RESEARCH NEEDS IN SEDIMENT HYDRAULICS

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SYNOPSIS

Considerable progress has been made in the past decade in the field of sediment hydraulics, particularly concerning the basic mechanics of the phenomena of sediment transport, erosion, and deposition. It is found, however, that there are many areas in which the tools available to the engineer for solution of sediment problems are inadequate. The Bureau of Reclamation in its existing and planned Federal projects is constantly faced with problems involving sediment. These problems include sampling techniques and methods of computing sediment load, design of stable channels in earth materials, channel stability when the natural regime of an existing channel becomes upset, sediment deposits in reservoirs and how they affect storage loss, aggradation above structures and degradation below structures, and exclusion of sediment from diversions into irrigation and powerplant canals. In the solution of these problems all the known knowledge and developments of sediment transport, scour, and deposition are used. However, in almost every phase there is need for research and development, particularly in the applied sense to increase the reliability and range of application of various formulas, and to develop practical procedures that can be applied in the solution of the various problems.

This paper points out some of the problems in which the Bureau of Reclamation in its work has experienced the need for more research in the field of sediment hydraulics.

INTRODUCTION

Because of the wide scope of the subject matter available, it has been necessary to limit the discussion to applying basic research to the solution of certain sediment problems. There are undoubtedly other important sediment problems requiring applied research, but which could not be covered in this paper. Computation and design methods are only touched upon and details on these methods can be obtained from the referenced publications.

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As the title implies, this paper points out areas in which improvement is needed and in which inconsistencies exist in the field of sediment hydraulics. Actually the science of sediment transport, deposition and design, has advanced to a point where it is as accurate as most other hydrologic fields, and perhaps more accurate than some.

TRANSPORT AND DEPOSITION IN CHANNELS

Suspended Sediment

In the determination of the suspended sediment load in streams we have progressed a long way in recent years with the development of more accurate sampling equipment, improved sampling techniques, and more applicable procedures for analyzing the data and computing sediment transport. Incorporated with these improvements is the increased basic knowledge of how sediment moves in channels.(1)* However, there is still room for improvement and simplification in all phases of determining the annual suspended sediment load of a stream. Those who have made actual sediment measurements in the field, especially during high flows, and who have been burdened with case upon case of pint milk bottles filled with sediment samples, are fully aware of the need for technique and equipment improvements.

Measurement

Standard samplers. Suspended sediment samplers currently in use by most Government agencies include the US D-43, US DH-48, US DH-49, and US P-46. The first three are depth-integrating samplers only; the DH-48 is a wading or hand sampler, and the latter is a point-integrating sampler that can be used for depth integration. The US D-49 is a later and revised model of the US D-43. The development of these and other suspended samplers is described in a publication by the Federal Inter-Agency River Basin Committee.(2)

In the determination of the total sediment transport of a stream it is usually necessary to combine measured data with empirical computations, except when it is possible to sample the total load. Part of the reason for this is the physical limitations of the available suspended sediment samplers (Figure 1). The distance between the sampling nozzle and the stream bottom is given for the various samplers as follows:

US P-46	0.49 foot
US D-43	0.43 foot
US D-49	0.33 foot
US DH-48	0.30 foot

*Numbers refer to references at the end of the paper.

The percentage of the total sediment measured, therefore, varies with the stream depth and with the sediment concentration curve. Also illustrated in Figure 1 is the problem that results when sampling in a stream with moving sand dunes. Here it is desirable to stay further away from the bottom than the limit of the sampler permits, to avoid obtaining erroneous suspended sediment concentrations. Using Imhoff cones in the field, the sand concentrations were determined for the Republican River near Wauneta, Nebraska. It was found that for point samples near the bed, obtained with a DH-48 sampler with valve adaptor, concentrations were measured which varied five-fold depending upon the location of the sampler nozzle with respect to the sand dunes.

Photoelectric cell method. Engineers are continuously searching for and devising methods which will do the required sampling and necessary intermediate work in a less costly and speedier manner. Use of the sediment sampling equipment which has become more or less standardized in the United States requires considerable time and manpower in obtaining the samples, analyzing them, and preparing the data in a form that is directly applicable for computing suspended sediment load. As an example, in an intermittent sampling program it is estimated that to sample a stream of 200 to 300 cfs at one station and analyze the sediment samples, assembling the data in a form that is applicable to plotting one point on a sediment rating curve would take about 1-1/2 man-days, counting travel time.

G. Bradeau, Engineer, National Hydraulic Laboratory, Chateau France, described a turbidimeter (3) that by using two photoelectric cells with light sources mounted in an instrument having a tunnel through which the sediment-laden water could pass, readings on an indicator would give the concentration and size analysis of sediment passing through the tunnel. Although the instrument is in the development stage, Mr. Bradeau indicated it could be utilized to determine sediment sizes and concentrations over a wide range. The use of an instrument such as this would cut down very considerably the time and manpower required to obtain and analyze sediment samples. The need for research and improvement is evident here.

