments on sediment sampling will be presented in this section. Programs that are typical of the work of various agencies are mentioned briefly and the improvement in sampling equipment subsequent to 1940 is indicated.

The records of ancient civilizations in China, Mesopotamia, and Egypt indicate that since the earliest times, man has experienced difficulties due to sediment carried by natural streams. Although a knowledge of the manner in which fluvial sediment is transported and deposited would have aided in avoiding or overcoming many of these difficulties, sediment investigations did not begin until 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 measurements of sediment carried by natural streams were made by Gorsse 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 [2] 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 observations of sediment discharge in the United States 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 Humphreys and Abbott in 1851 and 1852 [35]. Sediment samples were taken in the South Pass near the mouth of the Mississippi from 1877 to 1898. Measurements were also made at several stations along the lower, middle, and upper Mississippi and in the Missouri River from 1879 to 1881.

The development of irrigation along the rivers of the southwestern part of this country was often difficult because of the heavy loads of sediment carried by these streams. In order to find a solution to the sediment problem, sediment discharge 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 by the Geological Survey and have been taken more or less continuously since 1897 by this and other agencies. Observations have been made regularly on the lower Colorado River by the Bureau of Reclamation since 1909, and in the Colorado River Basin by the Geological Survey since 1925.

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*Numbers in brackets refer to references, pages 142 to 148.

The initiation of studies for flood control structures and power development on the Missouri River and for navigation and related sediment problems on the Upper Mississippi River created a renewed interest in sediment discharge measurements. Extensive sediment observations were made by the Army Corps of Engineers on the Missouri River and its tributaries in 1929 and 1930 [70], and continually since 1937, and on the Upper Mississippi River in 1930 and 1931 and continually since 1943. The program on the Missouri River was expanded in 1946 to obtain extensive sediment data for design, construction and maintenance of the multiple purpose dams and reservoirs of the Missouri River Basin Development Program.

Since 1945 the Geological Survey has measured suspended-sediment loads on streams in many basins. Several new methods and concepts have been developed by the Survey. The turbulence flume [4] was developed to obtain total sediment discharge so that the relations between total suspended-sediment discharge and bed-load discharge, and between measured sediment discharge and unmeasured sediment discharge could be studied. The modified Einstein method [14] and direct velocity relationships [12] were devised to aid in determination of the coarse-sediment discharge.

While the interest in sediment information and the practice of making sediment discharge measurements were 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 [36].

The foregoing history deals primarily with determinations of suspended-sediment discharge. Measurements of the heavier material moving on or near the streambed apparently were made first by Davis in 1898 in connection with studies for a proposed Nicaraguan Canal. Twenty years later Kurtzman made measurements in the Tirol Rivers in central Europe. This type of work using bed-load discharge samplers has been developed extensively in Europe since 1930, but very little progress in this direction has been made in America. Details of the development of bed-load discharge samplers and bed-material samplers are given in Report No. 2 [37]. Recently developed methods for computing total-load discharge from bed-material measurements are discussed in Section 38.

Total sediment discharge is being measured effectively by the Tennessee Valley Authority on two small streams, one in eastern Tennessee, [72], the other in western North Carolina. Suspended sediment that passes a weir is measured by means of an automatic suspended-sediment sampler that continuously diverts a small portion of the flow into a tank. The volume of sediment that is deposited in the basin upstream from the weir is measured at regular intervals by standard surveying methods, and samples of the deposited sediment are analyzed for density and grain size.

Since 1935 the Soil Conservation Service and Agricultural Research Service have obtained many of their sediment yield data from sedimentation surveys of hundreds of reservoirs and ponds. The surveys provide information on the sediment yield of the contributing watersheds from the date storage began to the date of survey. Reservoirs and ponds that retain most of the incoming sediment are usually selected for these surveys to minimize adjustments for loss of sediment. Data obtained from such reservoirs are used to determine the long-term average annual sediment yields from the watershed.

The construction of several large dams on the Lower Colorado River disrupted the natural regime and brought about a change in the sediment loads being transported [79]. The relatively clear water released from each dam picks up a sediment load from the channel bed and banks, causing degradation below each dam and aggradation in the backwater area of the next reservoir downstream. These channel adjustments cause problems of channel control and flooding along the river.

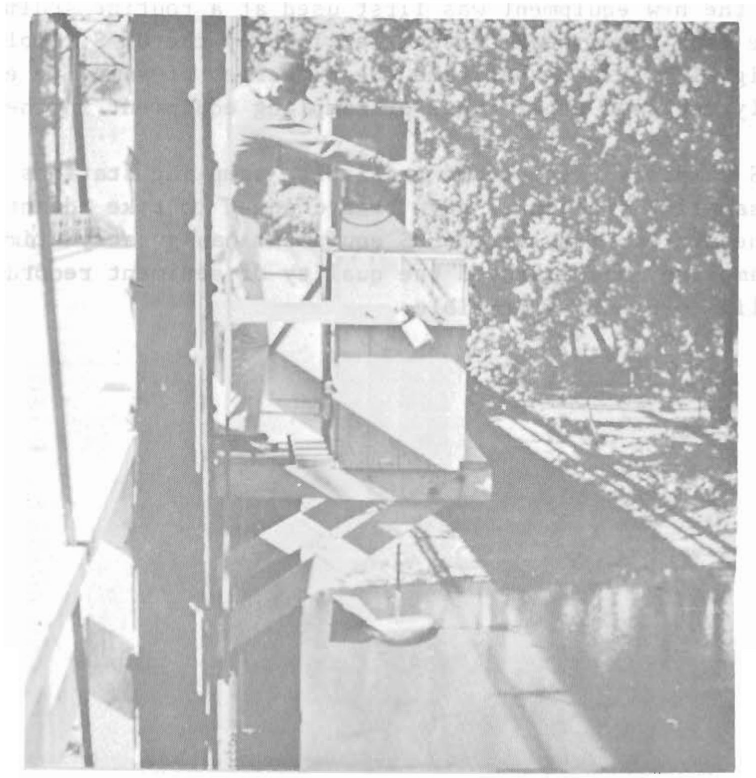
To assist in the analysis, planning, and designing of channelization and river control works, and to aid in evaluating and predicting future river conditions and probable maintenance after completion of channelization works, a sampling program to determine total sediment discharge in the Lower Colorado River was initiated in 1955 by the Bureau of Reclamation, Department of Interior [79]. From the data collected at various sampling stations the total sediment discharge was computed by the modified Einstein procedure [14] for each station through the river reach. A technical analysis of the sediment loads picked up and carried by the river was necessary to evaluate the sediment problems and design corrective measures through the reach. The flow-duration curve [60] developed from the flow record at each station and the total load sediment transport-rating curves developed from the computed total sediment discharge, were used to estimate total yearly discharge at each station.

In 1951 the Bureau of Reclamation began the collection of basic sediment data to determine the total transport of sediment through a 155-mile reach on the Rio Grande [6]. The total sediment discharges computed by the modified Einstein procedure for key points in the reach are used in conjunction with rating curves of suspended-sediment discharge at the daily sediment sampling stations to determine the long-time average total sediment discharge.

A comprehensive program for the development of a US series of sediment sampling equipment was begun in 1940 as a cooperative "Study of Methods Used in Measurement and Analysis of Sediment Loads in Streams". The samplers developed by the project [40] [44] have revolutionized sediment sampling techniques in the United States and in many foreign countries as well. Use of these samplers by foreign engineers also provides a basis for comparing foreign data with those of studies conducted in this country.

In 1943, the new equipment was first used at a routine sediment sampling station on the Iowa River near Coralville, Iowa, by the U. S. Geological Survey [45]. (See Fig. 1.) Since that time the US series of sampling equipment has almost entirely replaced other types of sampling equipment in the United States.

As new US samplers have become available, sampling stations have been modified and sampling procedures have been changed to take advantage of the new equipment. The availability of the US equipment has greatly stimulated interest in sediment sampling, has improved the quality of sediment records, and has made many new sampling procedures feasible.



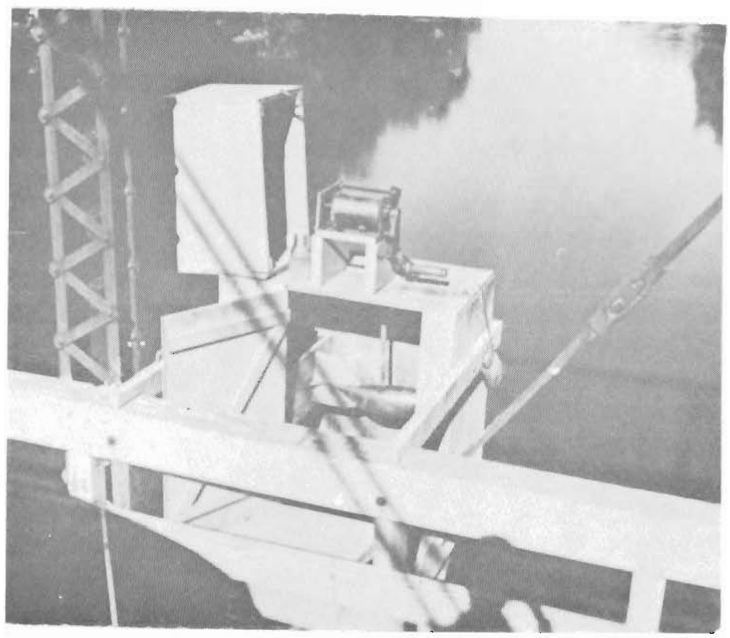


FIG. 1--EARLY US DEPTH-INTEGRATING SEDIMENT SAMPLING INSTALLATION
IOWA RIVER, CORALVILLE, IOWA, 1943

Reference 45 (See list of references pp. 142 to 148)

II. DISTRIBUTION OF SEDIMENT IN A STREAM

6. Types of sediment transportation--Sediment transport is a coordinated or dependent combination of bed movement, saltation, and suspension, the parts of which cannot be accurately considered separately except in the case of bed movement when no material is in suspension. Because the phenomena are not understood sufficiently to enable one to satisfactorily consider them together, they are generally discussed separately.

An excellent description of how these movements take place is given by G. F. Deacon (1894) [17] based on the observed 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 behavior 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 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 process by which material is moved in streams is given by Gilbert (1914) [28] 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 (1935) [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.

Students of sediment transportation and related problems have recognized three methods by which solid particles are moved in a stream:

a. Contact load which is the sediment that rolls or slides along on the streambed. The particles are in contact with the bed practically all of the time.

b. Saltation load which is the sediment bounced along the streambed by the flow or by the impact of other particles. The initial impetus which launches a particle into the flow 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. Suspended load which is the sediment that is supported by vertical components of the velocities in turbulent flow while being carried forward in the stream by horizontal components of these velocities. All particles that are small enough to be in suspension shift up and down in the flow and presumably move readily into and out of the bed layer.

7. Types of sediment concentration--The distribution of sediment throughout a stream cross section is expressed in terms of sediment concentration. Two types of suspended-sediment concentration should be recognized: (1) spatial, or static, concentration, and (2) discharge-weighted concentration.

SPATIAL CONCENTRATION is the quantity of sediment relative to the quantity of fluid in a fluid-sediment mixture. In this report it is dry weight of sediment per unit volume of water-sediment mixture or the ratio of the dry weight of sediment to the total weight of water-sediment mixture, in a sample or unit volume. SPATIAL CONCENTRATION AT A POINT in the cross section is the sediment concentration in a small volume of the water-sediment mixture at the point (any arrow of Fig. 12b, on page 38 represents a spatial concentration at a point). SPATIAL CONCENTRATION IN A VERTICAL is the sediment concentration in the water-sediment mixture in a small uniform column that is located at the vertical, and that extends vertically from the stream bed to the water surface (average concentration of Fig. 12e). SPATIAL CONCENTRATION IN A CROSS SECTION is the concentration of sediment in the water-sediment mixture contained in a unit length of channel at the cross section. The spatial concentration for the cross section of Fig. 12b is represented by the average distance between the plane passing through ABCDEF and the irregular surface passing through the points of the arrows projected from plane ABCDEF.

The turbidity, density, and other fluid properties of the water-sediment mixture are related to the spatial concentration.

Ideally, spatial concentration could best be sampled by instantaneously enclosing the desired volume of the water-sediment mixture and removing that volume as a sample. However, if both sediment and water move downstream at the same velocity, the concentration in a point-integrated sample is the same as the spatial concentration at the sampling point, and point-integration sampling is a practical way to obtain spatial concentration. If the spatial concentration is known at several points in a sampling vertical, the average spatial concentration for the vertical can be obtained by weighting the point concentrations according to the fraction of the depth each represents. If the spatial concentration is known at several verticals in the cross section, the average for the cross section can be obtained by weighting the concentrations in the verticals according to the fraction of the total cross-sectional area that each vertical represents.

DISCHARGE-WEIGHTED SEDIMENT CONCENTRATION is the quantity of sediment discharged relative to the discharge of transporting fluid, or fluid-sediment mixture; or the concentration of sediment in a fluid-sediment discharge. In this report it is the dry weight of sediment in a unit volume of discharge, or the ratio of the dry weight of sediment discharge to the weight of the water-sediment discharge. DISCHARGE-WEIGHTED CONCENTRATION AT A POINT in the cross section is the concentration of sediment in the water-sediment discharge through a small area of cross section at the point. DISCHARGE-WEIGHTED CONCENTRATION IN A VERTICAL is the concentration of sediment in the discharge through the area of a cross section of unit width with the vertical in the middle of the width. DISCHARGE-WEIGHTED CONCENTRATION IN A CROSS SECTION is the concentration of sediment in the discharge through the entire cross section.

The discharge-weighted concentration may be multiplied by the stream discharge to obtain the discharge of sediment.

The discharge-weighted concentration at a point in the cross section can be obtained from a point-integrated sediment sample. The discharge-weighted concentration in a sampling vertical can be obtained from the concentration in a depth-integrated sample for the vertical or from point-integrated samples that are weighted according to the velocity and depth each sample represents in the vertical. The discharge-weighted concentration in a stream is obtained by weighting the discharge-weighted concentration at each vertical according to the fraction of the total discharge that each vertical represents.

The concentrations discussed throughout this report will generally be clearly understood without specifying spatial, or discharge-weighted, as long as the reader understands the basic differences between the two.

The weight-ratio method of expressing sediment concentration in percent, or in parts per million (1 percent = 10,000 ppm) is now in general use in this country and in foreign countries as well. 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 sediment divided by the weight of the entire water-sediment sample,

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

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

Although the first method is generally used, sometimes the determination of concentration is simpler by the second or third method; particularly the third when the volume of the water-sediment mixture can be measured in the field, thus eliminating errors from evaporation before the sample is analyzed in the laboratory. The graphs shown in Fig. 2 [38] may be used to convert the second and third types of concentration 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 a concentration of 0.1 percent (1,000 ppm), and even at a concentration of 1 percent (10,000 ppm) they do not exceed 1 percent.

If concentration is expressed as the ratio of weight of sediment to total weight of water-sediment mixture, the discharge of sediment can be obtained by multiplying the weight of the mixture that is discharged by the discharge-weighted concentration. Generally the discharge is in terms of volume and the discharge is multiplied by the weight of a unit volume of water to obtain the weight of discharge. One should remember that as the sediment concentration goes up, the weight of a unit volume of discharge increases slightly. Consequently, it is not theoretically precise to use volume of discharge to compute discharge-weighted concentrations directly from samples with sediment to water ratios such as (1) and (2) above. If the change in weight per unit volume of water-sediment mixture is ignored, the errors are generally small as may be seen in Fig. 3, which shows the percentage corrections which apply to computations based on the weight of pure water.

8. Theory of sediment suspension--A great many theories have been proposed concerning the suspension of sediment in flowing water but only within the past two decades 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 (55, 56). The analytical basis for this concept is briefly presented in this report, as an understanding of the turbulence concept will 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. Similarly the velocity of the water also changes, fluctuating about a mean value in an irregular manner. Fig. 4 [50] illustrates how the velocity as determined with a current meter fluctuated at three points in a vertical in the Mississippi River.

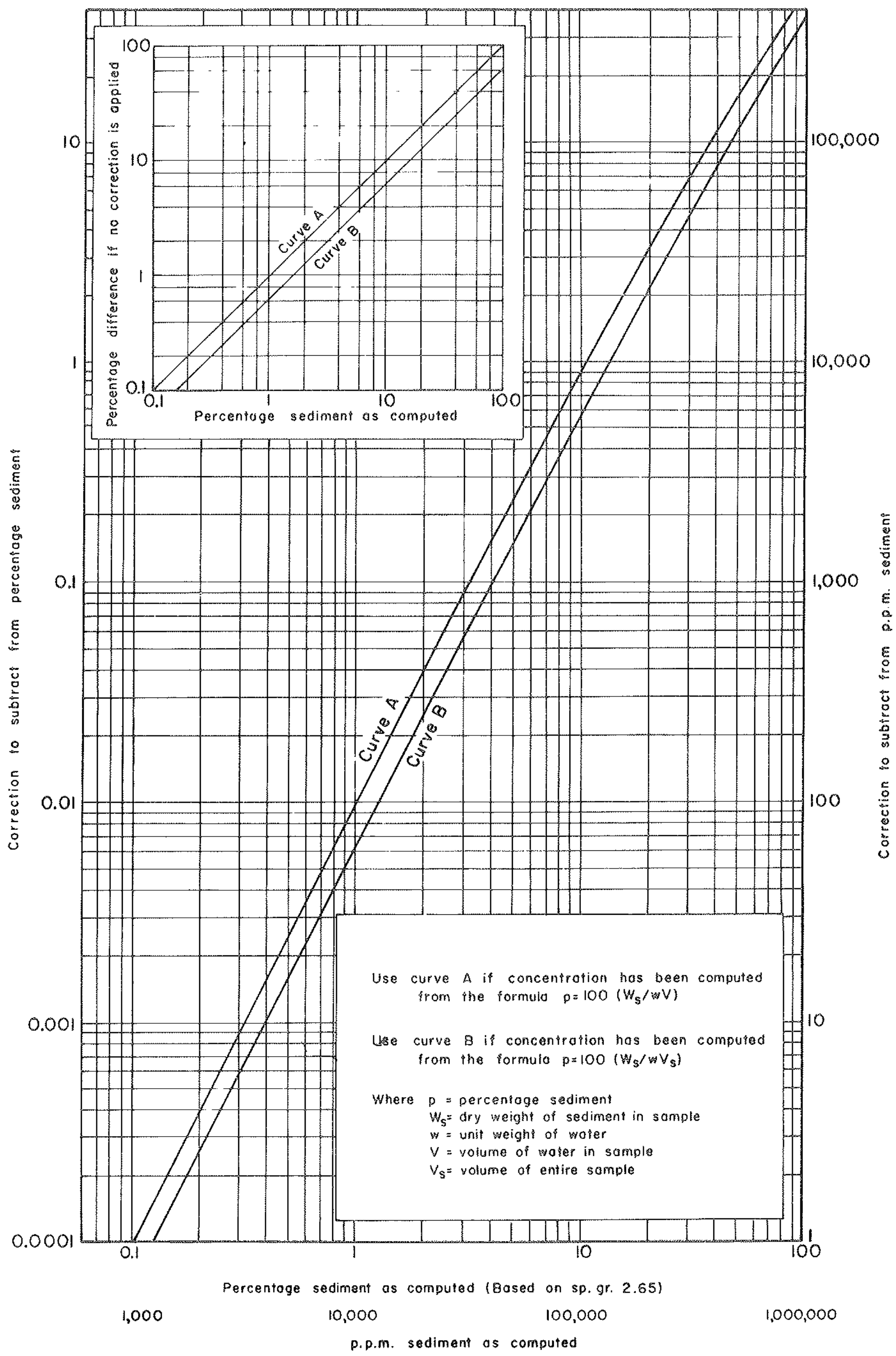


FIG. 2--CORRECTION CHART TO DETERMINE SEDIMENT CONCENTRATION BASED ON TOTAL WEIGHT OF SAMPLE

Adapted from Fig. 81 of reference 38

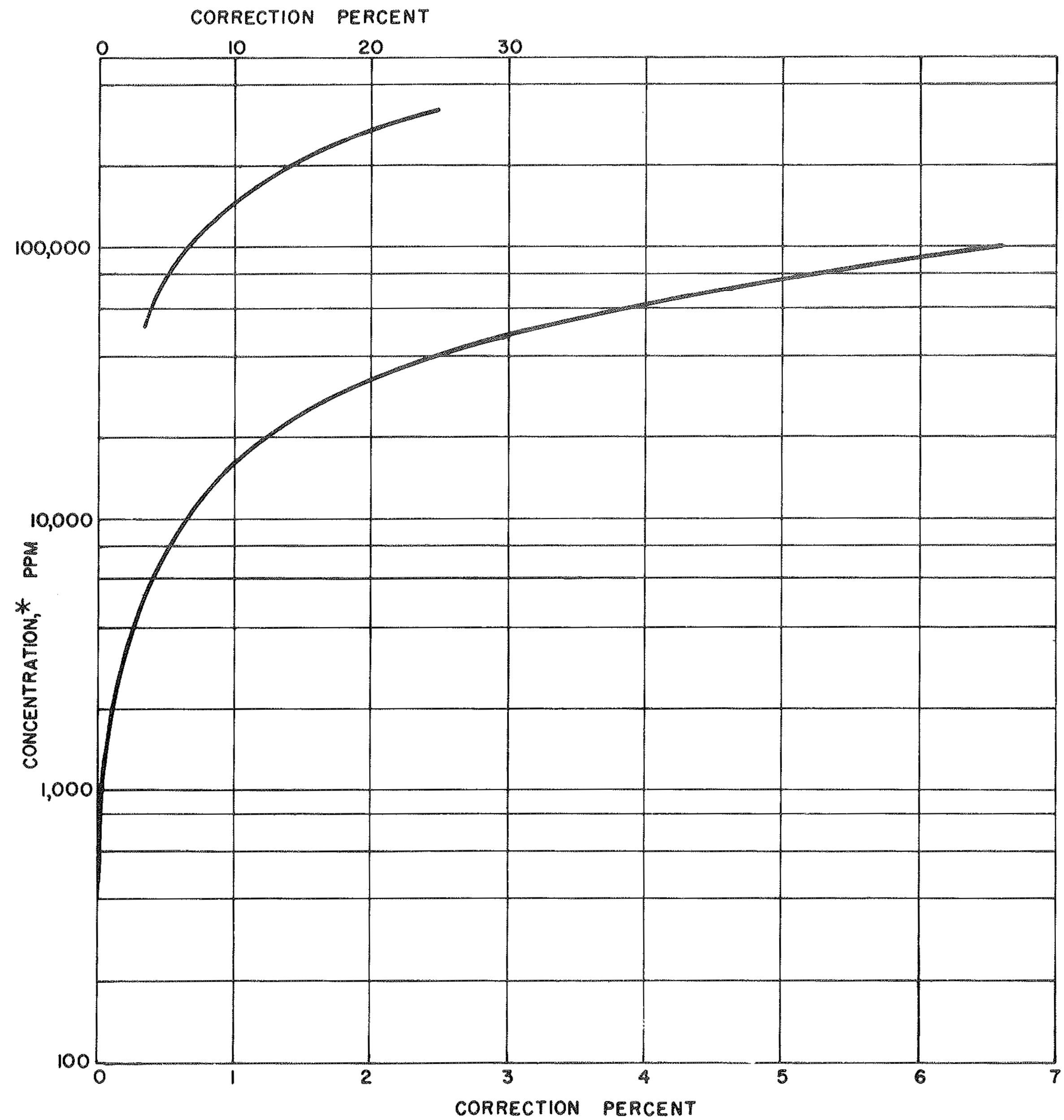


FIG. 3--CORRECTIONS THAT APPLY TO SEDIMENT WEIGHTS COMPUTED BY MULTIPLYING SEDIMENT CONCENTRATION* BY WEIGHT OF PURE WATER

* Concentration used here is the ratio of weight of sediment to total weight of water-sediment mixture. Specific gravity of sediment, 2.65

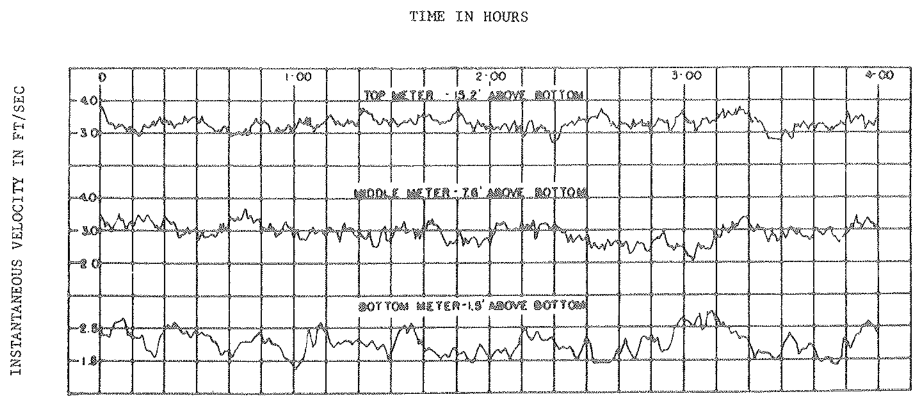


FIG. 4--FLUCTUATIONS IN VELOCITY OBSERVED IN THE MISSISSIPPI RIVER NEAR MUSCATINE, IOWA

Adapted from Fig. 1 of reference 50

Sediment carried in suspension is acted on in the vertical direction by momentary currents which move upward or downward in the stream. Because the water level in the stream remains unchanged, the quantity of upward and downward flow must be equal. 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, all particles of specific gravity greater than that of water settle steadily downward. Under the combined action of vertical currents and gravitational force, a particle caught in a current moving upward at a rate greater than the settling velocity of the 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, whereas for the downward currents the opposite relation 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 acted upon by the rising than by the 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.

Assume that the equilibrium distribution of suspended-sediment concentration in the vertical is represented by the curve BC (Fig. 5a) [41], and consider a section of a horizontal plane at P having an area A. Turbulent currents pass through this area, some having upward and others having 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. The currents 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 velocity and the corresponding sediment concentration must be greater in the upward direction. When equilibrium exists the amount of material which settles through area A owing to the force of gravity equals the excess of that carried upward over that carried downward by the vertical currents.

Coarse particles tend to settle through area A faster than do fine particles. 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, with the concentration increasing more toward the bottom for coarse than for fine sediment. In Fig. 5b, curve BC might represent the distribution for fine sand, and curve DE for a coarser sand. For silts and clays the concentration would be essentially equal throughout the depth.

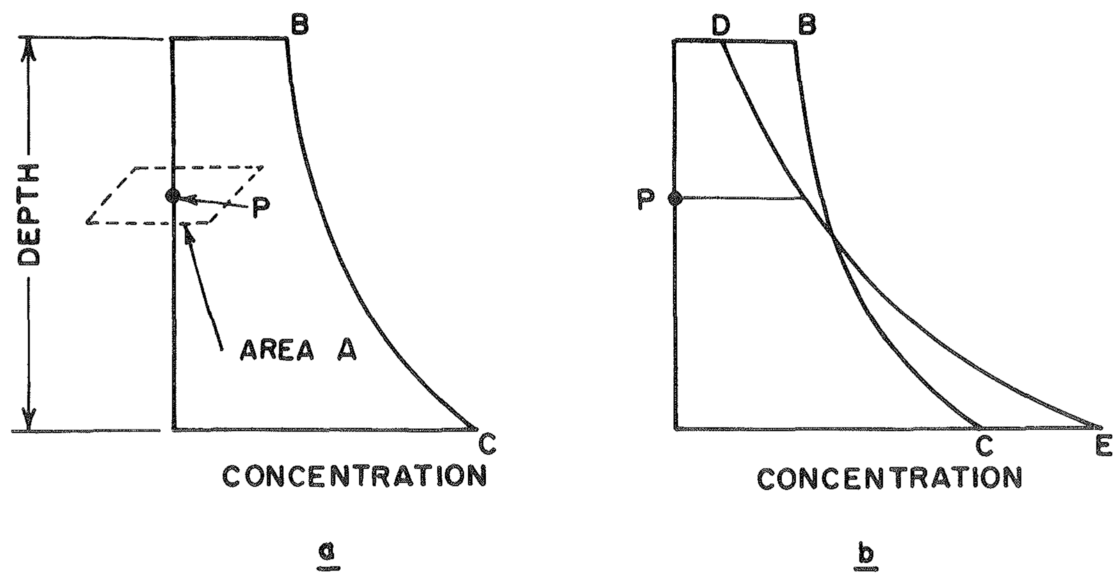


FIG. 5--TYPICAL VERTICAL SEDIMENT DISTRIBUTIONS FOR SANDS

Adapted from Fig. 2 of reference 41

For sediment particles of uniform density, the settling rate increases with size, but not proportionally. The settling rate for particles smaller than about 0.062 mm in size varies approximately as the square of the particle diameter, whereas particles of coarse sand settle at rates which vary approximately as the square root of the diameter. Particles of intermediate size have settling velocities which vary at intermediate rates. The 0.062-mm size is the approximate division point between sediments classed as silts and those classed as sands. Clay particles (which are finer than silts) and silt particles are ordinarily fairly uniformly distributed in a stream, but sand particles are usually more concentrated near the bottom than near the surface, the degree of variation being a function of the coarseness of the particle (Fig. 6) [41].

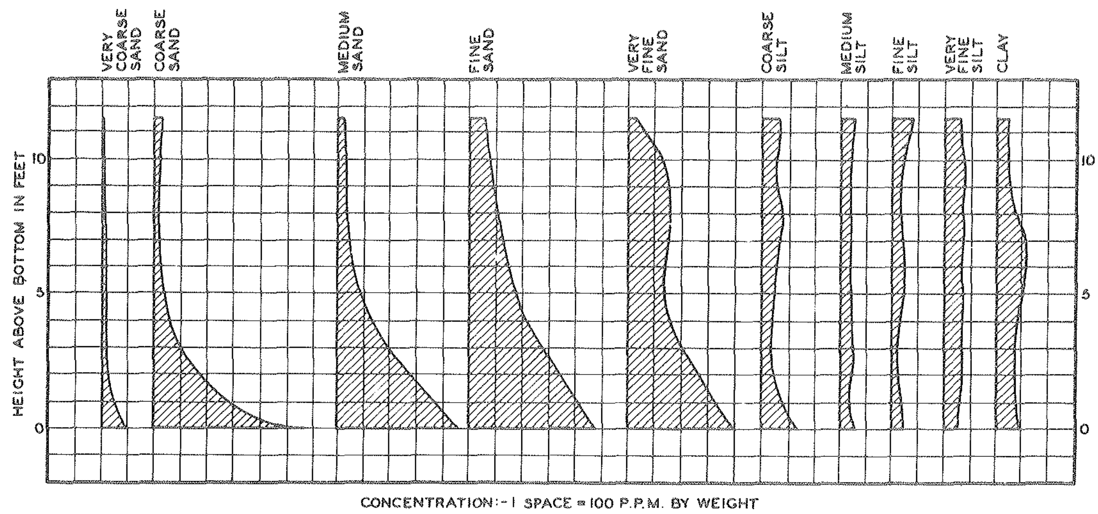


FIG. 6--VERTICAL DISTRIBUTION OF SEDIMENT IN THE MISSOURI RIVER AT KANSAS CITY, MO.

Adapted from Fig. 3 of reference 41

9. Vertical distribution of velocity and suspended-sediment--When measured stream velocities are plotted on semi-logarithmic paper against height above the bed, they generally fit the von Karman logarithmic law [54, 78, 82], which can be expressed by

$$\frac{u - \bar{u}}{u_*} = \frac{1}{k} + \frac{2.3}{k} \log_{10} (y/d)$$

in which u is the point velocity at a distance y up from the bed, $\bar{u}$ is the mean velocity at the vertical, u_* is the shear velocity ($= \sqrt{gsd}$, in which s is the slope of the energy gradient), d is the flow depth at the vertical, and k is the von Karman universal coefficient for turbulent exchange, which has a value of 0.4 for clear-water flow over plane beds. Field measurements in clear-water rivers verify this value [5]. If m is the slope of the straight line through plotted points, then a value for k can be computed from

$$k = \frac{2.30u_*}{m}.$$

Vanoni and Brooks [82] made measurements of velocity distribution in the vertical at the center of a 33.5-in. wide laboratory flume. Results for two flows of the same slope and depth, one with clear water and the other with a mean sediment concentration of 15.8 grams per liter of 0.1-mm sediment, are shown by the semi-log plot in Fig. 7. The sediment-laden flow had a higher velocity and a lower friction factor represented by k_s than the clear-water flow. In theory the value of k_c for clear-water flow and k_s for sediment-laden flow should be the same [5] but actually they are different partly because k_s is not a true turbulence constant. They both represent functions of the vertical distribution of velocity, but they are neither constant nor equal. Results of field measurements on the Middle Loup River at Dunning, Nebraska, have shown the value of k_s may be as high as 4.00 for sediment-laden flow over sand-dune beds [34].

Measurements of velocity and sediment distribution were made in a study of sediment transport characteristics in a reach of the Missouri River at Omaha, Nebraska, in 1952 [74]. The data (Figs. 8 and 9) correspond to the general form of the commonly accepted logarithmic formulae. However, as would be expected, the measured data are not in agreement with the von Karman constant for the flow of clear water over fixed boundaries. The measured velocities plot in straight lines with respect to log y, (Fig. 8) but the slopes of the straight lines are not the same.

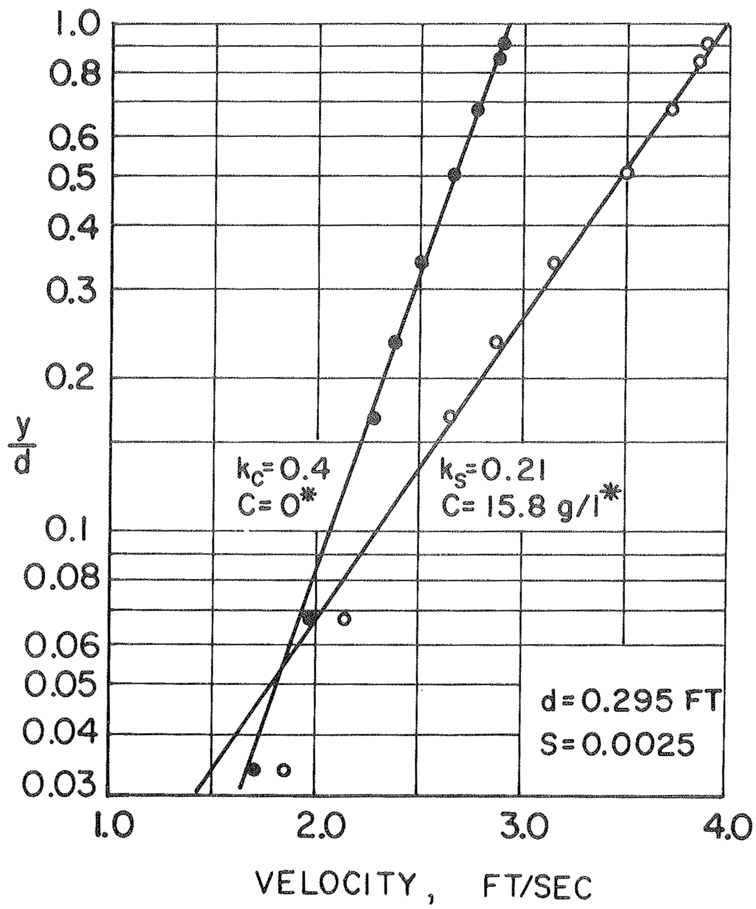
The relation of sediment concentration to depth can be expressed in the form

$$C = \left(\frac{d-y}{y}\right)^Z$$

or, if a reference level y = a is adopted, the more common form [82] [66]

$$\frac{C_y}{C_a} = \left(\frac{d-y}{y} \times \frac{a}{d-a}\right)^Z$$

may be used where C_y is the concentration of a specified size of sediment at any distance, y, above the streambed, C_a is the concentration of the same size of sediment at reference level $y = a$, d is the stream depth at the vertical, and Z is the theoretical exponent that describes the vertical distribution of suspended sediment. The theoretical Z for flows over a plane bed is equal to w/ku_* where w is the settling velocity of a given size of sediment, k the coefficient for turbulent exchange, and u_* the shear velocity which is equal to $\sqrt{gsd}$. However, the theoretical Z is not very reliable. Whenever possible it should be replaced by Z_1 which is the slope of the log-log plot of (d-y)/y versus C for measured data. Z_1 values, which are computed from measured data, are functions



k_c = clear water data
k_s = sediment laden flow data
d = depth of flow
y = distance up from streambed
s = slope of energy gradient
C = sediment concentration
* Concentration of sediment in the discharge which included both suspended load and bed load

FIG. 7--EFFECT OF SEDIMENT CONCENTRATION ON VERTICAL VELOCITY DISTRIBUTION

Adapted from Fig. 2 of reference 82

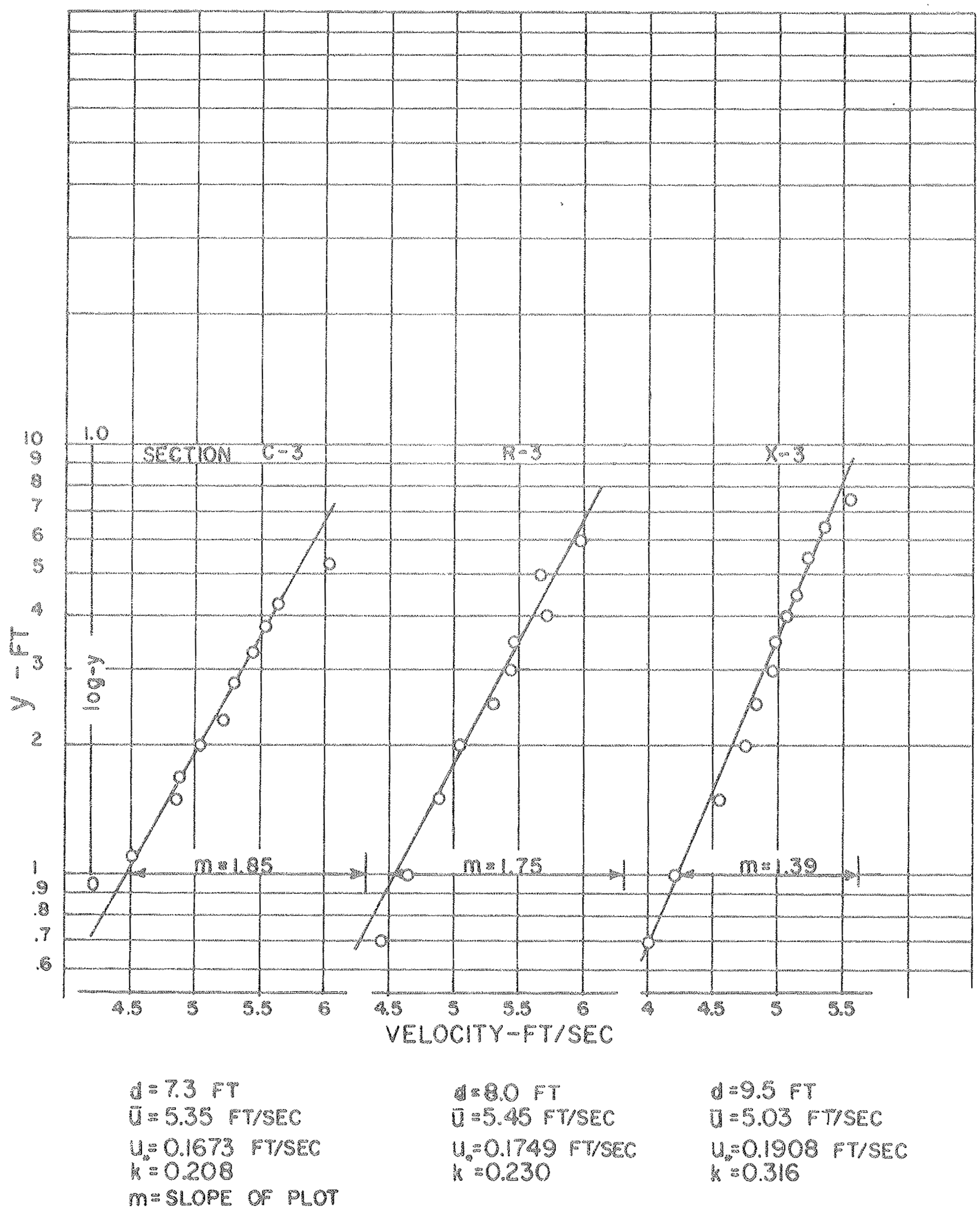
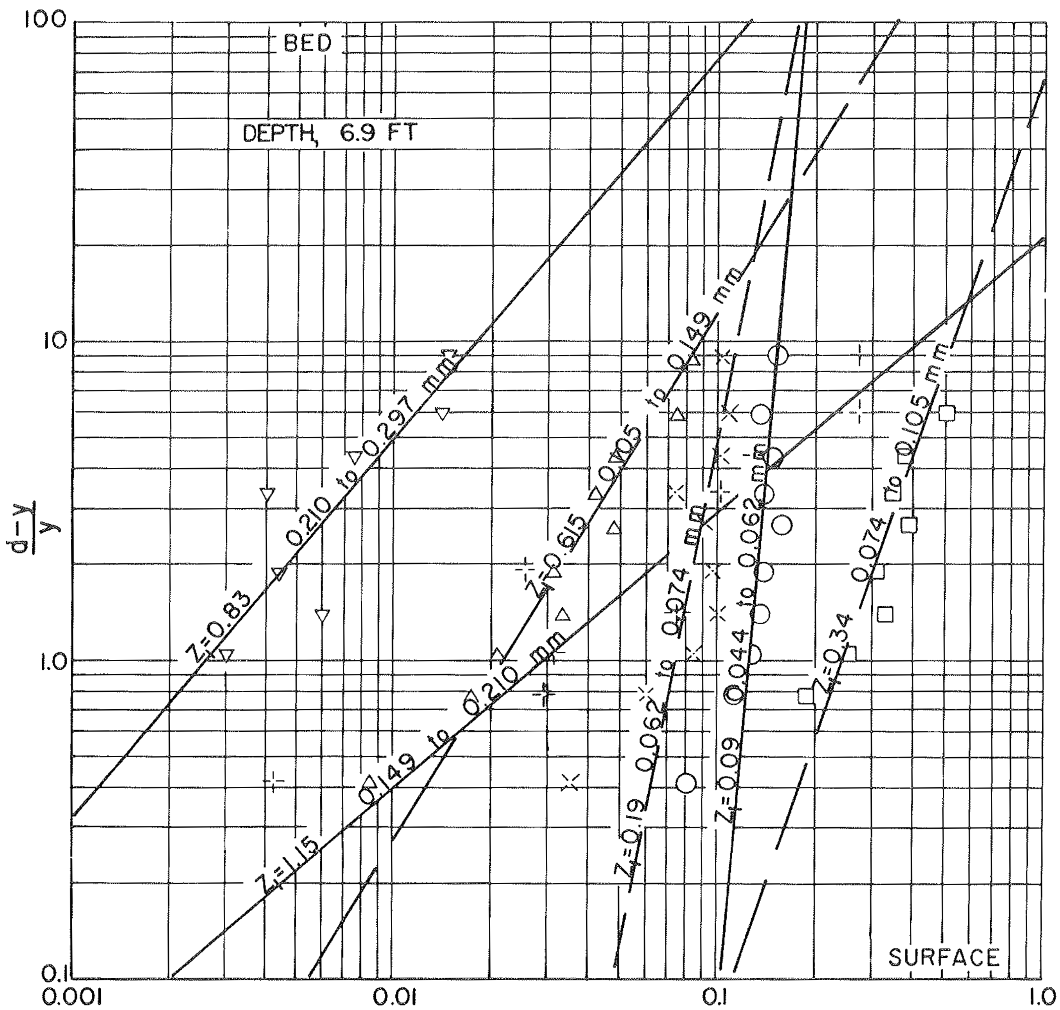


FIG. 8--VELOCITY PROFILES IN THE MISSOURI RIVER AT OMAHA, NEBR.

