92-1403

**United States
Department of
Agriculture**

Forest Service

**Watershed and
Air Management
Staff**

Methods for Collection and Analysis of Fluvial-Sediment Data

METHODS FOR COLLECTION AND ANALYSIS OF FLUVIAL-SEDIMENT DATA

by

Owen R. Williams
Robert B. Thomas
and
Richard L. Daddow

USDA FOREST SERVICE
WSDG-TP-00012
1988

Preface

The authors would like to thank those who helped type and edit this report, including Pamela Daddow, Rhey Solomon, Steve Glasser, Eve Lewis, and Raeonda Pfeifer. In addition, the use of names of commercial products mentioned in this report does not constitute an endorsement, whether directly or indirectly, of that product by the authors or the United States Government or its agents.

TABLE OF CONTENTS

1.0 Introduction . . . 1
    1.1 Management Needs for Fluvial-Sediment Data . . . 2
    1.2 Designing a Fluvial-Sediment Data Collection Plan . . . 3

2.0 Fluvial-Sediment Processes . . . 6
    2.1 Types of Fluvial Sediment . . . 6
    2.2 Suspended-Sediment Transport . . . 8
    2.3 Bedload Sediment Transport . . . 11

3.0 Fluvial-Sediment Sampling Equipment . . . 13
    3.1 Suspended-Sediment Samplers . . . 13
    3.2 Bedload Samplers . . . 17
    3.3 Bed-Material Samplers . . . 19

4.0 Fluvial-Sediment Sample Collection . . . 20
    4.1 Suspended-Sediment Sample Collection . . . 20
    4.2 Bedload Sample Collection . . . 22
    4.3 Bed-Material Sample Collection . . . 26

5.0 Handling Fluvial-Sediment Samples . . . 27

6.0 Field and Laboratory Methods for Fluvial-Sediment Analysis . . . 28

7.0 Turbidity . . . 30

8.0 Statistical Sampling and Analysis of Fluvial-Sediment Data . . . 32
    8.1 Introduction . . . 32
    8.2 Characteristics and Measurement Problems of Suspended-Sediment Data . . . 33
    8.3 Objectives of a Suspended-Sediment Sampling Program . . . 38
    8.4 Sampling Techniques . . . 40
    8.5 Summary of Suspended-Sediment Sampling . . . 55

9.0 Fluvial-Sediment Data Interpretation for Management Decisions . . . 56

10.0 Summary . . . 56

References . . . 58

Appendix A – Fluvial-Sediment Terminology . . . 65

Appendix B – Line Drawings and Photographs of Fluvial-Sediment Samplers . . . 69

LIST OF FIGURES

Figure 1. Diagrammatic Relationship of a Stable Channel Balance . . . 5
Figure 2. Diagram of the Flow Velocity and Sediment (Sand) Concentration Profiles in a Stream . . 9
Figure 3. Vertical Distribution of Suspended Sediment in the Missouri River at Kansas City, MO . . 9
Figure 4. An Example of a Suspended-Sediment Transport Hysteresis Loop During a Flood Event 10
Figure 5. Neyman Stratified Random Sampling Allocation Formulas . . . 45
Figure 6. Percentage of Suspended Sediment and Discharge Volumes Occurring at Greater than Indicated Flows . . . 46
Figure 7. Selection At List Time (SALT) Formulas . . . 50
Figure 8. Suspended-Sediment Transport Hydrograph and Corresponding Sampling Interval Axis for SALT Sampling . . . 54
Figure 9. US DH-48 Depth-Integrating Suspended-Sediment Wading-Type Sampler . . . 70
Figure 10. Photograph of the US DH-48 Sampler . . . 71
Figure 11. US DH-59 Depth-Integrating Suspended-Sediment Hand-Held Sampler . . . 72
Figure 12. Photograph of the US DH-59 Sampler . . . 73
Figure 13. US DH-75 Depth-Integrating Suspended-Sediment Wading-Type Sampler . . . 74
Figure 14. Photograph of the US DH-75 Sampler . . . 75
Figure 15. US D-74 Depth-Integrating Suspended-Sediment Cable-and-Reel Sampler . . . 76
Figure 16. Photograph of the US D-74 Sampler . . . 77
Figure 17. US P-61AL Point-Integrating Suspended-Sediment Cable-and-Reel Sampler . . . 78
Figure 18. Photograph of the US P-61AL Sampler . . . 79
Figure 19. Photograph of the New "Standard" Helley-Smith Bedload Sampler . . . 80
Figure 20. Original Helley-Smith Bedload Sampler . . . 81
Figure 21. US BMH-53 Piston-Type Bed-Material Hand-Held Sampler . . . 82
Figure 22. Photograph of the US BMH-53 Sampler . . . 83
Figure 23. US BMH-60 Bed-Material Hand-Held Sampler . . . 84
Figure 24. Photograph of the US BMH-60 Sampler . . . 85

LIST OF TABLES

Table 1. Grade Scale of Fluvial-Sediment Particle Sizes 8

Table 2. Physical Characteristics of US-Series Depth-Integrating and Point-Integrating Suspended-Sediment Samplers 16

Table 3. Sample Size Data and Calculations 47

Table 4. Calculations for Five Classes Formed by Grouping Classes in Table 3 to Reallocate 100 Samples 47

1.0 INTRODUCTION

Fluvial-sediment data is an important source of information to assess water quality conditions and changes in the environment. This type of information is important to individuals and agencies involved in the management of water and land resources. Fluvial-sediment data has been collected by Forest Service hydrologists for many years at many locations. However, collection and analysis of fluvial-sediment data is a complex task and the data have not always been collected by the proper techniques, collected with an appropriate purpose, or analyzed by the proper methods.

The purpose of this report is to present in one document the 1988 state-of-the-art fluvial-sediment data collection and analysis methods used commonly in wildland management. This report is addressed from the perspective of the Forest Service hydrologist and the information needs of the organization.

Planning, equipment, methods, and statistical sampling related to the collection and analysis of fluvial-sediment data is covered in this report. The basic hydrogeomorphologic processes associated with sediment are also presented. Because of its diverse origins, terminology used to describe fluvial-sediment has been subject to misunderstanding. To help avoid this misunderstanding, fluvial-sediment terminology has been included in Appendix A. This list of sediment related terms was obtained from various reference sources: Interagency Committee on Water Resources (1963), Leopold and others (1964), Guy (1970), Office of Water Data Coordination [OWDC] (1978), American Society for Testing and Materials [ASTM] (1983), and Edwards and Glysson (1988).

This report does not attempt to cover all the technical aspects related to fluvial-sediment data collection and analysis. There are two major publications available which address these topics in more detail. These publications are described next and should be considered as companion references or supplements to this report.

Recently the U.S. Geological Survey prepared Open File Report 86-531, *Field Methods for Measurement of Fluvial-Sediment* (Edwards and Glysson, 1988). This new open file report was written as a revision of the U.S. Geological Survey publication *Field Methods for Measurement of Fluvial Sediment*, Techniques of Water Resources Investigations (TWRI), Book 3, Chapter C2 (Guy and Norman, 1970) and is the most up-to-date, comprehensive guide and review for sediment sampling equipment and methods. It is available from the U.S. Geological Survey, Books and Open File Reports, Denver Federal Center, Box 25425, Denver, CO 80225, (303) 236-7476 or (FTS) 776-7476. For more information on this report, contact Thomas K. Edwards, U.S. Geological Survey, Water Resources Division. 847 NE 19th Avenue, Suite 300, Portland, OR 97232, (503) 231-2017 or (FTS) 429-2017.

The other publication, *National Handbook of Recommended Methods for Water Data Acquisition, Chapter 3, Sediment* (OWDC, 1978) was written by individuals from various Federal agencies and summarizes much of the research in sediment transport and data collection techniques prior to 1978. This publication is available free of charge from the Office of Water Data Coordination, U.S. Geological Survey, MS-417. National Center, Reston, VA 22092, (703) 648-5016 or (FTS) 959-5016.

1.1 MANAGEMENT NEEDS FOR FLUVIAL-SEDIMENT DATA

The purpose of collecting and analyzing sediment data is to provide information related to an identified management need. Management needs for sediment data usually fall into one of the following two general categories:

A. Compliance with Regulations and Standards

The Forest Service as a land management agency must abide by all federal, state, and local laws which relate to water quality and environmental impacts. Many land management activities on National Forests influence water quality. This is particularly true for nonpoint source pollution, of which sediment is usually the greatest contributor.

The Federal Water Pollution Control Act, amended many times since 1956, is the principal legislation affecting Forest Service activity in regard to water quality. While this Act does not specify standards for sediment, it does charge the states with the development of standards for nonpoint source pollution and sedimentation.

Under Sections 208 and 319 of this Act, some states have developed standards for nonpoint source pollution. Other states have chosen to rely upon prudent application of best management practices. In either case, the manager of National Forest lands must be assured that standards, or legislative intent, are being met. Many sediment collection efforts are initiated to provide this assurance.

In addition to water quality legislation, the Forest Service complies with the National Environmental Policy Act of 1969 when proposing activities which could affect the environment. To comply with this Act, the land manager examines the onsite, offsite, and cumulative impact of management activities upon other resources and human activities. Fluvial-sediment data is one of the hydrologic related factors which is often collected to measure or predict the potential impacts on watershed and other resource values.

B. Monitor and Evaluate Responses to Land Management Activities

The collection of fluvial-sediment data has been used to estimate and monitor changes in fluvial systems due to land management activities or treatment. The objective is to guide land management practices so as to avoid, minimize, or mitigate the impacts to the fluvial system and its associated resource values.

Fluvial-sediment data is also collected to evaluate and monitor the response of the watershed as a whole to land management activities. This data helps assess the overall watershed condition. The information generated is then used to suggest modifications to improve existing management practices.

1.2 DESIGNING A FLUVIAL-SEDIMENT DATA COLLECTION PLAN

Planning is an essential element of any successful data collection program. Adequate resources should be provided for its completion just as they are for the actual data collection. The plan must explicitly identify the study objectives and the management needs to ensure that the data collection and the analysis techniques will provide the needed information. The analysis technique will also determine the methods and equipment to be used as well as the location and timing of sampling. A well designed plan is essential to provide the information needed by management in a timely and efficient manner. Many poorly designed studies collect the wrong kind of fluvial-sediment data or too much sediment data for the analysis technique necessary to meet the management objective. Logistics, funding, manpower, time, and practicality must all be considered in a well designed plan. Adequate time should be allowed for data analysis in order to interpret the data and provide the information needed by management. Additional guidelines for designing a sediment data collection program are available in *Water Quality Monitoring Programs* (Ponce, 1980a).

Perhaps the most frequent failing of sediment studies is caused by lack of an explicit statement of study objectives. While general goals are usually considered, these are often not made explicit in a way that can be tested with a statistical analysis procedure. As an example, suppose a manager wants to know if a particular logging operation increases the instream sediment production of a river draining the area. This is acceptable as a general goal, but is inadequate as an objective for a field study. Questions like the following must be answered before an acceptable sampling plan can be formed: Will the suspended load be an adequate indicator of sediment production? At what point along the stream will data be collected? What criteria will be used to show change: above and below, sediment rating curve, total for storm or year? Will the comparison be made on a single basin (before and after) or using a control? Until these kinds of questions are answered for a given study, an acceptable sampling plan cannot be defined.

The objectives of the study should dictate which type of fluvial sediment (suspended and/or bedload, or bed material) should be measured and analyzed. For example, if the objective is to assure that management activities are not affecting beneficial uses, for instance municipal water supplies, then suspended sediment might be of greatest concern. If, on the other hand, reduction of flood areaway beneath a bridge is the concern then bedload and bed material would be of interest. A problem with spawning gravel siltation or accelerated filling in of a check dam or stock pond might necessitate measuring both suspended and bedload sediment. If the objective is to assess and monitor treatment responses to specific management activities, there are several sediment data analysis methods which can be used to detect changes. Again, the appropriate one (or ones) will depend on the particular study objectives.

Site selection, the timing of measurements, the selection of equipment, and the choice of collection method are all important decisions and each can be affected by study objectives as well as physical setting. For example, measurement of sediment for compliance purposes will require an approach much different from that used for purposes to evaluate changes due to management activities. More detailed information regarding the objectives of a sediment sampling program is described in Section 8.3 of this report.

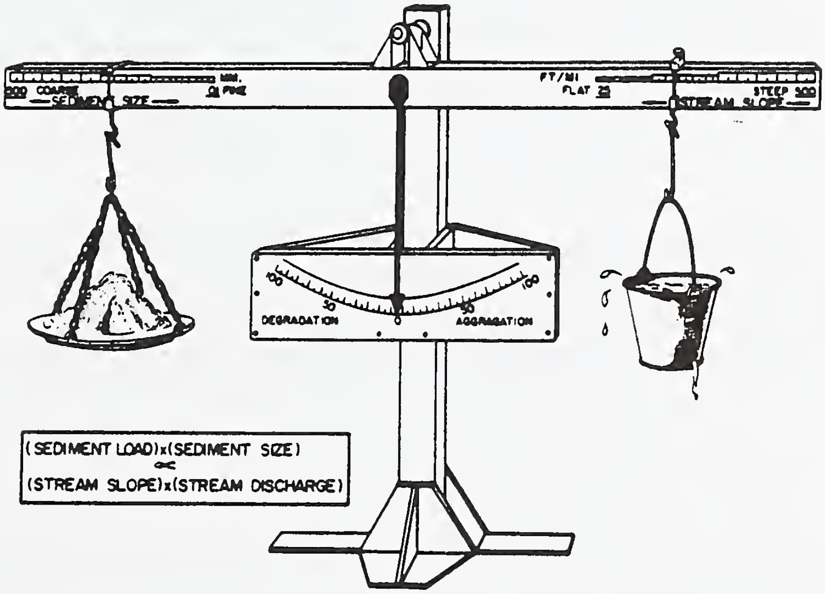


Figure 1. Diagrammatic Relationship of a Stable Channel Balance (Simons, 1971, after Borland, 1963, after Lane, 1955).

2.0 FLUVIAL-SEDIMENT PROCESSES

A basic understanding of fluvial processes is necessary for hydrologists to effectively collect, analyze, and interpret sediment data. A review of these processes is presented here.

The stable channel *balance* (Simons, 1971) as shown in Figure 1 is probably the best graphical expression of river mechanics available. It illustrates the complex interdependencies operating in stream and river systems. It also shows that a fluvial system strives for a balance between energy (stream power) and supply (available sediment) and that a change in one will affect the other. A manager who understands the principles depicted in this figure will better understand the role of sediment data in answering specific management needs. For example, the manager will understand that aggradation of the channel can be a consequence of the introduction of sediment to the system through road construction. A decrease in channel slope and/or sediment size may result as equilibrium or *balance* is reestablished. An increase in peak flows due to a catastrophic wildfire or intensively roaded watershed may result in stream degradation with a resulting increase in slope and/or sediment size. The *balance* concept helps to explain changes in sediment size, bed forms, stream channel patterns, shapes, and longitudinal profiles.

At least 30 variables are involved in the sediment transport processes (Heede, 1980). Lane's (1957) eight most important variables are: 1) discharge, 2) channel slope, 3) sediment load, 4) bank and bed resistance, 5) vegetation, 6) temperature, 7) geology, and 8) works of humans. Leopold and others (1964) state there are *...eight interrelated variables involved in the downstream changes in river slope and channel form: width, depth, velocity, slope, sediment load, size of sediment debris, hydraulic roughness, and discharge.*

Understanding the relationships between these important variables is necessary to advise management in decision making. It is also necessary in designing effective sediment data collection and analysis plans.

2.1 TYPES OF FLUVIAL SEDIMENT

Fluvial sediment can be categorized by the method of transport or by the source. Two broad categories are used for method of transport: suspended sediment transport and bedload transport.

According to Emmett (1981, p. 4): *In the sediment transport process, individual bed material particles are lifted from the stream bed and set into motion. If the motion includes frequent contact of a particle with the stream bed, the particle constitutes part of the bedload. If the motion includes no contact with the stream bed, the particle is literally a part of the suspended load, regardless of how close to the stream bed the motion occurs. Depending on the hydraulics of flow in various reaches of a channel, particles may alternate between being a part of the bedload or a part of the suspended load. At a given* *cross section of channel, particles that are a part of the bedload at one stage may be part of the suspended load at another stage. Any particle in motion may come to rest; for bedload, downstream progress is likely to be a succession of movements and rest periods. Particles at rest are part of the bed material. Obviously, there is an intimate relation between bed material, bedload, and suspended load.*

Fluvial sediment is also classified in terms of its source. Einstein (1964, p. 17-36) stated that: *Every sediment particle which passes a particular cross section of the stream must satisfy the following two conditions: (1) It must have been eroded somewhere in the watershed above the cross section and (2) it must be transported by the flow from the place of erosion to the cross section. Each of these two conditions may limit the sediment rate at the cross section, depending on the relative magnitude of two controls: the availability of the material in the watershed and the transporting ability of the stream. In most streams the finer part of the load, i.e., the part which the flow can easily carry in large quantities, is limited by its availability in the watershed. This part of the load is designated as* **wash load**. *The coarser part of the load, i.e., the part which is more difficult to move by flowing water, is limited in its rate by the transporting ability of the flow between the source and the section. This part of the load is designated as* **bed material load**.

As described above, there are two sources of sediment transported by a stream: 1) the bed material which makes up the stream bed, and 2) the fine material (wash load) which comes primarily from stream banks and eroded material delivered to the stream. Separating fluvial sediments into these two classes is important because bed material transport is dependent on stream power and is functionally related to measured hydraulic variables. In comparison, movement of wash load depends on availability/supply and is not functionally linked to measurable hydraulic variables.

In terms of particle size class, there is no sharp demarcation between wash load and bed material load. However, it is generally assumed that bed material load is made up of sediment equal to or greater than the 0.062 millimeter (mm) size. Wash load is considered to be composed of sediment smaller than the 0.062 mm size. Another convention used to separate bed material and wash load is to define sediment finer than the smallest 10% of bed material as the wash load. It is very important to note that in steep, high velocity mountain streams which have cobble or boulder beds, that the wash load may be composed of coarse sand sizes (Richardson and others, 1975).

Fluvial sediment (suspended sediment, bedload, and bed material) may be differentiated on the basis of particle size using Table 1. As shown in this table, the classification of fluvial sediment is an artificial process, at best, which merely serves as a convenience.

Table 1. Grade scale of fluvial-sediment particle sizes (Einstein, 1964, Section 17-II, pp. 17-61 to 17-62)

	CLASS NAME	SIZE	RANGE
	millimeters	microns	inches
Very large boulders	4,096-2.048		160-80
Large boulders	2,048-1,024		80-40
Medium boulders	1,024-512		40-20
Small boulders	512-256		20-10
Large cobbles	256-128		10-5
Small cobbles	128-64		5-2.5
Very coarse gravel	64-32		2.5-1.3
Coarse gravel	32-16		1.3-0.6
Medium gravel	16-8		0.6-0.3
Fine gravel	8-4		0.3-0.16
Very fine gravel	4-2		0.16-0.08
Very coarse sand	2.000-1.000	2,000-1,000	
Coarse sand	1.000-0.500	1,000-500	
Medium sand	0.500-0.250	500-250	
Fine sand	0.250-0 125	250-125	
Very fine sand	0.125-0.062	125-62	
Coarse silt	0.062-0.031	62-31	
Medium silt	0.031-0.016	31-16	
Fine silt	0.016-0.008	16-8	
Very fine silt	0.008-0.004	8-4	
Coarse clay	0.004-0.002	4-2	
Medium clay	0.002-0.001	2-1	
Fine clay	0.001-0.0005	1.0-0.5	
Very fine clay	0.0005-0.00024	0.5-0.24	

2.2 SUSPENDED SEDIMENT TRANSPORT

As might be expected, suspended sediment transport is a direct function of water velocity. Hence, it follows that as velocity varies, so does suspended sediment transport. Since the term suspended sediment describes a **range** of particle sizes from colloidal through some of the sand sizes (in some cases even larger particles), the effects of velocity and turbulence will vary as a function of the particle sizes in transport. Thus, suspended sediment transport through a stream cross section varies spatially both in the vertical and the horizontal planes. Also, this variation in transport varies longitudinally along the stream reach. Figures 2 and 3 depict examples of the variation in suspended sediment in a vertical profile through a cross section.

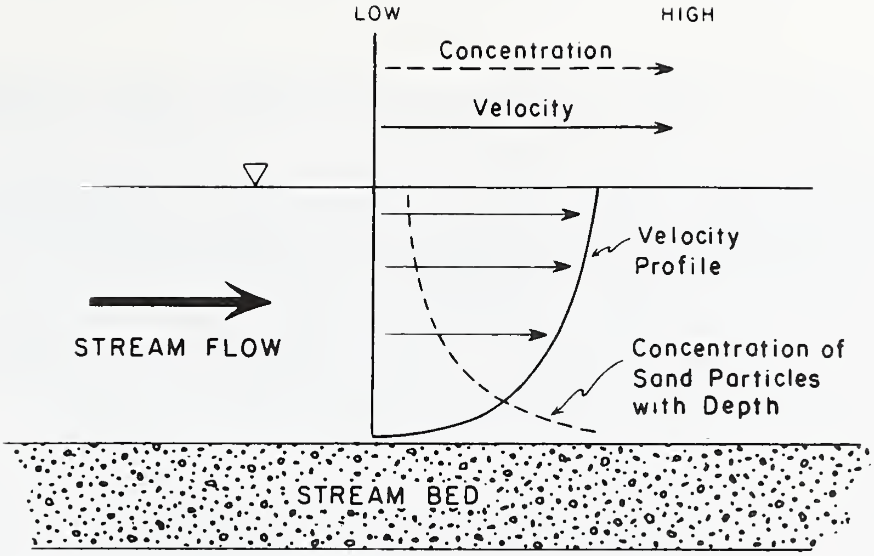


Figure 2. Diagram of the flow velocity and sediment (sand) concentration profiles in a stream (written communication, R. Beschta, 1985).

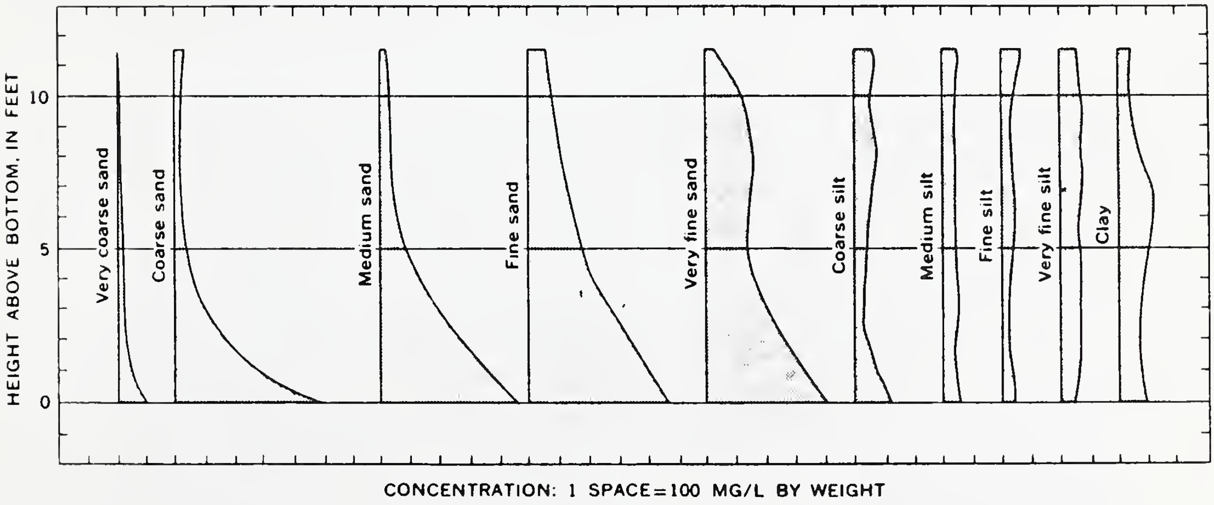


Figure 3. Vertical distribution of suspended sediment in the Missouri River at Kansas City, MO (Guy, 1970, p. 15).

Hysteresis of suspended sediment transport is a phenomenon of significant interest. Specifically, hysteresis can be due to position on the storm hydrograph and due to seasonal changes. Dunne and Leopold (1978), Paustian and Beschta (1979), Beschta and others (1981b), and Van Sickle and Beschta (1983) suggest that availability, or more importantly, changing availability of sediment is the primary mechanism causing hysteresis. This changing availability is time dependent, as is the hysteresis phenomenon itself. An example of a suspended sediment transport hysteresis loop during a flood event is shown in Figure 4: Other variations in sediment discharge may be observed with changes in water temperature which result in altered transport potential through changes in fluid viscosity.