The St. Anthony Falls Hydraulic Laboratory in Minneapolis, Minnesota, under the sponsorship of the Federal Inter-Agency River Basin Committee, is continually improving present samplers and working on the development of new ones. Perhaps the samplers have been improved more rapidly than have our sampling techniques.

Equal-transit-rate. Suspended sediment sampling is usually carried out by sampling at a given number of verticals across a stream channel or at centroids of sections giving equal discharge. A recent improvement in sampling technique is the equal-transit-rate (E.T.R.) method which has been developed by the United

States Geological Survey. This method results in a more realistic sampling of the sediment movement since it integrates the product of concentration and velocity. It also results in a reduction in laboratory costs. Briefly, the procedure is to obtain samples at equidistant verticals while lowering and raising the sampler always at the same rate. The rate of raising and lowering the sampler is set by the deepest part of the stream where it is necessary to move the sampler fast enough to get not more than a pint bottle full in the deepest vertical. The samples thus obtained are consolidated for analysis. The E.T.R. procedure may be refined to the point where the water discharge could be determined from the sediment sampling data. The water obtained in the sampling process is actually a measure of discharge if a coefficient for the nozzle can be combined with the speed of raising and lowering the sampler to give an accurate integration of the velocity distribution.

There are, of course, limitations to the applicability of the E.T.R. procedure, and these limitations should also be established. It is impractical to set down a definite sampling procedure that will fit all field conditions but guide-type information is valuable.

Point sampling. It is sometimes desirable or necessary to obtain point samples in measuring suspended sediment. Experience with existing point samplers has indicated that improved models are needed. The mechanical features of the US P-46 (4), for example, make it a somewhat delicate instrument and therefore susceptible to operational troubles when field personnel are not familiar with the operation. Some improvements have been made to the US P-46 sampler recently.

A point sampling adaptor has been used by the Bureau of Reclamation in some instances (Figure 2A). This adaptor can be used on either the US DH-48 hand sampler or the heavier depth-integrating samplers. It fits over the sampling nozzle and has a spring attachment which opens and closes a flap at the entrance to the nozzle by pulling a line. Where the depths are shallow the amount of water entering the exhaust port is so small that it can be neglected. For greater depths a flap or plug valve is used on the exhaust port. Although some small errors are introduced by the initial inrush conditions and the slight interference with the velocity pattern around the nozzle, they are not considered serious enough to effect the quantitative answers significantly. This adaptor has not received any laboratory analysis to determine its effect on accuracy of sampling. It is a field-developed piece of equipment that fulfills the need for a dependable point-sampling device that can be readily adapted to a depth-integrating sampler where for some reason the P-46 sampler cannot be used.

Another type point sampler recently developed by the United States Geological Survey is operated by an air mechanism. In this sampler a small compressed air chamber is attached to the sampler and a valve in the sampler nozzle is actuated by this pressure. The sampler has been developed primarily for wading-type samples and is currently receiving field tests that thus far indicate good results.

Sampling near the bottom of a stream. To obtain sediment samples near the bed in streams having hard bottoms, a special sampler has been developed. This sampler was made by the Bureau of Reclamation to obtain samples near the bottom in a constricted section on Fivemile Creek, Wyoming. It consists of a plastic tube 1-3/4 inches inside diameter and 12 inches long with a flap gate fitted on each end as shown in Figure 2B. The standard sampler DH-48 would not allow a sample to be taken close enough to the bed and the nozzles were too small for the largest sediment.

Computation of suspended load. The length of sediment sampling records on most streams in the United States rarely exceeds a few years. It is necessary in many cases to determine the probable long-time sediment transport of a stream using the available small amount of data. Suspended sediment loads for stations sampled by the United States Geological Survey are published in Quality of Water Supply Papers by River Basins.

Practically all reclamation projects require space to be allocated for sediment storage in proposed reservoirs. Reservoirs now constructed by the Bureau of Reclamation usually have space for 100 years of sediment accumulation before any of the water storage allocations are encroached upon. In providing such space, consideration is given to the cost of the additional investment over the period of years before the additional space is needed. Of course, many reservoirs on streams with relatively low sediment loads will have no appreciable storage loss for many hundreds of years.

Several methods are currently in use by various engineers and agencies to predict the long-time sediment flow of a stream. The Bureau of Reclamation uses the flow-duration, sediment-rating curve method.(5) This procedure, as well as most others, is affected by many factors such as the amount of sampling data available to define a sediment-rating curve, the seasonal variation of the data, and the flow-duration curve for the years of sampling which may be wet or dry years. An example of this method, including seasonal variation, is shown in Figures 3 to 5 for the San Juan River at Bluff, Utah.