Adapted from reference 74



CONCENTRATION g/l

Z_1 = slope of measured suspended sand concentration curves

$$\frac{\Delta \log C}{\Delta \log \frac{d-y}{y}}$$

FIG. 9--SUSPENDED-SEDIMENT DISTRIBUTION IN THE MISSOURI RIVER AT OMAHA, NEBR.

Adapted from reference 74

of k. A log-log plot of concentration and relative depth, (d-y)/y, for Missouri River data is shown on Fig. 9.

Available data on mean ratios of spatial sediment concentrations near the mid-depth and near the bottom to those near the surface are summarized in Fig. 10 [41]. The data are for 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 [36]. The concentrations near the mid-depth and near the bottom were almost always greater than those near the surface. The bottom concentration ratios were nearly 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. 10 is the mean of a number of observations at a single station. There were over 1,000 observations at some stations.

10. Transverse distribution of velocity and suspended sediment--In long reaches of uniform channel, the horizontal distribution of velocity across a stream generally follows the square root of the stream depth. This is indicated by the Chezy empirical formula, $V=C\sqrt{RS}$, where the slope is assumed to be the same at all points across the channel and the hydraulic radius is the depth. Consequently the distribution is relatively uniform for many stream channels.

Except below large important tributaries, or in streams with irregular cross sections, the suspended-sediment concentration is ordinarily fairly uniform across a stream. However, water entering from a tributary tends to stay on its side of the channel for a considerable distance down-stream. If the sediment content of the main and tributary streams differ appreciably, the sediment concentration may not become uniform across the stream for a long distance below the junction.

The available data on transverse distribution of suspended sediment given in Table 2 of Report No. 1 [36] have been arranged in Fig. 11 [41] to show the frequency of deviations of concentration from the mean for the cross section. A comparison of Fig. 11 with Fig. 10 indicates that the transverse variation of suspended-sediment concentration is ordinarily less than the vertical variation.

Other data (Missouri River data [5]), however, indicate that although the distribution of sediment discharge in a cross section may be relatively constant, the concentration may vary radically in accordance with the character of the bed form (i.e., smooth bed or dune forms). For example, in a cross section consisting of a partial width of relatively deep flow and a partial width of shallow flow, the deep section may contain dune forms, with relatively low relocity and concentration while the shallow portion may contain a smooth bed with high velocity and concentration. (See also laboratory report by Kennedy [53].)

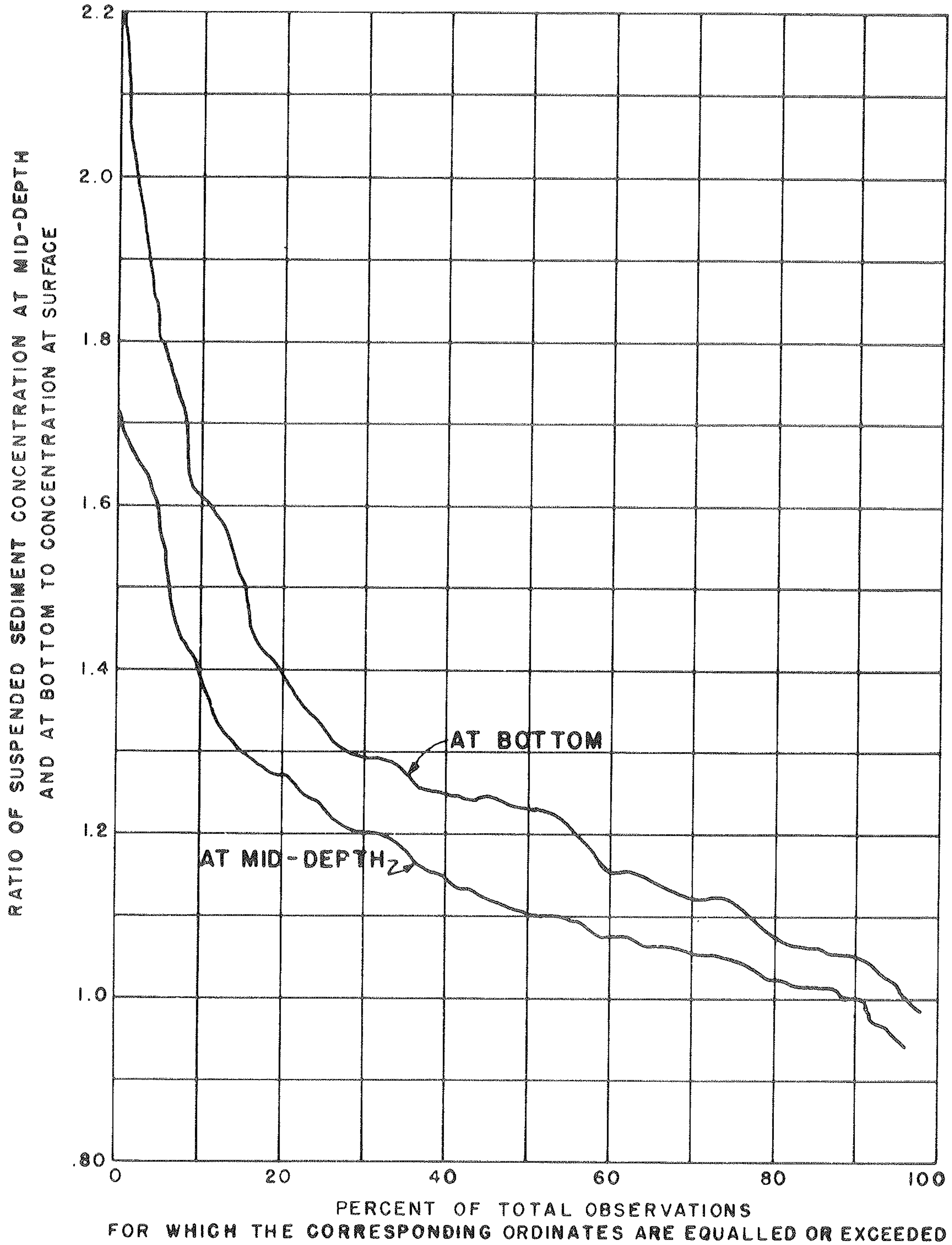


FIG. 10--OBSERVED VERTICAL DISTRIBUTION OF SUSPENDED SEDIMENT

Adapted from Fig. 5 of reference 41

Thus, in many cases the location of sampling points in the cross section would not be critical while in other cases it would be important. Also, in the proximity of tributary inflow, below caving banks, or when depths vary across the section, the variation of sediment concentration may be greater from one side of the stream to the other than between different points in a given vertical section.

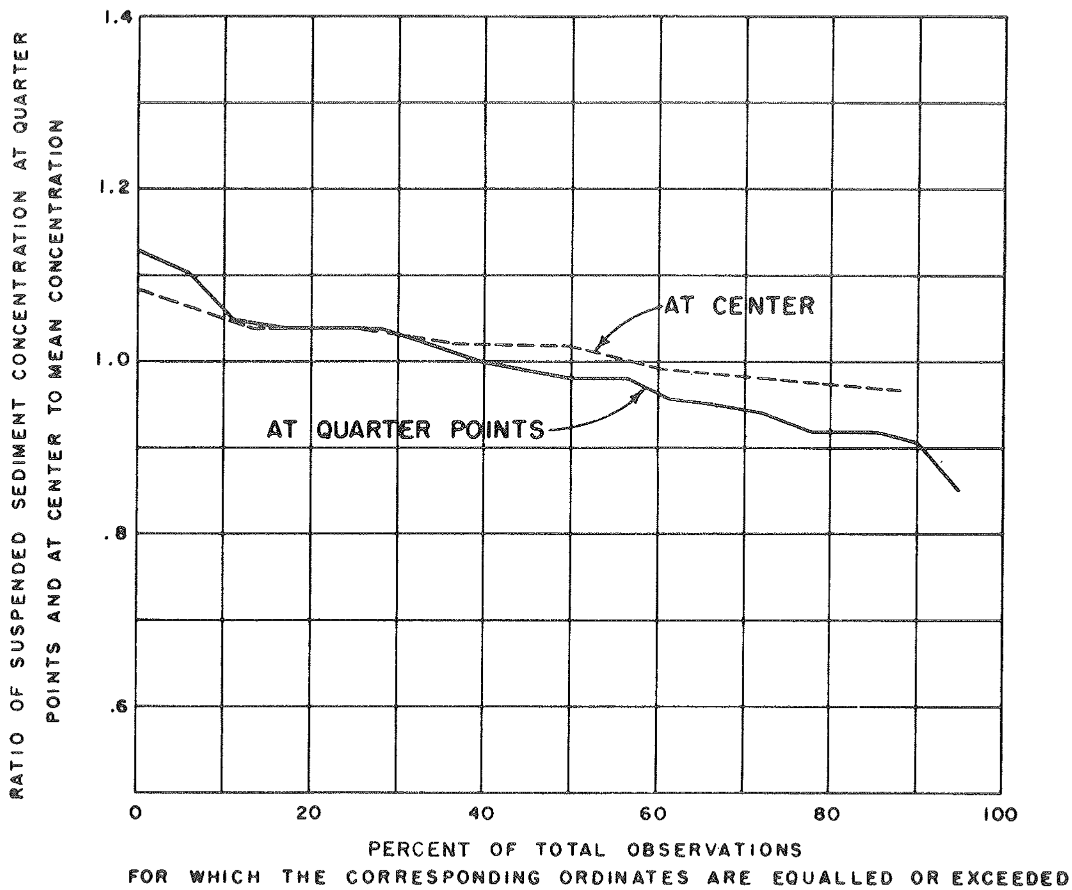


FIG. 11--OBSERVED TRANSVERSE DISTRIBUTION OF SUSPENDED SEDIMENT

Adapted from Fig. 7 of reference 41

III. MEASUREMENT OF SUSPENDED-SEDIMENT DISCHARGE

11. General conditions--Generally suspended-sediment samples are taken to determine the sediment discharge of the stream, or to determine both the sediment discharge and the particle size distribution. These measurements actually apply only to the short period of time for which the samples represent stream conditions. Determination of the suspended-sediment discharge continues to be the predominant phase of sediment investigation, but increasing emphasis is being placed upon studies of particle size and size distribution. A knowledge of the turbulence theory of suspended-sediment transportation has shown that information on particle size is necessary for the solution of practically all fluvial sediment problems.

The following discussion will emphasize methods of determining suspended-sediment discharge because of the importance of this phase of sediment work. However, particle size distribution in a stream is usually determined from samples obtained in the same manner. Therefore, a discussion of the methods used to determine the discharge of suspended sediment in a stream will cover most sediment sampling problems.

If the sediment carried in suspension were uniformly distributed within a stream cross section, the suspended-sediment discharge could be determined fairly simply. Then a single sample taken at any point would indicate the average suspended-sediment concentration for the cross section. The sediment discharge would be the product of the sediment concentration, the stream discharge, and a conversion factor for the units of measurement used. Unfortunately, however, the concentration of fluvial sediment varies more or less throughout any cross section of a stream, and these variations must be taken into account if an accurate measurement of sediment discharge is to be made.

Ordinarily, suspended-sediment concentrations are based on laboratory analyses of samples of the water-sediment mixture obtained with a suspended-sediment sampler. The corresponding water velocity and discharge are usually obtained from current-meter measurements. The sediment discharge per unit area at a point, or per unit width at a vertical, in the stream is computed from the sediment concentration and stream discharge.

It is important to obtain at least some basic data on any stream where a sediment problem is to be studied. Although computations based on meager data may be considerably in error, they will generally be better than estimates based entirely on data from other streams. Sediment concentration may vary widely from one stream to another. For example, the Gasconade River at Rich Fountain, Missouri, carries an average sediment concentration of about 0.0076 percent whereas the Rio Grande at San Marcial has a concentration of about 1.42 percent, or nearly 200 times as much. Thus, without local data, an estimate of sediment concentration may be in error several hundred percent.

The error may be significantly reduced with only a few field measurements and the improved accuracy will usually justify the cost of at least a small sampling program.

12. Determination of water discharge--Streamflow data must be obtained for any detailed suspended-sediment study. If no gaging station is maintained near the sampling point on the stream, one should be established. 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 near the bottom. The maximum velocity usually occurs at or 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. 12a [41]. The velocities at various points normal to the cross section ABCDEF 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 average distance between the plane passing through ABCDEF and the irregular surface passing through the points of the arrows which might be projected from all points in the cross section. The volume based on the velocity arrows for all points in the cross section, as described by the four lines joining A and D, represents the discharge of the stream. The volume of the figure that is bounded by the four lines can be divided by the area of cross section ABCDEF to determine the mean velocity.

It is impractical to measure the velocity at every point in a cross section. Measurements are made at a number of systematically located points and the velocity is assumed to vary between measured 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 by methods customarily used for stream gaging [16]. Extensive investigations have shown that the mean velocity in a stream vertical can usually be determined with an ample degree of accuracy from measurements at one, or only a few, properly selected points in the vertical. The velocity and depth at a vertical may be assumed to apply for half the distance to the next vertical. If verticals are equally spaced, the discharge for a given vertical is multiplied by the width between verticals to obtain the discharge that the vertical represents. In another method that gives approximately the same results, the discharge for the section between the verticals BF and CE is obtained by multiplying the area BCEF by the average of the mean velocities at verticals BF and CE (Fig. 12a). The total of all the partial discharges in the cross section equals the total stream discharge.

13. Determination of instantaneous suspended-sediment discharge--The suspended-sediment concentration in a stream usually varies from the surface to the bottom, and in some instances from side to side. The sediment distribution may be illustrated by Fig. 12b where the lengths of the arrows represent sediment concentrations at the same points at which velocities were shown in Fig. 12a. Fig. 12d represents the velocity distribution at vertical CE, and Fig. 12e the

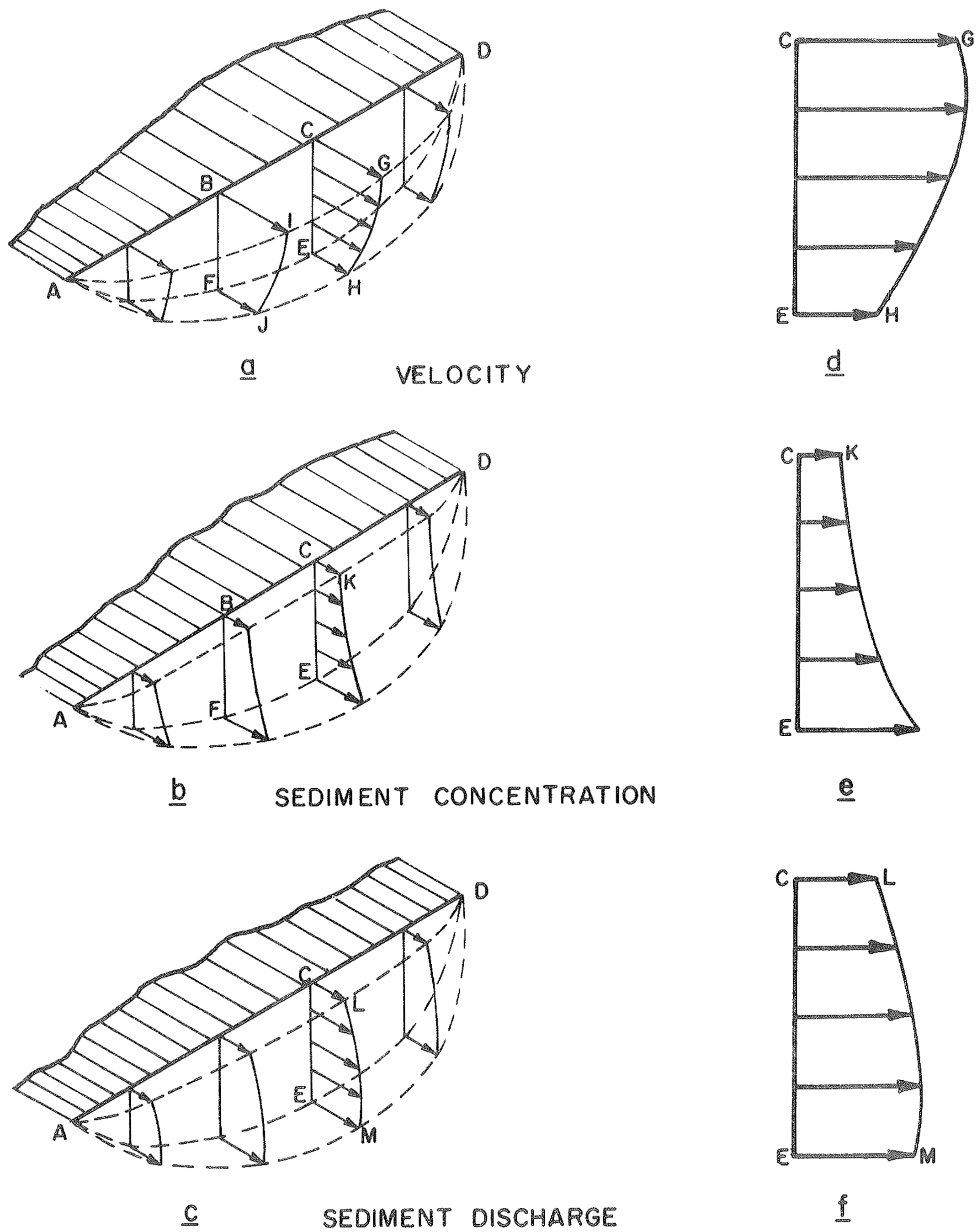


FIG. 12--VELOCITY, SEDIMENT CONCENTRATION, AND SEDIMENT DISCHARGE IN STREAMS

Adapted from Fig. 4 of reference 41

distribution of sediment concentration in that vertical. The mean sediment concentration in vertical 12e is the spatial concentration for the sampling vertical. The sediment discharges for the vertical CE are shown in Fig. 12f. They were obtained by multiplying the velocities in Fig. 12d by the corresponding concentrations in Fig. 12e. Velocity can be expressed quantitatively as volume per unit time and unit cross-sectional area; concentration can be expressed as weight of sediment per unit volume; therefore, the product of the two equals weight of sediment discharged per unit of time, per unit of area. The mean discharge in vertical 12f divided by the mean velocity from 12d equals the discharge-weighted concentration for the sampling vertical.

The sediment discharge, or the weight of suspended sediment passing the cross section per unit time, is represented by the enclosed volume of Fig. 12c in the same way that the stream discharge is represented in Fig. 12a. Sediment discharge is generally obtained by multiplying the discharge-weighted concentration in each vertical by the stream discharge that the vertical represents and adding the products.

The basic concept of the computation of sediment discharge is often modified to fit the needs of a specific sampling program. Computations based on point-integrated samples (See Section 18) are a modification of the basic method of determining suspended-sediment discharge. Depth-integrated samples require a different treatment. If sediment is fine and most of the total depth is sampled, the concentration in the depth-integrated sample may be taken as equal to that for the entire vertical. However, if coarse material is encountered in suspension near the streambed, corrections should be made for the difference between the concentration in the sampled zone and that in the total depth at a vertical. The corrections can be made with the modified Einstein method (Section 38); from occasional series of point samples; or from analytical computations based on sediment size and velocity or other flow characteristics.

14. Number and location of sampling verticals--For practical reasons sediment concentration should not be measured at a large number of sampling verticals. Consequently, some system for selecting a limited number of sampling verticals must be used.

The common methods that have been used to locate the transverse position of sampling 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 at mid-points of equal-width sections across the streams.
f. Verticals at centroids of sections of equal water discharge.

The number and locations of verticals to be sampled should be governed by the degree of accuracy sought in the investigation, the size and shape of cross section, the particle size of the sediment, the ratio of the sediment discharge being carried at the time of sampling to the total sediment discharge during the period under consideration, and other characteristics of the stream (Section 15). The particle size and the accuracy sought 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 sampling verticals should be located, or their mean discharge-weighted concentrations should be weighted, with respect to the transverse distribution of stream discharge. That is, either the sampling verticals should represent equal parts of the total water discharge, or the value of the mean discharge-weighted concentration for each vertical should be weighted in proportion to the fraction of the stream discharge that it represents.

15. Selection of sampling verticals--If much sediment sampling is to be done at a given site, the distribution of both water and sediment should be established at several stream stages. Then the number and location of sampling verticals that will give the required accuracy with a minimum of work should be determined as a basis for economic sampling.

The methods of selecting sampling verticals can be divided into three general groups.

Verticals spaced arbitrarily in the cross section--Obviously, the simplest practice is the selection of a single sampling vertical at midstream or at the point of greatest depth. The vertical at the point of greatest depth is better because the greatest percentage of water discharge generally occurs in the deepest part of the stream. However, a single vertical should be used only in a very small stream or in certain types of routine sampling.

A method that uses sampling verticals at the 1/4-, 1/2-, and 3/4-points in the width of a stream cross section is convenient and practical. It may be used when distribution of stream discharge is not known. This method provides more information concerning the distribution of sediment and a more accurate sediment discharge than the single-vertical method.

A few investigators have located the sampling verticals at 1/6, 1/2, and 5/6 of the stream width. In wide streams of uniform depth and uniform velocity distribution these verticals essentially bisect three sections of equal water discharge. However, such conditions of stream flow are unusual; in most streams the mid-point for the outer thirds of the water discharge would be approximately at the quarter-points or even closer together.

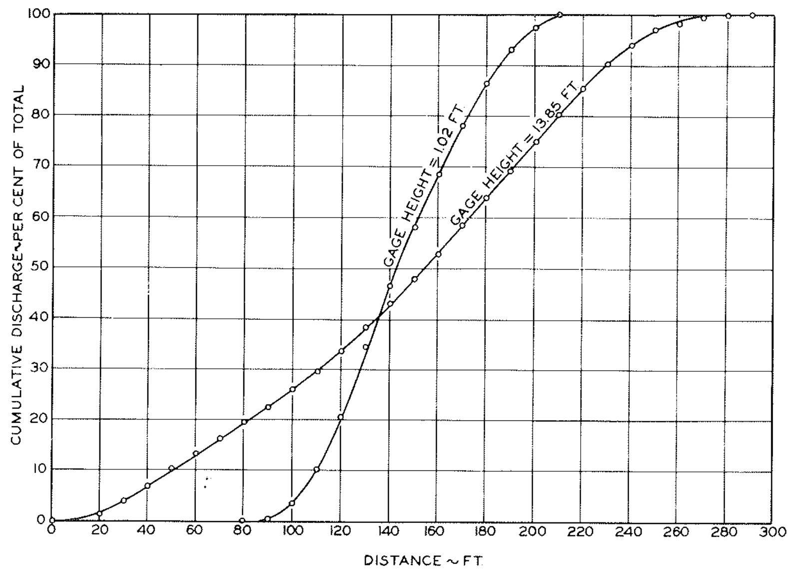
Several verticals uniformly spaced in the cross section--In important investigations it has been common practice to select a relatively large number of sampling verticals at the mid-point of equal fractions of the stream width. This method gives a good indication of the distribution of sediment across the stream, but it is exact only when the discharge-weighted concentration for each vertical is weighted with respect to the stream discharge in the section represented by the vertical.

The discharge integration method, commonly called the equal-transit-rate (ETR) sampling procedure, first used by B. C. Colby in 1946, eliminates the need for a knowledge of the distribution of stream discharge in the stream cross section because it provides samples weighted for discharge distribution. The stream cross section is divided into 10 to 25 increments of equal width, and a sampling vertical is located at the middle of each increment. The number of increments depends on channel width and uniformity of sediment or velocity distribution across the stream. If a depth-integrating sampler, which samples at stream velocity, traverses the depth (this explanation ignores the unsampled zone) at each vertical at a uniform rate from the surface to the bed and back to the surface, and at the same rate in each vertical in the cross section regardless of stream depth and velocity, the sample volume taken from each vertical is proportional to the average stream discharge per unit width at that vertical. The sample volumes taken from each vertical will not be equal because, although the sampler traverses each vertical at the same rate, the depths and flow velocities may be different. All the samples from the cross section may be mixed together to make a composite sample that represents the concentration in the cross section. The concentration multiplied by the stream discharge gives sediment discharge. Composite samples minimize laboratory work and yield more material for analysis when the sediment concentration in the stream is low. The ETR method is a good method for use on most streams that can be waded but it is often unnecessarily laborious for large streams.

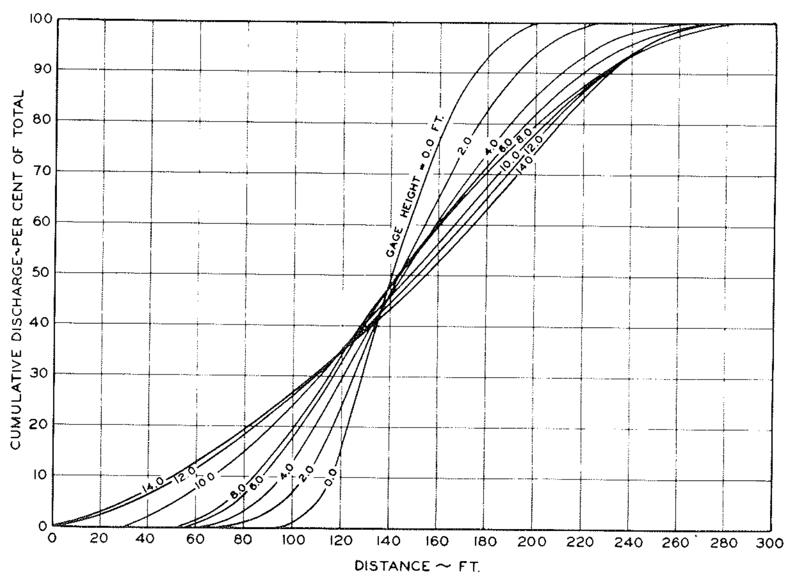
Verticals at centroids of equal discharge in the cross section--Selection of sampling verticals so that they represent equal portions of stream discharge is another rational practice. However, this method is usually only approximated in the field. The sections of equal water discharge are determined 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 judgment and care used by the observer in dividing the stream cross section.

A relatively simple graphical method devised by E. W. Lane for locating sampling verticals which represent equal proportions of the total stream discharge is illustrated by Fig. 13 [41]. The discharge distribution in a cross section for different stages at a station on the Iowa River was computed as a cumulative percentage of the total stream discharge (Fig. 13a).

In Fig. 13b the percentages of discharge are plotted as ordinates and the distance to verticals of observation as abscissas for various stages of the river. The location of verticals to be sampled can be determined from the



a. Individual measurements of discharge



b. Discharge variation with gage height

FIG. 13--DISTRIBUTION OF WATER DISCHARGE IN CROSS SECTION OF IOWA RIVER AT IOWA CITY, IOWA

Adapted from Fig. 9 of reference 41

information given in Table 1 and Fig. 13b. For example, if the observer selects six sampling verticals, Table 1 shows that they should be located where the cumulative stream discharges are 8, 25, 42, 58, 75, and 92 percent of the total. Fig. 13b shows that for a gage height of 4.0 ft six sampling verticals should be located 92, 114, 134, 157, 180, and 215 ft from the reference station. This method can be applied to gaging stations where sediment and stream discharge measurements are made regularly. If the river cross section changes considerably, it may be necessary to revise the curves, but minor channel changes will have little effect on the accuracy of this procedure.

If the sampling verticals represent equal stream discharges, if the samples are taken by the depth-integration method, and if all samples have the same volume; then 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 characteristic size distribution of the sediment discharge.

TABLE 1

CUMULATIVE PERCENTAGE OF STREAMFLOW AT EACH VERTICAL

No. of sampling verticals	Cumulative stream discharge - percent of total													
	Vertical number													
	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

16. Sampling a vertical by depth integration--There are two basic methods of sampling to obtain the concentration in a stream vertical. The depth-integration method is used for most routine measurements of sediment discharge. The point-integration method is used in some large streams and to define vertical distribution of sediment.

Depth-integrated samples are taken with a sampler (Sections 22 and 23) that has an intake that points directly into the current. The sample is collected at a rate about proportional to the stream velocity at the intake. The sampler traverses the depth of the stream at a uniform speed;* the sampling time in any fraction of the vertical is about proportional to the depth of the fraction; and the volume of the partial sample from any fraction is about proportional to the depth and velocity (discharge per unit width) of the fraction.

Streams less than 15 feet deep are usually depth-integrated on a round-trip basis. The sampler is lowered to the bottom of the stream at a uniform rate and raised back to the surface at a uniform rate, but not necessarily the same rate. The sampler is stopped only momentarily at the bottom to reverse direction, and sampling is continuous during both periods of transit. Streams from 15 to 30 feet deep are usually integrated in one direction only, either from the surface to the streambed or from the bed to the surface. Deeper streams are integrated in more than one sampling trip. If the sampling trips are at the same transit rate the samples can be combined into a composite sample.

There are limits on the transit rates for depth-integration. However, if a 1/8-in. intake nozzle is used with a uniform transit rate such that a sample of 350 to 400 ml is obtained by one-way integration in depths less than 30 feet, or by two-way integration in depths less than 15 feet, all other requirements are automatically satisfied.

The maximum and minimum transit rates for round-trip depth-integration with 1/8-, 3/16-, and 1/4-in. nozzles are shown in Fig. 14. The permissible transit rates are given as a ratio R_T/v_m in which R_T is the transit rate and v_m is the mean velocity in the sampling vertical. The solid lines of Fig. 14 indicate the maximum allowable lowering rates based on a one-pint sample container (a sample of 350 to 400 ml) and the limitations imposed on the transit rates by the rate of compression of the air in the sample container. The maximum lowering rates are the same for round-trip and for one-way depth integration. The maximum raising or lowering rates should not exceed 4/10 of the mean velocity to avoid excessive angles between the nozzle and the approaching flow.

The minimum allowable transit rates are those that will avoid an excessively large sample. For one-way integration the minimum allowable transit rate for a given depth is one half of that for round-trip integration. That is, the minimum transit rate for one-way integration at 20 feet depth is the same as that for round-trip integration over a depth of 10 feet. The maximum sampling

* See also Appendix Section 50.

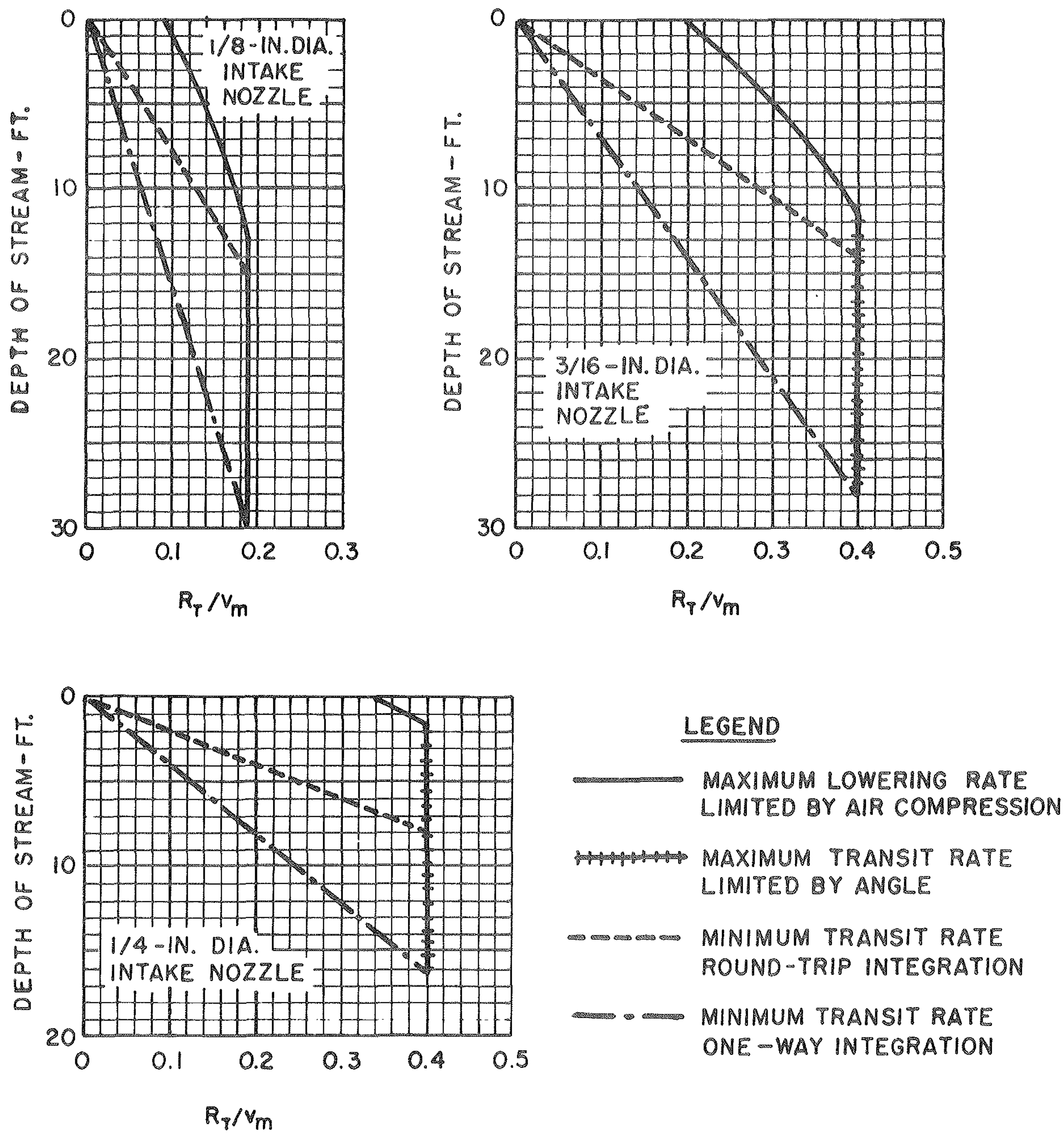


FIG. 14--ALLOWABLE RATIO OF UNIFORM TRANSIT RATE R_T TO MEAN VELOCITY v_m FOR DEPTH INTEGRATION - ONE-PINT CONTAINER

depths are those at which the maximum and minimum transit rates are the same. For round trip integration the maximum sampling depths are 15, 14, and 8 feet for 1/8-, 3/16-, and 1/4-in. nozzles respectively, and twice those depths for one-way integration. Sampling depths can be increased slightly if sample volumes are kept between 400 to 420 ml.

The advantage of depth-integration sampling is that a single sample provides a discharge-weighted concentration for a complete sampling vertical--or in a very deep stream, for a major fraction of a sampling vertical. The disadvantage of depth-integration sampling is the unsampled zone which may require special computations of unmeasured suspended sediment (See discussion of modified Einstein method, Section 38).

17. Sampling a vertical by point integration--A point-integrated sample is accumulated continuously in a sampler (Section 23) that is held at a relatively fixed point in a stream cross section. The sample enters a nozzle that points directly into the approaching flow and enters at a velocity about equal to the instantaneous stream velocity at the point. A point-integrating sampler must be equipped with a valve that can be operated, usually electrically, by the observer after the sampler has been lowered to the sampling point. A sample is taken by lowering the sampler to the sampling point, opening the valve for the desired sampling time, then closing the valve at the end of the sampling period.

Sampling procedures to determine sediment discharge will be emphasized in the following sections. Occasionally, point-integrated samples are taken at specific points in a stream cross section to determine sediment distribution only, but the sampling procedures are basically the same as for measurement of sediment discharge.

18. Selection of sampling points in a vertical--The wide range that occurs in the vertical distribution of sediment concentration (Fig. 10) emphasizes the difficulty of selecting sampling points which accurately define the sediment concentration in the vertical, without sampling so many points that the whole procedure becomes impractical. In the past, methods used for selecting sampling points have varied greatly. Sometimes the method was based on a thorough consideration of the principles involved, whereas in other instances the sampling points were selected in a more or less arbitrary manner, mainly to simplify the sampling procedure. Empirical methods were sometimes used in choosing sampling points, and coefficients based on results of more exact sampling procedures were applied to the data. Semirational methods, based on an analysis of the principles involved in sampling fluvial sediment combined with simplifying assumptions, have also been used.

The following are some of the more common methods of point-integration sampling which have been used to define the sediment concentration in a sampling vertical:

a. A single sample taken at the surface.
b. A single sample taken at 0.6 depth.
c. Two samples, one taken near the surface, and the other near the bottom, weighted equally.
d. Three samples, taken near the surface, at mid-depth, and near the bottom, weighted equally.
e. Three samples, taken near the surface, at mid-depth, and near the bottom, with the mid-depth sample given twice the weight of the others.
f. Samples taken at several points to establish the vertical distribution with the required degree of accuracy.
g. Samples taken at definite locations with corrections based on previous observations.

The accuracy of point-sampling methods can be expected to increase with the number of samples. The simplest method, sampling near the water surface, is well suited to unskilled observers and to conditions where excessive debris and ice flows are encountered, but, because coefficients applicable to surface samples are unreliable, this method is the least accurate. Surface samples are especially undesirable for size analysis because 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. This method may be satisfactory for some streams in which sediments are in the silt and clay size range, but for other streams this method would be inaccurate. This method would also be unreliable for size analyses. Sampling at two points in a vertical, near the surface and bottom, is of doubtful accuracy although it is better than sampling only at the surface. If the surface and the bottom samples have the same volume, a single analysis can be made of the combined samples.

Of the three-point methods, the second is preferable. The mean of the upper half of the concentration will be approximated 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 concentration 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, approximately represents both concentration and size distribution. Actually samples cannot be taken on the bottom. The bottom sample should be taken at about 0.9 depth. The methods involving three samples are more accurate than the surface and the bottom method, and they are sufficiently simple to be handled by unskilled observers.

The Straub method of point sampling, [70] which was developed in connection with sediment investigations in the Missouri River system, is based on the assumptions that the vertical distribution of velocity follows an exponential law, and that the sediment concentration increases linearly from the surface to the bottom. 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 sampling verticals in the Missouri River,

$$C_m = \frac{3}{8} C_{0.8d} + \frac{5}{8} C_{0.2d}$$

where C_m, the discharge-weighted concentration in a vertical, was computed by adding 3/8 of the concentration, $C_{0.8d}$, from a sample taken at 0.8 depth below the water surface; to 5/8 of the concentration $C_{0.2d}$, determined from a sample at 0.2 depth. This method is simple, it requires only two samples, and, as shown in Table 2, it gives accurate results over a considerable range of conditions. This sampling method may not be satisfactory, however, if sediment size distribution is required.

The preceding methods are empirical and do not require a knowledge of the distribution of velocity in the vertical. The following methods require knowledge of the velocity distribution but they are more rational and often more accurate.

The Luby method was originated in sediment studies of the Upper Mississippi River and tributaries. Basically, this method consists of obtaining samples from areas of equal stream discharge in the vertical. The area under the curve of velocity distribution in the sampling vertical 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 discharge-weighted 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 [36]. However, Fig. 4b and the accompanying discussion in Report No. 1 are erroneous in that they evaluate the Luby method in terms of spatial concentration and not in terms of the accuracy of the measurement of discharge (discharge-weighted concentration).

Although the Luby method is moderately satisfactory, it requires advance information on velocity distribution, and the sampling points are at different relative depths in each vertical. If the samples are of equal volume they can be combined and analyzed as a single composite. Samples of equal volume can be obtained only by a study of the velocity distribution curve for each vertical and the use of different sampling times for each sample. The Luby method is discussed here mainly because the following method was not evaluated in Table 2, which is presented on page 51.

B. C. Colby recommends a method that is much simpler and slightly more accurate than the Luby method. The depth at a vertical is divided into equal units of depth and samples are taken at the middle of each unit. For example, for a 5-point measurement samples are taken with a point-integrating sampler at 1/10, 3/10, 5/10, 7/10, and 9/10 depth in each vertical. The concentrations are then weighted according to the velocities at each sampling depth. The velocity distribution can be obtained before or after the samples are taken and even on shifting streams the computations can be made in the office rather than in the field. Also the samples are taken a little lower in the vertical than for the Luby method so that they sample the higher and more variable concentrations more effectively.

Two modifications of this basic method are important because they eliminate the need for independent knowledge of the velocity distribution in the vertical.

a. The sampling time can be recorded for each sample and the weight of sample collected per second can be used instead of stream velocity for weighting the concentrations in a vertical and from vertical to vertical.

b. If a composite sample for the vertical is desirable, all samples in the vertical can be taken for the same sampling time. They can then be combined into a single composite sample for the vertical. The weight of the composite sample per second of total sampling time in the vertical can be used with depth and spacing of the verticals to weight the concentration from vertical to vertical. Or, if the distribution of discharge in the cross section is known, the concentrations in the verticals can be weighted according to the stream discharge that each vertical represents.

The precise method requires velocity and sediment concentration determinations at several points in each vertical. Concentration and velocity curves are drawn from these data, as shown in Fig. 12, and the discharge-weighted sediment concentration is computed as described in the discussion of that figure in Section 13. This method is more laborious than necessary for most routine sediment investigations. However, it does provide a means for determining accurately the suspended-sediment discharge and for making a complete analysis of the vertical distribution of particle sizes.

