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TABLE OF CONTENTS

Page

FOREWORD i
LIST OF ATTENDANCE v
ADDRESS OF WELCOME, by L. N. McClellan 1
PERSPECTIVE ON SEDIMENTATION - PURPOSE OF CONFERENCE, by Carl B. Brown 3

FIRST SESSION - STATEMENT OF SEDIMENTATION PROBLEMS

RESERVOIR PROBLEMS WITH RESPECT TO SEDIMENTATION, by Thomas Maddock, Jr. 9
Discussion by Gunnar M. Brune and Vito A. Vanoni 14
SEDIMENTATION PROBLEMS RELATED TO FLOODWAYS, NAVIGATION CHANNELS AND HARBORS, by Gail A. Hathaway 18
Discussion by Elliott Flaxman, Carl B. Brown, Gerard H. Matthes, J. W. Dixon, and Ralph F. Rhodes 24
SEDIMENTATION PROBLEMS OF THE LAND, by E. N. Munns 29
Discussion by John N. Spencer, Harold B. Elmendorf, and Ranbir Singh Shrikant 34

Select Papers

SECOND SESSION - PART I - AGENCY SEDIMENTATION PROGRAMS

SEDIMENTATION PROGRAM OF THE CORPS OF ENGINEERS, by H. K. Armstrong 39
SEDIMENTATION PROGRAM OF THE BUREAU OF RECLAMATION, by Whitney M. Borland 43
SEDIMENTATION PROGRAM OF THE GEOLOGICAL SURVEY, by S. K. Love 46
SEDIMENTATION PROGRAM OF THE DEPARTMENT OF AGRICULTURE, by Bernard Frank 49
THE SILT INVESTIGATIONS PROGRAM OF THE TENNESSEE VALLEY AUTHORITY, by M. A. Churchill 52
Discussion by Col. C. L. Hall 54

SECOND SESSION - PART II - DETERMINATION AND INTERPRETATION OF SEDIMENT LOAD

DETERMINATION OF THE SUSPENDED SEDIMENT DISCHARGE OF STREAMS, by Paul C. Benedict 55
Discussion by R. J. Pafford, Jr. 65
SEDIMENT ENGINEERING AS A QUANTITATIVE SCIENCE, by E. W. Lane 68
Discussion by S. K. Love, Victor H. Jones, Parker D. Trask, Thomas Maddock, Jr., and Albert S. Fry 72
DETERMINATION OF RATES OF BED-LOAD MOVEMENT, by Hans A. Einstein 75
Discussion by H. K. Armstrong, Billy T. Mitchell, and D. V. C. Birrell 91

SECOND SESSION - PART I - AGENCY SEDIMENTATION PROGRAMS

Gail A. Hathaway,* Presiding

SEDIMENTATION PROGRAM OF THE CORPS OF ENGINEERS

by H. K. Armstrong **

Introduction

The preceding papers on this program have been devoted principally to statements concerning the scope and importance of the sedimentation problem. A natural question arises, "What steps are being taken to improve the situation and what is the plan of action?" The complete answer to this question would be as broad as the field of interest. A partial answer was contained in the action of the Federal Inter-Agency River Basin Committee when that body established the sub-committee on sedimentation. A means of exchange of ideas and interests was established upon effecting the distribution of minutes of the sub-committee, and through the publication and distribution of the sub-committee's newsletter supplement. Further action was taken by the parent committee when it sponsored this conference. Each of the foregoing accomplishments has a single distinction - cooperative action. Through cooperative action, all concerned have undertaken an approach to a solution of the problem.

In view of the diversity of responsibilities and interests of the various agencies, a problem that involves such numerous ramifications can be successfully engaged and eliminated, or at least confined, only through a program of associated and mutual effort.

Since first charged with the responsibility of developing and maintaining rivers and harbors for flood control and navigation purposes, the Corps of Engineers has been actively engaged in combating the sedimentation problem. A few items included in the present program of the Corps of Engineers will be briefly mentioned in this paper. For the purpose of establishing geographical orientation, areas of activities are identified by Division Offices of the Corps of Engineers.

Program of Activities

New England Division

The New England Division has completed a sedimentation observation system on Franklin Falls Reservoir, and work is 50 percent completed on the system for Blackwater Reservoir. Plans have been completed for similar systems at Knightville, Surry Mountain and Birch Hill Reservoirs.

Regulatory work has been authorized and initiated on the Connecticut River to reduce sediment deposition in this stream. On Press Barn Bar, where dikes were built in 1939, the annual volume of maintenance dredging in the channel has dropped from about 40,000 cubic yards to about 10,000 cubic yards. As additional works are constructed, the value of such means of control should become more conclusive. A series of eight dikes was constructed at the Glastonbury bend in 1945, and a series of eight is proposed to be constructed at the Wethersfield bend this year.

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Comparative data available from this additional regulation within the next few years should indicate the effective value of the method.

Worthy of mention in connection with the sedimentation program in the New England Division are the annual maintenance dredging operations that involve an estimated average quantity of 1,300,000 cubic yards of material.

North Atlantic Division

In connection with the design of three flood-control reservoir projects authorized for construction in the North Atlantic Division, an average annual rate of 50 acre-feet per 100 square miles of drainage area was used in estimating the effect of silting. This conclusion was drawn from a few surveys on reservoirs in the Piedmont Plateau made by the U. S. Department of Agriculture, turbidity records of water plants, and experience in the dredging of the James River below Richmond, Va. Although the anticipated silting in these reservoirs will be small in relation to reservoir capacities, plans will be made for obtaining regular sedimentation surveys.

The current program of the North Atlantic Division will also include:

a. Periodic cross-sectioning of existing channels to determine the quantity and location of debris;

b. Removal of sediment from channels of existing flood protection projects;

c. Observation of sedimentation changes at existing and authorized projects; and

d. Monumentation and cross-sectioning of ranges in the reservoir area of the three completed flood control reservoirs.

South Atlantic Division

The South Atlantic Division is preparing plans for a comprehensive suspended load sampling program for the Allatoona Reservoir project for the purpose of determining as near as possible the annual amount of silting likely to occur. It is expected that preliminary field work in connection with that program will be initiated in the near future. On the assumption that silting will occur at the rate of 50 acre-feet per 100 square miles of drainage area per year, serious results are not anticipated during the economic life of the Allatoona project due to the large capacity of the reservoir.

As there is little information available on reservoir sedimentation for this general area, the Allatoona study will provide valuable data for future studies in connection with the comprehensive development of river systems presently authorized by Congress in this area.

Mississippi River Commission

In connection with reservoir sedimentation surveys, the Mississippi River Commission has completed plans for the observation and reporting of sedimentation in Enid, Grenada, Lake Wallace and Wappapello Reservoirs, and plans are in process for surveys of the Narrows and Blakely Mountain Reservoirs. Sedimentation ranges were established in Sardis Reservoir in 1939 and in Arkabutla Reservoir in 1941. A resurvey of the Sardis ranges in 1943 showed no appreciable sedimentation in the reservoir area, with deposits largely confined to the old river channel.

The Waterways Experiment Station is now engaged in a study of existing data to determine what conclusions can be drawn therefrom and what further investigations, both in the laboratory and in the field, are desirable and practicable for a better understanding of the following phenomena:

a. The action of sediment in suspension in salt or brackish water, with special reference to the outlets of the Mississippi River and the Calcasieu channel;

b. The action of sediment in suspension in the Mississippi, Arkansas, and Red Rivers; and

c. The characteristics of bed load.

This study has been hampered by limitations of funds, but it is expected that it will be resumed in 1947.

Southwestern Division

An extensive sedimentation program currently underway in the Southwestern Division includes the establishment of sedimentation survey systems on numerous reservoirs, and the establishment and periodic observation of retrogression ranges downstream from reservoir projects. Borings will be obtained at channel range locations, and determinations made as to the physical properties of the bed materials. Special studies and investigations will be undertaken for the purpose of providing information and data concerning channel aggradation and degradation, reservoir sedimentation, and density deposits in reservoirs. In addition, a comprehensive program of sediment sampling that is now under way and the analysis and interpretation of sampling data will be continued.

South Pacific Division

A program is currently underway in the South Pacific Division, consisting of periodic survey and analysis of sediment inflow of existing reservoirs and continuing study of degradation in down-stream channels. In addition a survey is being made of San Carlos Reservoir on the Gila River in cooperation with the Soil Conservation Service, Bureau of Reclamation, and Gila Water Commission.

As a part of the administration of the Debris Act of 1893 and of the operation of two existing debris dams in the Sierra Nevada, a program of weekly sampling of suspended load at some twenty regular points, with occasional check sampling at other key points, has been carried on since the construction of the debris dams. This program has been inactive for the last year but will be resumed when need arises.

North Pacific Division

While sedimentation is relatively less serious in the North Pacific Division than in other Western areas, the importance and need for better factual data on this problem have long been recognized.

A contemplated program consists of determining the rates of silting in Cottage Grove and Fern Ridge Reservoirs and conducting suspended sediment determinations on all streams on which storage projects are proposed for early construction. The data obtained from these studies should prove of considerable value in the planning of proposed dams and reservoirs, and the need for such data has frequently been a matter of interest in connection with questions raised as to the useful life of flood control projects in the Columbia Basin.

The sedimentation problem in the Columbia River Basin will be considered and statement regarding it will be made in the forthcoming "308" Columbia River Review Report.

Ohio River Division

Sedimentation surveys of reservoirs in the Ohio River Basin are proceeding according to schedule. Surveys on four reservoirs have been completed. Survey work on one reservoir is nearing completion and work will be initiated on another in the near future. The sediment sampling program in this Division is at present in an inactive status. Upon resumption of this program it is planned to concentrate activities on the collection of data for use in investigations and studies of aggradation and degradation problems in rectified channels.

Great Lakes Division

To the present time the program of the Great Lakes Division of the Corps of Engineers has been largely in connection with shoaling of improved harbors and navigation channels of the Great Lakes and the Illinois Waterway. Over a period of years annual dredging of a quantity in excess of one and three quarter million yards of material has been required to maintain project dimensions.

The sedimentation program of the Division with regard to shoaling in harbors and navigation channels will consist of required maintenance of authorized projects and determining the

quantities of material accumulated and removed from within project depths. In conjunction with pertinent reports, studies will be made as to the feasibility of constructing sedimentation basins, reservoirs or channels that will concentrate sediment deposition in pre-determined locations and if possible reduce maintenance dredging requirements.

Flood control for the Illinois River Basin is presently under study and the comprehensive plan under consideration includes a number of reservoirs on tributary streams. Upon authorization of the plan, surveys will be made to determine rates of sedimentation in reservoirs, and studies initiated to determine project requirements considered necessary as a result of anticipated sedimentation.

Upper Mississippi Valley Division

The cooperative investigations and studies in connection with the design and development of sampling equipment have been stepped up in the Upper Mississippi Valley Division in keeping with an accelerated post-war program. Activities in the Division will include the operation of sampling stations, the collection and analysis of pertinent data, silt range observations, and special studies as required, in addition to dredging operations necessary for the maintenance of proper depth in navigation channels.

Missouri River Division

Extensive sediment investigations in the Missouri River Basin were first undertaken in 1929-1932, when the Missouri River "308" Report Studies were being made. Following a period of reduced activities, the sampling program has been recently expanded and at present 40 stations are being operated regularly. Investigations have included the regular systematic collection of samples, laboratory analyses using standard methods of determination of sediment concentrations and grain sizes, and in most cases preliminary computations of suspended sediment loads by approximate "rating curve" methods. Bed material samples have been regularly secured at many of the sampling stations, and size analyses made. Activities have also included the development and testing of sampling equipment and techniques, and special analytical studies of potential sediment problems to be expected as the result of reservoir construction.

Sedimentation ranges were installed in Fort Peck Reservoir prior to the time it was placed in operation, and have since been resurveyed, and retrogression surveys and bed material sampling have been carried on systematically below the Fort Peck Dam.

The future program proposes the ultimate establishment and operation of additional suspended sediment and bed material sampling stations; special field and office investigation programs aimed at better knowledge of actual movement and deposition of bed-load and suspended sedimentary materials; and fundamental research aimed at better quantitative as well as qualitative evaluation of sediment problems.

Summary

The items contained in this resume of activities have been selected on a basis of importance and variety of interest. Stated in a few words, the over-all sedimentation program of the Corps of Engineers will involve the collection and analyses of basic data, special studies, investigations and research projects, to be undertaken for the purpose of obtaining factual knowledge for use in effecting a solution of some of the many problems.

Acknowledgments

Included in this paper are extracts from reports furnished by Division and District Engineers in response to requests for statements concerning current and proposed sedimentation programs. Little originality is claimed by the writer for this paper, and it is desired to thank the many contributors for information made available for inclusion herein.

SEDIMENTATION PROGRAM OF THE BUREAU OF RECLAMATION

by Whitney M. Borland *

Previous to the planning of Hoover Dam, the Bureau of Reclamation had considered its sedimentation problem as a part of an individual project, but beginning with this dam and its associated developments, sedimentation was recognized as both a drainage basin problem and a river control problem. The different phases of the problem were studied and analyzed with this wider and more comprehensive understanding of its influence on the complete development of the whole basin. While World War II interrupted many important and essential programs, yet the surveys and records of changing sediment and river conditions after the closure of Hoover Dam in 1935 have been published annually.

After the War, attention was again more sharply focused on some of the essential and perpetual problems of the nation's economic welfare. One of these problems is the development of the nation's water resources by comprehensive basin planning. With the complete utilization of stream flow, all available head, and storage capacity, sedimentation must be given a great deal of consideration. It is recognized that there is no absolute solution for many of the sedimentation problems, yet it seems logical that certain methods of flow regulations, carefully planned development, and land management would often eliminate serious conditions accompanying sedimentation problems. To meet this large phase of development, the Commissioner of Reclamation outlined a broad and aggressive sedimentation program of field and laboratory investigations to secure facts necessary to complement the economics, planning, design and operation of present and future projects.

Reservoir surveys have been made in the past by the Bureau to anticipate the useful life of the reservoir and to determine the storage elevations required so as to provide the proper storage space for irrigation power and flood control requirements as set forth in state and national water compacts and agreements. Under the new program, a permanent reservoir survey party will map all Bureau reservoirs where sediment deposition is any problem. The crew has been equipped with a new supersonic echo-depth sounder and recorder to speed up their hydrographic survey work. It is planned to make full use of modern photogrammetric methods in establishing the necessary horizontal control.

Special attention will be given to the survey of the upstream end of the delta, for many of our present problems in sedimentation originate there. Vegetal cover over the upper delta region caused much of the coarser sediment transported by the stream to be deposited above the maximum water surface elevation in the reservoir. Such deposition of sediment does not decrease the storage capacity, but there are two detrimental effects. First, early deposition of sediment will increase the region of backwater which may damage property upstream, and also the deposits themselves may damage agricultural or pastural lands. Second, the vegetal cover will have a high consumptive use of water so that while storage space is conserved, the water losses from the reservoir and river will be increased. Reservoir surveys provide a positive volumetric measure of the sediment yield of a drainage basin and serve to partially check sediment sampling stations. By means of such measurements, studies can be made of the geological, hydrological, and botanical factors influencing sediment production. Such surveys serve as a basis for planning the amount and distribution of sediment capacity in future reservoirs. They also provide data for determining the current rate of loss of storage capacity and for estimating future changes in rate.

A 2' x 2' x 130' drag flume has been constructed and preliminary tests have been made in the Bureau's new hydraulic laboratory located at the Denver Federal Center. This flume is equipped with apparatus for feeding sand into the upstream end and a sampling device at the downstream end will indicate the amount of sediment that is transported through the flume. The contemplated program proposes to study the degradation and aggradation of a river channel and the factors which cause this action. All factors will be held as constant as possible except

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one factor, which will be varied throughout its complete range of variation. The seven factors which will thus be studied are:

1. Concentration of sediment - the amount of material moved by the flow of water either as traction or suspended load and what relationship it bears to aggradation or degradation.

2. The amount of flow - how does the sediment carrying power of a stream vary with discharge?

3. The slope of energy gradient.

4. Size and gradation of bed material.

5. The flow variability - assuming the total amount of water passed through the flume is the same, will degradation or aggradation be larger with an average flow or with the flow being 500 percent of the average for 14 percent of the time, and for the remainder of the time being only 35 percent of the normal flow?

6. Structures such as diversion dams, canal headworks, wasteways, and drain outlets - what effect do such structures have on the degradation and aggradation of the river channel?

7. The availability of fine particles in a stream bed composed of well graded material - when a stream is degrading, normal discharges will pick up all available material smaller than a certain size, thus a sorting of material and a shingling of the stream bed with coarser particles is accomplished. How does this action effect retrogression at discharges above normal flow? Will fine size particles become available above normal flows and possibly to flows equal to or below normal?

An outdoor hydraulic laboratory has been planned and designs are complete for a portion of the installation. A basin 20 feet wide and 250 feet long will provide space for the studying of certain reaches of the Rio Grande Valley, and later for other studies of a fluvial morphological nature. Specific problems on the Rio Grande include practical methods for bank protection and river training structures, narrowing of the river channel to promote degradation, also an attempt to work out a practical plan for depositing and storing sediment outside the river channel, allowing sediment-free water to return to the channel and further degrade the river bed. General problems are the relationship between the tendency of a river to become crooked or to form a braided stream pattern and the amount of sediment it carries; the old problem of horizontal and vertical scale distortion and correlation between model and prototype, so as to obtain quantitative rather than qualitative solution to problems of aggradation and degradation.

The rapid aggradation of the Rio Grande River from the head of Elephant Butte Reservoir to its confluence with the Chama River has increased flood hazards, caused poor drainage of irrigable lands, and excessive waste of water through the consumptive use of uncontrolled vegetation. By use of debris barriers, channel improvement and flow regulation, it is hoped that the river can be induced to degrade its channel. To estimate the amount and rate of degradation, both the analytical and inductive process of study will be used. Past records of the retrogression of the Colorado River below Hoover Dam should provide useful information for comparative studies. Mr. E. W. Lane and Dr. H. A. Einstein are making a series of studies to investigate the reliability of the various formulae for computing the contact and suspended sediment load of the river. Questions and problems growing out of such studies may add to the laboratory test program for the drag flume, so that it will include experiments on turbulence and sediment concentration. The zone just above the bed of the stream and below the truly suspended material still challenges the hydraulic experimenter and the mathematician. A complete investigation and thorough analysis of this zone should go far in perfecting a formula or method of computation to determine the total sediment load transported by a stream. Certain conflicting observations have been noted concerning the effect of water temperature on the transportation of sediments in streams. It is hoped that both laboratory experiments and careful analysis of field data will clarify and explain these observations.

The Bureau expects to set up a sedimentation laboratory to make additional studies on the physical characteristics of sediment, such as settling velocities in water, shape, size and density. Such a laboratory is necessary to analyze samples taken from the drag flume experiments and will prove useful in making an analysis of field samples which are taken in connection with special sedimentation problems.

All problems cannot be solved in the laboratory, for the prototype rivers and canals must be measured, observed, and appraised, so that there can be a correlation between laboratory and existing full sized phenomena. The extensive survey and sampling program that has been carried out below Hoover Dam since 1935 is a good example of such field measurement and should prove to be of inestimable value in solving many future problems. Much can be learned about the ability and capacity of a stream to transport sediment by determining its form and alignment and the shape of its prism. Measurements must also be made of its discharge depth, width, and slope. In addition, some other factors such as velocity distribution, turbulence, temperature, sediment concentration, variability of discharge, and vegetal growth must also be determined. Such data gathered from all parts of the country and covering all types of streams will form a basis for valley and stream morphological studies with the view of anticipating aggradation or degradation of stream channel and valley floors. The changes in ground water levels which always accompany such changes in stream slope could be predicted and provision could be made for corrective action. These studies will provide a basis for the design and development of adequate flood protection, river training measures, intake or diversion structures and adequate drainage systems.

There are many unsolved sediment problems to be found in the procedure of diverting the water from the stream and delivering it to the farmer, but more progress seems to have been made in this field than in those previously discussed. The Bureau's program includes a search for the answer to old vexing problems, such as (1) The best location for intake and diversion structures, (2) Economical design and efficient operation of desilting works, (3) Proper design of canals so as to have non-silting and non-scouring velocities, yet allowing the sediment to provide a beneficial seal on the canal's wetter surface, and (4) Effects of sediment on carrying capacity of canals and on vegetal growth both in the canals and on the irrigated lands.

No discussion of the Bureau's program will be complete without mention of cooperative studies with other governmental agencies and of the Federal Inter-Agency Subcommittee on Sedimentation, whose function is to disseminate information, to coordinate and prevent duplication of effort in research and planning work, and to act as a clearing house for ideas of various agencies. All suspended sediment sampling of a general and routine nature is performed by the Geological Survey, and also a cooperative geomorphological study is being made to evaluate the effects of various erosion control measures on soil erosion and sediment production with a view of planning development of water and land resources and assigning priorities for future development. A joint program on erosion evaluation of the Rio Grande drainage basin is being carried on with the Soil Conservation Service, and data for degradation studies of the Rio Grande River previously mentioned are being supplied by the Corps of Engineers, Soil Conservation Service, and the Bureau. Several surveys of reservoirs are being made in cooperation with the Corps of Engineers.

SEDIMENTATION PROGRAM OF THE GEOLOGICAL SURVEY

by S. K. Love *

The transportation of sediment by flowing water is part of a geologic process that has been taking place ever since land masses have existed above sea level. As the land rises, forces of erosion act to wear it down. The presence of sediment in streams is but one phase of the erosion process which has as its ultimate objective the reduction of all land masses to sea level.

When considered in the light of geologic history, the rate of denudation of land masses can be altered but very little by reason of human activities. In a narrower sense, however, when considered in terms of decades and in connection with specific land areas, it is obvious that sediment production in streams can be accelerated or retarded to a measurable degree depending on disregard or recognition of natural forces and laws controlling the erosion process.

The Geological Survey has long been interested in the rate of denudation of the land area in the United States and has been actively engaged in studies of the laws and the rates of sediment transportation by streams. Among the earliest contributions by the Survey to the fundamental knowledge governing the movement of sediment in streams was the treatise by G. K. Gilbert entitled, "The Transportation of Debris by Running Water," published in 1914 as Professional Paper 86. Other papers on this subject have been written in more recent years.

Probably the first systematic computations of the rate of denudation of the larger drainage basins of the United States were those made by Dole and Stabler which were published in 1909 in Geological Survey Water-Supply Paper 234. Although these records were in many instances based on meager and not too reliable data, they were, nevertheless, the only records of this kind available and they were widely accepted for many years as the best measure of the rates of denudation throughout the country.

The Geological Survey has been engaged in comprehensive programs for measuring the sediment loads in streams since 1925. In that year a sediment station was established on the Colorado River at Grand Canyon, Arizona, which, except for a brief period of a few months, has been in continuous operation until the present time. The sampling equipment used at this station and later at other stations in the Colorado River Basin became known as the Colorado River sampler. Constructed of an inexpensive brass frame designed to hold a standard pint milk bottle, the Colorado River sampler was among the first to be used for the collection of integrated samples in connection with continuous sampling programs.

The data collected at several stations in the Colorado River Basin over a period of from 10 to 22 years have been of great value in connection with large scale development projects, both completed and projected. The Geological Survey is currently operating four sediment measuring stations in the Colorado River Basin and one or two more will probably be in operation before the end of the 1947 fiscal year. The U. S. D-43 sampler developed at the University of Iowa under the auspices of the Federal Interdepartmental Committee was adopted for use in the Basin just as soon as it became available and is now being used at all stations.

Early in 1934 the Geological Survey in cooperation with the Soil Erosion Service (later the Soil Conservation Service) began a program for the measurement of sediment loads carried past 34 gaging stations on streams on eight demonstration projects. These measurements were made over a period of from 3 to 6 years on small drainage basins which ranged from less than 20 to about 200 square miles in area. The runoff was flashy and the sediment concentration ranged between wide limits. Concentrations of 50,000 to 100,000 parts per million were not uncommon for some streams on which measurements were made.

Because of the large and sudden changes in both water discharge and sediment concentrations, samples had to be collected at frequent intervals if reliable records were to be obtained. It was found that up to 90 percent of the annual sediment loads were carried in less than 5

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percent of the time in some streams. This made it mandatory to give the closest supervision to the collection of the proper number of samples at the right time to adequately define the concentration curves.

Late in 1938, at the request of the Flood Control Coordinating Committee of the Department of Agriculture, the Geological Survey engaged in a program for measuring the sediment loads carried past 13 stream flow gaging stations on streams in the Boise River drainage basin in Idaho. Because of the large proportion of coarse sediment transported by some of the small streams in steep mountainous terrain, it was necessary to construct special weir structures in the streams and special sampling equipment to measure the total sediment load, including bed load.

In 1945 the Survey began sediment measurement programs in the Missouri River Basin as a part of a comprehensive investigation of the natural resources. The selection of stations on streams for sediment measurements was based largely on the immediate needs of other Federal agencies in connection with construction and development programs. Some of the stations are at key locations which, if maintained over a long enough period of time, will give reliable data on the rate of sediment movement out of major drainage basins. Other stations will probably be maintained in their present locations only long enough to furnish a basis for computing an approximate estimate of the rate of sediment movement.

At the present time sediment loads are being measured at 43 stations on streams in seven States in the Missouri River Basin. The sampling equipment used at all stations for routine operation is the depth integrating D-43 sampler developed at the University of Iowa. At some stations the sampler is mounted in a fixed position on a bridge rail and at others portable bridge cranes are used, depending on conditions.

The sediment samples are processed in four laboratories at strategic locations in the Basin. The main laboratory and administrative office is in Lincoln, Nebr., which is also equipped to make complete chemical analyses of water samples. Field laboratories designed for sediment analysis only are located in Wyoming, North Dakota, and Kansas.

In July 1946 the Geological Survey took over the responsibility for measuring sediment loads on the Rio Grande at San Marcial which was formerly operated by the International Boundary and Water Commission. This station is being operated in connection with the station at San Acacia, about 25 miles up stream, in an attempt to correlate the records at the two stations.

Arrangements were made in April 1947 by the Bureau of Reclamation for the Geological Survey to install and operate four sediment stations on streams in the Washita River Basin in southwestern Oklahoma.

For the past three years the Geological Survey has operated three sediment stations on streams in Iowa in cooperation with the State of Iowa. The excessive soil losses caused by major floods in Iowa have led interested agencies in the State to enter into a cooperative program with the Geological Survey to measure the quantities of sediment washed away in some of the larger streams.

At the present time the only sediment station being operated by the Survey east of the Mississippi River is located on a small stream in Delaware. Interest in the conservation of natural resources in a small drainage basin in a farming region led to a cooperative program with the Survey for measuring the amount of sediment being washed away into the Delaware River.

There is a major pollution problem in an eastern State involving sediments consisting largely of finely divided coal. Preliminary plans have already been made for the Geological Survey to measure the amount of this coal transported in a small river basin in which the pollution problem is particularly acute.

In connection with measurements of sediment loads a great deal of work is being done to determine the sizes of the sediment particles. A systematic study has been made in our Albuquerque laboratory of the bottom withdrawal tube method of size analysis using the results of analysis of many hundreds of samples. Detailed results of this study will be presented in another paper.

The relation of geologic features to recent floods in the Connecticut River Valley in Massachusetts, in which sediment plays a dominant role, is discussed in a comprehensive report issued recently as Water-Supply Paper 996.

The Geological Survey is also engaged in a study of the physical processes of erosion and sedimentation in upland portions of the public domain. The study is aimed at a determination of the climate, vegetation, geomorphology and soils during deposition of the sediments and an evaluation of the physical conditions leading to their erosion. The comparison, or perhaps the contrast if discernible, should permit drawing some conclusions regarding the causes of the present epicycle of erosion, and judging the value of methods of arresting or ameliorating its adverse effects.

Because of its interest in the collection and interpretation of basic sediment data, including the source of the sediment, the physical processes of erosion, the transportation of sediment by streams, and the deposition of sediment in stream channels, reservoirs, canals, and ultimately the sea, it is believed that the Geological Survey has made effective contributions to the science of sedimentation and plans are being formulated to continue and expand these investigations.

SEDIMENTATION PROGRAM OF THE DEPARTMENT OF AGRICULTURE

by Bernard Frank *

The Department of Agriculture's interest in sedimentation is twofold. First, large agricultural and other land values are at stake. The fertile bottom lands and valleys of the nation's major and minor streams have been subjected to repeated heavy damages by flood-borne sediments. In the May 1943 floods of the Central Mississippi Valley, in which more than 3,700,000 acres of agricultural lands were inundated, land damages by sedimentation and scour were estimated to amount to over half the total losses. Furthermore, the Department is concerned over the serious social and economic effects of sedimentation on the millions of acres of agricultural land in irrigation and drainage projects and on recreational lands exposed to the flood hazard. Second, a significant part of the production of harmful sediments originates directly or indirectly on agricultural, range, brush or forested uplands subjected to varying degrees of misuse.

The national scope of the problem, the growing concern over its cumulative effects and the tangible contribution that upstream corrective and preventive measures can make towards its solution have long been recognized. For example, the Organic Act of 1897 provided for the administration and protection of the forest reserves primarily in the interest of watershed protection; the Weeks Law of 1911 provided for national forest acquisition on headwater areas "for the purpose of conserving the navigability of navigable rivers;" the McNary-McSweeney Forest Research Act and the Clarke-McNary Law authorizing forest acquisition, fire control, and forest planting stressed watershed research and improvement in the interest of navigation and conservation of domestic and irrigation water supplies; Public Law No. 46 in 1935 established the Soil Conservation Service "to provide permanently for the control and prevention of soil erosion and thereby to preserve natural resources, control floods, prevent impairment of reservoirs, and maintain the navigability of rivers and harbors;" and the Omnibus Flood Control Act of 1936 and its amendments authorized "measures for run-off and waterflow retardation and soil erosion prevention on watersheds." These legislative acts have provided the authority and impetus for the research, survey, and action programs currently being undertaken by this Department through the Soil Conservation Service and the Forest Service.

The primary objectives in the field of sedimentation control are being achieved by means of four closely related activities: basic and applied research, removal of the causes of sedimentation, land management, and the application of remedial and preventive measures on the watersheds and in minor waterways. A corollary objective is that the measures must not only be sound technically on their own merits, but must also be integrated with other measures applied on an overall watershed basis for the maintenance of soil, water, timber, grass, and other natural resources. Furthermore, they must be designed to operate at a continuing level of effectivenesss.

These objectives place strong emphasis upon the maximum possible degree of continuing physical protection of the land in headwater areas, which is the primary source of sediment in most watersheds. They fully take into account, however, the necessity for correction of unstable conditions in and along channels and other drainageways regardless of the original causes.

The sedimentation activities of the Soil Conservation Service and the Forest Service are along roughly parallel lines, with maximum coordination of the work in order to avoid duplication of effort. The work of both Services has the same broad objectives - investigation and control of sedimentation in waterways and on the land respectively. The work of the Soil Conservation Service relates primarily to cultivated, pasture or range lands, mainly in private ownership, whereas the work of the Forest Service relates primarily to forest and brush lands and to range land mainly in public ownership.

The Soil Conservation Service activities are organized into two parts: (1) research and (2) surveys and operations. One of the administrative units of the Office of Research is a sedimentation section which conducts field investigations for developing methods of sediment

* Assistant Chief, Division of Forest Influences, U.S. Forest Service, Washington, D. C. (read by Leon Lassen, Forest Service).

control in reservoirs, stream channels, floodways, harbors, drainage canals, and on valley agricultural lands. It maintains a sedimentation laboratory in cooperation with the California Institute of Technology at Pasadena, Calif., for basic research in the mechanics of sediment transportation - in suspension and in channel flow, as bed load and as density currents in reservoirs. This laboratory also plans the application of the findings to practical field problems. The Office of Research also maintains a number of conservation research stations and watersheds where investigations are made on the types and rates of soil losses which are the primary source of sediments.

The Farm Irrigation Division of the Office of Research has carried on suspended-load sampling on Texas streams in cooperation with the Texas Board of Water Engineers since 1924. It is conducting other types of sediment research relating to irrigation such as the design of sand traps for removing coarse material from irrigation canals.

To date sedimentation surveys have been made on about 450 reservoirs in 36 States, including detailed surveys on 150 reservoirs and reconnaissance surveys on about 300 others. The results have encouraged many municipalities to support soil conservation programs on municipally owned lands above their reservoirs and to cooperate with soil conservation districts throughout the drainage areas concerned.

Considerable attention has been paid to the development of methods for more effective channel stabilization and stream-bank erosion control, including intensive studies of bed-load movement. Analytical studies of existing sediment-load data have been made in order to develop sediment-production indices on a regional basis for drainage basins of various sizes. Soils of different characteristics have been classified as to their potential contribution to sediment on the basis of texture, structure, and other features. Land-use planning work has been aided by the development of techniques for evaluating sediment damage, as for example, to valley agricultural lands. Such techniques have been extensively used in connection with flood-control surveys, water-conservation surveys, and for other purposes.

Survey and operations are carried out administratively through seven regional offices. Surveys and planning activities related to flood control, irrigation, and drainage are under the technical supervision of the Water Conservation Division in the Washington office and the seven regional offices. A considerable body of experience is being built up in the development of more effective stream-bank stabilization methods, water-disposal systems, and other devices for controlling the movement of harmful sediments.