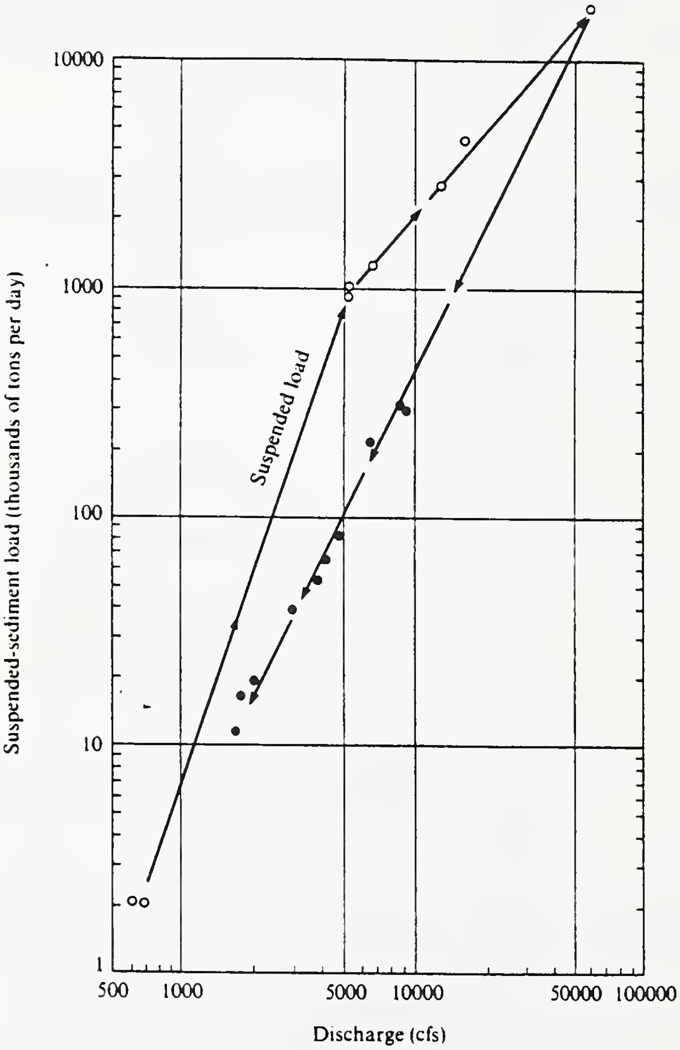


Figure 4. An example of a suspended sediment transport hysteresis loop during a flood event (Dunne and Leopold, 1978, p. 679).

2.3 BEDLOAD SEDIMENT TRANSPORT

Emmett (1980a, p. 992) stated: *Bedload is that sediment carried down a river by rolling and saltation on or near the stream bed. Though bedload may best be defined as that part of the sediment load supported by frequent solid contact with the unmoving bed, in practice it is the sediment moving on or near the stream bed rather than in the bulk of the flowing water.* While the definition of bedload sediment and its transport may be somewhat ambiguous, the significance of both the material and the process is not. Sediment transport by saltation, rolling and sliding is of particular interest because movement of bedload is usually sustained by flows for brief periods. Thus, bedload sediment is that material which is most readily deposited by a decrease in stream power. Dunne and Leopold (1978) describe stream power in units of kilograms per meter second while Emmett and others (1983) use watts per meter which is equivalent to newtons per second. The essential point, regardless of the units, is: as the time rate of energy available decreases, deposition of bedload increases. For example, a decrease in flow velocity or water slope will result in increased deposition.

Bedload transport is a highly variable process. The movement of bedload varies both in space and time to an even greater degree than suspended sediment. While bedload transport is usually not as variable in the vertical plane as suspended sediment, it is far more so in the horizontal and longitudinal planes. The causes of variability are complex, and not completely understood. However, since bedload transport is a direct function of velocity, slope, fluid mass density, and particle size, small variations in any of these variables across a channel cross section will cause changes in bedload transport.

The changing transport of bedload with time and position in cross section has been noted by, among others, Leopold and Emmett (1976), Beschta and others (1981a,b) and O'Leary and Beschta (1981), who ascribe it to, at least, nonuniform channel geometry, nonuniform particle size, and transient flows. The movement of bedload under such circumstances may be likened to waves or pulses of sediment passing a cross section. In fact, in an extreme example of such a process Schumm and others (1982) describe a bed form dependent pulsating flow which is characterized by surface water crests (or water bores) thought to be produced through the cyclic formation and destruction of antidune bed forms. In laboratory and field studies, Hubbell and Stevens (1986) have shown that even at constant flow conditions, bedload transport rates at a point vary with time from near zero to approximately four times the mean rate. A field study by Carey (1985) also showed that individual bedload rates sampled at a point can be expected to vary from near zero to four times the mean rate, and that 60% of the samples will be equal to or less than the mean rate. In addition, significant cross channel variations may also occur (Leopold and Emmett, 1976). For example, Jones and Seitz (1980) describe finding almost all of the bedload transport occurring in only about one half of the total channel width in an Idaho study.

Bedload is usually a much smaller percentage of total sediment discharge than is suspended sediment. Jones and Seitz (1980) describe bedload transport as running from 1 to 9% of suspended sediment transport in their Idaho study. Similarly, Andrews (1980) points to a typical computed bedload transport rate of less than 20% of total sediment load in the Yampa River in Colorado and Wyoming. Another study showed that the annual bedload transport rate represented 1 to 1.5% of the suspended sediment load in Alaska (Burrows and others, 1981). There are exceptions to the above examples, such as noted by Nndrews (1981) where shallow streams with medium to coarse sand beds may have 50% of total bed material discharge transported as bedload. However, even though bedload transport is usually substantially less than suspended sediment transport, bedload transport is extremely important in affecting the morphology and flow characteristics of stream channels.

3.0 FLUVIAL-SEDIMENT SAMPLING EQUIPMENT

Fluvial-sediment sampling equipment is relatively easy to use and most procedures have been standardized. Since 1939, the development of standard measurement apparatus and techniques has been accomplished by the Federal Interagency Sedimentation Project (FISP) of the Interagency Advisory Committee on Water Data, Subcommittee on Sedimentation. The Forest Service is a participating agency in this project. This Committee has produced numerous publications describing equipment and techniques. Most of these reports have been condensed and combined in the U.S. Geological Survey report by Edwards and Glysson (1988).

A catalog and price list (FISP, 1986) are available for ordering sediment sampling equipment and reports from FISP at the following address:

Federal Interagency Sedimentation Project
St. Anthony Falls Hydraulic Laboratory
Third Avenue SE and Hennepin Island
Minneapolis, MN 55414-2196
Telephone: (612) 370-2361
FTS: 777-2361

Fluvial-sediment samplers developed by FISP are of five basic types: depth integrating, point integrating, bed material, single-stage, and pumping samplers. As an aid in identifying samplers, FISP developed the following designation codes (Edwards and Glysson, 1988):

US	United States standard sampler
D	depth integrating
P	point integrating
H	hand held (omission indicates cable and reel suspension)
BM	bed material
BP	battery pack
HS	Helley-Smith type bedload sampler
U or SS	single stage
PS or CS	pumping type sampler
Year	Year of development

For example, the code US DH-48 indicates the United States standard (US) depth integrating (D) hand held (H) sampler developed in 1948 (48).

3.1 SUSPENDED SEDIMENT SAMPLERS

The purpose of a suspended sediment sampler is to obtain a representative sample of the water sediment mixture in the vicinity of the sampler (Edwards and Glysson, 1988). There are four types of suspended sediment samplers: depth integrating, point integrating, single-stage, and pumping samplers.

A depth integrating sampler is designed to collect and accumulate the water sediment sample as it is lowered to the stream bottom and raised to the surface. The lowering and raising of the sampler at one point is commonly called a sampling vertical. The sampler must be moved at a constant rate in a given direction but not necessarily at equal rates in both directions (Edwards and Glysson. 1988).

There are currently seven hand held samplers and three cable and reel samplers available for depth integrated measurement. The hand held samplers are (omitting the US designation): DH-48, DH-59, DH- 75H, DH-75P, DH-75Q, DH-76, and DH-81. The cable and reel samplers include: D-74, D-74AL, and D-77. Table 2 summarizes most of the depth integrating samplers identified above in terms of size, weight, composition, velocity, etc. Appendix B contains line drawings and photographs of the DH-48, DH-59, DH-75, D-74, and other samplers.

Not included in Table 2 is the DHS-48 sampler. The DHS-48 sampler is a DH-48 sampler that is fitted with removable tail vanes and a suspension hanger bar. The primary use of the DHS-48 is sampling from bridges in very low velocity water discharge conditions. It is available from FISP by special order.

The DH-81 sampler was developed primarily for microbiological sampling so that all parts of the sampler could be easily sterilized. This sampler can also be used for suspended sediment and trace metal sampling. The DH-81 can be adapted to use three different nozzle sizes (3/16, 1/4, and 5/16 inch) and any size sample container such as a pint, quart, or half gallon that has a *mason jar* type thread. Plastic caps are available from the FISP for trace metal sampling (personal communication, J. Skinner, 1985). The DH-81 is also useful for sampling during cold weather because it uses a plastic sampler head and nozzle which helps minimize freeze up conditions (Edwards and Glysson, 1988).

Of the hand held samplers, five samplers (DH-48, DH-75H, DH-75P, DH-75Q, DH-81) use wading rods. The DHS-48, DH-59 and DH-76 samplers use hand lines for sampling deeper streams. The weights of samplers range from 0.5 to 22 pounds and samples varying from one pint to two liters can be collected. They may be used in streams with maximum velocities of 5.0 to 8.9 feet per second and have *unsampled* zones of 3.15 to 4.49 inches.

The DH-48 and DH-59 are probably the two suspended sediment samplers most commonly used by the Forest Service. They are easy to transport and use, especially on the small streams commonly encountered in Forest Service monitoring efforts.

The cable and reel depth integrating samplers (D-74 and D-77) are much larger and heavier than the hand held models. They weigh 62 and 75 pounds respectively and are designed to be suspended beneath a bridge or cableway on deeper streams. Their maximum calibrated velocity is similar to the hand held samplers (6.6 and 8.0 feet per second) as is the size of their unsampled zone (4.06 and 7.0).

The principal difference between a point integrating sampler and a depth integrating sampler is a valve assembly in the point integrating sampler which allows the measurement to be taken at a desired depth or depths. This feature is especially valuable when sampling extremely deep or fast rivers where a depth integrating sampler would fill too quickly. Another obvious difference between these two types of samplers is size. The smallest point integrating sampler (P-72) weighs 41 pounds. The other samplers (P-61 and P-63) weigh 105 and 200 pounds respectively. These devices are designed to be operated at maximum depths which range from 50.9 feet to 180 feet depending upon sampler and container size.

Table 2 describes all of the point integrating samplers mentioned above. In addition, Appendix B contains a line drawing and photograph of the P-61 sampler.

All of the samplers described above also have trace metal versions. These special samplers have an epoxy paint covering, silicone rubber gaskets, and, if applicable, teflon sleeved valves.

The single stage samplers (U-59 and U-73) may be considered variants of point-integrating samplers. The U-59 consists essentially of a corked vessel with two inverted U-tubes inserted through the cork. The tubes are of different lengths with the shorter, hence, lower, tube serving as an inlet and the longer (higher) tube serving as an air exhaust port. This stationary device essentially samples a small range of stream stage during the rising limb of a storm hydrograph by filling and expelling air as the inlet tube fills with water. The exhaust tube prevents overfilling. The U-73 functions in much the same way as the U-59 but employs a different design, a Z shaped flow through container with spring loaded stoppers on each end.

Table 2 – Physical characteristics of US-series depth-integrating and point-integrating suspended-sediment samplers (Edwards and Glysson, 1988

Designation US –	Construction material	Sampler weight (pounds)	Nozzle distance from bottom (inches)	Suspension	Maximum Velocity (feet/second)	Maximum Depth (feet)	Sampler container size Pint	Sampler container size Quart	Intake size (inches)
DH-48	aluminum	4.5	3.5	rod	8.86	8.86	X	–	1/4
DH-75P	cd-plated	1.5	3.27	rod	6.6	16	X	–	3/16
DH-75Q	cd-plated	1.5	4.49	rod	6.6	16	–	X	3/16
DH-75H	cd-plated	1.5	–	rod	6.6	–	(2 liter)	–	3/16
DH-59	bronze	22	4.49	handline	5.0	19	X	–	1/8
DH-59	bronze	22	4.49	handline	5.0	16	X	–	3/16
DH-59	bronze	22	4.49	handline	5.0	9	X	–	1/4
DH-76	bronze	22	3.15	handline	6.6	16	–	X	1/8
DH-76	bronze	22	3.15	handline	6.6	16	–	X	3/16
DH-76	bronze	22	3.15	handline	6.6	16	–	X	1/4
DH-81	plastic	0.5	*d*	rod	8.9	*e*	*f*	–	3/16
DH-81	plastic	0.5	*d*	rod	8.9	9	*f*	–	1/4
DH-81	plastic	0.5	*d*	rod	8.9	9	*f*	–	5/16
D-74	bronze	62	4.06	cable reel	6.6	19[a]16[b]	X[c]	X	1/8
D-74	bronze	62	4.06	cable reel	6.6	19[a]16[b]	X[c]	X	3/16
D-74	bronze	62	4.06	cable reel	6.6	19[a]16[b]	X[c]	X	1/4
D-74AL	aluminum	42	4.06	cable reel	5.9	19[a]16[b]	X[c]	X	1/8
D-74AL	aluminum	42	4.06	cable reel	5.9	19[a]16[b]	X[c]	X	3/16
D-74AL	aluminum	42	4.06	cable reel	5.9	19[a]16[b]	X[c]	X	1/4
D-77	bronze	75	7.0	cable reel	8.0	15.5	(3 liter)	–	5/16
P-61	bronze	105	4.29	cable reel	6.6	180[a], 120[b]	X[c]	X	3/16
P-63	bronze	200	5.91	cable reel	6.6	180[a], 120[b]	X[c]	X	3/16
P-72	aluminum	41	4.29	cable reel	5.3	72.2[a],50.9[b]	X[c]	X	3/16

[a] Depth using pint sample container.
[b] Depth using quart sample container.
[c] Pint milk bottle can be used with adapter sleeve.
[d] Depends on bottle size used.
[e] Depends on specific nozzle and bottle size used.
[f] Any size bottle with standard mason jar threads.

Neither of these samplers require external power. The primary purpose of these samplers is *automatic* sample collection. For example, they might be used in remote ephemeral channels where flows are uncommon and investment of more sophisticated samplers is unwarranted. However, this purpose should be carefully evaluated since installation of automatic pumping samplers may avoid the many limitations inherent in the U-59 and the U-73.

Commercially available powered automatic pumping samplers are frequently used for suspended sediment sampling. The Water Resources Field Support Laboratory of the National Park Service prepared a report which reviewed the major features of eleven automatic water samplers (National Park Service, 1983). All the samplers evaluated were relatively portable, self-contained (battery and/or gas operated) and designed for field use. In addition, other studies such as Beschta (1980a) and Thomas and Eads (1983) have shown ways to modify and improve automatic pumping samplers for water quality monitoring use under wildland conditions.

Table 2 assists the hydrologist in making a reasonable choice in suspended sediment samplers. Selecting the right sampler for the sampling conditions involves trade-off and compromise. The first choice is that of depth integrating sampler versus point integrating sampler. The depth integrated approach is preferable to sampling at a point (instantaneously trapping) since the depth integrated sample is less affected by short term fluctuations in concentration (ASTM, 1983). However, the point integrating sampler may also be used for depth integrated sampling. It should be used in place of a depth integrating sampler on streams with depths in excess of 7.5 feet (15 feet round trip) and where stream depth and velocity either cause the depth integrating sampler bottle to overfill at the maximum allowable transit rate or make the lighter samplers unstable. Generally speaking, it is seldom practical to use point integrating samplers in wildland conditions.

The choice of hand held versus cable and reel devices is quite straightforward. Discharge and access are the principal concerns. A stream must be wadable to employ the hand held device. For faster and/or deeper streams the cable and reel devices are appropriate for use from bridges, but this then limits the stream locations that can be sampled.

The selection of the particular sampler to use also will be a function of hydraulic variables, whether or not the sample will be analyzed for trace metals, and the volume of sample desired. Also, since the depth of the unsampled zone varies somewhat, the choice of a suspended sediment sampler may be influenced by the bedload sampler used.

3.2 BEDLOAD SAMPLERS

Some hydrologists question the effectiveness of any device which is used to measure bedload. They contend that such devices measure the *unmeasured* load (bedload plus suspended load moving close to the bottom) rather than true bedload (the load moving by sliding, rolling, or bouncing on or very near the streambed). Further, any device placed on or very near the streambed disturbs fluid flow and hence bedload transport. In addition, since sediment and fluid movement near the bed vary greatly in space and time, the data tend to be highly variable.

Efforts have been directed towards the development of suitable bedload measurement devices since the early 1930's. The early devices, some of which are still used, fell into four categories: box or basket samplers, pan or tray samplers, pressure difference samplers and slot or pit samplers. Bedload sampling devices currently used fall into two general categories: direct or indirect measuring samplers. The direct measuring samplers are mostly improved versions of the pressure difference samplers.

Direct measuring devices measure bedload as it passes a point. Indirect measuring devices measure some **characteristic** of bedload movement. Examples of indirect measuring devices include an acoustic apparatus to *hear* sediment collision and passage; an ultrasonic apparatus, to measure sound absorption by the water sediment mixture; a tiltmeter apparatus to measure bed deposition; photography; and dune mapping or large particle counting with ultrasound (Hubbell, 1964; Edwards and Glysson, 1988).

All of the above devices appear to have problems of one sort or another and efficiencies vary by sampler, particle size, sediment distribution, and discharge (Hubbell, 1964). However, one pressure difference direct measuring device has become a tool widely used in the sampling of bedload. The Helley-Smith bedload sampler (Helley and Smith, 1971), a modification of the Arnhem or Dutch sampler, is currently used by government, university, and private organizations throughout the world.

The Helley-Smith bedload sampler is produced in three forms, a hand held version, a cable suspension version, and a larger scale cable suspension version. Basically, the sampler has a square nozzle entrance with an outward flaring nozzle exit to which is attached a sample bag, a tubing frame, and a stabilizing vane and wings. The nozzle entrance is 3" square for the standard sized sampler and 6" square for the larger version. The hydraulic efficiency of both sizes of sampler is approximately 1:54 for a range of low conditions applicable to many natural streamflow conditions (Druffel and others, 1976; Emmett, 1980b). Hydraulic efficiency is defined as *...the ratio of the mean velocity of flow through the sampler entrance to the mean velocity of flow through the area occupied by the sampler entrance when the sampler is not present, [which] expresses the extent of (or lack of) flow retardation* (Hubbell and others, 1985, p. 678).

Rigorous laboratory testing of the sampler has been conducted by FISP, and in May 1985, a new version of the Helley-Smith bedload sampler was approved by the Technical Committtee on sediment of FISP as a provisional standard sampler for use by Federal agencies (Edwards and Glysson, 1988). The primary difference between the new version of the Helley-Smith bedload sampler and the commonly used older design is in the area ratio of the sampler nozzle opening (ratio of nozzle exit area to entrance area). The original Helley-Smith sampler has an area ratio of 3:22 which results in a hydraulic efficiency of 1:54. The new *standard* Helley-Smith sampler has a nozzle with less pronounced angle in its outward flaring exit as compared to the original version. This new *standard* design has an area ratio of 1:40 and an estimated hydraulic efficiency of 1:35 (personal communication, D. Hubbell, 1985; Hubbell and others, 1985). A photograph (Figure 19) of the new *standard* Helley-Smith bedload sampler (HS-85) is included in Appendix B. Also included in Appendix B is a line drawing (Figure 20) of the original Helley-Smith sampler. Until the new Helley-Smith sampler (HS-85) with the 1:40 area ratio nozzle is tested further and becomes available for use, the original Helley-Smith bedload sampler should be used (Edwards and Glysson, 1988).

3.3 BED MATERIAL SAMPLERS

Standard bed material samplers are used to sample the material (particles) on the streambed. Their use is limited to material sizes smaller than coarse gravel (32 mm diameter). For bed material smaller than 32 mm in diameter, four samplers are available: BMH-53, BMH-60, BMH-80, and BM-54.

The BMH-53, BMH-60, and BMH-80 are hand held samplers. The BMH-53 sampler is a piston type device in which a cylinder on a T-shaped wading rod handle is pressed into the streambed. The piston retains a partial vacuum as the cylinder, containing the sample, is removed from the bed. Pressing the piston back into the cylinder extracts the sample. The BMH-60 sampler weighs 32 pounds and is a streamlined, finned sampler with an opening in its flat bottom. When the device rests on the bottom, weight is taken off the attached handline and as a result, a curved, spring loaded scoop is released and arcs downward from the flat bottom and encompasses approximately 175 cubic centimeters of material. The hand operated BMH-80 sampler has a semicylindrical bucket for collecting the sample. The bucket is opened and closed by using a lever on the handle.

The BM-54 sampler is the cable and reel version of the BMH-60. It is basically a heavier (100 pounds) and more powerful copy of the BMH-60. This sampler is also triggered by the release of tension on the attached cable. Appendix B contains line drawings and photographs of the BMH-53 and BMH-60 bed material samplers.

The selection of a bed material sampler will be largely governed by the bed material size and the type of water body to be sampled. On coarse gravel, cobble, or boulder bed streams other techniques such as shovel collection and toe point pebble counting can be used. These techniques involve picking bed material particles in a random fashion and developing frequency distributions. These methods are described in more detail in Section 4.3 (Bed Material Sample Collection).

Where finer bed material is to be sampled, the BMH-53 or BMH-80 hand held devices are the most convenient samplers. For deeper or faster streams the use of the BMH-60 or BM-54 becomes necessary and consequently sampling is more difficult. These devices tend to be tripped inadvertently and can be a hazard to fingers and hands.

An additional approach for bed material analysis is the Zeiss particle size analyzer (Ritter and Helley, 1968) which utilizes a 35 mm photograph of the bed. There are obvious problems with such an approach, such as turbidity. Where conditions permit, however, this approach may prove advantageous.

4.0 FLUVIAL-SEDIMENT SAMPLE COLLECTION

Collection of fluvial-sediment samples includes consideration of the purpose and required accuracy of the data, site selection for sampling, and techniques to obtain a representative sample. These tasks are governed by the hydrologic and sediment characteristics of the stream. The accurate determination of fluvial-sediment discharge is an inherently difficult task since the sediment to be measured is incorporated in a moving medium and both the sediment and the fluid are varying spatially and temporally. To collect a representative sample, one must obtain a sample that adequately defines the natural variation of sediment transport which occurs in a stream.

This section includes discussion of various techniques of sample collection, site selection, and problems associated with collecting samples of suspended sediment, bedload, and bed material. Additional detailed information on fluvial-sediment sample collection can be found in the USGS report by Edwards and Glysson (1988).

4.1 SUSPENDED SEDIMENT SAMPLE COLLECTION

Three sample collection techniques are commonly used to evaluate instantaneous suspended sediment concentration through a cross section. The techniques are point integration, area integration, and depth integration.

In point integration, spatial concentrations at a series of points throughout a cross sectional area are measured. These measurements, along with point velocity measurements, are used to develop concentration and velocity gradients (ASTM, 1983).

Point integrated measurements require the flow area to be divided into lateral increments which are sampled at various depths along a vertical. Increment widths and vertical points of sample collection are selected so that concentration and velocity differences between adjacent points are small. The point integration technique is not commonly used in wildland hydrology. It is usually time consuming and expensive.

Area integration and depth integration rely upon the measurement apparatus and measurement procedure to integrate the flow area through mechanical and hydraulic means. These methods use an isokinetic sampler which moves through the flow collecting incremental volumes from every element of traversed area. These volumes are *in the same proportion to the sample volume as the stream discharge in each corresponding element is to stream discharge in the sampled area* (ASTM, 1983, p. 927). The resulting discharge weighted sediment concentration can be multiplied by stream discharge to yield instantaneous suspended sediment discharge.