In the absence of a detailed study the method of sampling at the mid-points of equal fractions of the depth is recommended. If a representative sample of the sediment size distribution as well as the concentration is desired, at least five points in each vertical should be sampled.

19. Accuracy of the different methods of point sampling--In general, the accuracy of point sampling in a vertical 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 sediment is exclusively within the silt and clay range. However, the percentage error increases with increasing particle size and with a decrease in velocity or turbulence.

The errors when the discharge-weighted sediment concentration in a vertical is obtained from different point-sampling methods are summarized in Table 2 [41]. 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 different stream velocities, particle sizes, and channel roughnesses. Data in Table 2 show that no single method is accurate for all conditions, although several are fairly reliable for ordinary stream conditions. Even in the more accurate methods the errors exceed 50 percent for some large sediment sizes and low velocities.

Table 2 uses a sediment distribution in the vertical that is based on the original turbulence theory. The actual distribution of sediment in a stream is more uniform [24] than the distribution used in computing Table 2. Therefore, the errors shown in Table 2 are larger than those for natural streams.

Fig. 6 of Report 8 [41] superseded by this report, illustrated errors in point-sampling methods. However, it showed the errors in determining spatial concentration in a vertical and not the errors in measuring the discharge, and so it is not an appropriate illustration of sampling errors.

Velocity measurements recorded continuously for a period of several hours, in the Missouri River [5] showed that a two-minute period was required to obtain a good average velocity. The velocity measurements shown in Fig. 8 do not deviate much from a straight line. However, because of the instantaneous fluctuation in velocities (Fig. 4), at least 6 velocity measurements in each vertical are required to determine the velocity distribution. Hence, a fairly long sampling time is required to obtain a representative sample of sediment concentration.

The points on the log-log sediment concentration plots (Fig. 9) show a greater scattering than the points on the corresponding velocity plots (Fig. 8) probably because the sampling time for sediment concentration was shorter and some of the sediment was sand. Point samples taken by the Army Corps of Engineers in over 300 verticals in the Missouri River at Omaha, Nebraska [5], show that fluctuation in sediment load is so great during a period of only 15 seconds, that any one sample may not be representative of the average sediment concentration. If an instrument will not sample continuously for as long as 1 minute, the average of several consecutive shorter sampling periods may be used. Not less than six 15-second samples and not less than three 30-second samples will probably be required to determine average concentration at a point. However, if a sediment discharge measurement is based on several samples, some will be high and some low and the instantaneous variations will tend to average out both within a vertical and for the entire stream. The fluctuations from the average concentration depend largely on particle size.

TABLE 2

ACCURACY OF POINT SAMPLING METHODS

Mean velocity in vertical ft./sec.	Sampling method*	Percentage error for various relative roughness conditions														
		Relative roughness $n/D^{1/6} = 0.010$					Relative roughness $n/D^{1/6} = 0.020$					Relative roughness $n/D^{1/6} = 0.030$				
		Particle size, mm.					Particle size, mm.					Particle size, mm.				
		0.010	0.025	0.05	0.115	0.35	0.010	0.025	0.05	0.115	0.35	0.010	0.025	0.05	0.115	0.35
	Surface	-12	-58	- 98	----	----	- 5.6	-32	-83	-100	----	- 3.9	-21	-64	- 99	----
	0.6 depth	+ 2.9	+10	- 51	----	----	+ 1.7	+10	+12	- 91	----	+ 1.2	+ 8.1	+21	- 58	----
	0, 0.5, 0.9 D	0.0	+ 4.5	+ 41	----	----	+ 0.2	+ 3.5	+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	+ 7.5	+60	----	----	+ 0.4	+ 5.3	+40	+480	----
0.5	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	+260	----
	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	----	- 0.8	- 0.2	+ 1.7	+ 5.0	----
	Luby - 3 point	- 0.1	- 1.0	- 22	----	----	- 0.2	- 0.8	- 7.0	- 70	----	- 0.3	- 0.5	- 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	----
	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	----
1.0	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	----
	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	+ 24	+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
2	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	+ 25	+220
	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	- 4.9	----	- 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
	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	+ 1.8	+ 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
3	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	+ 0.8	+ 3.1	+ 25	+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
	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
4	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	- 0.6	- 8.4	- 0.2	- 0.1	- 0.2	- 0.4	- 3.0
	Surface	- 1.0	- 6.1	- 22	- 73	-100	- 0.5	- 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	+ 18	+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
6	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	- 1.8
	Surface	- 0.6	- 3.5	- 14	- 52	-100	- 0.3	- 1.9	- 6.9	- 28	- 87	- 0.3	- 1.2	- 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	+ 0.6	+ 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	----	+ 0.9	+ 5.4	+ 72	- 0.1	0.0	+ 0.5	+ 4.3	+ 46
10	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	+ 58	----	----	----	+ 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	- 2.8	- 0.1	- 0.1	- 0.2	- 0.1	- 1.0
	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	+ 0.5	+ 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
15	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.

20. Types of suspended-sediment samplers--Considerable thought and ingenuity have been expended in the development of instruments for sampling fluvial sediment. More than sixty-five so-called suspended-sediment samplers are described in Report No. 1 [36]. 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 into the following six general types:

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

As an ordinary vertical pipe sampler is lowered to the sampling depth, the water-sediment mixture flows upward through the open sample container. When the lowering is stopped, valves at both ends of the pipe close and the sample is trapped. The simplicity of design has been the reason for extensive use of this type in the past, but many adverse sampling characteristics have practically eliminated it from current use.

In the instantaneous vertical sampler a messenger weight that is dropped down the suspension line releases the sample cylinder which falls vertically, or is forced down by a spring, to close against a flat plate and seal the sampler opening. Besides the difference in the sampling action of an instantaneous vertical sampler and an ordinary vertical pipe sampler, the instantaneous sampler obtains a specimen from a smaller part of the vertical.

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 [10]. The stream is allowed to flow through the horizontal cylinder as the sampler is lowered to the desired depth. The horizontal trap sampler has been widely used in sediment investigations. The principal advantages of this type of sampler are relative simplicity of design and operation, ability to sample close to hard bottoms, and adaptability to shallow and deep streams under wide variations in velocity. Instantaneous horizontal samplers obtain a spatial concentration of sediment that cannot be used to compute sediment discharge unless the velocity of the sediment in relation to the velocity of the stream flow is known. For sampling near the streambed, the sediment cannot be assumed to move at the same velocity as the water.

The Tennessee Valley Authority sampler (Fig. 15) is one kind of instantaneous horizontal sampler. It 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. A pull on an auxiliary line releases the valves and traps the sample. A spring extending through the cylinder holds the valves closed. The sampler has sufficient weight for ordinary conditions in shallow streams but additional weights may be used if desired.

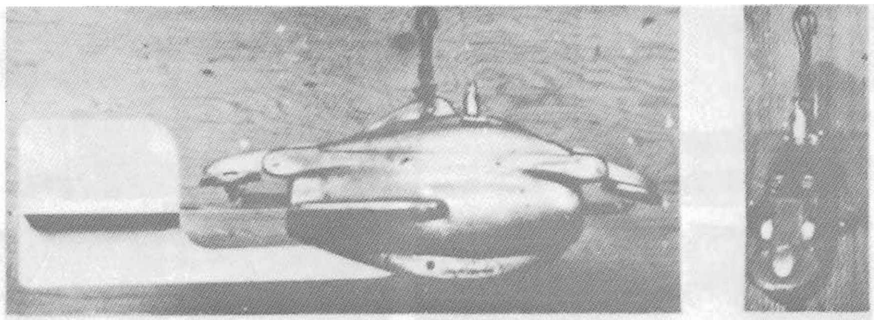


FIG. 15--TENNESSEE VALLEY AUTHORITY SAMPLER

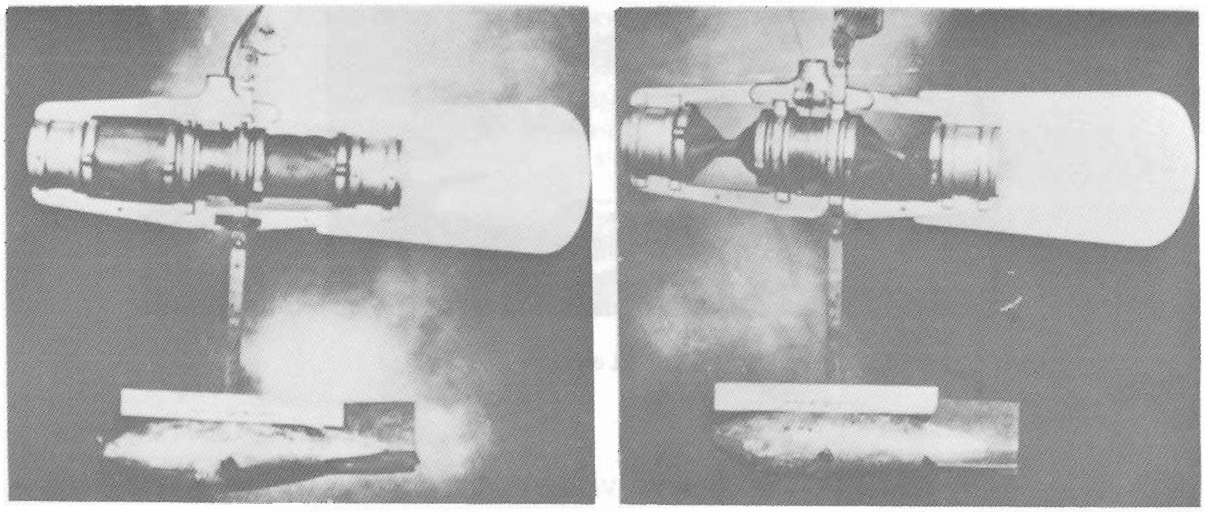
From Fig. 11 of reference 41

Another instantaneous horizontal sampler is the Tait-Binckley (Fig. 16), which consists of three metal tubes of equal diameter mounted coaxially a short distance apart in a horizontal metal frame. The middle tube is mounted on bearings for free rotation about its axis and is connected to the two rigidly mounted end cylinders by sections of thin rubber tubing. A sample is trapped by rotating the middle section by a pull on an auxiliary line wound around the section. The resulting twist in the connecting sections of rubber tubing seals the ends of the sample container.

The simplest device for sediment sampling is an ordinary milk bottle, fruit jar, or other standard container with provisions for lowering it to the sampling point. The bottle type sampler is provided with an entrance varying in size from about 1/4 inches in diameter up to the full opening of the container. As air within the bottle is displaced by the incoming sample, an undesirable bubbling action is produced at the entrance. Because of the time required to fill the sampler and because of the air bubbles that escape through the intake, bottle samplers are sometimes classed as slow-filling bubbling samplers.

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

Suspended-sediment samplers can be classified as instantaneous and integrating samplers. Many samplers do not completely qualify for either classification because of their design, sampling action, or method of operation. As the name implies, the instantaneous sampler traps a specimen of the water-sediment mixture



Sample chamber open Sample chamber closed

FIG. 16--TAIT-BINKLEY SAMPLER

From Fig. 12 of reference 41

passing the sampling point at a selected instant. On the other hand, the integrating sampler takes the sample over an extended period of time to average momentary concentrations at a point, or to integrate the concentrations in a sampling vertical. Integrated samples are obtained with either a point-integrating sampler or a depth-integrating sampler.

21. Some characteristics of the sampling process--Conditions at the mouth of a sampler intake may be represented by the flow pattern of the water-sediment suspension approaching and entering the sampler. If this flow pattern is distorted by changes in velocity or disturbances set up by the sampler itself, the sediment will tend to segregate from the filament of water in which it is conveyed. This segregation occurs because the sediment has greater density and inertia and changes direction less readily than the water. The flow pattern at a sampler intake 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. Then the stream lines diverge as the sample filament approaches the mouth of the sampler (Fig. 17) [41]. The sediment just outside the border of sampled filament diverges less rapidly than the water and enters the mouth of the sampler as an excess. For the converse condition, in which the velocity in the mouth of the sampler is greater than the natural stream velocity, the sediment in the sample filament converges to a lesser degree than the water and the sediment concentration in the sample is too low.

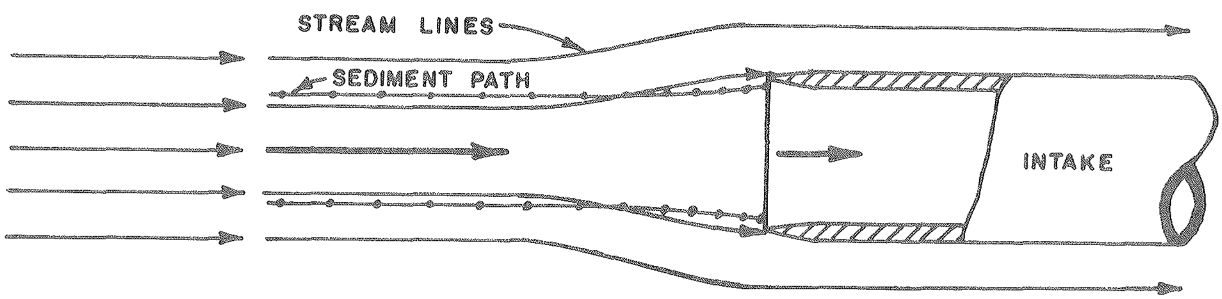


FIG. 17--FLOW PATTERN AT MOUTH OF SAMPLER INTAKE,
SAMPLING RATE BELOW NORMAL

Adapted from Fig. 13 of reference 41

Experiments described in Report No. 5 [39] show that errors from sampling rates below normal are considerably larger than errors from sampling rates a like amount 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 an intake velocity to stream velocity ratio of 0.25 the error in sediment concentration was 8 percent too great for sediments of 0.06-mm diameter, and 100 percent too great for sediments of 0.45-mm diameter. Obviously, proper entrance conditions are important, especially when a sampler is to be used in streams carrying relatively coarse sediments.

Any slow-filling sediment sampler with a container of fixed volume will fill at an uneven rate when subjected to a pronounced pressure differential between the sampling point and the air in the container. When the air in the sample container remains at atmospheric pressure and the sampler is opened below the water surface, there occurs an initial inrush of the water-sediment mixture which is volumetrically a function of the depth of submergence and the size of the container. As the air in the sample container is compressed, both pressure differential and filling rate quickly reduce until the filling operation becomes the normal action involving displacement of air. The initial inrush period was found to be less than 1 sec in experiments described in Report No. 5 [39]. In still-water tests on five different sampler designs the observed initial inrush deviated less than 1 percent from the theoretical curve shown in Fig. 18 [41]. For samplers with fixed-volume containers, the initial inrush can be eliminated by providing a means of pressure balance between the air in the container and hydrostatic pressure surrounding the sampler. A pressure differential between

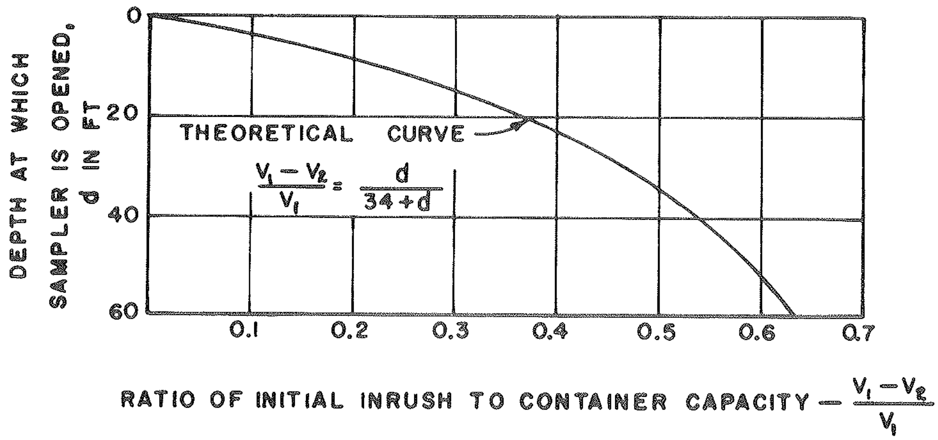


FIG. 18--INITIAL INRUSH FOR SLOW-FILLING SAMPLERS

Adapted from Fig. 14 of reference 41

the sampling point and the container can cause sampling errors in the following ways:

a. The excessive sampling rate during the initial inrush period tends to segregate sediment from the water filament resulting in a sample too low in concentration.

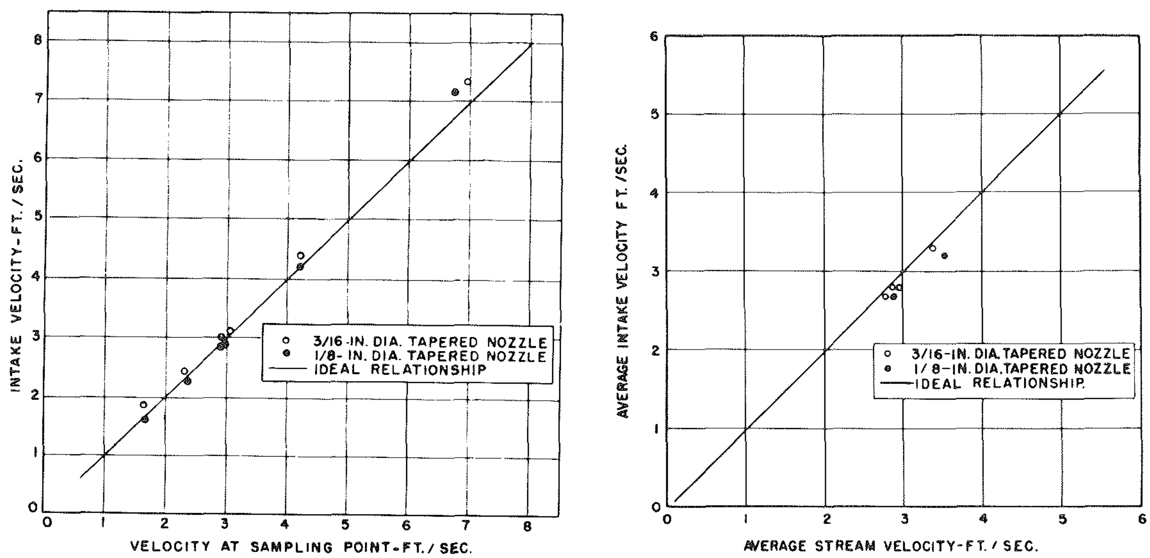
b. If a relatively large portion of the sample container is filled in less than 1 sec, the sample will not represent the mean sediment concentration at the sampling point.

c. If the sample is collected only on the upward trip by the depth-integration method, too large a fraction of the total sample will be taken from the zone of highest sediment concentration near the streambed.

22. The US series of depth-integrating samplers--The Inter-Agency Project has designed a series of depth-integrating samplers. These samplers have many things in common:

An intake nozzle points directly into the approaching streamflow. An air-exhaust tube has an outlet on the side of the sampler head so that air can escape from the sample container as the sample is taken. There are no valves on the intake or exhaust lines. Sampling begins when a sampler is first submerged and ceases when the sampler is removed from the water. This round-trip sampling limits the maximum sampling depth to about 17 feet for a sample of about 400 ml.

The sample container is a one-point round milk bottle. A hinged sampler head provides access to the sample container in some models, but in others the container is only partially enclosed and it is held in place by a spring. The container rests at an angle so that sample will not be lost when the container is nearly full. The intake velocity was made equal to the stream velocity for proper sample integration and accurate sampling (Fig. 19) [41].



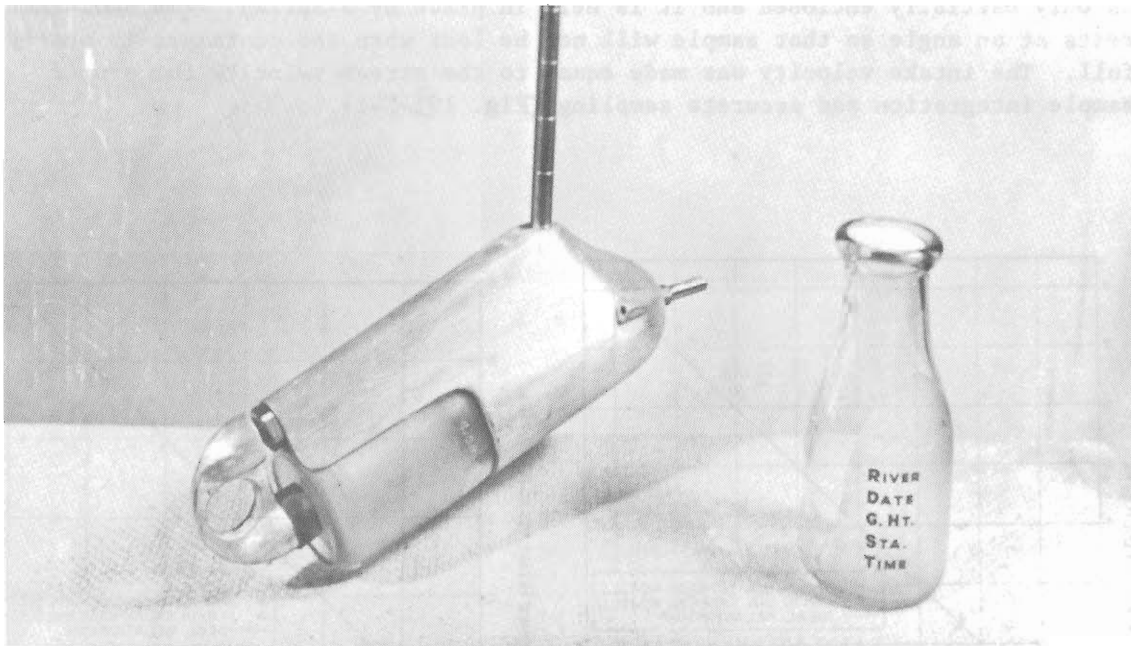
Laboratory tests Field tests

FIG. 19--INTAKE CHARACTERISTICS OF A US SUSPENDED-SEDIMENT SAMPLER

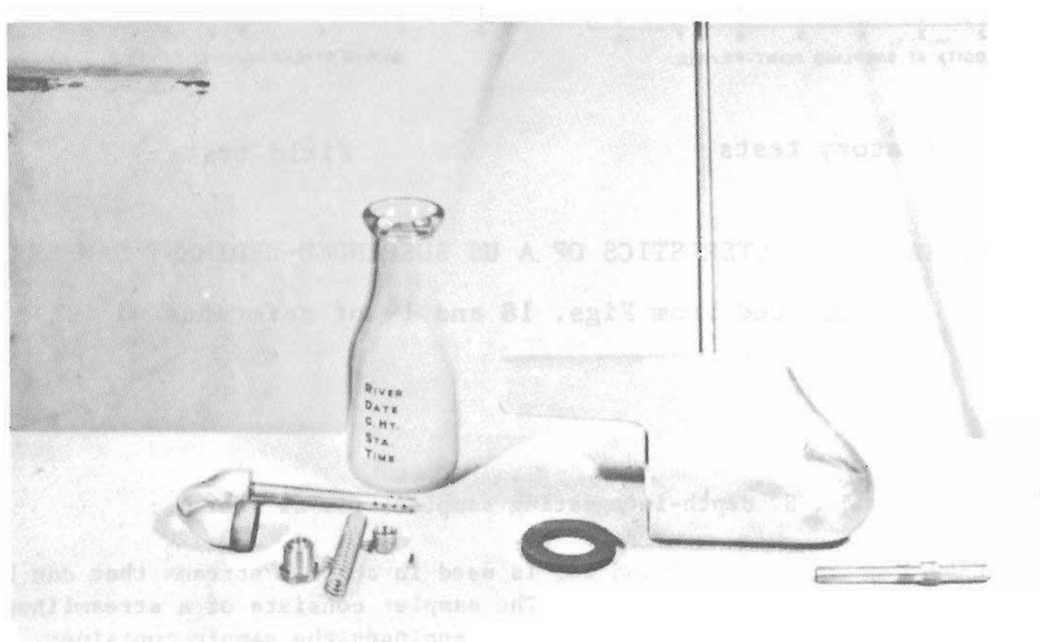
Adapted from Figs. 18 and 19 of reference 41

The four common U. S. depth-integrating samplers are as follows:

A US DH-48 sampler (Figs. 20 and 21) is used in shallow streams that can be waded or sampled from a very low bridge. The sampler consists of a streamlined aluminum casting, 13 in. long, which partially encloses the sample container. A spring-tension clamp holds the sample container against a rubber seal in the sampler head. The sampler, including the container, weighs 4 1/2 pounds. A standard stream-gaging wading rod is threaded into the top of the sampler body



Assembled sampler with extra pint milk bottle



Disassembled sampler

FIG. 20--DEPTH-INTEGRATING WADING TYPE HAND SAMPLER, US DH-48

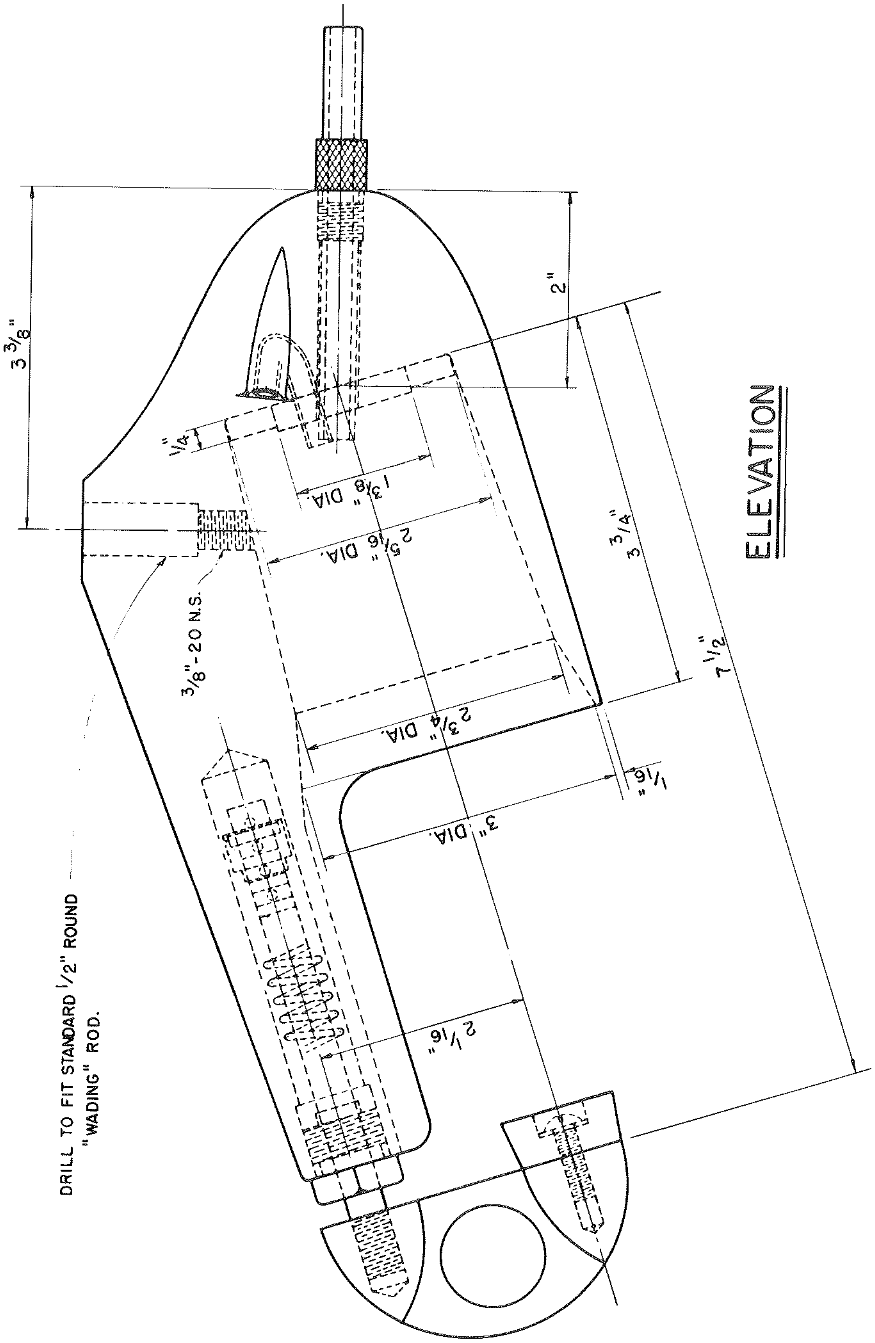


FIG. 21--DEPTH-INTEGRATING WADING TYPE HAND SAMPLER, US DH-48

for suspending the sampler. The instrument can sample to within 3 1/2 in. of the streambed. The sampler is calibrated with a 1/4-in. inside-diameter nozzle. However, a 3/16-in. nozzle may also be used.

A US DH-59 sampler (Figs. 22 and 23) was specially designed for use with a hand-line suspension, primarily in streams that cannot be waded, but which have velocities less than 6 ft per sec. The sampler weighs 24 pounds and is 15 in. long. It is similar to the US DH-48 except that tailvanes orient the sampler in the streamflow.

The US D-43 sampler is suitable for depth-integration of streams less than 17 feet deep in which the velocities preferably do not exceed 7 ft per sec. The sampler weighs about 50 pounds and is hung on a steel cable and suspended from a reel and crane.

The US D-49 sampler is an improved design of the D-43. The D-49 is heavier (about 62 pounds) and more stable in high velocity or turbulent flow. It is easier to operate, more rugged, and cheaper to manufacture. The D-49 samples to the same depth but is adapted to slightly higher velocities than the D-43. The sampler, which is shown in Figs. 24 and 25, has a cast bronze streamlined body 24 in. long, in which the sample container is enclosed. Integrally-cast tail vanes orient the instrument in the streamflow. The nose of the sampler is drilled and tapped for intake nozzles, 1/4-, 3/16-, and 1/8-in. in diameter.

Development of the US D-43, US DH-48, and US D-49 samplers is discussed in Report 6 [40].

23. The US series of point-integrating samplers--Point-integrating samplers are more versatile than the simpler depth-integrating types. They can be used to collect a sample that represents the mean sediment concentration at any selected point beneath the surface of a stream except within a few inches of the bed, and also to sample continuously over a range in depth. They are used for depth-integration in streams too deep to sample in a single round-trip integration. In depth integration, sampling can start at any depth and continue in either an upward or downward direction for a maximum vertical distance of about 30 feet.

A point-integrating sampler has a 3/16-in. nozzle that points directly into the streamflow, and an air exhaust that permits air to leave the sample container as the sample enters. The intake and exhaust passages are controlled by a valve. When the valve is in the sampling position the sampling action is the same as in a depth-integrating sampler. A pressure-equalizing chamber (diving-bell principle) is enclosed in the sampler body to equalize the air pressure in the container with the external hydrostatic head at the intake nozzle at all depths. The inrush, which would otherwise occur when the intake and air exhaust are opened below the surface of the stream, is thereby eliminated.

Shown with pint milk bottle in place.

Shown with pint milk bottle removed from sampler body.

FIG. 22--DEPTH-INTEGRATING HAND-LINE SAMPLER, US DH-59

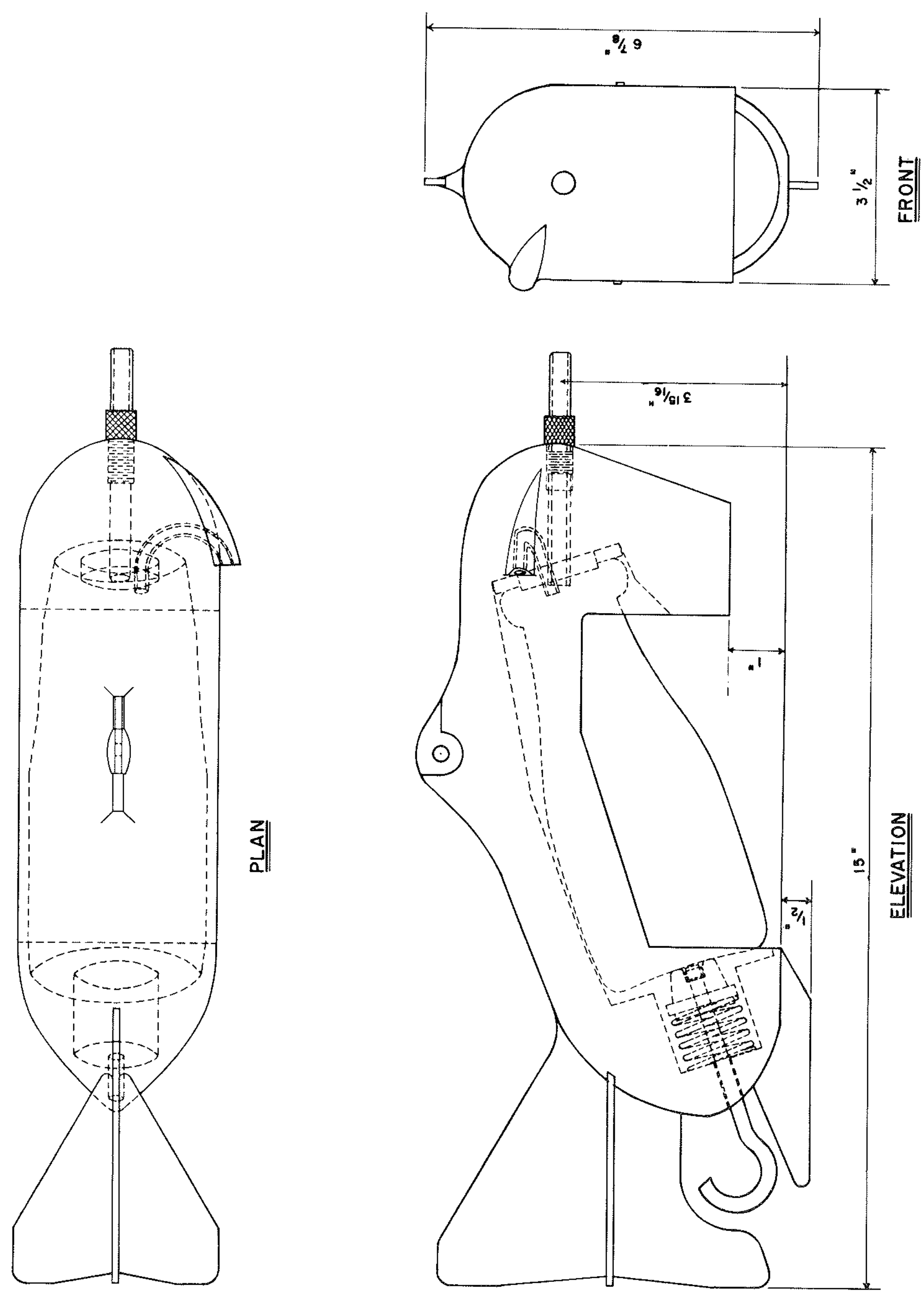
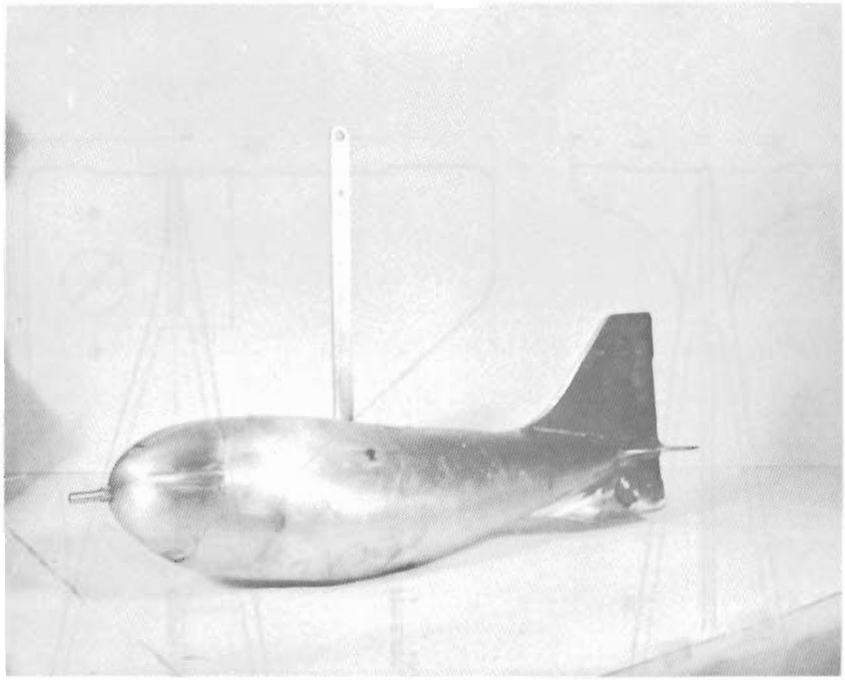
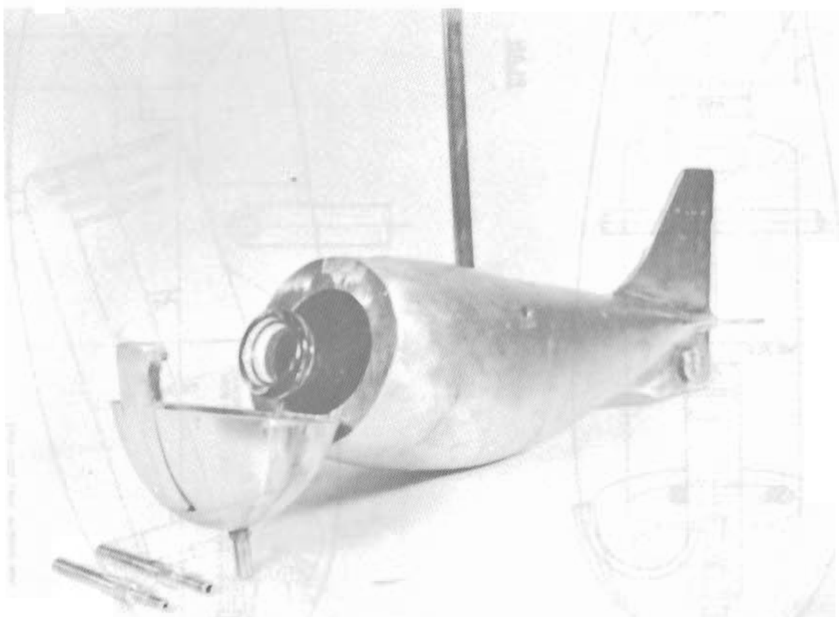


FIG. 23--DEPTH-INTEGRATING HAND LINE SAMPLER, US DH-59



Assembled sampler



Head open

FIG. 24--DEPTH-INTEGRATING SAMPLER, US D-49

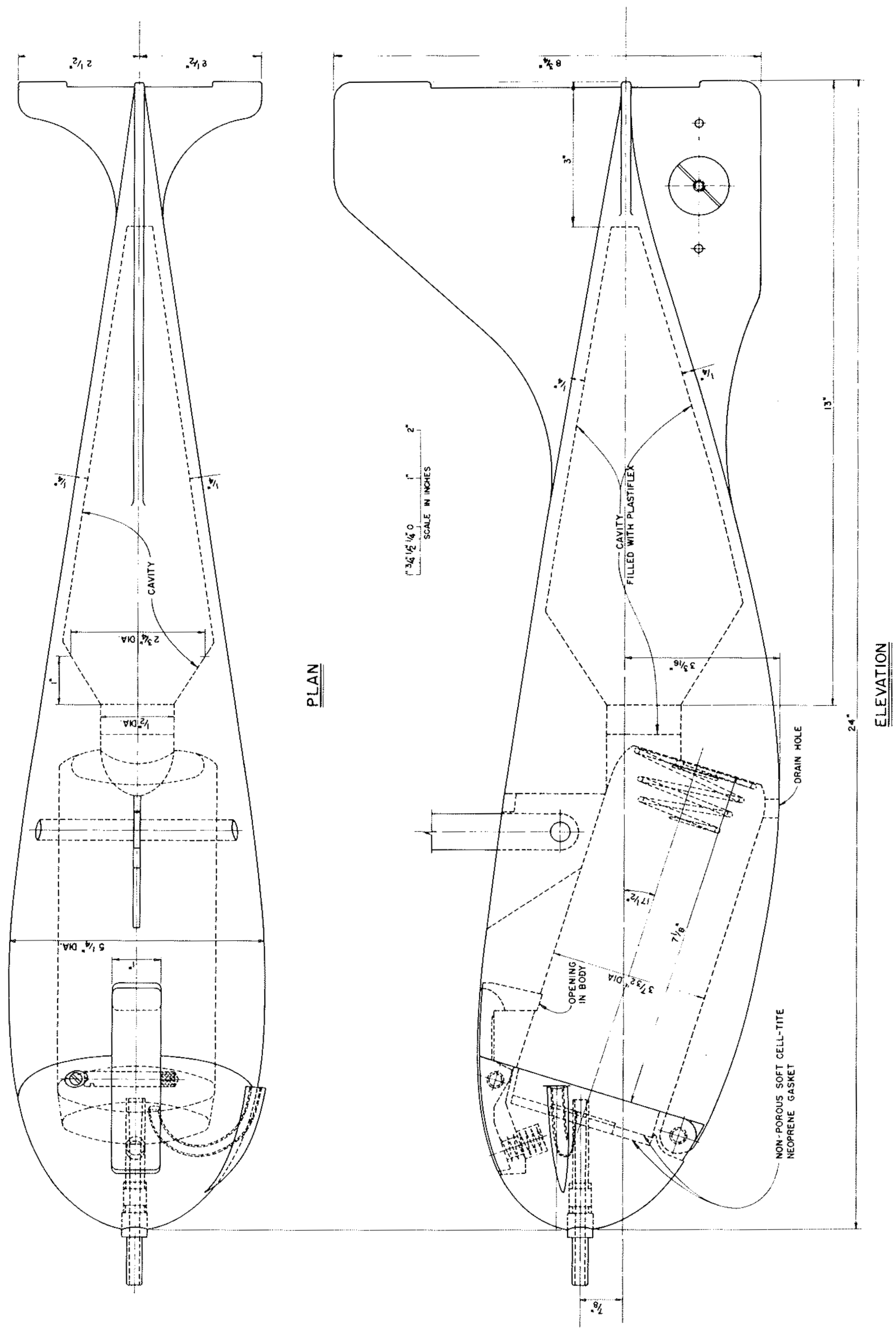


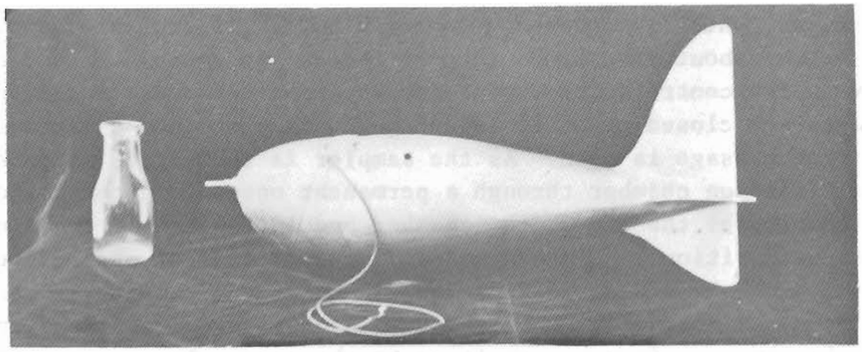
FIG. 25--DEPTH-INTEGRATING SAMPLER, US D-49

The body of the 100-pound US P-46 point-integrating sampler (Figs. 26, 27, and 28) consists of a streamlined cast bronze shell; an inner recess to hold the sample container, which is a round pint milk bottle; a pressure-equalizing chamber with a volume about five times that of the sample container; and a tapered rotary valve which controls the sample-intake and air-exhaust passages. When these passages are closed prior to lowering the sampler into a stream, the pressure-equalizing passage is open. As the sampler is submerged, water enters the pressure-equalization chamber through a permanent opening in the bottom of the shell, and compresses the air in the chamber and in the sample container. The valve has three positions: a intake and air exhaust closed, pressure-equalizing passage open; b intake and air exhaust open, equalizing passage closed; c all passages closed. A solenoid, energized by six or eight 6-volt lantern batteries, moves the valve in turn from one position to the next. The current from the batteries, which are located on the operating rig, flows to the solenoid through a two-conductor current-meter cable which suspends the sampler. The sampler can be used to depths of at least 75 or 120 feet depending on the arrangement of the air exhaust line in the sampler head.