The Forest Service's sedimentation activities have essentially the same objectives as those of the Soil Conservation Service. Strong emphasis is being placed on stopping sediment at its original sources by means of better forest and forest-range land practices and by the restoration of the plant cover on damaged and eroding areas. Investigations have revealed specific causes of silt, mud, and rock flows and debris damages to reservoirs, water-spreading grounds, and valley lands. These causes vary in different parts of the country. In mountain areas, particularly, sediment and debris movements originate on road and highway cuts, fills, and overcast material. Improperly logged, overgrazed, or burned areas constitute other sources of serious sedimentation. In the waterway phase of the Forest Service program particular attention is given to the stabilization of mountain torrents above valuable areas of high hazard, such as intensively developed urban, agricultural, residential, and recreational land and irrigation water-supply reservoirs. Tests are being made of various types of channel barriers for debris catchment and channel stabilization. Experiments are under way with various types of slope stabilization and channel-training structures in order to prevent further slope unraveling and to prevent or minimize downward cutting. Work of this kind is now being undertaken on the upper tributaries of the Los Angeles River along with the installation of erosion-control measures on the slope themselves. Highly satisfactory results in stopping soil erosion at the source have been achieved by the successful airplane sowing of mustard seed.

As part of its basic objectives the Forest Service is constantly trying to develop better methods of forest land management and protection, including revegetation and reseeding, timber harvesting, grazing practices, and road and trail construction in order to minimize the loss of sediment-producing soil from the slopes. Studies based on these objectives are currently under way on a national basis at nine Forest Service research centers. Emphasis varies, however, according to the nature and severity of the problem in the region served by each center.

The national forests were established primarily to prevent or reduce unfavorable conditions of stream flow and to minimize harmful sedimentation. To an increasing degree, and as the

results of research become available, the management plans are fulfilling these objectives. In some areas, as in Davis County, Utah, the Forest Service has gone a considerable distance in effectively stabilizing sediment-source areas.

One of the lessons derived from the sediment investigations thus far undertaken is that the successful solution to this problem depends upon the close integration of the land and waterway investigations and operations. An outstanding example of this type of approach is represented both by the watershed flood control surveys and the specific studies of watershed areas which contribute sediment to reservoirs. In both cases, solution to the sediment problem is bound up with conservation and control of soil and runoff on the land as well as the rehabilitation or stabilization of already disturbed stream channels.

THE SILT INVESTIGATIONS PROGRAM

OF THE TENNESSEE VALLEY AUTHORITY

by M. A. Churchill *

Objectives

The Tennessee Valley Authority, realizing the need for information on silt carried in the streams within the Tennessee River watershed, instituted investigations early in 1934 to determine the amount of sediment transported by the Tennessee River and its major tributaries.

The primary objective of this program was to determine the probable rates at which the reservoirs in the TVA system will fill with sediment. This system includes nine reservoirs on the main Tennessee River, totalling 650 miles in length with one reservoir directly downstream from the one next above, together with eleven large storage reservoirs and a number of smaller ones located on the major tributary streams. Other objectives include determining probable silting in navigation channels and probable clarity of pooled waters near potential industrial and recreational sites in connection with development of lands and public parks along the reservoirs.

The Tennessee River and Its Basin

The Tennessee River drains 40,910 square miles ranging in elevation from over 6,000 feet above mean sea level along the eastern edge of the basin to about 300 feet at the mouth of the Tennessee River. Some 40 percent, or about 16,000 square miles, is mountainous. The soils of the area are fine textured, absorb water slowly and erode freely unless protected by adequate vegetal cover. The Tennessee Basin as a whole is 52 percent forested.

Mean annual rainfall varies from 40 to 85 inches. Average rainfall for the entire basin is approximately 52 inches. Mean annual runoff for the basin as a whole is approximately 40 percent of the rainfall or about 21 inches.

Silt Investigations Program of the Tennessee Valley Authority

The silt investigations program of the Authority divides into three components: (1) Suspended sediment in streams, (2) Deposited sediment in reservoirs, and (3) Special studies.

Suspended Sediment Studies

Field Procedure - During 1934 and 1935 a total of 49 suspended silt sampling stations were established. These are at or near the sites of major projects and on the larger tributaries to proposed reservoirs and are at or near Geological Survey stream gaging stations where discharge data are available. The majority of the stations were maintained in operation for a period of three to four years during the interval from 1934 to 1938. Eleven key stations were maintained for approximately eight years. Each station was operated long enough so that a measure of the total silt passing that location was obtained. The regular suspended sediment investigations program, as such, was terminated in 1942, mainly because of curtailments in personnel and car mileage resulting from the entry of this country into World War II.

At the beginning of the sampling program, the research project on silt samplers had not been carried out at the University of Iowa and a horizontal tube sampler of original design was developed by engineers of the Authority. This sampler was designed to collect an instantaneous sample from any desired point in the river cross section.

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In order to determine the silt concentration in the river cross section at any particular time, instantaneous samples were collected from three points in each of three to five river verticals. The three points in the vertical at which samples were collected were (1) one-half foot below the water surface, (2) at mid-depth, and (3) one-half foot above the river bed. On small streams sometimes less than three verticals were used, and on large rivers occasionally more than five verticals were sampled.

The frequency of sampling at any one station varied depending upon the size of the stream and upon stream-flow conditions. During periods when the river discharge is composed principally of ground-water flow, one set of samples per week was taken. During periods of both small and large floods, samples were taken at frequent time intervals because during such periods silt concentrations change rapidly. It was realized early in the program that more silt may be transported by a river during one major flood than by an entire year of stream flow during which no major rise in flow occurs.

Laboratory Procedure - At the laboratory, the silt concentration in parts per million by weight in each sample was determined separately by using the filter paper process.

Results of Suspended Sediment Investigations - From the suspended silt investigations program it has been determined that the total quantity of silt carried into the streams of the Tennessee River Basin averages 14,000 acre-feet per year. At Johnsonville, near the mouth of the Tennessee River, the mean concentration prior to construction of Pickwick Reservoir was 110 parts per million. The maximum concentration found at this station was 1,190 parts per million. The maximum silt concentration found, 84,700 parts per million, occurred on Potato Creek in a local small area denuded by copper mining operations.

One of the principal results of the suspended sedimentation program was the determination of the sedimentation efficiency of two mainstream reservoirs. Sampling stations were maintained both above and below Hales Bar and Wilson Reservoirs, from which determinations were made of the quantity of sediment being deposited in both reservoirs under varying stream flow conditions. The information on reservoir sedimentation efficiency thus obtained is being used in conjunction with data on suspended silt loads and on silt volumes determined by reservoir surveys, to estimate future rates of silting to be expected in all TVA reservoirs.

Deposited Sediment Studies

Reservoir Sedimentation Surveys - Concurrently with the suspended sediment program, a program for determining actual volumes of deposited sediment in reservoirs was also carried on. Base surveys have been made in all reservoirs prior to or just after filling. One or more resurveys to determine the quantity of deposited sediment have been made on many of the reservoirs. Surveys have also been made on relatively small privately owned reservoirs in the Tennessee Valley.

Future Silting of Reservoirs - Estimates have been prepared of the rates of silting of TVA reservoirs. These rates are all low. For example, it is estimated that it will require approximately 800 years for the 624,000 acre-feet of storage below minimum operating level in Norris Reservoir to be filled with sediment. At Fontana it will require some 700 years to fill the 287,000 acre-feet of unused storage. In the case of the largest main river reservoir, Kentucky, it is estimated that only four percent of the 6,000,000 acre-feet of total storage in this pool will be filled within the first 100 years of the reservoir's existence.

Specific Weight of Deposited Sediment - The specific weight of deposited sediment has been determined in several reservoirs by means of a special volumetric sampler designed for this purpose. This operates under water as well as in the dry and has been used successfully under as much as 40 feet of water.

Specific weights of deposited sediment vary widely in every reservoir as anyone experienced in this field well knows. However, the bulk of the sediment deposited in the larger reservoirs in the Tennessee Valley has a specific weight of about 60 pounds per cubic foot. As more silt accumulates in the pools, the underlying material will be compressed. In making estimates of future silting of reservoirs, a specific weight of 70 pounds per cubic foot has been used as a mean value.

Grain Size of Deposited Sediment - Grain size analyses are made on samples of deposited sediment and in some cases on suspended sediment.

Analysis of a number of deposited sediment samples from Wilson Reservoir by the sieve and hydrometer method shows over 95 percent of all particles have diameters less than 0.074 millimeter, the size openings in a 200-mesh sieve. On the tributary streams, reservoir deposits are naturally coarser grained than those found in reservoirs on the flatter main river. For example, the sediment in a reservoir on the Nolichucky River is composed of material 70 percent of which is smaller than 0.074 millimeter. On the whole, the silt carried by streams in the Tennessee Valley reflects the fine texture of the soils and is fine grained. Such material is kept in suspension by low degrees of turbulence, which gives many streams the appearance of carrying a much greater sediment load than they really are.

DISCUSSION

COLONEL C. L. HALL*. I am a retired officer - retired for age from active duty. I have been considering this subject all my life, although I cannot pretend to have ever studied it as most of you gentlemen have. After a career of 40 years I confess that I am a complete pessimist, and I am even more of a pessimist, after listening to the remarks this morning, than I was when I started. It has recently been stated, in a professional paper with wide circulation, that if we adopted the best possible erosion practices we couldn't cut down the amount of soil entering our streams more than 10 percent. In other words, we can only cut our casualty rate 10 percent. I hope that the discussions for the rest of the day and tomorrow will bring that point out and decide whether that is correct. Because here we are, fighting a battle in which the best we can do is to cut down the casualties 10 percent. If this is true we have what the doctors might call a very unfavorable prognosis. I just want to leave the thought that, just as none of us can prevent winding up in a cemetery, except by jumping overboard, so the best we can do will not be good enough. If we are on the wrong track in our attempts to control this water supply by reservoirs destined to a fatal end, maybe the best thing we can do for the taxpayers is to find that out in advance.

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DETERMINATION OF THE SUSPENDED SEDIMENT DISCHARGE OF STREAMS

by Paul C. Benedict *

For the past century the suspended sediment discharge of certain streams in the United States has been measured on an intermittent basis, using uncertain methods and varying procedures. This situation was recognized in 1939 by Federal and State agencies and a cooperative project was established at the Hydraulics Laboratory of the University of Iowa to investigate sediment sampling equipment and techniques. Results of studies made by representatives of the several agencies have been published as a part of the cooperative project 1/ together with a summary report 2/which was prepared for presentation to the American Society of Civil Engineers Joint Committee on Sedimentation in Reservoirs.

This paper is intended to supplement the information presented in the previously mentioned reports and is largely based upon the experience gained by personnel engaged in sediment and stream flow investigations for the Geological Survey and cooperating agencies. The concurrent investigations have led to the conclusion that the procedures now in general use by Federal and State agencies to determine the suspended sediment discharge of streams are based on local office policies, available funds, and technical procedures developed or established during the past 20 years. Furthermore the suggestions made in the series of reports published as a part of the cooperative project have only been followed in part. A reluctance to change from arbitrary and empirical methods to rational practices based on present concepts of the theory governing the transportation of suspended sediments is still evident.

Suspended Sediment Sampling. - The suspended sediment discharge of any stream can be readily determined for any period of time if the observations are adequate in number to delineate the change in sediment concentration during the same interval of time, assuming that the water discharge has been measured or can be computed from stage-discharge rating curves based on the results of current meter or weir measurements. For identical conditions of flow the number of samples required depends on the type of sampler used, the change in sediment concentration with stage, and the fluctuation of the concentration with time. For purposes of comparison it will be assumed that measuring conditions are such that any of three types of samplers can be used; namely, depth-integrating, point-integrating, or instantaneous. One sample collected with the depth-integrating sampler is equivalent to about four samples collected with the point-integrating or instantaneous samplers. Assuming a normal sediment-distribution curve with the samples representing equal volumes of discharge in the vertical section, the accuracy of the results obtained with the point-integrating sampler probably exceeds that of the depth-integrating or instantaneous samplers owing to the length of the filament of fluid collected. It will, of course, be necessary to determine the concentration of each point-integrated sample unless the volume of fluid collected is controlled by using the same sampling interval for all samples.

Under average conditions of flow the suspended sediment discharge can be determined at less cost with the depth-integrating sampler than with the point-integrating or instantaneous samplers. The D-43 depth-integrating sampler developed at Iowa City is used at all Geological Survey sediment stations at which this type of instrument can be employed. For streams with depths beyond the range of the depth-integrating sampler, it is necessary to use the point-integrating sampler. In its present state of development the instantaneous sampler is not considered by the writer to be a satisfactory field instrument except possibly for special studies. In addition, it is not easily adapted to general field use, and furthermore, computation procedures require velocity

* District Engineer, Quality of Water Division, Geological Survey, Lincoln, Nebr.
1/ 2/ See "References" at close of comments.

measurements in the vertical section at the points sampled if the concentration is to be weighted with velocity.

The depth-integration method of sampling will give accurate average sediment concentrations in the vertical section as well as average size distribution of the sediment load. The point-integration method of sampling provides necessary information for defining the shape of the sediment concentration curve and the size of sediment particles at predetermined depths and related velocities. The data obtained by means of the point-integrating sampler are of major importance in that pertinent field information is provided for further study of the theory governing the movement of fluvial sediments. This sampler has a broad application in experimental work and its use should not be restricted to deep streams.

Sampling Installations. - Sediment sampling installations utilizing the D-43 sampler may be classified as movable and non-movable or fixed. In the first classification the sampler is operated from a cable car or from a bridge using a 4-wheel stream-gaging crane or other equipment. In the second classification the installation is attached to the side of a bridge and is considered semi-permanent.

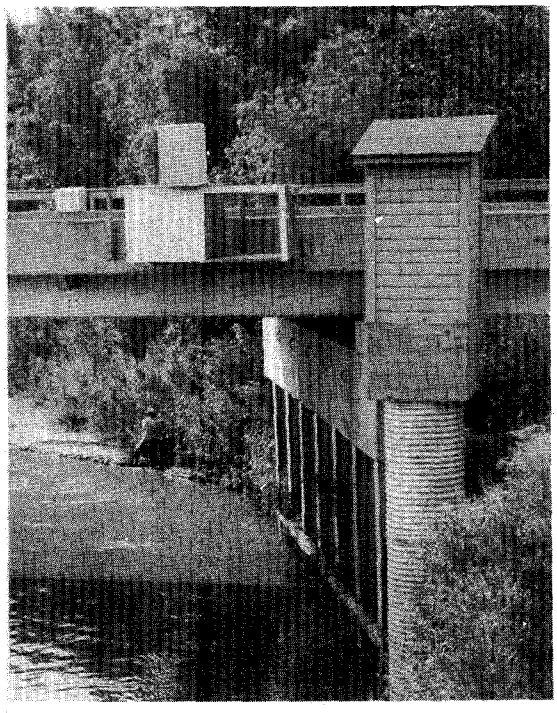
The selection of the type of installation depends upon the characteristics of the stream and related watershed and the personnel available for collecting samples. In streams having semi-stable stage-discharge relationships, the non-movable installation gives satisfactory results particularly where it is possible to make concurrent measurements of the water and sediment discharge. In streams having easily erodible channels and an unstable low-water section, the movable installation provides a more flexible arrangement which permits the collection of samples at any stream vertical in the cross section.

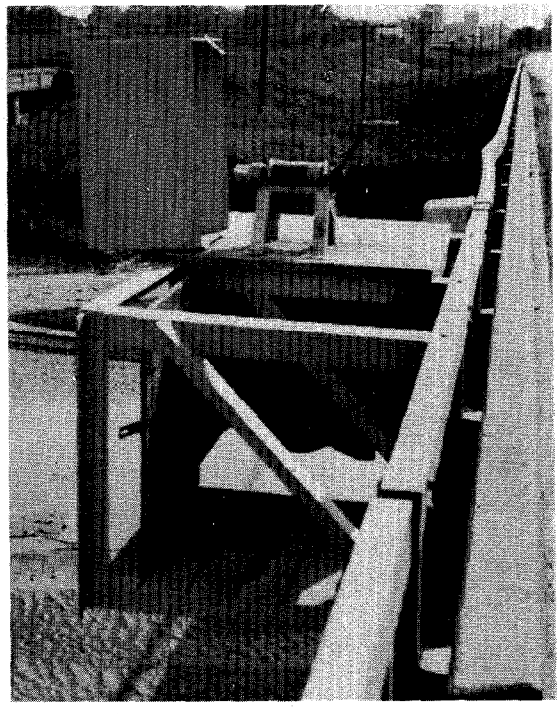
The non-movable installation requires less effort on the part of the observer to operate and is less hazardous. Many observers are reluctant to work from cable cars and equally reluctant to operate a 4-wheel crane on a narrow highway bridge if no walkway is provided. The two kinds of installations are illustrated in Figures 1 and 2, respectively.

Frequency of Sampling and Location of Sampling Verticals.- The frequency and number of samples required to define adequately the suspended sediment concentration in a stream are functions of the runoff characteristics of the stream and of the size of sediment particles in suspension. On some research projects it has been possible to collect a sufficient number of samples to define accurately the concentration graph. Such a procedure is not possible in any extended program similar to that now in effect on tributary streams in the Missouri River Basin. For practical reasons the number of observations during any one day is limited to a maximum of from 5 to 10 at one or more points in the cross section. The minimum is limited to one daily observation during the non-ice period to insure that the observer will visit the station. This procedure is necessary so that "rises" resulting from rain in upstream areas will be covered. If full-time personnel are employed to collect the samples it may not be necessary to make daily observations for certain conditions of flow, particularly in large rivers.

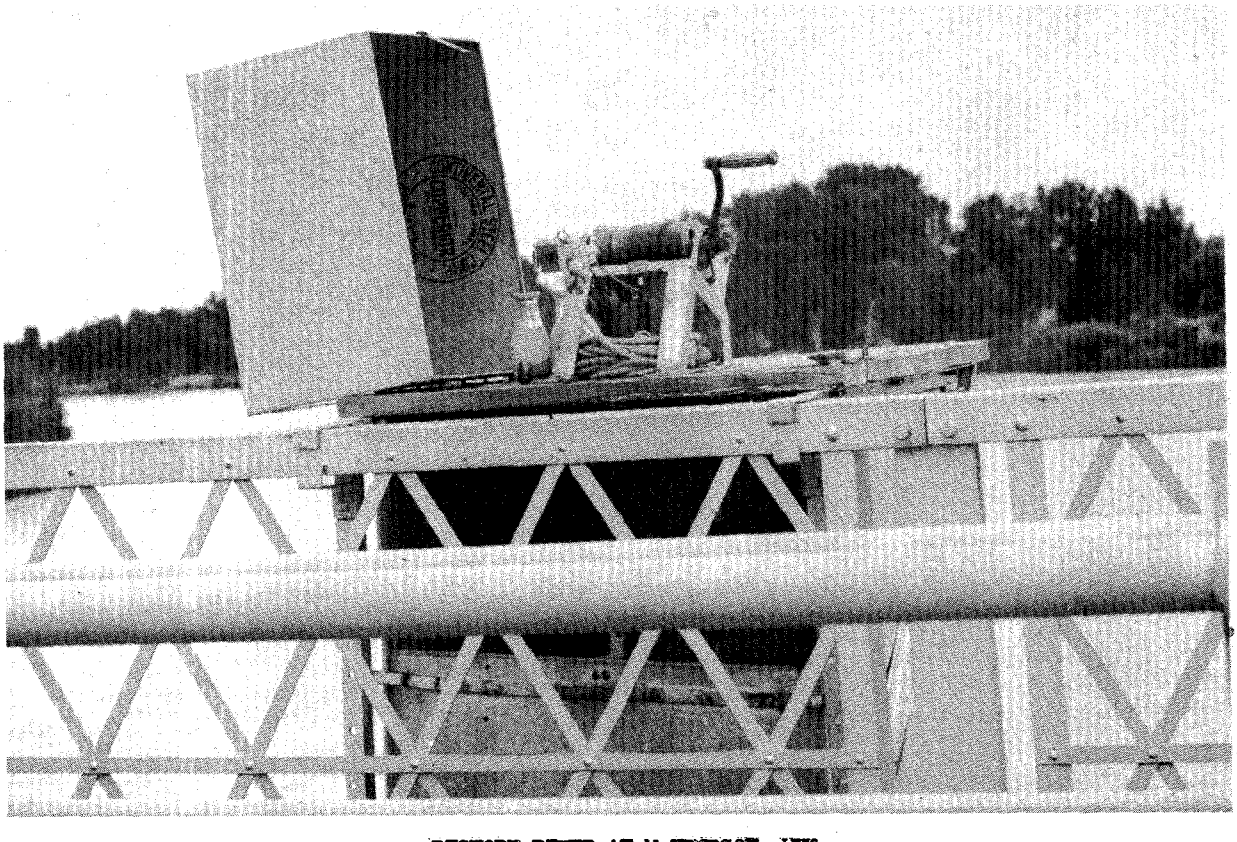
In addition to the samples collected by the observer at non-movable sampling installations, periodic determination of the concentration in three to five vertical sections representing points of equal water discharge is required. These sediment discharge measurements should be made at least twice monthly and more often during floods to determine as accurately as possible the average concentration in the cross section. In streams having unstable channels, overflow sections, and a wide range of concentration in the cross section, it is desirable to obtain samples at three to five verticals on the same schedule as previously mentioned for the non-movable sampling installation.

The location of the sampling verticals is determined from current meter measurements. At river stations where the stage-discharge relation is quite stable, the location of verticals can be ascertained for all stages as outlined in the previously mentioned series of reports. At stations having an unstable stage-discharge relationship, which usually obtains on streams transporting heavy sediment loads, the location of the verticals is checked after each current meter measurement and corrections made accordingly.





MEDICINE CREEK AT CAMBRIDGE, NEBR.



BIGHORN RIVER AT MANDERSON, WYO.

Figure 1. - Non-movable sediment sampling installations equipped with D-43 samplers.

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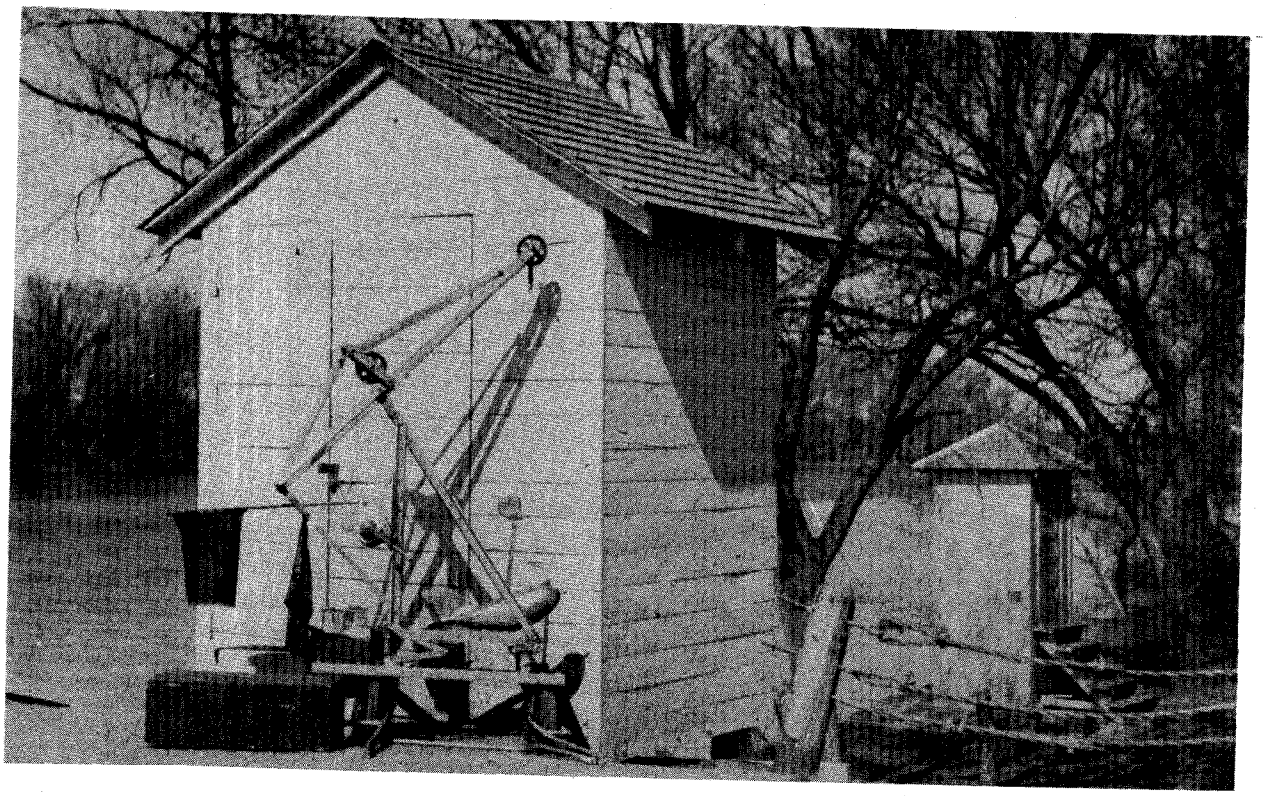
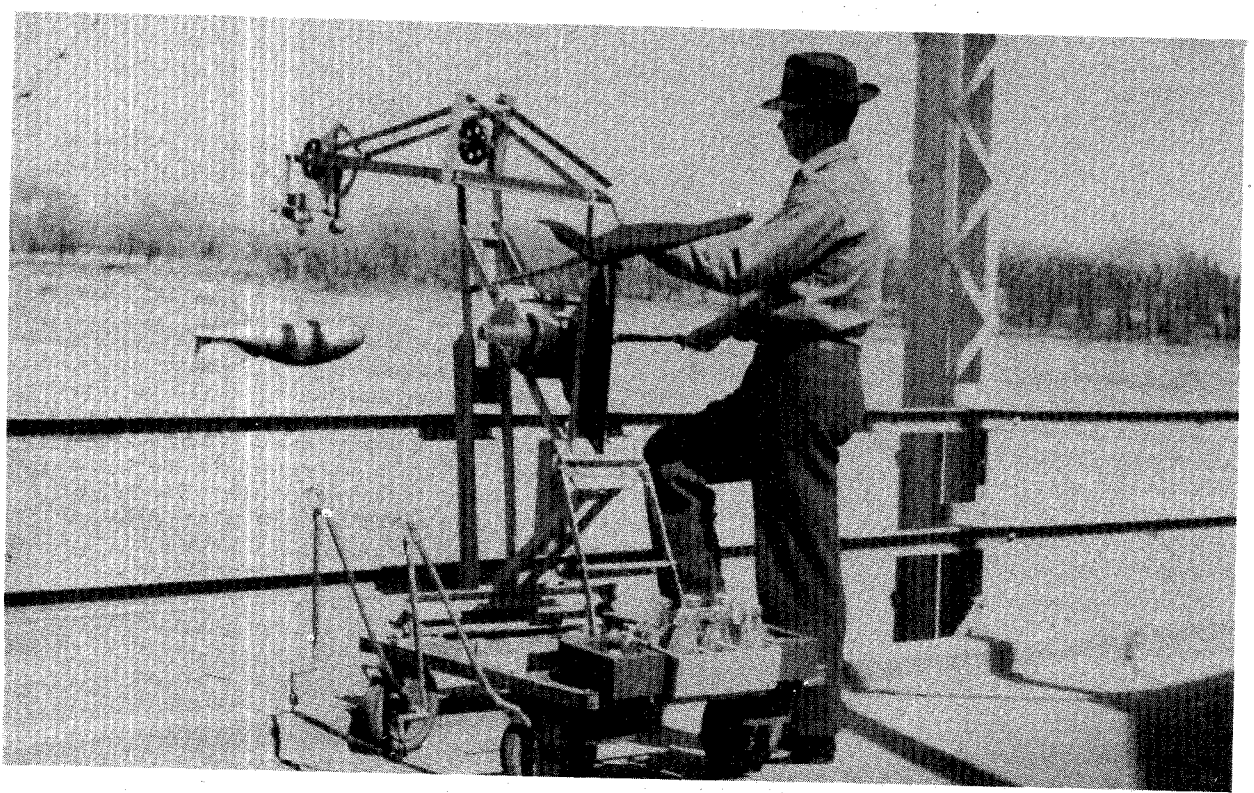


NORTH LOUP RIVER NEAR ST. PAUL, NEBR.



MIDDLE LOUP RIVER NEAR ST. PAUL, NEBR.

[1]Figure 2. - Movable sediment sampling installations - four-wheel stream-gaging crane equipped with D-43 sampler.

The sampling in three to five verticals is somewhat empirical and should be checked occasionally by collecting samples at ten or more verticals, the number depending upon the width of the stream and related characteristics.

Suspended Sediment Concentration. - The sediment-suspension phenomenon has been discussed in the previously mentioned reports and related engineering literature. Therefore, only the factors governing the collection of a sufficient number of samples for computing the average daily concentration and related suspended sediment discharge are discussed in this paper.

The concentration of suspended sediment in any stream has no constant relationship to stage or to changes in stage. It may be affected by (1) intensity of precipitation or rate of snow melt, (2) vegetal cover, (3) season of the year, (4) condition and kind of surface soil, (5) topography, (6) size of stream, (7) stability of channel, (8) return flow from irrigation tracts, (9) shape of drainage basin of main stream and tributaries above measuring station, and (10) storage in reservoirs and retarding basins. The sediment concentration usually increases with an increase in stage, and, generally but not always, precedes the peak of the water discharge. The maximum concentration in large streams may occur either several days in advance or a day after the peak of the water discharge. The rising side of the concentration curve is usually quite steep and sharp changes often occur as the major part of the inflow from each tributary reaches the measuring station. The commingling of flow from the tributaries usually produces a more uniform curve on the recession side.

The concentration of suspended sediment at any river station is affected by the type of stream bed at and above the station. For purposes of discussion, water courses may be divided into two groups: those having semi-stable channels with rough cobblestone or rock bottoms which change infrequently or only with major floods, and those having unstable channels composed of sand or fine sediments. In the former group, an increase in water discharge merely means a related increase in stage, whereas in the latter group an increase in water discharge raises the stage but not in a fixed relation to the discharge owing to changes in the stream bed. In erodible channels the velocity relationships are unstable and are interrelated with changes in the shape and elevation of the stream bed. These changes may include the formation of sand bars and dunes, and degradation and aggradation of the stream bed. Streams having unstable channels usually exhibit the maximum fluctuation in concentration at all stages. In both types of streams the concentration of the suspended sediment at any point is affected by pulsating flow and boils, the latter being formed at random intervals. In snow-fed streams some change in the sediment concentration results from diurnal fluctuation of the water discharge, the amount depending on the size of the stream.

Typical examples of "rises" for several streams are shown in Figures 3 and 4. A study of these examples indicates that the peak sediment concentration may occur simultaneously with the peak of the water discharge (Medicine Creek at Cambridge, Nebr.) or as much as nearly four days in advance of the peak stage (Iowa River at Iowa City, Iowa). This and other information indicate that the time-of-lead concept introduced by Professor Johnson 3/respecting the occurrence of the peak sediment concentration and peak water discharge, while applicable to certain small streams, is not generally applicable to all streams.

Under ideal conditions the suspended sediment load is in equilibrium with the bed material. In natural streams this condition seldom exists. Under certain conditions of flow the sediment concentration appears to fluctuate about a mean value but in other instances the fluctuations appear to be neither momentary nor periodic but vary at random. The sampling time required to obtain an average value of the sediment concentration for certain conditions of flow has been discussed by Professor Kalinske 4/. For practical purposes it may be determined in the field by the collection of consecutive samples at any point or in any vertical section. The variation of the concentration in a stream vertical for several streams based on samples collected consecutively with a D-43 sampler is illustrated in Figure 5.

3/ 4/ See "References" at close of comments.