Generally speaking, most of the sediment transported by a stream, in any given period, is carried by discharges that exceed the median, see Figure 5. Sampling programs could perhaps be modified to reduce the number of samples obtained during low flows and increase the number obtained during higher flows. Sediment studies consistently indicate that there is a narrow range of discharges in any stream which, if sampled, would give a measure of the average sediment load carried by that stream. These factors all point to the possibility of using selective sampling in arriving at the average sediment load. Examination and analysis of flow-duration and sediment-rating curves would lead to a definition of the range in discharges that, if sampled, would give the average annual sediment load for various stream types.

Pump sampling. Often the sediment concentration in a particular stream or channel is so small it cannot be accurately determined with the ordinary suspended sediment samplers because it is not possible to integrate the flow over a sufficient period of time. In most cases this low sediment concentration would not be important, but there are times when its determination both in quantity and size is important. An example is the diversion of water into a powerplant. One method of sampling this type of flow is to use a water pump connected to a pipe so arranged as to sample the flows and discharge into a container of known volume such as a 50-gallon oil drum. The velocity of the water at the intake is adjusted to stream velocity by means of a valve. In this way the flow can be sampled over a long period of time, the necessary information obtained to determine concentration, and sufficient material obtained to analyze for size and quantity. This procedure, however, is cumbersome, and a simpler procedure is desirable. Undoubtedly others have been and will be confronted with this sampling problem.

Size analysis of suspended sediments. One of the greatest costs in a sediment sampling program is the size analysis. Therefore, any sampling procedure that will result in fewer samples for laboratory analysis without decreasing data accuracy or increasing field costs would be desirable. Present procedures require from three to seven verticals with two samples at each vertical to arrive at one river station sediment concentration and size analysis. If a single sample could be obtained for a given station in a stream at a certain discharge that would give a representative answer, only one concentration and size distribution analysis would be necessary. The E.T.R. sampling procedure mentioned previously accomplishes this to some degree.

Reduction in size analysis costs could also be accomplished by improved laboratory techniques. The visual accumulation tube (6) method of size analysis for sands which is becoming more and more widely used in this country is one result of searching for faster and less costly methods.

Accuracy of determining the size distribution in a given sample is of prime importance since this size distribution reflects directly into the methods of determining sediment load. Sediment transport determination by such procedures as those advocated by Einstein (7) and Schroeder and Raitt (8) depends upon the size distribution. The above points are covered in more detail elsewhere but are mentioned here to illustrate the need for accurate size analysis determinations.

Most sediment sampling programs are necessarily restrictive because of high sample analysis costs. A single size analysis costs approximately $15, and a single concentration analysis costs $2. Any method that can be developed to reduce size analysis costs would be advantageous.

Unit yield method of determining sediment transport. From the sediment sampling that has been carried out in various sections of the country and from data obtained from the resurvey of existing reservoirs, the unit yield or sediment runoff per square mile of drainage area, with time, is available for many streams and in many locations. When it is necessary to make a reconnaissance-type estimate of the sediment transport at a particular location on which no data are available, the unit yield from a similar type of drainage basin is often used. It would therefore be helpful to all agencies involved in making sediment estimates if all available data on sediment yields by type of drainage basin were readily available. The Federal Inter-Agency River Basin Committee has accomplished much along this line by its recent publications "Bibliography on Reservoir Resurveys"(9) and "An Inventory on Published and Unpublished Sediment Load Data."(10) It is expected these reports will be kept up-to-date. Most agencies have carried out sediment studies for many streams by analyzing sampling records, and availability of these data would be helpful. Although some disagreement is inevitable in certain instances, a compilation of unit yield data from these studies would be helpful to all agencies and would reduce duplication of effort. In some drainage basins a large percentage of the total sediment is contributed by a few tributaries that produce only a small portion of the basin water runoff. To obtain an overall picture of the sediment and water yield distribution for the same drainage areas, a basin balance is prepared which shows water and sediment for the various sub-basins as a percentage of the total basin runoff (Figure 6).

BEDLOAD

Involved in the determination of unmeasured or bedload is the definition of channel hydraulics and bed material size distribution. In certain streams the unmeasured load is insignificant; in others it embraces a large percentage of the total sediment in transport. For example, on the Middle Loup River at

Dunning, Nebraska, more than 50 percent of the total load is unmeasured whereas on the Milk River near Nashua, Montana, the unmeasured load is estimated at 5 to 10 percent of the total transport.

Sampling bed material. An important part of the field data needed in determining the bed material transport and total transport of a particular stream is the bed material size distribution. The importance of obtaining representative samples of this type cannot be underestimated since most formulas for computing bed sediment transport require a determination of bed material size distribution. An error in the mean sediment size can result in an erroneous answer on the unmeasured load. For example, in the Schoklitsch bedload formula (11) a change in mean bed size (50 percent finer) from 1.1 mm to 0.8 mm results in a 100 percent increase in the bedload transport, all other factors remaining the same.