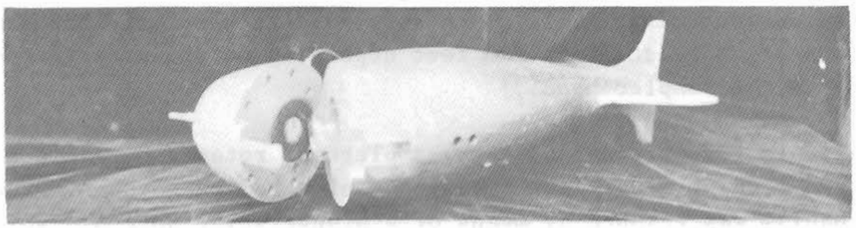
The valve in the original US P-46 sampler was rotated by a clock-type spring which required winding after four or five samples had been taken. The valve ratchet mechanism was tripped by means of a plunger-type solenoid which was energized when a push button switch was pressed. Each time the valve ratchet was tripped the valve rotated to the next position.

The US P-46 R sampler utilizes a rotary solenoid to turn the valve to each position. The rotary solenoid is activated by a telephone-dial switch at the observer's station on the bridge or cableway. A signaling device indicates when the valve is in the sampling position. Details of this mechanism are shown in Fig. 28.

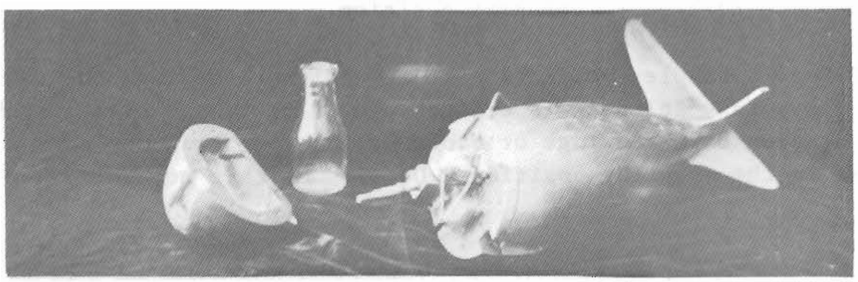
The 100-pound US P-61 (Figs. 29, 30, and 31) is a point-integrating sampler that is similar to the US P-46 in size, shape, weight, construction material, use of pressure-equalization chamber, sample container, tapered rotary valve, two-conductor suspension cable, and power supply. The US P-61 is simpler and less expensive than the US P-46. It can be used for depth-integration as well as for point-integration to stream depths of at least 150 feet. The sampler valve is operated by a rotary solenoid which turns the rotary valve through an angle of 45^{o}. The valve has two positions instead of three as in the US P-46 sampler. When the solenoid is not energized the valve is in the equalizing position, in which position the intake and air-exhaust passages are closed, the air chamber in the body is connected to the cavity in the sampler head and the head cavity is connected through the valve to the sample container. When the solenoid is energized, the valve is in the sampling position; that is, the intake and air-exhaust passages are open and the connection from the sample container to the head cavity is closed. In normal sampling operation, the sampler is lowered to the desired sampling position and a switch is held closed to energize the



Assembled sampler



Head swung back



Head cover removed

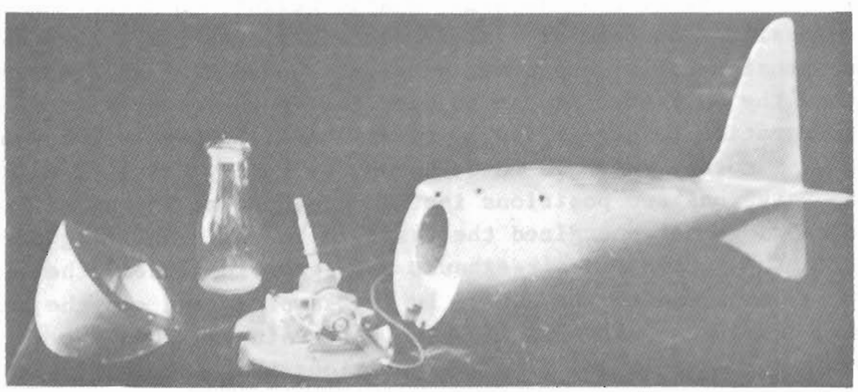


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FIG. 26--POINT-INTEGRATING SAMPLER, US P-46 R

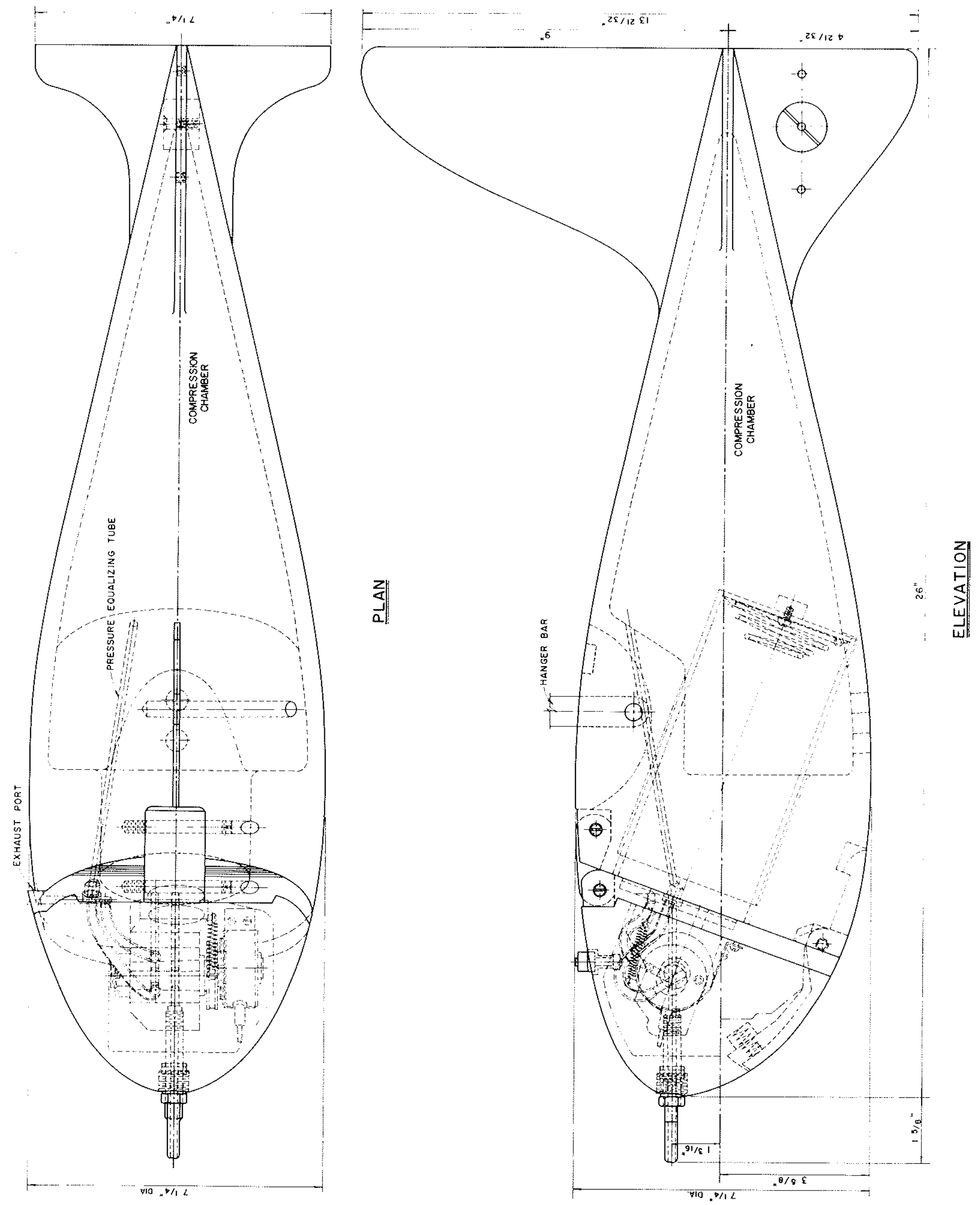


FIG. 27--POINT-INTEGRATING SAMPLER, US P-46 R

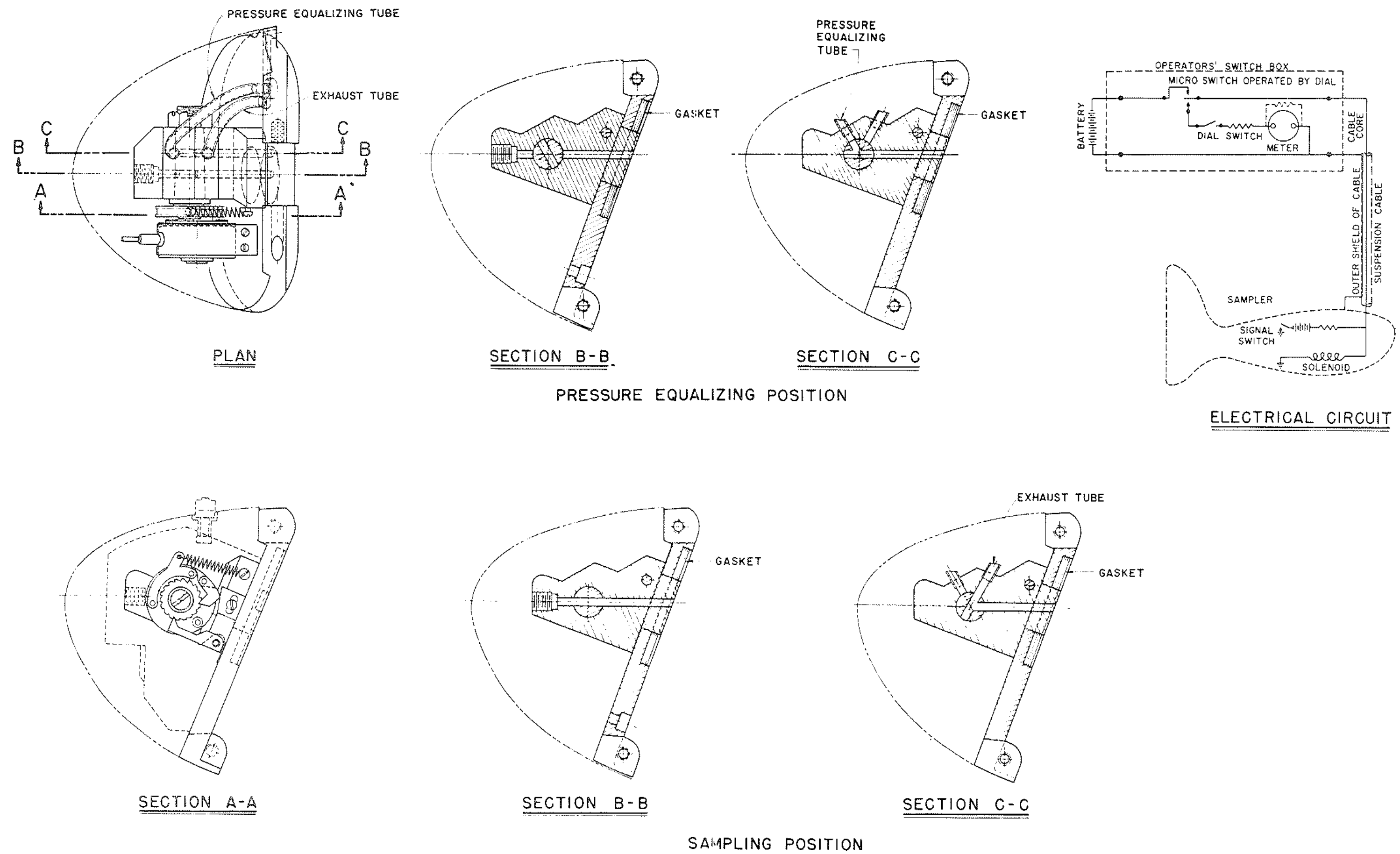
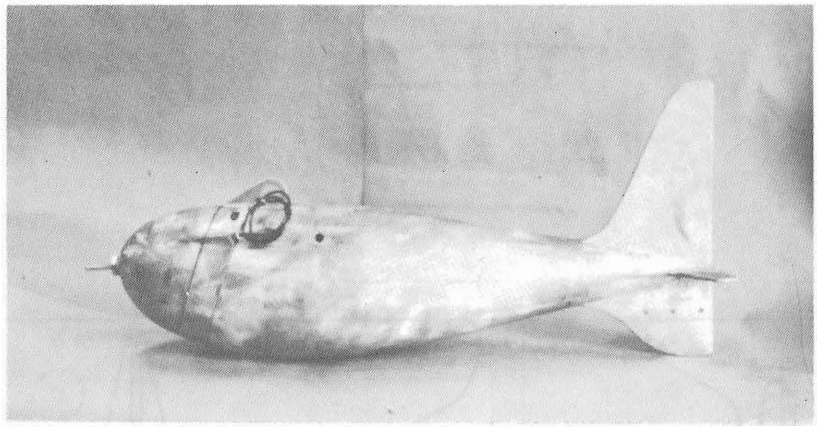
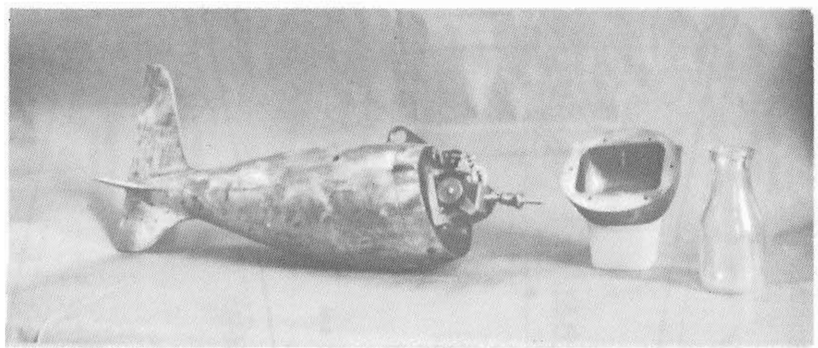


FIG. 28--POINT-INTEGRATING SAMPLER, US P-46 R, VALVE MECHANISM



Assembled sampler



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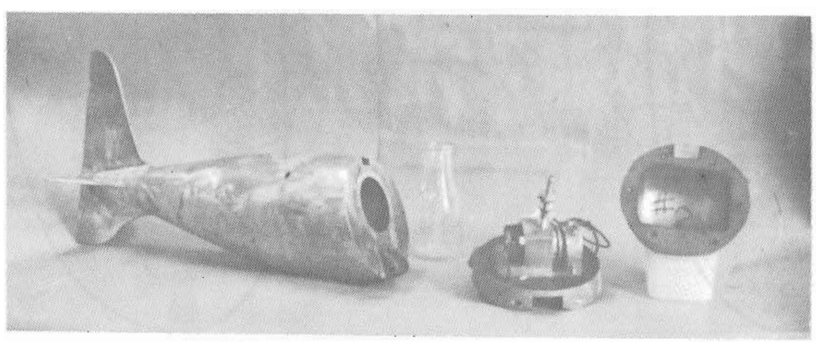

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FIG. 29--POINT-INTEGRATING SAMPLER, US P-61

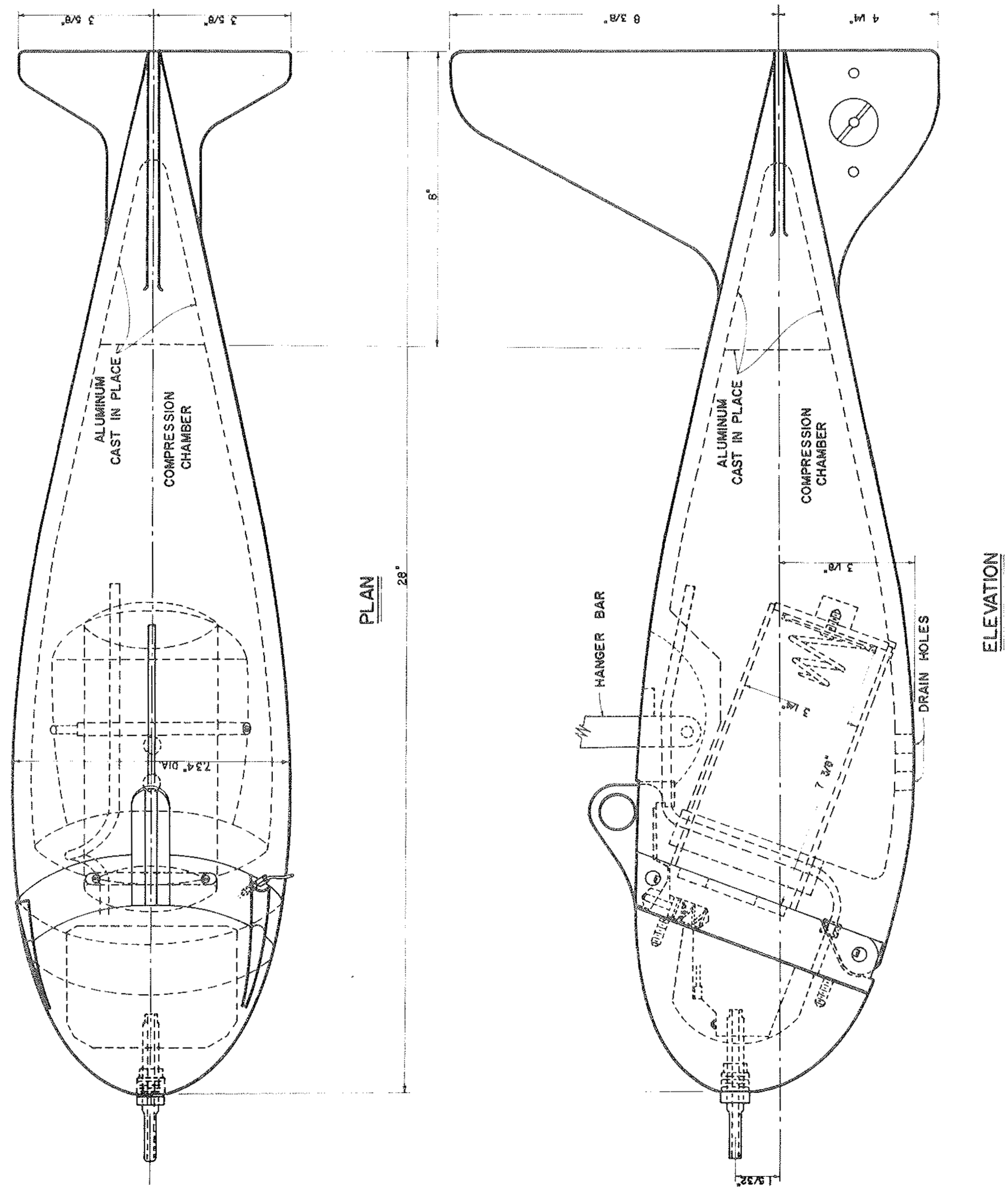


FIG. 30--POINT-INTEGRATING SAMPLER, US P-61

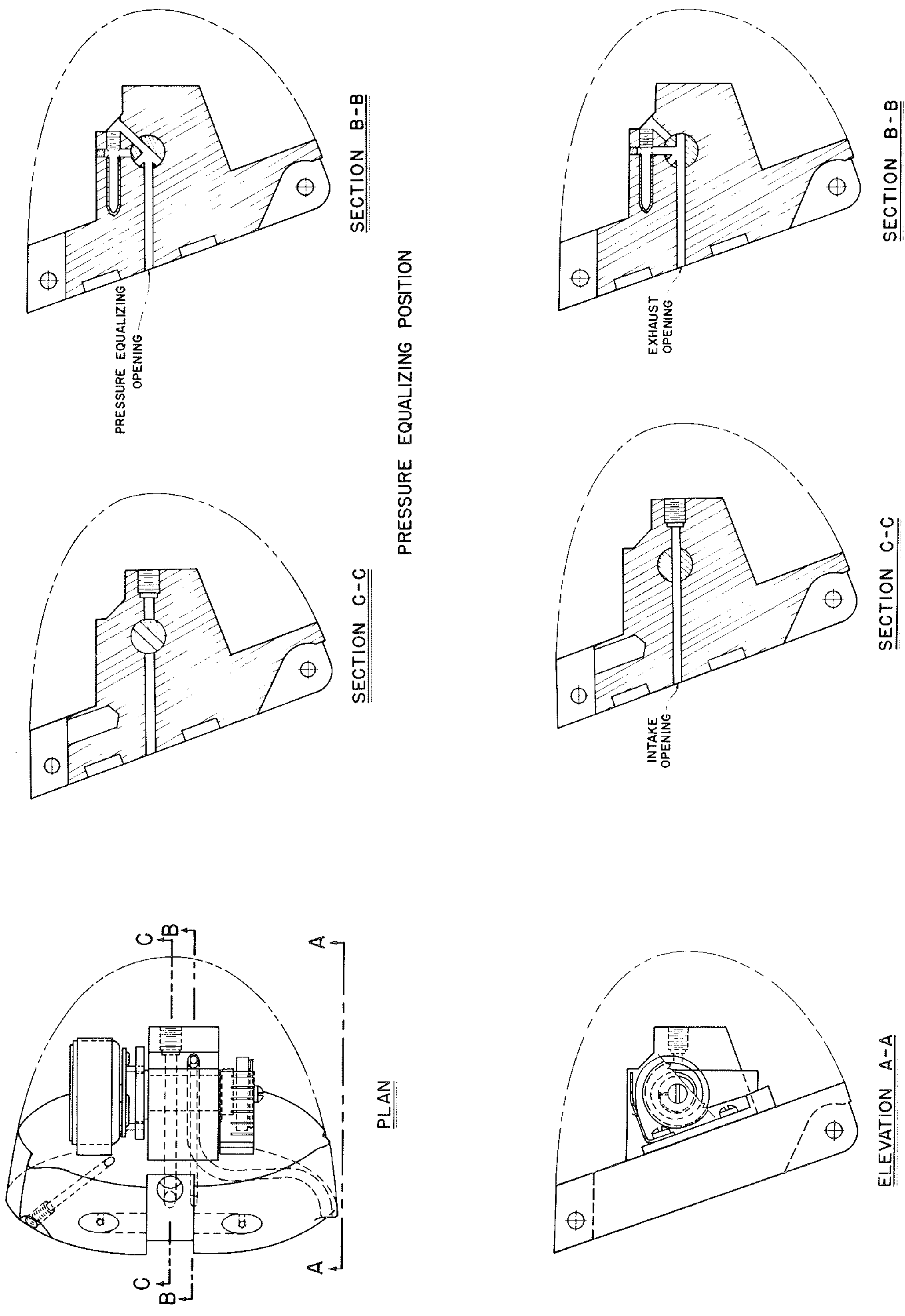


FIG. 31--POINT-INTEGRATING SAMPLER, US P-61, VALVE MECHANISM

solenoid for the length of time that sampling is to continue. A 200-pound US P-63 point-integrating sampler (Figs. 32 and 33) is also available. The valve mechanism and operation of the US P-61 and US P-63 are identical. However, the US P-63 provides for both pint and quart sample containers.

The 300-pound US P-50 sampler (Figs. 34, 35, and 36) was developed to take suspended-sediment samples in extremely deep streams of high velocity. The body of the sampler is cast bronze, 44-in. long, streamlined, and equipped with integral tailvanes to orient it in the flow. The sampler head is hinged to provide access to the sample container, a round quart milk bottle. An electrically actuated valve mechanism to start and stop the sampling process is located in the head. The sliding valve has two positions; a, the equalizing position, in which the pressure in the sample container is balanced with the hydrostatic pressure at the nozzle, and in which the intake and exhaust passages are both closed; and b, the sampling position, in which the intake and air exhaust are open. The valve is held in the equalizing position by a spring. Solenoids, when electrically energized, hold the valve in the sampling position. About 1 ampere of direct current at 50 volts is required for dependable operation. The compression chamber in the body of the sampler has a volume adequate for operation to depths of 200 feet. Because of its weight, the sampler requires a rugged cable, reel, and crane suspension.

Development of the US P-46 and US P-50 samplers is discussed in Report No. 6 [40].

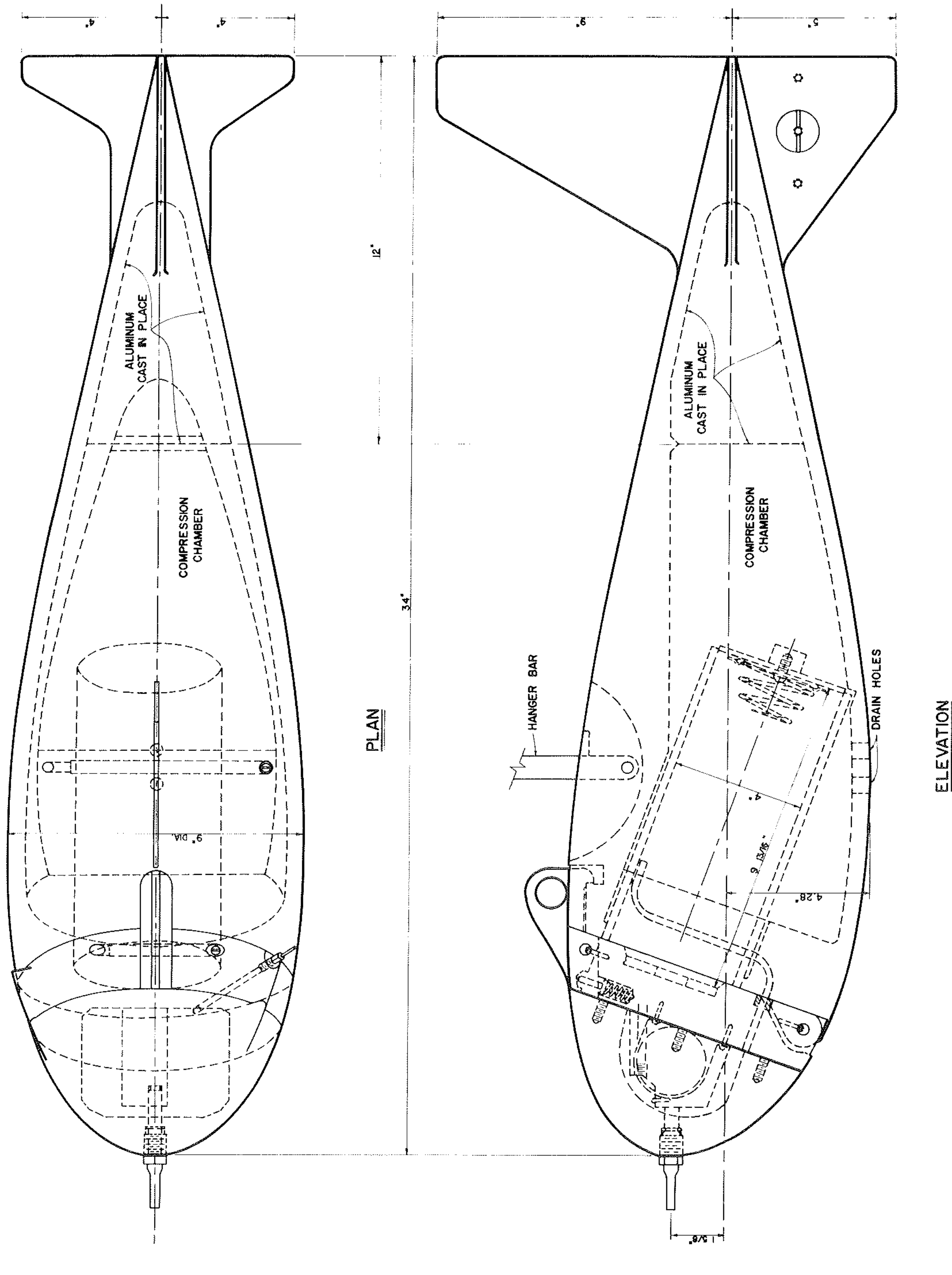


FIG. 32--POINT-INTEGRATING SAMPLER, US P-63

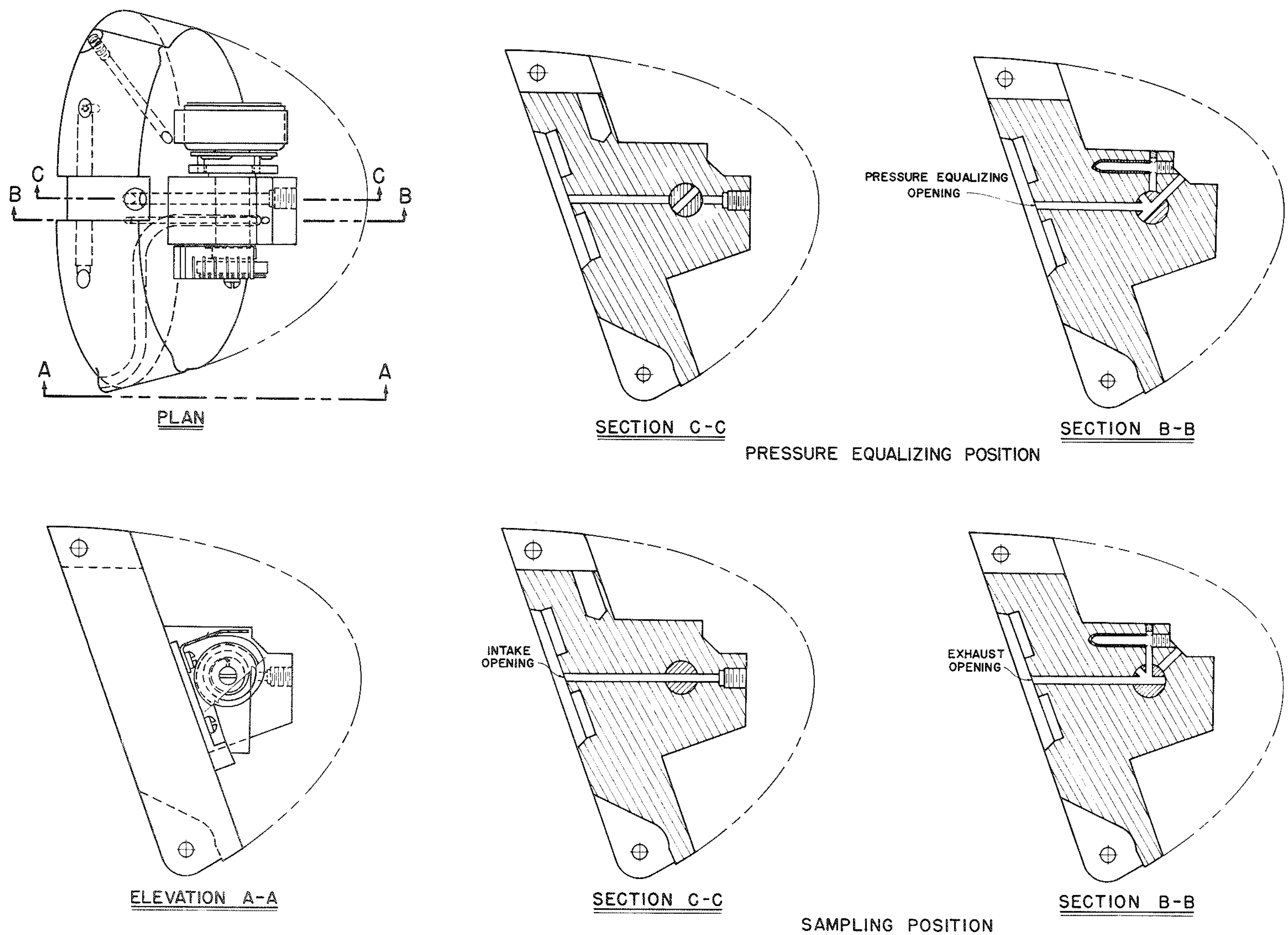
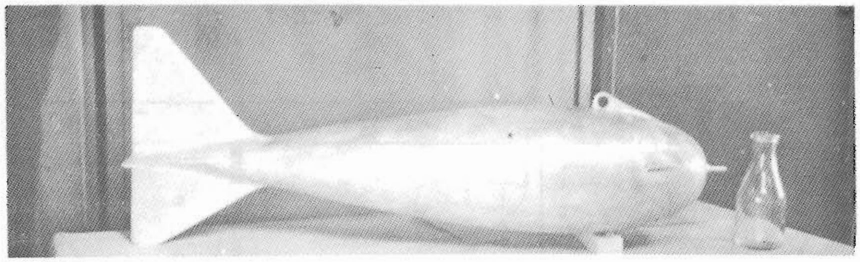
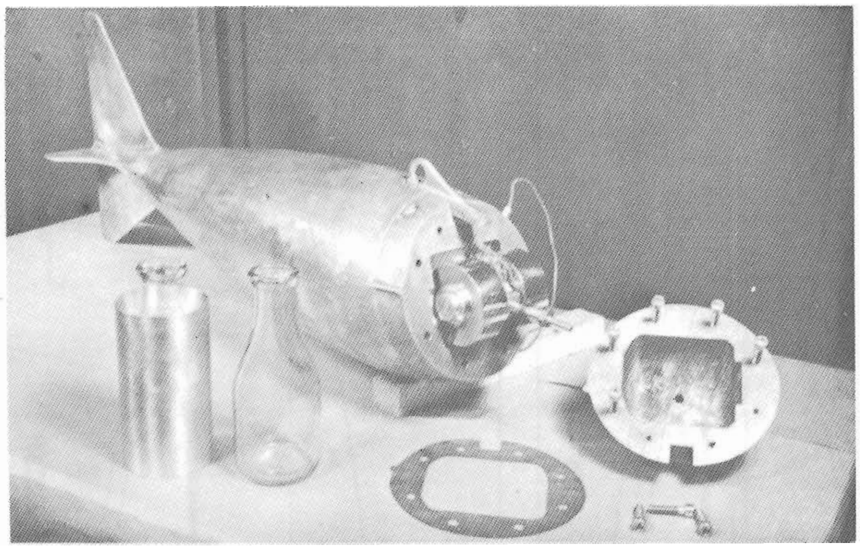


FIG. 33--POINT-INTEGRATING SAMPLER, US P-63, VALVE MECHANISM



Assembled sampler



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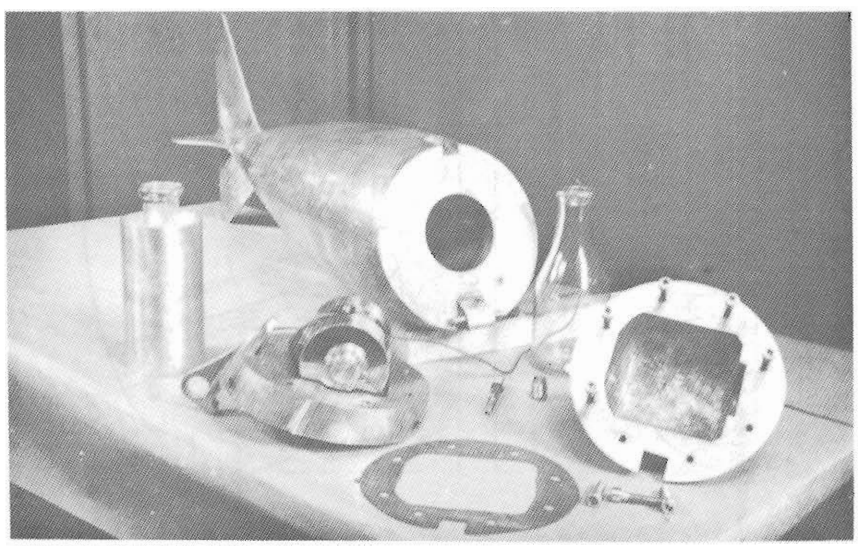

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FIG. 34--POINT-INTEGRATING SAMPLER, US P-50

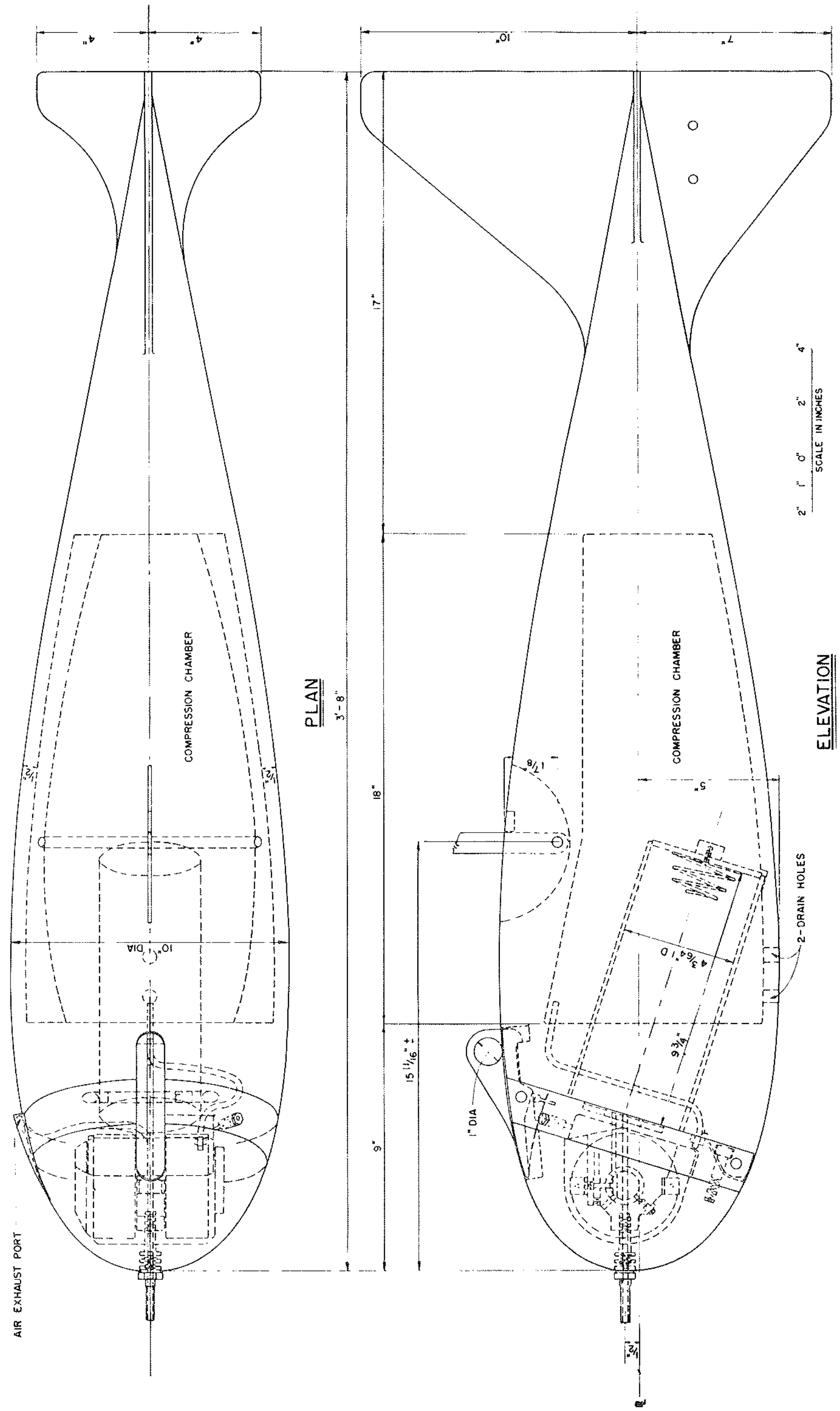


FIG. 35--POINT-INTEGRATING SAMPLER, US P-50

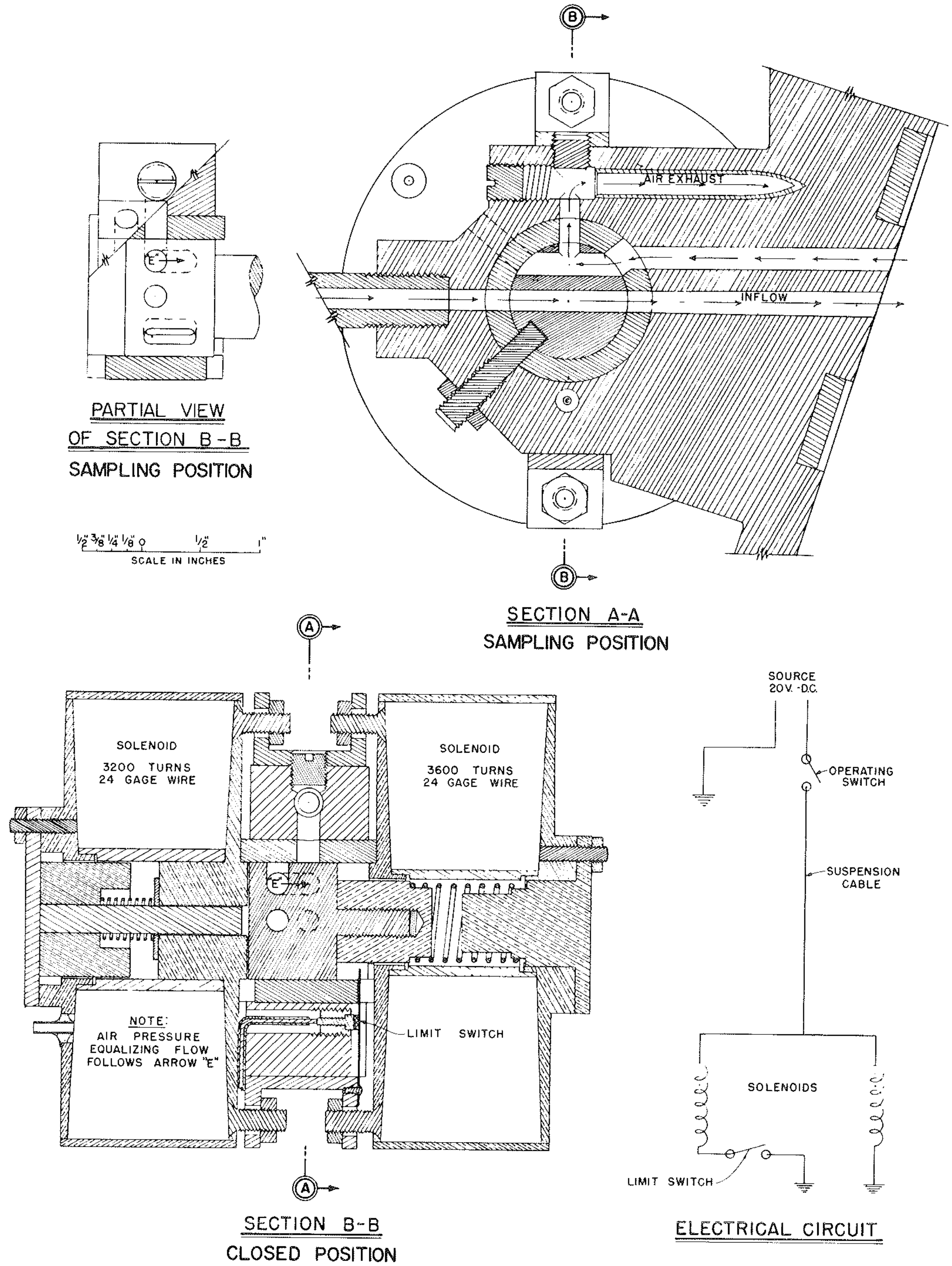


FIG. 36--POINT-INTEGRATING SAMPLER, US P-50, VALVE MECHANISM

IV. DETERMINATION OF BED-LOAD DISCHARGE

24. Ways of determining bed-load discharge--Fluvial sediment investigations often involve the measurement and analysis of the suspended sediment only, and although the suspended-sediment discharge is the major part of the total sediment discharge the bed-load discharge may be significant also. The bed-load discharge, i.e., the quantity per unit time of sediment that moves past a section by bouncing, rolling, or sliding along the streambed, may be measured, or it may be computed by indirect methods.