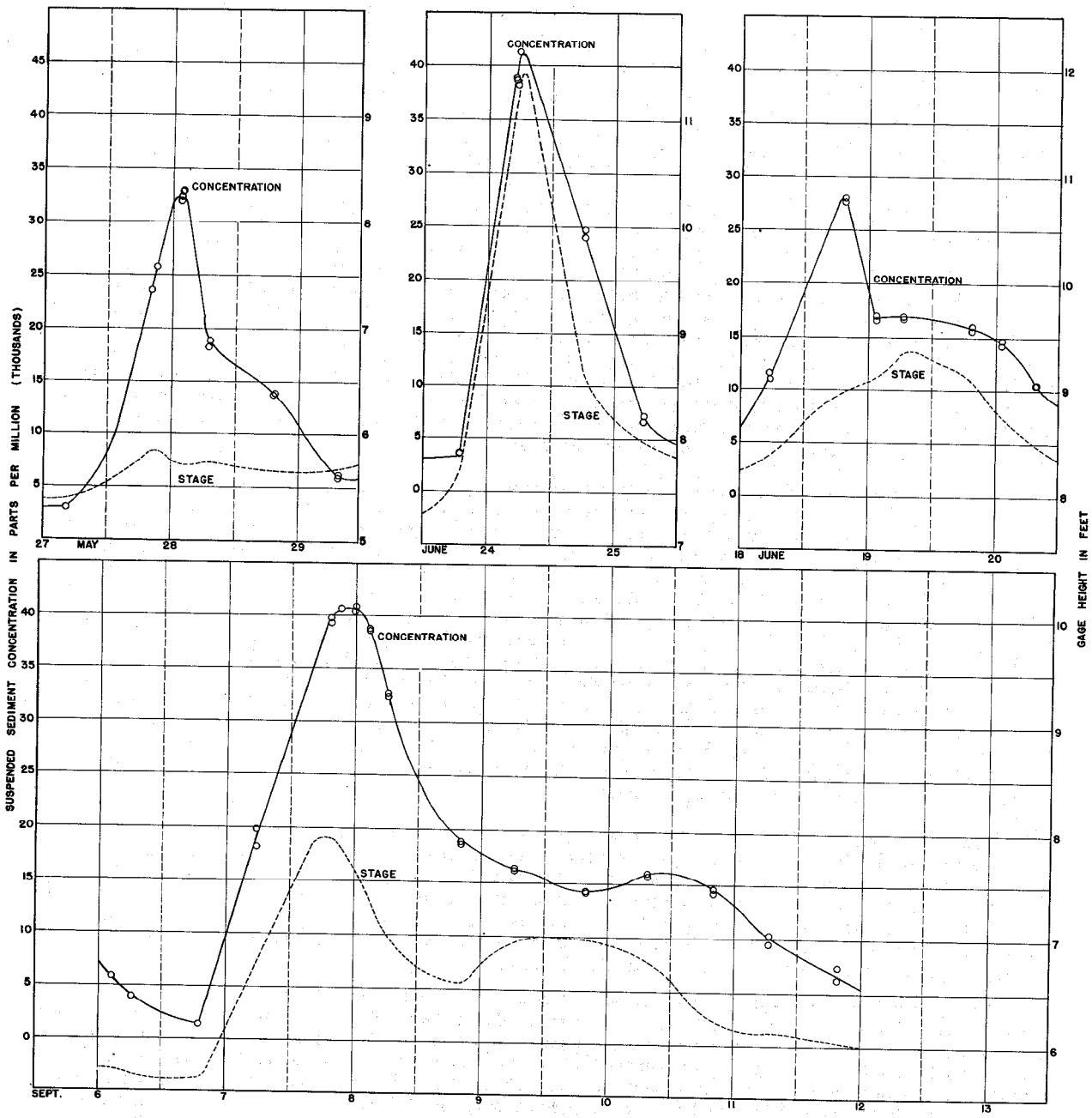


FIGURE 3. TYPICAL STAGE AND CONCENTRATION GRAPHS, BIGHORN RIVER AT MANDERSON, WYOMING

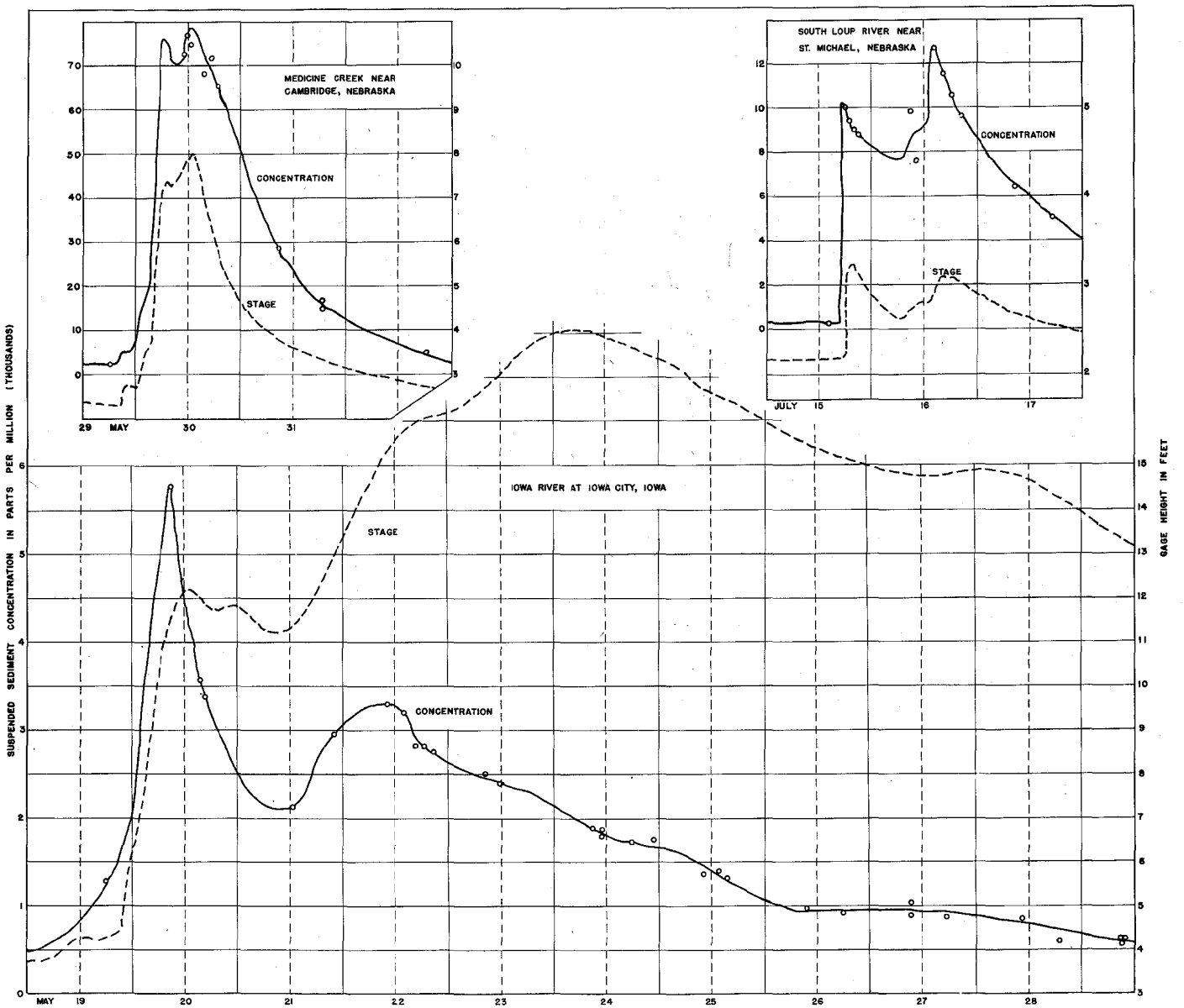


FIGURE 4. TYPICAL STAGE AND CONCENTRATION GRAPHS

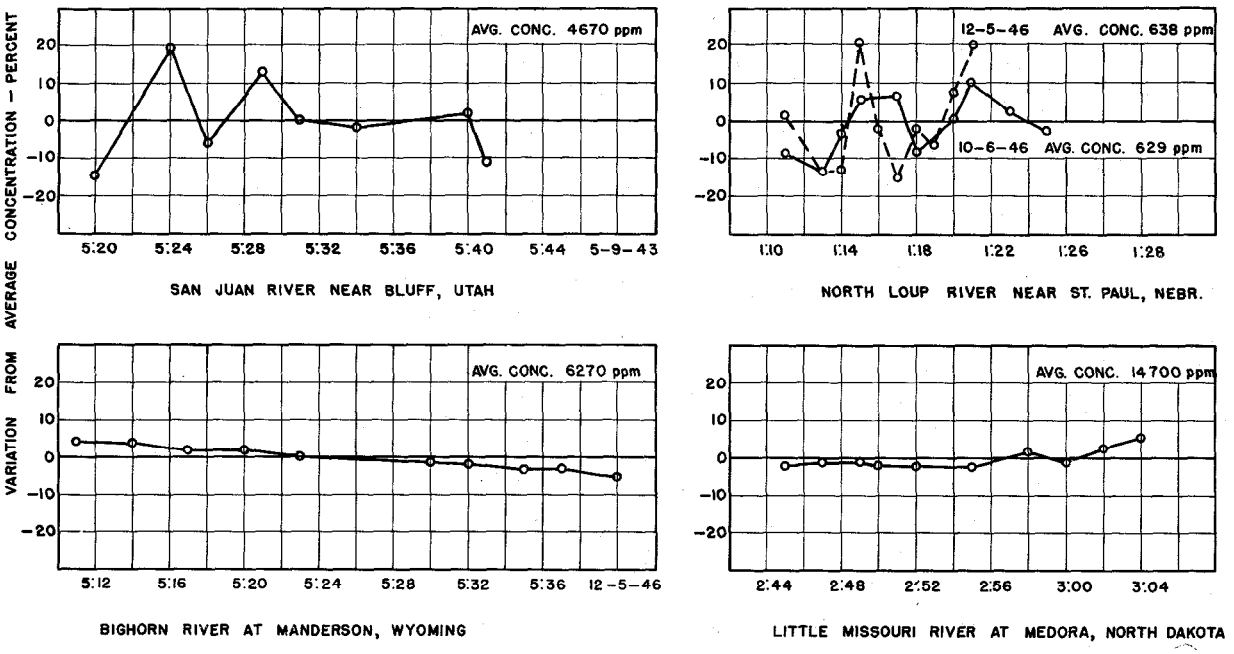


FIGURE 5 FLUCTUATION OF SUSPENDED SEDIMENT CONCENTRATION IN A STREAM VERTICAL

To the present time it has not been practicable to carry on a simultaneous sampling program in several stream verticals to obtain information respecting the fluctuation of the sediment concentration in the horizontal section. The distribution of the suspended sediment in the horizontal section for several small rivers is illustrated in Figure 6. The sampling stations for the Iowa River at Iowa City and Cedar River at Cedar Rapids are about 3/4 mile below low storage dams. The station on the Des Moines River is about one mile below a large tributary, the Raccoon River, which enters from the right bank and just above a low dam. The other two streams, Bighorn River at Kane, Wyoming, and Powder River at Arvada, Wyo., have only small ephemeral streams entering above the respective measuring stations.

Computation of Suspended Sediment Discharge. - The methods used to compute the suspended sediment discharge of streams vary with each organization now engaged in investigation of fluvial sediments. No attempt will be made to describe each for comparative purposes. Rather this discussion will be confined to present practices now being used by the Geological Survey in the Missouri River Basin.

The present procedure depends upon the type of sampling installation in use. In the nonmovable type the results of the sediment discharge measurements are tabulated and the relationship between the daily sampling station and that for the entire cross section is determined. This procedure is similar to that now used in tabulating water discharge measurements, except the relationship is shown as a ratio instead of a "percent difference." If the study indicates that the sediment concentrations obtained at the daily sampling station approximate the average found in the cross section within 10 percent, and the average variation is equal to unity, no corrections are made unless the error is consistently in one direction. If the variation is greater than 10 percent and consistently larger or smaller, appropriate corrections are made to the concentration in a manner similar to that used in making "shift corrections" to water discharge measurements. Typical studies are shown graphically in Figure 7.

At stations equipped with movable installations the results of sediment discharge measurements are used to verify the data obtained by the resident observer particularly during floods and to obtain adequate information about the variation of the concentration in the cross section.

The sediment concentration for each observation, which may consist of one or more samples, is plotted on the gage-height chart for each day. These points are connected or averaged by a smooth graph as previously illustrated in Figures 3 and 4, the pattern of which is similar to the gage-height graph.

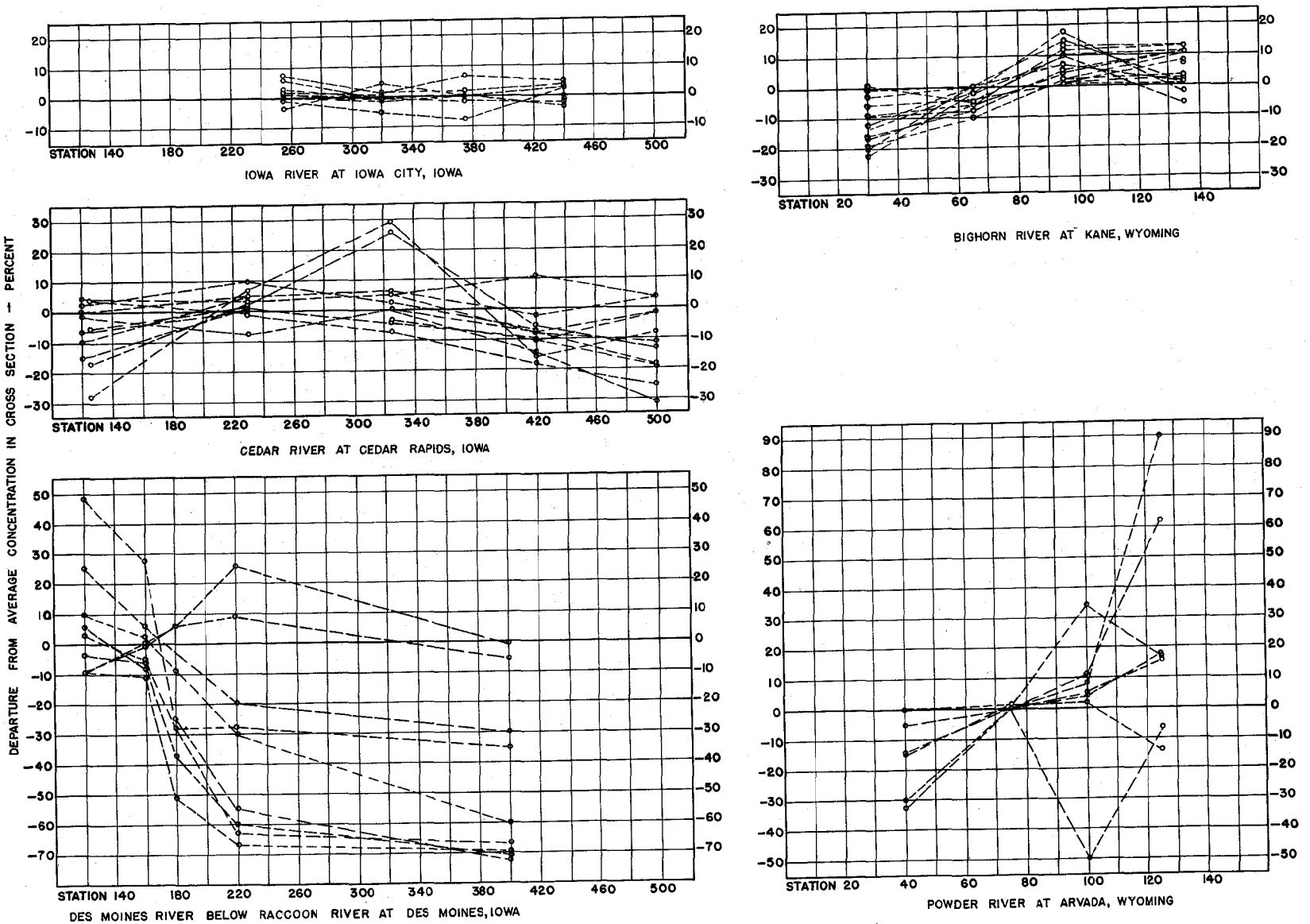


FIGURE 6. STUDY OF THE RELATIONSHIP BETWEEN THE CONCENTRATION AT THE SAMPLING POINTS AND THE AVERAGE CONCENTRATION IN THE CROSS SECTION

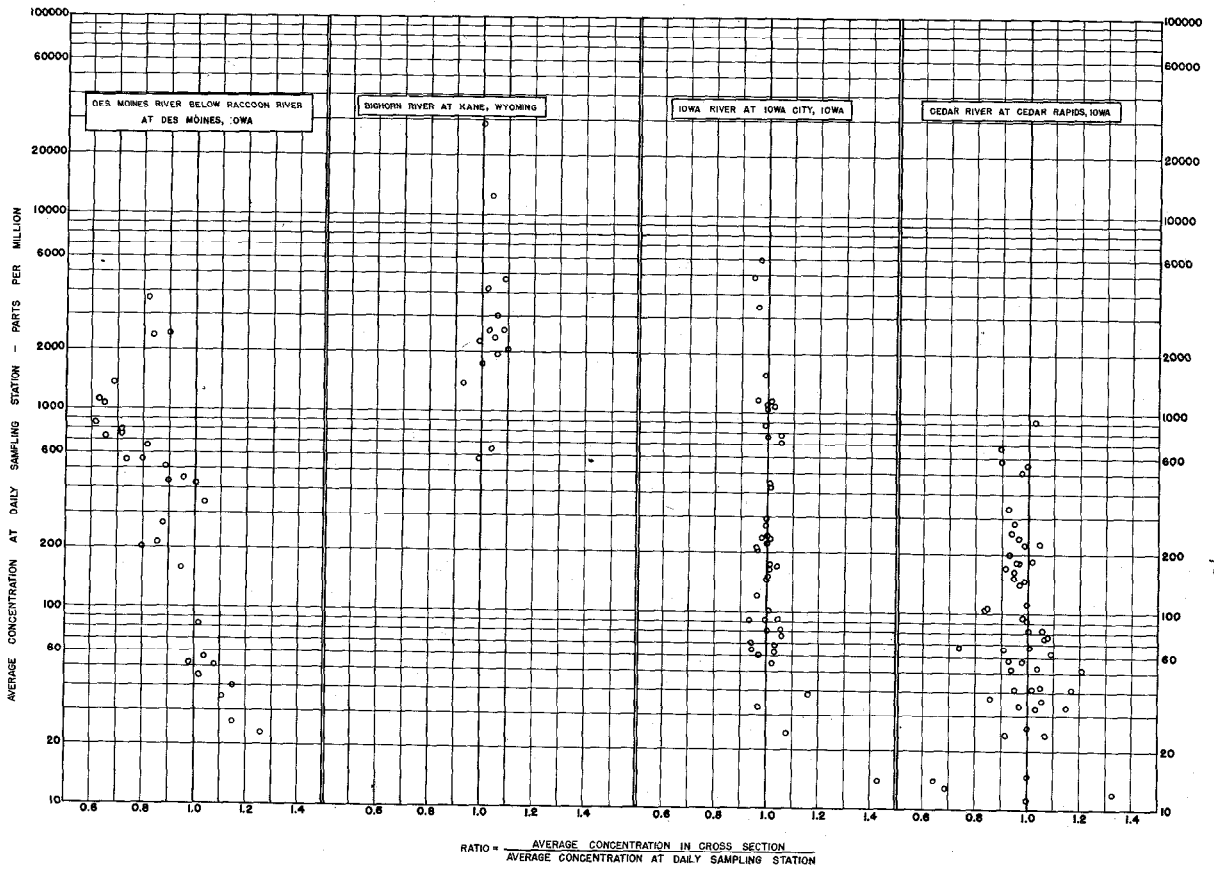


FIGURE 7. STUDY OF THE RELATIONSHIP BETWEEN AVERAGE CONCENTRATION AT THE DAILY SAMPLING STATION AND THE AVERAGE CONCENTRATION FOR THE CROSS SECTION

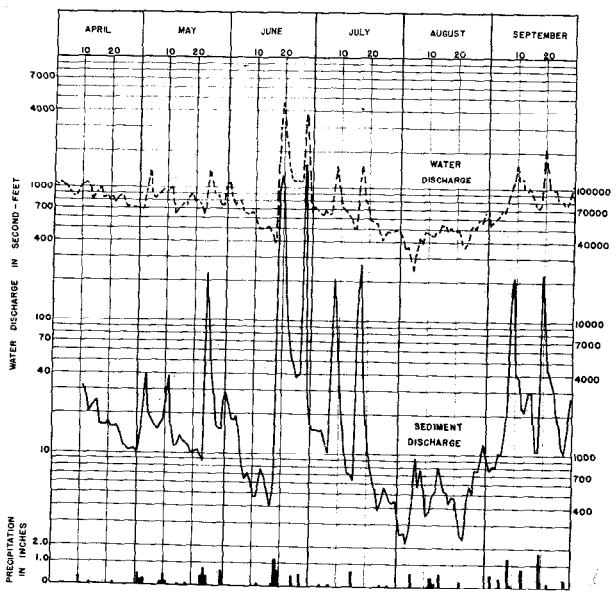


FIGURE 8. WATER AND SEDIMENT DISCHARGE HYDROGRAPH
MIDDLE LOUP RIVER AT ST PAUL, NEBRASKA
1945

The mean daily sediment concentration is obtained from this graph by "hand integration" or by means of a planimeter. For some periods the variation in the concentration may be quite small in which event it is not necessary to plot the data.

The sediment discharge in tons per day is computed from the mean daily water discharge and mean daily sediment concentration except on days when the concentration and water discharge are changing rapidly. During these periods each day is subdivided in accordance with accepted practice if the error introduced by not "subdividing" would be from two to five percent or greater. Further studies and comparison of the sediment and water discharge are made for each station or group of stations in the same drainage basin as shown in Figure 8.

Particle Size Data. - The determination of the suspended sediment discharge of a stream is not complete without information respecting the size of sediment particles in suspension. Size analyses should be made for both depth- and point-integrating samples, the number and frequency of which depending upon the information needed. On the

assumption that it will require a number of years to obtain a measure of the sediment transported by a stream, sufficient particle-size data should be obtained to define the range in water discharge experienced.

Summary. - The methods now in current use to determine the suspended sediment discharge of streams are governed to some degree by previously established procedures in each office or region, and by the sampling equipment available for use. In connection therewith it must be pointed out that although the methods used to ascertain the location of the sampling points and frequency of sampling are those outlined, the accuracy of the data obtained is still dependent on the sampling equipment used. The standardization of sampling equipment will therefore eliminate one major source of error in investigations of suspended sediment.

The sampling and computing procedures discussed in this paper are those (1) outlined in the series of reports issued in connection with the joint investigation of sediment sampling and technique conducted at the Hydraulics Laboratory at the University of Iowa, and (2) certain techniques developed by the Geological Survey. These procedures and techniques appear to have advantages not only of increasing the accuracy of results but also of simplifying the field, laboratory, and office work.

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DISCUSSION

R. J. PAFFORD, JR.* - The Corps of Engineers has been actively engaged in the observation of sediment discharges in the Missouri River Basin, and in the evaluation and analyses of various types of sediment problems associated with Corps of Engineers projects, for many years. A systematic suspended sediment observation program, which now includes some 40 regular stations, has been in operation continuously since 1937. In recent years, particularly since 1942, a great deal of attention has been focused on improvement of sediment records through improvement of field, laboratory and office techniques. The Omaha District of the Corps of Engineers has been particularly active in this regard, both in cooperation with personnel of the former Interdepartmental Committee and on its own initiative. This discussion, therefore, is a review of the information presented by Mr. Benedict, based on independent experience gained by personnel of an active field agency, aggressively interested in the accumulation of the most useful possible records of sediment discharges for use by that agency in evaluating and solving important sedimentation problems.

So far as the determination of total suspended sediment discharges are concerned, the main opinions expressed and practices described in Mr. Benedict's paper are in good general agreement with ideas which have been developed and conclusions which have been reached during evolution and development of the Corps of Engineers sediment observation program in the Missouri Basin. Of course, there is some disagreement concerning details, but this generally is minor.

Mr. Benedict's paper places considerable emphasis on the desirability of a general change by all field agencies to the use of modern practices for determining the suspended sediment discharge of streams, and particularly on the desirability of standardization of sampling equipment. For the past four years we of the Corps of Engineers in the Missouri River Basin have been dissatisfied with the equipment and some of the practices being used in conducting our suspended sediment observation program; first, because of the belief that better equipment and practices would result in improved accuracy of results and second, because only by the use of

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standardized equipment can suspended sediment data collected by the various operating field agencies throughout the country be truly comparative. It appears that this latter point may be even more important than the former.

Although we became dissatisfied with our sampling equipment and practices four years ago, no suspended sediment sampling equipment of proven superiority was available. Also we were faced with the necessity of continuing collection of sediment data to meet our current needs, and for the sake of consistent continuity of records were reluctant to make any general change until there was reasonable assurance that the change would be (1) to equipment of proven superiority to that in use, and (2) to equipment which it was reasonably assured might be standardized and placed in general use. Therefore, the existing sampling program was continued without any general change, and a semi-independent program was undertaken of assisting in development of new equipment and intensively testing the adaptability of this new equipment to our needs. Based on independent experience and tests, as well as on the work of the Interdepartmental Committee group, we became convinced by 1946 that a change-over was warranted to the P-46 type point integrating sampler for Missouri River and certain tributary work as soon as final mechanical complications of this sampler can be overcome, to the D-43 type depth integrating sampler for certain types of tributary work, and to an economical standard-type, simple operating, depth integrating sampler for certain types of work on the Missouri River and deep tributaries as soon as it can be developed. This change-over is now scheduled for Corps of Engineers work in the Missouri Basin at the earliest date when equipment can be obtained. It is believed that other field agencies will find it advantageous to change over to similar standardized equipment, and it is hoped that all field agencies will be using standardized suspended sediment sampling equipment in the very near future.

It is felt that there is a general tendency to underemphasize the importance of determination of suspended sediment load particle size gradation. To the engineer using suspended sediment discharge data in analyses of specific sediment problems associated with reservoirs and other river improvement works, accurate knowledge of the kind of sediment, and the amounts of sediments of various particle sizes is vitally important as well as reliable data on the total suspended sediment load involved. In fact, in certain problems, accurate knowledge of the amount of suspended sediment in a specific size range (for instance, fine suspended sands) may be found more important than accurate knowledge of the total discharge of all other sizes of suspended sediments. Experience gained from the Corps of Engineers sediment program in the Missouri Basin indicates unwarranted optimism by any implication that an adequate amount of particle-size data can be secured more-or-less as convenience permits during the number of years assumed to be required to obtain a measure of the total suspended sediment load transported by a stream. Data we have collected, while not completely conclusive, indicate that in many cases particle size gradation varies from a consistent relationship with stage or discharge in much the same manner as total suspended sediment concentration varies from such consistent relationships. Apparently the variation is not quite so severe in the case of very fine materials, and more severe in the case of fine suspended sands. Also, in some cases at least, this variation in particle size gradation does not appear to be directly related to or associated with the variations in sediment concentrations. Based on experience and data obtained to date, there appears to be a real need for agencies engaged in suspended sediment load determinations to place more emphasis on carefully systematized estimating of quantities of suspended materials in various particle size ranges, as well as on increasing accuracy of determination of total suspended sediment loads.

Limitations on the length of this discussion preclude extensive comments based on data and experience of the Corps of Engineers in the Missouri Basin on several interesting and important details presented in Mr. Benedict's paper. It seems pertinent, however, to briefly mention certain items.

To begin with, it is agreed that the suspended sediment discharge of any stream can be readily determined at any gaging station if an adequate number of observations are made to delineate the changes in concentration for any specific period for which the sediment discharge is desired. However, this could become embarrassingly expensive. It has been found that to keep suspended sediment operations on a practical basis there must be a very careful balancing between field and office operations, and a careful weighing of operation costs against the usefullness and accuracy of sediment data which may be obtained. Attempts to operate on too limited a budget can result in such serious deficiencies in the data collected as to make it worthless. On the other hand, rashly undertaken attempts for perfection of records can easily betray us into great increases in operation costs for certain tempting refinements, which are entirely unjustified by the quite minor increases in accuracy of over-all results which may be secured.

Corps of Engineers experience in the Missouri River Basin results in general agreement with practices at the tributary stations the Geological Survey is operating in the Missouri River Basin. However, it appears that the frequency of observations, and selection of number and locations of sampling verticals, at other stations, particularly on larger streams, should not arbitrarily be patterned after this program without careful analysis of the many factors which may be pertinent at various individual stations.

Mr. Benedict presents several interesting examples of variation of sediment concentrations from any "characteristic" or "normal" pattern for various rises at several stations, of marked variation of sediment concentrations between different verticals in stream cross sections, and of substantial fluctuations of sediment concentrations in a vertical in short time periods. All of these phenomena, to quite comparable degrees, have been observed during routine sampling or in special tests in the Missouri River which have been conducted by the Omaha District during extensive experimental investigations.

In closing, I would like to reemphasize the importance of obtaining good records of the quantities of suspended sediments of various specific particle size ranges, as well as good records of total suspended sediment loads such as are being collected by the methods outlined in Mr. Benedict's paper. Also, I would like to repeat the full concurrence of personnel, as individuals, engaged on the Corps of Engineers sediment program in the Missouri Basin, with the desirability of prompt adoption and general use of modern standardized suspended sediment sampling equipment by all agencies involved in sediment data collection.

SEDIMENT ENGINEERING AS A QUANTITATIVE SCIENCE

by E. W. Lane*

In the past two decades a branch of hydraulic engineering has been rapidly developing which may be called Sediment Engineering. It deals with the problems arising from the fact that practically all natural streams carry more or less sediment. In hydraulic engineering projects, the principal interest has been in handling the water, and in the past the plans and structures have often been developed considering only the water, neglecting the sediment carried with it. This has led to a great deal of trouble, in many cases involving large monetary losses. Sediment engineering is concerned with the anticipation of trouble from sediment, and the planning of hydraulic engineering works to avoid or minimize these difficulties. In the case of trouble with works already in service, it is used to work out the remedy in as far as possible.

Many of the general principles of sediment engineering have been known for years, but this knowledge is not very helpful unless it can be expressed in quantitative terms. For example, it is known that a stream carrying sediment into a reservoir will gradually fill up the reservoir. Whether or not the useful life of this basin is seriously affected by this fact depends largely upon the rate at which the sediment is carried in, and the capacity available to store it. Under some conditions the reservoir may fill up in 10 years, and under other conditions it may fill in 1,000 years. If the life is going to be 10 years, it may not be worth while to build it, but if it will not fill for 1,000 years, the sediment difficulties may, of course, be entirely ignored.

Since sediment engineering is so vitally concerned with quantities, the development of this branch of engineering had to await the discovery of quantitative relations. The first steps seem to have been made over a century ago, when the amount of sediment carried in a river was first determined from samples taken in the stream. Since that time, the science advanced gradually along with the development of hydraulic engineering works, but the greatest expansion of knowledge was made in the past two decades as a result of the rapid utilization of the resources of the streams of this and other countries.

The purpose of this paper is to report on the present status of sediment engineering, and to show that it has now developed to a point where we can make quantitative solutions of many of the problems relating to sediment with which engineers are confronted. Those of us who are most actively engaged in this work know only too well how far this knowledge is from being complete, and in many cases even from being adequate. When we compare the present knowledge with that of 20 years ago, however, it is evident that much progress has been made in this period, and there is reason to believe that the next few years will continue to show rapid advance. This paper will present the state of the science and practice by briefly reviewing the condition in the principal phases of the subject and by giving, by way of illustration of sediment engineering processes, an explanation of how some problems are attached.

Standard Terminology

An important aid to real progress in any branch of engineering is a standard terminology. In the early stages of development the terminology is bound to be inexact and nonuniform, and sediment science is no exception to this rule. The American Geophysical Union has been making an effort to correct the difficulty in the sediment field, and a committee of this society has recently suggested a number of definitions to clear up the uncertainty which arises when the same term is used with several meanings. This work was carried on by experienced sediment men, both geologists and engineers, several connected with the Governmental agencies having important sediment problems.

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Present Status of Development

In recent years a great deal of attention has been given to determining the physical properties of sediment. The way sediment acts in any situation usually depends on its settling rate. A knowledge of this rate or of the particle size, which is closely related to it, is very important in the solution of most problems. A standard classification of particle size has been worked out by this American Geophysical Union committee. The development of these size classifications is largely the work of the geologist. Quantitative expressions for particle shape have also been developed by the geologists, and the sediment engineer is very much indebted to these men for this work, which will assume more importance as the sediment engineering processes become more exact. At present there is a gap in our knowledge in relating particle size and shape to settling rate, but this will no doubt be filled before long. Another area in which considerable knowledge has been gained in recent years is the density of sediment deposits in reservoirs. It is now possible to make reasonably exact predictions of the density which will result under a wide range of conditions.

Among the most important tools of the sediment engineer are the laws of sediment transportation in flowing water. Many problems involve a determination of the amount of sedimentary material which a stream can transport. Considerable progress has been made during the last decade, but much remains to be done before these laws become a commonly used tool in solving sediment problems. As previously stated, the first quantitative step in sediment engineering was the measurement of sediment in streams. From the standpoint of time and money expended, this is the most important part of sediment engineering. Here also considerable progress has been made in recent years. An extensive study of the methods and apparatus for sediment discharge determination has been made by the cooperation of the Government agencies and Iowa University. The design of earth canals that will not fill up or scour is one of the difficult problems often encountered, especially if the water to be carried in the canal has a high sediment content. This problem has been extensively studied in India and much progress has been made there, but considerably more study is needed to obtain a completely satisfactory answer. A great deal of quantitative work on the filling of reservoirs by sediment has been done, which will enable much more accurate estimates of filling rates in many cases than was possible some years ago. These studies also give a more thorough understanding of where in the reservoir these deposits will take place. The control of reservoir silting has also been extensively investigated. Still another problem which the sediment engineer meets is the design of devices for removing the sediment from the water to prevent the filling of canals or damage to hydraulic machinery by the sediment carried in the water. Some work in this field has been done, but much remains to be accomplished.

One of the most useful aids in the development of sediment engineering science and in solving specific problems is the hydraulic laboratory. It has been extensively used in developing and checking the laws of sediment transport, in determining the stream channel forms produced by various water flows and sediment conditions, and in the perfection of instrumentation for sediment measurement. It can also be used to work out and demonstrate river control procedures. Although the quantitative relations between model and prototype are not completely understood, progress along this line is being made and the future will no doubt see considerably better results than the past. In general, it may be said that a hydraulic laboratory is an indispensable part of the equipment of any large group engaged in sediment studies.