Area integration samples the entire area (flow) of a cross section, so a traversing slot (splitter) must be installed in conjunction with an outfall flume, weir, or other discharge measurement device wherein the flow is well mixed. The sample is extracted from *...every element of area that is in the same proportion to the total sample volume as the stream discharge through the corresponding element is to the total stream discharge* (ASTM, 1983,

p. 929). The sample is thus discharge weighted. This measurement approach requires specialized slot samples and thus, is not frequently employed in wildland field applications due to its cost and maintenance requirements.

Depth integration samples only the area traversed by the sampler intake as the sampler is moved through a vertical. Sampling a cross section using the depth integration method requires a vertical or a series of verticals to be sampled. There are two methods of depth integration: the equal width increment (EWI) method (formerly called the equal transit rate (ETR) method) and the equal discharge increment (EDI) method.

In the nWI method a stream cross section is divided into a number of equal, or nearly equal, width increments or sections. The sampler is passed through verticals in the center of these sections at a transit rate which is uniform from section to section. The result is a sample which is proportional to the total streamflow. Generally, 10 to 20 verticals by the EWI method will provide an accurate mean discharge weighted concentration (OWDC, 1978). This method is well suited for all types of streams. It is probably the preferred method in order to achieve the best consistency of results when different individuals do the sampling.

The EDI method requires that discharge at various points across a section be determined. The cross sectional area is then divided into a number of equal subsections, each of which conveys the same water discharge. Each subsection is sampled and represents the same proportion of total discharge as every other sample. Transit rates in the EDI method must be uniform within a subsection but need not be so between subsections. Usually, if six or more subsections are sampled, an accurate mean discharge weighted concentration can be obtained. The major disadvantage of the EDI method is that the lateral contribution of water discharge must be measured prior to sampling (OWDC, 1978).

Guidelines have been developed (Edwards and Glysson, 1988) for selecting suitable transit rates for various samplers, nozzle sizes, stream velocities and depths, bridge heights, and particle sizes. Generally, where suspended sediment is measured in smaller streams, these refinements are not consequential. However, when measurements involve larger systems and equipment, careful attention should be given to these details.

The selection of a site for suspended sediment sample collection will be governed by several factors, most important of which is study objectives. This will be further modified by costs, data accuracy, access, etc. On a more technical level, the site must be located at or very near a gaging station or discharge measurement location. While it may be obvious that stream discharge and sediment measurement must be determined jointly, the need for these two efforts to be accomplished at nearly the same location is often overlooked. Appreciable inflows from groundwater or tributaries between sites or between the gage site and the sediment sampling site should be avoided. Similarly, areas of turbulence, backwater, incomplete tributary mixing, and active bank erosion should be avoided. A straight reach or the crossover section of a sinuous channel generally provides the most uniform channel conditions for sampling (Edwards and Glysson, 1988).

As a practical matter, most suspended sediment sampling is done at bridges. This follows from the need to measure sediment at all flow conditions, especially at flood flow. However, there is a channel restriction problem when sampling from bridges. At bridge sites, channels are controlled (restricted) either naturally or through bridge abutments, embankments, and piers. Such restrictions tend to affect sediment transport processes, especially in sand bed channels.

The effects of channel restriction can frequently be seen in bed scour beneath and around piers and in a change in channel pattern in the reach downstream of the bridge. Such effects cannot be completely compensated by sampling on the upstream side of the bridge. The hydrologist must rely upon judgment when using data collected from a bridge.

Problems associated with the accurate determination of suspended sediment discharge are numerous. As already discussed, natural variation of sediment transport, site selection, and channel changes introduce variability to the data collected. The sampling process and equipment may also create inconsistencies in the data collected. For example, overfilling of sample bottles tends to systematically bias data towards larger values since sediment continues to accumulate once the bottle has filled. In addition, channels with soft bottom material and those with dunes create a situation where scooping could result in oversampling.

The transit rate problem should be kept in mind when measuring deep and/or fast streams, especially when using heavy equipment. The large samplers and long cables needed for deep/fast streams result in an increase in the time required to reverse sampler transit direction. This lag time coupled with increased sediment concentration near the bed also results in a tendency to oversample (ASTM, 1983).

4.2 BEDLOAD SAMPLE COLLECTION

The U.S. Geological Survey has established general guidelines and methods for collecting bedload samples in Edwards and Glysson (1988). This USGS report provides a good introduction and discusses in depth the high variability associated with bedload transport and related problems in collecting a representative bedload sample.

The following bedload sample collection guidelines and methods are from this USGS report (Edwards and Glysson, 1988):

> In order to make bedload sampling practical, methods must be used that minimize the number of samples required to obtain a reasonable estimate of the mean cross-sectional bedload discharge rate. Field experience has shown that the collection of about 40 individual bedload transport rate measurements per cross-section sample is, in most cases, practical and economically feasible. The following are three general methods by which one might collect 40 samples per measurement.

(1) Starting at one bank and proceeding to the other, collect one sample per vertical at 20 evenly spaced verticals in the cross section, return to the bank, and repeat the process. We will refer to this method as the Single Equal Width Increment (SEWI) method.

(2) Starting at one bank and proceeding to the other, collect 8 to 10 samples at 4 to 5 verticals, for a total of 40 samples per cross section. We will refer to this method as the Multiple Equal Width Increment (MEWI) method.

(3) Starting at one bank and proceeding to the other, collect 4 to 10 samples from 4 to 10 unevenly spaced verticals, for a total of 40 samples per cross section. We will refer to this method as the Uneven Width Increment (UWI) method. This method would require some prior knowledge of the depths and velocities across the section. The sampling verticals would be spaced unevenly according to observed uniformity of depth and velocity, with samples collected midway between breaks in the lateral bed slope and closer together in segments of high velocity and changing lateral bed slope.

...no one method works best in all situations and no one standard sampling protocol can be used at all stations. A unique sampling protocol must be derived for each site at which bedload discharge data is to be collected. The following is a procedure which can be used to develop a sampling protocol for a given site.

(1) Using a modification of the SEWI method, collect samples at approximately 20 equally spaced verticals in the cross section. The spacing and location of the verticals should be determined by the sampling procedure used in the EWI method. For very wide sections, where large variations in bedload rates are suspected, sampling stations should not be spaced more than 50 feet apart. For narrow cross sections, sampling stations need not be closer than 1 foot apart.

(2) Lower the sampler to the streambed and use a stopwatch to measure the time interval during which the sampler is on the streambed. The sampling time interval should be the same for each vertical sampled in the cross section. The time required to collect a proper sample can vary from 5 seconds or less to several hours or more. Generally a sampling time of 30 to 60 seconds is preferred, and 60 seconds should be considered a maximum time. Because of the temporal variations in bedload transport rates, there is no easy way to determine the appropriate sampling time. Several test samples, as many as 10 or more collected sequentially at a vertical with a suspected high transport rate, may be needed in order to estimate the proper sampling time interval to be used. The sample time should be short enough to allow for the collection of a sample from the section with the highest transport rate, without filling the sample bag more than about 40% full.

(3) One sample should be collected at each vertical, starting at one bank and proceeding to the other. If the same sampling time was used for all verticals sampled, the samples may be placed in separate bags for individual analysis and labeled with the verticals' station number, or they may be composited into one or several sample bags for a composite analysis. If more than one sample time was used to collect the cross-section sample, the sample from each vertical must be placed in a separate container. This sample must be analyzed separately and the mean bedload rate computed mathematically.

(4) A second sample should be collected using a modification of the UWI or MEWI methods. Four or five verticals should be sampled four or five times each, obtaining a total of 20 samples. Samples should be collected using the same procedure as described in (2) above. However, the sample time for each sample need not be the same. All samples should be bagged and tagged for separate analysis.

(5) The following data must be recorded on a field note sheet for each cross-section sample:

Station name/number
Date
Cross-section sample starting and ending times
Gage height at the start and end of sample collection
Total width of the cross section
Width between verticals
Number of verticals sampled
Time sampler was on the bottom at each vertical
Type sampler used
Name of person collecting sample

In addition, the following information should be recorded on each sample container:

Station name
Date
Designation of cross-section sample to which the container belongs (that is, if two cross-section samples were collected, one would be *A* and the other *B*)
Number of containers for that cross section (for example, *1 of 2* or *2 of 2*)
Collector's initials
Time sampler was on the bottom at each vertical

This procedure should be considered the minimum to be followed when first collecting bedload data at a site. Additional samples should be collected to help define the temporal and spatial variation at the site for all flow ranges. Until these variations have been defined, all samples collected with the SEWI, UWI, or MEWI methods should be bagged and analyzed separately. This will help in defining cross-sectional variability. After these variations have been defined, a more efficient sampling protocol can be developed to address the specific conditions at the site.

A few additional sampling techniques not mentioned specifically in the above guidelines and methods should be noted. Measure the width of the stream where bedload samples are taken so that total bedload can be calculated. The Helley-Smith sampler should be placed on the bottom, tail first and, for the hand held model, rocked gently forward. Do not lean on the handle during sampling. The sampler must be oriented perpendicular to the flow with the top parallel to the streambed and the front and back of the bottom plate in contact with the streambed. The hand held model should be removed from the bottom front first and then rocked gently backward. The suspension models should be attached to the cable in a tail heavy attitude and allowed to stabilize at the proper orientation in the streamflow before being allowed to touch bottom. Care must be exercised to prevent dragging and scour by either the hand held or suspended version of the sampler. A modification to the suspended version of the Helley-Smith sampler has been developed which employs a quick release connector, and a quick release tether which prevents downstream drift during sampler placement and scooping during sampler retrieval (Hubbell and others, 1985). Caution must be employed when using the hand held version to avoid disturbing the streambed in front of the sampler.

The selection of a cross-section location for bedload sample collection must be highly influenced by the purpose of the study and the geomorphic character of the reach. Important geomorphic considerations include: whether the reach is aggrading or degrading, whether it is straight, meandering, or braided, or whether significant tributaries are located above or below the cross section.

It is usually preferable to sample straight reaches which are in dynamic equilibrium and identify the separate contributions from significant tributaries. Important changes in geology/parent material (for example, a glacial valley transition to steep gradient bedrock controlled canyon) should be identified and sampled.

The timing of measurement in relation to discharge flow is also important. Since bedload transport is a flow dependent phenomenon, most transport occurs during the relatively short periods characterized by high flows. Little is gained by intensively measuring low flow bedload transport. Measurements should instead concentrate on higher flow periods when most of the material is moved.

A number of problems exist in sampling bedload, the most important of which is the inherent variability of the bedload transport process. As noted by Andrews (1981, p. 133): *Because of these extreme temporal and spatial variations, the bedload discharge should be sampled at many locations in a stream channel during an extended period of time in order to obtain an accurate estimate of the true mean bedload discharge.*

The various bedload sample collection methods discussed previously attempt to compensate for spatial and temporal variations in bedload transport primarily through the use of many sample points across a channel and extended sampling time. The degree to which it succeeds remains to be seen. Based on the results of a computer model that simulates bedload transport, Hubbell and Stevens (1986) noted that temporal variations affect sampling errors to a greater degree than spatial variations. Sampling efforts, therefore, could be decreased substantially without decreasing accuracy, by measuring at fewer sampling points many times rather than sampling at many points only a few times.

Another problem is the clogging of the bedload sample bag by organic material and fine sands. Studies by Johnson and others (1977) and Beschta (1981) have shown that fine sands and organic matter can rapidly decrease the sampling efficiency of a Helley-Smith bedload sampler having a standard collection bag of 0.2 mm mesh and surface area of 1,950 square cm. A threefold increase in bag size to a surface area of 6,000 square cm while still retaining the 0.2 mm mesh size was shown to greatly reduce the clogging problem. In addition, maintaining bedload sampling times at 30 seconds or less at each subsampling point further reduced the potential for bag clogging. The loss of material finer than the bag mesh may slightly bias the results under some conditions. Conversely, bias may result from the trapping of an unknown quantity of suspended sediment in the bedload sampler.

While some of the above problems can be corrected, other problems have an unknown effect upon the measured bedload. The hydrologist must, therefore, view the resultant data with some degree of uncertainty. As long as the hydrologist understands both the shortcomings and the strengths of measurements, it should be a feasible task to put the data into perspective and develop appropriate interpretations from the data collected.

4.3 BED MATERIAL SAMPLE COLLECTION

Bed material samples should generally be collected at the same cross section location used for discharge, suspended sediment, etc. The bed material samples should be collected before taking other measurements to be assured of an undisturbed streambed. The number of samples to collect at the cross section should be a function of the heterogeneity of particle sizes, that is, the greater the range of sizes the greater the number of samples necessary to predict a given size class (d_{15}, d_{50}, d_{85}) with a specified statistical confidence level.

The selection of a bed material sampling technique appropriate at any given situation is one of the most difficult decisions in sediment measurement. Samplers must be matched to flow, depth, and particle size. In addition, they are largely inappropriate for the larger sized materials commonly found in the streams on National Forest System lands.

In nonwadable situations sample collection is more difficult. Since some of the bed material samplers trip with a reduction in line tension, any upward force, such as turbulence, has the potential of triggering the device. Further, a pebble blocking the sampler bucket from closing can allow all or part of the sample to escape as the sampler is retrieved.

For some stream systems and/or study objectives it is desirable to deviate from the procedure of collecting samples at a cross section. In wadable systems with large bottom materials (larger than coarse gravel) a manual sampling approach must be used. This approach may entail using a grid pattern, random sampling, or a series of bank to bank channel transects which identify the points for sample collection. Wolman (1954) and OWDC (1978, pp. 38-39) describe in detail how to use a grid pattern to sample coarse bed material.

Another method involves picking up, at random from the bed surface, at least 100 particles (pebbles) which are measured and then recorded by size. This method is sometimes called a toe point pebble count. The usual situation where this method would be applied is in a relatively homogeneous area or feature in a stream channel such as a gravel bar. According to Dunne and Leopold (1978, p. 666), *The procedure is to select a zone or area considered homogeneous. As the researcher walks over the selected area, he reaches over the toe of his boot with eyes closed or averted and touches with an extended finger a rock. The rock is picked up and measured with a scale along its intermediate, or b, axis being neither the longest nor the shortest axis. The measurement is made in millimeters and recorded as the lower limit of the size class into which the rock falls.* Leopold (1970) and Dunne and Leopold (1978, pp. 666-669) also describe how the data collected using this procedure can be tabulated and summarized to derive the particle size distribution and dominant particle size of the area sampled.

A variation of the above described procedure is to sample bed material particles when walking bank to bank transects across a selected stream reach. This method uses the same toe point pebble count sampling techniques as described above except the samples are picked up, measured, and recorded every few feet while walking a bank to bank transect. To obtain a representative sample of at least 100 particles (pebbles), several transects should be walked across the reach. This method can be used to determine the particle size distribution of a selected reach which is nonhomogeneous, such as a reach with a series of pool riffle features. Under these conditions, an equal number of transects should cross the pool zones as well as the riffle zones to obtain a sample representative of the entire selected reach.

If the study objective is to determine a size class percentage which is in transport during bankfull flows, it may be appropriate to measure particle sizes at high water deposition sites, for example, the downstream extent of a point bar.

The depth of sample collection may also be influenced by the objectives of the study. Sometimes only the top inch or so is needed in bed material studies but more commonly, greater depth is necessary to characterize the bed.

5.0 HANDLING FLUVIAL-SEDIMENT SAMPLES

Common sense governs most sediment sampling handling requirements, such as careful packaging to avoid breakage, securely attached labeling, and avoiding freezing. Analysis should be completed immediately or as soon as possible. If samples are to be stored they should be weighed in the bottle and then placed in a cool, dark place to avoid excessive growth of organics. Reweighing and subtracting the first measurement will account for such growth if it does occur.

Suspended sediment samples have some special handling requirements. For example, upon collection of a suspended sediment sample, the sample container should be examined and compared to other sample containers to determine: (1) if an unexplained increase in sediment has occurred, as in scour; and (2) if the bottle has overfilled (fluid level within two inches of top). Questionable samples should be discarded. Transferring suspended sediment samples to another container should be avoided since losses may occur. If a transfer is necessary then a careful measurement of volume should be made, the original container washed with distilled water to remove residue, and the wash water transferred to the storage container. The storage container should not have sharp angles since these serve as collection points for residue which are difficult to clear.

Bedload samples may be conveniently handled in two ways. First, samples may be transferred from the sample bag to some type of plastic bag while wet. The removal procedure should be consistent since a residue will remain in the collection bag and can be ignored if essentially constant in volume from one sample to another. For example, if sample removal is accomplished by vigorous shaking or by *flicking* the index finger against the bag, then the procedure should be repeated precisely for all samples. Other studies have shown that pouring water onto the sample bag will easily and completely wash all the sediment out (written communication, R. Beschta, 1985). Second, if a number of sampler bags are available, then the bag may be removed and placed in a plastic bag and sealed. Later, this bag can be unsealed and the sample air dried which provides for nearly complete and easy removal of bedload from the sample bag.

Bed material samples measured in the field using pebble counts require no specific handling requirements. However, if samples are to be analyzed in the lab, the same requirements apply as above.

6.0 FIELD AND LABORATORY METHODS FOR FLUVIAL-SEDIMENT ANALYSIS

The methods of fluvial-sediment analysis are largely the same for all three types of sediment: suspended, bedload, and bed material. These methods primarily involve determining sediment weight through evaporation and/or filtration procedures, and particle size analysis.

In the analysis of suspended sediment either of two procedures may be used: evaporation or filtration. The evaporation technique is preferred only in those situations where samples have high sediment concentrations. Use of this technique on low concentration samples requires a dissolved solids correction (OWDC, 1978). If the sample is difficult to settle, the procedure necessitates the use of a filtration tube or a flocculating agent, neither of which is desirable. Thus, if the sample does not readily settle, the use of filtration instead of evaporation is recommended (Guy, 1969).

In using the evaporation procedure all but 20 to 50 ml supernatant liquid is decanted from the sample. The sediment and remaining liquid are washed onto an evaporating dish with distilled water. The sample is dried in an oven at a temperature slightly less than boiling. Once all visible moisture is gone the temperature is raised to 110° C for one hour. The desiccated samples can then be weighed (Guy, 1969; OWDC, 1978).

The filtration technique can be accomplished using a Gooch crucible or a fritted glass crucible and glass microfiber filter papers. The use of glass microfiber filters on the suction manifolds used for bacterialogical sampling is a common field practice. If such a procedure is used, it is recommended that a sample of filters be oven dried, weighed, and then have distilled water run through under suction in a volume roughly equivalent to the volume in the sediment samples. The filters are again oven dried and weighed. The difference in starting and ending weights represents the residue loss due to the mechanical effect of a volume of water passing under suction through the filter. An average residue loss value is computed for the sample of filters and this value then can be used for the remainder of the filters in the same box.

The filter or the filter plus crucible are oven dried, desiccated, and weighed for tare. They are then placed on a suction apparatus through which is passed the water sediment mixture. Before the sample is poured through the funnel and filter, it is measured in a graduated cylinder. The sample is next poured from the cylinder onto the filter and both the sample bottle and the cylinder are washed with distilled water which is also poured onto the filter. The sediment laden filter is then removed, oven dried (105-110° C for 24 hours), desiccated and reweighed. The weight of suspended sediment is represented by the change in filter weight corrected for residue loss.

The use of flocculating or absorbing agents is discussed by Guy (1969) and OWDC (1978). The reader is directed to these sources for the procedure and discussions on handling the fine sediments which remain in a dispersed state.

The above procedures provide total suspended sediment concentration. The next step is the determination of size distribution of the suspended sediment particles. A given suspended sediment sample will usually require more than one analysis method because of the wide range of particle sizes. The methods for determining the size distribution of sand size (0.062-2.0 mm) particles are sieve, VA (visual accumulation) tube, and BW (bottom withdrawal) tube methods. The methods for the silt clay fractions are hydrometer, pipet and BW tube. Guy (1969) and OWDC (1978) describe in detail the use of these methods to determine the suspended sediment particle size distribution.

Bedload is generally analyzed by size class. This requires a set of nested sieves and can either be done wet or dry. A commonly used set of sieves has 0.062, 0.125, 0.250, 0.50, 1.0, 2.0, 4.0, 8.0, 16.0, 32.0, and 64.0 mm screens. The wet method involves immersing a sieve in water, washing the sample onto the sieve, shaking the sieve, and pouring the wash water onto the next smaller sieve. This same process is continued for all sieve screen sizes. The material from each sieve is transferred to preweighed (tared) containers and dried for approximately 24 hours at 105-110° C. The dried samples are then weighed by size class

(OWDC, 1978). The material passing the finest sieve is dried, weighed, and retained for measurement by one of the suspended sediment particle size analysis methods.

Dry sieving involves placing the composite, air dried sample in the coarsest sieve at the top of the stack and covering. The stack of sieves, with bottom pan attached, is placed on a mechanical shaker for about ten minutes. After shaking, samples are oven dried and weighed in tared containers. As a practical matter, sieves themselves are often used as the tared container if few samples are to be analyzed.

An alternative to analyzing bedload by particle size was developed by Carey (1984) by using a field technique for weighing composite bedload samples which eliminates costly and time consuming steps involved in laboratory analysis. The technique involves measuring the submerged weight of bedload samples. The submerged weight is then converted to dry weight based on the estimated specific gravity of the bedload.

Bed material larger than coarse gravel (64 mm) is generally analyzed manually in the field. Bed material composed of gravel and sand size classes are dry or wet sieved as described above. The finer sized bed material (less than 0.062 mm) is analyzed the same as suspended sediment.

7.0 TURBIDITY

Turbidity, or the optical character of water, has long been viewed as a possible way to more quickly, effectively, and cheaply measure sediment in streams. However, sediment laden water is not always more cloudy or murky than sediment poor water (Beschta, 1980b). This results from several causes: (1) the numerous approaches and instruments used to measure turbidity, (2) the many different optical properties actually measured, (3) the units of measure, and (4) the sometimes poor relationship of the optical effect of a particle to its mass/volume, especially with organic substances.

Many State water quality standards are written in terms of turbidity. Therefore, turbidity should be a concern of the hydrologist.

An interest in standardizing turbidity measurement in terms of equipment and measurement units has surfaced on occasion (OWDC, 1978). It is possible that this water quality characteristic will one day be more useful and amenable to description in scientific terms. Until such time, however, it would seem likely that this variable will continue to be measured where usable and/or where required by State standards.

The field method for collection of turbidity samples is not well defined. Commonly, a grab sample is used, although a depth integrated sample may reinforce confidence of representativeness.

Turbidity measurements should be read the same day the sample is collected, but samples may be stored in a dark place for up to 24 hours. Storage for longer periods requires treatment with mercuric chloride (1.0 gram per liter) (American Public Health Association,

1976) to stabilize the sample. The laboratory analysis should be done in compliance with the turbidimeter/nephelometer manufacturer's instructions using clean, polished sample vials/bottles. Particular attention must be paid to machine warm up and calibration requirements.

8.0 STATISTICAL SAMPLING AND ANALYSIS OF FLUVIAL-SEDIMENT DATA

When to collect sediment samples and how many samples to collect are common problems facing most hydrologists who sample sediment. This section is an assessment of statistical sampling methods for fluvial sediment. Included in this section are statistical aspects related to characteristics of suspended sediment data, problems encountered when sampling suspended sediment, objectives of a suspended sediment sampling program, use of automatic suspended sediment pumping samplers, and sampling techniques. While this section is written primarily for suspended sediment, some of the background information and procedures presented can be applied to the sampling of bedload and bed material.

A wide variety of books are available which cover all aspects of statistical analysis. However, three books related to the analysis of "biological/natural resource" type data are recommended: *Biometry* by Sokal and Rohlf (1969), *Principles and Procedures of Statistics with Special Reference to the Biological Sciences* by Steel and Torrie (1960), and *Some Methods for the Statistical Analysis of Benthic Invertebrates* by Elliot (1977). Two additional reports are suggested which provide a good review and examples of statistical methods: *Statistical Methods Commonly Used in Water Quality Data Analysis* by Ponce (1980b) and *Statistical Methods Commonly Used in Soil Data Analysis* by Blaney and others (1984).

8.1 INTRODUCTION

Quantifying any natural phenomenon involves measurement, and measurement virtually always involves sampling. For a variety of reasons, usually we cannot measure all of what we want to study, and so we must measure a part. We take a sample and then make inferences about the whole population from which it was drawn.

Sampling is certainly required when studying suspended sediment in rivers. For technical and logistical reasons the suspended material being carried by a river cannot be measured in its entirety, but must be sampled at isolated points in a cross section and generally at isolated times. Usually the suspended sediment concentration data are then combined with continuous streamflow information to estimate totals and evaluate changes due to watershed treatments.