There are many types of equipment available for obtaining underwater bed material samples in normal alluvial stream channels. However, there are certain phases of the procedure that are not yet adequately defined, for example:

a. How many samples are necessary to define the mean?

b. Is there a change in the mean bed size with discharge?

c. How is a representative sample obtained in a cobble-bedded stream?

d. How are representative samples obtained under deep flowing water?

e. How deep should a sample be taken to give particle size information applicable to the various bedload formulas.

Typical bed material size analysis curves for the Middle Rio Grande River at Section F in the Bernalillo Study reach are shown in Figure 7. Considerable variation in size across the river bed at this section can be noted. The studies being carried out by the Bureau of Reclamation in cooperation with the United States Geological Survey utilizing the data obtained in this study reach include the application of the Einstein bedload function and the Modified Einstein Procedure to an alluvial-type stream having a large change in the stage-discharge relationship.

The problem of obtaining a representative sample from the bed of a channel containing a preponderance of cobbles or gravel has become more prominent in recent years in this country as additional developments are planned and constructed in mountainous areas. The particular nature of some projects, such as diversions into powerplants, makes it necessary to remove the material in transport. Various methods are employed at present such as obtaining several sacks of material by use of a shovel, at low flow stream bank water surface level, or perhaps by a pickup method such as described by Wolman.(12)

Bedload samplers. Bedload problems have not been as numerous in the United States as those of suspended load because most of the important rivers have beds composed of fine material and therefore carry much more sediment in suspension than along the bed. Because of this, the development and use of bedload samplers in this country have not kept up with that of suspended sediment samplers. In the 1940 Report No. 2 "Equipment Used for Sampling Bed Load and Bed Material,"(13) various bedload samplers are described. Except for a few experimental cases the samplers discussed were developed in foreign countries and used there.

It is believed that a bedload sampler for sand bed material could be developed which would give a better indication of actual bed movement than is indicated by use of bedload formulas.

One of the difficulties in developing an adequate bedload sampler has been preventing scour around the apparatus and having the sampler conform to the sand waves of the stream bed. Possibly using one of the new tough pliable plastics for a bottom would work. For sands a comparatively small opening upstream with a Venturi-type pressure reducer to extract the water and leave the sediment in a reservoir of the sampler may work effectively. The Venturi principle is used on some suspended load samplers to obtain the proper intake velocity. This same principle could be used on bedload samplers to obtain the proper intake velocity. Any bedload sampler could be used if calibrated for conditions similar to those in which it will be used. Obtaining a few bedload samples would give greater confidence in using bedload formulas that give comparable answers.

In streams where the bed material is very coarse, the question frequently arises: At what flow does the coarse material begin to move? Georges Labaye (14) describes the use of a hydrophonic detector in which the beginning of transport of coarse material was indicated by sound against an immersed plate and amplified by a microphone pickup. For wide streams this method could be used to determine the fraction of the total width over which the bedload was moving.

Computing bedload. In computing the sediment loads of streams for planning reservoirs, an estimate based on empirical formulas is usually made for the unmeasured load. Most bedload formulas are based on drag flume experiments, and when applied to river problems may not give accurate results. Different formulas give widely different bedloads for the same stream, as shown in Figure 8. This is probably due to the fact that each formula works well for the conditions under which it was developed, but these conditions were different for different formulas, and when applied to river problems they give widely varied answers. Each of the various formulas that have been developed requires essentially the same basic data; channel cross section, water temperature, water discharge, energy gradient, and size distribution of bed material. Some of these factors can be defined fairly accurately by field measurement, while others are not so easily obtained. Some recent procedures for determining the bed material load have been developed that do narrow down the deviation in answers obtained.(7)(15)(16)

It should be the ultimate goal to produce sediment records that evaluate the total transport of sediment and its size distribution for a particular river and section. Most suspended sampling is currently being carried out by the United States Geological Survey, often at their regular stream gaging stations, and records are published in Water Supply Papers. If the total sediment load was published or some ratio or percentage of measured to unmeasured load, it would be much more valuable to those concerned with using sediment records. The suspended sediment records are only a partial measure of the total transport.

Since there does seem to be a definite relationship between suspended sediment load and bedload for varying stream types, it might be possible to improve or elaborate on relationships such as developed by Lane and Borland (17) by evaluating existing data from streams in this country and throughout the world. This method of arriving at bedload transport is considered good only for reconnaissance-type estimates. It can, however, point out the relative magnitude of the unmeasured load and help determine the need for any further more detailed investigation.