Sediment Engineering Practice

The foregoing discussion has dealt largely with what might be considered to be sediment engineering science. The application of this science to actual engineering problems constitutes sediment engineering practice. One of the most interesting examples of the application of sediment engineering is on the Middle Rio Grande River Valley in New Mexico, where as a result of increased sediment production due to overgrazing, and decreased stream flow due to irrigation, the bed of the river has been steadily rising and the continued prosperity of this valley has been seriously threatened by floods and waterlogging. Engineering plans have been proposed to remedy this situation and are under active study by several of the Government agencies acting individually and in cooperation. The prediction of the results which will follow the construction of such works presents a difficult problem to the sediment engineer.

One of the earliest examples in this country of the application of sediment engineering to determining in advance the results of a program of engineering construction was the prediction of the conditions in the lower end of the Colorado River which would be caused by the deposition of the sediment carried by that river in Lake Mead. Another paper presented to this conference tells of these effects, but it may be said here that most of them were predicted and their

magnitudes estimated by sediment engineering methods. Considering the entire lack of precedent for these predictions, they worked out quite well.

Prediction of the Location of Deposits in Reservoirs

One of the problems frequently met by the sediment engineer is the prediction of the position of sediment deposits in reservoirs and the rate at which the reservoir will fill. The method of attack of this problem is typical of the techniques which are being developed in sediment engineering practice. To understand this process it is necessary to understand the process of reservoir sedimentation.

In many respects the deposits in a reservoir resemble those made by a stream where it enters a lake or the ocean. Geologists have classified the deposits which are formed in three parts: bottom-set beds, fore-set beds, and top-set beds. Figure 1 shows a longitudinal cross-section through a reservoir and the position which each of these deposits take. The bottom-set beds are formed of the fine sediment brought down by the stream, which settles slowly and is carried long distances out into the reservoir, depositing over much of the bottom in a thin layer. The fore-set beds are composed of the coarse material transported by the stream and are deposited where the velocity of the stream is retarded as it reaches the lake level. These beds are steeply inclined. As more and more material is brought into the reservoir, the point where the fore-set beds are being formed moves further and further out into the reservoir, covering the upstream ends of the bottom-set beds previously deposited. As the fore-set beds move out, the current in the river upstream is retarded because its slope is reduced and the stream deposits part of its coarse material, not only on top of the fore-set beds previously laid down, but also on the bed of the stream above the water level in the reservoir. These deposits, which are slightly sloping layers, are called top-set beds.

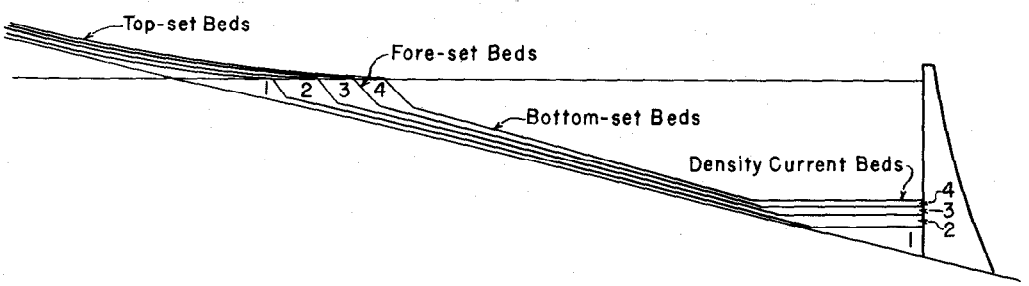


Figure 1. Longitudinal Cross-section through a Reservoir, Showing Various Types of Deposits.

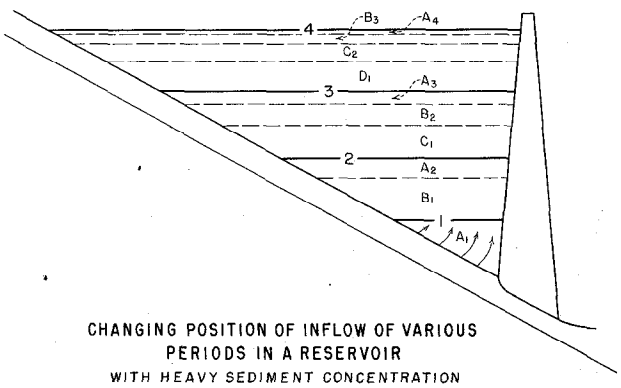
There is also a fourth kind of deposit found in many reservoirs which has recently aroused considerable interest, namely that due to density currents. When a flow coming into a reservoir is composed in large part of colloidal or other very fine particles, the action of the water containing the sediment may be like that of a dense fluid. When it reaches a reservoir of clearer water, because of its greater density, the muddy water sinks to the bottom and flows down the bottom of the reservoir beneath the level water surface of the clear water above, until it is stopped by the dam. It then spreads out, filling up the lower part of the reservoir and very slowly deposits nearly level beds as shown in Figure 1. Such density currents will move many miles down a reservoir without visible indication on the surface. In the Elephant Butte Reservoir in New Mexico they have been known to flow 30 to 40 miles, and in Lake Mead above Hoover Dam it was observed at the dam when the reservoir was 70 to 90 miles long.

From the shape of the reservoir, if the amount of coarse and fine material brought in per year is known, the position which each will take can be roughly determined. The sediment brought in the first year will somewhat change the shape of the reservoir and cause the deposits brought in the second year to occur in a slightly different place. Those deposits in turn will influence the position of the deposits the third year and so on. The sediment engineer estimates the position of the deposits step by step, using periods of a length depending on the degree of accuracy he desires in his results. Knowing the amount of coarse and fine material brought down on the average for the period used, he determines where the coarse material would deposit and where the fine material would settle, and how much space it would occupy. For example, on Figure 1 the material deposited in the first period could be represented by the area numbered 1. The volumes in the top and fore-set beds would be equal to the average load of coarse sediment brought down by the stream during that period. The volume on the profile represented by the bottom-set and density current beds for the first period would be the average loads for the period of these

materials. During the second period the materials would be deposited in the position represented by the area marked 2. Again the volumes added would be those occupied by the average sediment load of the respective classes for the period. These deposits would again change the position of deposition and in the third period that represented by area 3 would be deposited. Space is not available to go into all of the steps in detail. One of the important factors is the density of the deposited sediment. This depends upon fineness of the material and on the exposure of the beds to drying. Another is the shape of the top-set beds. This cannot be determined with great exactness, especially where the reservoir is broad, as the stream tends to form natural levees along its banks and build up the bed higher than the adjacent area. In a flood it may break through these naturally formed levees and flow into the low land, changing its course entirely. It is doubtful if we yet have sufficient knowledge on the material and conditions which give rise to density currents to differentiate between bottom-set and density current beds, but as additional knowledge is gained, it is hoped that we will be able to do so.

Deposits in Retarding Basins on Streams with Heavy Sediment Loads

Another example which can be used to illustrate the type of approach which the sediment engineer employs is the method developed for predicting the deposits which would occur in a flood-retarding basin on streams carrying heavy sediment loads. Two such basins were planned and about to be constructed before the war on the Yung Ting River in northern China. This stream carries a very heavy sediment load, and considerable deposit in the reservoirs was expected, but no method was available for estimating how much this would be. By breaking the problem down into steps and by making certain simplifying assumptions, which are probably quite close to the truth, it is possible to compute the deposits which would occur in the basins in any flood if the data on stream discharge and sediment concentration and composition are available throughout that period.



CHANGING POSITION OF INFLOW OF VARIOUS PERIODS IN A RESERVOIR WITH HEAVY SEDIMENT CONCENTRATION

FIGURE 2

When the water of a flood first starts to store in a retarding basin it rises above the outlet, as shown in Figure 2. Most of the water flows directly through the outlet, but the remainder begins to fill up the bottom of the basin, occupying the space A_1 with a water surface at 1. As time goes on more water is stored until Level 2 is reached, and for a reason which will be explained later, the water which occupied the space A_1 moves up to the space A_2, and the bottom of the reservoir is occupied by the water B_1. After another period of time the reservoir has been filled to a Level 3, and the A water has moved up to A_3, the B water moved to B_2, and C_1 water occupies the bottom of the reservoir. After another period, the reservoir has filled to Level 4, the A water occupying the position A_4, the position B_3, the C water the position C_2, and D water occupying the remainder of the reservoir.

The sediment particles in the water, however, do not rise at the same rate as the water since each particle of sediment settles down at a definite rate with respect to the water surrounding it, the larger particles settling faster than the finer ones. If the particles settle down through the water at a faster rate than the water surrounding them rises, they will settle toward the bottom of the reservoir. The A water, for example, in a given time has risen from the bottom to the top of the reservoir, but a particle of sediment which would settle faster than this water rose would have settled down rather than risen up. As considerable time has elapsed between the time the A water entered and the time the reservoir reached Level 4, and all during this time the sediment particles brought in with the A water were settling, all particles except those which sink very slowly would have settled out of the A water and it would be relatively clear. The B water would have been in the reservoir a shorter time and less sediment would have settled out of it. It would therefore be denser than the A water, and because of this higher density the lighter A water would tend to stay on top of it and not mix with it. We would thus have a gradually increasing density from the surface to the bottom of the reservoir, which would oppose the mixing of the water and tend to maintain the vertical distribution of the water in the order that it entered the reservoir. The inflowing water, having a greater sediment content, would flow down the bottom of the reservoir to the dam as a density current and the portion which could not pass out would rise in the reservoir beneath the water which previously entered.

By breaking this process down into steps and following through the position of the water entering at various times and also of the particles of various settling rates and their concentrations, it is possible to compute the amount which would settle to the bottom of the reservoir before the reservoir empties itself after the flood subsides. This would be a very long, tedious process, but the use of a slide rule invented for flood routing in reservoirs was found to be capable of transformation into a tool for tracing the sediment movement, and the process was thereby greatly speeded up. In the above discussion for simplicity the density of the concentration of sediment in the inflowing water has been assumed to be constant, but a varying concentration can also be handled.

Conclusion

In concluding it may be repeated that the purpose of this paper is to point out that a branch of hydraulic engineering has been developing with a quantitative science behind it which will be of great assistance in enabling engineers to cope with the problems which are arising because of the transportation and deposition of sediment in streams. As this is a new development, too much must not be expected of it in its present form, but rapid advances in this field are being made and we can expect that much better results will be possible as time goes on.

Acknowledgements

The development of sediment engineering has been the work of a great many men, of many races and nations, scattered all over the face of the earth. It has not been confined to hydraulic engineers, as geologists and others have contributed greatly. To mention specifically even the most important contributions and the men who made them would exceed the space available, and it is difficult to draw a line between important and non-important contributions. It may be said, however, that many of the important contributions have been made by those whose papers appear in this report.

DISCUSSION

S. K. LOVE.* As pointed out by Mr. Lane, sediment engineering has been assuming the proportions of a quantitative science only during the past two decades. Prior thereto the importance of obtaining reliable information about the detrital load of streams was realized by relatively few far-sighted investigators. The presence of sediment in streams was largely ignored even by scientifically trained persons charged with the responsibility of design, construction, and operation of hydraulic structures. One has only to look at a fairly large number of dams constructed 20 or more years ago to find that all too many are either filled with sediment or that the live storage has been so greatly reduced that the operation of them has become an economic liability. It is recognized that the paucity of quantitative data about the sediment production of streams on which some of the dams were constructed made it practically impossible to make proper allowance for sediment storage. On the other hand it appears that too little thought was given to the possibility of loss of reservoir capacity through the deposition of detrital loads above the dams.

Because of the increasing emphasis on the need for reliable and comprehensive information about the sediment transported by streams, it is doubtful if a large or even a medium-sized dam would be constructed today without making the best possible use of existing sediment data and without allocating dead storage to provide for sediment accumulations.

It may be pertinent to inquire about the future useful life of dams and reservoirs in this country resulting from the gradual filling up of the large reservoirs recently constructed or now under construction in regions where the sediment production of streams is relatively large. To what extent will the quantitative science of sediment engineering be employed to assure a useful life of 50, 100, or 200 years or even longer for these reservoirs?

The deposition of sediment in Lake Mead has already reached serious proportions and it is understood that plans are being made for a comprehensive sediment survey to determine the depth and distribution of deposited sediment above Hoover Dam. The allocation of a storage pocket of about 8 million acre-feet for sediment deposition was undoubtedly a wise provision. However, when it is recalled that approximately 1.7 billion tons of sediment as measured at the Grand Canyon gaging station have already entered the Lake since storage began in 1935, and that the

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sediment probably occupies at least 1.5 million acre-feet of storage capacity (assuming 50 pounds per cubic feet on a dry weight basis), it is readily realized that nearly one-fifth of the 8 million acre-feet allocated to sediment storage has already been filled. Some of the sediment has been deposited in the delta area at the head of the Lake which may not be included in the 8 million acre-feet allocated for sediment storage. Furthermore, ultimate consolidation of these sediments will tend to decrease the volume occupied. Nevertheless, unless upstream reservoirs are constructed for sediment retention it may be that the useful life of Lake Mead will be considerably less than originally expected.

What is true for Lake Mead is also true for other reservoirs except that the time of filling sufficient to impair their useful life will depend on the size of the reservoirs and the rates of sediment production.

It cannot be urged too strongly that quantitative measurements of detrital materials should be obtained and utilized in connection with all major hydraulic developments on streams in which sediment is or may become a menace. Although a great deal remains to be learned about the laws of sediment transportation and effective means of measuring the sediment discharge of streams, the knowledge and tools now available are sufficient to provide much of the information needed for the solution of present-day problems relating to the construction and operation of hydraulic structures.

VICTOR H. JONES.* The diagram illustrating sediment in reservoirs was very interesting to me. I think it showed the general relationships very well. And yet I would like to emphasize the fact that the relationships between the bottom set beds and the density current beds are not very clear. For instance, in many reservoir surveys which we have made in the Soil Conservation Service, especially in those reservoirs where the shape of the basin is rather wide and where the reservoir is very shallow, we find a rather equable distribution of sediment over broad parts of that basin. The depth of that sediment over a period of years is not appreciably greater in most cases near the dam. In some cases it may be, in other cases the distribution may be affected by restrictions in the basin itself in which we get a concentration above that constriction. In most reservoirs of this type, however, I doubt if it is practicable or possible to distinguish between such effects as regular bottom set beds and density current beds. It will not be easy to distinguish them by texture. Practically all such sediments in large flat reservoirs are predominantly clay with some intermixture of silt. Generally we have found no sands or sandy sediment in such a basin below the extreme headwater portion.

Another point which I think well worth emphasis is the fact that in large reservoirs in which sediment storage pools are planned, these pools are not pools which have tops parallel to the water surface. They are more nearly parallel to the bottom of the reservoir and will occupy a segment of the reservoir bottom.

PARKER D. TRASK.** Mr. Lane's paper is very stimulating and focuses attention on the very important problem of control of density currents in reservoirs. Density currents, as Mr. Lane points out, are influenced by the distribution of salinity and temperature of the water in the reservoir. In order for a density layer to be effective in flushing sediment out of a reservoir, it should be underlain by heavier water, which will buoy the layer up so that sediment-laden water can flow through the reservoir. It seems to me that if the density layer extends to the bottom of the reservoir, friction on the bottom would impede the flow of water and thus tend to cause sediment to settle out.

As the density of fresh water reaches its maximum at 39° Fahrenheit, and as heavier water tends to sink through lighter water, density layers in reservoirs will be influenced by the variations in temperature in the surface water and in the river water entering the reservoir. In reservoirs such as the Hoover Dam, where the winters are not severe, density layers should persist in a more stable state than in reservoirs in the upper Missouri River where the surface water cools to its maximum density at 39° as winter approaches, thus tending to cause a turnover of the warmer bottom water and a disturbing effect on density layers. Any study of density

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** Geological Survey, Washington, D. C.

layers should include a careful investigation of the distribution of temperature throughout the reservoir from one season to another during the year.

With respect to Mr. Lane's illustration of topset, foreset and bottomset beds in reservoirs, it seems to me that the bottom configuration of the reservoir near the inflow of the master stream has considerable effect upon the angle of inclination of the layers of sediment. For example, if the floor of the master stream has a gradient of a few feet per mile near the headwaters of the reservoir, the initial sediments that are laid down can hardly have a greater inclination. Not until the delta has been pushed a considerable distance forward can the inclination of deposited sediments become great and then only if the size-distribution of the sediment load is such that a sort of a wall is formed at the front of the delta down which sediments can fall as the delta is pushed forward. It seems to me that unless the coarser particles are deposited at a materially more rapid rate than the finer particles, steep foreset beds cannot develop. If steep slopes do not develop, then the difference between topset, foreset and bottomset beds may not be very great. The critical question is the relative rates of deposition of coarse and fine particles with respect to distance from the head of the reservoir. Longitudinal profiles taken at the heads of reservoirs on a few master streams could settle this problem very simply.

THOMAS MADDOCK, JR. * For Dr. Trask's information I would like to point out that Mr. Lane in his paper makes specific reference to high concentration of sediments entering the reservoir and therefore he realizes that you do have differences due to temperature. Furthermore Mr. Lane's method of approach was limited to dams with temporary storage where temperature differences are not important. Thus there are two limits to this method which disregard temperature effects, high concentrations of sediment in the inflowing water and short period of storage.

ALBERT S. FRY.** I would like to emphasize the point that Dr. Trask made. In the TVA reservoirs, different conditions occur than those discussed by Mr. Lane. We are much concerned with density currents which we have found to greatly affect the flow of water through a reservoir. These currents in our reservoirs are caused by temperature differences and not by silt load. It is important that no one should get the impression that deposition will occur in any reservoir according to Mr. Lane's diagram, as this will take place only in those cases where the sediment load is so heavy that it overbalances the effect of water temperatures in setting up density currents.

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** Chief, Hydraulic Data Division, Tennessee Valley Authority, Knoxville, Tenn.

DETERMINATION OF RATES OF BED-LOAD MOVEMENT

by Hans A. Einstein *

The rates of bed-load movement in streams can usually be determined by two entirely different methods: either by direct measurement or analytically from the way the stream and its load have shaped the channel. The method of direct measurement will be described first, together with some comments on the instruments used, and then the analytical method will be discussed. A critical comparison will finally show the advantages and disadvantages of each method and will suggest their fields of application.

Direct Measurement of Bed-Load

Before we can organize the measurement of any physical variable like the rate of bed-load transport, we must first define this variable. Quoting the recommendations of the A.G.U. Committee on Sediment Terminology, bed-load may be defined as "coarse material moving on or near the bed." This definition is not very precise, but in a general way it conveys the two ideas that the large grains of the load should be included and that these larger grains are supposed to move near or on the bed. We all know that the largest grains transported by a stream have a tendency to move near the bed and in this general way the qualification "coarse material" in the definition of bed-load is synonymous with the second one saying that it moves near the bed. However, only too often we find the coarsest grains of the load all the way up to the surface while the finest particles are always as plentiful at the bed as in the rest of the cross section. Because of this complication and because of the extreme variability of conditions from stream to stream, it is customary for each investigator to draw his own line of demarcation between bed-load and the rest of the moving solids in order to fit the special conditions of a particular stream and of the instrument used. For this reason, the above mentioned Committee allows the alternate definition of bed-load as "the material collected in or computed from samples collected in a bed-load sampler or trap."

This brings us to the conclusion that bed-load is that part of the load which is measured with a bed-load sampler and a bed-load sampler is an instrument used to sample bed-load. It seems doubtful whether this definition has any real value. A more usable definition of a bed-load sampler, however, results from the problem of determining the total load in a stream. Beginning at the water surface, we can measure all suspended load in the upper layers with the help of suspended load samplers, i.e., instruments which take water samples from different points of the flow. These water samples are used to determine the concentration of sediment in the water, and the rate of transport of such particles can then be obtained by multiplying the measured sediment concentration by the corresponding water discharge. Implicitly, the assumption is made that the average horizontal speed of sediment particles is the same as that of the surrounding water.

This assumption is permissible in all parts of the flow except in the immediate proximity of the bed. There the integration of the product of concentration times flow breaks down for several reasons:

1. The velocity gradient becomes too large.
2. The concentration gradient becomes too large.
3. The solid particles cease to have the same velocity as the surrounding water.

A different type of measuring instrument, which measures directly the rate at which sediment passes this part of the section, must be used to measure the sediment transport in this bottom layer. From this we can define a bed-load sampler as an instrument which measures directly the rate at which sediment moves in a given layer adjacent to the bed. The thickness

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of this layer must be chosen individually for different streams. It must at least equal the diameter of the largest grain and must include all the flow up to the lowest possible level at which the suspended load sampler may be used to complete the measurement. On the other hand, ease of handling makes it imperative not to choose the bed-load layer any thicker than absolutely necessary. The layer thickness chosen in measuring the bed-load in the Aare, for instance, was 12 inches because particles up to this size are moved by that mountain stream. The Dutch engineers, on the other hand, who measured sand transport in the lower Rhine River, where the maximum grain is about 1 mm., developed a sampler with only 2 inches vertical opening.

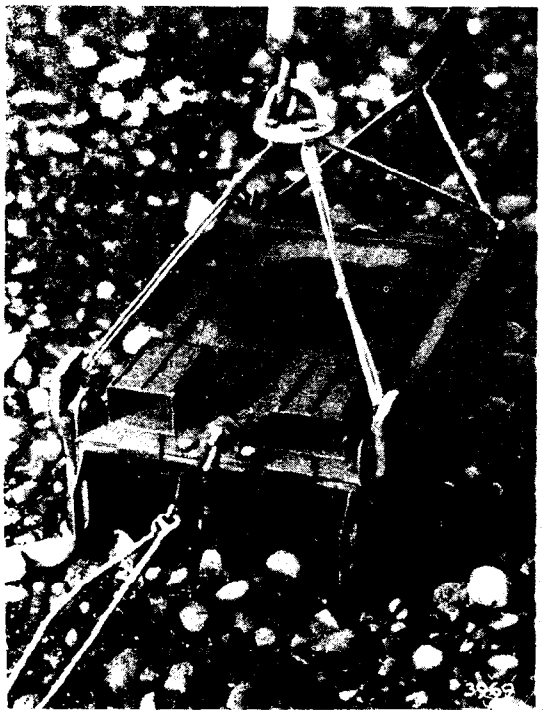


Figure 1. 1:2.5 model of the bed-load sampler used by Nesper in measuring the transport in the Rhine River. The photograph was taken at the end of a sampling period. Note sediment accumulated in front of entrance due to hydraulic resistance of sampler.

Box-type Samplers

All bed-load samplers, or traps of the so-called box type, are built according to the following principle: the water and sediment together enter the sampler through a rectangular entrance frame. Inside the body of the trap the flow velocity is reduced and by this velocity reduction alone, or with the aid of a screen, the sediment is deposited in the trap, while the water is allowed to flow out at the rear end. In normal operation, the sampler is brought down to the bed as fast as possible and left there for a given period of time, during which time water flows through the sampler while the sediment is deposited. At the end of the measuring period, the sampler is lifted again from the bed and out of the water. The catch is removed and measured.

The main sources of error in using such

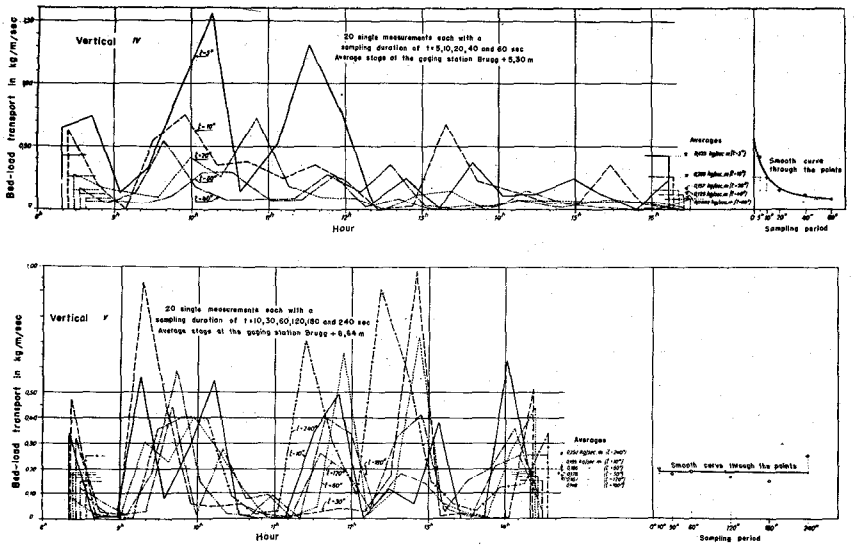


Figure 2. Continuous sampling by Nesper in a section of the Rhine at constant stage shows the extremely high fluctuations of the rate of movement. Alternately, different sampling durations were used. Diagrams to the right give average rate in terms of sampling duration. Top diagram gives results of sampling with elastic horizontal cable support; bottom diagram is obtained with stiff horizontal support. Note difference between rate-time relationships at the right.

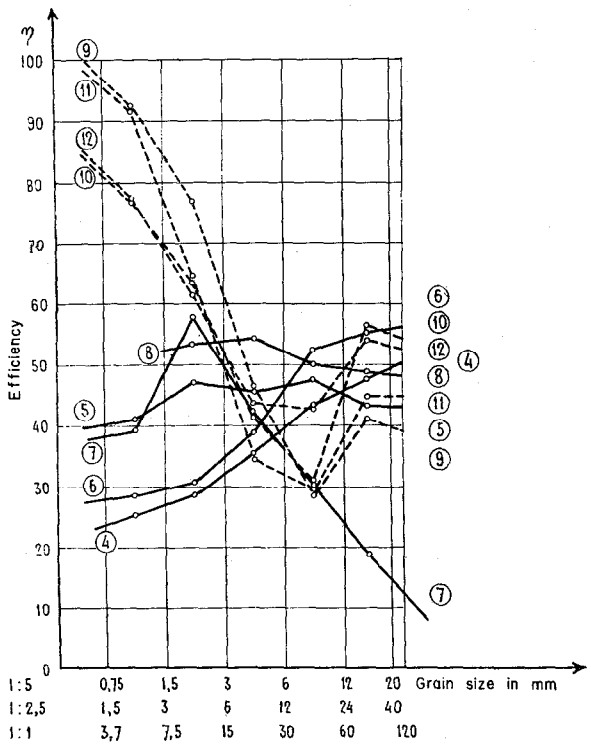


Figure 3. Laboratory calibration of Nespers sampler shows efficiencies for individual grain sizes. Curves 9 ÷ 12 represent a high rate of transport; the others a medium rate. The systematic change of these curves with the rate of transport is characteristic for all box-type samplers.

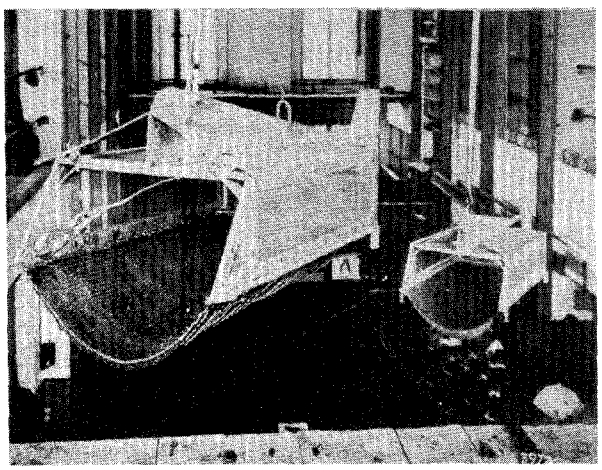


Figure 4. Bed-load sampler of the Swiss Amt fur Wasserwirtschaft and its 1:2.5 model. Note flexible bottom which prevents by-passing of sediment under the sampler. Little contact feet visible on model, dismounted on prototype, give electric signals when sampler reaches the ground.

sampling devices are the following:

Sampling Period. - If the particles of which the bed-load consists are moving in part in suspension, it is possible that such particles are collected during the lowering and raising periods. They tend to increase the measured rate.

An ingenious device has been used on some very heavy samplers. The front end is supported by two little foot plates which close electrical contacts as soon as the weight of the trap rests on them. These contacts are connected to little signal lights at the bridge from which the sampler is guided. The operator can see from the behavior of the lights whether or not the sampler is in solid contact with the bed and can thus easily measure the exact duration of the sampling period with a stop watch.

Velocity Reduction at the Entrance. - In working position the sampler offers a sizeable resistance to the flow under all conditions. In general this resistance will cause a pressure increase in the entrance, which again reduces the velocity of water inflow. Any such local pressure increase is felt especially by the slow-flowing bottom layers which carry most of the bed-load. Thus, an average velocity reduction at the entrance of 10 percent may cause a reduction of the measured bed-load rates of 50 percent, as was learned from the performance of such samplers in calibration tests. Some designers of bed-load samplers tried, therefore, to move the effect of the resistance away from the entrance either up into the free flow (see Ehrenberger's fin) or behind the entrance (see the elongated entrance of the Arnhem sampler). These measures are very effective in bringing the average efficiency of the instrument up to 100 percent, but this efficiency may still vary with the velocity distribution around the sampler, which changes with the character of the bed and with the ratio between the sampler size and the water depth. This means that any such sampler should be calibrated for the type of bed and flow for which it is intended to be used.

When it became known that samplers had to be calibrated individually for different applications, later designers such as Nesper and the Schweiz. Amt fur Wasserwirtschaft did not think it was important to have an efficiency near 100 percent, and they developed their instruments from Ehrenberger's sampler rather for convenience of handling, leaving out the fins. Their instruments have an efficiency of 30 to 60 percent, but have a much larger capacity per unit of weight. Calibration tests on these samplers in different scales showed that their performance is consistent if they are properly used.

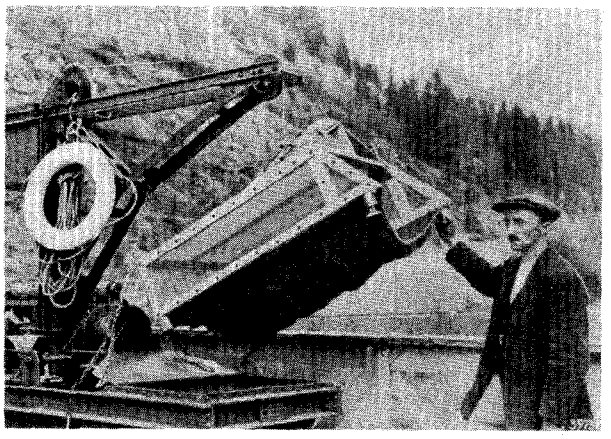
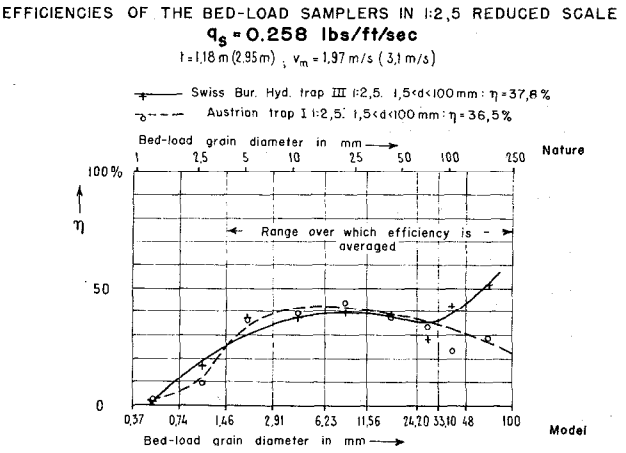


Figure 5. Swiss sampler ready to be emptied after sampling in the Aare. All box samplers must be supported in such a way that the tail end hangs down low and reaches the bed first. Otherwise, the sampler digs into the bed.



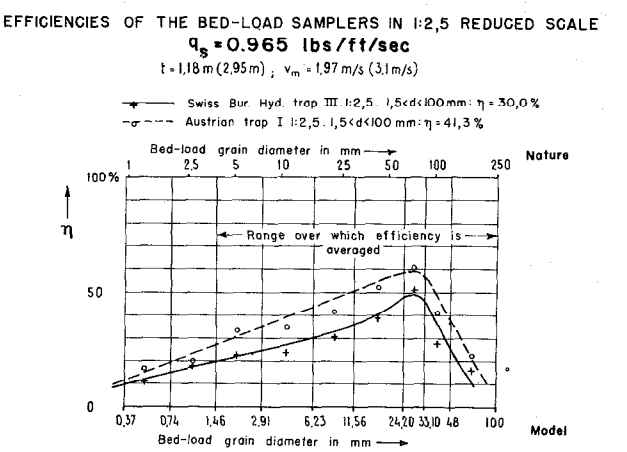


Figure 6. Comparison of the efficiencies of the Nesper sampler (o) and of the Swiss sampler (+) at two rates of transport. The two samplers behave very similarly, both are calibrated on the Aare sediment.

Scour under the Sampler. - One of the greatest difficulties in the development of bed-load samplers is to make them sit flat on a naturally rough and irregular bed. If any passage is left open between the bed and the sampler entrance, water will flow through this opening and will wash through under the sampler some of the finer constituents of the load, seriously biasing the result. The most effective solution in preventing this mistake has been used by the Schweiz. Amt fur Wasserwirtschaft in their sampler for measurements in the Hasli-Aare. They built the entire bottom of the sampler, including the bottom part of the entrance section extremely pliable and sufficiently heavy so it would always fit the bed snugly. For material they used a loose sheet of chain link mail fastened to the frame with wire. By this measure certain inconsistencies common to all other samplers were eliminated.