Bed load may be determined in four main ways:

a. The most direct method of measuring bed-load discharge is with a slot or trap that extends across the bed of a stream and catches the bed load that comes down the stream. The quantity of bed load collected per unit of time is the bed-load discharge of the stream (Section 25).

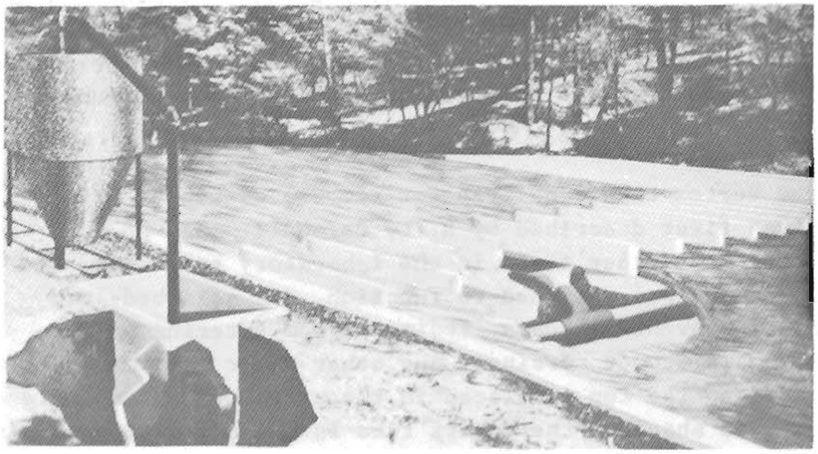
b. Bed-load discharge can be determined from several samples taken with a portable sampler that collects the bed-load discharge from a narrow width of the streambed (Sections 26 to 29). Sometimes estimates of bed-load discharge can be made from indirect measurements (Section 30).

c. Bed-load discharge can be computed from bed-material samples and the hydraulic parameters of the stream flow (Section 31).

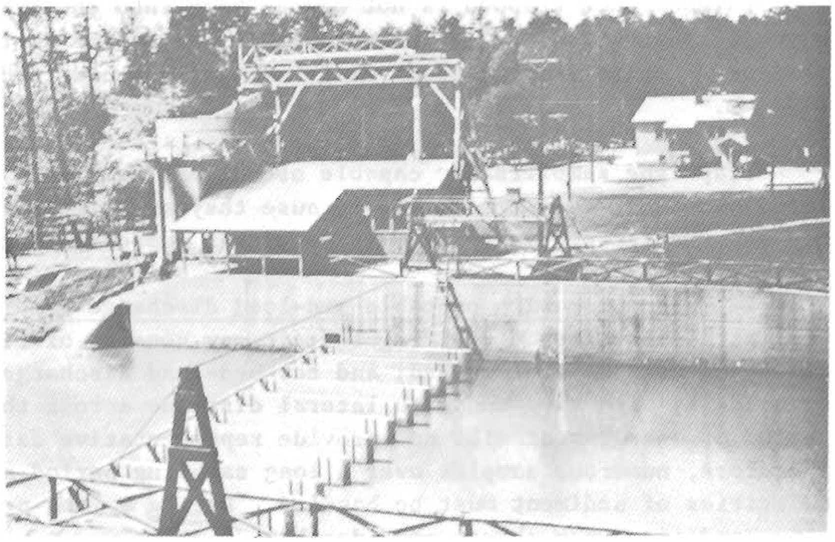
d. Bed-load discharge can be obtained by subtracting suspended-sediment discharge from total sediment discharge.

25. Bed-load traps--Bed-load traps are slots, trenches, or small pits that are placed in the streambed to catch sediment that moves as bed load. The sediment caught in the trap is removed and measured.

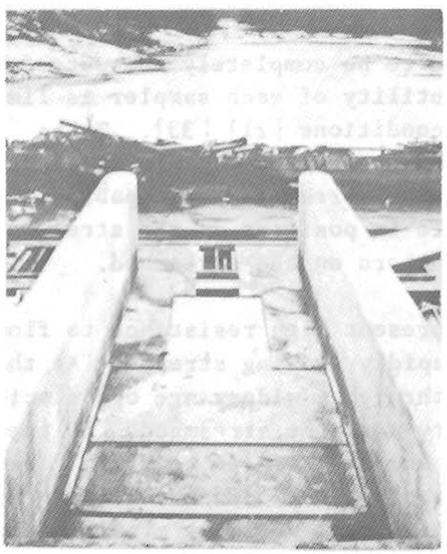
The Soil Conservation Service built an elaborate apparatus of the fixed-slot type to measure the bed-load discharge in the Enoree River at Greenville, South Carolina (Fig. 37) [19]. The entire river bed width of about 100 feet was paved with concrete for a length of about 100 feet. Near the lower end of this pavement the river was divided by concrete vanes into 14 sub-channels, 5 feet wide, each having a gated slot in the bottom which could be opened and closed. Bed load that dropped into the slots was periodically pumped out through a pipe beneath the floor to a hopper on the bank. The bed-load was deposited in the hopper and the water wasted over a spillway crest. Continuous records of bed-load discharge were obtained with this apparatus, [23].



a. Artist's conception of apparatus



b. View of actual apparatus



c. Door to slot in closed position

FIG. 37--BED-LOAD COLLECTING APPARATUS USED BY THE SOIL CONSERVATION SERVICE EXPERIMENT STATION, ENOREE RIVER, GREENVILLE, SOUTH CAROLINA

Reference 19

Other less elaborate slot-type samplers have been used. The Mountain Creek Sampler installed near Greenville, South Carolina, [20], was a semiportable slot-type sampler for use on small streams. It operated on the same principle as the permanent sampler. The bed load trapped in the slot was continuously pumped out and weighed.

A device called the vortex-tube sand trap for removal of coarse bed load from a stream or canal was first described by R. L. Parshall, 1933 [63]. A. R. Robinson (1960) [65] made other tests in the laboratory and under some field conditions. This device was designed to function, not as a bed-load sampler, but as a means of preventing coarse sediment from entering and depositing in irrigation canals, power turbines, and other water systems. The vortex tube with a slot along the top is placed in the streambed at an angle of 45 degrees to the flow. The shape of the vortex tube is not crticial providing the sediment once trapped is not washed back into the stream. The sediment and a small amount of water is wasted out one end of the vortex tube. The tubes that were tested removed about 80 percent of the bed load that was coarser than 0.50 mm.

Trap-type samplers are capable of collecting nearly 100 percent of the bedload. However, they are costly because they are difficult to place in a streambed and the trapped material must be either pumped or dug out of the sampler.

26. Sampling with portable bed-load discharge samplers--The bed of an alluvial stream is often very irregular; it may consist of ripples, dunes or antidunes, as well as a plane bed; and the bed-load discharge varies rapidly and erratically with time and with lateral distance across the stream. A short period of measurement will not provide representative data at a sampling point. Therefore, numerous samples over a long sampling period are necessary and large quantities of sediment must be handled. During a long period, however, the flow conditions may change considerably.

No single apparatus or procedure has proved to be completely adequate for the sampling of bed-load discharge because the utility of each sampler is limited to a narrow range of sediment and hydraulic conditions [21] [33]. To be universally acceptable, a bed-load discharge sampler must be capable of trapping the largest and smallest particles moving along the streambed, be capable of orienting itself into the flow, and remain stable in position on the streambed. The sampler should not alter the natural flow pattern on the streambed.

Most portable bed-load discharge samplers present high resistance to flow and require an elaborate suspension system in rapidly flowing streams. As the sampler is lowered to the streambed, it passes through a wide range of velocities and enters a zone of relatively low velocity near the streambed. In the lower velocity, the downstream force is reduced and the sampler tends to move upstream, to dive into the streambed, and to scoop up bed sediment which is not in transport. Turbulent flow and fluctuations in stream velocity also may cause the sampler to oscillate and scoop sediment from the bed.

Because of the uncertainties involved in sampling with bed-load discharge samplers, it is necessary to determine an efficiency coefficient. The sampling efficiency of a bed-load discharge sampler can be defined as the ratio of the weight of bed load collected during a given sampling time to the weight of bed load that would have passed through the sampler width in the same time had the sampler not been there. True efficiency factors for a sampler are not easily determined because it is difficult to measure accurately the amount of bed load that would have passed through the width occupied by the sampler had it not been there.

Some laboratory flume tests have been made to calibrate samplers for hydraulic and sampling efficiency. However, because it is difficult to maintain a uniform distribution of sediment across the flume in the laboratory, and a uniform rate of transport of bed material over the width and length of the flume, the problems of calibrating bed-load discharge samplers are complex. Calibrations have been attempted both in flumes with fixed beds and in flumes with movable beds. Full size bed-load discharge samplers are usually too large to test in a laboratory flume without altering the flow conditions, and, therefore, scale models are used for the calibration. Complete similitude of all the factors involved is not readily obtainable in model tests, and because hydraulic and sediment conditions in a natural stream differ greatly from those attainable in the model, efficiencies determined in flumes are questionable.

27. Early bed-load discharge samplers--Bed-load discharge may be determined from the amount of material trapped per unit time in a sampler located at one or more points across the streambed. In general bed-load discharge samplers can be classified according to their design or principle of operation into four types: basket, pan, pressure-difference, and slot. [33].

The earliest type of bed-load discharge sampler of record consisted of a basket or box which was generally made of mesh material. In most designs of this type the upstream end of the sampler had a rigid opening through which the water-sediment mixture entered. The mesh material had openings of a size that passed the suspended-sediment load but retained the bed load. This sort of sampler was used extensively in Europe in the 1930's. The basket sampler tended to drift downstream in fast water and then drag upstream as it settled into the slower moving water near the bed. The upstream movement sometimes scooped up some dormant material from the streambed. On the other hand, the presence of the sampler increased the resistance to flow, lowered the velocity upstream from the sampler, and caused some of the bed load to stop before reaching the sampler.

The basket sampler made by the Swiss Federal Authority for Water Utilization [71] (Fig. 38) is probably the most extensively developed of this type. It consists of a prismatic steel frame, 70 by 30 by 100 cm, enclosed on the top and three sides with screen, and on the bottom with loosely interwoven rings of metal similar to the mail formerly used as defensive armor. The sampler is lowered in a tilted position to keep the sampler entrance from digging into the bed.

When the sampler rests on the streambed the ring mesh conforms to the shape of the bed. After the sampler is raised it is emptied through a hinged flap in the down-stream end. The Swiss Federal Authority found that the efficiency of this sampler varied with the rate of bed-load movement and the sampling duration. Because basket samplers usually have a large capacity they are suitable for trapping large particles.

FIG. 38--SWISS FEDERAL AUTHORITY SAMPLER

Reference 71

Pan-type samplers, which have been used principally in Russia, are usually wedge-shaped in longitudinal section. They are placed on the streambed with the point of the wedge cutting the current. In the Polyakov sampler (Fig. 39) the bed load moves along the top of the pan and is trapped in the transverse slots at the downstream end. Because pan-type samplers cause obstruction to stream flow, their efficiency should be determined by calibration. The Polyakov sampler was calibrated in a flume in which the true bed-load discharge was determined from the amount of sediment trapped at the end of the flume. The low efficiency, reported by G. I. Shamov, [68] to be only 46 percent, was due mainly to the adverse slope of the surface leading to the catchment section. Mounds of sediment formed on the inclined surface and some sediment rolled over the mounds into the sampler, but other grains rolled off to the sides, thus reducing the catch.

In the pressure-difference type sampler the cross section is expanded in the direction of flow to produce a pressure drop at the exit. The pressure drop compensates for energy losses, and thus obtains an entrance velocity and a sediment discharge approximately equal to that of the undisturbed stream. The bed load deposits in the expanded section or in a screen bag attached downstream. If the flared section is long, a collecting screen at the exit may not be necessary.

The sampler (Fig. 40) of the Scientific Research Institute of Hydrotechnics [68] is a Russian sampler with features of both the pressure-difference type and the pan type. This sampler, somewhat similar to the Polyakov design, has a flat pan with transverse partitions in the catchment section, but the entrance is at the front of the pan and the cross section diverges toward the rear of the sampler. Its trap efficiency has been reported by Shamov to be about 75 percent.

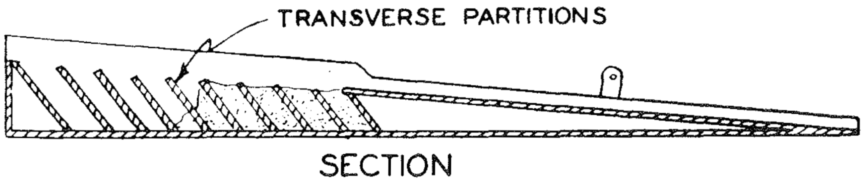


FIG. 39--POLYAKOV SAMPLER

Reference 68

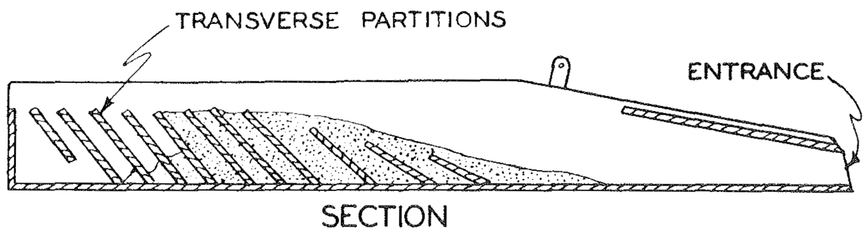


FIG. 40--SAMPLER OF THE SCIENTIFIC RESEARCH INSTITUTE OF HYDROTECHNICS

Reference 68

The Hydraulic Structures Bureau of the Dutch Government designed a pressure-difference type sampler [67] for which an efficiency of 100 percent is claimed. This design, called the Arnhem or Dutch sampler (Fig. 41) has a rigid entrance which is joined by a rubber section to a wire-mesh bag with 0.2 to 0.3 mm openings. A flared section at the rubber connection produces a pressure drop at the downstream end so that the entrance velocity is about the same as that of the undisturbed stream. The large frame work surrounding the collecting apparatus is balanced in suspension so that the curved surface of the rudder comes in contact with the streambed before the upstream end of the sampler touches the bed. In the sampling position the entrance is held firmly against the streambed by a spring, the pressure of which can be adjusted as required. The moving bed material enters the mouth of the sampler and the particles which are larger than the openings in the wire-mesh bag are caught. A loss coefficient for the finer particles can be determined by calibration. The sampler is suitable for sampling bed load having a size range from about 0.15 to 5 mm. A disadvantage of the sampler is that the fine mesh may become clogged, thus reducing the velocity through the sampler until it is no longer equal to that in the stream.

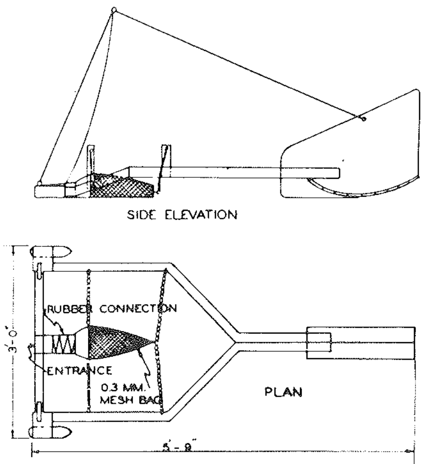


FIG. 41--ARNHEM OR DUTCH SAMPLER

Reference 67

Other early bed-load discharge samplers are described in Report No. 2 [37] of this series.

28. Recent bed-load discharge samplers--Since 1940 several direct-measuring bed-load discharge samplers have been developed, the most important of which are improved models of the early pressure-difference samplers.

A pressure-difference sampler called "Sphinx" (Fig. 42) was developed at the Hydraulic Laboratory in Delft, Netherlands, [18, 83] for measuring bed-load discharge of fine sand size. The rectangular mouth of the sampler rests on the streambed. There is a reduction in pressure at the outlet end of the sampler body so that the water enters the mouth with a velocity equal to the stream velocity. The water passes through a spiral tube to the top of a sampling chamber where the velocity decreases suddenly, causing the sediment to settle out. The flow leaves the instrument through a wide slit across the top of the back plate. Part of the finest fraction of the sediment escapes from the instrument along with the water. The amount of this loss is determined by calibration. The mouth piece, which is pressed to the streambed by means of an adjustable spring, is suitable for trapping sand of about 90 microns and coarser. Tests by Novak [62] showed this sampler to have an efficiency of 100 percent.

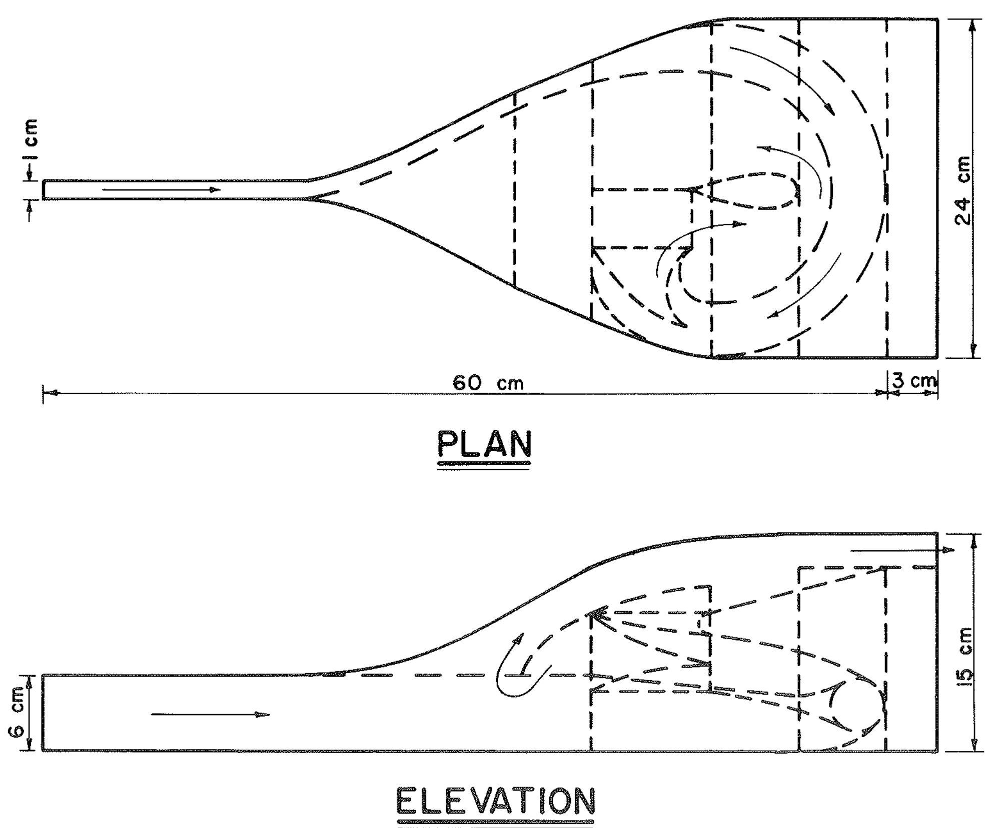
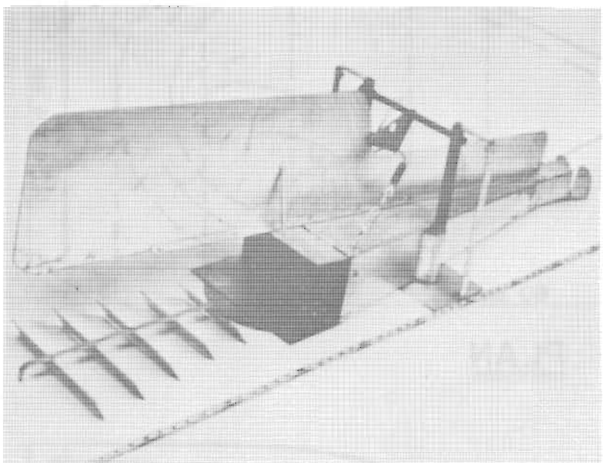


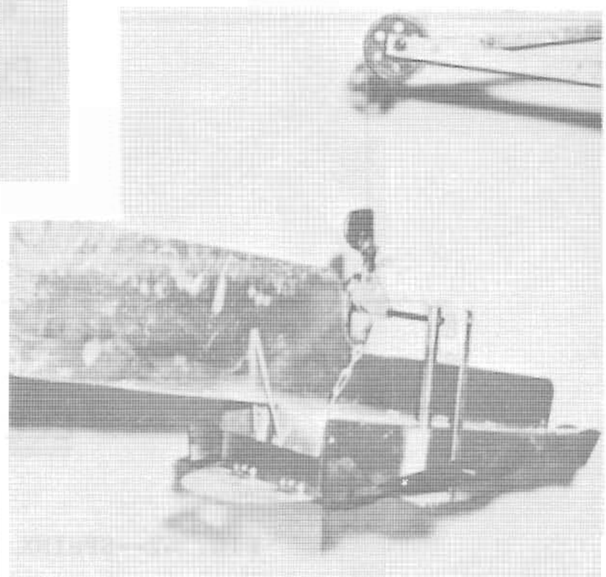
FIG. 42--SPHINX BED-LOAD SAMPLER

References 83 and 18

A bed-load discharge sampler to measure discharge of sand and gravel was developed by the Corps of Engineers, U. S. Army Engineer District, Little Rock, Arkansas [33]. The sampler (Fig. 43) utilizes a pan in conjunction with the pressure-difference principle. It consists of a diverging rectangular tube with a series of control baffles that retain the skipping, rolling, and sliding particles as they settle out because of the decrease in velocity through the sampler. An expanding flow chamber provides mean entrance velocities about equal to stream velocities at the sampling point. The entrance is pressed against the streambed by means of a spring and by the weight of the supporting frame. Both the entrance ramp and the exit gate close automatically when the sampler is supported by the suspension cable.



View of parts

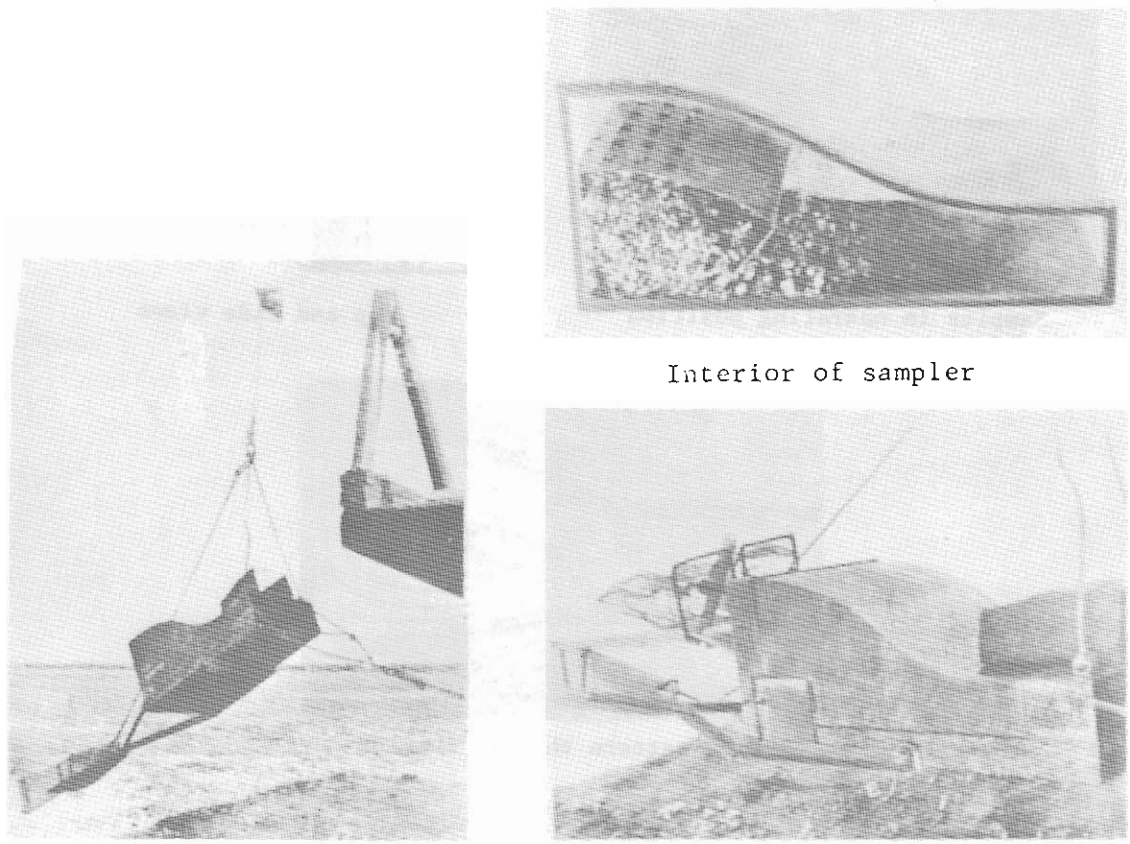


Sampler in position for use

FIG. 43--LITTLE ROCK, ARK., US ARMY ENGINEER DISTRICT SAMPLER

Reference 33

A pressure-difference sampler for measuring bed-load discharge or coarse sand and gravel was developed by Karolyi (1947) [52]. A perforated curved diaphragm in the expanding rear part of the sampler divides the lower sediment-retaining chamber from the upper exit chamber of the instrument (Fig. 44). The flow enters beneath the curved diaphragm, and after dropping its sediment load the water rises through the perforations and passes out of the sampler at the exit. In large rivers the sampler requires an elaborate suspension system. Novak [62] found in laboratory calibration tests that the hydraulic efficiency of the sampler was about 80 percent and that the sediment-sampling efficiency was about 45 percent. He found also that the efficiencies were consistent regardless of velocity or particle size.



Interior of sampler

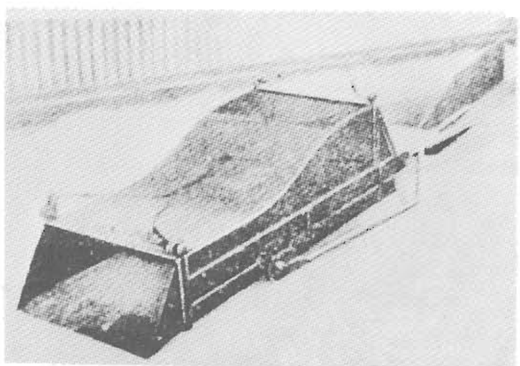
Sampler suspension

Side view

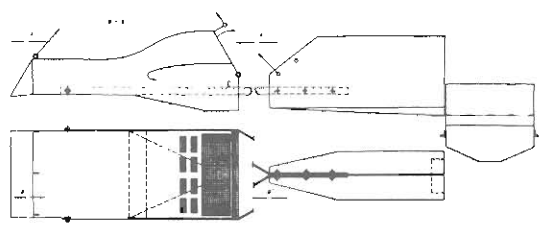
FIG. 44--KAROLYI SAMPLER

Reference 52

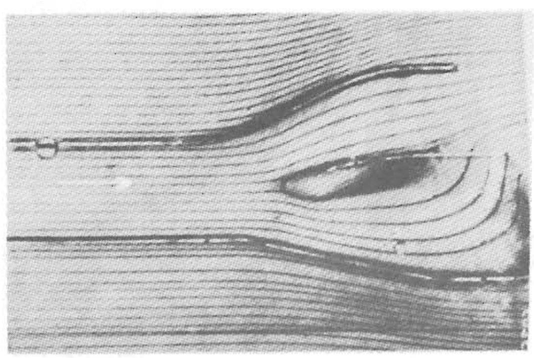
A pressure-difference sampler called the VUV sampler (Hungarian), (Fig. 45) was developed by Novak (1957) [62] for measuring the discharge of sediment particles 1 to 100 mm in diameter. Basically this sampler is an improved Karolyi sampler. Like the Karolyi sampler the VUV sampler has a diaphragm with openings covered with wire mesh. The sampler is 130 cm long, 45 cm high, 50 cm wide and collects about a 25-kg sample. Novak found the sampler to have a hydraulic efficiency of about 100 percent and sampling efficiency of about 70 percent.



Sampler in operating position



Top and side views



Flow pattern through sampler

FIG. 45--VUV HUNGARIAN SAMPLER

Reference 62

29. Selection of a bed-load discharge sampler--The ideal bed-load discharge sampler cuts out, or samples, a definite width of the stream sediment transported as bed-load and it collects all the solids from this sampled width. Such performance can be obtained only by careful design of the entrance and the separating mechanism to fit the conditions encountered in different streams. The ideal sampler does not alter the flow upstream, it offers no obstruction to particles approaching the sampler, and it rests securely in contact with the bed. Generally the dimensions of the entrance will be governed by the size of particles in the bed. The height of the opening should be at least twice the maximum grain size, while its width may vary from about 100 to 200 times the average diameter of particles in the bed. Whenever possible a screen should be used for the separating mechanism but when the stream carries great quantities of organic material that would clog a screen during the sampling period, separation must be obtained by a local velocity reduction.

The box or basket-type sampler is the only one which can be used in mountainous streams carrying coarse gravel. For given entrance dimensions, it is the smallest and the least cumbersome sampler to handle. It has the disadvantage of creating considerable back pressure which deflects the slow-moving bottom layers around the sampler but only retards the faster-flowing upper layers. Therefore, a high percentage of the fine material rolling or sliding along the bottom at a low velocity is deflected, while the same size material moving by saltation at a higher velocity is more readily trapped.

The pan-type samplers seem to be best suited for streams which have comparatively smooth sand beds with a relatively slow rate of bed-load discharge all of which takes place 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.

Novak concluded from tests on basket, pan, and pressure-difference type bed-load samplers that:

a. The efficiency of a sampler with a thin lower front edge increases slightly with an increase in particle size of bed sediment having a uniform size.

b. In general, if the lower front edge of the sampler completely sinks into the river bed, the sampler retains correctly the material moving as bed-load, except for fine particles that pass through the fine mesh.

c. The efficiency of a sampler having a thin lower front edge is usually independent of the velocity of flow but may increase slightly with increase in flow.

d. If the lower front edge of the sampler projects above the streambed, the efficiency is adversely affected, especially if grain diameters are smaller than, or equal to, the height of this edge. Therefore, a sampler should have a thin sharp front edge and a gradually sloping inlet.

e. The sampler must be placed on the river bed very carefully to avoid scooping up sediment from the bed.

f. The size of the load in the sampler does not affect its efficiency providing not more than 25-30 percent of its capacity is used.

g. Hydraulic efficiency is only a qualitative indication of sampler efficiency.

The final selection of the best bed-load discharge sampler for the particular conditions in a given stream can be based only on a thorough calibration that duplicates 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 sediment size, discharge, etc. Regardless of the type of sampler that is used, the calibration is as important as the measurements themselves. With the exception of the slot-type sampler, no bed-load discharge sampler that has been designed is completely adequate for anything but a boulder- or gravel-bed stream [21].

30. Indirect measurements of bed-load discharge--Acoustic and ultrasonic instruments have recently been developed for indirect measurement of bed-load discharge. Further development will be required before any of them are ready for routine use in quantitative measurements.

One of these instruments known as the hydrophonic detector is an improvement made by Braudeau (1951) [7] at the Service des Etudes et Recherches Hydrauliques, d'Electricite de France of an earlier detector constructed at Grenoble, France. The sound made by gravel and coarse sand sliding over, or beating against, a plate installed on the streambed is picked up with a microphone and transmitted to a tape recorder or to earphones. The instrument has been used to detect when movement of bed material starts and when it stops. It also registers continuous movement of sediment, and it can be used in qualitative studies of scour in a cross section.

Juniet (1952) [49], developed an instrument called L'Arenaphone, which consists of a fork-shaped rod about 20 cm. long attached to a transducer. The whole assembly is supported in a tripod, so that the forked rod is inserted a few centimeters into the streambed. Moving sediment particles collide with the forked rod causing it to vibrate. The vibrations are transmitted by the rod to the transducer where an electric current is produced. The current is amplified and supplied to headphone, oscilloscope, or a tape recorder.

An instrument which measures the sound of interparticle collisions was developed by Ivicsics (1956) [48]. It can be suspended several feet above the streambed, and thus does not disturb normal bed movement. The instrument consists of a streamlined body which houses a microphone that faces downward toward the streambed, so that only sounds originating directly below the instrument are picked up. The sound is amplified and transmitted to an ammeter or to headphones. The instrument indicates relative movement of sediment in cross sections and variations of movement with time.

A device using high frequency (ultrasonic) sound waves was developed by Smoltczyk (1955) [69] to measure bed-load discharge of streams having bed material of fine sand. The sampler is an open-end rectangular tube which rests on the streambed and through which flow passes. The inner walls of the tube are convex toward the center thus causing an increase in flow velocity. A transducer and a reflector are housed on opposite sides of the tubes. The transducer transmits and receives the reflected high-frequency sound waves. Different amounts of acoustic energy are absorbed by different sediment concentrations. The size distribution of the load must be known to measure its concentration; the distribution is assumed to be the same as that of the bed sediment. It is assumed also that the bed load is transported some distance above the bed and that the hydraulic and sampling efficiencies are close to 100 percent. The attenuation is an indication of the spatial sediment concentration in the flow.

Some other experimental apparatus and methods for measuring bed-load discharge are a portable pit sampler; motion-picture analysis of bed-material movement; tracking of dune movement by ultrasonic sound or pressure transducers and computation of bed-load discharge from the average dune height and crest velocity; and the use of nuclear tracers.

31. Determination of bed-load discharge by analytical methods--Measurements of suspended-sediment discharge do not include the bed-load discharge of the stream. The available methods of measuring bed-load discharge are difficult and costly, and often not very accurate. Flow near the streambed normally contains high concentrations and coarse particles. In some design problems the discharge of the coarser sizes near the streambed is more important than the discharge of the finer sediments that are in suspension.

Several analytical methods for computing the discharge of coarse sediment have been proposed; some of these will be discussed briefly. In general the suspended-sediment discharge is measured and bed-load discharge is computed. However some analytical methods compute bed-load discharge only and some compute the total discharge of sediment of given sizes or size ranges. Whenever necessary, corrections must be made for the suspended-sediment included in the computed discharge.

The following three methods for obtaining total sediment or total bed-material discharge determine bed-load discharge as a part of the total sediment discharge: The H. A. Einstein method (1950) [22], the modified Einstein procedure (Colby and Hembree, 1955) [14], and the E. M. Laursen method (1958) [57]. These methods will be discussed in detail in Section 38.

A. A. Kalinske, (1947) [51] has developed an equation for computation of bed-load discharge which is based on consideration of the forces which start movement of the individual sand grains and the turbulence mechanism in the flow above the streambed. All of the numerical constants in the method are based on measurements of the sediment and hydraulic characteristics of the stream. The bed-load discharge is determined for each of several size ranges and the total bed-load discharge is found by summation. Results of computations with this equation are in fair agreement with experimental data obtained under a wide variety of field and laboratory conditions.

Meyer-Peter and Müller (1948) [59] also developed an equation for computation of bed-load discharge of sediment in natural streams. They related bed-load discharge to an effective shearing stress on the sediment particles on the streambed. Their equation was derived from data obtained in the region of fully developed turbulence in laboratory flumes of various sizes. These tests, which were made over wide ranges of slope, water depth, velocity, particle size, and specific gravities of sediment, showed that the shearing stress is an important factor in bed-load transport. Bed-load discharge computed by this equation was roughly consistent with the difference between total sediment discharge and measured suspended-sediment discharge in the Middle Loup River at Dunning, Nebraska, [34].

One of the newest and simplest methods of computing unmeasured sediment discharge (total sediment discharge minus measured suspended-sediment discharge) is from a simple relation to mean stream velocity, Colby (1957) [12]. On many streams the simple relationship will give answers as accurate as those from more elaborate and costly methods. The basic parameter is the stream velocity, but the measured bed-material concentration, and the width and depth of the stream cross section are also factors.

The same approach can be used for bed-load discharge. Even though some bed-load discharges for a section may be computed by one of the more elaborate methods, the direct velocity relation is very useful for interpolating bed-load discharges between the times of those primary determinations.

32. Sampling bed material--Bed-material samplers are used to obtain samples of the sediment of which the streambed is composed. They should not be confused with bed-load discharge samplers which are used to determine the discharge of sediment as bed load.

Methods of measuring bed-load discharge are usually so costly or so unsatisfactory that they are not used for routine sediment discharge measurements. Rather bed-material samples are taken to determine the size distribution of the bed material so that bed-load discharges can be computed by analytical methods.

If the particle size of the bed sediment varies either laterally or along the stream, a large number of bed-material samples may have to be taken and analyzed to determine the average size distribution of the bed sediment.

33. Early bed-material samplers--Samplers used to obtain specimens of bed material have been grouped into three classes: drag-bucket or scoop, vertical-pipe or cylinder, and clamshell.

The drag-bucket sampler, consists of a weighted bucket or cylinder with a cutting edge. As the bucket is dragged along the streambed, it scoops up a layer of sediment from 1/2 to 2 in. thick. The sampler may have a weighted central stem, which is hinged inside the bucket to the bottom plate, as in the simplified Rock Island sampler (Fig. 46) [70]. The weight tends to counteract the upward pull of the line that is used to drag the sampler. Because of exposure to the streamflow, some of the finer material caught in a drag bucket may be lost in transit to the water surface.

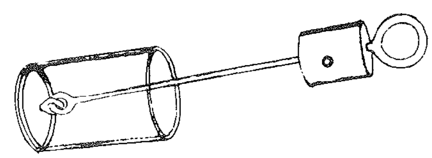
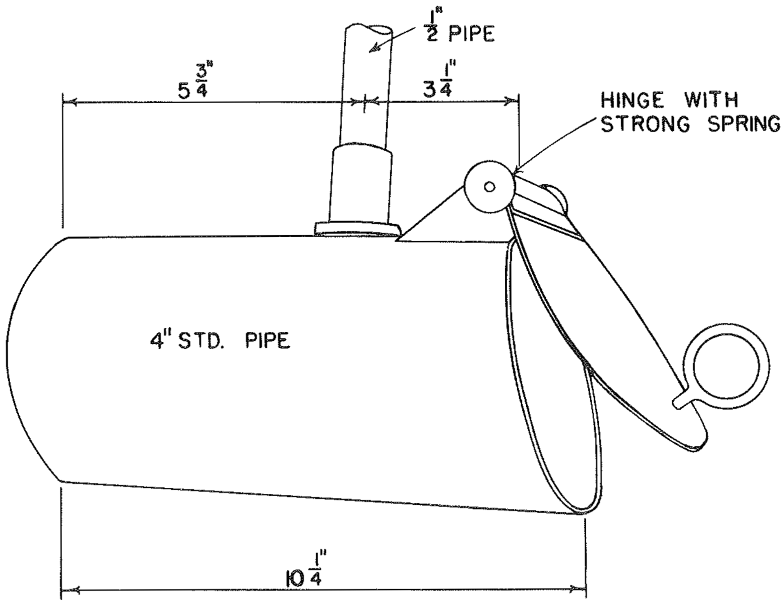


FIG. 46--SIMPLIFIED ROCK ISLAND DRAG BUCKET SAMPLER

Reference 70

In relatively shallow streams a scoop-type sampler (Fig. 47) [6, 75] that is supported on a long rod can be used from a boat more conveniently than the drag-bucket sampler. This scoop sampler can be made of a 6-or 8-in. section of 4-in. pipe, one end of which is closed by a plate and the other beveled for a cutting edge. The sampler is handled on a 12- to 15-ft rod of 3/4-in. pipe (in convenient lengths) attached to the top of the scoop. A hinged cover, which is held closed by a spring, may be placed over the cutting end of the scoop to prevent the sample from being washed out by the current. A rope attached to the cover plate is used to open the cover and drag the sampler along the streambed to scoop up the sample.