CHANNEL STABILITY

Cohesive materials and apparent cohesive materials. The reclamation engineer is continually faced with the problem of choosing proper design criteria in designing canals in earth materials. The problem is to select the smallest cross section for economy but which is large enough to carry the design discharge on a slope that will not cause the earth material to scour. A method for design of canals in noncohesive materials (18) has been developed in the Hydraulic Laboratory of the Bureau of Reclamation. It is based on the critical tractive force principle, i.e., a given size of sediment on a stream bed requires a certain tractive force τ_c = (wds) to move it. The use of this principle to design the shape of the canal (19) in conjunction with the slope is not difficult for noncohesive materials. However, for clays and other plastic soils where cohesion is a predominant force (greater than resistance due to weight of individual particles) this process cannot be used directly because the resistance to erosion due to cohesive forces has not been determined. There is possibly a soil mechanics test or group of tests that can be correlated with resistance to scour or critical tractive force. The plasticity index, which is the difference in percent of moisture between plastic limit and liquid limit in Atterberg soils tests,(20) has been suggested as a soil characteristic that can be used to indicate resistance to scour. For canal design it has been mentioned that a plasticity index (P.I.) of 7 is the critical value, with scour occurring for moderate tractive forces below this value. Cases frequently occur where the P.I. is above 7, but we still get scour. Some fine silty type soils such as volcanic ash and glacial flour may have an apparent cohesion and even show a P.I. higher than 7. However, if observed under water, their soil structure breaks down readily when subjected to a hydraulic tractive force.

This emphasizes the need for laboratory tests and field data correlating soils characteristics with critical tractive force and resistance to shear. Plasticity index in combination with consolidated shear tests may be characteristics that can be used.

Vegetation. In many waste channels and some canals it is desirable to increase the stability of the soil by planting or encouraging growth of vegetation. For slow velocities, grass causes considerable resistance to flow, but for high velocities, where grass is forced to lie down, the resistance to flow may even be decreased. Certainly on ephemeral drains grass would be desirable, but if a complete grass cover cannot be assured over the full length of the wasteway, scour will result from high velocities in the denuded areas.(21) It may be desirable to allow enough water to escape into a drain to assure a vegetative growth. Research in the field of channel stability should include an evaluation of the influence of vegetation on the resistance to erosive forces.

Channels carrying suspended sediment. There is a definite effect on channel stability where suspended sediment is carried in the stream, but just to what degree has not been determined on a scientific basis. Fortier and Scobey (22) observed the stability of several canals some of which carried clear water and others carried suspended sediment. Their table shows allowable or critical velocities for both conditions. Lane (18) plotted allowable tractive forces for clear water, water with low content of fine sediment, and for water with high content of fine sediment. The data of these researchers indicate a higher allowable tractive force for water-carrying suspended sediment. Fortier and Scobey say, for water-carrying colloids, there should be a relationship relating characteristics of bed sediment, suspended sediment, and hydraulic characteristics of the stream that will show just how the allowable tractive force can be raised for a given concentration of suspended sediment. The concentration of suspended sediment very likely affects the stability of cohesive soils as well as bedload movement and formation of dunes in noncohesive soils.

Ephemeral and perennial streams. The degree of stability of stream channels, such as proposed project drains, is dependent to a large extent on whether the channel is or will be ephemeral or perennial. For the purpose of this paper, an ephemeral stream is one in which the flow is discontinuous and is directly related to storm runoff in rivers and to irrigation return flow in drains and occurs for short periods of time, seldom exceeding a few days. A perennial stream is one in which the flow is continuous for long periods of time each year, even though the stream may become dry at the end of the runoff season. It is known that an ephemeral channel can withstand higher tractive forces than a perennial channel. Since in ephemeral channels vegetation can develop and damaging high flows are of short duration, the bed and the banks do not become saturated and therefore do not deteriorate under the same tractive forces as a perennial channel. Vegetation, in most cases, cannot develop under constantly flowing water conditions, and this is one reason why perennial streams are not as resistant to forces of flowing water as ephemeral streams. It is necessary in the design of a surface drain to determine the probable nature of the flow and then design the channel so that the occurring tractive forces will not produce excessive channel deterioration.

The most striking examples of the effect of the flow duration pattern on channel stability are those in which flows introduced into a channel are different from the flow duration pattern for which the channel was developed and became stable. The new flow in a channel that has alluvial-type materials will cause rapid deterioration as the channel attempts to adjust to the new conditions--often resulting in expensive damage and costly repair.(23)

Research is therefore needed to define adequately the limiting tractive forces for various types of channel conditions. This research can be a combination of laboratory and field data. There are numerous channels on irrigation projects in this country where field data can be obtained for a wide variety of conditions. Some work has been done along this line, and additional studies are currently underway by the Bureau of Reclamation and others.