Excessive Filling. - Up to a filling of about 30 percent of the total sampler volume, most instruments show no change of the efficiency with the degree of filling. For higher degrees of filling, the efficiency usually drops considerably. It is preferable not to use the samplers in this range as results become inconsistent.

Elastic Support. - Bed-load samplers are usually handled from a bridge. Especially for the heavier models (Schweiz.Amt. fur Wasserwirtschaft model weighs about 300 lbs), this is the only possibility outside of the use of boats in large rivers. Whenever the current is swift as is usually the case where the bed-load is coarse, the sampler experiences a considerable drag in the water. They are then usually braced horizontally by a system of cables that are elastic to some degree. The drag varies roughly as the square of the water velocity. As the sampler is lowered through the water towards the bed it moves first through layers of high velocity. The flow velocity, and simultaneously, the drag, diminish as the sampler approaches the bed. There they are a minimum. As the drag is reduced, the elastic cable suspension pulls the sampler upstream. If the last foot or two approaching the bed are travelled rather fast, the elastic suspension does not find time to adjust its displacement and when the sampler reaches the bed, it is located further downstream than would correspond to the average drag there. The elastic suspension aided by irregularities of the drag force due to turbulence, gradually pulls the sampler upstream during the sampling period, shovelling bed material into its entrance, which otherwise would not have moved during this period. From this action a systematic increase of the samples results, which is known to have amounted to 100 percent of the average sample under normal conditions. By

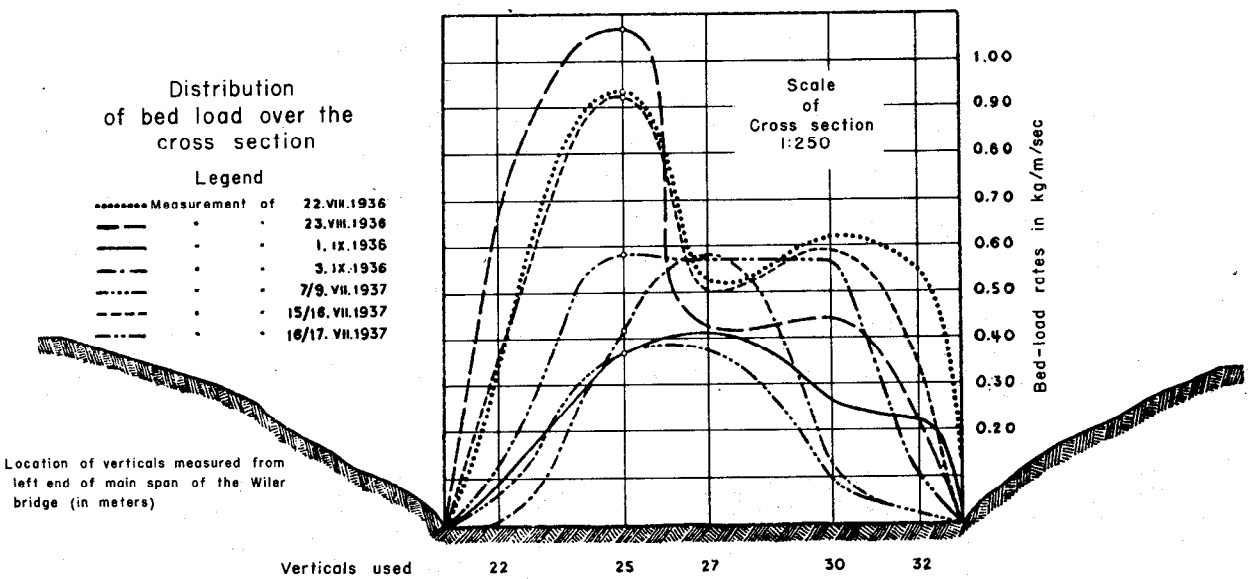


Figure 7. Measured distribution of the transport over the Aare cross section at different stages. Despite the regularity of the channel and of the bed, the bed-load moves in irregular patterns, making full cross-section measurements necessary.

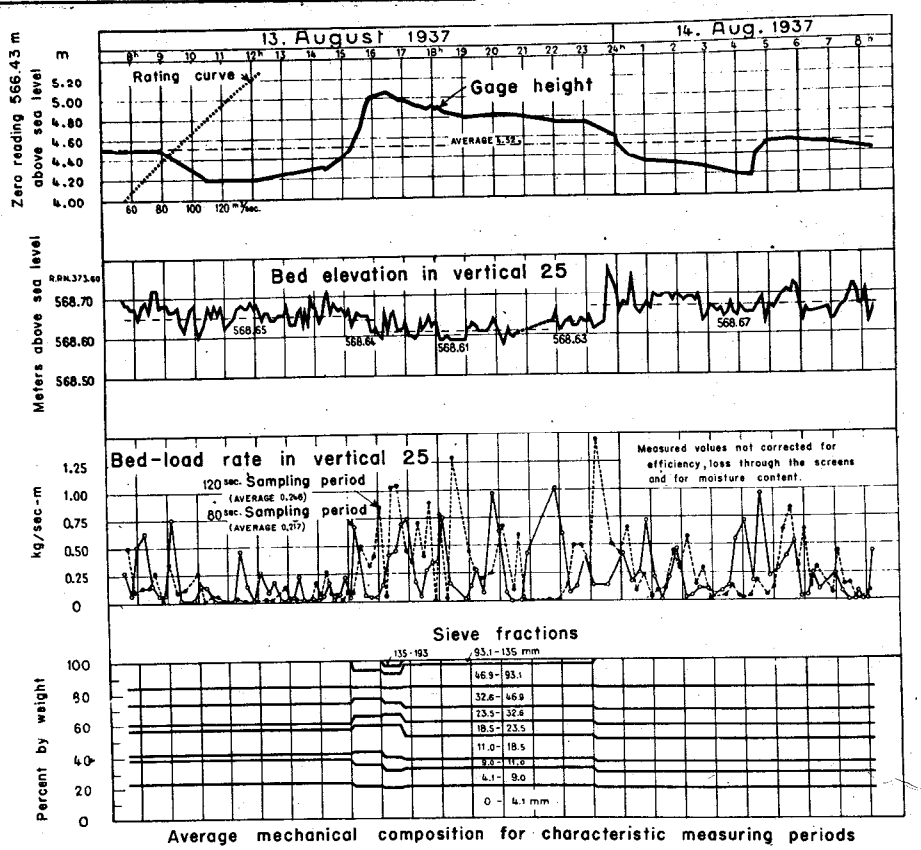


Fig. 8. Continuous sampling in the Aare for 24 hours shows changes in stage, bed elevation, rate of transport and mechanical analysis of load. The stage changes significantly during the period due to water releases from hydroelectric power plant. Bed-load rates follow that change. Bed elevation stays constant. The only significant change of the mechanical analysis of the load is in the coarsest sizes.

all means this error must be eliminated if usable and reliable results are to be expected. Elimination of this shovelling action is possible by elimination of the elasticity of the horizontal suspension.

Irregularity of the Sediment Movement. - The greatest difficulty encountered in the task of measuring the bed-load in a stream is caused by the irregularity of the transport itself. Not only does the rate of transport fluctuate continuously in any one spot with all frequencies and with amplitudes of the same order as the average transport, but also these same variations are found from point to point in a cross section. This makes it necessary to repeat all measurements a great number of times. With normal equipment, it thus takes about a full day to measure the average load in one cross section.

From this we can conclude that box-type bed-load samplers can be used only to measure the rates of bed-load movement in streams in which the flow does not change drastically during an 8 to 12-hour period. In streams with flash floods with a total peak of only a day or so, bed-load samplers of this type are therefore not usable.

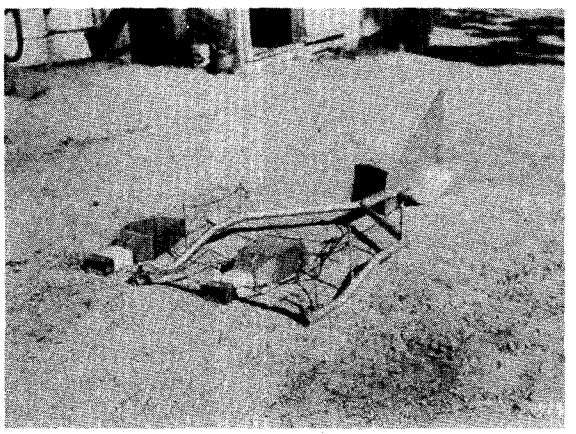


Figure 9. The Arnhem-type sampler was developed by Dutch government engineers and the Delft Hydraulic Laboratory for 100 percent efficiency. The model shown in the picture was built in this country according to Dutch specifications and was found to be unusable in southern streams because the fine screens almost immediately clogged with fine, floating vegetal fibres. A screenless model (mounted in frame) was developed and found to be reasonably satisfactory.

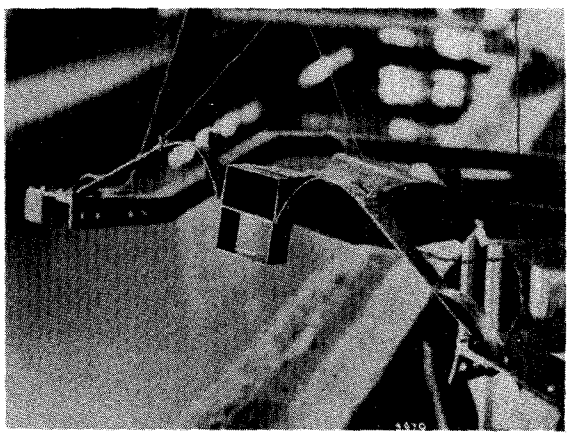


Figure 10. The original Dutch sampler with the entrance section supported by a 2-inch footing, in order to sample the second two inches from the bed, where suspended load sampling appeared to give unsatisfactory results.

Figure 11. This sampler must also be supported in such a way that it reaches the bed first with its tail. The entrance section is supported separately and is the last part of the structure to touch the ground. The drag on this sampler is relatively small. Its own weight will hold it in place during the sampling operation.

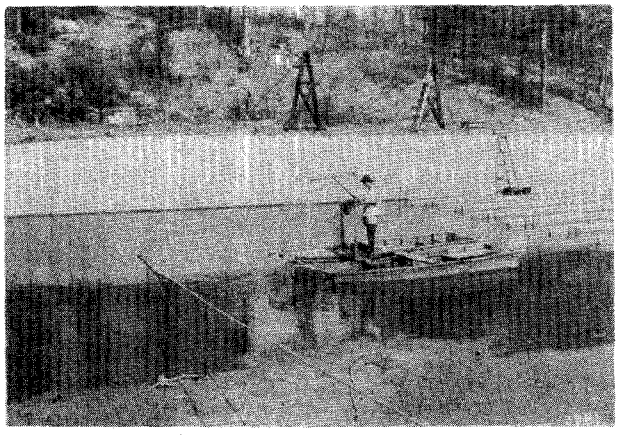


Figure 12. This sampler may be used easily from boats. The cables across the channel provide anchorage for the boat; the sampler is not directly supported for thrust. The sampling station in this picture is immediately upstream the slot-sampling installation at Greenville, S.C., allowing comparison of the two methods.

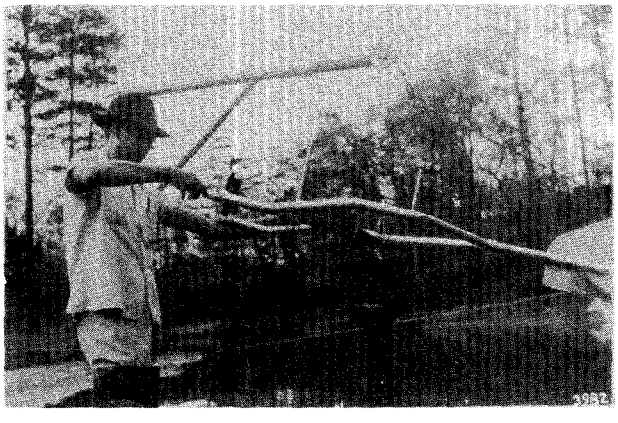


Figure 13. The catch is removed from the sampler through an opening in the rear end by flushing water through its body.

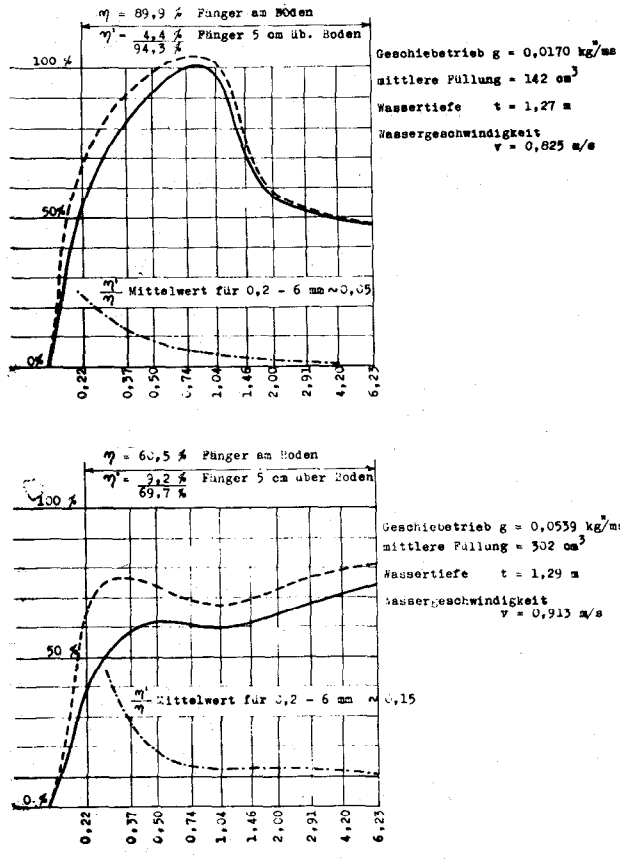


Figure 14. The calibration curves for this sampler and for different grain sizes is given for two different rates. The solid line gives the rates caught in the first two inches above the bed. The dashed line gives the amount caught in the first four inches. The dot-dash line shows the ratio between amounts caught in first and in second position. Again, the shape of the efficiency curve changes with the rate of transport.

Pan-type Samplers

For small rates of bed-load movement, it seems especially important to eliminate the influences which tend to reduce the efficiency of the sampler. For these streams, which usually are characterized by moderate flow velocities, there often exists a very marked division between bed-load and suspended load. In fact, a size limit can be chosen so that all coarser particles move exclusively as bed-load, while all finer particles move almost exclusively in suspension and may be neglected in the bed-load. With these flows in mind, the pan-type bed-load samplers have been developed. They may be described as a pan having a bottom and two side walls. They include usually some containers or baffles which are open at the top and have the double purpose of deflecting the water slightly and of storing the deposited bed-load. The construction must be such that the entire deposition of bed-load occurs in the boxes. This type has two great advantages over the box-type sampler: (1) the velocity reduction at the entrance can be reduced almost to zero because the water does not pass any screens and is only very slightly deflected, and (2) the drag on the instrument is reduced so much that a horizontal support becomes unnecessary, thus eliminating the dangers of an elastic horizontal support. From this one is led to conclude that pan-type samplers should be used wherever the flow is favorable for their application. However, since the writer never has had occasion to test this type of sampler, he does not know whether or not these samplers have some additional "bugs" which are not mentioned here. For descriptions of such samplers and a list of publications on the subject, the reader is referred to Report No. 2 on "Equipment Used for Sampling Bed-Load and Bed Material," written jointly by a number of govern-

ment agencies and the Iowa Institute of Hydraulic Research. The report was published by the St. Paul Engineer District Sub-Office, Hydraulic Laboratory, University of Iowa, Iowa City, Iowa, September 1940.

Slot-type Samplers

While the pan-type sampler is a solution for flows of long duration and low rates of transport, an entirely different approach must be used for streams with fast-changing flow. Here an attempt must be made to sample a larger percentage of the transport, or in extreme cases, to measure the entire load. A solution for this approach was found, based on the observation that a sufficiently large hole or slot dug into the bed will catch all bed-load transport until it is filled. The width of such a slot seems to be sufficient if it measures 100 to 200 grain diameters. Wooden slots of this sort built into the bed are easily recognized later and have been used often in order to obtain samples of the material moving at the bottom of streams.

The next step in the development of this type of sampler was the addition of a mechanical device which continuously moves the sediment that settles in the slot up to the stream bank. There it can be measured, analyzed for size, and then returned to the river below the slot. The Soil Conservation Service of the U.S. Department of Agriculture has developed two sets of equipment of this kind. One is stationary and is located at the Greenville, S.C., Bed-Load Station; the other is movable and was built for use in small streams. In both cases the bed-load consisted of sand and could be pumped from the slot to the banks. The movable sampler was especially successful, and is described extensively in Technical Report SCS-TP-55, August 1944, of the Soil Conservation Service. Neither piece of equipment is any longer in use.

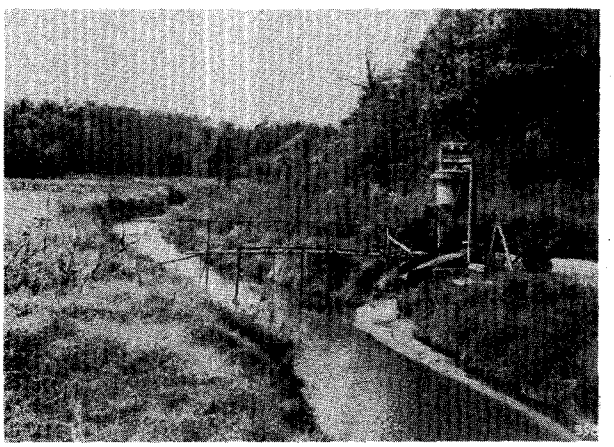


Figure 15. Movable slot-sampling equipment mounted at Mountain Creek near Greenville, S. C. A metal hopper is lowered into the stream bed and all sediment pumped out of it continuously as it settles inside the hopper. The tank to the right separates the sand from the water and continuously weighs it.

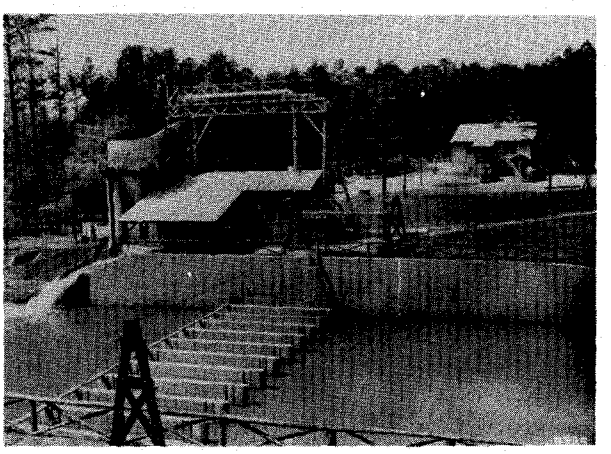


Figure 16. Permanent slot-type bed-load measuring device in Enoree River near Greenville, S. C. The sediment can be pumped separately from the slots between the short walls into the large tank for measurement.

This type of sampling equipment gives us a continuous record of all bed-load transport reaching the slot section. It has the disadvantage that it involves the construction of the slot and of the mechanical moving device. It also has the disadvantage of all slot and pan-type samplers that the thickness of the layer in which the sampled sediment was moving is not known. This implies that we do not know how much of the measured sediment moved as bed-load and how much actually was suspended load. But this uncertainty is much less serious than the errors due to the integration of spot samples as they occur with other pieces of equipment. It is possible, furthermore, to get some information about this point by means of special calibration runs where either the results are compared with those of other samplers, or where the sediment is artificially introduced at certain points in the cross section.

Another method of determining the bed-load in streams is to survey delta growth, where such rivers happen to deposit their bed-load in a lake or reservoir. This method gives a reasonable estimate of the total bed-load for long periods. The instantaneous rates cannot be determined; on the other hand, the method does not involve the use of new instruments which must be developed and calibrated. Good records of the average annual load in streams may be obtained by this method. Unfortunately, it is restricted to locations with natural lakes or artificial reservoirs.

In some instances where the entire bed-load of streams consists of fine-grained material, the rates could be determined by means of suspended samplers. This becomes possible below rapids or in other places where, due to locally-increased turbulence, the entire load goes into suspension. The bed-load rate may be determined in such streams as the difference between the total load as measured in these places of high turbulence and the suspended load as measured by sampling in a normal section.

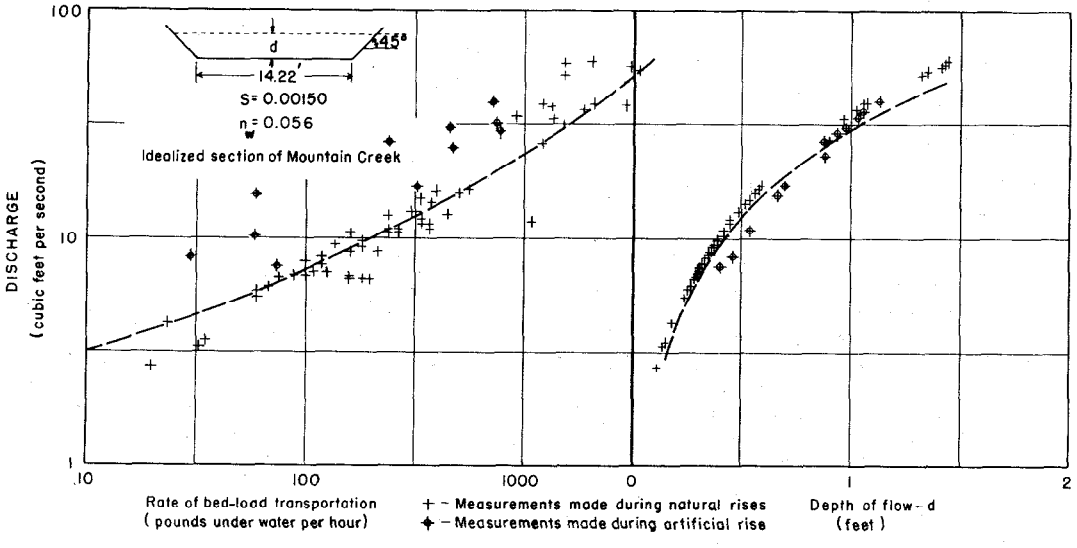
Analytical Determination of Bed-Load

So far we have seen how the bed-load rates can be measured, but nothing has been said about the significance of the results that we may obtain. Let is assume that we have been able to measure continuously during a year or more the rates at which the different grain sizes of the bed-load moved through a given river section. This knowledge alone will help us very little. It alone will not tell us anything about the transport in another section of the same stream, much less will it help us to determine the load of a different stream or the load that might occur in the same location at a different time. We would be in about the same position if we had the discharge record of a stream section for a given length of time. We could not read anything from those records except the flow of water that took place in this section during the time of observation. Again we would not be able to draw any conclusions on the flow in another section or at another time unless we were able to find some relationship that linked our measured variable with something else. Assuming that we also know the precipitation in the watershed and that we are able to find a relationship between flow and precipitation during the period of discharge measurement, then we may assume with some reason that this relationship will hold after the end of the observation period. This would allow the determination of the discharge for later years from the precipitation pattern without direct discharge measurement. After having studied a number of such relationships between precipitation and runoff in different watersheds, we may find that it is possible to predict the character of this relationship from a pertinent description of the watershed. In that case we could go into any new watershed and predict the runoff for any year for which we know the precipitations. We all know that direct runoff measurement during a given storm is much more reliable than its derivation from the rain pattern. But what if the storm had not yet occurred and we could only conjecture the rain pattern that might create the maximum probable storm? Do we have to sit back and wait until this storm occurs before we are able to measure the maximum flow for which the structures along the stream are to be designed? Definitely not. The analytical method may not be very accurate, but it has the great advantage that it allows us to predict a result which must be expected under conditions that are not yet realized.

For the same reason, engineers have tried to find relationships involving the rate of sediment movement. They knew that such relationships wherever they exist enable them to predict the behavior of bed-load-carrying channels. If we know why and where such relationships exist, the first big step in this direction is made. It is then a second but infinitely more involved step to find the exact form of those relationships and to apply them.

Let us pick up the bed-load problem now where we left it before we diverged into the hydrologic analogy. We assumed that we were able to measure continuously for a year or more the rates at which the grains of different sizes are moved as bed-load through a given river section. In trying to find and formulate all the relationships in which this rate is involved, it is very important to think of it in two different ways. First, we must think of these rates as of the sediment which is eroded and removed from the watershed. Second, we may interpret them as the rates at which the stream in the vicinity of the measuring section is moving sediment under the existing flow conditions. This double interpretation implies that there may be either a relationship of the transport in the measuring section with the erosion conditions in the watershed, or with the local flow conditions or both. If we analyze the data obtained in our hypothetical measuring section we shall find (unless we were very unfortunate in selecting the measuring section) that at least for the coarser grain sizes the rates will follow closely a single curve if plotted against the discharges. Such a relationship is definitely one of the second type because it holds, no matter from which part of the water shed the specific discharge originates. Let us try to explain now why and where such a relationship, which may be called the bed-load function of the stream, exists. We all know that a stream which is flowing over a deposit of loose granular material has a tendency to scour into this material, removing part of it if its flow is sufficiently fast. We also know that a stream which is carrying sediment will deposit on its bed whatever part it is not able to move. It has been found by experiment that these two actions of scour and deposition occur continuously over such a deposit of loose sediment. An equilibrium results from their interaction which determines the rate at which sediment is moved over this deposit by a given flow. This equilibrium rate is the rate which all the known bed-load formulas try to describe. It is also responsible for the existence of the bed-load function which we have found in our hypothetical bed-load measurement. This explanation lets us define

the stream sections where such a bed-load function exists. They are sections which are preceded by a channel reach containing a bed of loose sediment of the same type as the bed-load. We call such a reach alluvial. In an alluvial reach, the stream is able to move any grain size only according to its bed-load function, and if the stream happens to enter the alluvial reach with a load different from that function, the load will be adjusted to conform with it by scour or deposition in the bed. Naturally, this scour and deposition change not only the load, but also the bed and it is understandable that unless the deviations of the incoming load from the bed-load functions are random and short in duration, a permanent change of the alluvial bed will occur and with it a permanent change of the bed-load function itself. The time necessary to change this function by systematic deviations of the incoming load depends mainly on the ratio of the total amount of sediment available in the alluvial bed and the deviation in the sediment rate. This time must be longer than a few years if an alluvial stretch may be used for reliable load determinations.



Measured values of bed-load transportation and depth of flow compared with values calculated for an idealized section. Mountain Creek, Greenville, S.C.

Figure 17. Measurements in Mountain Greek showed that transport of bed-load plotted against discharge gave a pronounced relationship. It showed, further, that deviations from this relationship resulted when the regime of the stream was changed artifically. The curves give the bed-load function as it was found analytically for this channel, using an idealized section.

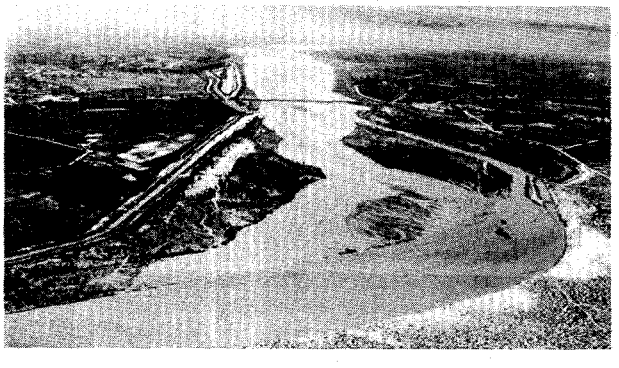


Figure 18. Rio Grande near Albuquerque. This channel has an alluvial bed, has no dams, sills, or other obstructions preventing scour. It is, therefore, a true alluvial reach. It is to be expected that a bed-load function exists for this stream section. It must be possible to find this function analytically or by measurement.

So far we have discussed the relationship between the bed-load rates and the flow in the alluvial reach. But by implication we have already hinted that the flow conditions in the alluvial reach are not absolutely constant but may, during a period of years or of decades, slowly change by scour or sediment deposition. Thus the bed-load function of the reach gradually adjusts itself to the long-time average rate at which sediment enters the reach. This fact must always be kept in mind if predictions of any kind are made. It also suggests that there is a relationship between the average annual rate at which the watershed yields sediment and the flow condition in the reach. We are tempted to assume that it might be possible to make some sort of an erosion survey covering the entire area of the watershed in order to find this average annual yield. Such a procedure seems possible for the fine-grain sediment,

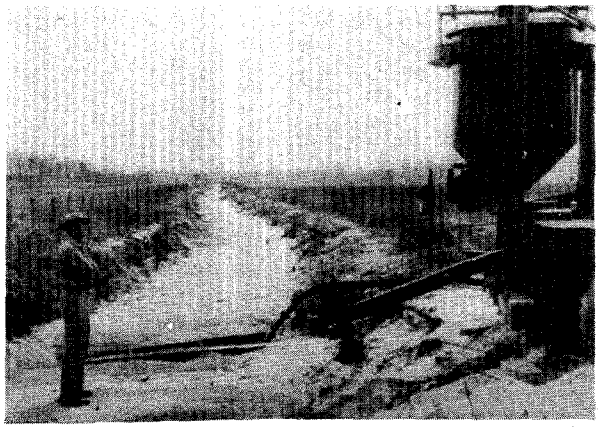


Figure 19. West Goose Creek near Oxford, Miss. Transportation in this channel was measured and the existence of a bed-load function was established. The same function was later found analytically. Despite its smaller size, the character of this stream is the same as that of the Rio Grande in Figure 18.

Figure 20. Smith Creek near Greenville, S. C. The existence of a bed-load function was established for this stream by measurement. It must be expected, however, that such a function does not exist for the very highest flood stages because this section of the stream is very near to the upper end of the alluvial valley.

Figure 21. No bed-load function may be derived from this channel. Upon digging, one will find that the alluvial deposit is only 1 foot deep and that it is underlined by basically different sediment. The sediment must be classed as a casual deposit. The channel is not an alluvial reach.

Figure 22. Channel on the upper part of a debris cone. A temporary bed-load function may exist for low flows, but this function will be different after the next flood. The section cannot be classed as a truly alluvial reach.

Figure 23. George Creek, Saluda County, S. C. Although flowing to a large part on a bed of alluvial sediment, this stream is not to be classed as an alluvial reach and does not have a bed-load function because its flow is essentially governed by numerous rock sills.

the clays and silts, which are only temporarily and to a very small amount deposited along the stream channel; for the larger grains which essentially constitute the bed-load, this method is not usable because of the extremely high modification which the bed-load rates experience by deposition and scour along the channel, as the following example shows.

In the Greenville Sediment Load Laboratory, the total load in the Enoree River at the laboratory was measured during 4 1/2 consecutive years. It was found that the average annual bed-load in the sand sizes was 14,700 cubic feet. Distributed over a drainage area of 64 square miles, the erosion of sediment in the sand sizes would be 230 cubic feet per annum per square mile. Simultaneously, the bed-load yield from one of the tributaries of the Enoree, Mountain Creek, which joins the Enoree several miles upstream from the measuring section, was measured and determined to be 70,000 cubic feet per annum, or considerably more than the main stream including Mountain Creek. With a drainage area of 11.4 square miles, Mountain Creek yields 6,400 cubic feet per annum per square mile, or about 28 times the average rate for the entire watershed. In order to appreciate the significance of these figures, it is necessary to know that a great part of the Mountain Creek watershed is part of a State park and as such is wooded and therefore contributes less sediment per unit area than some of the other tributaries. The explanation of these seemingly contradictory figures lies in the excessive deposition of sand along the main channel which is almost entirely choked by vegetation in some places between Mountain Creek and the measuring section. This may show that an erosion survey, which might allow an estimate of the silt and clay supply of a watershed, cannot be used to estimate the supply of bed material.

This fundamentally different behavior of the fine and the coarse particles was in the minds of the authors of the article, "A Distinction between Bed-load and Suspended Load in Natural Streams," 1/ when they proposed the division of the load according to the relationships determining their rates of transport in a particular section. According to the proposal advanced in that article, all the fine particles, the amount of which is essentially determined by erosion in the watershed, should be called "wash-load" (it is merely washed through the channel), while the coarser particles which follow a bed-load function are called "bed-load," or more specifically, "bed-material load."

Here we encounter a very significant difference between the determination of bed-load by direct measurement and by analytical methods. While a bed-load sampler samples the particles coarser than a limiting grain size, as given by the sampler, which move in a bottom layer, the thickness of which is given by the samples, the bed-load function, whether this function is found analytically or by measurement, describes the motion of all particles coarser than a limiting size which is defined by the river itself. It includes the movement of these particles in all parts of the cross section, whether they are moving near the bed as bed-load, or in higher layers, as suspended load. The analytical method which is based on the existence of relationships between flow and transport, covers all movement within the limitations of this relationship.