Vertical-pipe samplers include pipe, cylinder, and cone-shaped containers which are forced into the streambed or settle into the bed of their own weight. 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. 48 [26]. After the sampler has been forced into the streambed 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 is withdrawn. A vertical-pipe sampler which must be forced into the streambed is obviously less adaptable to deep than to shallow streams.



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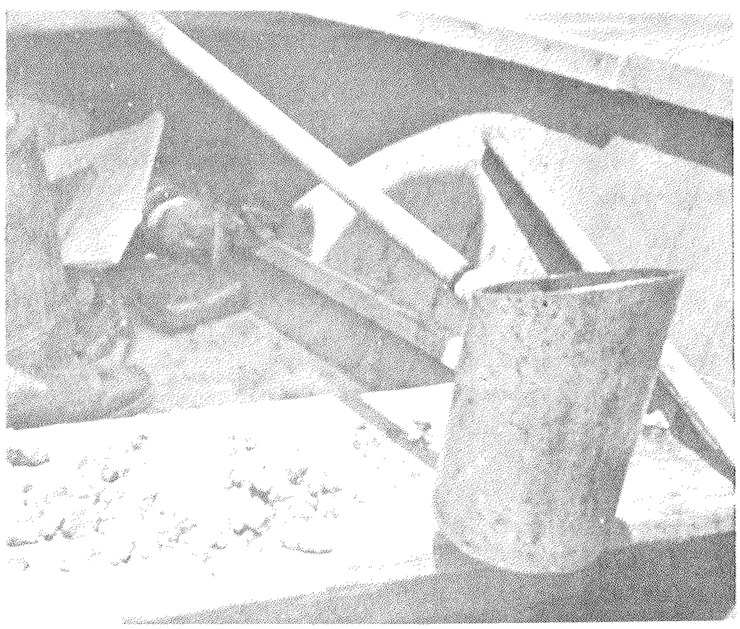


FIG. 47--SCOOP TYPE BED-MATERIAL SAMPLER

Photograph courtesy of Bureau
of Reclamation Reference 6

The Ross clamshell sampler is similar to the clamshell bucket used in earth-work operations. The cupped jaws of the bucket may be closed on reaching the streambed, either by a pull on an auxiliary line or by an automatic spring arrangement. A disadvantage of this type is the washing of the sample as the buckets close and the possibility that large particles may be caught in the jaws and allow some of the fine material to escape. The automatic spring arrangement is used in the Ross clamshell sampler shown in Fig. 49 [32]. Other early bed-material samplers are described in Report No. 2 [37] of this series.

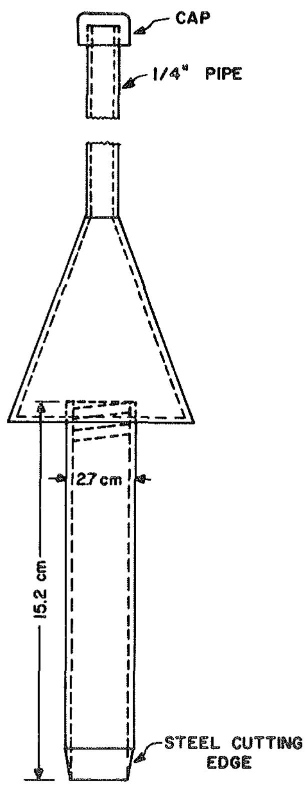


FIG. 48--PIPE SAMPLER USED IN IMPERIAL VALLEY CANALS

Reference 26

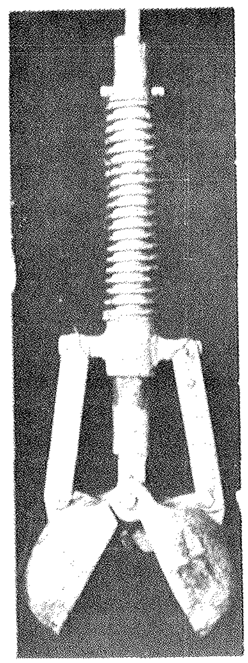


FIG. 49--ROSS CLAMSHELL SAMPLER

Reference 32

34. Recent bed-material samplers--The vacuum principle is used in a vertical pipe sampler which was developed recently by the Agricultural Research Service [31]. The sampler shown in Figs. 50 and 51 has a 3-ft sampling tube with interchangeable 9-ft tube (standing along side in the picture). On top of the 3-ft tube is the driving weight (same size as tube) which is raised by a line and dropped to force the tube into the bed material. A piston inside the tube is held stationary by another line as the tube is driven into the bed material, thus creating a partial vacuum which assists in holding the sample in the tube while the equipment is being raised. This sampler is designed to be suitable for sampling sediment from the bed of a reservoir as well as from a streambed.

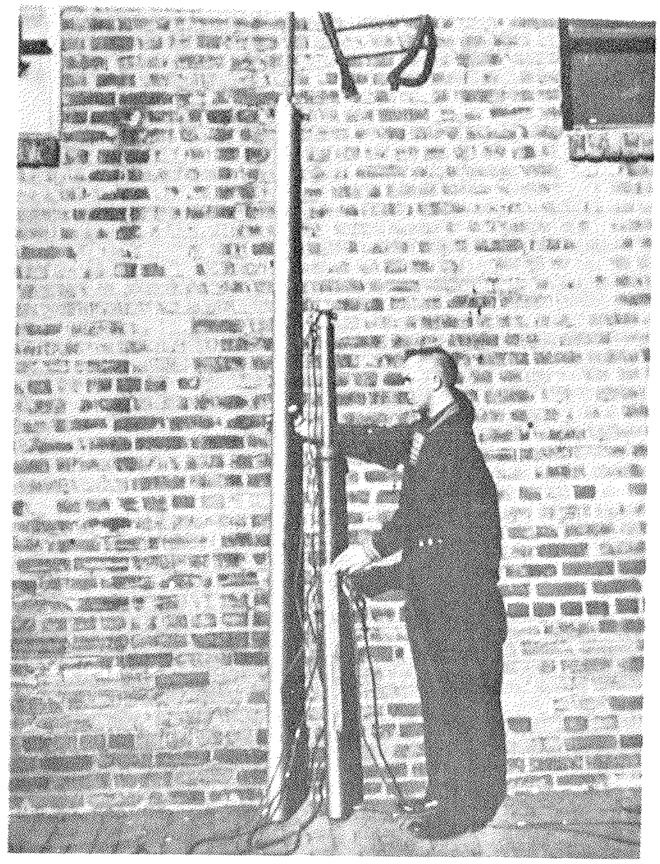


FIG. 50--AGRICULTURAL RESEARCH SERVICE VERTICAL PIPE BED-MATERIAL SAMPLER

Reference 31

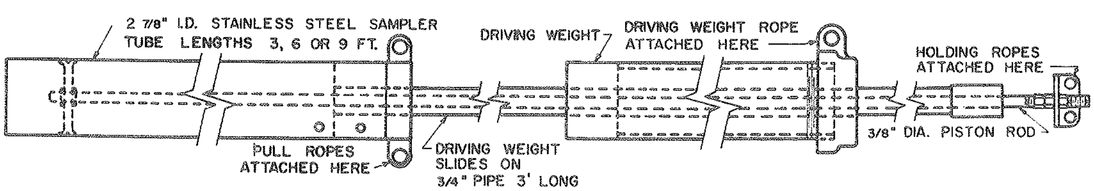


FIG. 51--AGRICULTURAL RESEARCH SERVICE VERTICAL PIPE BED-MATERIAL SAMPLER

Reference 31

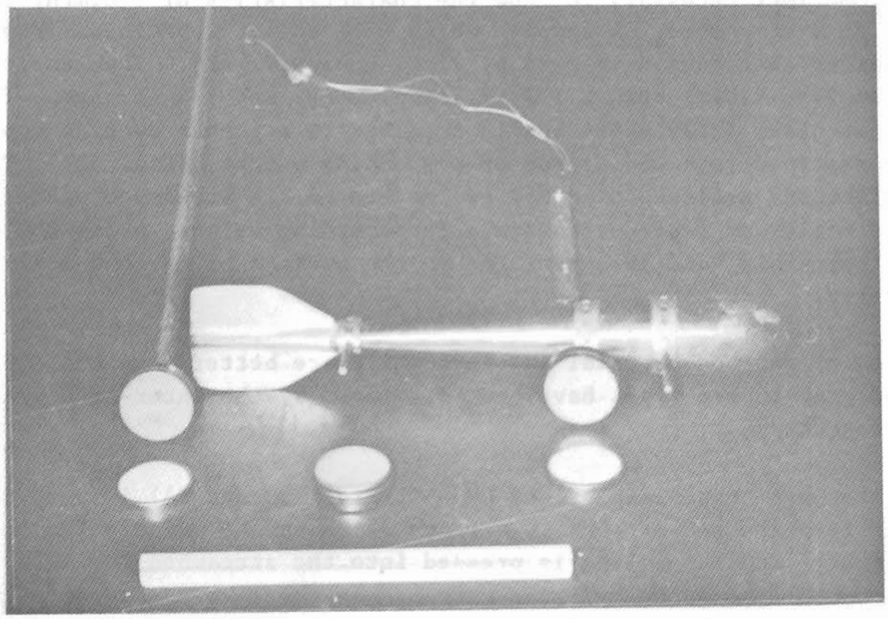
It is sometimes necessary to know the characteristics of sediment forming the surface of a streambed. A sampler which will collect particles from the streambed surface has been developed by J. C. Mundorff [61]. The sampler consists of a small circular box, 2 1/2 in. in diameter and 3/4 in. deep, filled with white petroleum jelly. The box is attached to a rubber suction cup or to a metal clamp fastened to a wading rod or a sounding weight, (Fig. 52). The sounding weight and attached disk may be lowered to the streambed with a hand line or on a cable and reel suspension. The sounding weight forces the disk against the streambed, and the particles on the surface of the bed adhere to the petroleum jelly.

A series of new bed-material samplers which are better than the early cylinder and grab-bucket types have been developed by the Inter-Agency Sedimentation Project.

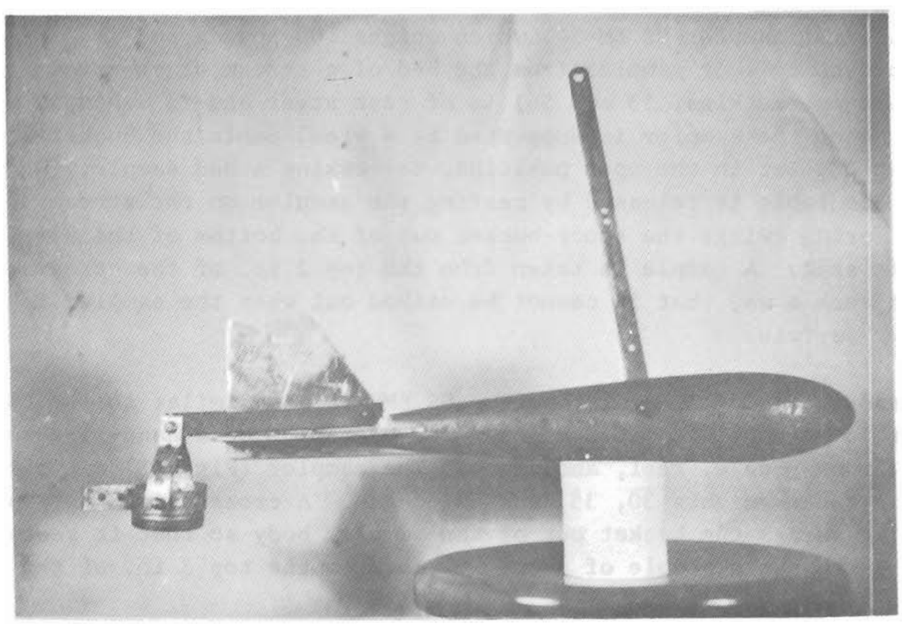
The piston-type hand sampler, US BMH-53 (Figs. 53 and 54) is used to collect samples from the bed of shallow streams which can be waded. A cylinder 2 in. in diameter and 8 in. long is pressed into the streambed to inclose the sample. A piston inside the cylinder retracts as the sample enters. A pipe extension is used as a handle and to press the cylinder into the bed. A rod attached to the piston passes through the handle to facilitate retracting the piston and to aid in removing the sample. A partial vacuum develops below the piston and helps to hold the sample in the cylinder.

Bed-material sampler US BM-54, which weighs 100 pounds and is 22-in. long was developed to collect samples from the bed of a stream or reservoir of any depth. The sampler (Figs. 55 and 56) is of cast steel and is equipped with tailvanes. When the sampler is supported by a steel cable the bucket may be cocked, that is, set in the open position, for taking a bed sample. When tension on the cable is released by resting the sampler on the streambed, a heavy coil spring swings the scoop-bucket out of the bottom of the sampler body and snaps it shut. A sample is taken from the top 2 in. of the streambed and inclosed in such a way that it cannot be washed out when the sampler is raised to the water surface.

The hand-line bed-material sampler, US BMH-60, is similar to the US BM-54, but lighter in weight. It was developed for operation on a hand-line suspension as well as from a cable, reel, and crane. The sampler (Figs. 57 and 58) is available in three weights 30, 35, and 40 pounds. A cross-curved constant-torque spring swings the bucket out of the sampler body so that it scoops up and completely surrounds a sample of about 160 cc from the top 2 in. of the streambed.



Rod and sounding weight with disks attached



Sounding weight and attached disk

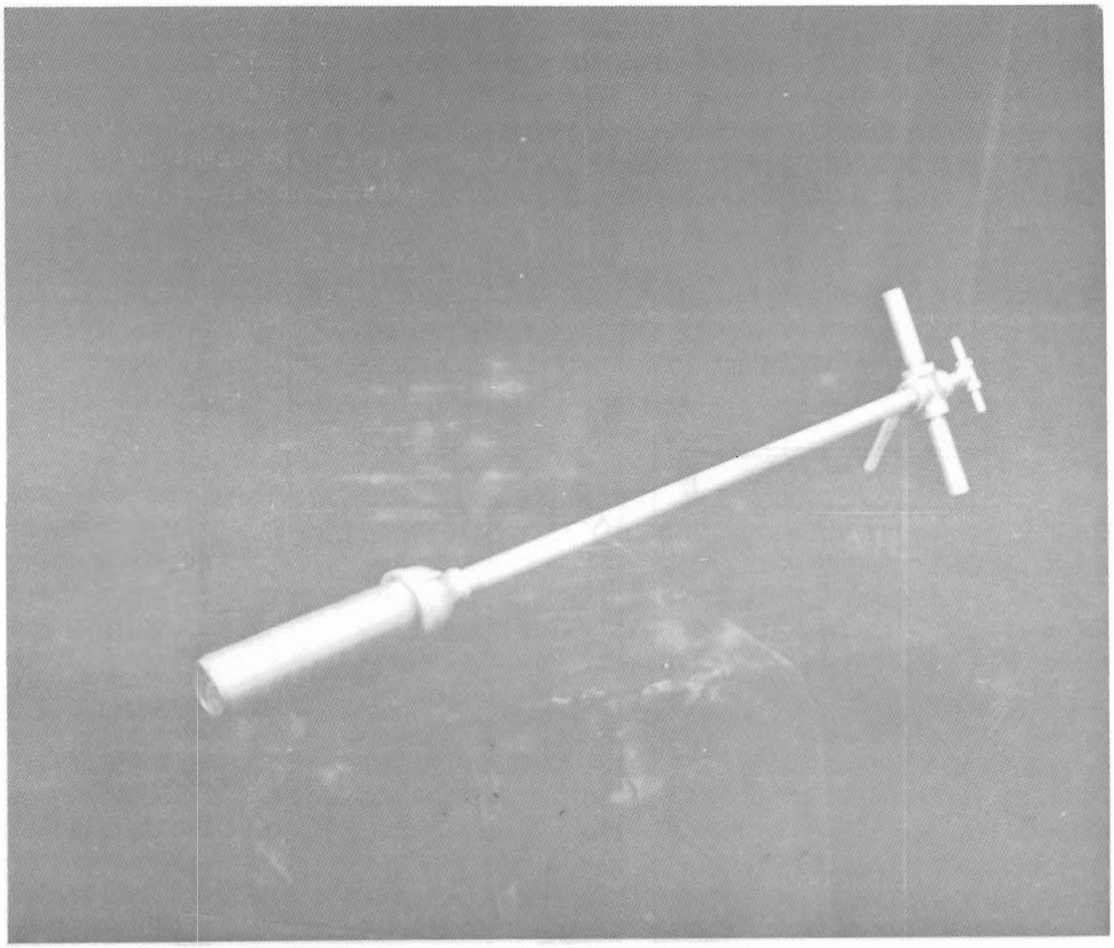


FIG. 53--PISTON-TYPE BED-MATERIAL HAND SAMPLER, US BMH-53

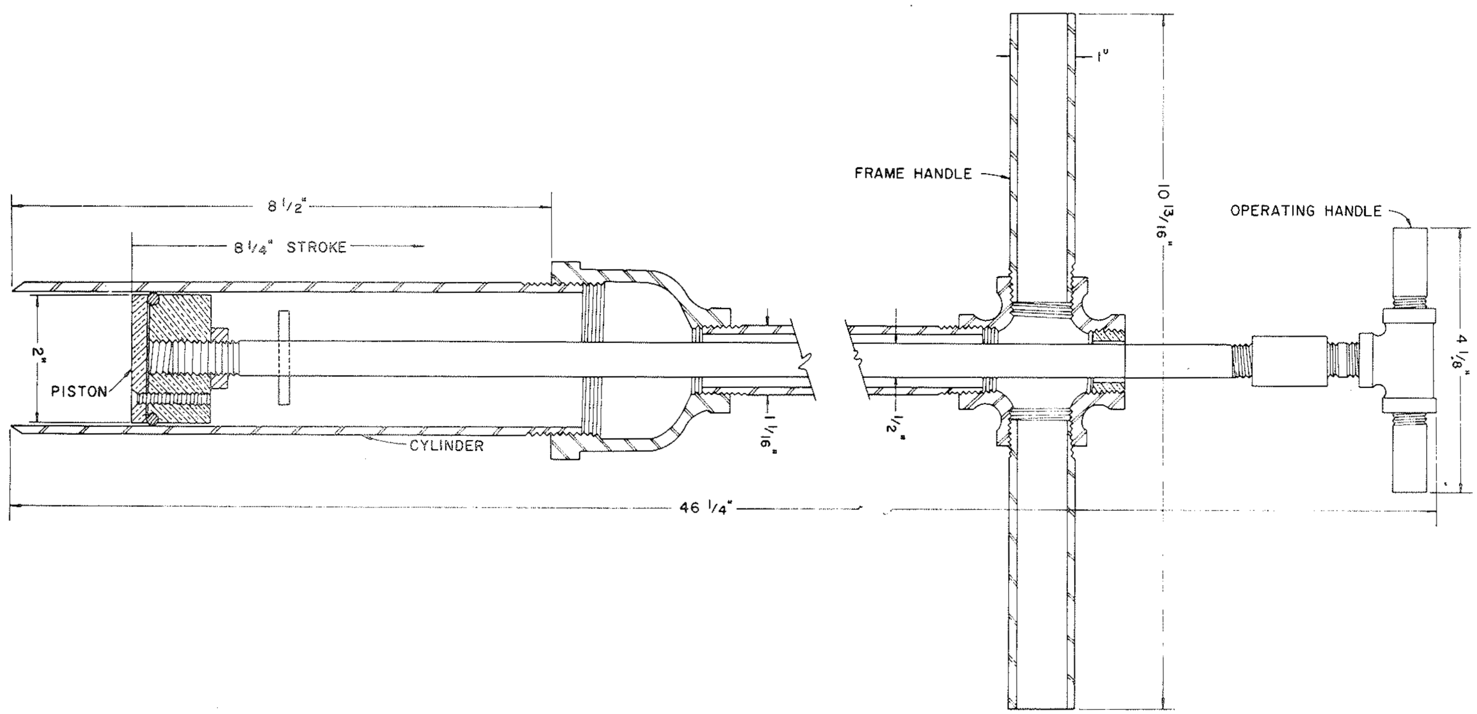


FIG. 54--PISTON-TYPE BED-MATERIAL HAND SAMPLER, US BMH-53

Bucket retracted

Bucket exposed

FIG. 55--BED-MATERIAL SAMPLER, US BM-54

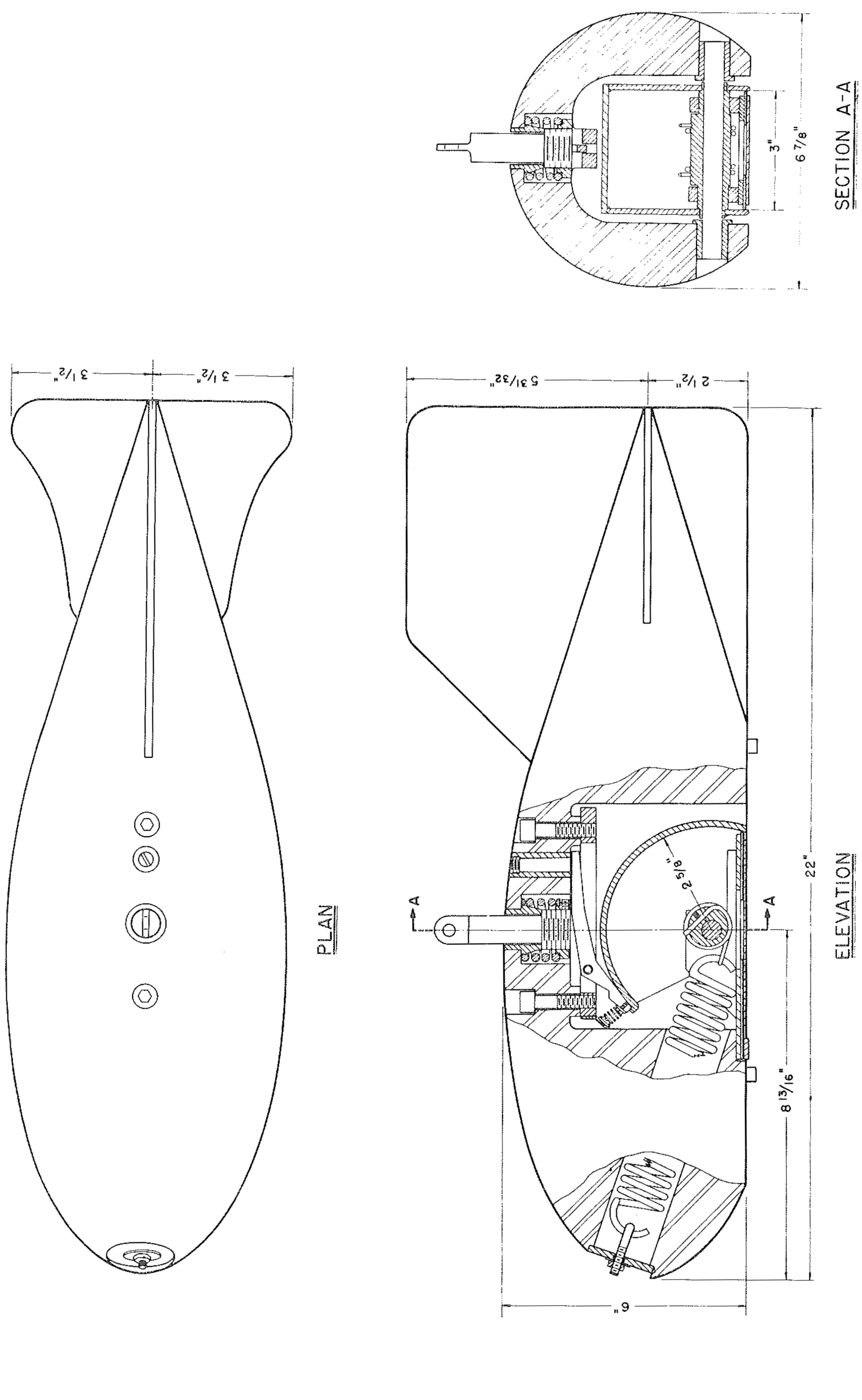
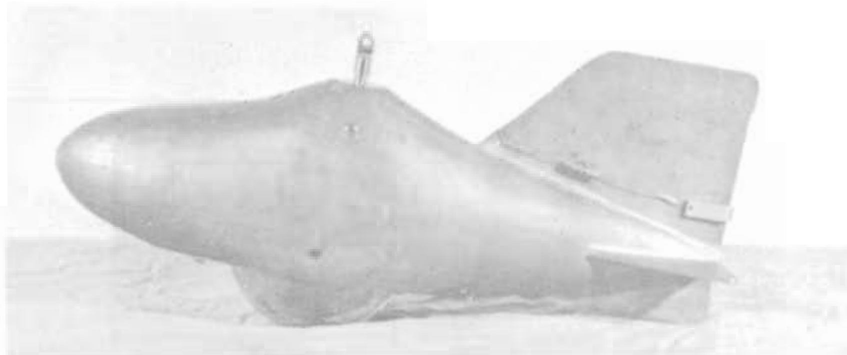
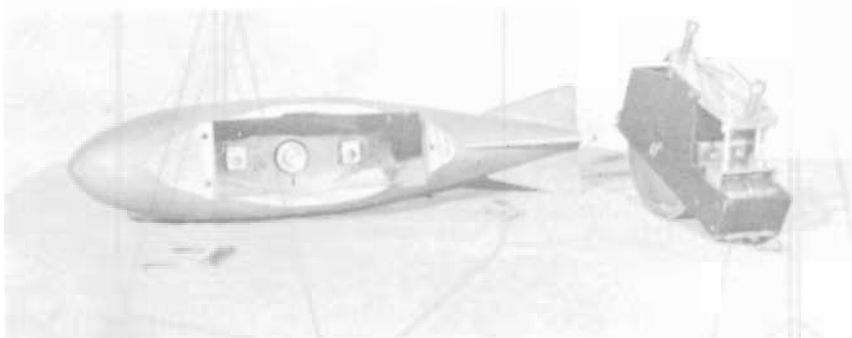


FIG. 56--BED-MATERIAL SAMPLER, US BM-54



Side view



Bottom view of sampler body with sampling bucket and mechanism assembly removed and shown at right.

Mechanism dismantled showing sampler bucket at upper left of photo.

FIG. 57--HAND-LINE BED-MATERIAL SAMPLER, US BMH-60

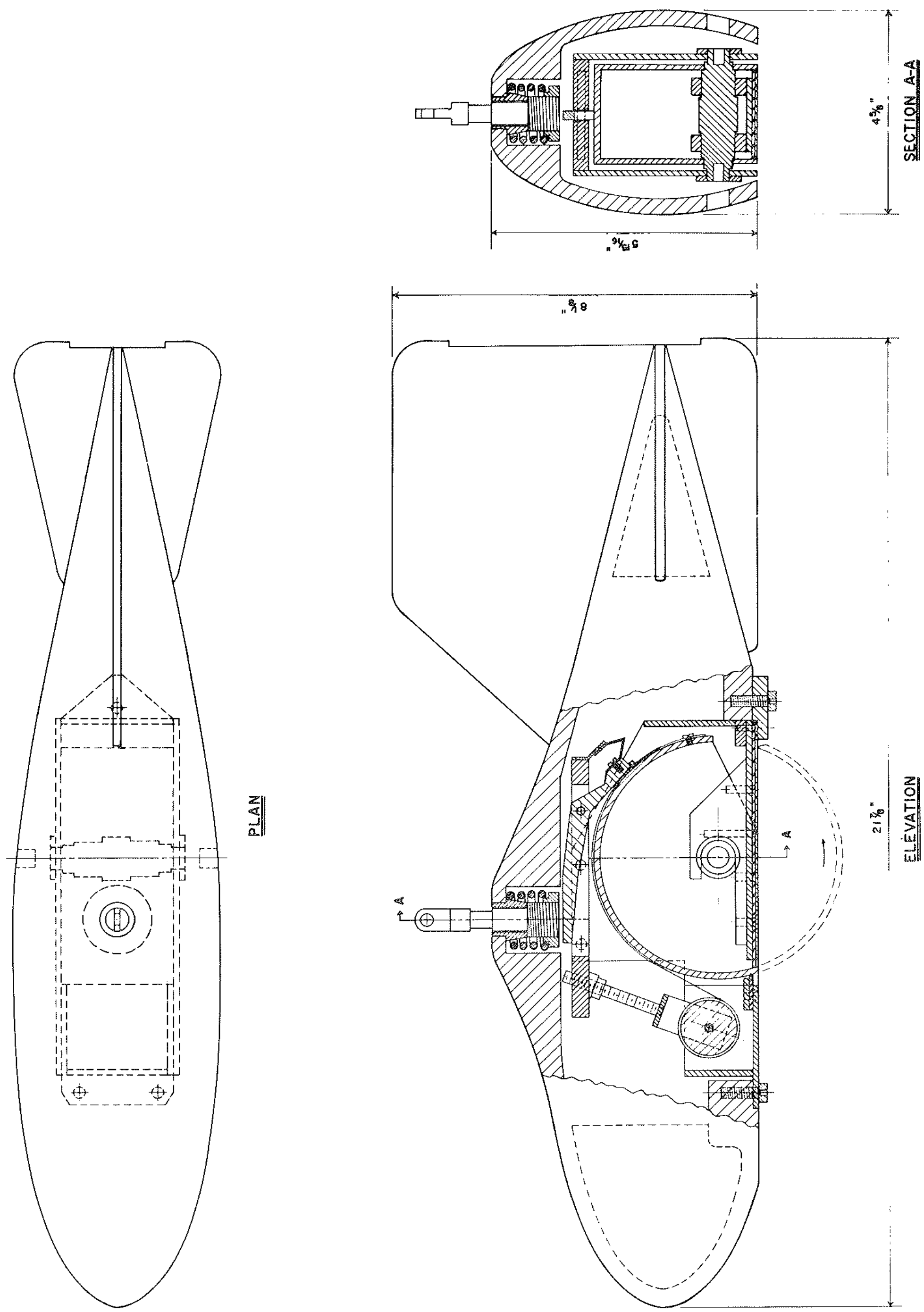


FIG. 58--HAND-LINE BED-MATERIAL SAMPLER, US BMH-60

V. DETERMINATION OF TOTAL SEDIMENT DISCHARGE

35. Methods of determining total sediment discharge--In routine sediment investigations suspended-sediment discharge is often measured and sometimes bed-load discharge is determined also. Generally the total sediment discharge of the stream is the answer actually desired.

There are several methods of determining total sediment discharge in a stream:

a. The total load may be suspended in a turbulence flume, a special weir, or a natural turbulence section, so that it can be sampled with a suspended-sediment sampler.

b. A portion of the flow can be diverted from the stream and analyzed for suspended-sediment concentration, and the bed load can be trapped in such a way that it can be measured.

c. The total sediment discharge can be computed from the measured suspended-sediment discharge, plus the bed-load discharge as computed by a transport formula based on sizes of bed sediment and characteristics of the flow.

d. The total sediment discharge can be determined from measurements of sediment deposits in a reservoir.

36. Turbulence flume method--A turbulence flume consists of a series of baffles and sills arranged to create artificial turbulence. The baffles should be designed so that all the sediment is suspended, and the capacity of the flow to transport sediment must be adequate to carry in suspension the quantity of sediment available for transport. Under favorable conditions a turbulence flume can be used to suspend the total sediment load so that it can be sampled with a suspended-sediment sampler.

Such a flume was used in an experimental study of the relation of suspended-sediment and bed-load discharge on the Middle Loup River at Dunning, Nebraska, where the sediment transport consists principally of medium to fine sand, Benedict, Albertson, Matejka (1955) [4].

The flume (Fig. 59) was constructed in a bridge opening. It consists of a reinforced concrete slab 82 ft wide and 38 ft long and an end sill that was designed to produce a reverse roller to prevent scour of the streambed immediately downstream. The turbulence is produced by baffle plates 2 ft long with a lateral spacing of 6 ft, arranged in 9 rows with a longitudinal spacing of 2 ft center to center, and a permanent continuous baffle 0.5 ft high and 2 ft downstream from the last row of baffle plates. A wooden measuring sill, 0.5 ft high by 1.33 ft wide, is located 2.33 ft downstream from the continuous baffle and

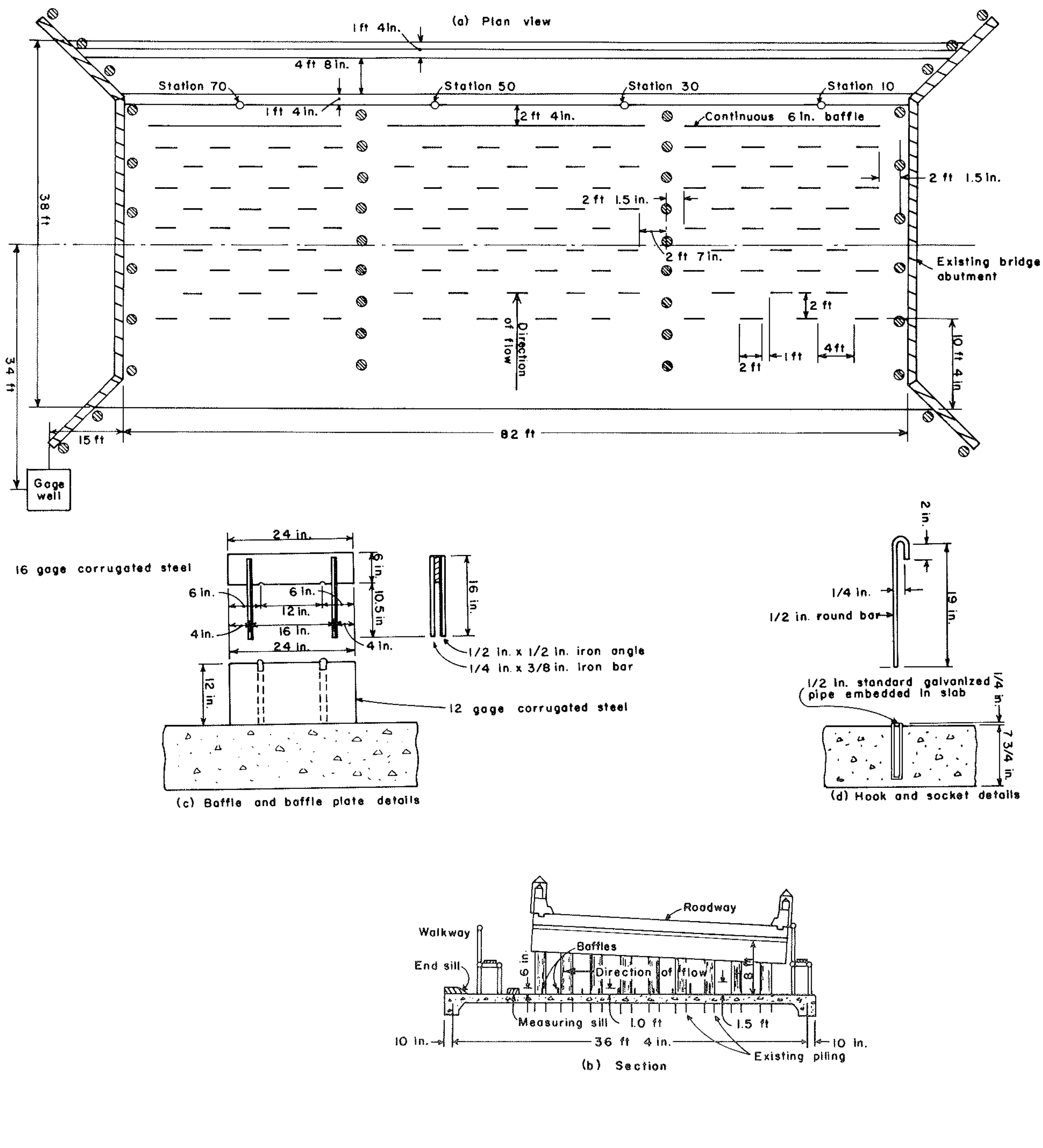


FIG. 59--TURBULENCE FLUME USED BY THE US GEOLOGICAL SURVEY ON THE MIDDLE LOUP RIVER AT DUNNING, NEBR.

Adapted from Fig. 9 of reference 4

6 ft upstream from the end sill. The 2-ft wide baffle plates are galvanized steel sheets supported by two steel rods inserted in pipe sockets embedded in the concrete slab. The first two rows are 1.5 ft high; the other seven rows are 1.0 ft high. The concrete slab, which is the floor of the flume, is supported at each end by interlocking sheet-steel piling driven to a depth of 10 ft. The top of the slab is just below the average elevation of the streambed at a discharge of approximately 400 cu ft per sec.

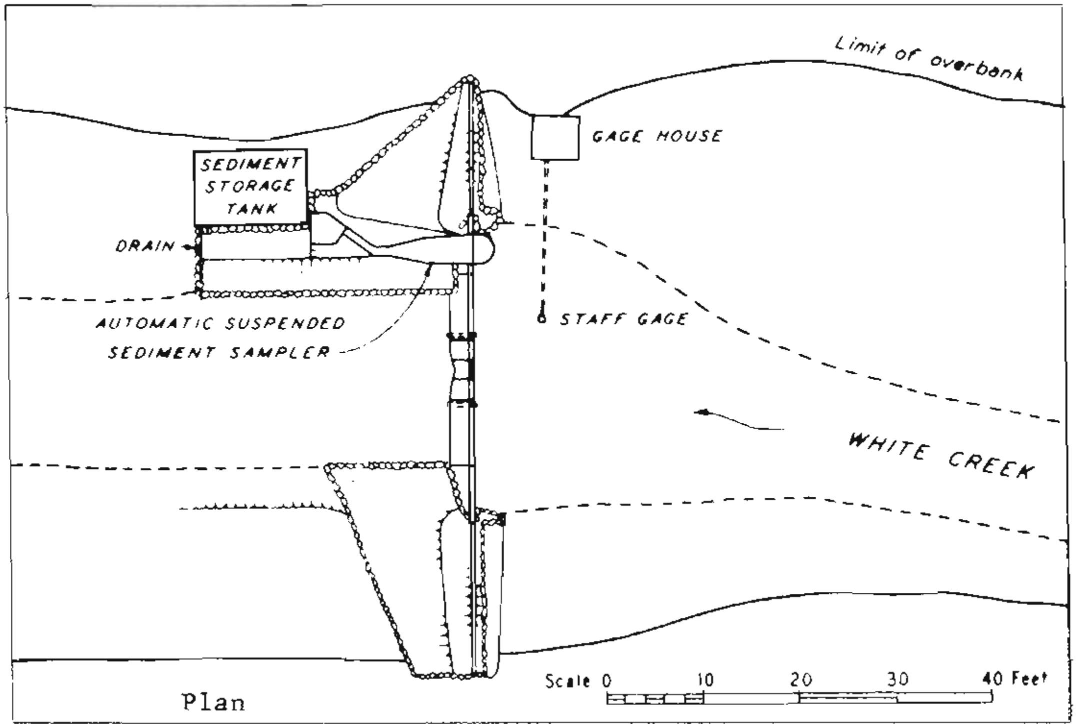
In the turbulence flume, samples are collected with a depth-integrating sampler at representative points in the cross section at the measuring sill. The sampler is held in position by a guide arrangement so that the intake nozzle remains horizontal and comes to rest momentarily on the measuring sill when the direction of transit is reversed. The measuring sill allows a standard sediment sampler to integrate the suspended-sediment load throughout the entire depth of flow. Samples thus obtained represent the total sediment discharge in the stream.

The turbulence flume is a satisfactory way to measure total sediment discharge. Sometimes the same general purpose can be obtained by sampling through the nappe of a weir, or by sampling at a naturally constricted section that suspends nearly all of the sediment load [14, 58].

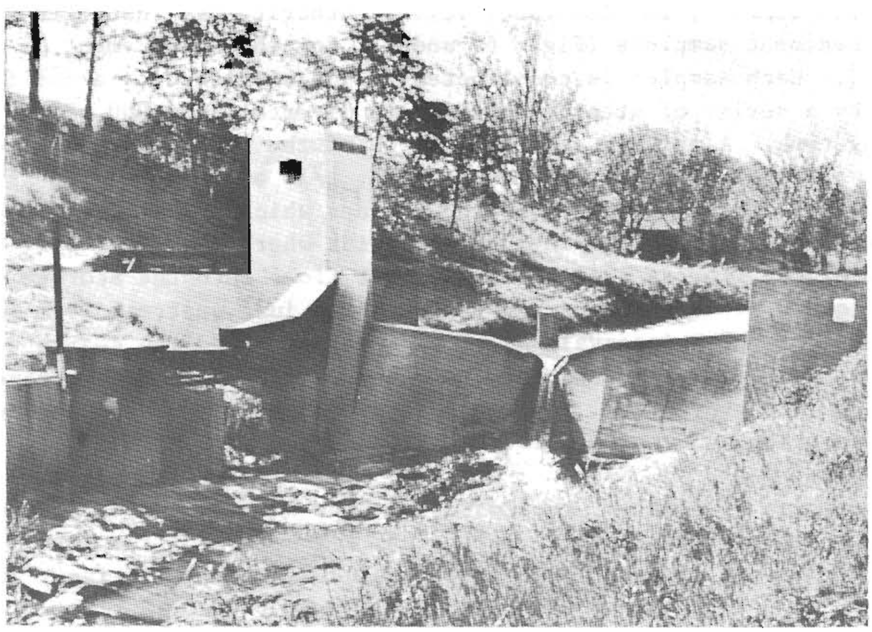
37. Special weir for sediment measurement--In connection with small watershed research studies, the Tennessee Valley Authority has installed automatic suspended-sediment samplers (Figs. 60 and 61) for the measurement of total discharge [72]. Each sampler is constructed in conjunction with a modified Albany weir and, by a series of steps, continuously diverts 1/100,000 of the flow into a measuring tank. A primary sample of 1/100 of the total flow is taken from the measuring weir. At the next splitting point, 1/10 of this reduced flow is retained, and this is followed by another divider which takes 1/2 of the remainder. The sample then goes to a tipping bucket device where the final splitting retains 1/50 of the flow as a final sample that flows into the storage tank. The volume of coarse sediment deposited in the basin just upstream from the weir, is measured at regular intervals by cross sectioning and the coarse sediment discharge is added to that from the storage tank. The basin is cleaned out periodically with a dragline. Just before cleaning, samples of the deposited sediment are taken and analyzed for density and particle size.

Another type of sampler, the Coshocton-Type Runoff Sampler [64] developed by the Soil Conservation Service, splits off a fraction of the stream discharge. This sampler is used to measure sediment production from relatively small watersheds.