Stabilizing methods. The need for research in the field of channel stability is not only one of determining what flow characteristics and sediment load result in a stable channel but also what method of control should be applied in stabilizing channels already deteriorating and in maintaining the channel shape determined by some applicable method. Assuming that the channel shape has been adequately defined, the type of control installations to hold this shape must be selected. Many types of channel control are used. These include jacks (wooden, concrete, and steel), groins (brush or rock-filled), riprap, check dams, pervious fencing, and vegetation. The engineer must determine the applicable type of protection that will result in the most economical design, minimum initial expenditure, and low future maintenance cost. It has been found that a single row of jacks is most effective for flows in which they are almost completely inundated and on streams that carry considerable debris and fine sediment. Wooden jacks or a more permanent type can be used. If wooden jacks are used it must be assumed that their life is only between 5 and 10 years. If they deteriorate, the question arises as to whether planted and/or natural vegetation will hold the shape created by the jacks. Usually vegetation is employed in conjunction with jack installations so the job of holding the channel will fall upon the vegetation that has developed. This being the case, it is necessary to evaluate the ability of the vegetation to resist erosion and the conditions under which it can no longer withstand the erosive forces.

Groins are found to be most effective in protecting banks at lower flows or flows at which they are not inundated. The correct spacing and the angle to the flow are all-important. Often groins and jacks are used in combination. If rock riprap is used the required thickness, the points in the channel layout where it is needed, and the quality of rock required must be established.

Riprap below structures. A special case of stable channel design is that of channels below hydraulic structures where turbulence and nonuniform velocity distribution occur. To take care of the extra forces which are created by drops, chutes, canal headworks, sluiceways, and other similar structures, stilling basins supplemented by riprap on earth slopes are provided. Choosing size and thickness of riprap and length of canal on which the riprap should be placed has been a matter of judgment and experience. Comparing scour patterns in coarse sand for model studies below spillways, stilling basins, canal drops, etc., has been used extensively to establish uniform distribution of erosive forces.

Canal beach slope. On practically all earth canals built of gravelly material that are operated at a constant depth a beach slope can be noticed at the water surface which is flatter than the side slope. At the water surface, the canal banks are subjected to waves caused by wind and other disturbances, and these waves exert forces which cause the earth material to wash down and take a flatter slope than the constructed side slope. On earth canals that are constructed with side slopes of 1-1/2 to 2:1, it is not uncommon to observe beaching slopes at the water surface of 5 or 6 to 1.

In conducting some wave studies in the Hydraulic Laboratory (24) to determine the required cover blanket to prevent fine base material from leaching due to wave action on Kennewick Main Canal, Yakima Project, Washington, several tests were made on the pit-run gravel shipped from the canal site. Figure 9 shows a beaching slope of 5.14 to 1 on the gravel material which had been subjected to 42 waves per minute with a wave height of 0.43-foot trough to crest for a period of 19 hours.

Canal design which could include a flatter slope in the water surface area would approach more closely the natural tendencies in canals constructed in gravelly materials. Because of this tendency to take a beach slope near the water surface, a design which included a flatter side slope near the water surface would be approaching more closely the natural tendency of the canal.

Gravel blanket over fine-grained noncohesive material. Many canals are built in areas where the earth material is fine-grained and noncohesive. The material is usually of rather uniform size which means once erosion begins it does not stop from the effect of larger particles being exposed. The canal is usually stabilized by artificial means. The use of a gravel blanket has proved quite satisfactory in this case. Especially where seepage is not a problem, the gravel blanket is very useful in providing resistance to higher critical tractive forces, resistance to freezing and thawing forces, and the cost is low compared to concrete and asphalt concrete.

A typical example of a canal under construction in fine-grained material is that of Kennewick Main Canal referred to under canal beach slope above. The base material has a median grain size of 0.05 mm with 20 percent coarser than 0.12 mm and 5 percent finer than 0.005 mm. This base material has an apparent cohesion when compacted at the best moisture content, but when placed under water, the cohesion readily breaks down. Hydraulic Laboratory Report No. Hyd-381 (24) describes wave studies made on the base material, a pit-run gravel, and an angular talus material to determine the best method of placing a protective blanket to give most resistance to leaching of the base material. The model studies showed that the angular talus material which had been separated on a 3/4-inch screen with the coarse fraction placed over the fine fraction gave the best protection to the base material.

The problem that is very important is how thick a gravel blanket to use and what restrictions must be made for the preparation and placing of the gravel blanket. For practical and economical reasons, a pit-run gravel offers the best solution, but from an operation and maintenance standpoint the pit-run gravel available may have a large preponderance of fines which will wash out, causing the coarser particles to settle or roll down the slope. The result may be a cover so thin it would not be adequate to give protection, and also, the canal prism may have a tendency to be filled up. The ideal gravel blanket is material that is placed so there are large enough particles on the surface to prevent movement from tractive forces and surface waves with enough sand between the coarse gravel and original bank material to prevent leaching of the bank material.

Methods of design of stable channels. The research needs in the design of stable canal sections in earth materials may be stated in this question, "What are the limiting tractive forces that can be successfully resisted by the material of which the canal perimeter is constructed, and what other factors may be present in the future to cause this critical tractive force to be higher or lower?" The other factors may include vegetative growth on the canal bed and banks, canal structures such as drops, chutes, bridges, and checks, and the number and degree of bends. These factors would tend to increase or decrease the forces of resistance to the forces which cause scour.