There are several ways to select samples. One is to choose the "units" (the constituent elements) from a population to be sampled "haphazardly"; that is, without any conscious plan. Another is to select the units purposefully, perhaps by relying on an expert on the phenomenon being sampled. Still another is to select units at equal intervals of some continuum. For example, measurements of suspended sediment can be made at equal intervals of time, or every tenth in a list of watersheds could be measured to characterize a population. Also, the units can be chosen by using some form of random selection. This technique is based on identifying each unit in a finite population, at least conceptually, and including units in the sample according to a procedure based on random sampling numbers.

It is obvious, but frequently forgotten, that the form of sampling used governs what type of analysis can be done and what interpretations can be made. One should not, for example, collect data purposefully and then use them to calculate a variance that was designed for data selected randomly. Of course, any data can be used in the variance formula, but the resultant estimate won't have the same properties that it would if based on random data. Statistical quantities or tests using variances calculated in this way will not perform as designed. The essential connection between the type of sample collected and the appropriate analysis that can be performed will be a central theme of this section.

The common aim of all types of sampling is, or ought to be, to "represent" in some useful sense the parent population from which it was drawn. Because samples vary, estimators should be chosen to have desirable properties such as unbiasedness (in other words, the absence of *systematic* error), and to provide estimates of sampling errors. The only class of sampling methods having these properties is probability (random) sampling (Cochran, 1963). These goals are achieved at the price of requiring adherence to random selection; however, there are "legitimate" techniques to restrict randomization to more efficiently sample particular populations.

Although suspended sediment data have been collected for years, the application of rigorous sampling theory to control the sampling process and to make estimates is in its infancy. This is due to several factors, including a highly variable process, difficulties of measurement, and serial correlation of systematic samples collected close together in time. The problem is illustrated by the existence of numerous techniques for estimating total yields; techniques that are usually biased to an unknown but often considerable degree, and that provide no valid estimate of error (Walling and Webb, 1981). Recent emphasis on instream monitoring, however, has encouraged work in developing valid sampling procedures. One such approach will be described later in this section. Before that is done, however, we will consider suspended sediment sampling and measurement problems in more detail.

8.2 CHARACTERISTICS AND MEASUREMENT PROBLEMS OF SUSPENDED SEDIMENT DATA

Most hydrological measurement is indirect, and measuring suspended sediment is no exception. It is not technically possible to measure suspended sediment discharge directly, so the product of concentration, water discharge, and a suitable constant is used instead. If both suspended sediment concentration and water discharge could be measured continuously, total suspended sediment yield could be derived by integrating the product function. Continuous monitoring of suspended sediment concentration can be done directly using a fluid density gage (Skinner and Beverage, 1982), or indirectly using a surrogate such as turbidity (Walling, 1977a; Walling, 1977b; Truhlar, 1978; Beschta, 1980b). For some research work or particularly sensitive management situations, the use of these techniques may be warranted, but the cost can be high and they usually require a standard 120 volt a.c. electrical source. Most Forest Service suspended sediment monitoring for the foreseeable future will probably be based on continuous stream discharge measurement and occasional suspended sediment concentration data collected manually or with automatic pumping samplers. The basic problem is how to decide when the concentration data should be collected and how to combine them with the streamflow data to give estimators that perform as desired.

A relationship between suspended sediment concentration and water discharge has long been recognized and is widely used. Because flowing water supplies the energy to move particles in suspension, this relationship is not surprising in channel systems that contain abundant suspendible material. Even in undisturbed steep mountain catchments that are more supply dependent, there is often a positive correlation between discharge and suspended sediment concentration.

This situation is both a problem and an opportunity. The problem comes from the fact that high flows occur episodically and for short periods of time (especially in rain dominated watersheds), and it is difficult and yet essential to collect the major share of suspended sediment concentration data during those events. The opportunity is that discharge is an easily measurable surrogate for suspended sediment discharge that can be used to control the sampling regime.

The discharge to suspended sediment concentration relationship is embodied in the ubiquitous sediment rating curve that is usually derived from the logarithms of simultaneously collected pairs of suspended sediment concentration and water discharge measurements (Walling, 1977a; Walling, 1977b; Ketcheson, 1986). Rating curves are widely used to estimate total sediment yields using various methods and to define the sediment production characteristics of a watershed for use in treatment comparisons. Rating curves can be useful, but there are problems associated with their use that should be recognized. Sediment concentration is not a univariate function of discharge. This is clearly illustrated by the "hysteresis loop" observed in many data sets wherein, for the same stage, the suspended sediment concentration is significantly higher on the rising limb than on the falling limb of a hydrograph. The relationship can often be improved by including additional explanatory variables in the equation, such as time since peak (Gregory and Walling, 1973). Another situation seen frequently is that the rating curve relationship changes seasonally.

The distribution and range of discharge data used to construct rating curves can also be a problem. The pattern of rating curve data for many small basins is concave upward, while most data are collected at the lower, more frequent flows. A least squares straight line fit of such data is strongly influenced by the more abundant low discharge data which have the general effect of reducing the slope of the estimated line resulting in underestimates of concentrations at higher flows. Large variation in concentration of a few data points collected at high flows adds another level of uncertainty. Rating curve models can be improved by using different transformations or additional explanatory variables (such as quadratic equations in log discharge for transformed data that are still curved, or some function of the day number in the hydrologic year to account for season). Of primary importance, however, is to collect data over an adequate range of discharges both for developing sediment rating curves, and especially for comparing them. Improved and standardized sampling plans should do much to reduce this problem.

An often remarked feature of suspended sediment concentration data that is also related to discharge is high variation. The sediment production process is dependent on many factors, some of which are subject to large random influences. Better methods of predicting suspended sediment concentration should reduce unexplained variation somewhat, but a significant amount is likely to remain. The association between high discharge and high variation is one major encouragment for increased sampling during these conditions.

To make matters worse, suspended sediment concentration samples are small, both in the sense that each bottle of water/sediment mixture is a very small fraction of the flow it purports to represent, and because there tend to be few bottles collected. Automatic samplers have helped increase the number of measurements taken, but, unfortunately, the machines are often operated at equal time intervals, which results in increased sampling during the more frequent lower but less important flows. Other schemes set sampling frequency for predefined ranges in stage. While this corrects the problem somewhat, the data are not random so there still is need for a sampling strategy that operates the samplers according to an algorithm based on recent discharge history.

In generally large streams where mixing is poor, automatic samplers can give a much less reliable estimate of the true cross-sectional concentration than that given by a depth integrated sample. A common reason for this disparity is poor placement of the intake nozzle. A fixed height nozzle samples a different proportion of depth as the stage varies, thus measuring a different part of the concentration's vertical profile at different stages. Also, if the fixed height is too close to the streambed, samples under high flow conditions can be unduly influenced by sediment moving close to the bottom. This material tends to be composed of coarse particles moving in pulses and can result in high concentrations and high variation. One way to reduce this effect is to mount the intake on a "boom" hinged upstream to the streambed with a float on the downstream end (Eads and Thomas, 1983). The float end of the boom rises and falls with stage, keeping the pumping sampler intake at the same proportion of depth.

Thought should also be given to intake position across the stream. While placement near a bank is more convenient, the thalweg probably gives a more representative sample. Some experimentation may be necessary for both lateral and depth proportional placement. In any case, it is essential to calibrate pumped and depth integrated measurements using a set of simultaneously collected pairs.

A final problem is serial correlation, which measures the dependence among data taken close together in time. Dependence can be informally taken as the condition that each value in the series does not contribute the same amount of "information" that an independent value would. As measurement frequency is increased to more intensively sample high sediment discharge events, the dependence increases. The amount of additional information, therefore, is not proportional to the increased effort. The appropriate techniques to deal with dependent data are those in time series analysis. These methods, however, are complicated to apply, require long series of values collected at equal time intervals, and are limited in the kinds of results available. Using dependent data in methods developed for independent samples will yield results with different properties from those expected. Selecting data according to a random scheme applied to the entire period of record removes this problem. It is possible to design such a plan to preferentially sample high flows and still maintain independence.

There are other problems surrounding the making of measurements in a field setting. Some of those not usually discussed will now be covered.

There are two classes of errors made when quantifying any phenomenon. To understand these types of errors, it is necessary to be familiar with the concepts of sampled and target populations. A target population is the entity that an investigator wishes to study. For a number of practical reasons associated with a particular inquiry, it is rarely possible to sample this population directly. Instead, an associated abstract population is created that is more amenable to carrying out the actual sampling. In many cases this step is taken without conscious effort or intent.

For example, the suspended material carried by a stream during a year is a continuous target population to be estimated. The year can be divided into "short" time periods and a single suspended sediment concentration and water discharge measurement taken as typical during each period, perhaps at its midpoint. A finite sampled population is thus created which can be randomly sampled to yield statistically valid estimates. The sampling is done on and the statistical estimates relate back to the sampled population only.

It can be seen that the sampled and target populations do not have identical characteristics. If the time periods are on the order of a minute in length, most hydrologists would probably agree that the difference between the two populations is unimportant. If the periods are much longer, say a day on a small highly variable stream, the correspondence may be very poor. When constructing such a population, a period length should be sought that is a compromise between logistical convenience and an appropriately small error between the sampled and target populations. Differences between the sampled and target populations must be assessed by professional judgment or by specially designed studies. The usual statistical estimators do not relate to this dichotomy, but to fluctuations in sample selection from the sampled population.

The first major class of errors when quantifying any phenomenon is sampling errors. These errors arise from the method used to obtain the sample from the sampled population. This source of errors derives from fluctuations in the set of units that comprise the sample resulting from the selection process. For random samples, the nature of these fluctuations can be expressed in probability, and the magnitude of this component of error is estimated by the sample variance. For nonrandom samples this error generally cannot be estimated.

This leaves nonsampling errors to compose the second class which can be further divided into two subclasses. One source of nonsampling error derives from the definition of the units that constitute the sampled population (Thomas, 1983). This error, therefore, measures the difference between the sampled and target populations. In our example, as the time periods are made smaller so is the nonsampling error from the definition of the units.

The second source of nonsampling error is due to the measurements made on the units selected for the sample. Any errors made during the course of field measurement or lab processing can contribute to this source. A large component of this nonsampling error is the difference between the true average cross-sectional concentration and the concentration of the sample itself. This error should be less for depth integrated samples taken at several positions across a stream than for pumped samples collected at a point in a cross section.

Another factor relating to field data collection involves instrumentation and data collection procedures. The existence of numerous techniques to accomplish a given hydrological measurement, the rapid evolution of instrumentation, and a tendency for hydrological data to be collected over long periods of time combine to create a problem of valid comparisons.

The primary reason for collecting data is to make comparisons of some kind, and it is important that such comparisons give a valid measure of actual differences in phenomena rather than resulting from an inadvertent comparison of measurement techniques. A common example comes from estimating suspended sediment yield from a river for a given time period. Numerous methods are used to estimate yield, and they can have markedly different characteristics (Walling and Webb, 1981). The primary difference comes from bias (systematic error) due to data collection and estimation methods and to the particular application. Usually the newest methods and technology should be used whenever possible, but for a given study it is probably best to use the same techniques for all treatments and time periods.

Because climate produces the hydrological phenomena studied by hydrologists, its variation and extremes are of primary importance for long term study design, especially in rain dominated regions. Events of varying severity occur with characteristic frequencies. These frequencies should be estimated, at least approximately, when a study is being planned. Enough time should be allowed for a reasonable probability of an adequate range of storm events to occur both before and after treatment. Only probability statements can be made about expected storm severity, and the period of record may be inadequate in one or more respects. Plans should be flexible enough to allow extension of calibration and treatment periods if circumstances warrant. These factors are less severe in snow dominated areas. For treatment comparisons, however, similar ranges of discharge should be covered before and after treatment.

These problems are exacerbated when annual data are the primary unit of analysis in comparing treatments. While storm data are often difficult to measure (due primarily to problems in storm definition in composite storms), they offer an opportunity to gather pertinent information over a wide range of conditions in a shorter period of time. Because of the need for a more rapid pace of management decisions, it is likely that storm based, or other short term approaches to data definition will increasingly be used in rain dominated regions.

A final comment concerns the need for collecting suspended sediment data during high flows. Hydrologists have often been encouraged to collect more data at high flows but appropriate detailed sampling plans have not been specified. Increased use of automatic pumping samplers has tended to raise the proportion of sampling at high discharges, which may have lulled hydrologists into a false sense that sampling is adequate. Frequently used automatic sampler schemes, however, tend to be inefficient in the sense of getting the most information for the effort and money expended.

Several approaches to sampling suspended sediment will be outlined in the following section. The techniques differ in the level of effort needed, but all require that appropriate flows be sampled according to the conditions of the method. Especially in small and rain dominated streams, a strongly disproportionate share of the total suspended sediment is transported during a small portion of the time under high flow conditions. If the methods are to perform as expected, these flows must be sampled as required. Hydrologists should not expect improved sampling schemes to relieve the emphasis on sampling high flows.

8.3 OBJECTIVES OF A SUSPENDED SEDIMENT SAMPLING PROGRAM

There are four broad classes of objectives for most Forest Service studies of suspended sediment:

A. Sediment Yield Estimation

This class of objectives is more commonly required for downstream applications such as reservoir filling, but may be needed for certain Forest Service activities. Both suspended sediment and bedload yields will probably need to be measured.

B. Inventory

This is a common reason given for monitoring suspended sediment, but it is seldom justified. In most instances there are concrete problems that should be addressed, and "measuring background" too often masks a lack of setting specific objectives. In most cases some kind of comparison is wanted. It should be based on an appropriate experiment designed to answer specific questions. Hydrologists contemplating "measuring background" should take a close look at their real objectives.

C. Regulation Compliance

This will vary greatly, depending on the regulation. Regulations should be stated completely enough to define the sampling requirements, but this is seldom the case. The hydrologist will have to work out an acceptable plan with the regulatory agency.

D. Treatment Response

This is by far the most frequent reason that the Forest Service monitors suspended sediment. It also requires the most care in setting up a study to make a valid estimate of differences due to treatment.

There are several criteria that can be measured to detect change. The appropriate one (or ones) will depend on the particular study and must be identified before the sampling scheme can be selected. Three of the more commonly used criteria to assess treatment response are discussed next.

Perhaps the most frequently used criterion is suspended sediment yield for a given period of time, such as a year. Numerous methods have traditionally been used to estimate suspended sediment yield (Walling and Webb, 1981), most of which can be called "nonstatistical" because there is no theoretical connection between sampling methodology and properties of the estimates. The results of this situation are estimates with unknown but large bias, and difficulty in designing sampling schemes. The SALT (Selection At List Time) sampling scheme described later is a valid statistical approach for estimating suspended sediment yield.

The period for which yield is measured is at choice. Annual values are often obtained, a year being a complete climatic cycle, making data somewhat comparable across time. Annual values accumulate slowly, however, and most management contexts cannot allow extensive periods for data collection. Shorter, arbitrary periods such as the time between station visits (a week or two), or individual storms, offer possibilities of obtaining useful data more quickly. It is difficult, however, to develop unambiguous and useful definitions of storms during complex events. Comparisons are generally made between "paired" catchments, but it may be possible to relate suspended sediment yield during a given period to other variables and thus develop techniques for single watershed comparisons over time.

A second criterion for assessing instream changes due to management activities is to make "simultaneous" measurements at two stations on the same stream, one above and one below the influence of the activity. The values compared can be suspended sediment concentration, suspended sediment transport, or perhaps even suspended sediment yield for a relatively short period of time. The hydrologist should keep in mind that these quantities can vary longitudinally along a stream even in an undisturbed state. While "above and below" monitoring can be effective, a calibration of the stations should be done before the treatment so that any differences found later can be confidently attributed to the treatment. Trying to measure the same parcel of water at the lower station that was measured at the upper station by accounting for the time it takes the parcel to travel between stations seems a practically unattainable goal. Therefore, measurements should be made simultaneously at the two stations, if possible, or with one station, probably the lower one, always measured a constant time difference after the other to reduce one source of variation.

A third criterion often used to make treatment comparisons is the sediment rating curve. Simultaneously collected pairs of water discharge and suspended sediment concentration values are used to form regressions representing before and after treatment periods. To detect change the regressions can be compared using any of several methods. While this is an appealing approach, there are problems that can make comparisons ambiguous. One is that suspended sediment concentration is not usually a simple univariate linear function of discharge (nor are their logs, which are usually used in analyses). Factors besides discharge govern concentration at a particular time and place. One variable found useful is the time of the suspended sediment concentration measurement from the associated storm peak, measured negative before and positive after the peak (Gregory and Walling, 1973). Rating curves using several explanatory variables should be tried in cases having high variation, because the increase in precision can reduce the amount of data needed for comparison. Another problem when comparing rating curves is deciding what differences are important. Because rating curves contain no flow frequency information, it is not easy to interpret the importance of a change in suspended sediment concentration at a particular discharge to overall suspended sediment yield.

A difficulty with rating curves is getting an adequate range of discharge data, again, primarily during high flows. The lack of well defined sampling schemes and the great predominance of time during low flows has often meant that too large a proportion of rating curve data is at low concentrations. Thus, low flow data tend to exert an undue influence on the position of the regression line, which often results in underestimating concentrations at higher discharges. This may in part account for the typical underestimation of suspended sediment yield by methods of estimation relying on rating curves (Walling and Webb, 1981). When collecting rating data, therefore, the hydrologist must ensure that data are collected throughout the range of flows for which the curve will be used. The SALT scheme described later to sample for estimating suspended sediment yield has the associated advantage of collecting data suitable for the development of rating curves.

8.4 SAMPLING TECHNIQUES

As with estimation procedures, many schemes are used to collect suspended sediment data. Confusion arises, therefore, when selecting a sampling method suitable for a given application. Costs of instrumenting a station and the logistics of operating it must also be considered. Keeping the study objectives firmly in mind and evaluating the strengths and weaknesses of candidate sampling schemes will help simplify the choice.

Three comments should be made before the various sampling techniques are discussed. One is that by "sampling" we mean *statistical sampling*. For suspended sediment sampling, this essentially means *when* to collect a sample for concentration of suspended sediment. This is usually a function of water discharge and when adequately answered also answers the associated question concerning *how many* samples to collect.

The second comment concerns making comparisons to assess the effects of treatment. Comparisons are often made over long time periods during which new instrumentation and methods of estimation may become available. Changing methods of data collection or estimation in the same study should be done with great caution. Of the many techniques available to estimate suspended sediment yield, for example, many are subject to large (60% and more) and unknown biases which are partly a function of particular applications. Indicated differences could therefore come from changes in techniques of measurement and estimation rather than from treatment. Methods should only be changed if all estimators are known to be unbiased (or if the bias is known) and estimates of variance are available.

The final comment relates to the field effort required to obtain adequate suspended sediment data. Pumping samplers are seen as a way to reduce human effort when measuring suspended sediment. While true in a sense, this should not be taken to mean that less effort is required to obtain good data. The more sophisticated sampling schemes will, of necessity, emphasize collecting a large portion of the data at high discharges. While automatic equipment is essential to collect the actual suspended sediment concentration samples, this means that the equipment and instruments must be serviced and collateral data (such as discharge rating measurements, depth integrated suspended sediment concentration calibration measurements) collected during those events. Inadequate funding or commitment to insure that these tasks are accomplished will greatly reduce the chances that study results will be useful. It is best to look on new sampling technology and methodology as improving the quality and reliability of estimates and allowing time and resources to better measure collateral data rather than reducing the overall effort required.

We now discuss six sampling schemes that are either widely used by Forest Service hydrologists or can be recommended for certain purposes. Due to changes in sampling technology and methods of estimation, new techniques can be expected to evolve in the near future. The present discussion is intended to be a state of the art assessment, but also gives a preview of new approaches now being developed.

1. Haphazard

Haphazard sampling is marked by the lack of a plan. Such data are often collected according to convenience, with little or no regard for the process being sampled. Water quality data of all kinds are often collected haphazardly. It is highly unlikely that haphazard sampling will give satisfactory results. The behavior of estimates made from haphazard data is not predictable and errors cannot be estimated. Haphazard sampling is not recommended for any purpose.

Haphazard should not be confused with random. Random sampling is characterized by a plan relying, in some well defined way, on a prepared or computed list of random numbers. Even though the random numbers have an aspect of unpredictability, and may appear "haphazard" in a sense, they are carefully selected to possess certain qualities and are used according to a strict procedure which insures that selection probabilities are known. With haphazard sampling, the selection probabilities are *not* known.

2. Timed Intervals

Sampling suspended sediment at timed intervals can be done by hand if the intervals are long enough, but high variation in water and suspended sediment discharge make this approach impractical in most streams likely to be studied by Forest Service hydrologists. The advent and proliferation of automatic pumping samplers has eased some of the problems of sampling suspended sediment, and the presence of timers on most of these machines has encouraged sampling at timed intervals. There are problems with this approach, however, especially in flashy, rain dominated streams.

Because suspended sediment transport is highly discharge dependent and high flows occur rarely, sampling should be very infrequent, if done at all, the vast majority of the time. During high flows, however, the sampling intensity should be high, due both to the large quantities of suspended sediment being transported under these conditions, and to high variation. Setting timers for either of these conditions makes the sampling highly inappropriate for the other. In the one case unimportant flows are sampled far too intensely with the resultant station servicing and data processing problems, and in the other case important suspended sediment discharges are inadequately defined.

This problem can be reduced by changing the timer interval for different flow conditions, which can be accomplished either manually or automatically. If done manually, it is difficult to ensure that the sampling frequency is always appropriate for the level of discharge unless the station is constantly manned, which defeats the main purpose of having an automatic sampler. Suspended sediment rating curves or total suspended sediment yields calculated with different sampling frequencies across discharge classes may be different due to the sampling method rather than to treatment. Changing the sampling frequency automatically, given that the frequencies are appropriate to the flow classes, not only improves the estimate, but also makes comparison more valid. A method to apportion samples across discharge classes will be described in the following section on stratified random sampling allocation.

Still, flow adjusted timed interval sampling cannot be recommended without reservation. The data are not random, so estimators with specified properties and estimates of error are not possible. The data actually form a time series, which is to say that they are serially correlated, and should be evaluated according to time series methods. Unfortunately, such methods are complex and do not yield statistics of major usefulness to forest managers. Also, most time series techniques require data collected at constant intervals, so one must either analyze separately each portion of data collected at one frequency, or collect all data at the same frequency which produces the problems just discussed.

The primary advantages of constant timed interval sampling are those of simplicity and low cost; in most cases nothing more being required than a pumping sampler. While discharge dependent timed interval sampling can be accomplished by a nimble hydrologist, it is much more convenient and reliable if stage sensing equipment is used to control sampling frequency automatically.

Constant timed interval sampling of suspended sediment should be used only in those rare cases where flow levels do not change rapidly or markedly and when suspended sediment concentration variance is low. Discharge dependent timed interval sampling is preferred, especially when accomplished automatically to ensure uniform sampling frequencies in defined flow classes. Direct estimation of suspended sediment yield in classes using these data is not recommended, but they may be used to develop suspended sediment rating curves. The rating curves can then be used to compare directly, or, with less confidence, to estimate total yields in flow duration curve classes.

3. Delta Stage

Another method to improve the sampling of higher flows involving relatively little instrumentation is to operate the pumping sampler at prescribed changes in stage. Instrumentation for "delta stage" techniques can be relatively modest;-one technique is to mount magnets on the float wheel of the chart recorder that operate a reed switch mounted on a nearby bracket. More sophisticated designs allow for different delta stage values at different ranges in stage.

The delta stage technique relies on *changes* in stage; the hydrograph staying steady at a high flow level causes no more sampling than a steady low flow. Although this means that the technique is not strictly discharge related there is a tendency for stage variation to be greater at higher flows so that they usually are more frequently sampled.

This technique is also nonstatistical because the sampling probabilities are not known, so these data should not be used directly to estimate suspended sediment yield. They may be adequate for developing suspended sediment rating curves, but this is likely to depend on the particular installation.

4. Estimated Discharge Proportional

With more sophisticated instrumentation it is possible to sample when specified amounts of water or suspended sediment have passed the station. Because these values (especially suspended sediment) are not known with certainty, we refer to this method as "estimated discharge proportional".

An electromechanical or electronic device can monitor a transducer attached to the chart recorder float wheel (or to a separate float) to keep track of stage. Water yield is estimated by stage for short intervals and the estimates accumulated with some suitable storage device. When a preselected amount of water has passed the station the pumping sampler is operated, the storage device cleared, and the process repeated. This has the effect of stretching out the time between samples at low flows while greatly reducing times between samples at high flows. Constant high flows work as well as those that vary.