Although considerable space was devoted in this paper to the discussion of the devices and methods of direct measurement of bed-load rates, it does not seem possible to describe appropriately the purely analytical method of the determination of bed-load rates. It should be mentioned, however, that considerable progress has been made in recent years in the solution of this problem. By the use of rather fine sediment (diameters of about 1/10 mm.) it became possible to realize in flume experiments such intensities of bed-load movement as occur in large streams. The interpretation of the results was made possible by a combination of the theories of suspension and of bed-load movement and by the introduction of a "bed layer" inside which the bed-load movement takes place and which is defined as the layer in which particles are unable to move in suspension. 2/

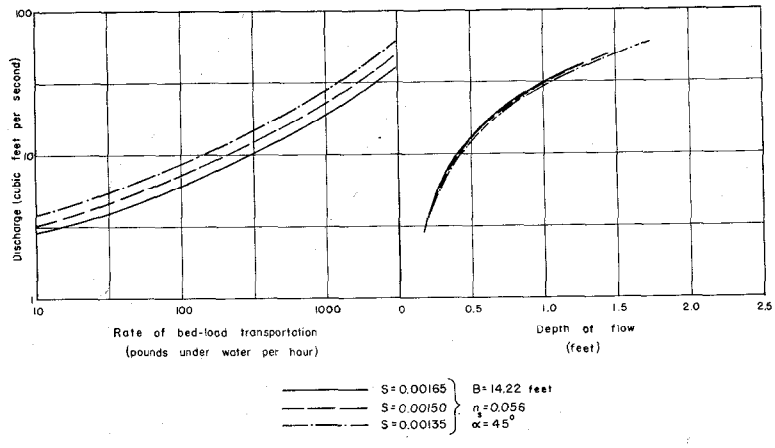
The mathematical treatment of the solution is based on the concepts of probability as they were advanced in 1942 3/. A strict and logical extension of the main ideas of that paper and the application of some results of modern turbulence research allowed the replacement of the empirical function between the parameters ϕ (intensity of the transport) and ψ (intensity of the flow) by a theoretically sound relationship, which seems to be valid in the entire known range of bed-load rates and for all sediment mixtures that behave essentially as if they were of uniform grain size. Most needed is more research in the fields of the sediment mixture and of the bed roughness. The problem of sediment mixture, which includes all influences of the presence of one grain size on the ability of the others to move, becomes especially important at lower rates of sediment movement and in the study of scour phenomena. The problem of the bed roughness seems to be intimately connected with the development of bars, ripples, and other types of

1/ 2/ 3/ See "References" at close of comments.

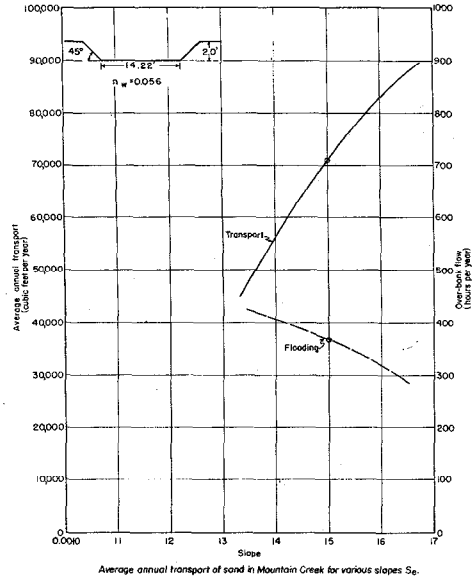
sand waves, and with the presence of trash and other foreign matter in and on the bed and with the shape and regularity of the stream channel. The solutions of these problems are not needed for the expression of the basic transportation laws, but they are very necessary for a reasonable application of those laws to natural rivers.

There seems to be scarcely sufficient room in this paper to outline the exact procedure of the analytical determination of the bed-load function for a given reach, but it may be appropriate to describe here the conditions under which such a determination is possible. We already know the basic condition which requires the presence of an alluvial reach upstream from the section for which we try to find the bed-load function. It is important to note that such an alluvial reach becomes effective only as long as the entire discharge which crosses our section also flows through the alluvial reach. If part of the discharge is by-passed through an artificial or natural side channel, such as an irrigation or power development, this part of the flow must be treated separately because we calculate the bed-load rates from the capacity of the alluvial reach to move sediment and only the water which flows through the reach can move sediment there. For the same reason, it is impossible to find a bed-load function for a section if a sizeable tributary joins the stream between the section and the alluvial reach. This can best be understood if we assume that there is an alluvial reach in both the main stream and the tributary

Figure 24. Wherever a bed-load function exists it must be possible, theoretically, to determine it by analytical methods. The analytical approach has a great advantage over the direct measurement because it allows one to determine the transportation rates before they occur. They can even be determined for a changed channel and can this way be used to predict the changes of a stream channel resulting from a changed sediment supply. From this diagram of transport in the Mountain Creek channel for different slopes we may read the change of the slope resulting from a changed sediment supply.

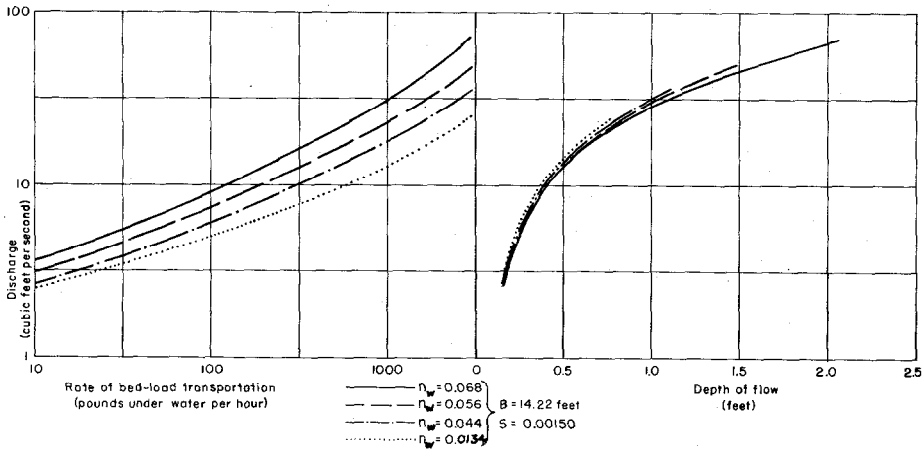


Channel capacity for water and bed load for various slopes.



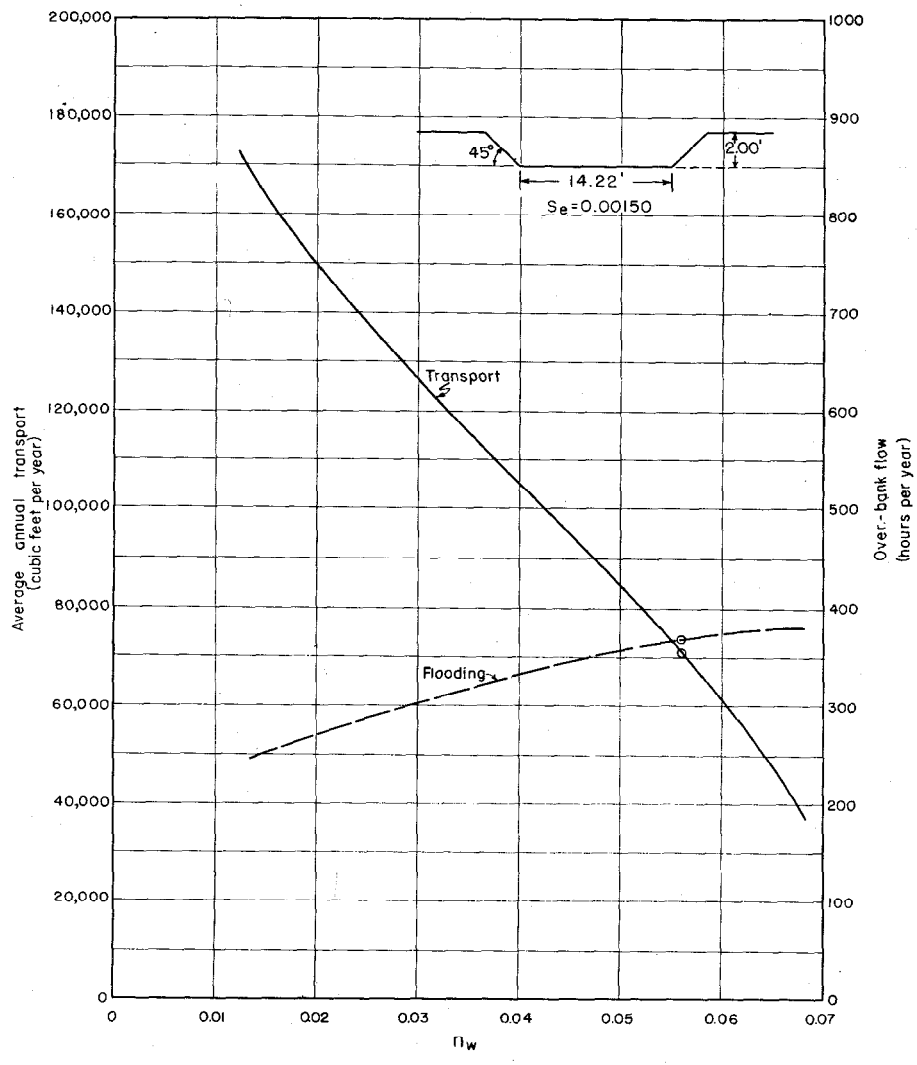
Average annual transport of sand in Mountain Creek for various slopes S_e.

Figure 25. Shows the average annual transport as derived from Figure 24 in function of the slope. The dashed line gives the number of hours per year during which overbank flow must be expected.



Channel capacity for water and bed load for various roughnesses of the banks

Figure 26. It was found from an analytical study of the narrow Mountain Creek channel that the roughness of the banks is of first importance when the bed-load function is determined.



Average annual transport of sand in Mountain Creek for various roughnesses of the banks.

Figure 27. The average capacity to transport sediment in Mountain Creek channel by the flows of an average year is three to four times greater if the banks are lined with concrete, compared with an irregular natural channel haphazardly covered with trees and brush.

immediately above the junction. Each reach will develop a bed-load function, according to the long range average sediment output of its own watershed. These two curves will never be identical. Below the junction the transport will consist in part of the load of one reach and in part of the load of the other, and therefore, the bed-load function will vary somewhere between the functions of the two reaches according to the relative stages in the two contributing streams. Here a bed-load function does not exist and therefore cannot be determined. The load of each of the contributing streams can be determined separately in the form of two bed-load functions for sections immediately above the junction. Below the junction the combined flow must first pass through another alluvial reach of sufficient length to permit a new bed-load function to develop. Similar conditions hold for sections below points where the flow is divided into two parts, such as below the inlet to irrigation and power canals.

Another very useful quasi-analytical method has been used to determine the relative contribution of joining streams. It is the heavy mineral method 4/ which is based on the idea that the relative contribution of two joining streams could very easily be determined if it were possible to dye all sediment in one stream with some characteristic dye and if the percentage of the dyed sediment in the combined flow could be determined later. Naturally, artificial dye cannot be used for this process, but it is usually possible to find some natural characteristic of the sediments in the two streams which differ sufficiently to allow the identification of their origin.

This method was used in the past for fine sands only, for which most grains consist of single minerals. Besides the great number of grains with normal specific gravity around 2.6, such as quartz and the different feldspars, each sand contains a number of heavy minerals which can be separated easily from the rest by flotation on a heavy liquid. The contamination with these heavy grains can be used in the same way to identify the origin of a mixture as the dye would identify a single grain. The difficulty that heavier grains move less readily than the light grains was very cleverly solved by studying quartz grains of a given size together with a contamination consisting of smaller grains of heavier minerals. We all know that light grains move more easily than heavy ones and that small grains move more easily than large ones. The assumption was then made in the development of the heavy mineral method that a smaller heavy grain can always be found which is equivalent in all respects of movement to some larger light grain. We know today that this assumption is not accurately fulfilled, because the size reduction must be chosen differently if the grain moves as bed-load or if it moves in suspension. But the method as worked out by Rittenhouse allows one to determine the most probable size reduction from the samples themselves, a size reduction which already takes care of the combined movement. This method is about as expensive as the direct analytical method, but much less expensive than direct measurement. It has the great advantage that it is not restricted to sections below an alluvial stretch, but it has the big drawback that it gives only total loads and never individual rates and that it only gives ratios between the loads and never absolute values. It may be used to good advantage, therefore, to supplement and check the other methods.

We have just a few more words about the alluvial reach which seems to be such an important factor in the bed-load economy of a stream. The rate of transport on a movable bed is a function of the bed composition and of the local velocity distribution. We can, therefore, only expect to find a constant bed-load function or relationship between discharge and bed-load rate if the velocity distribution in an alluvial reach is always the same for a given discharge. This is definitely not fulfilled in a channel with artificial or natural grade-stabilizing cross-sills. In such a channel a very small deposition of sediment is able to increase the slope between sills considerably, simultaneously reducing the local head loss at the sills. Thus the average velocity between sills is increased and so is the ability to transport bed-load. Although such a channel has an alluvial bed, it is not qualified to act as an alluvial reach because its capacity to store and to furnish sediment is extremely small. Any other grade-stabilizing device has the same effect.

Summary and Comparison of the Methods

1. Direct sediment measurement allows only the determination of the load in existing stream channels under existing flow conditions. The average annual sediment supply from a given watershed may be determined by this method, whether or not a bed-load function exists. Wherever a bed-load function does exist, it may be determined by this method.

2. Direct bed-load measurement can be performed with the help of a number of different instruments. The box-type samplers are useful especially for large-size sediment and flows of

4/ See "References" at close of comments.

long duration. The pan-type samplers may be used for fine sediment moving at lower rates, and the slot-type may be applied in all cases, but is most expensive to build and to operate. All bed-load samplers must be calibrated.

3. The analytical determination of bed-load rates is based on the existence of a bed-load function, i.e., of a unique relationship between discharge and bed-load rate in a given cross section. Such a relationship exists below an alluvial river reach of sufficient length. The bed-load function may be determined either by direct measurement in the cross section or by an analysis of the stream's transporting capacity in the alluvial reach.

4. No predictions of future sediment rates may be made from direct measurement alone. However, if either the average sediment supply or the bed-load function for a section have been determined by direct measurement, these functions may be used for the prediction of future loads. The analytical determination of the load in a channel is entirely independent from the occurrence of the flows causing the transport. Only the analytical method can be used in the design of new stream channels and in the prediction of their stability.

5. None of the methods described in this paper can solve all problems. Each method can solve some problems. The river engineer in working with sediment-laden rivers must use them all in their proper place in determining the rates of bed-load transport.

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DISCUSSION

H. K. ARMSTRONG.* - Doctor Einstein is to be commended on his excellent description and treatment of the methods involved in bed-load measurement. Of the many factors associated with the phenomenon of sediment movement, the bed-load function of the stream, to use the author's terminology, is a complete measure of the ability of local flow conditions to transport sediment, providing all of the pertinent variables that make up the bed-load function have been considered. It follows that a function involving pertinent characteristic variables of the sediment is of equal importance. The author states that the bed-load function describes the ".....motion of all particles coarser than a limiting size, whereby the size is defined by the river itself....." and includes the ".....movement of these particles in all parts of the cross-section, whether they are moving near the bed as bed-load or in higher layers as suspended load." The ability of the bed-load function to contain this implicit quality, relating to the characteristics of the sediment, is quite acceptable. However, it is often considered desirable as demonstrated by the author in the phi-psi theorem to express a sediment function as an independent argument that contains only qualitative and quantitative variables that reflect the characteristics of the solid particles.

For particles that are uniform in size, grading, shape, and density, no particular difficulty is encountered in deriving a functional expression. In the case of size distributions and shape factor combinations that extent over wide ranges, we run into trouble. For that matter, experimental data on the transport of such sediment, even when obtained under controlled laboratory conditions, often require manipulation in order to establish satisfactory and acceptable correlation, and then, in many cases, results are not applicable for general or practical use.

Several methods have been proposed for dealing with size distribution and grading. Often the diameter of particles is simply defined by 50 percent of the sample passing a given screen. Mean diameter is sometimes obtained by weighing a sample, counting the number of grains, and computing the diameter of an average sphere. Kramer's "uniformity modulus" is an example of a method for dealing with grading. The author's limiting size method has also been successfully employed. Methods described by Rouse involving the use of size frequency diagrams and cumulative probability plots of mechanical analysis, together with the geometric mean diameter and the standard deviation from this diameter, offer a promising method for handling size and grading.

In addition to the demand for a characteristic parameter describing the quality of the sediment, a quantity parameter concerning the amount of sediment involved is equally essential in the development of a particle function for general application. Quite a few formulae have been proposed that allege to express the transport of sediment without specific reference to the amount of sediment. Such formulae usually deal with competent velocities. The conditions under which sediment transport first occurs are often described by a "critical value," of some flow function, at which movement of an "appreciable quantity" of material takes place. Such terms are descriptive in themselves, but do not afford a quantitative measure.

A critical examination of data on sediment transport suggests the use of a density that concerns the mass rate of sediment discharge per volume rate of bulk discharge. A modification of such variable was used by Shields in his work on transport. As the solid particles are submerged, the buoyancy effect of the fluid medium is also considered, which allows a simplification of the pseudo-density expression.

The utilization of this pseudo-density variable in the analysis of transport data has been instrumental in obtaining an acceptable degree of correlation for most of the data examined. In a majority of cases, deviations from correlation standards can usually be attributed to grading. The pseudo-density involves the dimensionless factor--the specific gravity of the bulk discharge minus unity--and this simple expression is of significant importance. For a bulk specific gravity of 1.00001 the mass of sediment in a cubic foot of discharge is 0.001 of a pound, and this specific gravity represents 86 pounds mass of solid particles per day-second foot. A channel discharging an average volume of 1,000 cubic feet per second would be carrying approximately 46 tons of sediment per day. For a specific gravity of 1.1 and a bulk discharge of 50 cubic feet per second, a dredge pipe will discharge approximately 500 pounds of solids per second. These figures are given as some indication of the range through which the pseudo-density

* Hydraulic Engineer, Office of the Chief of Engineers, Department of the Army, Washington, D. C.

may be employed, both for open channels and for closed conduits. When plotted against the stream function on log-log paper, a straight line relationship is usually obtained.

When dealing with sediment transport in pipes varying in size through 1, 1½, 2, 3 and 4 inches and including 28-inch diameter, the boundary roughness could, to all indications, be disregarded in view of the influence of the size and the amount of solid materials in transport. When the stream function or the bed-load function, which in the case of pipes is essentially the local Reynolds number, attains a sufficient value (depending on the size and the quantity of the solids), rational methods may be employed to determine the energy gradient. However, in the case of open channels the boundary roughness plays a more predominant role, and a solution to the problem of transport in open channels has yet to be found.

The author has stated the need for more research in the fields of the sediment mixture and of the bed roughness. This need can not be over-emphasized--for the grading and the roughness factors are probably of major order of importance in any rational expression describing the phenomenon of sediment transport.

BILLY T. MITCHELL.* Dr. Einstein has presented a very interesting and informative paper on the determination of rates of bed-load movement. There are two or three points, however, that I would like to discuss concerning bed-load samplers. A year or so ago we in the Omaha District understood that some work was being done by the Corps of Engineers in the Little Rock District on developing a bed-load sampler along the same lines as the sampler Dr. Einstein showed you. We got some specifications from them and built one as nearly identical to theirs as possible. It is considerably larger than the one he illustrated here, but it has to be that large in order to be used in the depths and velocities of the Missouri River. We had some pretty poor luck with it. In the first place, when we put it down to the bed of the stream, held it there for a couple of minutes, and brought it up, there wouldn't be anything in it. When we put it down again and held it there for a matter of five minutes or so, it might be brought up half full. There is hardly a straight line relationship of filling under such conditions. We began to wonder if it might not be possible that this action was due to the lip of the sampler resting on the top of a sand wave. We don't know. We did try it out, though, in a small stream in western Nebraska where the depth was relatively shallow, a matter of a foot or so, and had cause for further consideration of its action. This sampler had a sort of lip that dropped down and made contact with the bed - the sampler was lowered in an inclined position, the back end touching first and then leveling up as the tension on the suspension cable was released. At the same time, this ramp in front would open down. Of course the difficulty may be partially a fault in our reproduction of the design the Little Rock District used, but nevertheless in trying it in this small stream we found that no sand would get into it. What happened? As soon as the lip touched the bed of the stream, and sand would start moving away leaving a gap in front of it which the sand couldn't jump over -- it would go underneath instead. I can see where, for larger sediment particles as shown in one of those pictures of Dr. Einstein's, it might be that this type of sampler might be quite satisfactory, but I fail to see how you can depend on it for use in small streams; and in the Missouri River where we can't see what is going on when the sampler is carried downstream after it is dropped in, I don't know how we can be sure that it is getting anything even like the representative bed-load movement.

DR. EINSTEIN. The sampler that was developed by the Dutch was developed for a stream of comparatively low rates of transport and of slow flow, and there was no trouble of that sort at all. Again, a question that comes up on instruments like we have discussed here is that it depends very much on the rates at which the sediment is transported.

MR. MITCHELL. That probably is the answer to the question. I would like to bring one more thing before the conference. It happens that we in the Omaha District had a chance to develop a slightly different use for the supersonic-echo sounding equipment during April of this year when the Missouri River reached a peak flow of about 145,000 second feet at Omaha. The original intent of the study was to watch the movement of the streambed at a single point continuously for a period of 48 to 72 hours during a period of rapidly changing flow. Mr. Pafford, whom you

* Omaha District, Corps of Engineers, Department of the Army, Omaha, Nebr.

heard a while ago, suggested that a few cross-sections of the river be taken as an indication of bed material inflow and outflow to the test reach, and for correlative purposes. The elaboration of this suggestion as the study progressed, and the results thus obtained are described in a paper which I have just drafted and is submitted for publication in the proceedings of this conference as an extension of my extemporaneous remarks.

Rapid Changes of Missouri River Streambed 1/

Introduction

One of the most pressing problems of the sediment engineer is the determination of bed load movement. Although there are a number of empirical formulas available to compute such movement from hydraulic and sediment characteristics, the opportunities to make even rough check measurements of bed movement on major rivers are infrequent indeed, and most checks must be made on a long-term basis, either as sedimentation of a reservoir or as aggradation or degradation of a floodway. The mixture of suspended sediments with bed material in deltas and bars further complicates the problem of checking bed movement quantitatively.

One of the newer tools available to the profession for observing streambed changes is the fathometer, or echo-sounding device, in its recently improved form. Its usual role is that of indicating water depth during navigation. The instrument is adaptable to other uses, however, as will be shown in this paper. A Bludworth Model ES 114 was obtained by the Omaha District, Corps of Engineers, in May 1946 primarily for study of bed sediment movement. It was not possible to make maximum use of it until the flood of April 1947.

The original intent of the study during this flood was to follow the vertical change of the streambed at one point continuously for many hours. In connection with this objective, however, it was decided to obtain a few exploratory repeat cross-sections of the river upstream and downstream from this point for correlative purposes. Most of the material presented herein resulted from this revision in objective during the flood, and for that reason is not as complete in some respects as might be desired.

Basis of Study

The study reach extended 1,800 feet upstream and 1,100 feet downstream from the Ak-Sar-Ben Bridge over the Missouri River at Omaha, Nebr. Eight cross-section ranges were selected as shown on Figure 1. The point for continuous observation was selected from study of cross-sections obtained through discharge measurements, and was located about 50 feet upstream from the bridge near the center of the river. Section C, located 200 feet upstream from the bridge, was sounded twice each day, as nearly as practicable, to provide correlation with the changes at the single point. It was originally intended that Sections B, C, D, and G be sounded at a stage of about 15 feet on the flood rise, at or just after the peak, and at a moderate stage after the peak.

It was necessary to have good horizontal positioning, particularly for the cross-sectional work. It is physically impossible to maintain the craft at a speed sufficiently uniform to prevent distortion of the section on the recorder chart, particularly on a fast river. Near the banks the current is considerably slower than in midstream. Even with a fairly powerful boat, it is necessary to change the angle of quartering into the stream to stay on the cross-section, which results in condensing or expanding the horizontal scale. If frequent "fixes" can be made, satisfactory adjustment of the horizontal scale can be obtained in the office. In this study, every fifth cross-member on the Ak-Sar-Ben Bridge was used as a "fix," making an adjustment possible every 125 feet. All cross-sections were made in duplicate by sounding both while going across and returning to the right bank.

The sounding equipment was mounted on the side of a steel ponton about halfway back from the bow. A 40-foot launch was used to push the ponton. The minimum crew consisted of the launch operator, the sounding operator, and two deck hands. Three complete crews were used during the period of continuous sounding.

Numerous difficulties were experienced during the first part of the study, particularly from floating debris. It was originally planned to use two bow and two stern anchors for the ponton. It was found immediately that this procedure was impracticable because there was no way to dodge the drift, which was quite heavy. Two bow anchors were used for a part of the time

1/ Not read at Conference.

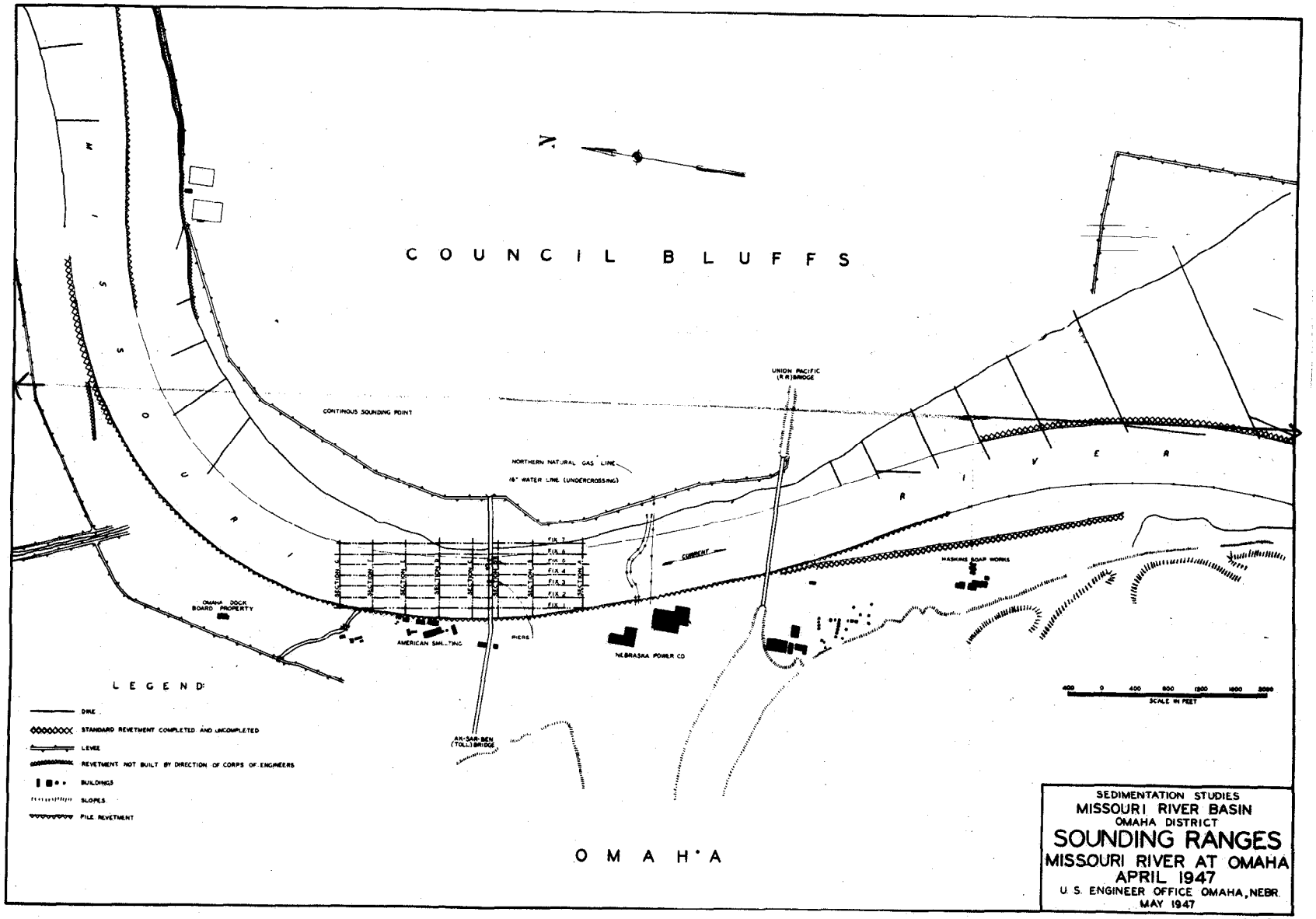

COUNCIL BLUFFS
OMAHA
MISSOURI RIVER
UNION PACIFIC (R.R.) BRIDGE
CONTINOUS SOUNDING POINT
NORTHERN NATURAL GAS LINE
18" WATER LINE (UNDERCROSSING)
CURRENT
FIX 7
FIX 6
FIX 5
FIX 4
FIX 3
FIX 2
FIX 1
SECTION 6
SECTION 5
SECTION 4
SECTION 3
SECTION 2
SECTION 1
OMAHA DOCK BOARD PROPERTY
AMERICAN SMELTING
PIERS
NEBRASKA POWER CO
HASKINS SOAP WORKS
AK-SAR-BEN (TOLL) BRIDGE
LEGEND:
DIKE
STANDARD REVETMENT COMPLETED AND UNCOMPLETED
LEVEE
REVETMENT NOT BUILT BY DIRECTION OF CORPS OF ENGINEERS
BUILDINGS
SLOPES
PILE REVETMENT
400 0 400 800 1200 1600 2000
SCALE IN FEET
SEDIMENTATION STUDIES
MISSOURI RIVER BASIN
OMAHA DISTRICT
SOUNDING RANGES
MISSOURI RIVER AT OMAHA
APRIL 1947
U. S. ENGINEER OFFICE OMAHA, NEBR.
MAY 1947

FIGURE 1

when the drift was not too heavy, but even so, four anchors were lost during the study. The hazard was considerably greater at night, since the approaching drift could not be seen in time to maneuver. It was necessary during certain periods to get bed soundings at this point intermittently, when the ponton could be maneuvered into position and a "fix" called.

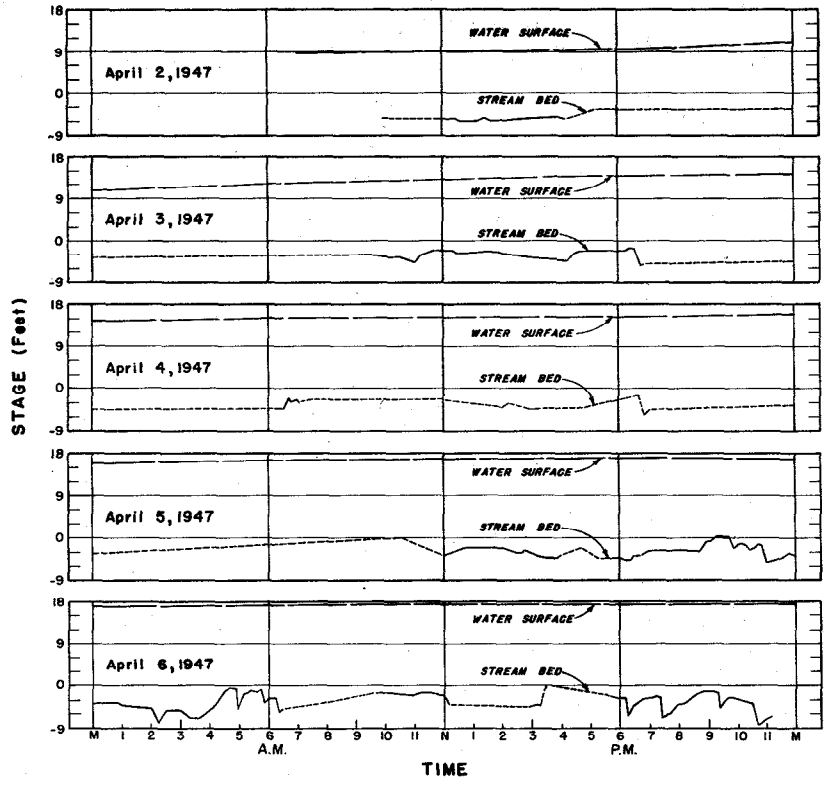
It was decided, about the time of the peak, that much more useful information could be obtained during the flood by concentrating on resurvey of all eight cross-sections at fairly frequent intervals. Consequently, 10 complete surveys of the eight sections and one partial survey covering five sections were made during a 73-hour period beginning just after the peak had passed. Each complete survey of the eight sections was made within an elapsed time of about one and one-half hours.

In addition to the operations just described, a detailed sounding of the streambed was conducted between Sections B and C at fifty-foot intervals across the stream. This part of the study was accomplished within a one and one-half hour period on the last day of the study.

Results

The continuous sounding operation at the single point showed that bed changes are very erratic and, at present, unpredictable (Figure 2). The changes may take place with great rapidity (as much as one foot within one-half minute or two feet within two minutes) or very gradually. There appears to be some tendency for the bed to fluctuate about some mean elevation for a given flow.

The cross-sectional soundings (Figure 3, sheet 1A)2/ indicate that there is a continuous shift of bed throughout the width of the stream, particularly at high flows. There is a tendency for the average section to become U-shaped at high flows, with the stream center shifting away from the bank, and to revert to the pre-flood conditions on receding stages. This tendency, in terms of change in cross-sectional area, below a reference plane, with discharge is shown in Figure 6. A loop curve, showing the average of the total area for all cross-sections in the reach plotted against the stage at the Ak-Sar-Ben Bridge, is shown in Figure 7.



NOTE

Location of sounding point shown on Figure 1.