38. Addition of suspended-sediment and bed-load discharge--Perhaps the most usual way of obtaining the total sediment discharge of a stream is by adding the measured suspended-sediment discharge to a bed-load discharge that is measured indirectly or that is obtained by analytical methods. The main



Plan

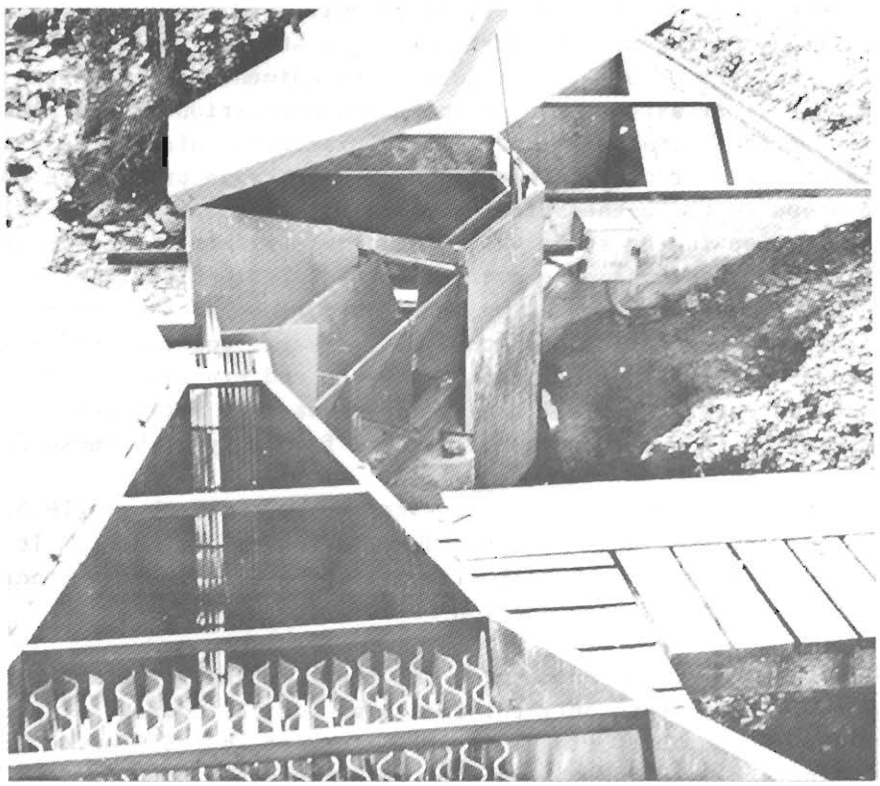


General view of sampler and weir

FIG. 60--TENNESSEE VALLEY AUTHORITY AUTOMATIC TOTAL SEDIMENT DISCHARGE SAMPLER STATION

Reference 72

Sampler intake



Sample splitter

FIG. 61--TENNESSEE VALLEY AUTHORITY AUTOMATIC TOTAL SEDIMENT DISCHARGE SAMPLER DETAILS

Reference 72

problems are the unsampled zone for suspended-sediment, selection of the best analytical method for computing bed-load discharge, and adjustment or correction of the computed discharges so that they represent the total sediment load but without overlap of the suspended-sediment and bed-load discharges. These problems were discussed under the sections on the determination of the suspended-sediment and bed-load discharges.

Some of the leading procedures for determining total suspended-sediment discharge are the Einstein method, the modified Einstein procedure, and the Laursen method.

In the Einstein method (1950) [22] the discharge of each of several size ranges of sediment found in the streambed is computed separately. The method does not apply to sediment particles smaller than 0.125 mm. The sum of the computed discharge and the measured suspended-sediment discharge of particles finer than 0.125 mm is assumed to be the total for the stream at the cross section in question.

The procedure for computing the sediment discharge involves an integration of the product of the theoretical velocity and the suspended-sediment concentration along representative verticals in a stream cross section in a long reach of fairly uniform channel. The suspended-sediment concentration at the top of the bed layer is equated to the computed concentration of sediment in a bed-load layer which is assumed to be 2 grain diameters thick. The concentration and the rate of movement of particles in each size range present in the bed-load layer are based on the mathematical probability that a given particle will move from its position in the streambed. The water-surface slope (assumed to be equal to the energy gradient), the average particle size distribution in the streambed, and the average cross section for a long reach of the stream channel are used in the computations. The method uses several formulas and graphs which are based on both theoretical considerations and experimental findings. The procedure is complex and tedious and involves many variables. Size distributions computed by this method do not compare favorably with those from actual samples.

The modified Einstein procedure, Colby and Hembree (1955) [14], differs from the original Einstein procedure in several respects. It is based on measurements of bed-material sizes, suspended sediment, velocity, depth, and width at a single cross section of a stream.

In the modified procedure, the total discharge of all particle sizes is computed rather than only the discharge for the coarser sizes. Computations are made for several ranges of particle size, but different methods of computation are used for the smaller particle sizes than for the larger sizes.

The discharge rate for each range of the small particle sizes is computed by applying a correction factor to the suspended-sediment discharge observed in the sampled zone. The correction factor, which is the ratio of theoretical total suspended-sediment discharge in a size range to the suspended-sediment discharge of the same particle size in the sampled zone, is obtained by dividing the integrated products of theoretical velocity and theoretical concentration between the stream surface and the top of the bed layer by similar integrated products from the stream surface to the lower limit of the sampled zone.

The total sediment discharge in the size ranges of the larger particles is computed about as explained by Einstein except that different methods of computation are used for the shear velocity with respect to the sediment particles, the exponential measure Z of the increase in sediment discharge with depth, and the intensity of bed-load transport. The shear velocity is computed from a transposed form of the equation used by Einstein and utilizes the measured average stream velocity. The exponent Z in the concentration distribution equation, the suspended-sediment discharge of a given size fraction moving through a cross section, and the total suspended-sediment discharge at the cross section are computed by formulas which are modifications of those proposed by Einstein. The modified procedure requires that all of the suspended sediment passing the section be measured to within a short distance from the bed of the stream. Measured sediment discharge of one or more size ranges is used as the basis for partly theoretical extrapolations that indicate total sediment discharge of the larger sediment particles. Any wash load which may be found in the sampled zone is automatically included in the total load whereas it is not included in the original Einstein procedure.

Colby and Hubbell (1961) [15] have simplified the computation of total sediment discharge and approximate particle size distribution with the modified Einstein procedure by providing several graphs for determining the unknown functions. The procedure requires the following basic data and information: Samples of bed material, depth-integrated suspended-sediment samples, streamflow measurements, and water temperature obtained at the cross section of a stream under study. The use of nomographs appreciably simplifies major steps in the computation. Drafting dividers can be used to multiply and divide values on the logarithmic scales of the graphs by adding and subtracting distances that represent the logarithms of various functions. The discharge of fine and coarse sediment is determined separately for each size range of the transported sediment and the total sediment discharge is obtained by adding all of these. The particle size distribution can be determined from the discharge of the different size ranges of particles.

The method devised by E. M. Laursen (1958) [57] determines bed-material concentration from particle diameter and flow depth, the ratio of shear velocity to fall velocity, considerations of critical shear and shear on the particle, and the Weisbach resistance coefficient.

A program to compute, by the modified Einstein procedure, total sediment discharge for an alluvial stream transporting primarily sand loads has been developed by the Bureau of Reclamation for an electronic digital computer [80].

39. Sediment discharge determined from deposits in reservoirs--The total sediment discharge of a stream during a long period of time can be estimated from the volume of sediment deposited in a reservoir to which the stream contributes its flow during the period. The volume of accumulated sediment is determined by surveys, and the specific weight of the sediment in place is determined or computed. Sometimes the sediment discharge or yield determined from reservoir surveys is more accurate than a determination based on suspended-sediment samples. If the retention time for the reservoir is so short that all the sediment is not deposited, the quantity lost in the outflow should be measured or estimated.

40. Measurement of sediment deposits in reservoirs--Surveys of sediment deposits, or of reaches in which deposits are to be measured later, are made by taking cross sections of the area at spacings sufficiently close to furnish data for a topographic map of the bed or to permit computation of the volume of deposit directly. Elevations may be taken by direct surveying methods above the water, and by soundings in submerged areas. Surveys should be referenced to permanent monuments.

Soundings are made from a boat that moves from one bank to the other along a cross section range line. The boat is kept on line by direct observation of line markers on shore, by radio or hand signals from an assistant with an engineer's transit set on line on the bank, or by following a wire stretched along the range line.

Soundings are oriented laterally by measurements of distance from a reference point on shore. Distance may be measured by stadia or sextant, or by radio equipment for very long ranges. Also a steel piano wire with distance markers on it may be used for distances up to 3,000 or 4,000 ft. The distances are measured by a device through which the wire passes as the boat moves along, and they are checked from the markers that are set at fixed intervals on the wire.

In the past, soundings for streambed elevation were made with a sounding pole or a sounding line. Now echo sounding devices are used on many surveys [27]. A transducer mounted over the side of the survey boat or installed in the boat hull sends out sound waves which are reflected back from the top surface of the sediment deposit or stream bottom. The reflected sound wave is picked up on the same, or a second, transducer. The time of travel to the streambed and return is shown as stream depth by a trace on a recorder chart. Frequently the echo sounder will show a trace for the original streambed and another for the top of a sediment deposit. A multiple trace is likely to be recorded whenever there is a distinct change in the particle size or the consolidation of sediment on the streambed. Echo soundings can be made in streams that are too deep and too swift for use of a sounding pole or sounding line.

Methods of measuring sediment deposits in reservoirs are explained in detail in several publications [8, 27, 29, 77, 81].

41. Determination of specific weight of sediment deposits--The volume of sediment discharged by a stream in a given period of time is a measure of the total sediment discharge, or sediment yield, but usually the discharge is desired in terms of weight. The specific weight of a sediment deposit is the dry weight of sediment per unit volume of sediment in place, and this is a simple and direct expression for converting volume to dry weight of sediment.

The specific weight of a sediment deposit depends primarily on the particle size of the sediment [42]. However, for a mixture of sediment sizes the sorting of the sizes also has an effect. Sediments consolidate with time, in response to overburden pressures, and as a result of alternate wetting and drying if exposed to the atmosphere by changes in water surface elevation. The important point for this discussion is that the specific weights can vary from 10 to 120 lbs per cu ft. Although there are formulas and tables for estimating the specific weight of sediment deposits the estimates are not very reliable.

In the past, various methods of removing an "undisturbed" volume of the sediment from a reservoir deposit have been used. Samples were taken with thin-walled boxes or tubes that were thrust into the surface of the sediment and with core samplers that could penetrate several feet into the sediment deposit. The sample was later dried and weighed in the laboratory. The sampling methods were laborious and the results were often unsatisfactory.

Nuclear density probes are a newer means of measuring in-place density of sediment deposits under water. The first practical in-place sediment density probe was developed by the Bureau of Reclamation [73]. It used gamma ray scattering from a cobalt 60 source enclosed in a metal tube that could be lowered into the sediment deposit. A self-reading ionization chamber (dosimeter) was enclosed in the tube but it was separated from the cobalt source by a lead shield. To make a density measurement, the dosimeter is removed from the probe, charged, read, and replaced in the probe. The probe is then lowered into the sediment. After a timed interval the probe is raised to the surface and the dosimeter is removed and read again. The difference in the two readings is a measure of the density of the water-sediment mixture in the immediate vicinity of the probe during the test. By calibration the dosimeter readings are related to the mixture density. The density can be converted to specific weight of the sediment by using the specific gravity of the sediment. The development of this probe was a big advance in the measurement of densities of sediment deposits.

An improved nuclear probe for determining sediment density was developed by Technical Operations Incorporated under contract with the Beach Erosion Board, Corps of Engineers [9]. The probe consists of a gamma ray source of 3 millicurries of radium installed in a stainless steel tube. Radiation counts are obtained from three Geiger counter tubes, which are shielded from the source to prevent counting of direct radiations. A preamplifier sends the count pulses back through a coaxial cable to the counter. The components are contained in a stainless-steel tube, 2 ft long and 1.5 in. in diameter. The probe, which weighs 12.5 pounds, may be suspended on a steel cable and additional weight may be attached to aid in forcing the probe into sediment deposits. For shallow depths the probe can be attached to 1.5-in. aluminum pipe and pushed down into the sediment. Measurements can be made only in sediments into which the probe can penetrate.

A scaler to count the number of impulses from the probe was developed by the Nuclear Chicago Corporation for the Ohio River Division Laboratory, Army Corps of Engineers. This is the Model 2800 Portable Scaler used in studies of soil moisture. Other scalers can be used also.

The instrument operates on the principle that the amount of scatter and adsorption of gamma rays is a function of the density of the medium through which the rays pass. The readings indicate the average density of material in a spherical region about 16 in. in diameter around the source and detectors. Specific weights can be determined from a calibration that relates number of counts per minute to known densities of water-sediment mixtures. In laboratory tests by the Beach Erosion Board the probe satisfactorily determined the specific weights of sediments in an area immediately surrounding the probe.

The probe is an accurate and practical instrument for measuring in-place bulk-densities of saturated sediments. The cost per measurement is less and the results are more accurate than for older methods. Sediments are less disturbed by placing the probe than by driving a sampling tube. Field tests by the Agricultural Research Service in sediment deposits in Sabetha Lake [30] and by the Army Corps of Engineers in San Francisco harbor areas [76] proved the probe to be satisfactory in field sampling. Readings were taken at several depths with one insertion of the probe. The results were more rapidly available than for conventional methods of sampling and laboratory analysis.

42. Sediment deposit problems--Some aspects of sediment deposits and the measurement of sediment deposits are outside the immediate field of the determination of fluvial sediment discharge, but are so closely related that they justify mention here.

Fluvial sediments often deposit in slack water areas or where velocities are retarded, as at natural river bends, on flood plains, at regulating structures, reservoirs, bridges, intakes, estuaries, and harbors. In general, sediment deposits which merit detailed study are surveyed and the specific weight of the sediment is estimated or determined by the methods in the preceding sections. Measurements may be made to determine rates of deposit or of consolidation as well as total sediment accumulation. Then corrective and maintenance measures may be taken to remove the deposits, as by dredging, or to prevent or retard the rate of deposit by channel or drainage basin improvements.

Deposition of sediment may reduce the capacity of a reservoir to store water for useful purposes. The sediment discharge of a stream is sometimes measured to estimate the rate of storage capacity loss in a proposed or existing reservoir. If the discharge is in weight, an estimate of the specific weight of the sediment deposits is made. A study of the sediment problem in a given reservoir may indicate that land erosion, stream bank erosion, and other sediment sources should be controlled to reduce the sediment inflow to the reservoir.

VI. RECORDS OF SEDIMENT DISCHARGE

43. Sediment-discharge records from periodic measurements--Some measurements of sediment discharge, such as those based on sediment samples continuously diverted as a fraction of the streamflow (Section 37), can be divided into records of sediment discharge for short periods of time. Records based on the deposition of sediment above a weir, or in a reservoir, are longer term records of total sediment discharge. For most purposes, a record of total sediment discharge that gives only the total for a period of months or years is satisfactory.

Most measurements of suspended-sediment in streams or over a turbulence weir are taken daily or every few days, while computations of bed-load discharge by the Einstein, modified Einstein, Meyer-Peter and Müller, and similar formulas are seldom made at frequent intervals. Under such sampling procedure the sediment record for the time of measurement is not likely to be seriously in error. The big errors are on those days for which no measurements were made or for which conditions change too rapidly to be defined by the measurements. The cost of making continuous measurements with manual sampling equipment would be prohibitive.

If a gaging station is at or near the sampling point on a river, the frequency of sampling may well be based on the flow duration pattern. It is recommended that as many samples be obtained as can be economically afforded in the 20- to 80-percent flow duration range, because the bulk of the sediment is discharged in this range. In small streams 95 percent of the sediment discharge may occur in 5 percent of the time.

A large part of the total sediment program is involved in making dependable estimates of the sediment discharge occurring between the times at which measurements are made. The adequacy with which the computations can be made affects the accuracy of the record and partly determines the cost of the record. If the interval betwen measurements can be handled well, the measurements can be made less frequently.

In sand-bed streams the mean stream velocity is a good guide for interpolation of bed-load discharge. Also the discharge of the coarser sands can be related to the stream discharge in terms of a sediment rating curve [11, 13].

The suspended-sediment discharge is usually from 50 to 95 percent of the total sediment discharge and it is often mainly fine sediment (less than 0.62mm). The fine-sediment discharge has no direct relation to the hydraulic parameters at the sampled cross section. Sometimes, but not always, the suspended-sediment discharge has a usable relation to stream discharge. If sediment records are to be accurate and are to be obtained at reasonable cost, some method must be used to simply and cheaply evaluate the concentration of suspended sediment between times of complete suspended-sediment measurements.

One common way to obtain daily sediment concentrations is to have a local observer take one or two samples of the suspended sediment at one sampling vertical in the cross section. The procedure can be made more elaborate by adding extra sampling times or verticals.

Whenever measurements are made of the suspended-sediment discharge in the entire stream cross section, the discharge-weighted concentration for the section is compared with the concentration from nearly simultaneous samples taken at the observer's sampling vertical. Thus a correction factor can be determined and applied to the observer's samples, if necessary. A continuous record of sediment concentration can then be based on the observer's samples and interpolation between sampling times.

The discussion in this and the following section is not intended to teach methods of computing records. It merely points out the problems so that a sampling program can be fitted to the need for field data.

44. Extension of sediment-discharge records--The computation of continuous sediment records involves interpolation between the time of actual sediment discharge measurements as discussed in the previous section. Many situations require estimates of sediment discharge for periods when there are few sediment measurements.

If it is necessary to estimate sediment discharge or sediment yield for a stream on which neither sediment observations nor continuous records of stream discharge are available, the best approach often is to use data from rates of sediment accumulation in reservoirs or from sediment measurements on streams with conditions as nearly like those of the stream in question as possible. This method does not provide a conclusive answer and should be used only in lieu of a better alternative.

Data on 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, 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 in this way will probably be questionable but may have to suffice.

A record of stream discharge together with some sediment measurements will provide a means for estimating sediment discharge for periods when samples were not taken. All available sediment samples should be correlated with corresponding water discharge, mean velocity, or stage, and the most plausible relationship should be applied to derive a sediment discharge hydrograph for the period. The relation of sediment to streamflow may vary to some extent with the seasons. To cover a short period of missing sediment record, the sediment discharge can be computed from records of daily stream discharge and the available water-sediment discharge relation. If a sediment estimate is needed for an interval of several years it can be computed from a flow-duration curve, Miller (1951) [60]. The procedure consists of developing, from a limited sediment sampling record, a correlation between sediment discharge and water discharge. This correlation is then applied to a long-term flow-duration curve and the resulting computation represents a long-term average sediment yield. Often the correlation between water discharge and sediment discharge of a stream plot in such a manner that no systematic relationship is readily apparent. However, if good judgment is used and records are properly analyzed and correlated with respect to seasons, periods, storm run-off, snowmelt, and other run-off characteristics, reasonably satisfactory results can generally be obtained in computing sediment discharge by this method.

45. Need for automatic sampling devices--The best solution to the problem of continuous sediment records would be an instrument that would automatically record, either continuously or at frequent intervals, the total sediment discharge of the stream. If adequate records of streamflow are available, as assumed throughout this report, a continuous or frequent record of the suspended-sediment concentration of the stream would supply a generally adequate record. Samples of suspended-sediment concentration obtained automatically at one point in the cross section of a stream would improve most records greatly. The concentration at the point could be checked against that for the cross section by occasional complete measurements of the suspended-sediment discharge of the stream. The following methods of automatic sampling are not intended to replace the manual methods of making sediment discharge measurements. They are intended to improve the sediment records between times of manual measurements; to reduce the need for, or eliminate entirely,the local observer; to reduce the frequency of manual sampling; and sometimes to reduce the number of samples to be handled and analyzed.

46. Single-stage samplers--A single-stage sampler [43] has been developed for use on flashy and intermittent streams, especially at remote or not easily accessible sites. The sample is obtained with respect to gage height, not to time, and on the rising stage only. The sampler is used to supplement other types of sampling to provide data where satisfactory manual coverage is not feasible. Single-stage samplers provide a means of obtaining some suspended-sediment data for streams or storms on which data would not be obtained otherwise.

The sampler consists of the following four basic parts as shown in Figs. 62 and 63:

a. A sample container such as a pint glass milk bottle.

b. A siphon-shaped air-exhaust tube having a smooth inside passage about 3/16 in. in diameter, usually made of copper tubing.

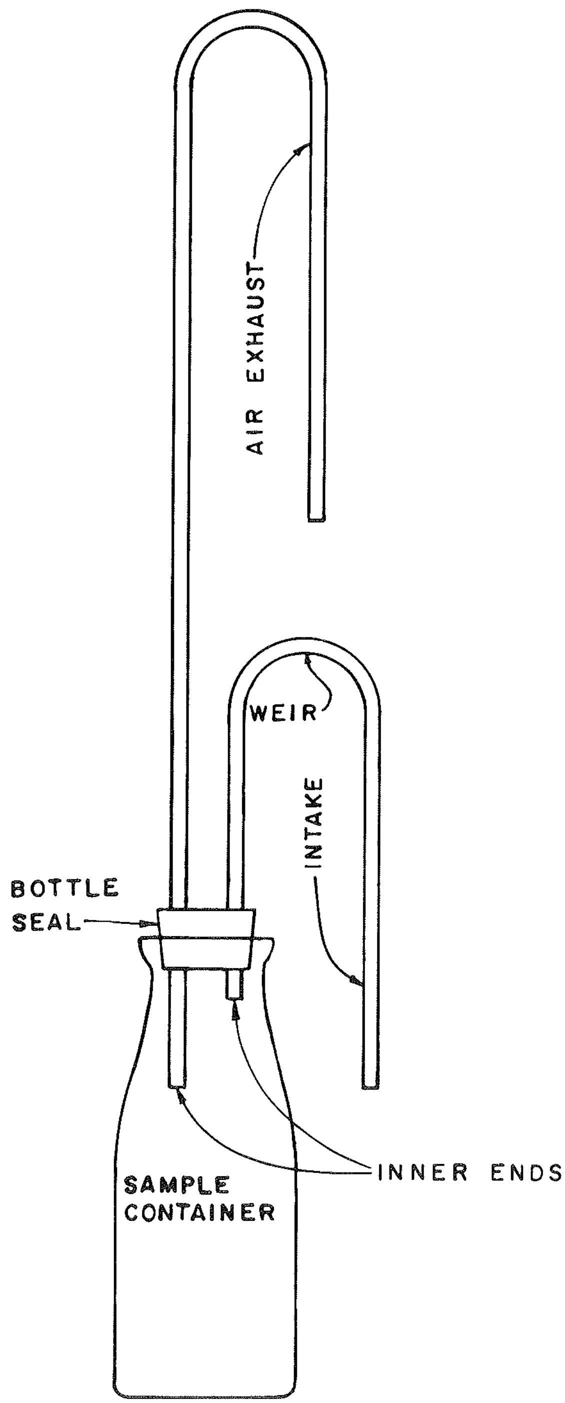


FIG. 62--SINGLE-STAGE SAMPLER--
VERTICAL INTAKE

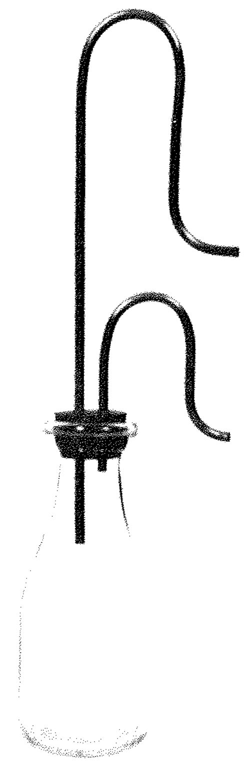


FIG. 63--SINGLE-STAGE SAMPLER--
HORIZONTAL INTAKE

c. A siphon-shaped intake tube usually made of copper tubing and having a smooth inside passage with a diameter of 3/16 in. at the nozzle and 3/16 or 1/4 in. from the nozzle into the bottle.

d. A bottle seal composed of a tight-fitting stopper having two holes which hold the tubes tightly in place.

The sampler should be mounted on a vertical support such as a timber pile or bridge pier, preferably near the center of the stream, with the tubes oriented into the current. One or more samplers may be mounted one above the other to collect samples at several selected stages.

When the river stage reaches the elevation of the intake nozzle water-sediment mixture begins to enter the nozzle. As the water surface in the stream continues to rise, the level in the intake rises until the combined potential and velocity-head pressure at the intake opening forces water over the crown of the siphon. When the siphon is primed, flow begins to fill the sample bottle. Filling continues until the sample rises to the inner end of the exhaust tube, sealing the tube and stopping the flow.

Single-stage samplers have the following inherent attributes:

a. Samplers can be installed at sampling stations well in advance of expected floods.

b. Personnel need not be present at the time of sampling.

c. Samples can be obtained at predetermined stages of the rising stream.

d. Sampling apparatus is simple and inexpensive.

e. The sampler may be left for a few days after sampling without significant contamination of, or evaporation from, the sample.

Two general types of single-stage sampler are in use, one with a vertical intake and the other with a horizontal intake.

The vertical-intake sampler (Fig. 62), which is the simplest of the series, is best for fine sediments. Its sampling efficiency usually is little affected by circulation through the sampler, or by a reasonable amount of shielding. It is accurate only for sediments finer than 62 microns, for water-surface surges less than 4 in., and for velocities that are reasonably low at the sampling point during primary sampling.

Horizontal-intake samplers may be used to sample sands as well as finer sediments. Fig. 63 shows a sampler for low stream velocities. The intake nozzles are smooth and sharp and are inclined downward between 10° to 20° to prevent deposition of sediment in the intake prior to sampling. The smaller angles are used in samplers which are to operate in relatively high velocity because the greater surges associated with these velocities reduce the tendency for sediment to deposit. Three basic horizontal intake samplers [43] cover most sampling conditions where the velocity at the sampling point does not exceed 7 ft per sec. Velocity, water-surface surge, and sediment size are the principal factors that govern the selection or design of a single-stage sampler for a specific location. The required heights of the siphon-shaped intake and air exhaust tubes are dictated by surge and velocity. A single sampler is adequate for only a limited range of surge and velocity. If none of the basic types are satisfactory, modifications can be custom designed for almost any sampling conditions.

The following limitations of the sampler may cause sampling errors particularly if coarse silts and sands are present:

a. Samples are collected at or near the stream surface and usually near the edge of the stream, or near a pier or an abutment.

b. Size, shape, and orientation of intake and air exhaust tubes may fail to provide intake ratios (ratio of average velocity in nozzle to stream velocity approaching nozzle) sufficiently close to unity to sample sands accurately.

c. Obstructions by trash, drift, or elements of the sampler mounting may create unnatural flow lines at the point of sampling.

d. Atmospheric condensation in the sample container prior to sampling may dilute the sample.

e. During the period of submergence subsequent to sampling, water-sediment mixture may circulate through the sampler and cause a faulty sample.

f. Contamination or loss of sample may occur from exposure to the elements after the flood has receded.

g. The time and gage height at which a sample was taken may be somewhat uncertain.

The effect of item a should be evaluated by occasional measurements of suspended-sediment discharge for the entire cross section. The effect of the other items can be minimized or eliminated by proper installation and maintenance. The single-stage samplers are widely used at the present time (1963).

47. Pumping samplers--Pumping samplers [47] appear to be one answer to the need for automatic sampling equipment. The Inter-Agency Project has developed pumping samplers for obtaining frequent samples of suspended-sediment concentration. Sampling is confined to one point in the cross section of a stream, that is, at the location of the pump intake, which may be near the stream bank or at any suitable structure in the channel. The equipment consists essentially of an intake and pumping system that takes a representative sample of the stream at the intake, and a collecting or recording apparatus for the samples.

In the first pumping samplers the intake consisted of a 1-in. pipe coupling welded to a steel plate which was mounted flush on the face of a guide wall that was parallel to the stream flow. Other types and sizes of intakes are being tested. A 3/8-in. by 1-in. constriction in the intake line blocks the passage of fish and debris which might jam the pump. Any objects caught against the constriction are removed by backflushing. The sampling pump with 1-in. pipe connections has a capacity of 10 gpm under a 42-ft total friction and potential head. The pumping system is controlled by an electrical cycling device that can be adjusted to take samples at any desired frequency.

Three systems for determining the sediment concentration in samples that are collected by the pumping sampler are under investigation: The acccumulative-weight, the volume-recording, and the bottling systems [47].

The accumulative-weight recording system collects samples in a large settling tank where the sediment settles onto a suspended tray (Fig. 64). Weight of the tray and sediment is measured continuously with a spring-transformer scale and recorded on a strip chart. The settling tank is 4 ft 8 in. square by 6 ft deep and the tray is 4 ft square by 3 ft deep. The equipment is housed in an 8 by 10-ft shelter.

Before each sampling period, the intake system is back-flushed with 28 gallons of the nearly clear water from the top of the settling tank. The back flushing removes any debris or sediment which may have collected between pumping cycles. Then at 30-minute intervals the sampling pump operates for 4 minutes, and pumps water from the intake into the splitter device. The splitter wastes the flow during the first 50 sec. and then diverts a 28-gallon sample into the settling tank. If for some reason the sampling procedure fails, safety switches at several points in the system interrupt the sampling process. The spring-transformer scale has a total capacity of 1,400 pounds. The differential transformer in this unit measures the deflection of the load spring by 1/4-in., or 100-pound increments. The pen moves the full scale on the recorder chart for each 100 pounds of sediment that accumulates on the tray. Then the recorder pen returns to the zero position automatically. The average concentration of suspended sediment is computed from the weight of sediment accumulated on the tray in a given time and the volume of water pumped during the same time.

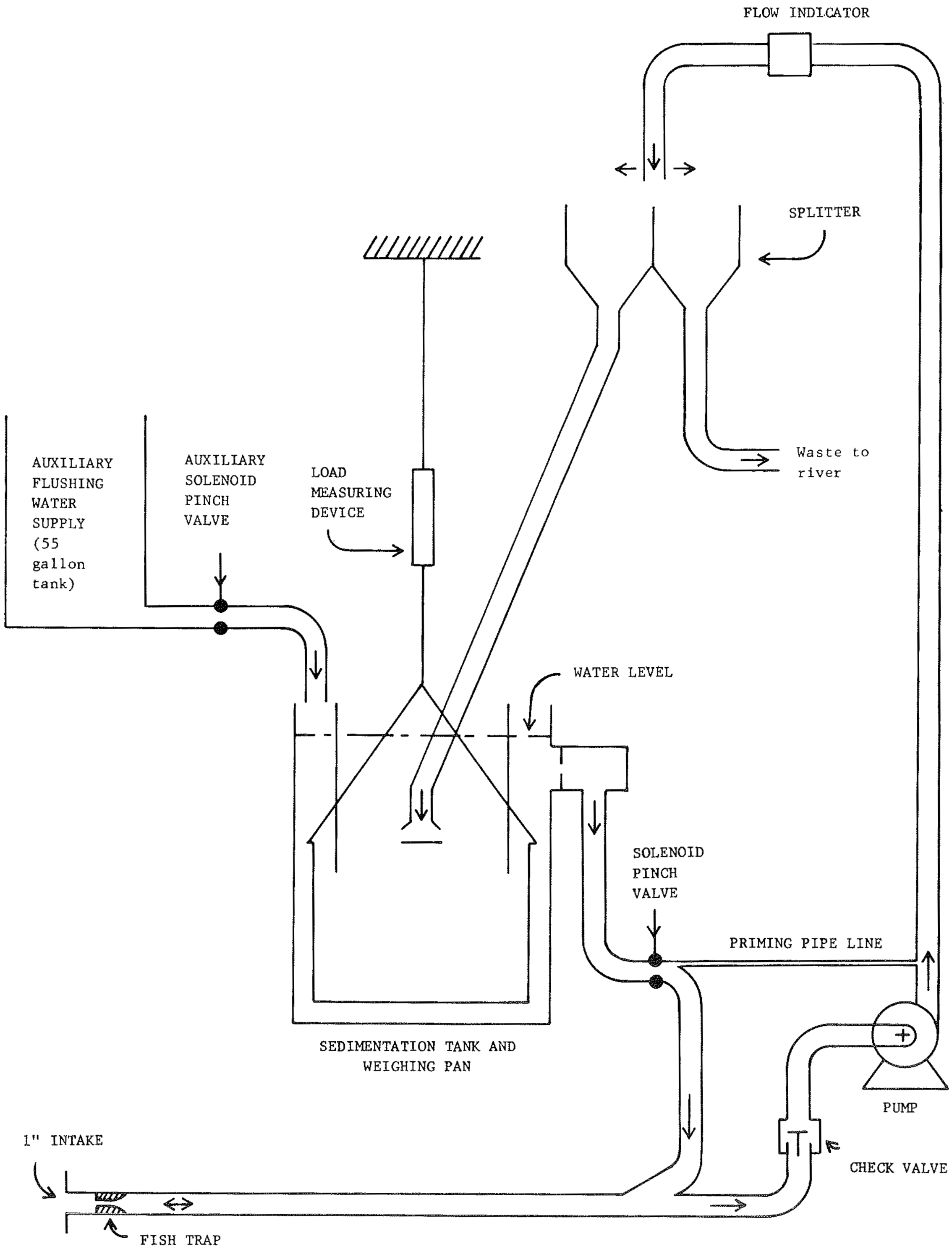


FIG. 64--PUMPING SAMPLER WITH ACCUMULATIVE-WEIGHT RECORDING SYSTEM

The sampler obtains a time-weighted concentration that is accurate for fine sands and coarse silts during periods of steady flow, but sudden or short time changes in concentration may not be defined. There is difficulty in determining the discharge of clays and fine silts because the finer particles do not always settle out of suspension onto the weighing tray. Only samples taken as a check on the accumulative system are analyzed in the laboratory.

The sediment-volume recording system consists of a revolving rack, which supports 12 sedimentation tubes each having a constricted section at the bottom; a 16-mm movie camera for recording the levels of sediment and water in the sedimentation tubes; and a concentric rack at a lower level which carries 72 sample containers (pint glass milk bottles). (See Fig. 65.) Every 30-minutes a sample is pumped from the stream into one of the sedimentation tubes. About 5 1/2 hours later the camera automatically takes a picture of the sediment accumulation in the constricted section of the tube and also of the height of the water column in the tube. The tube then drains in preparation for taking another sample in the same tube one-half hour later. Each sedimentation tube is calibrated (the calibration may require adjustment for certain seasons or storms) so that the pictures can be used to determine sediment concentration by weight.

A splitter on top of one of the 12 sedimentation tubes diverts part of the pumped sample into one of the bottles every 6 hours. The sample in the bottle may be analyzed later in the laboratory as a check on the concentration of sediment obtained from the picture record. This system has been satisfactory except where the percentage of silt or clay is so high that the suspended fine material obscures the interface between the accumulated sediment and the turbid liquid in the sedimentation tube. However, the volume-recording system is not well adapted to very flashy streams because the settling time limits frequency of sampling.

The individual-sample bottling system has a revolving double-rack which stores the samples in pint milk bottles for later analysis in the laboratory. The sampler carries 145 sample containers (Fig. 66). In each sampling cycle water-sediment mixture is pumped from the stream through a splitter mechanism which diverts the flow into a sample container. When stream flow is low a sample is taken every 12 hours, but above a selected stage samples are taken at hourly intervals. The sampling frequency is controlled by a float switch that is actuated by the rising and falling water level in the stream.

The individual-sample bottling system is satisfactory for use on many types of streams. Because all of the samples must be analyzed in the laboratory, the system is best adapted to ephemeral streams on which the total number of samples per season is not large.

Although the pumping samplers are still being field tested, they are probably sufficiently developed to be of use for routine sampling programs at certain sites.

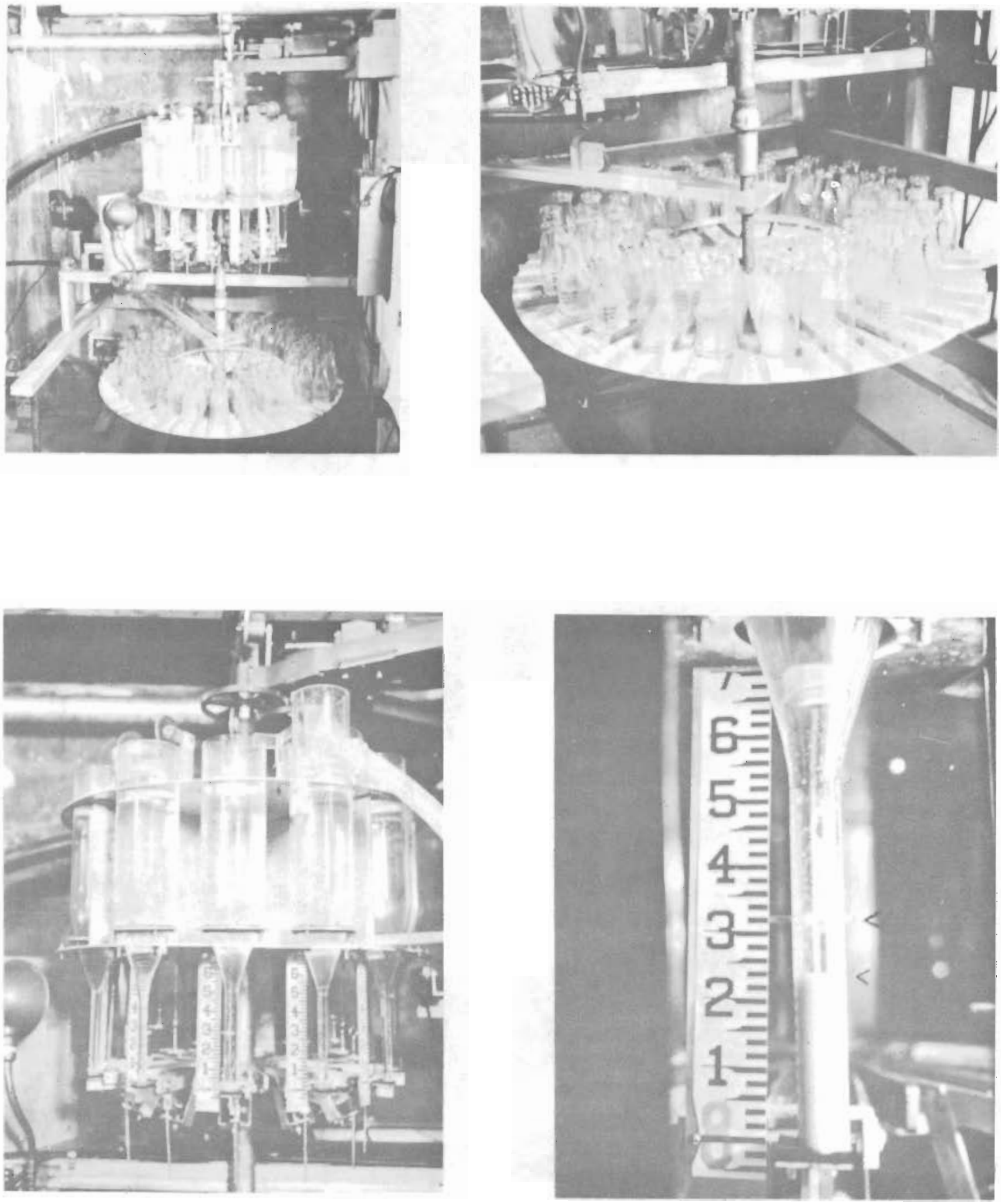


FIG. 65--SEDIMENT-VOLUME RECORDING SYSTEM

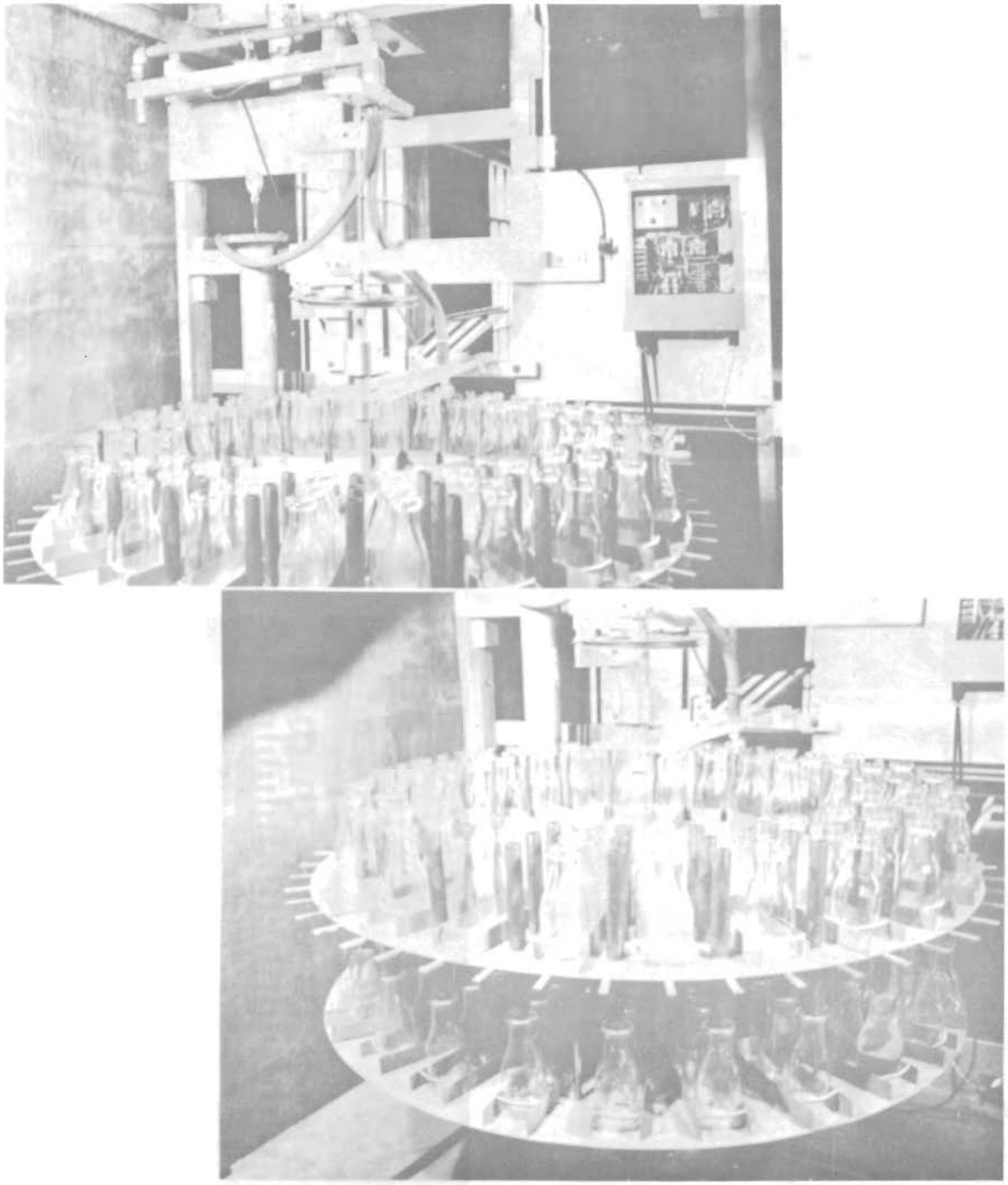


FIG. 66--INDIVIDUAL-SAMPLE BOTTLING SYSTEM

48. Research on automatic sensing of sediment--An ultimate objective of the Inter-Agency Project program is the development of instruments that will automatically sense and record the quantity and character of sediment loads transported by natural streams. The ideal device could be installed permanently in the stream to detect and record the amount and size spectrum of sediment discharge. The record should be continuous, or intermittent at sufficient frequency to define a continuous record of the sediment discharge. The feasibility of various approaches to the problem are being studied and those that show promise are being developed further. The immediate goal is the determination of suspended-sediment concentration at one point in a stream cross section, or the development of an instrument that gives an indirect indication of concentration.