If an acceptable suspended sediment rating curve is available, a similar procedure can be carried out with estimated suspended sediment discharge. The major difference between this method and the estimated water discharge proportional method is that the sediment discharge procedure samples the higher flows relatively more often. Also, of course, some sediment rating curve, however rudimentary, is required.

The estimated discharge proportional methods make a continuous and automatic transition between sampling "frequency" at different discharge levels that is intuitively reasonable. Sample selection probabilities are unknown, so these data must be considered nonstatistical and should not be used for direct estimation of suspended sediment yield. They appear to be quite satisfactory, however, for developing (or refining) rating curves. Again, the parameters (the rating curves) of a sampling scheme should not be changed between data sets to be compared, as this could cause a difference by itself.

E. Stratified Random Sampling Allocation

A widely applied method of random sampling partitions the population of interest into two or more strata in such a way that each stratum is relatively homogeneous. Separate simple random samples taken in each stratum are then used to estimate totals or means in the parent population. Such estimates are nearly always better for a given level of effort (and reasonably good definition of strata) than when data are collected from the populations as a whole.

Stratified random sampling with flow classes as strata was used by Yaksich and Verhoff (1983) to sample large "event response" rivers where daily suspended sediment yields can be characterized by a single sample. They also recommend Neyman allocation (Cochran, 1963) to apportion the samples into different flow classes. There are operational problems in applying this scheme to smaller mountain catchments, however, due to higher variation and difficulties in selecting random samples in the several strata. In the next section we describe a new technique that is more acceptable for suspended sediment sampling in small rivers and is recommended for collecting samples suitable for direct estimation of totals. In this section we focus only on stratified sampling allocation as a reasonable, if heuristic, approach to apportioning sampling effort across flows (Thomas, 1985a). This approach is primarily intended for guidance in using the flow dependent timed interval method.

Equation (1) in Figure 5 gives the basic Neyman allocation formula. For each stratum the product of its size and its standard deviation is formed; the proportion of the sample to take in that stratum is this product divided by the sum of the corresponding products across all strata. This formula makes intuitive sense; it directs larger portions of the sample to strata that are large and more variable.

If the strata sizes are known and some data are available to estimate the standard deviation, Equation (1) in Figure 5 can be used directly. More often this will not be the case, so usable surrogate variables must be found. A reasonable surrogate for the size, or number of members in a stratum, is the amount of suspended sediment transported in a flow class, expressed as volume, mass, or percent.

A useful replacement for the standard deviation is the *range* of the flow class boundaries, in terms of either suspended sediment concentration or discharge (Murthy, 1967). Suspended sediment rating curves are often developed for different time periods and hydraulic conditions, so there may be no unique suspended sediment concentration associated with a flow class boundary. Because discharge is used to define the classes, the ranges in discharge are available and useful as a surrogate for the standard deviations. Equation (2) in Figure 5 presents a more usable, if approximate, approach to allocation.

To illustrate the application of Equation (2) in Figure 5, data collected from Caspar Creek (Rice and others, 1979) were used (Figure 6). The percent axis was partitioned into 20 classes each containing 5% of the flow volume. Discharge rates corresponding to class boundaries were then read from the graph and percentages of sediment delivered at flows greater than these values were determined. The data selected from Figure 6 and the calculations made from them are shown in Table 3. For this stream the allocation indicates that samples should be heavily concentrated in the higher flow classes; in fact, it shows that nearly three quarters of the measurements should be taken in the highest flow class alone. This is not surprising when it is considered that more than half of the range of flows occur here as well as 30% of the suspended sediment volume, so this class contains a large portion of the suspended sediment as well as being highly variable.

$$p_i = \frac{N_i v_i}{\sum_{j=1}^{k} N_j v_j} \tag{1}$$

$$p_i = \frac{S_i R_i}{\sum_{j=1}^{k} S_j R_j} \tag{2}$$

Figure 5. Neyman stratified random sampling allocation formulas.

Each class should be allocated a minimum of about five samples so that mean discharge for the class and its variance can be estimated. For example, if 100 samples are to be collected, most classes in Table 3 are too small. By experimenting with the number of discharge classes and their boundaries an allocation can be produced that has at least five samples in each class. To accomplish this, the 2 highest flow classes in Table 3 were left intact and the next 2, the following 3, and the last 13 classes were grouped to form a 5 class allocation (Table 4). With 100 samples under this allocation, 6 would go into each of the 2 lowest flow classes.

Obtaining a minimum number of samples in the low flow classes was achieved at the expense of samples previously allocated to the high flow classes. This is because the ranges and sediment contributions of the composite classes increase, making the denominator of Equation (2) of Figure 5 larger. A practical compromise must be struck between having many classes to reduce the overall variance and having fewer classes so that each class will contain at least a minimum number of samples. For most suspended sediment sampling programs five or six strata should be adequate.

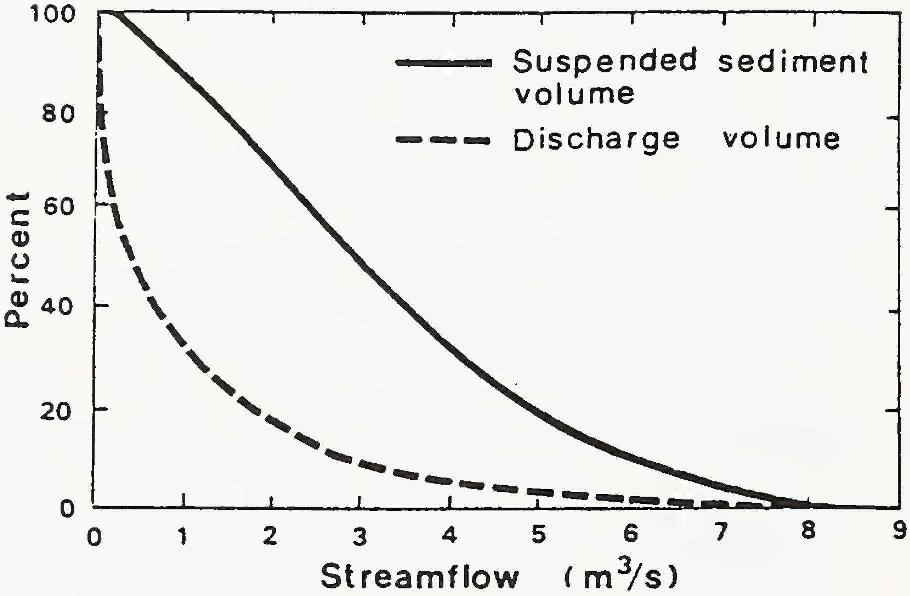


Figure 6. Percentage of suspended sediment and discharge volumes occurring at greater than indicated flows (from Rice, et al. 1979).

% Water Volume Yielded at Greater than Indicated Flows	Flows at Class Boundaries (m^3/s)	% Sediment Volume Yielded at Greater than Indicated Flows	R_i Flow Range (m^3/s)	S_i Percent Sediment Volume in Class	R_iS_i	P_i
0	8.5	0				
5	4.1	30	4.4	30	132.0	73
10	2.7	55	1.4	25	35.0	20
15	2.1	64	0.6	9	3.6	2
20	1.7	72	0.4	8	3.2	2
25	1.4	79	0.3	7	2.1	1
30	1.1	84	0.3	5	1.5	1
35	0.9	87	0.2	3	0.6	
40	0.7	91	0.2	4	0.8	
45	0.6	93	0.1	2	0.2	
50	0.4	95	0.2	2	0.4	
55	0.3	96	0.1	1	0.1	
60	0.2	97	0.1	1	0.1	
65	0.2	97	*		*	1
70	0.1	98	*		*	
75	0.1	98	*		*	
80	*	99	*		*	
85	*	100	*		*	
90	*	100	*		*	
95	*	100	*		*	
100	0.0	100	*		*	
				ΣR_iS_i =	179.8	

* <0.05

TABLE 3. Sample size data and calculations (from Rice, et al. 1979).

% Water Volume Yielded at Greater than Indicated Flows	Flows at Class Boundaries (m^3/s)	% Sediment Volume Yielded at Greater than Indicated Flows	R_i Flow Range (m^3/s)	S_i Percent Sediment Volume in Class	R_iS_i	P_i
0	8.5	0				
5	4.1	30	4.4	30	132.0	63
10	2.7	55	1.4	25	35.0	17
20	1.7	72	1.0	17	17.0	8
35	0.9	87	0.8	15	12.0	6
100	0.0	100	0.9	13	12.0	6
				ΣR_iS_i =	208.0	

TABLE 4. Calculations for five classes formed by grouping classes in Table 3 to reallocate 100 samples.

The primary benefit of using this technique is to emphasize the need to collect suspended sediment concentration data at higher flows and to estimate *approximate* proportions of sampling effort to expend at different flows. Equation (2) of Figure 5 should be kept in perspective and not used slavishly. It should be useful to the practicing hydrologist to look at several existing data sets and to compare suspended sediment concentration data that were actually collected with this "ideal." Scenarios based on synthesized flow and sediment volume curves can be developed that bracket a particular set of field conditions. Applying the allocation formula to these scenarios using tentative class boundaries can help develop reasonable sampling programs which should serve to emphasize the need to sample more heavily in the higher flow classes than is typically done.

Several factors are not addressed by Equation (2) in Figure 5. One of these is the total sample size. Formulas to estimate total sample size in stratified random sampling are available (Cochran, 1963), but either cost information or specification of the variance of the total suspended sediment volume are required, in addition to variance and size estimates in all strata. This complex of assumptions strains credibility in applying the total sample size formulas to this case, especially when data are limited.

Also, the formula does not indicate when to take the prescribed number of samples in each class. The data in each class should be randomly selected for the mean and variance estimating formulas to be correct. Because this is difficult to accomplish, these data should be used mainly to develop rating curves.

If flow duration information is available (or can be estimated) for the classes it can be used in conjunction with this allocation procedure to define sampling frequencies. The average duration of each flow class is divided by the number of samples required by the allocation process to obtain an approximate sampling interval.

F. Variable Probability Sampling

Finally, we outline a method of sampling that is truly statistical in that the estimators take the sampling scheme into account. The method gives estimates of total suspended sediment yield for arbitrary periods and estimates of error, both of which are unbiased. It also provides data over a nearly uniform distribution of discharges that is suitable for developing suspended sediment rating curves. A sample sizing method ensures specified performance.

The technique is new (Thomas, 1983; Thomas, 1985b) and the first field trials are at two stations on the Six Rivers National Forest in California. The usual application requires a pumping sampler and a small battery powered computer (programmable calculators are being used) that monitors river stage with a transducer attached to the float wheel shaft of a chart recorder.

Data stored in the calculator are read into a digital tape recorder for direct transfer to an office computer when the stations are serviced. The Redwood Sciences Labaoratory of the Pacific Southwest Forest and Range Station in Arcata, California has developed a package to perform this type of sampling that includes a hand held calculator and an electronics unit to connect the calculator, transducer, and pumping sampler (Eads and Boolootian, 1985). The calculator logs streamflow data as well as controlling the suspended sediment sampling process, so the $800 to $1,000 cost of the system could be partially offset by omitting the water stage recorder (although a float and tape system is still required to operate the transducer). If another sampling scheme is wanted, such as the ones described earlier, the calculator can be reprogrammed to execute it without hardware changes. The following description is only intended to be a preview; a field operation manual is planned after adequate field experience is gained in applying the technique.

An abstract and finite population to be sampled is created by partitioning the total sample period into relatively short time periods of equal length. The period length is at choice, but should be related to expected variation, and the hydrologist should be satisfied that the concentration of the period can be represented adequately by a single sample. Periods of 5 to 30 minutes have been used.

More specifically, the population consists of the measures of suspended sediment yielded in these periods. The measure for the ith period, denoted by y_i, is derived from a single pumped suspended sediment concentration sample collected at the midpoint of the period, multiplied by the water discharge at the midpoint, the length of the period, and a constant to adjust units (Equation (1) of Figure 7). Thus, for each period there is a quantity of suspended sediment delivered that could be measured (given adequate resources), and that if measured, would satisfy the hydrologist as being an adequate representation of the yield of the true continuous (or "target") population. It is these quantities, one for each time period, that form the discrete population of "units."

Measuring all units is not feasible, so they must be sampled. Simple random sampling would be very inefficient, because each unit receives an equal probability of selection, and the vast majority of units have low water sediment discharge and are therefore insignificant in estimating suspended sediment yield. A method is needed that will select the "important" units for the sample while still retaining the desirable properties of a statistical sample.

$$y_i = q_i c_i \Delta t k \tag{1}$$

$$x_i = q_i \hat{c}_i \Delta t k \tag{2}$$

$$X = \sum_{i=1}^{N} x_i \tag{3}$$

$$n = \sum_{i=1}^{N} r_i \tag{4}$$

$$\hat{Y} = \frac{X}{n} \sum_{i=1}^{N} r_i \frac{y_i}{x_i} \tag{5}$$

$$\hat{Y} = \frac{1}{n} \sum_{i=1}^{N} r_i \frac{y_i}{p_i} \tag{6}$$

$$S^2(\hat{Y}) = \frac{1}{n(n-1)} \sum_{i=1}^{N} r_i (X y_i / x_i - \hat{Y})^2 \tag{7}$$

Where, for period i;

y_i = the value of the *measured* supended sediment yield,

x_i = the value of the *estimated* supended sediment yield (i.e., auxiliary variable),

q_i = water discharge at midpoint,

c_i = pumped sample measure of the suspended sediment concentration at midpoint,

$\hat{c}_i$ = rating curve estimate of suspended sediment concentration at midpoint,

$p_i = x_i/X$ = probability of a random number falling within,

r_i = number of random numbers contained within,

and,

X = the total of the N values of the auxiliary variable,

N = the total number of samplingperiods (or intevals) in the population,

n = the total of randompoints in all N sampling intervals (i.e., the sample size),

$\hat{Y}$ = the SALT estimate of the true total Y,

S_2 ($\hat{Y}$) = the sample estimate of the variance of, and

Δ = length of sampling periods.

Figure 7. Selection At List Time (SALT) formulas. Note: The sum to N (rather than n) in formulas 6 and 7, though mathematically correct, may be confusing. The index variable

r_i acts to eliminate all terms from the nonsampled intervals (those y_i's are not known in any case) and to include terms from the sampled intervals the proper number of times (i.e., equal to the number of random numbers in the interval). Each sum can be written as having exactly n nonzero terms, one for each random number contained in all intervals actually sampled.

To maintain these properties, it is not necessary to sample with *equal* probabilities provided the sampling probabilities are known. One approach is to use an auxiliary variable that is related to the primary variable, and can be easily and cheaply measured for *every unit* in the population. This variable is then used to define the probabilities of selection, and if related in a certain way to the primary variable, it will increase the probability of important units being sampled. (If the auxiliary variable is positively correlated with the square of the primary variable divided by the auxiliary variable, then variable probability sampling will have lower variance than simple random sampling (Raj, 1968).

For suspended sediment sampling, a convenient surrogate variable is an *estimate* of suspended sediment transport in an interval. This quantity is identical to the measured value just described, except that the pumped suspended sediment concentration sample is replaced by a rating curve estimate. That is, the auxiliary variable for the ith period, denoted by x_i, is the product of the average water discharge for the period, a rating curve estimate of suspended sediment concentration, the period length, and the same constant for adjusting units (Equation (2), Figure 7). The computer contains discharge and suspended sediment rating information, and by monitoring the stage, can automatically calculate the values of x_i.

Some preliminary information is required before sampling can begin. This is a common situation in sampling programs. The procedure can be started with limited knowledge and revised as data accumulate. A rudimentary rating curve can be developed from actual data, data in a comparable watershed, or merely estimated. Using a “bad” suspended sediment rating curve does not affect the unbiasedness of the estimators, but it does reduce sampling efficiency by increasing the variance.

The variable probability scheme applied to suspended sediment sampling is called Selection At List Time, or SALT sampling. It depends on an estimate of the total suspended sediment yield expected and on preselection of random sampling values which are stored in the computer. A brief outline of the procedure is given with references to Figures 7 and 8.

Before sampling begins, the total mass of sediment to be expected during the time period of interest is estimated. This value is multiplied by a factor, for example 10, so that the probability of the actual total exceeding this value is essentially zero. Call this value Y^*. An estimate of the required number of random values, n^*, is calculated so that the actual sampling process will yield a minimum sample size with an acceptable probability. (Sampling depends on values of the auxiliary variable, which are not all known until sampling is completed. The actual sample size, n, therefore, is a random variable.) The n^* uniform random numbers between 0 and Y^* are chosen, sorted into increasing order, and stored in the computer. The n^* random points lie on an axis from 0 to Y^* which will be referred to as the Y^* or sampling interval axis. These values govern which units will be selected for the sample and, being random, ensure that the units in the sample are mutually independent (see Figure 8).

The SALT process depends on forming one interval on the Y^*-axis for each sampling period monitored. In the middle of the ith time peRiod the computer reads the stage signal given by the shaft mounted transducer and calculates the value of the auxiliary variable, x_i. An interval of length x_i is then placed on the Y^*-axis immediately after the previous one. The list of random numbers is checked to see if any of the random values lie in this interval. If none do, no pumped sample is taken, the cumulative value of x_i is retained, and the computer waits until the next sampling period. If *one or more* random numbers falls in the interval, *one* pumped sample is taken. In this situation, not only is the cumulative value of x_i retained, but the number of random values in the interval (r_i in Figure 7), the value of x_i, and the discharge are stored as well.

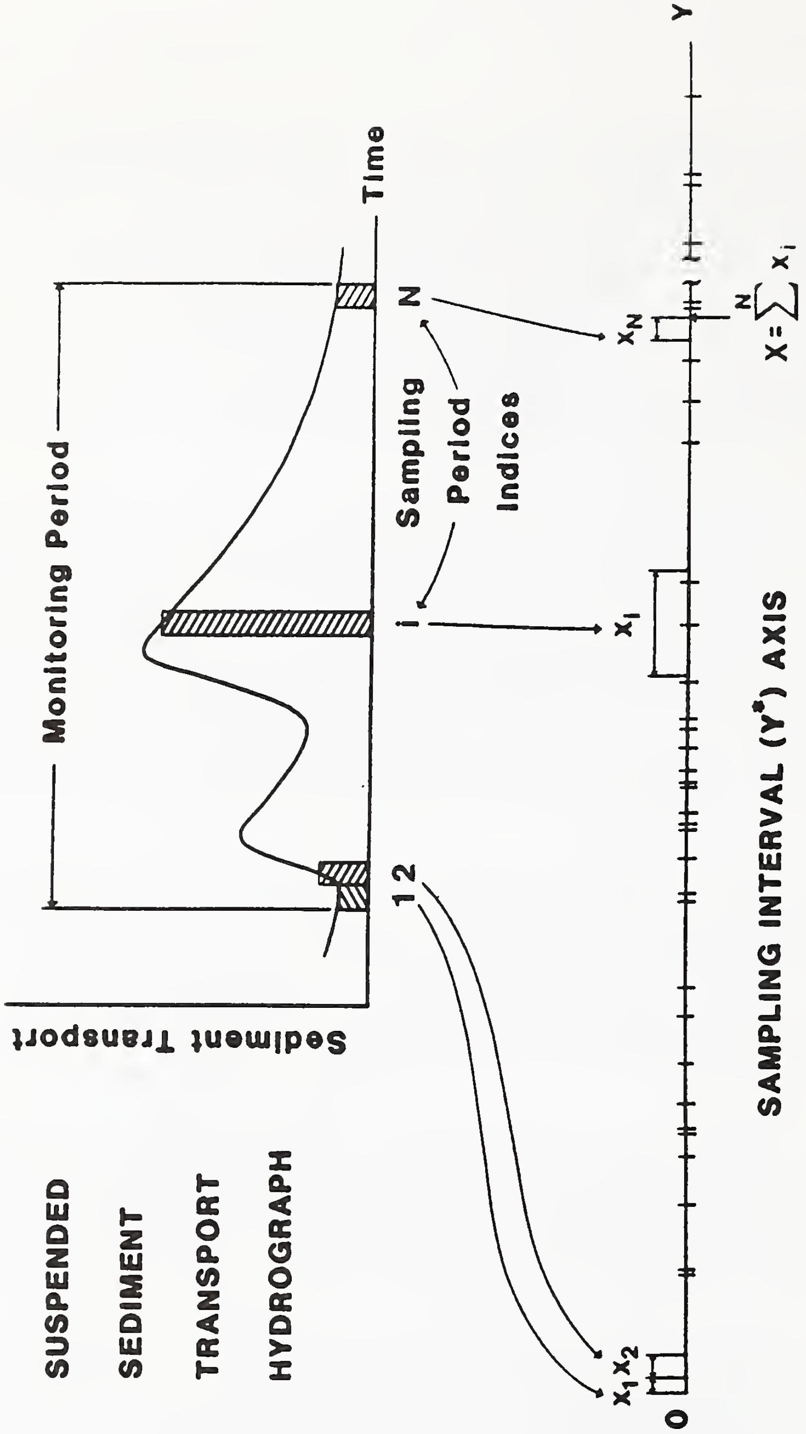


Figure 8. Suspended sediment transport hydrograph and corresponding sampling interval axis for SALT sampling. Note: The correspondence is between the equal duration sampling periods on the time axis and the variable length intervals of estimated suspended sediment discharge on the sampling interval axis. Ticks on the sampling interval axis denote random sampling numbers.

When all N sampling periods have passed, the total of the estimated suspended sediment transport values, X, can be calculated (Equation 3, Figure 7). Then the probability p_i of sampling the ith period is known. Those periods having large values of x_i form longer intervals on the Y^*-axis, and consequently have a greater probability of being sampled. Consequently, the efficiency of sampling depends on the ability of the sediment rating curve to estimate the "true" sediment discharge y_i. Once the pumped samples are analyzed in the laboratory, the *measured* values of suspended sediment yield for the periods actually sampled can be calculated from the associated discharges stored in the computer. The formula for an estimate, Y "hat", of the "true" total sediment yield, Y, is given in Equation (5) of Figure 7.

The sum in Equation (5) runs from 1 to N, but it is actually the sum of n nonzero terms, all derived from the sampled periods. Equation (4) in Figure 7 defines the sample size n, which is the total number of random points in the N intervals on the Y^*-axis that correspond to the N monitored sampling periods. The index variable r_i gives the number of random numbers contained in each interval. For intervals where r_i equals zero, no sample is taken and the term does not appear in the sum. If r_i does not equal zero, the corresponding y_i/x_i is multiplied by r_i (usually one) in the sum which is the same as y_i/x_i being included in the sum r_i times. Thus there are always n terms.

Equation (6) in Figure 7 is a minor algebraic rearrangement of Equation (5) showing that this estimate is an average of n estimates of the total, each consisting of the measure of mass transport for a sampling period divided by the probability of that period being selected for the sample. The estimated variance of the estimate of the total is given in Equation (7) of Figure 7.

The SALT estimates of the total and of the variance are both essentially unbiased (there is a small bias due to n being a random variable). The technique can be applied to periods between station visits and the separate estimates combined to give estimates for longer periods. Sample sizes can be selected to ensure that estimates of totals are within specified percentages of true values with stated probabilities (Thomas, 1985b).

8.5 SUMMARY OF SUSPENDED SEDIMENT SAMPLING

In spite of improved equipment and methodology, sampling for suspended sediment is a difficult undertaking. Sediment production is sporadic and highly variable which makes proper sampling difficult and effective sampling programs expensive. It is important that anyone contemplating such a program goes through an intensive planning period before any measurements are made.

It is difficult to overemphasize the need for adequate planning, especially because many studies of suspended sediment have not lived up to expectations. The hydrologist should take a hard look at the likely benefits of a study in light of management needs and available resources. There will be cases where the best decision is not to monitor. It is better to discover this before any data have been collected.

This section has covered material intended to be useful in planning a suspended sediment monitoring study. Above all, remember that such monitoring *is* a sampling process and should be designed to enable valid comparisons between populations. The only known methods for making such comparisons are statistical ones and those rely on appropriate random samples. It is for this reason that this section has emphasized the use of the SALT method for sampling to estimate total suspended sediment yield. The other techniques may be useful for certain applications, and the limitations of any proposed technique should be kept in mind during the planning process.

9.0 FLUVIAL-SEDIMENT DATA INTERPRETATION FOR MANAGEMENT DECISIONS

After collecting samples, making measurements, compiling data, and completing statistical analyses the hydrologist must convert the data into information to answer the management question which established the purpose of the data collection effort. The distinction between data and information is an important one. Based on statistical analyses, the hydrologist has an understanding of the character of data sets describing the samples of some population. The statistics provide yes/no answers about the differences between data sets, but it is up to the hydrologist to interpret these differences. Generally, such interpretation derives from an estimate of consequence.