Designing a channel that will be stable in an alluvial-type material, or stabilizing a channel that is already in a state of deterioration, poses many problems. There are several methods of approach that can be utilized, but the selection and application of any method is dependent upon the engineer's judgment and the existing conditions. The procedures advocated by various engineers can serve only as guides and none of them are completely applicable to every situation. P. W. Terrell and W. M. Borland (25) have presented some of the requirements and Bureau experience in the design of earth canals and other channels. Some of the more familiar publications on stable channel design are those by Lane (18), Lacey (26), Blench (27), and Maddock and Leopold.(28)

The Lacey and Blench equations for stable channel design are developed from conditions in canals and channels in India where conditions of flow, bed and bank materials, and channel hydraulics differ from those encountered in the western United States. Their equations also require considerable judgment or basic assumptions on the part of the designing engineer. This may be difficult where insufficient data or knowledge of the particular channel are available to influence adequately the engineers' judgment or assumptions within a reasonable degree of accuracy. Lane's design criteria consider the tractive forces acting on the periphery of a canal. The Maddock-Leopold relationships require knowledge of certain factors such as sediment transport and settling velocity of the sediments in transport that may not be available or are difficult to determine. These relationships are based on analysis of many streams in the western United States and are overall concepts that may not always be applicable to a particular reach of a given stream. The Maddock-Leopold equation currently in use by the Bureau of Reclamation is as follows:

$$\frac{W}{d} = \left[\frac{\frac{S^{1/2}}{n}}{0.225(C_s V_s)^{0.395}}\right]^3 Q^{0.555}$$

where

Q = discharge in cfs
V_s = weighted mean settling velocity for total sediment load
S = stream gradient
C_s = total load sediment concentration
n = Manning roughness coefficient
W = channel width
d = channel mean depth

In this equation the sediment concentration is required and is therefore unsatisfactory for clear water conditions such as may occur below a dam or where the sediment load is eliminated by channel rectification.

Research is currently being carried out by the Bureau of Reclamation using data obtained in the field from existing canals, drains, and other natural and artificial channels, to evaluate more clearly the requirements for stability. Of particular concern are the requirements for stability in materials within the coarse silt and fine sand bracket where there is a transition from cohesive to noncohesive conditions.

In the design of a stable channel, one of the first factors that must be determined is the so-called "dominant discharge." This might be defined as that discharge of a natural channel which determines the characteristics and principal dimensions of the channel or is most influential in dictating the general condition of stability. In some cases it is easily determined, whereas in others it is not. Many rules have been presented to arrive at this discharge, none of which necessarily give the same answer. We find that the dominant discharge varies with the sediment characteristics, with the relationship between maximum and mean discharge, with the shape of the flow duration curve, and with the flood frequency. The establishment of the dominant discharge is still one of the most difficult problems in channel design work.

Another factor that is not always easily evaluated is the size distribution of the bed materials under design conditions. Will it be the same as for the channel before rectification, or will it have an entirely different size distribution curve?

Still another factor that enters into the design is the probable sediment transport under stabilized conditions. For example, when the sediment in transport is being derived from the bed and banks what will be the transport conditions and the channel requirements for such transport after rectification reduces or eliminates the source of sediment as compared with the design based on existing conditions of sediment transport?

The above discussion points out only some of the elusive factors in channel design work. Engineers working on channel design problems do the best they can with the tools available and attain a surprising degree of success considering the inadequacy of these tools, but the need for more exacting methods of design is evident.

DEPOSITION BEHIND STRUCTURES

Distribution of sediment in reservoirs. One of the more common problems with which the sedimentologist is faced is the prediction of how the sediment will be deposited within a proposed reservoir. This prediction is necessary to aid the designers in the location and type of outlet works and to determine the probable loss of storage capacity within the various storage allocations over a given period of time. Most of the present procedures used to predict sediment distribution are based on information obtained from resurvey of other reservoirs. The old assumption that all the sediment will deposit in the bottom of the reservoir has been refuted.

The sediment distribution in reservoirs is primarily dependent upon the following:

a. Type of reservoir operation
b. Reservoir configuration
c. Size distribution of the inflowing sediments
d. Flood detention period

There are, of course, other factors that influence the distribution to varying degrees such as the trap efficiency, narrow necks within the reservoir area, vegetative growth in the delta area, heavy sediment contributing tributaries within the reservoir area, and density currents.