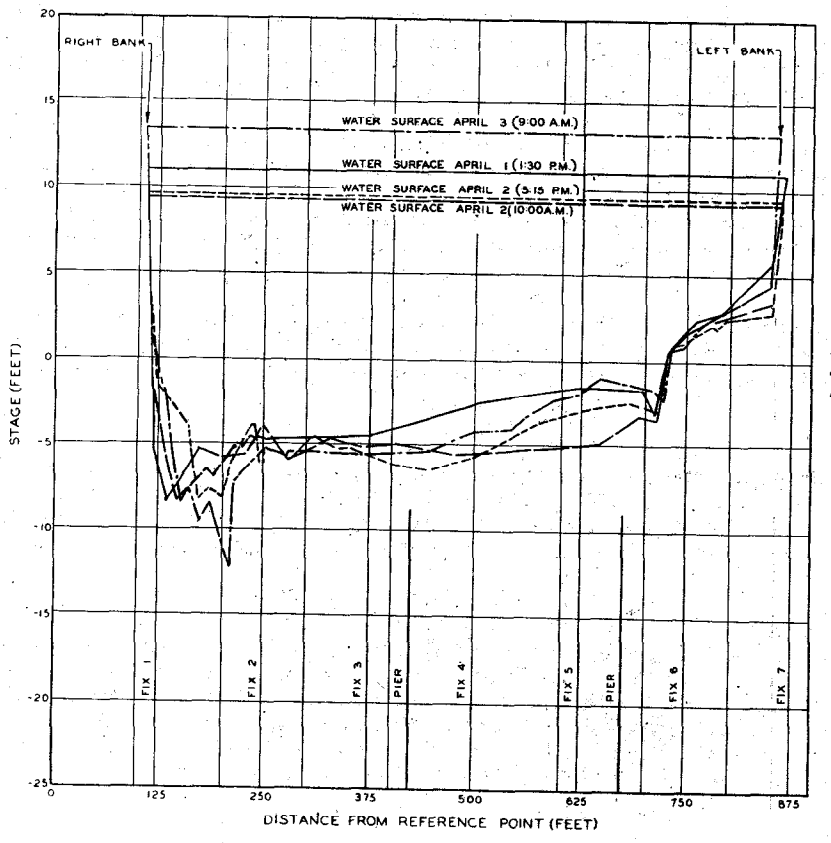
Soundings made by supersonic-echo fathometer mounted on a barge.

Solid line shows where sounding was continuous. Short dashed line indicates interpolation, as correlated with soundings of Section C.

SEDIMENTATION STUDIES
MISSOURI RIVER BASIN
OMAHA DISTRICT
STREAM BED CHANGES AT ONE POINT
MISSOURI RIVER AT OMAHA
U.S. ENGINEER OFFICE OMAHA, NEBR.
MAY 1947

FIGURE 2

2/ Presented in lieu of Figures 3, 4 and 5 of original paper.

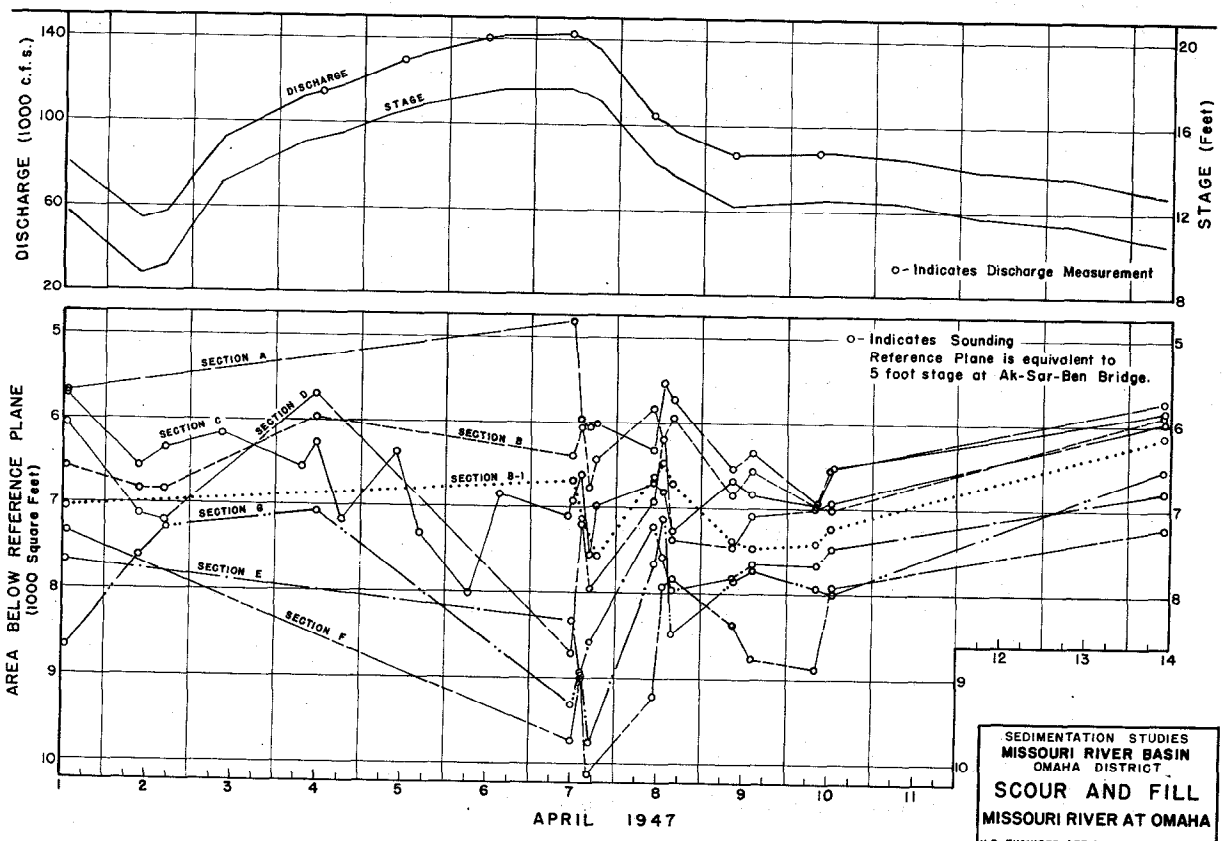


NOTES

	AREA BELOW 5 FT STAGE (SQ. FEET)	TOTAL AREA (SQ. FEET)
APRIL 1 (1:30 P.M.)	5,700	10,010
APRIL 2 (10:00 A.M.)	6,560	9,405
APRIL 2 (5:15 P.M.)	6,355	9,540
APRIL 3 (9:00 A.M.)	6,170	12,280

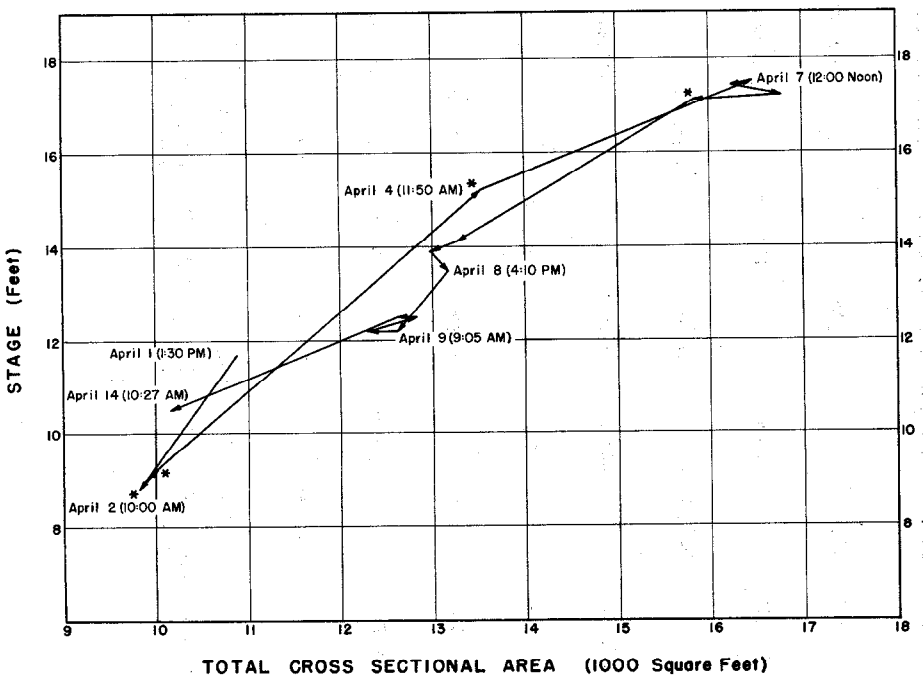
SEDIMENTATION STUDIES
MISSOURI RIVER BASIN
OMAHA DISTRICT
SECTION C
MISSOURI RIVER AT OMAHA
APRIL 1947
U.S. ENGINEER OFFICE OMAHA, NEBR.
MAY 1947

FIGURE 3 (SHEET 1 OF 6)



SEDIMENTATION STUDIES
MISSOURI RIVER BASIN
OMAHA DISTRICT
SCOUR AND FILL
MISSOURI RIVER AT OMAHA
U.S. ENGINEER OFFICE OMAHA, NEBR.
MAY 1947

FIGURE 6



NOTE:
Values marked * are averages of four sections.
All others are averages of eight sections.
Period of observation is April 1-14, 1947.

SEDIMENTATION STUDIES
MISSOURI RIVER BASIN
OMAHA DISTRICT
AREA - STAGE
MISSOURI RIVER AT OMAHA
U.S. ENGINEER OFFICE OMAHA, NEBR.
MAY 1947

FIGURE 7

It is probable that the flow in this reach of the Missouri River is helical because of the long, regular curve immediately upstream from the reach. (Figure 1). The flow conditions at the lower end of the reach are somewhat different than at the bridge, but are similar to those at the upper end of the reach. It is not known why the flow should be divergent just upstream from the bridge, but it is possible that a limitation of scour in the usual channel, due to rock or similar conditions on the bottom, with a rise in stage causes this phenomenon.

TABLE 1

RAPID CHANGES OF MISSOURI RIVER STREAMBED AT OMAHA

CROSS SECTIONAL AREAS IN SQUARE FEET

Period 1947	Average Time	Sect. A A.R.P.	Sect. A B.R.P.	Sect. B A.R.P.	Sect. B B.R.P.	Sect. B1 A.R.P.	Sect. B1 B.R.P.	Sect. C A.R.P.	Sect. C B.R.P.	Sect. D A.R.P.	Sect. D B.R.P.	Sect. E A.R.P.	Sect. E B.R.P.	Sect. F A.R.P.	Sect. F B.R.P.	Sect. G A.R.P.	Sect. G B.R.P.	Average of Total Area
Apr. 1	1:30 PM	4150	5685	4405	6580	4205	7050	4310	5700	3930	6055	3730	7675	3790	7345	3790	8670	10,885
2	10:00 AM			2870	6880			2845	6560	2575	7115					2775	7610	9,807
2	5:15 PM			3250	6880			3185	6355	2880	7205					2920	7295	9,992
3	9:00 AM							6110	6170									
4	7:30 AM							7470	6560									
4	11:50 AM			7885	5970			7600	6270	6880	5690					6725	7085	13,526
4	6:40 PM							7830	7165									
5	10:30 AM							8665	6375									
5	4:40 PM							8765	7325									
6	7:25 AM							9110	8020									
6	3:30 PM							9410	6860									
7	11:00 AM							9440	7105									
7	12:00 N.	9145	4835	9640	6400	9025	6700	9305	6925	8590	8710	8125	8330	8700	9745	8405	9330	16,490
7	2:30 PM	9130	5940	9405	6060	8340	7160	9240	6620	8365	7210	8120	8965	8495	9005	8420	8915	16,235
7	4:45 PM	9140	6070	9440	6790	8980	7385	9105	7565	8475	7960	8280	8585	8185	10,160	8375	9780	16,785
7	6:30 PM	8760	6015	9115	6445	8730	7575	9165	7500									15,826
8	11:00 AM	5910	6320	6875	5820	6510	6645	6690	6700	6165	6940	5945	7215	5430	9210	6030	7665	13,260
8	1:50 PM	6660	5540	6570	6155	6455	6455	6545	6810	6050	6185	5845	7585	6155	7925	5815	7120	12,985
8	4:10 PM	6260	5730	6380	5945	6160	6740	6270	7265	5785	7365	5720	7960	5820	7825	5610	8485	13,165
9	9:05 AM	5470	6530	5680	6855	5380	7380	5545	6680	5035	7455	4865	7815	5045	8370	4920	7860	12,615
9	2:33 PM	5145	6340	5420	6560	5150	7470	5205	6840	4865	7095	4525	7640	4775	8750	4750	7740	12,285
10	8:50 AM	5605	6940	5780	6990	5445	7410	5650	6960	5130	7005	4965	7660	5115	8870	5080	7935	12,820
10	1:00 PM	5625	6545	5895	7015	5615	7230	5655	6525	5220	6945	5025	7465	5115	7925	5185	7995	12,620
14	10:27 AM	4040	5715	4140	5895	4050	6135	4105	5840	3745	5985	3620	6790	3680	7215	3705	6545	10,150

A.R.P. = Above reference plane.
B.R.P. = Below " "

Reference Plane = 5.0' above zero of gage.

TABLE 2

RAPID CHANGES OF MISSOURI RIVER STREAMBED
AT OMAHA
MINIMUM MOVEMENT OF BED MATERIAL IN CUBIC FEET

Period 1947	Section G to F Agg.	Section G to F Retro.	Section F to E Agg.	Section F to E Retro.	Section E to D Agg.	Section E to D Retro.	Section D to C Agg.	Section D to C Retro.	Section C-B1 Agg.	Section C-B1 Retro.	Section B1-B Agg.	Section B1-B Retro.	Section B to A Agg.	Section B to A Retro.	Total G-A Agg.	Total G-A Retro.
Apr. 1 1:30 PM Apr. 7 12:00 N.		612,000		611,000		662,000		776,000		142,000	112,500		309,000			2,381,500
Apr. 7 12:00 N. Apr. 7 4:45 PM		173,000		134,000	99,000		22,000			215,500		228,500		487,500		1,117,500
Apr. 7 4:45 PM Apr. 8 11:00 AM	613,000		464,000		478,000		377,000		261,000		363,500		216,000		2,772,500	
Apr. 8 11:00 AM Apr. 8 4:10 PM	113,000		128,000			234,000		198,000		107,250		46,750	139,500			205,500
Apr. 8 4:10 PM Apr. 9 9:05 AM	16,000			80,000	11,000		99,000			8,950		329,500		513,000		805,450
Apr. 9 9:05 AM Apr. 9 2:33 PM		52,000		41,000	107,000		40,000			40,600	43,600		145,500		202,500	
Apr. 9 2:33 PM Apr. 10 8:50 AM		63,000		28,000	14,000			6,000		9,750		78,500		309,000		480,250
Apr. 10 8:50 AM Apr. 10 1:00 PM	177,000		228,000		51,000		99,000		99,500		32,900		111,000		798,400	
Apr. 10 1: PM Apr. 14 10:27 AM	432,000		277,800		327,000		329,000		288,500		500,000		585,000		2,739,300	
TOTAL	1,351,000	900,000	1,097,800	894,000	1,087,000	896,000	966,000	980,000	649,000	524,050	1,052,500	683,250	1,506,000	1,309,500	6,512,700	4,873,200
NET	451,000		203,800		191,000			14,000	124,950		369,250		196,500		1,522,500	

One of the most important results of this study is the demonstration that rapid sounding of a reach by this process allows a computation of minimum bed load movement to be made. Table 1 shows the areas at each cross-section for each sounding, and Table 2 gives the computed retrogression or aggradation in each section of the reach and the entire reach during certain intervals. All sets of soundings were not used in this latter computation, since the time required to make a complete set of soundings for the reach was of the same order of magnitude as the elapsed time between the beginning of one resurvey and the beginning of the succeeding one. Such short periods between surveys will require more careful consideration of the changes in each fraction of the reach than has been possible up to this time.

A tentative check of the observed bed movement during an 8-hour period on 7 April was made by use of the Straub bed load formula

$$G = \psi \frac{i^{1.4}\, Q^{.6}}{C^{1.2}\, B^{.2}} \left(Q^{.6} - Q_0^{.6} \right)$$

where

G is the total quantity of bed sediment transported

ψ is the sediment characteristic

i is the slope of the water surface

C is the coefficient of roughness in Manning's formula ($C = \frac{1.486}{n}$)

B is the width of the river

Q is the water discharge

Q_0 is the water discharge at which sediment transportation begins.

The values for ψ and Q_0 were obtained from Appendix XV of the Missouri River "308" report (House Document No. 238, 73d Congress, 2d Session) where the formula was developed. Because of the late decision to make the repeated cross-sectional surveys, no gages were available during the flood except at the bridge. Consequently, the high water marks on both banks were located and the water surface slope at the peak of the flood was obtained (Figure 8) for use in the formula. The theoretical movement from the formula was about 2,000,000 cubic feet. The total retrogression in the reach as obtained from the soundings, was 1,000,500 cubic feet, which probably is only a portion of the total bed load movement which includes material which moved entirely through the reach during the observation period. The comparison is not strict, since the bed-load formula contemplates a change in transporting capacity with each change in slope, and the surveyed loss in volume is only a portion of that which should be transported with the given slope. The bed condition during the succeeding period shows considerable aggradation, which could only occur with a major flattening of slope, according to the formula. Without a record of the change in slope from section to section and from time to time, no true comparison could be made, even if helical flow were not present.

The fathometer was found quite useful for rapid streambed mapping. A representative of the Geological Survey was interested in determining the streambed configuration in the vicinity of the discharge measuring section at the Ak-Sar-Ben Bridge. The profiles taken to make the map are shown on Figure 9 3/. The completed map is shown on Figure 10. Since the data were collected within one and one-half hours, the errors in determining contour locations are probably greater than those due to lapse of time. The map clearly shows the effects of bridge piers and of cross currents upstream and downstream from the bridge.

It should be mentioned that excessive turbulence absorbs the transmitted impulse to such an extent that no chart record can be obtained under such conditions. These conditions were experienced a number of times near the right bank on Section F, due to the sewer discharge immediately upstream, and downstream from the piers on Section B-1. The only solution now seen is to

3/ Sheets 2 and 3 not printed.

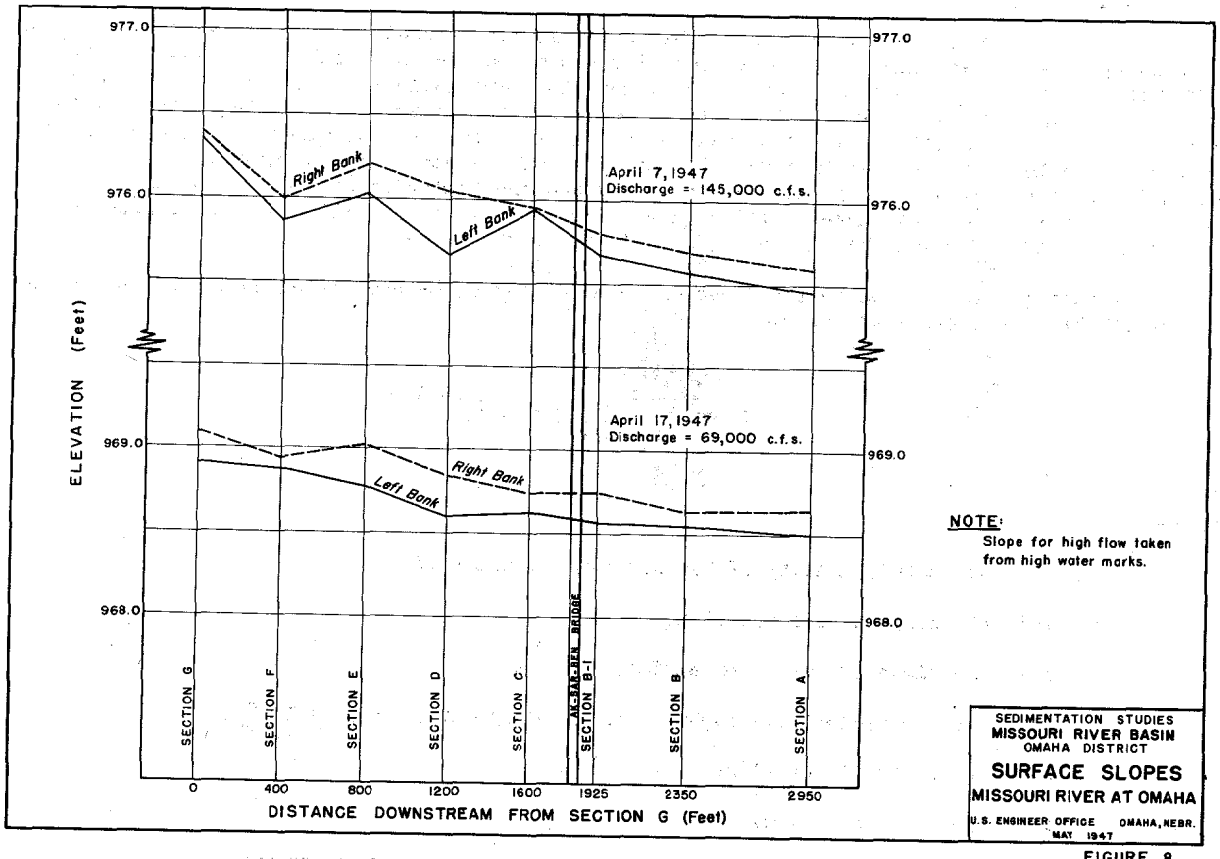


FIGURE 8

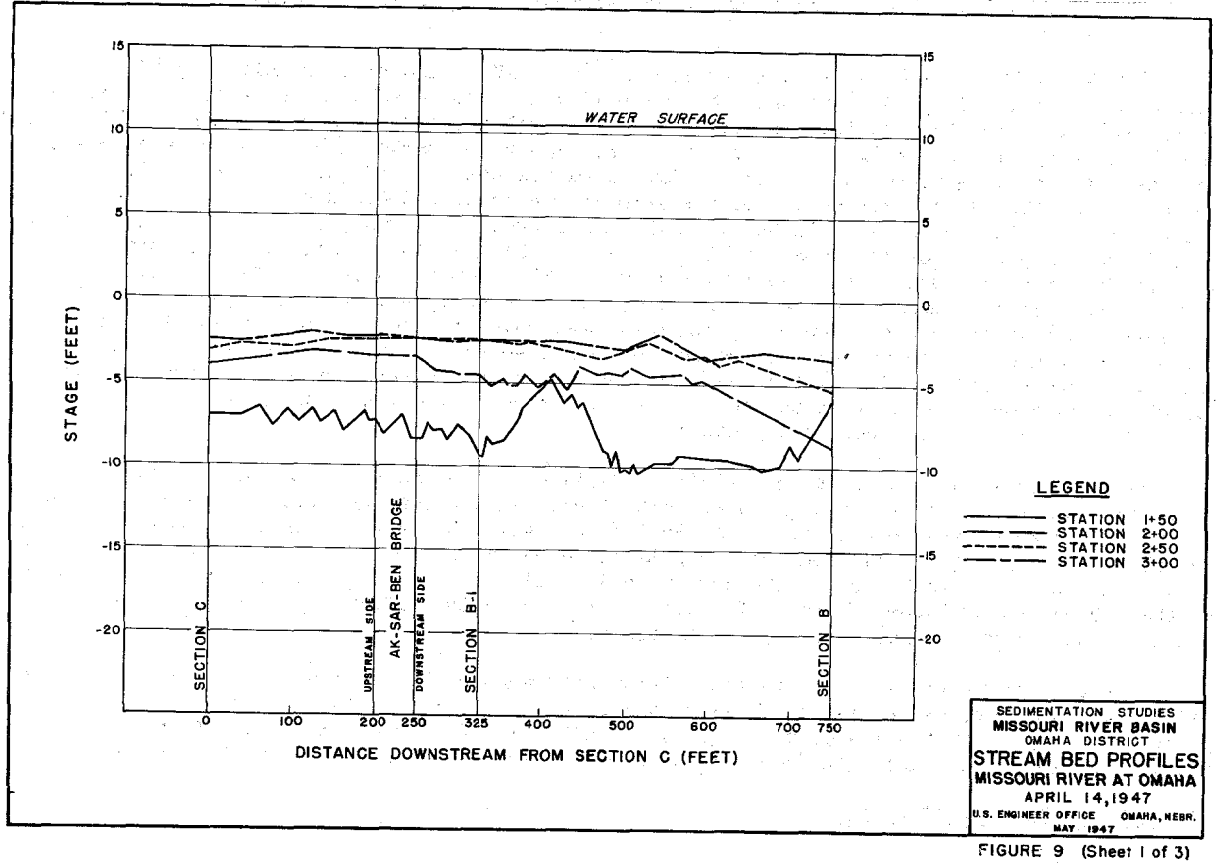
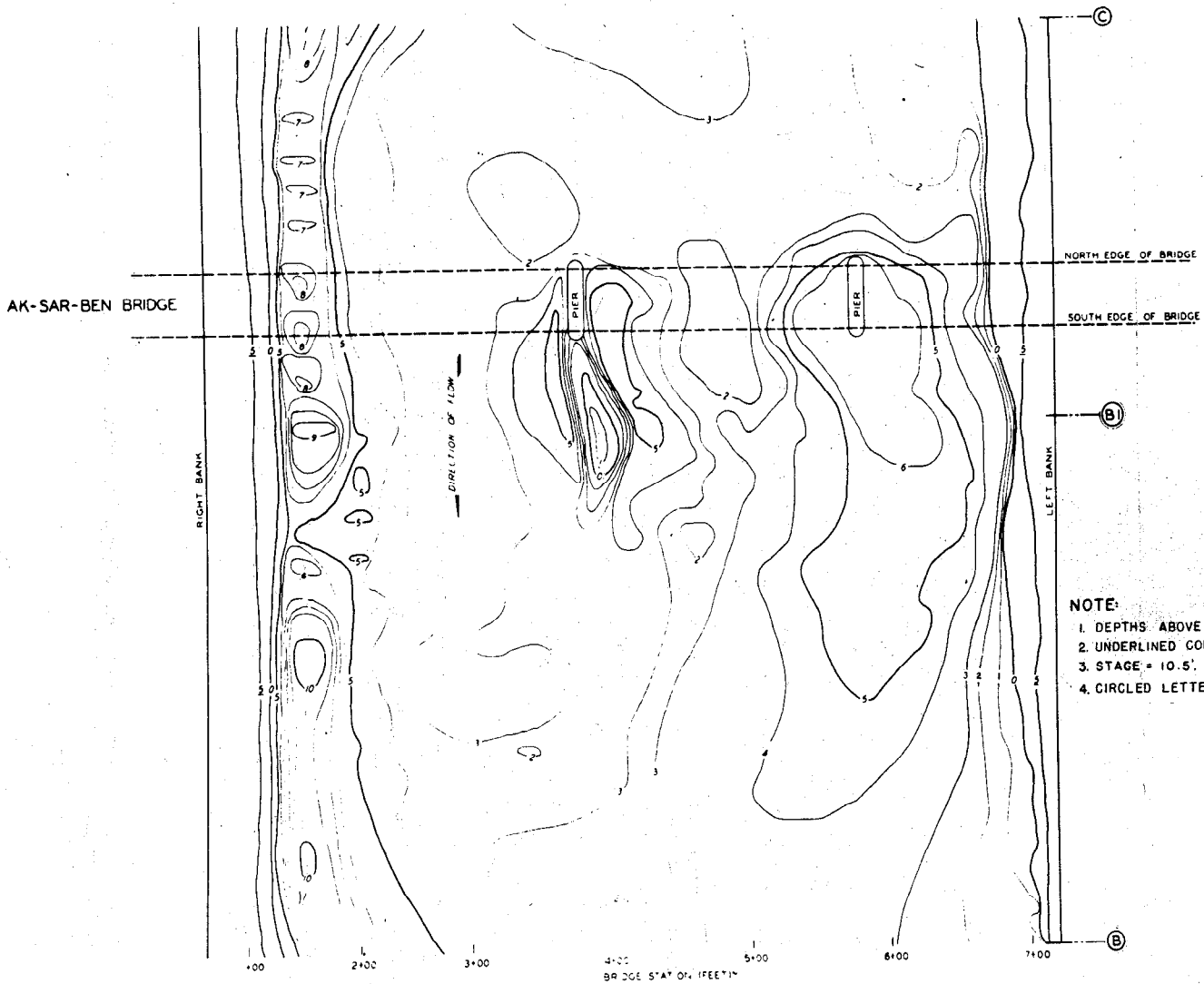


FIGURE 9 (Sheet 1 of 3)



NOTE:

1. DEPTHS ABOVE OR BELOW GAGE DATUM.
2. UNDERLINED CONTOUR FIGURES = ABOVE GAGE DATUM.
3. STAGE = 10.5'.
4. CIRCLED LETTERS ARE LOCATIONS OF CROSS SECTIONS.

SEDIMENTATION STUDIES
MISSOURI RIVER BASIN
OMAHA DISTRICT

BED TOPOGRAPHY
MISSOURI RIVER AT OMAHA
APRIL 14, 1947

U.S. ENGINEER OFFICE OMAHA, NEBR.
MAY 1947

FIGURE 10

use a sounding pole or lead line in such areas.

Conclusions

The survey and study reviewed in this paper establish the usefulness of the supersonic-echo depth recorder in making rapid quantitative measurements of bed changes in large alluvial streams. The techniques employed will no doubt be greatly modified as a result of further experience, and the intent of this paper is not to present a perfected technique, but to describe the technique used, evaluate the resultant data, and set forth the difficulties encountered for the guidance of others who may desire to conduct similar measurements. It is hoped that this presentation may initiate an exchange of experiences which will lead to development of better techniques in the conduct of measurements of bed changes and to accumulation of data which may be correlated with and improve the usefulness of the empirical bed sediment formulae.

Acknowledgments

This study was made by personnel of the Omaha District, Corps of Engineers, Department of the Army. The suggestions of R. J. Pafford, Missouri River Division, Corps of Engineers, and Jack A. Gardner, Omaha District, are gratefully acknowleged. Personnel assisting in direction of the field work included James C. Cannon, James A. Constant, Ben J. Wilson and E. L. Phillips. The writer was greatly assisted in the office work by Leland Meyer and Robert H. Livesey.

D. V. C. BIRRELL.* - The following paper 1/ is presented as being of interest to those engaged in research and experimentation in problems of transportation of sediment. The paper represents the results of efforts by the Washington District Office, Corps of Engineers, to find from available literature, basic data for design of stable flood channels in order to minimize maintenance dredging. The Lacey formulas, which have been derived mainly from observations on canals and rivers in India and Egypt, are also in agreement with data on European and North American rivers and resolve these observations to basic concepts which involve sediment grain size in addition to the usual hydraulic elements. No quantitative determinations were developed. The Meyer-Peters formula was developed as the result of extensive experiments in Switzerland and conforms basically to the quantitative relationships of bed load transportation developed by other experimenters in that field, as has been illustrated by Vanoni in a subsequent paper.

The Meyer-Peters formula has been used to determine channel bed-load transportation capacity by integration across any hydraulic section. It has been used in this paper to integrate the Lacey hydraulic channel section on the assumption that rivers in flood will determine, unless restricted, their own stable section. The channel characteristics, which are a function of the silt factor according to the Lacey concept, may be determined by measurement of discharge and slope or by the measurement of the average diameter of the silt composing the channel bed. Since the silt factor in many cases is not available, or is difficult to determine, except by extensive sampling, the discharge and slope when measured over a long reach of the river in flood is perhaps a more reliable measure of its characteristics, and collection of such data is already an established practice.

The examples included in the paper have been checked against observed or calculated bed load movement using such limited data as was available, which leaves much to be desired. However, the remarkably close agreement in each case would seem to be more than merely fortuitous, and even agreements of the same general magnitude would be sufficient to warrant further examination and trial.

The paper also includes a development of the Lacey formulas to illustrate relationships of scale and distortion in model tests, which seem to be of considerable value in the absence of any general agreement among the laboratories engaged in such experiments as to the basic laws involved.

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* Chief, Flood Control and Power Branch, Washington District, Corps of Engineers, Department of the Arry, Washington, D. C.

1/ Paper not read at Conference.

STABLE CHANNELS IN ALLUVIUM (A DIGEST)

The following is a digest and resume of a paper entitled "Stable Channels in Alluvium," presented by Gerald Lacey before the Institution of Civil Engineers, London, England, 28 January 1930, and printed in the Minutes of Proceedings, Vol. 229. The author has collated reliable data of stable channels from a variety of sources and has deduced general formulas which fit with reasonable accuracy a very extensive range of hydraulic conditions. Since the article is not generally available to American engineers and the subject is of such importance with respect to the design of stable channels for navigation, flood control and irrigation where low maintenance charges are essential, the substance of the paper has been briefly presented with formulas and explanations sufficient for a practical understanding thereof. This review implies no indorsement of the author's conclusions but is presented as a remarkable conciliation of widely isolated hydraulic phenomena that is worthy of trial and test by practicing engineers of this country.

Previous expressions of the elements of flow in stable channels, transporting and flowing in their own silt have been generally written as

$$Vo = cD^n$$

where Vo is the regime or critical mean velocity, D is the vertical depth with c and n empirical constants of observation. The inability to generalize these expressions covering a wide range of channel sizes and character of silt lead to the author's general formula which substituted the hydraulic radius R for D and the inclusion of a silt factor f. The first general formula is:

$$Vo = 1.17\ R^{\frac{1}{2}}\ f^{\frac{1}{2}} \qquad (1)$$

The silt factor f is a scalar quantity which is dependent on the size of the silt particle and has been arbitrarily given the value of one for a standard silt, defined in a later paragraph.