Although a statistically significant difference may be observed in the data, the magnitude of difference may be inconsequential from a management perspective. On the other hand, a statement of no statistical significance, while a strong indicator, does not in itself mean that the effects being measured do not exist or are inconsequential.

When interpreting data there are many approaches available to display information. Such are beyond the scope of this report, however, the use of relative changes may have application to many Forest Service management situations. If one can assume reasonable consistency in the measurement of both the control and the treatment sites, then the *change* in sediment yield, due to treatment, from background values may be more useful to management than absolute values. This approach minimizes the likelihood of systematically high or low values being treated as though they, in themselves, depict the real world. Furthermore, this approach reduces the likelihood that such data can be erroneously used to evaluate the quality of land management practices.

10.0 SUMMARY

The collection of sediment data is a difficult, costly, and time consuming process. The data generated is subject to many forms of error and can be difficult to interpret. However, sediment data and its interpretations are an important source of information in the management of National Forest System lands. Its value is a direct function of how well the data collection program is designed.

A sediment data collection program must have the management questions to be addressed and the statistical analysis approach to be used prominently included in the earliest stages of program design. A failure to do so will result in a largely wasted effort.

Similarly, the collection and analysis of samples entails many decisions regarding equipment, location, measurement, and analysis technique. These decisions must be made in light of the purpose and statistical approach as well as practical considerations. Using the material presented in this report, the hydrologist should be able to select the proper physical and analytical tools for the job.

The value of the entire effort hinges upon the interpretations placed upon the data. The statistical analyses discussed should aid in this effort, but they cannot replace good professional judgment.

REFERENCES

American Public Health Association. 1976. Standard methods for the examination of water and wastewater. 14th ed. Washington, D.C.: American Water Works Association and Water Pollution Control Federation. pp. 38-45.

American Society for Testing and Materials (ASTM). 1983. 1983 annual book of ASTM standards, Section 11 – Water and Environmental Technology, Volume 11.02 - Water (II). Philadelphia, PA: ASTM. pp. 718-726 and 920-943.

Andrews, E.D. 1981. Measurement and computation of bed material discharge in a shallow sand-bed stream, Muddy Creek, Wyoming. Water Resources Research. 17:131-141.

Beschta, R.L. 1980a. Modifying automated pumping samplers for use in small mountain streams. Water Resources Bulletin. 16:137-138.

Beschta, R.L. 1980b. Turbidity and suspended sediment relationships. In: Proceedings, Symposium on watershed management; July 21-23, 1980; Boise, ID. New York: American Society of Civil Engineers. pp. 271-282.

Beschta, R.L. 1981. Increased bag size improves Helley-Smith bedload sampler for use in streams with high sand and organic matter transport. In: Erosion and sediment transport measurement: Proceedings of the Florence symposium; June 1981. IAHS Publ. 133. Wallingford, U.K.: International Association of Hydrological Sciences. pp. 17-25.

Beschta, R.L.; O'Leary, S.J.; Edwards, R.E.; Knoop, K.D. 1981a. Sediment and organic matter transport in Oregon Coast Range streams. WRRI-70. Corvallis, OR: Oregon State University, Water Resources Research Institute. 67 p.

Beschta, R.L.; Jackson, W.L.; Knoop, K.D. 1981b. Sediment transport during a controlled reservoir release. Water Resources Bulletin. 17:635-641.

Blaney, D.G.; Ponce, S.L.; Warrington, G.E. 1984. Statistical methods commonly used in soil data analysis. WSDG Report WSDG-TP-00011. Fort Collins, CO: Watershed Systems Development Group, USDA Forest Service. 223 p.

Borland, W. 1963. Unpublished figure. Denver, CO: U.S. Bureau of Reclamation.

Carey, W.P. 1984. A field technique for weighing bedload samples. Water Resources Bulletin. 20:261-265.

Carey, W.P. 1985. Variability in measured bedload transport rates. Water Resources Bulletin. 21:39-48.

Cochran, W.G. 1963. Sampling techniques. 2nd ed. New York: John Wiley and Sons. 413 p.

Druffel, L.; Emmett, W.W.; Schneider, V.R.; Skinner, J.V. 1976. Laboratory hydraulic calibration of the Helley-Smith bedload sediment sampler. U.S. Geological Survey Open File Report 76-752. 63 p.

Dunne, T.; Leopold, L.B. 1978. Water in environmental planning. San Francisco: W.H. Freeman and Co. 818 p.

Eads, R.E.; Boolootian, M.R. 1985. Controlling suspended sediment samplers by programmable calculator and interface circuitry. Research Note PSW-376. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, USDA Forest Service. 8 p.

Eads, R.E.; Thomas, R.B. 1983. Evaluation of a depth proportional intake device for automatic pumping samplers. Water Resources Bulletin. 19(2):289-292.

Edwards, T.K.; Glysson, G.D. 1988. Field methods for measurement of fluvial sediment. U.S. Geological Survey Open File Report 86-531.

Einstein, H.A. 1964. Sedimentation, Part II: River sedimentation. In: Handbook of Applied Hydrology, Section 17-II. V.T. Chow, ed. New York: McGraw-Hill. pp. 17-35 to 17-67.

Elliot, J.M. 1977. Some methods for the statistical analysis of benthic invertebrates. Fresh Water Biol. Assoc. Sci. Pub. 25. 144 p.

Emmett, W.W. 1980a. Bedload sampling in rivers. International symposium on river sedimentation; March 24-29, 1980; Beijing, China. pp. 991-1014.

Emmett, W.W. 1980b. A field calibration of the sediment trapping characteristics of the Helley-Smith bedload sampler. U.S. Geological Survey Professional Paper 1139. 44 p.

Emmett, W.W. 1981. Measurement of bedload in rivers. In: Erosion and sediment transport measurement: Proceedings of the Florence symposium; June 1981. IAHS Publ. 133. Wallingford, U.K.: International Association of Hydrological Sciences. pp. 3-15.

Emmett, W.W. 1984. Measurement of bedload in rivers. Chapter 5. In: Erosion and sediment: Methods of measurement and modelling. R.F. Hadley and D.E. Wallings, eds. Norwich, England: Geo Books. pp. 91-109.

Emmett, W.W.; Leopold, L.B.; Myrick, R.M. 1983. Some characteristics of fluvial processes in rivers. Preprinted from Proceedings of the second international symposium on river sedimentation; October 11-16, 1983; Nanjing, China. pp. 730-754.

Federal Interagency Sedimentation Project (FISP). 1986. Catalog: Instruments and reports for fluvial sediment investigations. Minneapolis, MN: St. Anthony Falls Hydraulic Laboratory; Interagency Advisory Committee on Water Data, Subcommittee on Sedimentation. 134 p.

Gomez, B. 1987. Bedload. Chapter 13. In: Glacio-fluvial sediment transfer. A.M. Gurnell and M.J. Clark, eds. New York: John Wiley and Sons Ltd. pp. 355-376.

Gregory, K.J.; Walling, D.E. 1973. Drainage basin form and process: a geomorphological approach. New York: John Wiley and Sons. 458 p.

Guy, H.P. 1969. Laboratory theory and methods for sediment analysis. U.S. Geological Survey Techniques of Water Resources Investigations. Book 5, Chapter Cl. 58 p.

Guy, H.P. 1970. Fluvial sediment concepts. U.S. Geological Survey Techniques of Water Resources Investigations. Book 3, Chapter Cl. 55 p.

Guy, H.P.; Norman, V.W. 1970. Field methods for measurement of fluvial sediment. U.S. Geological Survey Techniques of Water Resources Investigations. Book 3, Chapter C2. 59 p.

Heede, B.H. 1980. Stream dynamics: an overview for land managers. Gen. Tech. Report RM-72. Fort Collins, CO: Rocky Mountain Forest and Range Experiment Station, USDA Forest Service. 26 p.

Helley, E.J.; Smith, W. 1971. Development and calibration of a pressure difference bedload sampler. U.S. Geological Survey Open File Report. 18 p.

Hubbell, D.W. 1964. Apparatus and techniques for measuring bedload. U.S. Geological Survey Water Supply Paper 1748. 74 p.

Hubbell, D.W.; Stevens, H.H. Jr. 1986. Factors affecting accuracy of bedload sampling. In: Proceedings, 4th Federal interagency sedimentation conference, Vol. 1. Minneapolis, MN: Interagency Advisory Committee on Water Data, Subcommittee on Sedimentation. pp. 4-20 to 4-29.

Hubbell, D.W.; Stevens, H.H. Jr.; Skinner, J.V.; Beverage, J.P. 1985. New approaches to calibrating bedload samplers. American Society of Civil Engineers. Journal of Hydraulic Engineering. 111:677-694.

Interagency Committee on Water Resources. 1963. Determination of fluvial sediment discharge. Report No. 14. A study of methods used in measurement and analysis of sediment loads in streams. Minneapolis, MN: Subcommittee on Sedimentation. 151 p.

Johnson, C.W.; Engleman, R.L.; Smith, J.P.; Hanson, C.L. 1977. Helley-Smith Bedload samplers. American Society of Civil Engineers. Journal of Hydraulics Division. 103(HY10):1217-1221.

Jones, M.L.; Seitz, H.R. 1980. Sediment transport in the Snake and Clearwater Rivers in the vicinity of Lewiston, Idaho. U.S. Geological Survey Open File Report 80-690. 179 p.

Ketcheson, G.L. 1986. Sediment rating equations: an evaluation for streams in the Idaho batholith. General Technical Report INT-213. Ogden, UT: Intermountain Research Station, USDA Forest Service. 12 p.

Klingeman, P.C.; Emmett, W.W. 1982. Gravel bedload transport processes. Chapter 7 In: Gravelbed rivers. R.D. Hey, J.C. Bathurst, and C.R. Thorne, eds. New York: John Wiley and Sons Ltd. pp. 141-179.

Lane, E.W. 1955. The importance of fluvial morphology in hydraulic engineering. American Society of Civil Engineers. Journal of Hydraulics Division. 81:745-1 to 745-17.

Lane, E.W. 1957. A study of the shape of channels formed by natural streams flowing in erodible material. Report 9. Omaha, NE: U.S. Army Corps of Engineers, 106 p.

Leopold, L.B. 1970. An improved method for size distribution of stream bedgravel. Water Resources Research. 6:1357-1366.

Leopold, L.B.; Emmett, W.W. 1976. Bedload measurements, East Fork River, Wyoming. Proc. Nat. Acad. Sci. 73:1000-1004.

Leopold, L.B.; Wolman, M.G.; Miller, J.P. 1964. Fluvial processes in geomorphology. San Francisco: W.H. Freeman and Co. 268 p.

Murthy, M.N. 1967. Sampling theory and methods. Calcutta: Statistical Publishing Society. 684 p.

National Park Service. 1983. Automatic water samplers for field use. WRFSL Report No. 83-1. Fort Collins, CO: Colorado State University, Water Resources Field Support Laboratory. 17 p.

Office of Water Data Coordination (OWDC). 1978. National handbook of recommended methods for water data acquisition, Chapter 3. Reston, VA: U.S. Geological Survey. pp. 3-1 to 3-100.

O'Leary, S.J.; Beschta, R.L. 1981. Bedload transport in an Oregon Coast Range stream. Water Resources Bulletin. 17(5):886-894.

Paustian, S.J.; Beschta, R.L. 1979. The suspended sediment regime of an Oregon Coast Range stream. Water Resources Bulletin. 15:144-154.

Pickering, R.J. 1979. Quality of Water Branch Technical Memorandum No. 79-17. October 2, 1979. Reston, VA: U.S. Geological Survey. 5 p.

Pickering, R.J. 1980. Quality of Water Branch Technical Memorandum No. 80.07. February 5, 1980. Reston, VA: U.S. Geological Survey. 1 p.

Ponce, S.L. 1980a. Water quality monitoring programs. WSDG Report WSDG-TP-00002. Fort Collins, CO: Watershed Systems Development Group, USDA Forest Service. 66 p.

Ponce, S.L. 1980b. Statistical methods commonly used in water quality data analysis. WSDG Report WSDG-TP-00001. Fort Collins, CO: Watershed Systems Development Group, USDA Forest Service. 136 p.

Potyondy, J.P. 1980. Technical guide for preparing water quality monitoring plans. Ogden, Utah: Intermountain Region, USDA Forest Service. 74 p.

Raj, D. 1968. Sampling theory. New York: McGraw-Hill. 302 p.

Reid, I.; Frostick, L.E. 1986. Dynamics of bedload transport in Turkey Brook, a coarse grained alluvial channel. Earth Surface Processes and Landforms. 11:143-155.

Reid, I.; Frostick, L.E. 1987. Toward a better understanding of bedload transport. In: Recent developments in fluvial sedimentology: Contributions from the third international fluvial sedimentology conference. April, 1987. Special Publication No. 39. Tulsa, OK: Society of Economic Paleontologists and Mineralogists. pp. 13-19.

Rice, R.M.; Tilley, F.B.; Datzman, P.A. 1979. A watershed's response to logging and roads: South Fork of Caspar Creek, CA, 1967-1976. Res. Paper PSW-146. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, USDA Forest Service. 12 p.

Richardson, E.V.; Simons, D.B.; Karaki, S.; Mammood, K.; Stevens, M.A. 1975. Highways in the river environment, hydraulic and environmental design considerations. Chapter III. In: Training and design manual. Federal Highway Administration. pp. III-1 to III-82.

Ritter, J.R.; Helley, E.J. 1968. An optical method for determining particle sizes of coarse sediment. U.S. Geological Survey Open File Report. 43 p.

Simons, D.B. 1971. River and canal morphology. In: Shen, H.W., ed. River mechanics. Fort Collins, CO: Colorado State University. pp. 20-1 to 20-38.

Skinner, J.V.; Beverage, J.P. 1982. A fluid density gage for measuring suspended sediment concentration. Report X. Minneapolis, MN: Federal Interagency Sedimentation Project. 125 p.

Sokal, R.R.; Rohlf, F.J. 1969. Biometry. San Francisco: W.H. Freeman and Co. 776 p.

Steel, R.G.D.; Torrie, J.H. 1960. Principles and procedures of statistics with special reference to the biological sciences. New York: McGraw-Hill. 481 p.

Thomas, R.B. 1983. Errors in estimating suspended sediment. In: Proceedings of the D.B. Simons symposium on erosion and sedimentation; July 27-29, 1983; Fort Collins, CO. pp. 1.162-1.177.

Thomas, R.B. 1985a. Measuring suspended sediment in small mountain streams. General Technical Report PSW-83. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, USDA Forest Service. 9 p.

Thomas, R.B. 1985b. Estimating total suspended sediment yield with probability sampling. Water Resources Research. 21(9):1381-1388.

Thomas, R.B.; Eads, R.E. 1983. Contamination of successive samples in portable pumping systems. Water Resources Research. 19(2):436-440.

Truhlar, J.F. 1978. Determining suspended sediment loads from turbidity records. Hydrological Sciences Bulletin. 23(4):409-417.

Van Sickle, J.; Beschta, R.L. 1983. Supply based models of suspended sediment transport in streams. Water Resources Research. 19(3):768-778.

Walling, D.E. 1977a. Assessing the accuracy of sediment rating curves for a small basin. Water Resources Research. 13(3):531-538.

Walling, D.E. 1977b. Limitations of the rating curve technique for estimating suspended sediment loads, with particular reference to British rivers. In: Proceedings of the symposium on erosion and solid matter transport in inland waters; July 1977; Paris. IAHS Publ. 122. Dorking, Surrey, U.K.: International Association of Hydrological Sciences. pp. 34-48.

Walling, D.E.; Webb, B.W. 1981. The reliability of sediment load data. In: Proceedings of the Florence symposium; June 1981. IAHS Publ. 133. Wallingford, U.K.: International Association of Hydrological Sciences. pp. 177-193.

Wolman, M.G. 1954. A method of sampling coarse river bed material. American Geophysical Union Trans. 35:951-956.

Yaksich, S.M.; Verhoff, F.H. 1983. Sampling strategy for river pollutant transport. Journal of Environmental Engineering. 109(1):219-231.

APPENDIX A

FLUVIAL-SEDIMENT TERMINOLOGY

Aggradation – The geologic process by which streambeds, floodplains, and the bottoms of other water bodies are raised in elevation by the deposition of material eroded and transported by water from other areas. It is the opposite of degradation.

Alluvial deposit – Clay, silt, sand, gravel, or other sediment deposited by the action of running or receding water.

Alluvial stream – A stream whose channel boundary is composed of appreciable quantities of the sediments transported by the flow, and which generally changes its bed form as the rate of flow changes.

Antidunes – A series of generally sinusoidal shaped bed forms that commonly move upstream accompanied by inphase waves on the water surface. Antidunes develop in a sand bed stream when the Froude number is close to or greater than one.

Armouring – The formation of a resistant layer of relatively large particles resulting from sorting of bed material and/or removal of finer particles by erosion.

Bedload – Material moving on or near the streambed by rolling, sliding, and sometimes bouncing into the flow a few diameters above the bed.

Bedload discharge – The quantity of bedload (mass or volume) passing a cross section in the stream per unit of time.

Bed material – The sediment mixture of which the streambed is composed. In alluvial streams bed material particles are likely to be moved during moderate or high flow conditions.

Bed material load – That part of the sediment load of a stream which is composed of particle sizes present in appreciable quantities in the streambed.

Concentration of sediment (by mass or weight) – The ratio of the mass or weight of dry sediment in a water sediment mixture to the mass or weight of the mixture.

Concentration of sediment (by volume) – The ratio of the mass or weight of dry sediment in a water sediment mixture to the volume of the mixture.

Degradation – The geologic process by which streambeds, floodplains, and the bottoms of other water bodies are lowered in elevation by the removal of material eroded by water. It is the opposite of aggradation.

D_{50} – The particle diameter size for which 50% of the sediment mixture is finer (similarly for D_{35}, D_{65}, D_{70}, D_{85}, D_{90}, etc.).

Deposition – The physical or chemical process through which sediments accumulate in a resting place.

Depth integration – A method of sampling at every point throughout the sampled depth whereby a water sediment mixture is collected so that the contribution to the sample from each point is proportional to the stream velocity at the point. This yields a discharge weighted sample.

Dunes – Bed forms which are generally transverse to the direction of flow with a triangular profile that advance downstream due to net deposition of particles from the gentle upstream slope onto the steep downstream slope. Dunes move downstream at velocities that are small relative to the stream flow velocity.

Equal-discharge increment (EDI) – A method for obtaining the discharge weighted suspended sediment concentration of flow at a stream cross section by (1) performing depth integration at the centers of three or more equal discharge increments of the cross section, and (2) using a uniform vertical transit rate at each sampling vertical.

Equal-transit rate (ETR) – Obsolete, replaced by the term "equal-width increment."

Equal-width increment (EWI) – A method for obtaining the discharge-weighted suspended-sediment concentration of flow at a stream cross section by: (1) performing depth integration at a series of verticals equally spaced across the cross section, and (2) using the same vertical transit rate at all sampling verticals.

Fine-material load – That part of the total sediment load that is composed of particles of a finer size than the particles present in appreciable quantities in the bed material. Normally the fine material load consists of material finer than 0.062 mm. Also called wash load.

Fluvial – (1) Pertaining to streams; (2) growing or living in streams or ponds; (3) produced by stream action, such as a fluvial plain.

Froude number – A dimensionless number expressing the ratio between the influence of inertia and gravity in a fluid. It is the velocity squared divided by the product of hydraulic depth times the acceleration due to gravity.

Graded stream – A stream in which a steady state has been reached such that over a period of time, the discharge and sediment load entering the system are balanced by the discharge and sediment load leaving the system.

Hysteresis – The behavior of a system wherein the system's response to a given level of an independent variable is a function of the system's immediate history.

Isokinetic sampling – Sampling in such a way that the water-sediment mixture does not accelerate as it enters the sampler intake.

Median diameter – The size of sediment such that one half of the mass of the material is composed of particles larger than the median diameter, and the other half is composed of particles smaller than the median diameter (also written as D_{50}).

Multiple equal-width increment (MEWI) – A method for collecting bedload samples. Starting at one bank and proceeding to the other, 8 to 10 samples are collected at 4 to 5 evenly spaced verticals for a total of 40 samples per stream cross section.

Nominal diameter – The diameter of a sphere that has the same volume as the sediment particle.

Particle size – A linear dimension, usually designated as "diameter", used to characterize the size of a particle. The dimension may be determined by any of several different techniques, including sedimentation, sieving, micrometric measurement, or direct measurement.

Particle size distribution – The frequency distribution of the relative amounts (by weight) of particles in a sample that are within specified size ranges, or a cumulative frequency distribution of the relative amounts (by weight) of particles coarser or finer than specified sizes.

Pebble count – A method of measuring bed material composition involving manual collection while wading a channel.

Point integration – A method of sampling at a relatively fixed point whereby the water sediment mixture is withdrawn isokinetically for a specified period of time.

Rating curve, sediment – A graph of the relationship between sediment discharge and stream discharge at a stream cross section.

Ripple – Small triangular shaped bed forms that are similar to dunes but have much smaller heights and lengths of 0.3 mm or less. They develop when the Froude number is less than approximately 0.3.

Sampling vertical – An approximately vertical path from the water surface to the bottom along which one or more samples are collected to define various properties of the flow, such as sediment concentration.

Scour – The localized enlargement of a flow section by the removal of boundary material through the action of the fluid in motion. It occurs during relatively short periods of time (minutes, hours, days, seasons) and may result in no net change in bed elevation of a stream reach.

Sediment – (1) Particles derived from rocks (inorganic sediment) or biological materials (organic sediment) that have been transported by a fluid; (2) solid material suspended in or settled from water.

Sedimentation – A broad term that pertains to the five fundamental processes responsible for the formation of sedimentary rocks: (1) weathering, (2) detachment, (3) transportation, (4) deposition, and (5) diagenesis (consolidation into rock); and to the gravitational settling of suspended particles that are heavier than water. More commonly the term is used to denote detachment, transporation, or deposition.

Sediment discharge – See sediment transport rate.

Sediment load – A general term that refers to material in suspension and/or in transport, but not to the quantity being moved. It is not synonymous with either discharge or concentration (see bedload and suspended load).

Sediment sample – A quantity of water sediment mixture or deposited sediment that is collected to characterize some property or properties of the sampled medium.

Sediment transport rate – The mass or volume of sediment (usually mass) passing a stream cross section in a unit of time. The term may be qualified, for example, as suspended sediment transport rate, bedload transport rate, or total sediment transport rate.

Sediment yield – The total sediment outflow from a drainage basin in a specific period of time. It includes bedload as well as suspended load, and usually is expressed in terms of mass or volume per unit of time.

Single equal-width increment (SEWI) – A method for collecting bedload samples. Starting at one bank and proceeding to the other, one bedload sample is collected per vertical at 20 evenly spaced verticals in the stream cross section. Returning to the same bank, the process is repeated for a total of 40 bedload samples per cross section.

Split sample – A single sample separated into two or more parts such that each part is representative of the original sample.

Standard fall diameter – Sometimes simply fall diameter. The diameter of a sphere that has a specific gravity of 2.65 and has the same standard fall velocity as the particle.

Standard fall velocity – The average rate of fall that a particle would finally attain if falling alone in quiescent distilled water of infinite extent at a temperature of 24° C.

Standard sedimentation diameter – The diameter of a sphere that has the same specific gravity and the same standard fall velocity as the given particle.

Stream power – The rate of doing work of a stream representing the product of gravitational acceleration, mass density of the fluid, discharge and water surface slope.

Streambank erosion – The removal of bank material by the force of flowing water and localized mass failures of streambanks.

Suspended load – That part of the sediment load which is suspended sediment.

Suspended sediment – Sediment that is carried in suspension by the turbulent components of the fluid or by Brownian movement.

Suspended-sediment concentration – See concentration of sediment.

Suspended-sediment discharge – The quantity (usually mass) of suspended sediment passing a stream cross section in a unit of time.

Thalweg – The line connecting the lowest or deepest points along a streambed, valley, or reservoir, whether under water or not.

Total sediment discharge – The total quantity of sediment passing a stream cross section in a unit of time.

Total sediment load (total load) – All of the sediment in transport which includes suspended-sediment load and bedload.

Turbidity – An expression of the optical properties of a sample which causes light rays to be scattered and absorbed rather than transmitted through the sample. Units depend upon method or type of instrumentation used for measurement.