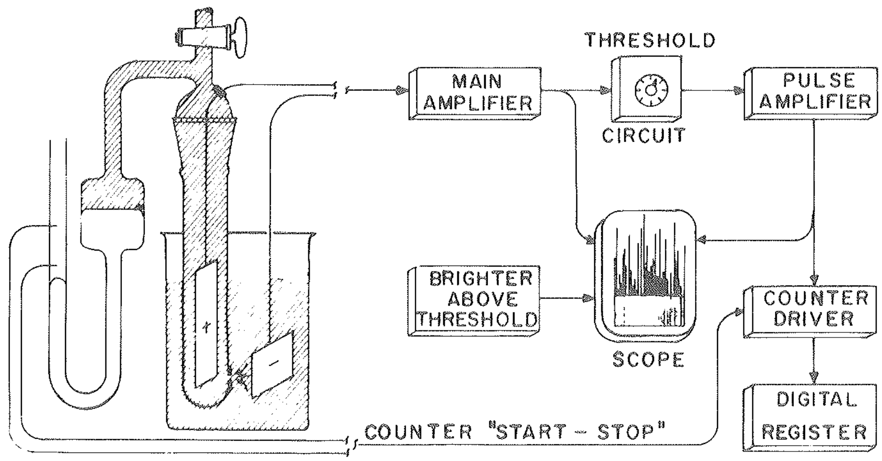
Several possible ways to determine automatically the concentration of suspended sediment have been or are being studied. These include differential pressure devices, direct electronic sensing, turbidimeters, ultrasonic equipment, and nuclear adaptations. In the development of these devices some work is done on size analyses features of the instruments when size is a parameter that must be determined before concentration can be measured. Possible laboratory uses of the instruments are considered also. However, the basic goal is development of the method for field use.

Differential-pressure devices--A pressure differential device to measure changes in pressure between two elevations in a flowing water-sediment mixture was investigated [46]. An attempt was made to improve the accuracy of differential-pressure measurement and to evade dynamic-pressure effects sufficiently to permit measurement of suspended-sediment concentration in normal streamflow.

Although a highly sensitive differential-pressure device was developed, attempts to determine the concentration of sediment in flowing water were not successful. The dynamic-pressure differences were so much greater than the pressure differences caused by changes in suspended-sediment concentration that the identification of differences in suspended-sediment concentration was practically impossible.

Electronic sensing of sediment--Electronic sensing equipment (Fig. 67) is being investigated to determine its capacity for analyzing suspended sediments for particle size distribution and concentration.

This commercially available equipment measures and counts individual particles as they pass through a small aperture. A known volume of a conductive liquid (electrolyte) that contains the particles in dilute suspension is drawn through the aperture. The resistance between electrodes on each side of the aperture changes whenever a particle displaces part of the liquid in the aperture. A constant voltage is imposed on the electrodes so that the change in resistance produces an electrical pulse that is proportional to particle volume. The electrical pulses are amplified so that they can be screened as to size and counted. The voltage pulses are also displayed on an oscilloscope screen as a pattern of vertical "spikes". Normally, each spike or voltage pulse indicates



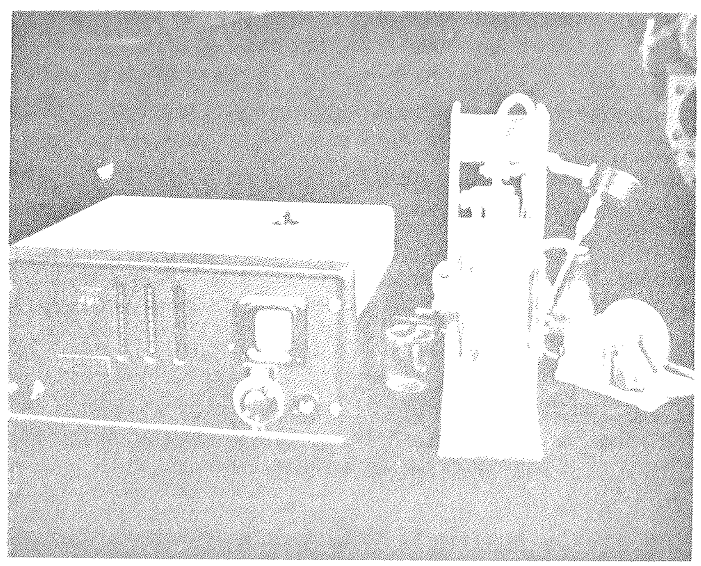


FIG. 67--ELECTRONIC SENSING SEDIMENT ANALYZER

the passage of a single particle. The pulse pattern serves as a guide for measurement and as a monitor of instrument performance.

The counter has an adjustable threshold level below which electrical pulses will not be counted. Threshold level is indicated on the screen by a brightening of pulse segments above the threshold level. The threshold can be set so high that none or only a few of the largest particles are counted. Then it can be lowered in successive steps and a count of pulses larger than each step can be taken. The relation of pulse height to particle volume can be established by calibration. Thus, the number of particles in each size range can be determined. The maximum particle diameter that the threshold adjustment can cover is about three times the minimum particle diameter. However, adjustments of amplification (gain) and voltage across the electrodes permit screening of particle diameters over a range of 20 to 1. By using apertures with diameters of 50, 140, and 400 microns, a range of particle diameters from 160 microns down to 1 micron can be measured. Because the measurement is of particle volume, particle diameter merely indicates the diameter of a sphere that has the same volume as the particle. Tests show that composition or density of the particles has little effect on the analyses. An approximately spherical particle with a given volume will have an equal effect whether it is of glass, quartz, or pollen. Duplicate analyses on the same sample generally agree closely.

The time required for a size analysis depends on the range of particle sizes in the sample. The operating time for an analysis in a single orifice varies from 10 minutes for a 400 micron aperture to 75 minutes for a 50-micron aperture. Most sediment samples require analysis in at least two aperture sizes and the computation of results takes additional time. The results are a complete size distribution analysis for the sample. Concentration of sediment can be determined also. The analyzer is an accurate method for laboratory determination of the physical size distribution of particles in the silt range. The present design is both too delicate and too complicated for use in the field. However, a complete size analysis is not needed in most field applications. If the analyzer can be modified to determine suspended-sediment concentration directly, it can be greatly simplified and the time for a determination of sediment concentration can be much reduced.

Turbidity method--Turbidity, which is the cloudiness in a liquid, is often used as a measure of suspended-sediment concentration. In the commercial turbidimeter that the Inter-Agency project is studying, turbidity is measured as the ratio of the intensity of the light scattered by the particles in the liquid to the intensity of light transmitted through the liquid. The photovoltaic cell in the detector is exposed to the transmitted light for 15 sec and then by means of solenoid-operated shutters it is exposed to the scattered light for 45 sec. This cycle is repeated continuously. The recorder pen responds to changes in turbidity only during the scattered-light portion (45 sec long) of the measuring cycle. Stability of the ratio measurement is achieved by using a single light source and a single photovoltaic cell to measure both scattered light and transmitted light.

The turbidimeter equipment used in the study consists of a pumping and recirculating system, sedimentation chamber, turbidity detector, and recording system (Fig. 68). The instrument measures, indicates, and records the degree of turbidity in a flowing liquid by means of a photovoltaic cell and a servo-operated self-balancing recorder. Turbidity is recorded on a strip chart, which travels at a rate of 3/4 in. per hour, except when the speed is changed to 12 in. per hour to give an expanded record for sedimentation size analysis.

The turbidimeter can be adjusted to monitor fluids with concentrations ranging from as low as 0 to 10 parts per million (ppm) to as high as 0 to 100,000 ppm on the silicon scale with an accuracy of 10 percent. In the low range, the instrument will measure concentration to an accuracy of 1 ppm. Unfortunately turbidity changes with both concentration and particle size of the sediment. The concentration of a sediment can not be determined from turbidity unless the particle size distribution is known.

Concentration and particle size distribution in suspended-sediment samples are determined in two steps. Turbidity of a sample being pumped through the detector is recorded continuously for determination of concentration. To determine particle size, the flow is suddenly stopped and turbidity is recorded against time as the particles settle out of suspension and out of the light beam in the sedimentation chamber.

Particles of uniform density and shape fall at rates proportional to their size, and an intersecting light beam is obscured in proportion to particle size and concentration. Theoretically an opaque particle should obscure light in direct relation to its great circle area. The relative weight of particles of a given size group required to obscure light to a specific degree is represented by a hiding factor. The weight of sediment in each size group of the sample is computed in percentage of the total for each incremental change in turbidity by using the equivalent hiding factor and making adjustment for concentration.

After the particle size spectrum has been determined, concentration is found from a calibration graph in which turbidity is plotted with respect to concentration, and size is shown as a parameter. The calibration graph is developed from turbidity tests on several known concentrations of a sample of material that has a known particle size distribution. Many samples are used to cover the range of size groups represented by the parameters. Particle size distribution in a sample can be expressed by the mean particle diameter, which is the 50 percent size by weight, and the geometric standard deviation, which is the 84.13 percent finer size divided by the 50 percent size.

Turbidity tests on several samples of known concentration and known particle size distribution were made for the purpose of determining the relation of turbidity to the characteristics of various types of sediment. Because turbidity readings are sensitive to both particle size distribution and sediment

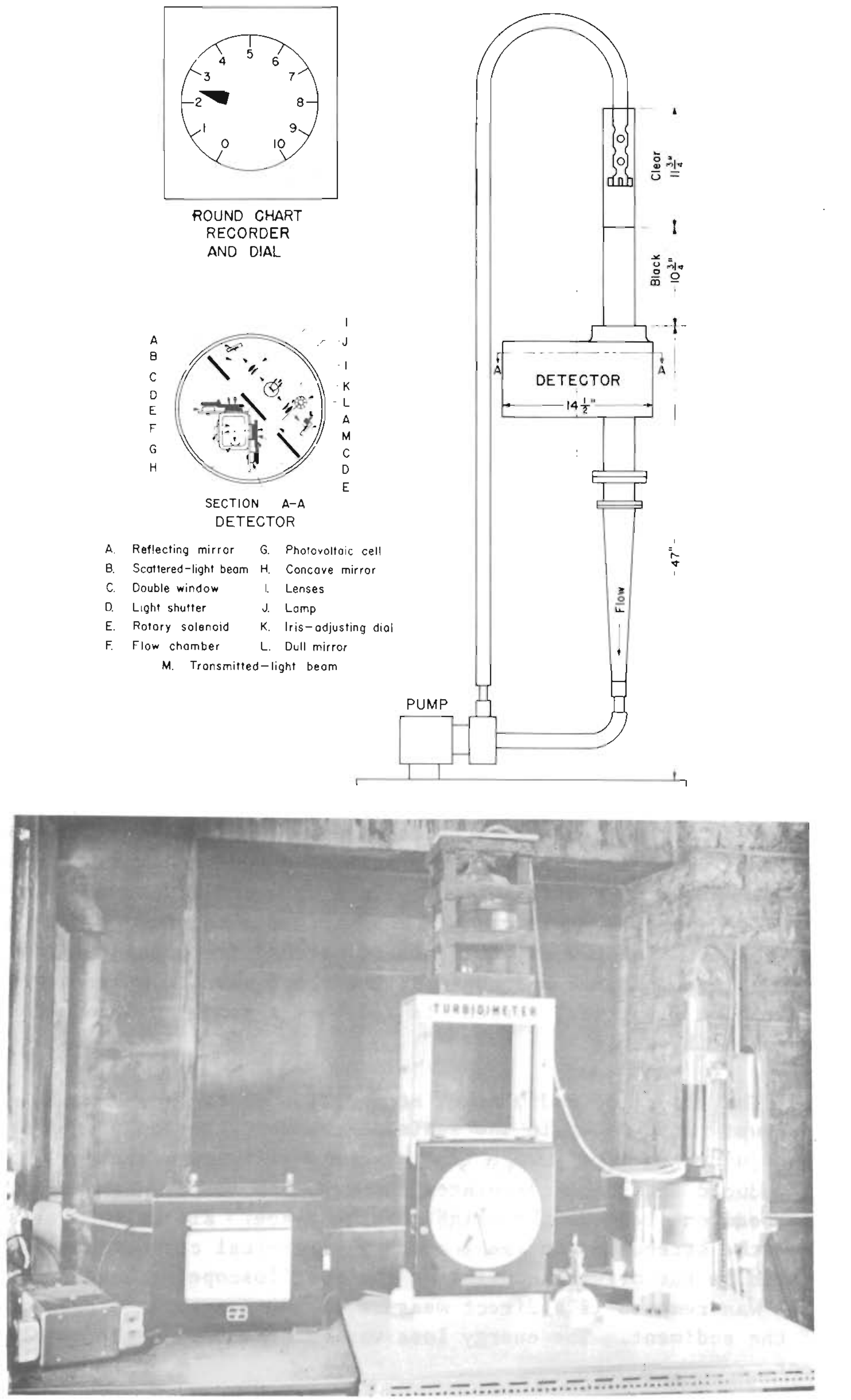


FIG. 68--TURBIDIMETER FOR SEDIMENT ANALYSIS

concentration, the size spectrum is determined by the settling procedure before the concentration is determined. The relation of turbidity to settling time as shown by the settling procedure is plotted. Then particle sizes corresponding to various observed settling times and temperatures are computed by Stokes' law. These computed values are plotted on the settling time scale of the turbidity-settling time graph which was developed from the test data. Turbidity values for each computed particle size can then be read directly from this graph.

The turbidimeter can measure particles which range in size from about 0.020 to 0.120 mm. Finer particles settle so slowly that the tests take an excessively long time, and coarser particles settle so rapidly that an unreasonably tall sedimentation chamber is required. The principle of the turbidimeter seems adaptable to a field instrument for determining concentration and particle-size distribution of suspended-sediment samples pumped from a stream. However, there are several instrumentation difficulties to overcome before a field instrument will be available.

Ultrasonic equipment--Ultrasonic equipment is being studied as a means to determine concentration and particle size distribution of suspended sediment from about 0.040 to 1.0 mm in size [25]. As a plane sound wave passes through a fluid containing solid particles in suspension its attenuation varies with the concentration of the particles.

The ultrasonic analyzer (Fig. 69) consists of a sediment chamber, circulating pump, crystal transducers, transmitter, pulse generator, attenuator, receiver and oscilloscope.

A high-frequency electrical current is imposed on a quartz crystal for about six microseconds at a repetitive rate of 200 times a second. The quartz crystal, which is mounted in the wall of a sediment chamber, converts the electrical pulses into displacement pulses or sound waves. The wave passes through the fluid in the sample chamber and strikes a second crystal in the wall on the other side. The two crystals are of matched frequencies. The second crystal acts as a transducer and converts the sound wave to a secondary electrical current. The electrical current is fed back through an attenuator and is indicated on an oscilloscope.

The effect of sediment on attenuation of the sound wave is determined as follows: with water in the sediment chamber, the top of the oscilloscope trace is adjusted to a reference line on the oscilloscope screen. Then sediment is introduced into, and circulated through, the sample chamber. The presence of the sediment reduces the height of the trace. Electrical resistance is removed from the attenuator in the secondary electrical circuit until the trace is restored to the original height on the oscilloscope. The electrical resistance that was removed is a direct measure of the energy loss caused by the addition of the sediment. The energy loss varies directly as the concentration of sediment.

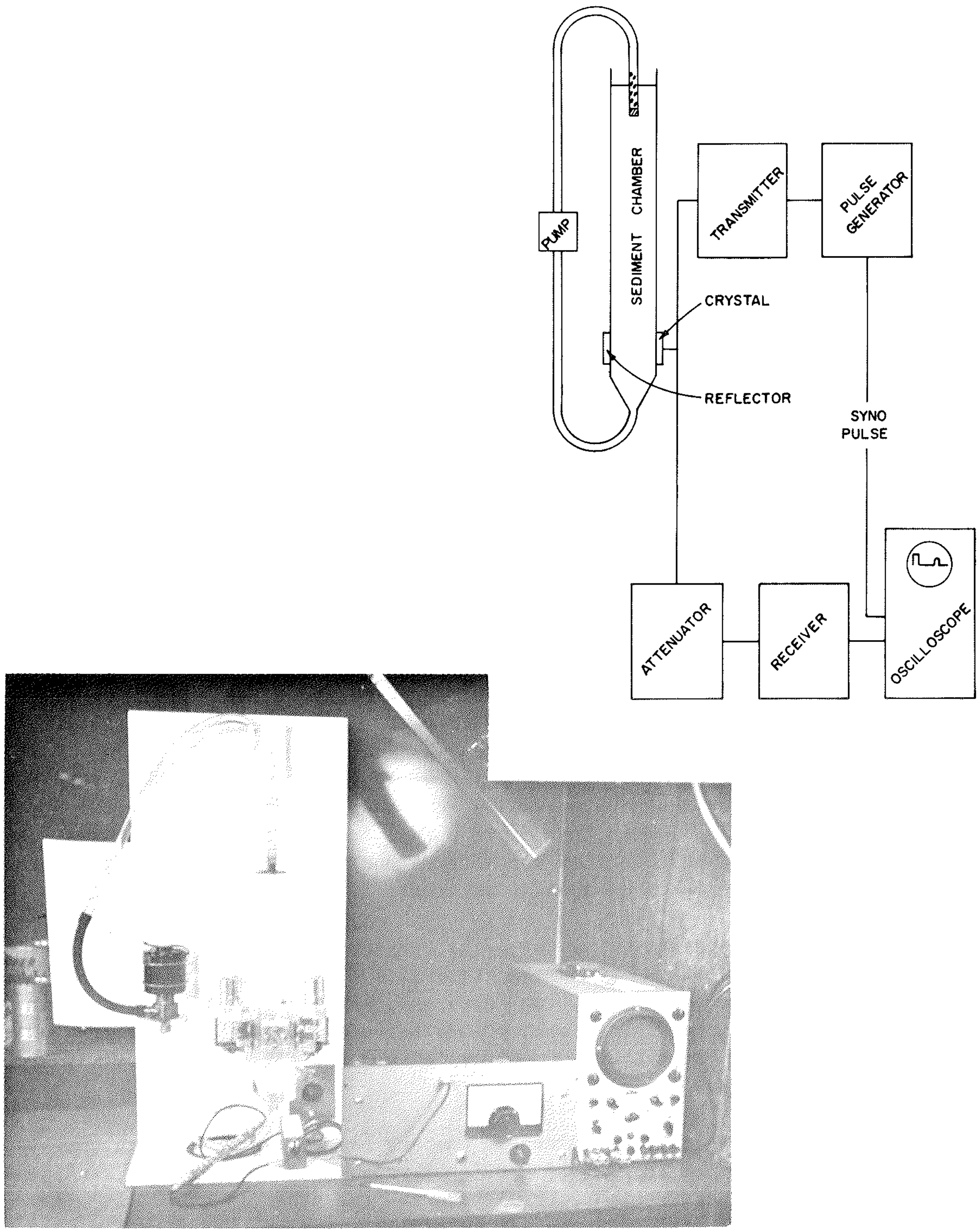


FIG. 69--ULTRASONIC EQUIPMENT FOR SEDIMENT ANALYSIS

Unfortunately, attenuation of ultrasonic energy depends as much on particle size as on concentration. Although the ultrasonic equipment can be calibrated to determine quickly and accurately the concentration of sediment of a known single size, or a single size distribution, the determination of the concentration of sediment of an unknown size distribution is difficult. For sediments that have a size distribution that can be expressed by two parameters such as the geometric mean diameter and the standard deviation, it is possible to determine the size distribution in an unknown sample. Calibration and analysis must cover a range of about 10 frequencies. After the size distribution is determined, the concentration can be found.

The ultrasonic equipment operates reasonably well in the laboratory, although further development will be needed before it will be competitive with more common laboratory methods of analysis. The potential for field use has not been evaluated.

Nuclear possibilities--The Atomic Energy Commission is cooperating with the Inter-Agency Sedimentation Project on a study of the possibilities of using radioisotopes for determining the concentration of suspended sediment. Under the first of a series of contracts with the Atomic Energy Commission, Parametrics, Inc., completed the initial phase of the investigation and prepared a favorable feasibility report in 1962. Under a second contract a pilot instrument for sensing the concentration of suspended sediment was produced. Preliminary tests of the pilot model were made in 1963 by employees of Parametrics, Inc., and of the Sedimentation Laboratory of the Agricultural Research Service, at Oxford, Miss. The tests were made in a flume at the Sedimentation Laboratory. Under a third, and presumably terminal, contract the pilot instrument is to be developed further and remodeled for use in field streams.

Commercial work on automatic sensing devices for suspended sediment--Several commercial organizations have worked on equipment for direct use in the sedimentation field or on equipment that could be adapted to sedimentation uses. At the present time (1963) personnel of the Inter-Agency Project are keeping informed on two specific developments of special interest.

The research department of one large company has developed an instrument for continuously recording the following properties of water in streams or lakes: Conductivity, dissolved oxygen, turbidity, pH, water temperature, air temperature, and sunlight intensity. The Branch of Quality of Water, U. S. Geological Survey, began testing this water-quality monitoring system in 1963, but conclusive results are not yet available.

The research facility of a second company has proposed the development of a multiple sensor device that would use light rays and two sources of x-ray energies, one in the "hard" (high energy) band and the other in the "soft" (low energy). The attenuation and scattering of light and of radiation for each band would be measured and recorded. Also, other properties of the flow such as conductivity and temperature could be recorded. Perhaps the use of different wave lengths, and of ratios of transmitted and scattered energy will permit evaluation of the particle size or the effect of the particle size in such a way that concentration can be obtained without a separate means of determining the particle size.

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VII APPENDIX

49. Unsampled zone--Usually, suspended-sediment discharge is obtained by multiplying the discharge-weighted concentration from depth-integrated samples in the sampled zone by the stream discharge. For silts and clays, the concentration in the sampled zone is considered equal to the concentration in the stream vertical.

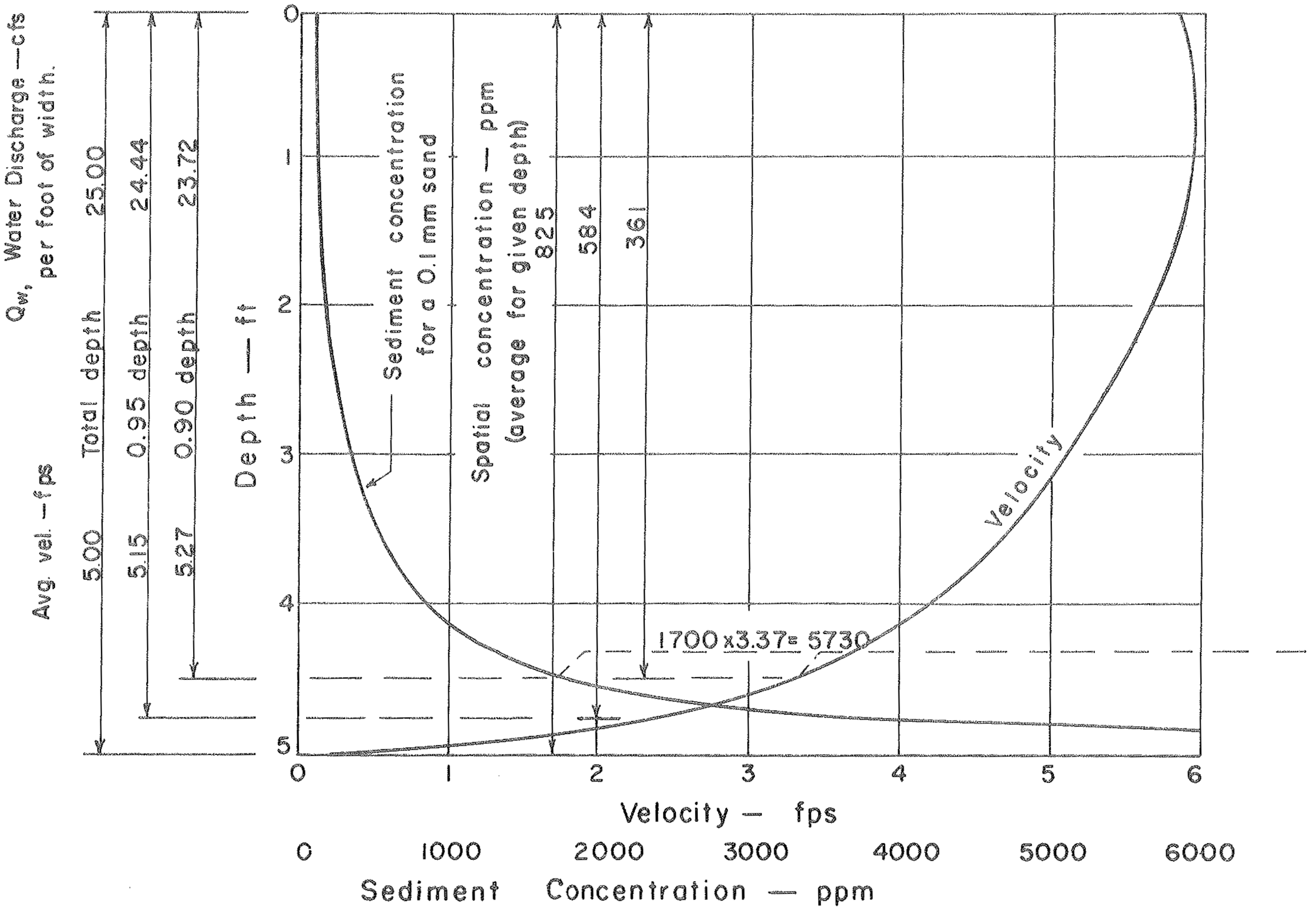
For sediments of sand sizes, the concentration in the unsampled zone will normally be greater than in the sampled zone. The apparent error in the normal method of computation depends on the unused discharge-weighted concentration in the unsampled zone and the stream discharge through the unsampled zone. In the depth-integration method the vertical transit of the sampler is reversed upon contact with the streambed, or if a point-integrating sampler is used, the sampling action may be started or stopped at the bottom of the sampling run. The result of the practical operation of the sampler is the collection of too large a proportion of the water-sediment mixture from a zone of higher than average concentration near the streambed where the sampler stops momentarily during reversal or at the beginning or end of vertical transit. This error partially compensates for the error introduced in not sampling the total depth.

When there is a high concentration of suspended-sediment of sand sizes near the streambed, determination of total sediment discharge requires computation of bed-load, or coarse-sediment, discharge. These computations frequently include the discharge of sands through the unsampled zone, or indicate the relative discharge through the unsampled zone. The computation of coarse-sediment discharge can be corrected for any unmeasured sediment discharge or any sediment discharge that is both measured and included in the computations.

Throughout the report it is assumed that the suspended-sediment discharge can be determined adequately from either depth-integrated or point-integrated samples, and no distinction is made between computed suspended-sediment discharge and total suspended-sediment discharge. A curve of the distribution of concentration of various sediment size ranges, based on point-integrated samples, can be determined for the sampled zone and extended into the unsampled zone if additional definition of concentration is necessary.

Fig. 70 shows some of the basic relationships of velocity, concentration, and sediment discharge for sands carried in suspension in a stream vertical.

The velocity curve can be obtained by stream-gaging methods. Usually it is approximated from observations of velocity at the 0.2 and 0.8 depths in the vertical. Although the two observations do not accurately define the curve for each vertical (especially over a dune bed) reliable averages can be obtained if care and judgment are used.



Computations of sediment discharge, Q_s, per foot of width

	Conc.*		Q_w		Q_s
For the total depth of 5 ft	463	x	25.00	=	11,580
Actually integrated to 0.90 depth	298	x	23.72	=	7,070
Actually integrated to 0.95 depth	358	x	24.44	=	8,750
As usually computed (integrated to 0.90 depth) .	298	x	25.00	=	7,450
As usually computed (integrated to 0.95 depth) .	358	x	25.00	=	8,950

If the sampler is lowered to the bottom of the sampled zone (0.90 depth) and allowed to stay there for the time that would be required for integrating the unsampled depth, the sampled sediment discharge would be 7,070 + 5,730/2 = 9,930

or 7,070 + 380 + 2,480 = 9,930

FIG. 70 --VELOCITY AND SUSPENDED SEDIMENT RELATIONSHIPS IN A STREAM VERTICAL-- ILLUSTRATING EFFECTS OF THE UNSAMPLED ZONE FOR SANDS

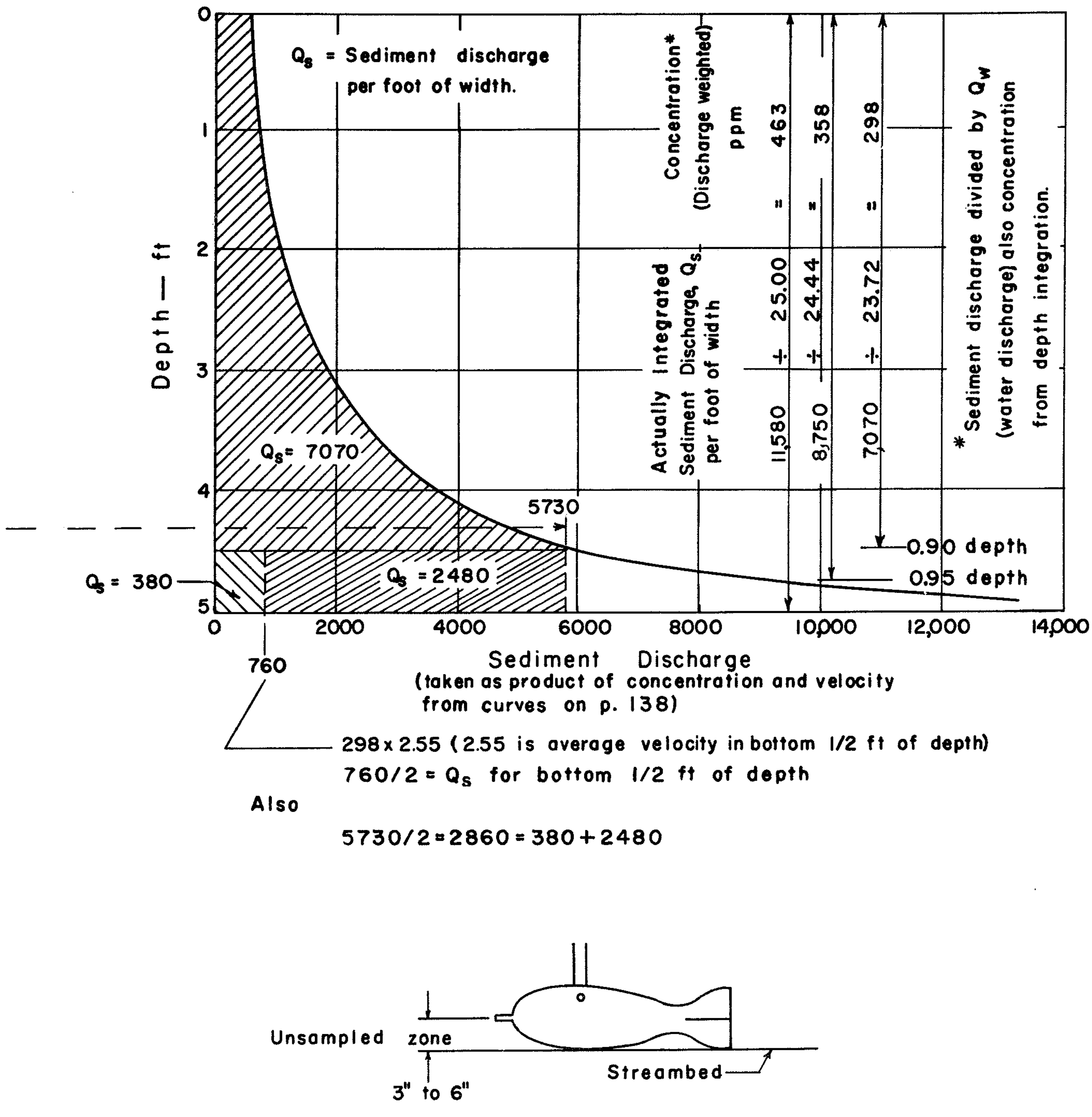


FIG. 70 (CONTINUED)--VELOCITY AND SUSPENDED SEDIMENT RELATIONSHIPS IN A STREAM VERTICAL--ILLUSTRATING EFFECTS OF THE UNSAMPLED ZONE FOR SANDS

Distribution of concentration in the vertical may be obtained by point-integration sampling. Samples at a few points in the vertical will approximately define the distribution in the vertical if some information on particle size is available. Note that the current meter does not measure velocity near the streambed but the need for recognition of an unsampled zone for velocity is not critical. The same general concept applies to point-integration sampling because the distribution of sediment is partly defined in the vertical.

Basically, sediment discharge at any point is the product of velocity and concentration. (For purposes of illustration corrections for the units of measurement and for the minor effects of changes in water-sediment density are ignored).

A careful study of Fig. 70 reveals many things in regard to sediment transportation and accuracy of sampling methods, but only a few of the major ones will be mentioned:

a. The unsampled zone is primarily a problem of depth-integration sampling of sediments of sand sizes.

b. The errors due to the unsampled zone increase as the ratio of depth of unsampled zone to total depth increases, and as the distribution of sediment in the vertical varies more from surface to streambed.

c. One modification of usual depth-integration procedure that provides a more representative sample is to allow the sampler to remain on the streambed and continue sampling during the time that would be required to integrate through the unsampled zone. The modification should not be used if the sample is to be corrected by some formula that requires the concentration in the sampled zone only.

50. Transit rates for depth integration--Accurate depth-integrated samples partly depend on a reasonably uniform transit rate of the sampler. An experienced operator who uses the depth-integration method frequently, will seldom have any trouble in maintaining an adequately uniform transit rate throughout a single sampling trip. A satisfactory volume of sample is more difficult to obtain than a reasonably constant transit rate.

The following techniques often aid in attaining satisfactory transit rates:

a. If the stream velocity is known from previous measurements or can be estimated from an observation of surface velocity, the sampling time can be obtained from a previously prepared velocity-sampling time chart. Also, if the sampling time is known for the sampler nozzle size and one velocity, it can be computed for other velocities because sampling time varies inversely as the velocity.

b. Determine the depth to be sampled, and for round-trip integration divide twice the sampling depth by the sampling time to obtain the required rate for lowering or raising the sampler.

c. The sampler should then be lowered or raised the necessary number of feet and tenths of feet per second. An operator working alone can count slowly to approximate a one-second interval. If two operators are available one can use a stop watch as a time control.

d. In round-trip integration the time required for lowering the sampler may be noted and if it is more or less than half the total time desired, the raising rate can be increased or decreased to improve the total time.

e. One should observe sample volumes and sampling rates carefully, so that the transit rate can be adjusted from one sample to the next.

f. In the ETR method, the transit rate should be the same in all verticals. Establish a transit rate and then determine the time (which depends on the depth) for sampling in each vertical. By watching the sampling time it is possible to maintain a nearly constant transit rate in the vertical. Because the sediment concentration often varies more in the vertical than in the horizontal direction, a uniform transit rate in the vertical is more important than a constant rate from one vertical to another.

g. Sampler transit rates should be kept within certain specified limits. (See Section 16 and Fig. 14.)

h. Depth-integrating suspended-sediment samplers do not sample down to the streambed. Suppose that the intake nozzle of a sampler is 0.3 ft above the bottom of the sampler. The sampler will not sample the lowest 0.3 ft of the vertical if the streambed is firm and level. If the bed is soft and dunes are present, the sampler may sink into the bed or may be lowered on top of, or downstream from, a dune. Presumably one should consider the sampling depth as 0.3 ft less than the total depth and reverse the sampler travel without hesitation when the sampler touches bottom. Because the reversal will almost never be instantaneous, too large a sample will be taken at the reversal point. Another method is to consider the whole depth as the sampling unit and allow the reversal of sampler travel to take up the same length of time that would normally be spent in integrating 0.6 ft of depth. Sampling procedure should be adapted to sediment discharge computation procedure at this point. Also a record should be kept of the sampling procedure that was actually used.

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FEDERAL INTER-AGENCY PROJECT REPORTS

Besides the present report, the general project, "A Study of Methods Used in Measurement and Analysis of Sediment Loads in Streams," has published the reports listed on the following pages.

Communications regarding purchase of reports may be addressed to:

Federal Inter-Agency Sedimentation Project
St. Anthony Falls Hydraulic Laboratory
Hennepin Island and Third Avenue, S. E.
Minneapolis, Minnesota
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or

District Engineer
U. S. Army Engineer District, St. Paul
Corps of Engineers
1217 U. S. Post Office and Custom House
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55101

ANNOTATIONS OF NUMBERED REPORTS

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 time of the earliest known investigations to 1940, with discussions of the advantages and disadvantages of the various methods and instruments used. The requirements of a sampler that would satisfy all field conditions are set forth. August 1940.

Report No. 2--"Equipment Used for Sampling Bed Load and Bed Material" is a review of the equipment and methods used in bed-load discharge and bed-material sampling in a manner similar to that in which Report No. 1 covers the sampling of suspended sediment. September 1940.

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. This analytical study is based on the application of turbulence theories to sediment transportation. November 1941.

Report No. 4--"Methods of Analyzing Sediment Samples" describes many methods for determining the size of small particles and for establishing the particle-size gradation and the total concentration of sediment in samples. Detailed instructions are given for many of the common methods that have been developed and used by agencies doing extensive work in sedimentation. November 1941.

Report No. 5--"Laboratory Investigations of Suspended-Sediment Samplers" reports the effects of intake conditions on the representativeness of sediment samples and on the filling characteristics of slow-filling samplers. December 1941.

Report No. 6--"The Design of Improved Types of Suspended-Sediment Samplers" describes the development of various integrating samplers suitable for taking vertically depth-integrated samples in flowing streams and others suitable for taking time-integrated samples at a fixed point. Details of the recommended types are given. May 1952.

Report No. 7--"A Study of New Methods for Size Analysis of Suspended-Sediment Samples" reports on research to develop methods of size analysis suitable for most suspended-sediment investigations and describes a new apparatus and technique, the bottom-withdrawal-tube method. June 1943.

Report No. 8--"Measurement of the Sediment Discharge of Streams" describes methods and equipment for use in making sediment measurements under the diverse conditions that are encountered in streams. March 1948. Report No. 8 is out of print. It is superceded by the report in hand, No. 14, "Determination of Fluvial Sediment Discharge".

Report No. 9--"Density of Sediments Deposited in Reservoirs" presents data on the apparent density of sediment deposited in various reservoirs. The results are summarized, and certain conclusions useful in engineering studies are given. November 1943.

Report No. 10--"Accuracy of Sediment Size Analyses Made by the Bottom-Withdrawal-Tube Method" recounts extensive tests made to evaluate the accuracy of the bottom-withdrawal-tube method. Glass spheres of sand sizes were used as the sediments. April 1953.

Report No. 11--"The Development and Calibration of the Visual-Accumulation-Tube" describes the design of equipment and methodology useful for a simple and accurate analysis of size gradation of sediments of sand sizes. 1957.

Report No. 12--"Some Fundamentals of Particle-Size Analysis" presents some of the basic concepts, definitions, and data on relationships in the field of particle size analysis. The relation of fall velocity to physical size is examined in detail. December 1957.

Report No. 13--"Single-Stage Sampler for Suspended Sediment" describes four types of samplers and discusses methods for obtaining samples automatically when the water surface first rises to a selected stage. 1961.

LETTERED REPORTS

Report AA -- Federal Inter-Agency Sedimentation Instruments and Reports, May 1959.

Report A ** -- Preliminary Field Tests of the U. S. Sediment-Sampling Equipment in the Colorado River Basin, April 1944.

Report B ** -- Field Conferences on Suspended-Sediment Sampling, September 1944.

Report C ** -- Comparative Field Tests on Suspended-Sediment Samplers, Progress Report, December 1944.

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Report E ** -- Measurement and Analysis of Sediment Loads in Streams, July 1946. (Amr. Soc. Civ. Engin., Trans. Vol. 116, p. 891, 1951).

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Report F ** -- Field Tests on Suspended-Sediment Samplers, Colorado River at Bright Angel Creek near Grand Canyon, Arizona, August 1951.

Report G ** -- Preliminary Report on U. S. DH-48 (Hand) Suspended-Sediment Sampler (Superseded by material in Report No. 6)

Report H ** -- Investigation of Intake Characteristics of Depth-Ingegrating Suspended-Sediment Samplers at the David Taylor Model Basin, November 1954.

Report I -- Operation and Maintenance of U. S. P-46 Suspended-Sediment Sampler, Revision, May 1962.

Report J -- Operating Instructions, Suspended-Sediment Hand Sampler, U.S. DH-48, Revision, October 1962.

Report K -- Operator's Manual, The Visual-Accumulation-Tube Method for Sedimentation Analysis of Sands, Revision, October 1958.

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Report M -- Operation and Maintenance of U. S. BM-54 Bed-Material Sampler, November 1958.

Report N -- Intermittent Pumping-Type Sampler, Progress Report, February 1960.

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Report P -- Investigation of Differential-Pressure Gages for Measuring Suspended-Sediment Concentrations, June 1961.

Report Q -- Investigation of a Pumping Sampler with Alternate Suspended-Sediment Handling Systems, Progress Report, June 1962.

Report S -- A Summary of the Work of the Federal Inter-Agency Sedimentation Project, January 1963.

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