A second general formula is required involving the velocity-discharge relationship in order to solve the silt transportation problem. From the first expression it is evident that in two channels having the same mean velocity but different silt factors that

$$Rf = R'f'$$

The author assumes also that the wetted perimeter has the same relationship or

$$Pwf = Pw'f'$$

and multiplying these two expressions together there results

$$Af^2 = A'f'^2$$

From an application of this relationship to data available to the author the following formula was obtained

$$Af^2 = 3.8\ Vo^5 \qquad (2)$$

Multiplying both sides of the equation by Vo

$$Qf^2 = 3.8\ Vo^6 \qquad (3)$$

From (1) $R = 0.7305\ Vo^2/f$

From (2) $A = 3.8\ Vo^5/f^2$

Hence $Pw = A/R = 3.8\ Vo^3/0.7305\ f$

but from (3) $Vo^3 = Q^{\frac{1}{2}}f/3.8^{\frac{1}{2}}$

substituting in the equation for Pw

$$Pw = 2.668 \; Q^{\frac{1}{2}} \qquad (4)$$

This somewhat remarkable formula shows that for a given discharge the wetted perimeter of a stable channel is constant and independent of the fineness of the silt transported, the silt merely controlling the shape. If channels with horizontal beds are considered, then by "shape" is understood the ratio of bed-width to depth; if channels are visualized as having semi-elliptical cross sections, then by shape is understood the ratio of the major axis to the semi-minor axis. The coarser the silt, the flatter the semi-ellipse and the greater the width of water-surface; the finer the silt the more nearly does the section approximate to a semi-circle.

When large rivers in alluvium are considered, the wetted perimeter approximates so closely to the width of water surface that for general purposes the difference is negligible and it is immaterial in this somewhat exceptional case what shape the channel assumes. The wetted perimeter equation therefore provides a useful approximate formula for the minimum width of a stable waterway of large rivers in alluvium, namely

$$Ws = 2.67 \; Q^{\frac{1}{2}} = \frac{8}{3} Q^{\frac{1}{2}} \qquad (5)$$

The author has checked this formula with available data on very large rivers with a gratifying degree of conformance.

The general formulas were checked against available data for scour. It has been generally observed that channels carrying silt not of the same material as the banks have nearly horizontal beds. Channels flowing not only on their own silt, but within banks composed of silt of the same kind as the bed, tend to assume a semi-elliptical cross section. If a section is truly elliptical the maximum depth should be equal to the mean depth divided by 0.7854. Therefore in a river flowing through a stable reach the maximum depth should approximate the mean depth multiplied by 1.273. On bends the depth is greatly increased with the severest type of bend or "right-angled" it is rational to infer that the section becomes triangular. The maximum depth would then become equal to twice the hydraulic mean depth. This rough rule was confirmed from several sources. As a matter of convenient classification the following table could be adopted for different types of bend:

$$Dmax = c \; R$$

Type of River Section	Value of c
Greatly constricted section	1.00
Natural sections	
Class A - Straight reach	1.27
Class B - Moderate bend	1.50
Class C - Severe bend	1.75
Class D - Right-angled bend	2.00

From a consideration of the silt factor f and Manning's N the author has evolved the following relationship

$$N_a = .0225 \; f^{\frac{1}{4}} \qquad (6)$$

Here N_a is a new coefficient of absolute rugosity having nothing to do with shock and applicable to all sizes of channel in a uniform straight reach when the size of the silt is known.

The grain size of silt for which the author has assumed a value for f of 1.0 had an average diameter of 0.4 millimeters. The diameter of the average large boulders transported by heavy floods on rivers for which the author had data for consideration was 24 inches. From this range of data the author has presented the following expression for the relationship of the silt factor f and the silt grain size in inches:

$$d = f^2/64 \qquad (7)$$

With the addition of formula (6) it was possible to expand the argument underlying the paper and to complete the theory of hydraulic flow in alluvial channels. An ideal channel as thus far considered was also to be regarded as uniform and free from shock. The alluvium in which it flowed was coherent and unlimited. The discharge was constant, and also were the temperature of the water, its density, and its viscosity, the specific gravity of the silt particles and their average size and shape. Such a channel when stable would be uniquely determined, and the silt-charge also would be constant. Abstraction of silt by an outside agency would lead to picking-up of fresh silt from the bed, which would thus be lowered; an addition of silt could lead only to the deposition of an equal increment and the raising of the bed. The basis of all hydraulic formulas was the replacement of a closed geometric section by a hydraulic development of the hydraulic mean depth elevated on the wetted perimeter as horizontal base. In the calculations that followed this would be understood, and all scales would be hydraulic and not geometric unless specified as such. If any two channels in alluvium were taken with hydraulic data R, Pw, V, S, etc., and R', Pw', V', S' etc., and these channels were designated for convenience the prototype and the model respectively, then it was clear, if the silt factor in each channel was the same, that

$$R'/R = V'^2/V^2 \qquad (8)$$

and the depth scale of the model was therefore R'/R. The relationship also showed that stable channels in initial regime fulfilled the first requirement of dynamic similarity. The model, however, so far as its hydraulic development was concerned would not be similar to the prototype.

The ratio of the hydraulic mean depth to the wetted perimeter would not be the same in the model and in the prototype but would increase with diminution in size. The ratio of the two identities gave the exaggeration in the depth scale, thus, since from (1) and (2)

$$R = 0.7305\ V^2/f$$

$$\text{and} \quad A = 3.8\ V^5/f^2$$

$$Pw = A/R = 3.8\ V^3/0.7305f$$

$$\text{The ratio } \frac{R}{Pw} = \frac{1}{7.1208\ V}$$

$$\text{and} \quad \frac{R'}{Pw'} = \frac{1}{7.1208\ V'}$$

$$\text{Therefore } \frac{R'Pw}{RPw'} = \frac{V}{V'} \qquad (9)$$

But the exaggeration in the depth scale in the model was also the exaggeration in the slope. Hence it was permissible to write

$$\frac{S'}{S} = \frac{V}{V'} \qquad (10)$$

This made it possible to derive the value of the variable c in Chezy's formula $V = C\ (RS)^{\frac{1}{2}}$ for any two channels of the same absolute rugosity.

$$\text{Thus } V/V' = c\ (RS)^{\frac{1}{2}}/c',\quad (R'S')^{\frac{1}{2}}$$

Substituting for R and S the values given in equations (8) and (10)

$$V/V' = (c/c')\ \ (V/V')\ \ (V'/V)^{\frac{1}{2}}$$

$$c/c' = (V/V')^{\frac{1}{2}} = (R/R')^{\frac{1}{4}}$$

$$V/V' = (R/R')^{\frac{1}{4}}\ \ (R/R')^{\frac{1}{2}}\ \ (S/S')^{\frac{1}{2}}$$

$$V = \left(\frac{V'}{R'^{3/4}\ S'^{\frac{1}{2}}}\right) R^{3/4}\ \ S^{\frac{1}{2}} \doteq K\ R^{3/4}\ S^{\frac{1}{2}}$$

which is the general equation for alluvial channels, K being a true constant for all channels of the same rugosity.

It was now necessary to evaluate K in terms of a known coefficient of rugosity. The characteristic of Kutter's N and that of Manning was that they were identical when the hydraulic mean depth was one meter (3.2808 ft.). Giving the author's coefficient of absolute rugosity, N_a, the same significance and equating.

$$V = (1.4858/N_a) \quad (3.2808)^{2/3} S^{\frac{1}{2}} = K (3.2808)^{3/4} S^{\frac{1}{2}}$$

and solving for K,

$$V = (1.3458/N_a) \quad R^{3/4} \quad S^{\frac{1}{2}} \qquad (11)$$

which the author suggested was the correct formula for the flow of water in alluvial channels. The coefficient was one of absolute rugosity equal to that of Kutter and Manning when the hydraulic depth was 1 meter, but remaining a true constant so long as the silt particles were constant. The need for varying the rugosity factor with the size of the channel was no longer necessary.

When the author's formula for the coefficient of rugosity $N_a = .0225 f^{\frac{1}{4}}$ was substituted in in the formula from (1) and (11)

$$V = 1.17 R^{\frac{1}{2}} f^{\frac{1}{2}} = (1.3458/N_a) R^{3/4} S^{\frac{1}{2}}$$

its value in terms of f the following relationship resulted

$$V = 64.70 \quad [(R/V)RS]^{\frac{1}{2}} \qquad (12)$$

for all channels in alluvium, irrespective of the type of silt transported.

Equation (12) could be written

$$V = 16.116 \quad R^{2/3} S^{1/3} \qquad (12a)$$

Equations (12) and (12a) represent the true Chezy concept of natural and similar channels flowing in alluvium and subject to natural laws. The application of such a formula to channels with rigid boundaries is manifestly improper. The similarity criterion for alluvial channels is the ratio R/V and all channels which preserve the same ratio are similar.

It is occasionally convenient when the discharge of a channel is known and also the silt factor to calculate the minimum stable slope that should be given to it to ensure regime, which could be compared with the actual ground slopes available. Equating equation (11) with equation (3) giving the velocity in terms of discharge, the following expression resulted.

$$S = f^{5/3} / \ 1788 \ Q^{1/6} \qquad (13)$$

Many practical engineers have urged that such streams are never in regime, yet as a fact whenever they employ a formula such as Kutter's they assume that the channel was in regime; for were it not it would have to be either actively scouring or silting when the discharge was taken, and that would vitiate the discharges calculated from the formula in which they placed implicit confidence. The rugosity of alluvial streams was implicit in the slope and the hydraulic mean depth which they demanded at full stage or in flood, and that was the basis of the new formula. A river that adopted a certain slope in flood and a corresponding hydraulic mean depth was asserting in plain terms what its rugosity was, and there was no necessity to have recourse to a formula in which the engineer had to estimate a rugosity coefficient that might not be strictly appropriate.

The author has checked the equation for the size of silt particles on a number of samples on different rivers and found close agreement. He also demonstrated that the following relations exist:

$$V^2/d = V'^2/d'$$

which relationship has been deduced from theoretical consideration; and

$$Pw/d = P'w/d'$$

or in respect to roughness, similar channels preserve a geometric similarity.

The author's general formulas have a limiting velocity which is common to all types of silt. It is evident that with a decrease in discharge, the silt factor being kept constant, the cross section will approach to a semi-circle as a limit. Hence at the limit

$$A = 2\pi R^2 = 3.8\ Vo^5/f^2$$

solving for f and substituting in equation (1) Vo = 0.882 foot per sec. for any type of silt. The author is inclined to accept this limiting velocity as a physical constant of water. The actual velocity in contact with the channel boundary would, of course, be somewhat less than the limiting mean velocity.

The author's conclusions are summarized as follows:

1. For a given discharge and a given silt factor the cross sectional area, wetted perimeter, and slope of a stable channel flowing in and transporting its own silt are uniquely determined.

2. The wetted perimeter of a stable silt transporting channel varies as the square root of the discharge and is independent of the type of silt transported, all stable channels of the same discharge having the same wetted perimeter, and the silt factor determining the "shape."

3. All stable silt - transporting channels of the same stable mean velocity have geometrically similar shapes, the silt factor determining the only difference, which is one of scale.

4. The minimum stable width of active waterway of large alluvial rivers in floods varies approximately as the square root of the discharge and is virtually independent of the silt factor.

5. The rugosity coefficient in Manning's formula is a simple function of the silt factor, and the silt factor is a function of the average size of the silt particles.

6. At some velocity between 1.0 and 0.6 foot per second viscous stream-line flow replaces turbulent flow, and the transport of silt other than colloids is rendered impossible.

For greater detail in derivation of formulas and description of basic data the reader is referred to the original paper.

SUMMARY OF EQUATIONS

(1) $$Vo = 1.17\ R^{\frac{1}{2}}\ f^{\frac{1}{2}}$$

(1a) $$R = 0.7305\ Vo^{2}/f$$

(2) $$Af^2 = 3.8\ Vo^5$$

(3) $$Qf^2 = 3.8\ Vo^6$$

(3a) $$Vo = (Qf^2/3.8)^{1/6}$$

To determine the depth to which scour will take place under normal flow, from (1a) and (3a)

$$R = 0.7305\ Vo^2/f$$

(3b) $$= 0.7305\ (Q/3.8f)^{1/3}$$

(3c) $$Dmax = c\ R \text{ (See table of Coefficients - c.)}$$

(4) $$Pw = 2.667\ Q^{\frac{1}{2}}$$

(5) $$Ws = \frac{8}{3}\ Q^{\frac{1}{2}}$$

The discharge per foot width of channel is given by

(5a) $$q = \frac{Q}{Ws} = \frac{Q}{2.67\,(Q)^{\frac{1}{2}}} = \frac{Q^{\frac{1}{2}}}{2.67}$$

In a channel where the waterway differs materially from the minimum stable water-way given by (4) or (5) the depth of scour obtained by (3b) and (3c) will apply only to that section of the channel whose unit discharge equals that given by (5a). Combining (3b) and (5a) the relationship between unit discharge and R = D, in a restricted section in a straight reach, results

$$Q = (2.67q)^{\frac{1}{2}}$$

$$R = 0.7305\,\frac{(2.67q)^{2/3}}{(3.8f)^{1/3}} = 0.9\,(q^{2}/f)^{1/3}$$

(6) $$N_a = .0225f^{\frac{1}{4}}$$

(7) $$d = f^{2}/64$$

(7a) $$f = 8d^{\frac{1}{2}}$$

(11) $$Vo = \frac{1.3458}{N_a}\,R^{3/4}\,S^{\frac{1}{2}}$$

(11a) $$Vo = \frac{59.813}{f^{\frac{1}{4}}}\,R^{3/4}\,S^{\frac{1}{2}}$$

(12) $$Vo = 64.70\,[(R/V)RS]^{\frac{1}{2}}$$

(12a) $$Vo = 16.116\,R^{2/3}\,S^{1/3}$$

(13) $$S = f^{5/3}/1788\,Q^{1/6}$$

(13a) $$f^{5/3} = 1788\,S\,Q^{1/6}$$

To determine R, given q and S:

from (13) (5a) and (3b)

(14) $$R = .1885\,q^{0.6}/S^{0.2}$$

To determine f given Q and A:

from (3)

(15) $$f = 1.953\,Q^{5/2}/A^{3}$$

To determine f given q and S:

from (13a) and (5a)

(16) $$f = 108\,S^{0.6}\,q^{0.2}$$

Model Similitudes

(Note: The following relationships have been developed from the basic equations by Lacey).

As pointed out by Lacey, the ratio of the hydraulic mean depth to the wetted perimeter would not be the same in the model as in the prototype but would increase with diminution in size. Thus all models of stable channels in alluvium would necessarily be distorted. A vast range of scales and exaggerations are permissible with limitations imposed by available space, water supply and size of bed material. From the foregoing formulas the ratios of the hydraulic elements may be expressed in accordance with column (1) of the attached Table 1. The derivation

is as follows, where subscripts indicate model and prototype respectively, r = the horizontal scale ratio of the model to the prototype, n = the ratio of horizontal scale to vertical scale or the exaggeration, and K is the ratio of size of silt particles in the model to those in prototype. All other symbols are as previously identified.

From (13) $$\frac{Sm}{Sp} = \left(\frac{fm}{f_p}\right)^{5/3} \times \left(\frac{Qp}{Qm}\right)^{1/6}$$

Let $$\frac{dm}{dp} = K \quad , \quad \frac{fm}{f_p} = K^{\frac{1}{2}}$$

$$\frac{Sm}{S_p} = K^{5/6}\left(\frac{Qp}{Qm}\right)^{1/6} \qquad \text{(a)}$$

From (1) $$\frac{Vm}{V_p} = \left(\frac{Rm}{Rp}\right)^{\frac{1}{2}} \times \left(\frac{fm}{fp}\right)^{\frac{1}{2}} = K^{\frac{1}{4}}\left(\frac{Rm}{R_p}\right)^{\frac{1}{2}} \qquad \text{(b)}$$

From (4) $$\frac{Pm}{P_p} = \left(\frac{Qm}{Q_p}\right)^{\frac{1}{2}} = \text{Horizontal Scale} = r \qquad \text{(c)}$$

and $$\frac{Qm}{Qp} = r^2 \qquad \text{(d)}$$

From (3) $$\left(\frac{Vm}{V_p}\right)^6 = \frac{Qm}{Q_p} \times \left(\frac{fm}{f_p}\right)^2 = K \times \frac{Qm}{Q_p} = K_r^{\,2}$$

and $$\frac{Vm}{V_p} = (K^{\frac{1}{2}}r)^{1/3} \qquad \text{(e)}$$

Equating (e) to (b)

$$K^{\frac{1}{4}}\left(\frac{Rm}{R_p}\right)^{\frac{1}{2}} = (K^{\frac{1}{2}}\,r)^{1/3}$$

$$\frac{Rm}{R_p} = \frac{r^{2/3}}{K^{1/6}} = \text{vertical scale} \qquad \text{(f)}$$

Substituting (d) in (a)

$$\frac{Sm}{S_p} = K^{5/6}\left(\frac{1}{r^2}\right)^{1/6} = K^{5/6}/r\ \ 1/3 \qquad \text{(g)}$$

Also $$\frac{Am}{A_p} = \frac{Qm}{Vm} \times \frac{V_p}{Q_p} = \frac{1}{(K^{\frac{1}{2}}\,r)^{1/3}} \times r^2 = \frac{r^{5/3}}{K^{1/6}} \qquad \text{(h)}$$

The scale exaggeration is equal to the ratio n and from(c) and (f)

$$n = \frac{r}{r^{2/3}/K^{1/6}} = r^{1/3}\ K^{1/6} \qquad \text{(i)}$$

Solving for K,

$$K = n^6/\,r^2 \qquad \text{(j)}$$

Hence $P_m = r\,P_p$ $\qquad S_m = \frac{n^5}{r^2}\,S_p$

$R_m = \frac{r}{n}\,R_p$ $\qquad d_m = \frac{n^6}{r^2}\,d_p$

$V_m = n\,V_p$ $\qquad f_m = \frac{n^3}{r}\,f_p$

$Q_m = r^2\,Q_p$

$A_m = \frac{r^2}{n}$

Exaggeration = n

Table 1 includes values of the various hydraulic elements for definite conditions; i.e., Column 2 for the same silt in both model and prototype or $n^6/r^2 = 1$; Column 3 for a geometrically scaled silt in the model or $n^6/r^2 = r$; Column 4 for model having the same slope as the prototype or $n^5/r^2 = 1$; Column 5 for the hypothetical case where the model has an undistorted vertical scale or n = 1.

Column 1 determines the proportion of the hydraulic elements for the model for any horizontal scale and any exaggeration of the vertical scale. It will be observed that in all cases the discharge varies as the square of the scale ratio and the velocity varies as the exaggeration. The limiting factors will be the availability of suitable silt at the required scale and the maintenance of turbulent flow. Column 2 determines the model proportions for the most convenient representation of the silt where the prototype silt can be used in the model. The model is then limited essentially only by the condition of turbulent flow. It is of interest to observe that the use of silt the same in model and prototype results in a less exaggeration than for the condition of Column 3 where the silt is at the same scale as the horizontal scale of the model. Column 4 gives the ratios when it is desirable to maintain the same slope in model and prototype. This arrangement it will be noted, affords a still smaller exaggeration and permits a larger size of silt in the model. The condition of Column 5 where both horizontal and vertical scales are the same imposes impossible conditions as to the scale of the silt except for very large model scales. The relationships are nevertheless valid within the scope of practicability as to the silt factor.

TABLE 1. MODEL SIMILITUDES FOR STABLE CHANNELS IN ALLUVIUM

Hydraulic Element	Exaggeration = n $n = \frac{\text{Hor. Scale}}{\text{Vert. Scale}}$	Same Silt Model and Prototype $n^6/r^2 = 1$	Geometrically Scaled Silt in Model $n^6/r^2 = r$	Equal Slopes in Model & Prototype $n^5/r^2 = 1$	Horiz. Scale in Model equals Vert. Scale n = 1
Col. No.	(1)	(2)	(3)	(4)	(5)
P_m/P_p	r	r	r	r	r
R_m/R_p	r/n	$r^{2/3}$	$r^{\frac{1}{2}}$	$r^{0.6}$	r
V_m/V_p	n	$r^{1/3}$	$r^{\frac{1}{2}}$	$r^{0.4}$	1.0
Q_m/Q_p	r^2	r^2	r^2	r^2	r^2
A_m/A_p	r^2/n	$r^{5/3}$	$r^{3/2}$	$r^{1.6}$	r^2
S_m/S_p	n^5/r^2	$1/r^{1/3}$	$r^{\frac{1}{2}}$	1.0	$1/r^2$
d_m/d_p	n^6/r^2	1.0	r	$r^{0.4}$	$1/r^2$
f_m/f_p	n^3/r	1.0	$r^{\frac{1}{2}}$	$r^{0.2}$	1/r
Exagg.	n	$r^{1/3}$	$r^{\frac{1}{2}}$	$r^{0.4}$	1.0

Computations for Bed Load Movement

A formula for computing bed load movement has been developed by Professor Meyer-Peters and his associates at the Federal Technical University, Zurich, Switzerland, and published in the Schweizerische Bauzeitung issues for 31 March 1934 and 2 March 1935 and introduced in this country by John Hedburg in Civil Engineering for March 1937. The experiments supplemented extensive studies by Grove K. Gilbert of the Geological Survey and published in Professional Paper No. 86 of that agency in 1914.

A review of the original papers has been made to determine the scope of the application and basic units in the formula. The equation in English units may be written as follows:

$$\frac{q^{2/3}S}{d'} = a + \frac{b\,G^{2/3}}{d'}$$

Where q = discharge per unit width of channel in cubic feet per second.

S = friction slope of the channel.

d' = average diameter in feet of the silt particles in a sample of the bed load from which 35 percent of the finer material has been omitted.

G = quantity in cubic feet per second of the bed load transported per unit width of channel. The experiments determined the quantity of bed load by weight, but the coefficients have been determined on the basis of the volume of the bed load in place in natural deposits of mixed river debris.

Thus $a = 0.253$

and $b = 0.756$ for bed load material having an average specific gravity of 2.6.

The size of bed load particles used in the experiments covered sizes from 1/8 inch to 2 inches. Results for sizes below 1/8 inch departed somewhat from the stated formula. The range covered, however, is found most generally in natural streams.

Professor Meyer-Peters utilized this formula for computing the bed load of natural streams by integrating the unit discharge across various type stream sections and then applied the resulting expression to the varying stream flow and calculated the annual bed load.

A similar procedure is possible utilizing the formulas developed by Lacey for stable channels in alluvium. His expression for the width of water surface

$$W_s = \frac{8}{3} Q^{\frac{1}{2}} \qquad (5)$$

may be resolved to find unit discharge to

$$q = \frac{3}{8} Q^{\frac{1}{2}} \qquad (5a)$$

which may be substituted into the Meyer-Peters formula. The Lacey expression for d in inches

$$d'' = f^2/64 \qquad (7)$$

becomes $d' = f^2/64 \times 12$ (in feet)

The Lacey expression for slope is $S = f^{5/3}/1788\ Q^{1/6}$ (13)

where f is the Lacey silt factor
and

$$f^2 = 8000 \; S^{1.2} \; Q^{0.2}$$

Substituting these values in the Meyer-Peters formula

$$\frac{q^{2/3} S}{d'} = a + \frac{b \, G^{2/3}}{d'}$$

or

$$q^{2/3} S = d' a + b \, G^{2/3}$$

$$(.375 \, Q^{\frac{1}{2}})^{2/3} x \, S = a \, f^2/768 + b \, G^{2/3}$$

$$.521 \, Q^{1/3} S = \frac{a \; x \; 8000}{768} S^{1.2} \; Q^{0.2} + b \, G^{2/3}$$

but the total bed load, B' equals G times the width of river surface or

$$B' = G \, W_s = G \; x \; \frac{8}{3} \; Q^{\frac{1}{2}}$$

and

$$G^{2/3} = \frac{B'^{2/3}}{1.923 Q^{1/3}}$$

therefore

$$.521 \, Q^{1/3} S = 10.41 \; a \; S^{1.2} \, Q^{0.2} + \frac{b \; B'^{2/3}}{1.923 Q^{1/3}}$$

solving for B'

$$B' = \frac{Q^{0.8} S^{3/2}}{b^{3/2}} (Q^{.1333} - 20 \; a \; S^{0.2})^{3/2}$$

When $a = 0.253$ and $b = 0.756$

$$B' = 1.53 \, Q^{0.8} S^{1.5} \; (Q^{.1333} - 5.06 \; S^{0.2})^{1.5}$$

which is the expression for total bed load movement in cubic feet per second in terms of the river discharge and the slope.

Since, according to Lacey, the slope varies with discharge it is most convenient to express B' in terms of f which is a constant for any stream in regime.

Substituting $S = f^{5/3}/1788 \; Q^{1/6}$

$$B' = 1.53 \, Q^{0.8} (f^{5/3}/1788 \, Q^{1/6})^{3/2} \, (Q^{.1333} - 5.06 \, (f^{5/3}/1788 \, Q^{1/6})^{0.2})^{3/2}$$

$$= \frac{Q^{\frac{1}{2}} f^{5/2}}{471000} \; (4.470 \, Q^{1/6} - 5.06 \, f^{1/3})^{3/2} \text{ (cubic feet per second)}$$

or expressed in cubic yards per day

$$B = .00678 \, Q^{\frac{1}{2}} f^{5/2} (4.470 \, Q^{1/6} - 5.06 \, f^{1/3})^{3/2}$$

$$= .0641 \; Q^{\frac{1}{2}} f^{5/2} \, (Q^{1/6} - 1.133 \, f^{1/3})^{3/2}$$

Plate No. 1 shows graphically the bed load movement in terms of f for values from 2 to 12, and Q from 100 c.f.s. to 500,000 c.f.s. The curves include values within the limits of the original experiments for d between 1/8 inch and 2 inches.

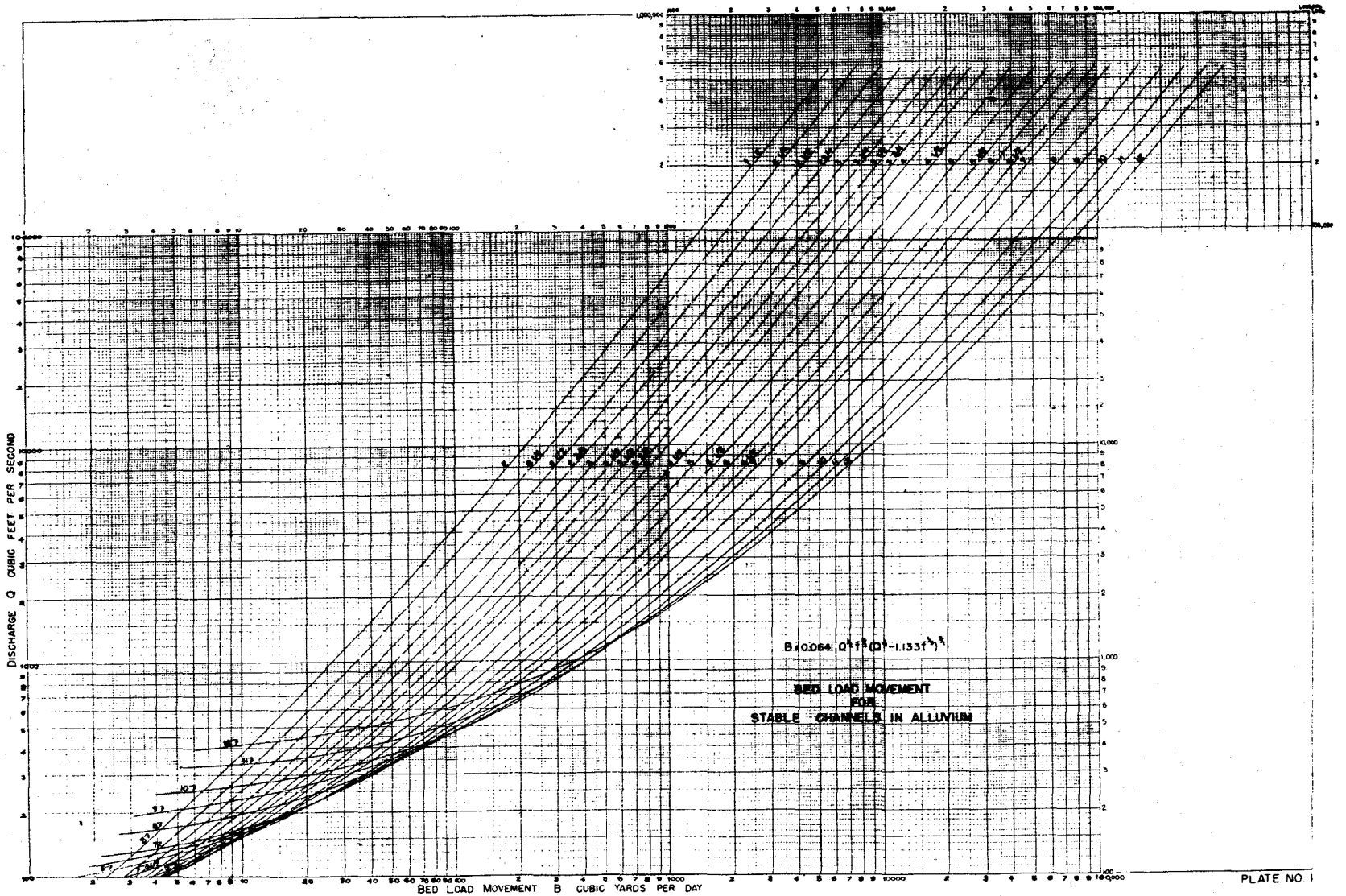
DISCHARGE Q CUBIC FEET PER SECOND
BED LOAD MOVEMENT B CUBIC YARDS PER DAY
$B = 0.064\, Q^{\frac{1}{3}} T^{\frac{2}{3}} (Q^{\frac{1}{3}} - 1.133 T^{\frac{1}{3}})^{\frac{2}{3}}$
BED LOAD MOVEMENT
FOR
STABLE CHANNELS IN ALLUVIUM

PLATE NO. I

The determination of d from a sample of bed load material is made from a sieve analysis and a standard curve of grain-size distribution. The average diameter of all grains is a linear dimension and is the reciprocal of the linear fineness. Linear fineness is a derivation of bulk fineness which is fundamentally the number of particles in a unit volume (1 cubic foot), it being assumed that there are no voids. If the particles are assumed to be spheres of diameter d the volume of each sphere is $\pi d^3/6$ and in one solid cubic foot there are 28,317,000 cubic millimeters, approximately, then for example if the mean diameter is one millimeter,

$$F \text{ (bulk fineness)} = \frac{28,317,000}{\pi \times 1^{3}/6} = 54,100,000$$

or the number of particles of average 1 mm. diameter in one cubic foot.

In a graded mixture the mean bulk fineness is the average of the mean finenesses of the component parts. Thus we may take the gradation curve of the sieve analysis and for separate percentages of the whole sample compute the number of particles in each. The mean bulk fineness of the total is the average bulk fineness of the separate portions. The size of the average particle is the diameter of the average sphere whose volume is one cubic foot divided by the number of particles therein or $1/F_{ave.}$, and

$$d' = \left(\frac{1}{F_{ave.}} \times \frac{6}{\pi} \right)^{1/3} \text{ where } d' \text{ is in feet}$$

For purposes of determining d' in the foregoing formulas, the 35 percent of the smallest sizes are eliminated on the assumption that this amount of material is held in suspension during bed load movement and on coming to rest is trapped in the voids of the coarser material and has no part in determining the effective size of the bed load material.

An example follows of the application of the formula for quantity of bed load movement on the Rappahannock River at Fredericksburg, for which data was readily available. The slope of the river during flood stage in 1937 was determined from surveyed highwater marks. The drop in water-surface in 9.1 miles was 46.1 feet in a reach above Fredericksburg not materially affected by obstructions, rapids or backwater from dams, etc. The slope was thus .000963 and the discharge approximately 120,000 c.f.s. From Lacey's formula

$$f^{5/3} = 1788\, S \times Q^{1/6} \qquad (13a)$$

$$f = 4.5$$

From the daily duration curve covering a record of 12,901 days the bed load for each daily flow was taken from Plate No. 1 for f = 4.5. The total bed load movement totalled 2,880,000 cubic yards, or 81,500 cubic yards per year. As a check on this figure the dredging in the channel of Fredericksburg for 32 years from 1909 to 1941 was 2,580,000 cubic yards, or 80,600 cubic yards per year.

It was also determined that the average daily bed load movement was 223 cubic yards per day and from the curves on Plate No. 1 the discharge moving this quantity with f = 4.5 is 1,660 c.f.s. The average annual discharge for the period of record is 1.05 c.f.s. per square mile or with a drainage area at Fredericksburg of 1,600 square miles the average annual flow is 1680 c.f.s.

Similar computations made for the Potomac River at Great Falls indicate a silt factor of 2.6 and an annual bed load movement of 157,000 cubic yards. The average daily bed load movement was 430 cubic yards which would be moved by a discharge of 11,800 c.f.s. The average annual discharge is approximately 11,000 c.f.s. Records indicated that from 1908 to 1943 an annual average of 150,000 cubic yards of dredging has been done in the Virginia Channel at Washington.