Unequal-width increment (UWI) – A method for collecting bedload samples. Starting at one bank and proceeding to the other, 4 to 10 samples are collected from 4 to 10 unevenly spaced verticals for a total of 40 samples per cross section. The verticals should be spaced unevenly according to observed uniformity in depth and velocity such as midway between major breaks in the lateral bed slope and closer together in sections of high velocity and changing lateral bed slope.

Unsampled depth – The unsampled part of the sampling vertical; usually within 8-15 cm of the streambed depending on the kind of suspended-sediment sampler used.

Wash load – See fine-material load.

APPENDIX B

LINE DRAWINGS AND PHOTOGRAPHS OF FLUVIAL-SEDIMENT SAMPLERS

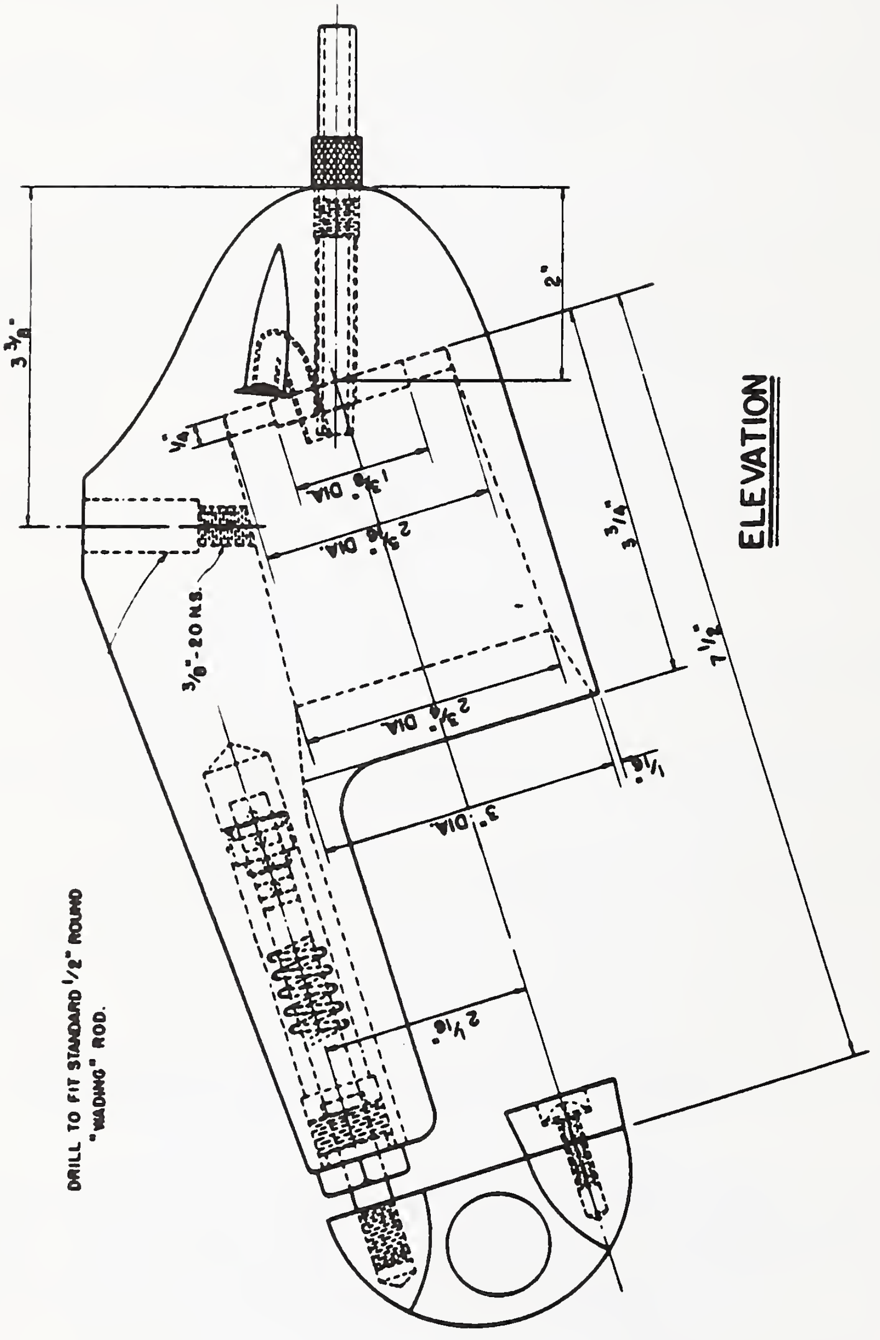


Figure 9. US DH-48 Depth-Integrating Suspended Sediment Wading-Type Sampler (FIASP, 1981, p. 3)

*U.S. GOVERNMENT PRINTING OFFICE: 1991--517-013/46554

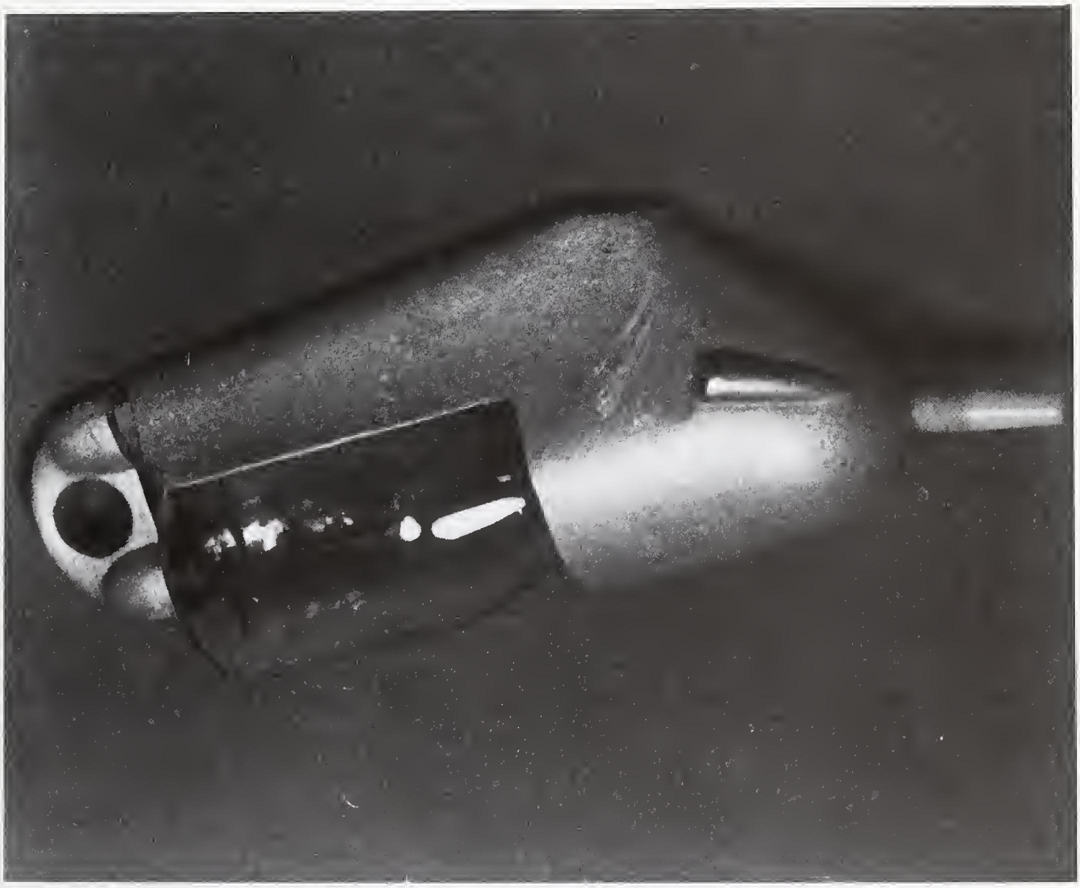


Figure 10. Photograph of the US DH-48 Sampler

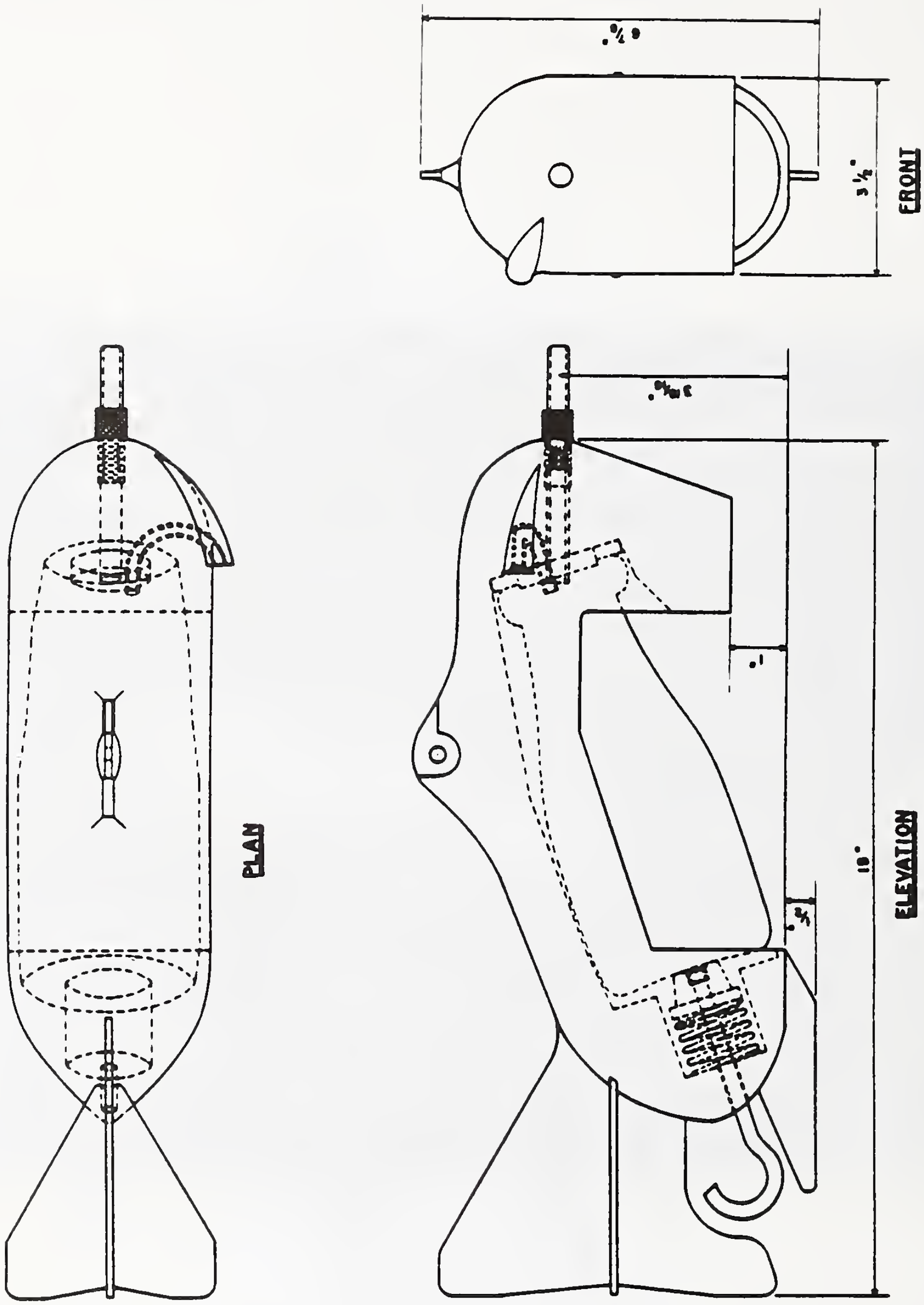


Figure 11. US DH-59 Depth-Integrating Suspended Sediment Hand-Line Sampler (FIASP, 1981, p. 11)

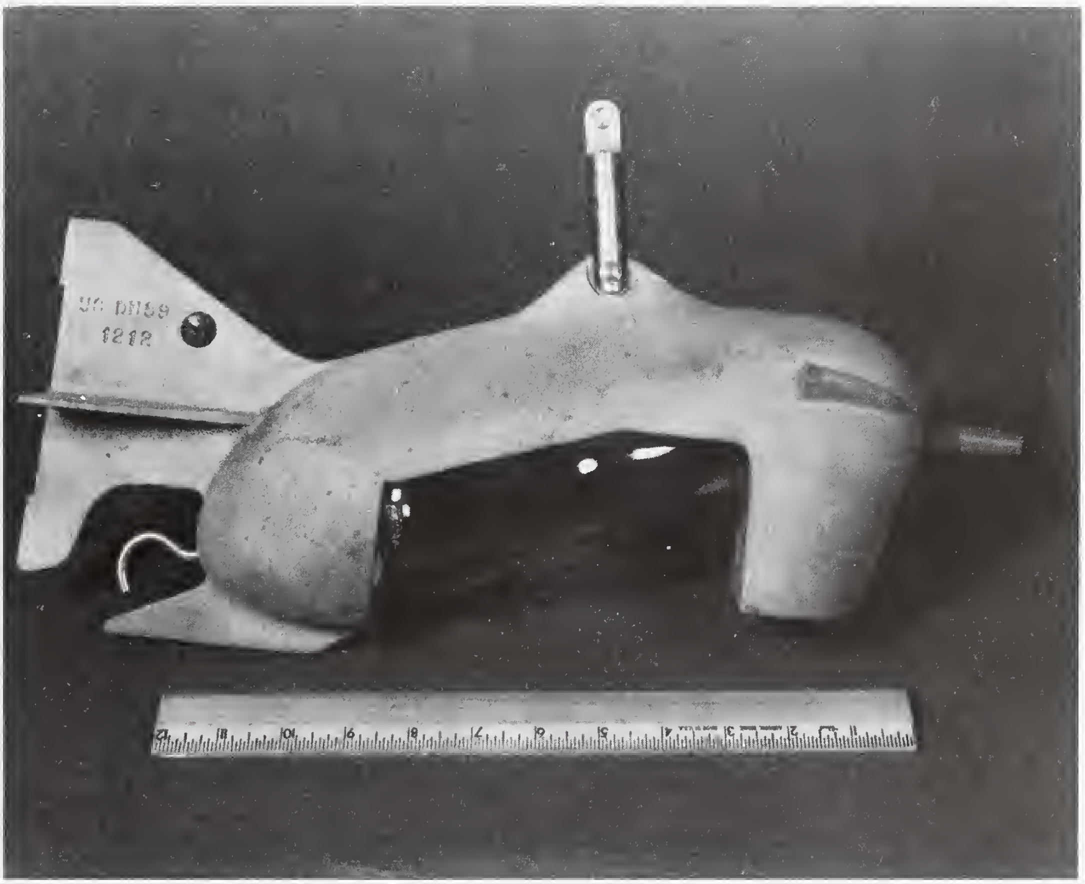


Figure 12. Photograph of the US DH-59 Sampler

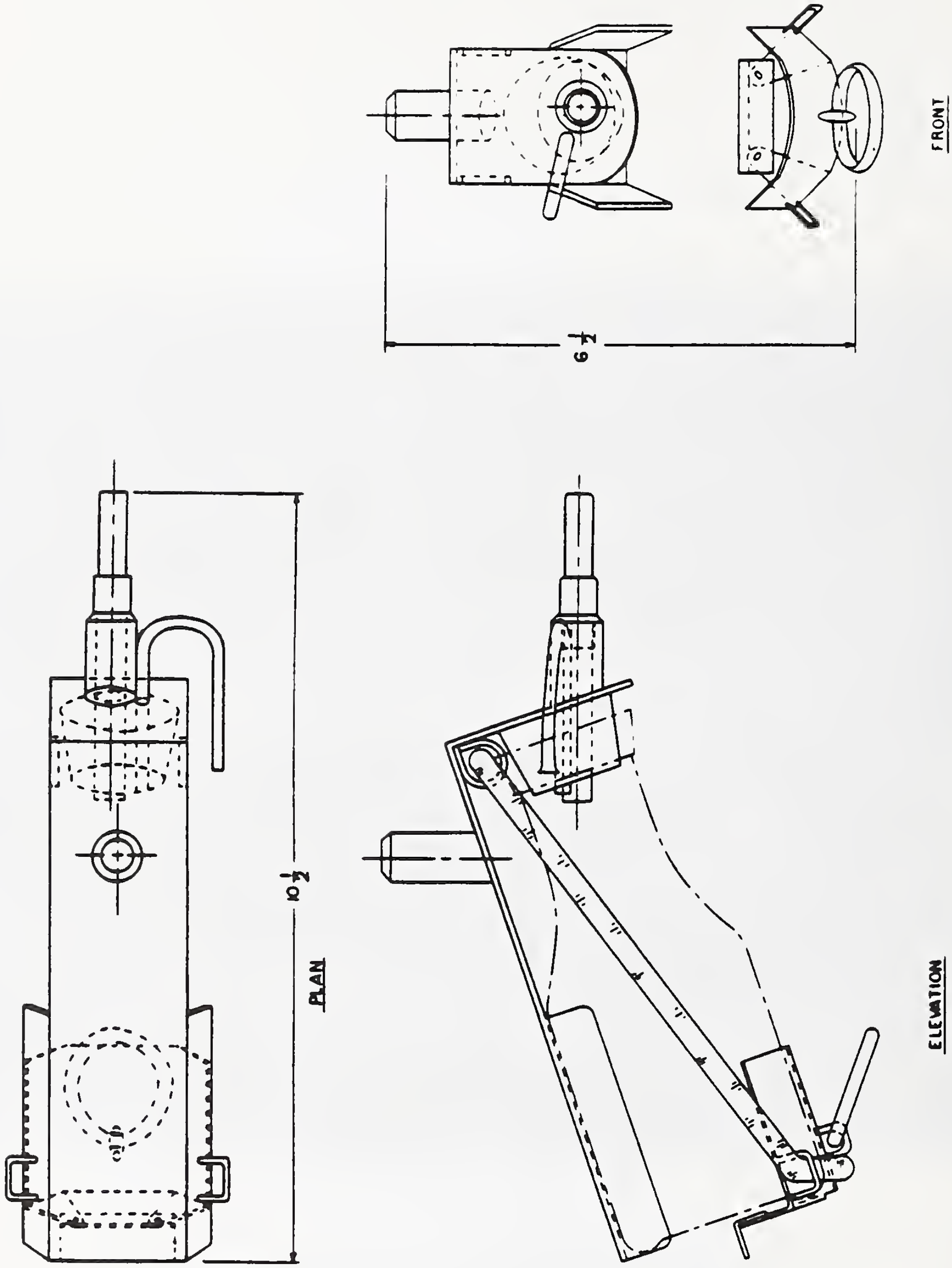


Figure 13. US DH-75 Depth-Integrating Suspended Sediment Wading-Type Sampler (FIASP, 1981, p. 8)

Figure 14. Photograph of the US DH-75 Sampler

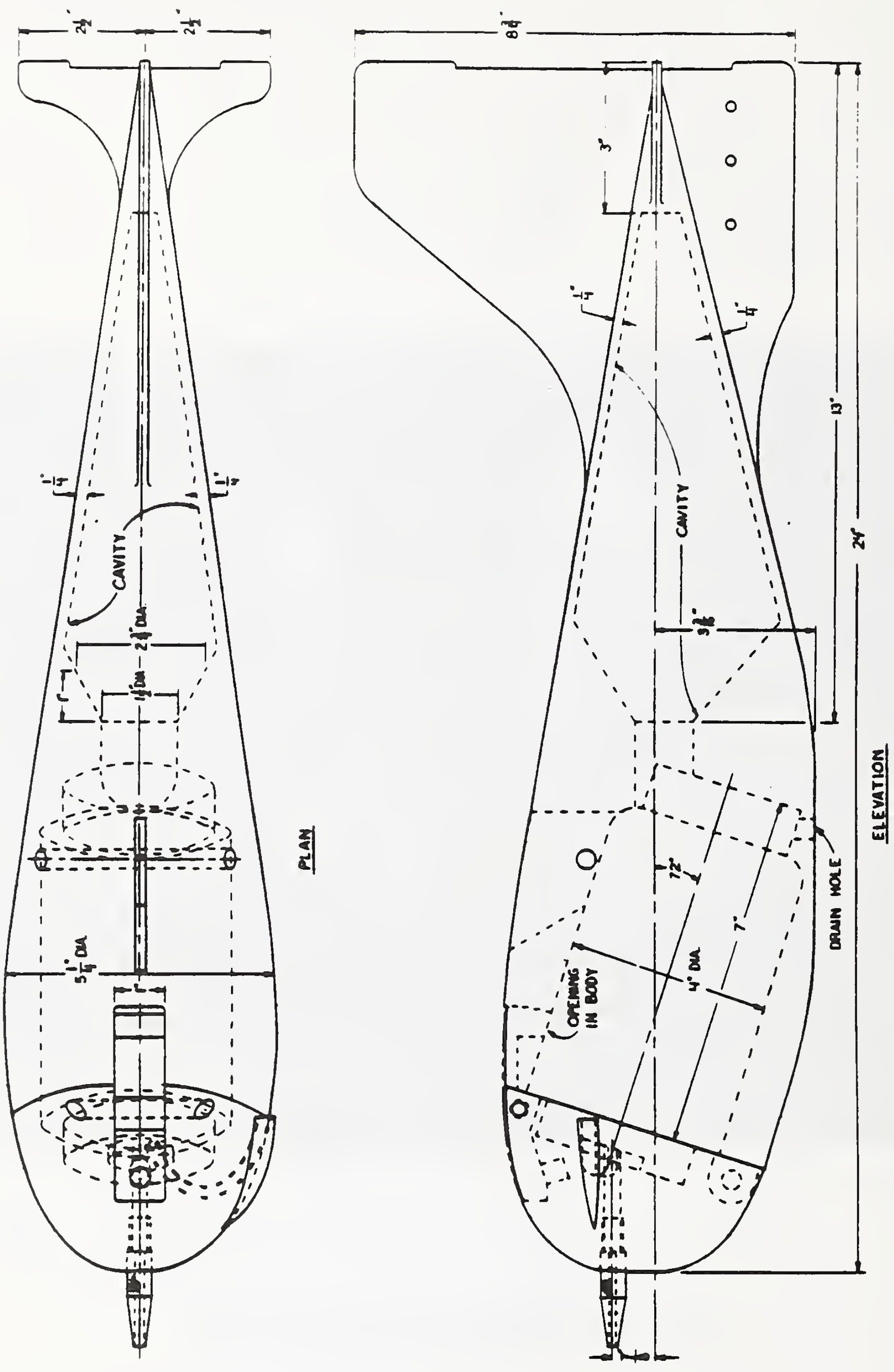


Figure 15. US D-74 Depth-Integrating Suspended Sediment Cable-and-Reel Sampler (FIASP, 1981, p. 17)

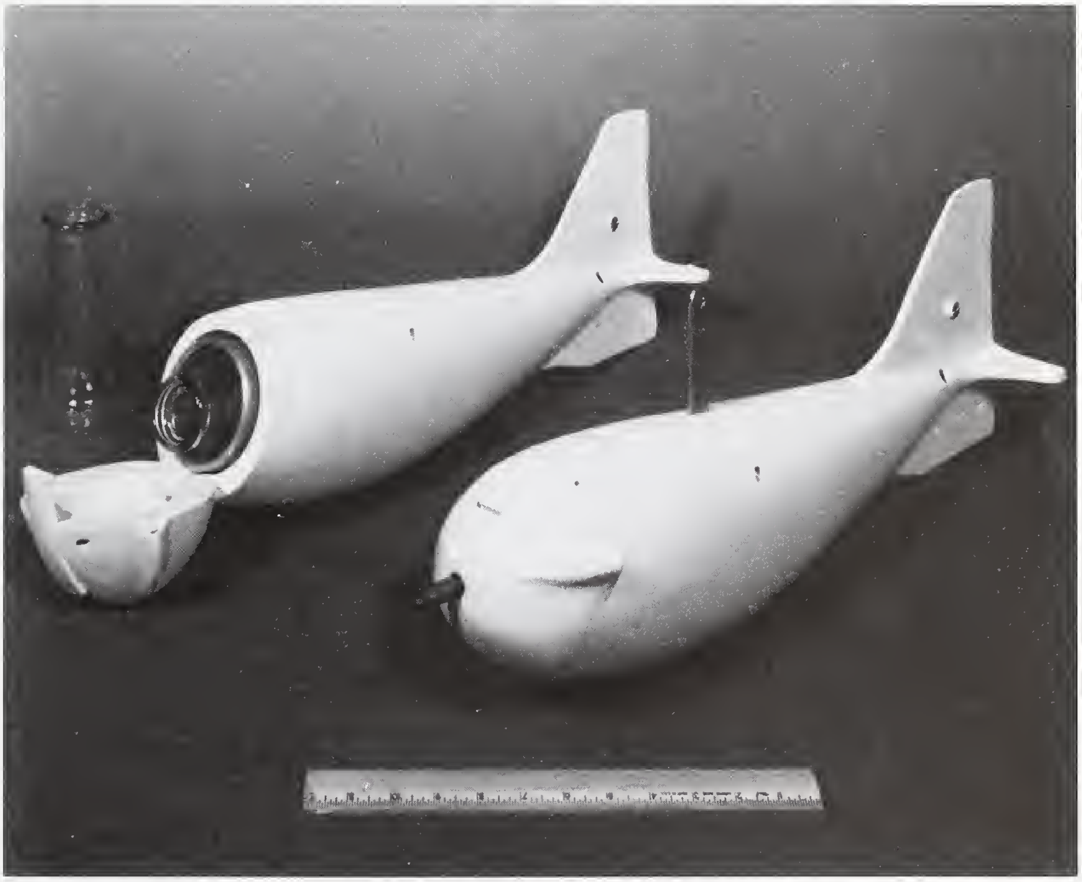
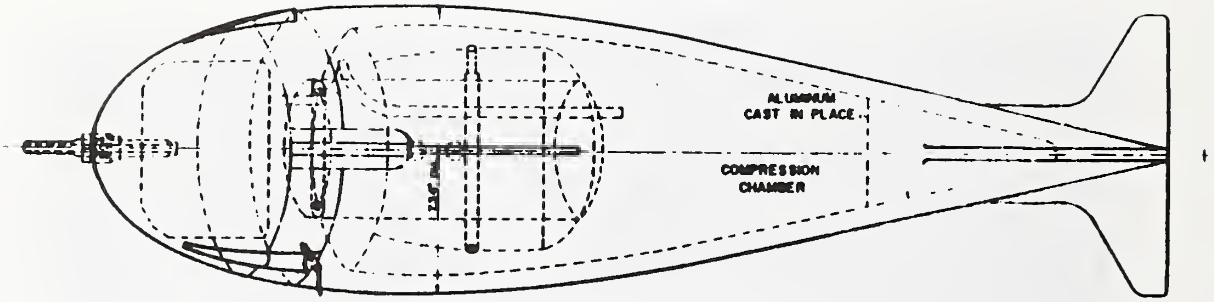
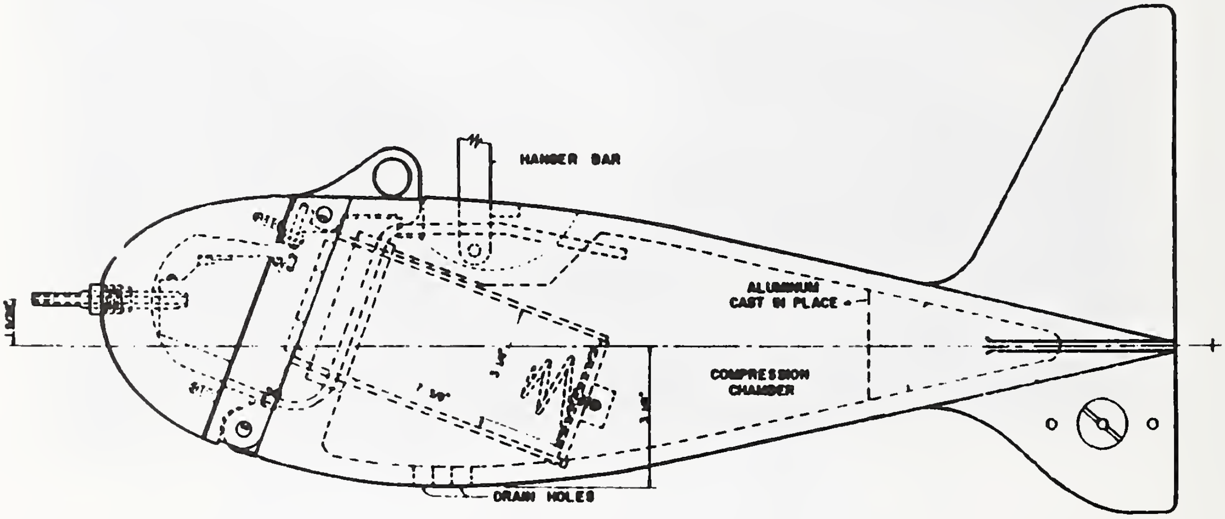


Figure 16. Photograph of the US D-74 Sampler



PLAN



ELEVATION

Figure 17. US P-61AL Point-Integrating Suspended Sediment Cable-and-Reel Sampler (FIASP, 1981, p. 32)

Figure 18. Photograph of the US P-61AL Sampler

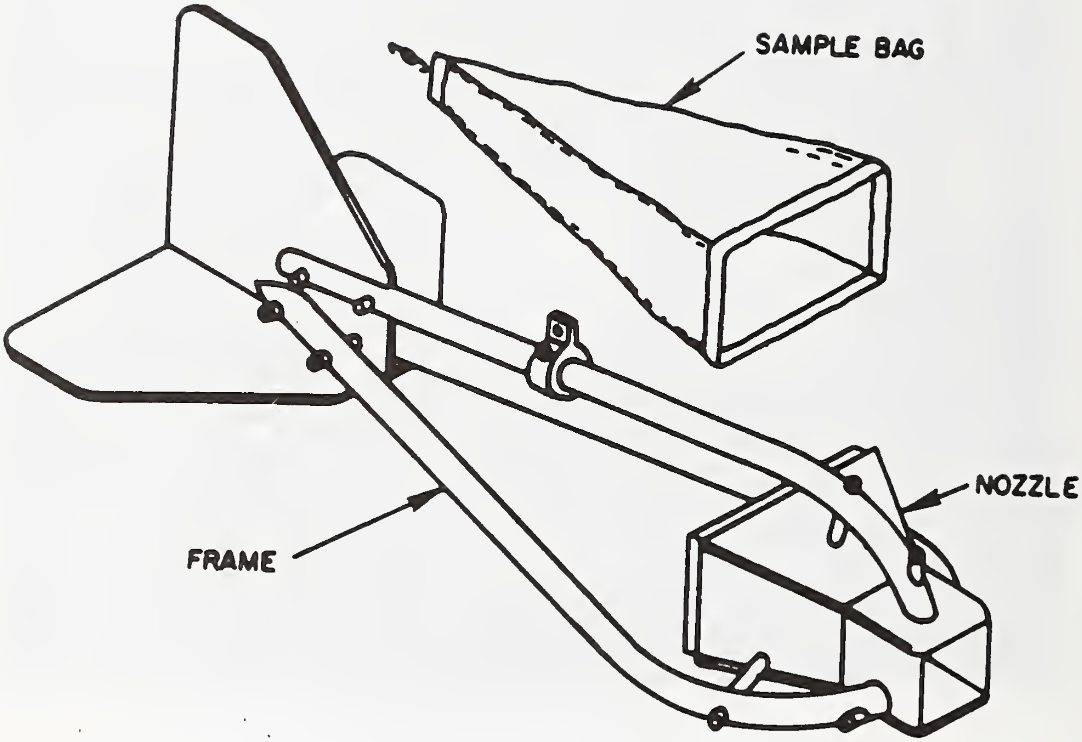


Figure 19. Original Helley-Smith Bedload Sampler
(Druffel, et al., 1976, p. 4)

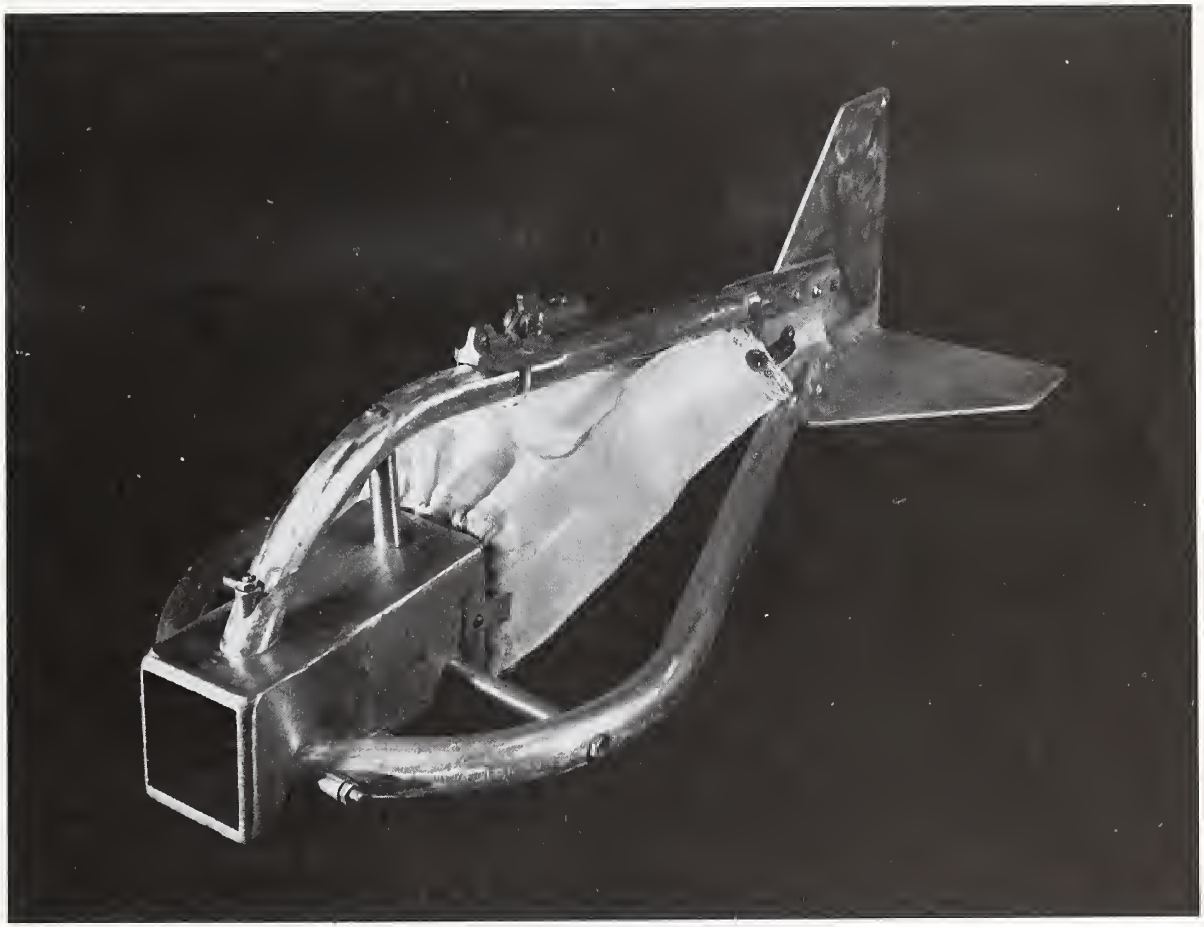


Figure 20. Photograph of the New "Standard" Helley-Smith Bedload Sampler

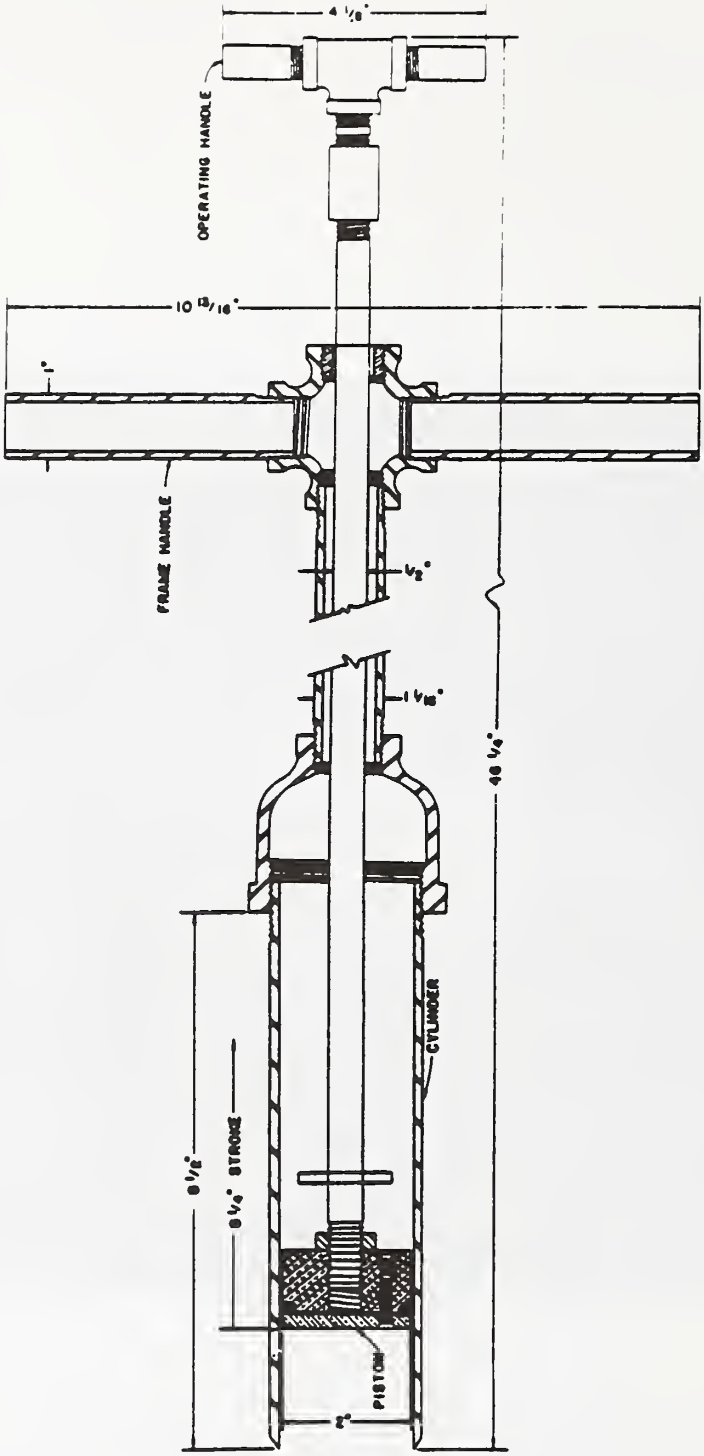


Figure 21. US BMH-53 Piston-Type Bed Material Hand Sampler (FIASP, 1981, p. 94)

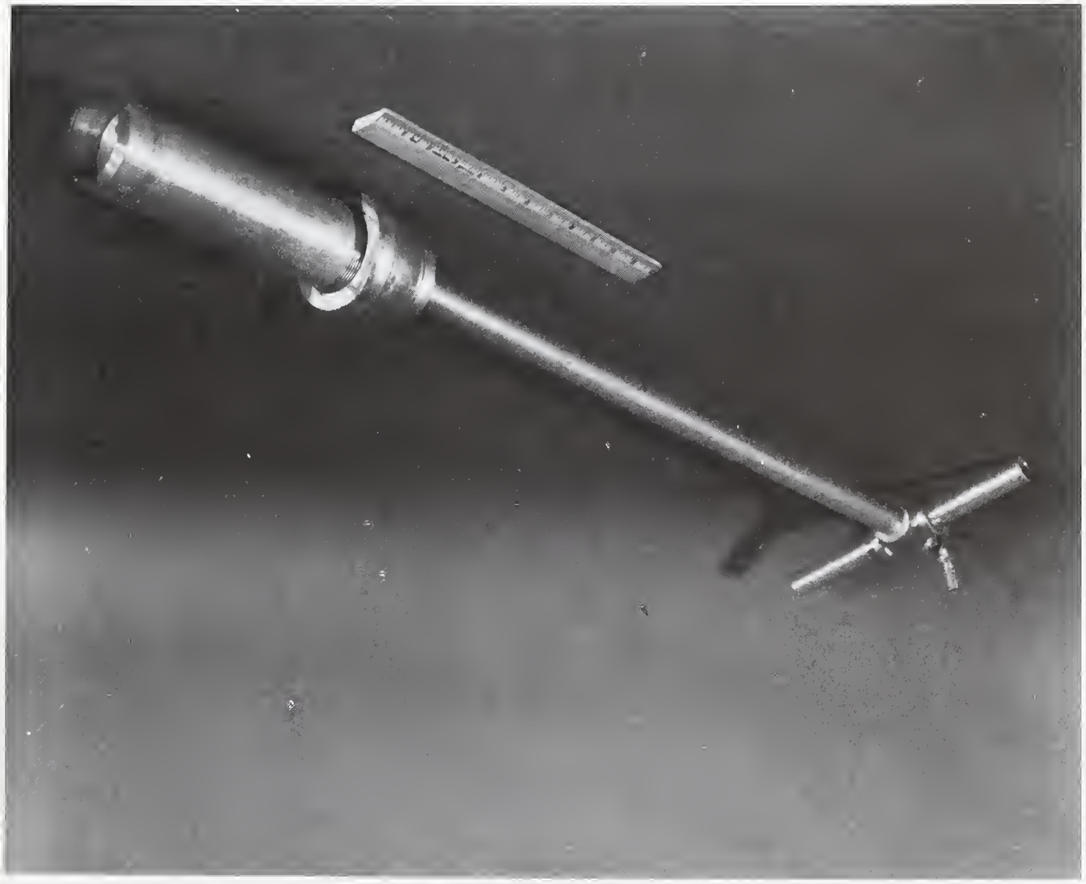


Figure 22. Photograph of the US BMH-53 Sampler

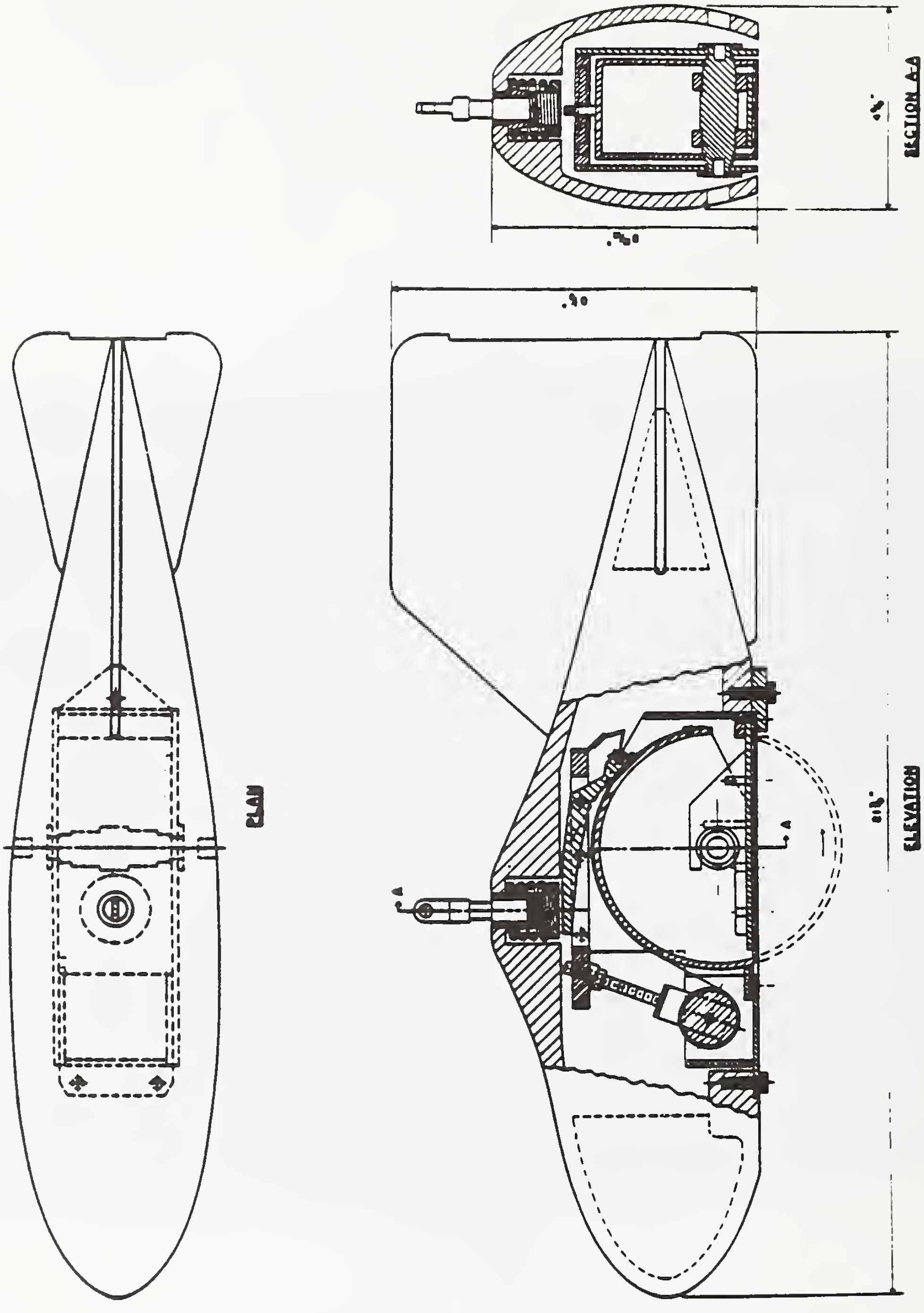


Figure 23. US BMH-60 Bed Material Hand-Line Sampler (FIASP, 1981, p. 98)

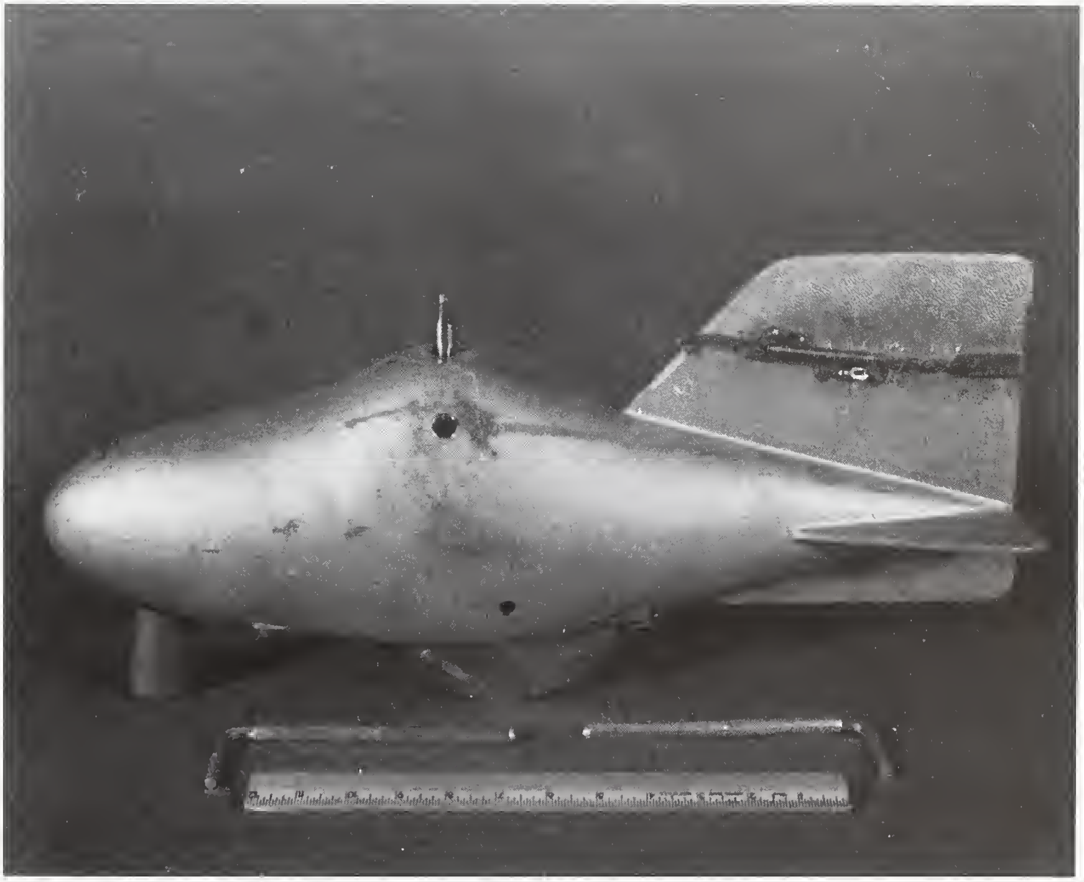


Figure 24. Photograph of the US BMH-60 Sampler