The publications available on sediment distribution do not completely evaluate the above-listed major items that influence distribution. Herein lies the need for research that can result in better procedures for predicting how the sediment will be deposited. A publication by the Bureau of Reclamation which is in the form of a progress report (29) has attempted to evaluate some of the influencing factors. Evaluation of other factors is still dependent to a large degree upon the engineers' judgment. Work is being continued to improve the procedures presented in these reports. Of course, the prediction of sediment distribution is not an important item in all reservoirs. In those where it is important, but not a major concern, rapid methods of approximating the distribution can be utilized.

We believe that there is sufficient data available on numerous existing reservoirs to correlate the influencing factors and arrive at more accurate methods of predicting sediment distribution. Assembling and evaluating these data would be a noteworthy contribution to the field of sediment hydraulics.

Deposition above spillway level. In computing a backwater curve above an obstruction in a river channel, one must assume a discharge, river cross sections, and value of channel resistance which can be used in conjunction with some stream flow formula. If the stream is a heavy sediment carrier the backwater curve will change with time as sediment deposition takes place. The rate of sediment deposition is dependent on the reduction in velocity. Locally this can be caused by a wide variety of obstructions that occur or are built into the stream channel, see Figure 10.

Density currents. Much literature has been devoted to the subject of density currents as indicated in the Bibliography of the Bureau of Reclamation Hydraulic Laboratory Report No. Hyd-373.(30) Experience has shown, in the United States, that very little sediment has passed through reservoirs as density currents, particularly as the reservoir becomes older. The reason for this seems to be the fact that the surface width of the sediment deposit becomes wider and wider as more sediment deposits in the reservoir. The turbidity current decreases its velocity and less sediment reaches the dam. Also, in cases where density currents do occur it may not be possible to release water to take advantage of the density currents.

Effect on intakes at diversions. Sediment deposition behind diversion structures on alluvial streams occurs rapidly as soon as the diversion dam is built. In at least two cases on the Republican River--Superior-Courtland and Cambridge Diversion Dams--the first floods occurring after the dams were completed practically filled their pools with sediment. It is common practice in the Bureau of Reclamation to include a gated sluiceway providing a low-level opening through the dam near the canal intake. One of the vital purposes of this sluiceway is to maintain an open channel leading to the canal headworks during the recession of a flood. Instructions are issued to operators in the field suggesting the sluice gates be opened during a receding flood in order to insure an open channel to the headworks. For low diversion dams, sediment deposited during a flood could very easily block off a canal headworks, causing the normal river flow to go over the spillway which may be a few feet higher than the headworks crest. After ~~dimensions~~ diversions are constructed the best operation criteria are developed by testing and utilizing the operation criteria supplied by the designers.

Where the dam is of low-head type and the sluiceway crest is only a few feet below the headworks crest the sediment concentration in the sluiceway and headworks is practically the same for continuous sluicing. Model studies on the Bartley Diversion Dam (31) showed intermittent sluicing increased the total sediment load through the sluiceway many times over that for continuous sluicing.

Channelization through depositional areas. One of the most perplexing problems that is associated with sediment deposition behind structures, particularly in the western United States, is delta development. The channel in the backwater area of a reservoir becomes plugged with a combination of sediment deposits and vegetation which is generally in the form of water-loving plants such as phreatophytes and tules. This in turn causes troubles upstream, especially during flood stages, such as interference with upstream structures and diversions, clogging of drain and sewer outlets, water loss to the water-loving plants by transpiration, and increased evaporation losses. The problem has become so acute in some delta areas that it has become necessary to take steps to relieve the situation. Typical examples are the Pecos River above Macmillan Reservoir and at various locations on the Colorado River. So far no completely effective method has been devised to annihilate the water-loving vegetation and there is no practical way to prevent the development of deltas.

The problem then is to convey the water and the sediment through the delta area without sediment deposition and with a minimum loss of precious water. The procedure generally followed to accomplish this is to construct a designed channel and then maintain that channel so that it will accomplish the job for which it was created. The methods used in the design of a channel such as this have been discussed elsewhere in this paper. In the Middle Rio Grande Valley the Bureau of Reclamation has utilized a separate conveyance channel and floodway and on the Colorado River a combined floodway and conveyance channel.(32)(33) These channelization works have not been observed under flood flow conditions as yet but the ability of a river channelization to withstand flood flow forces is the ultimate test of their adequacy. The need for adequate tools with which to approach these delta problems is evident. How can we effectively eliminate the phreatophyte and tule growth which is taking such a large toll in water in an area of the country where all the water is needed for beneficial use? How can we create a channel through the delta that will prevent the adverse developments upstream and at the same time be economically and engineeringly sound? Much progress has been made in finding the solution to these problems in recent years but considerable research and development remain to be undertaken.

CHANNEL DEGRADATION

Release of clear water from a dam or introduction of irrigation return flows to a channel usually result in a degradation cycle if the channel consists of unconsolidated materials. Degradation below Davis Dam is shown on Figure 10. It is necessary for the engineer to predict when and to what degree this degradation, with accompanying water surface lowering, will occur and how it affects the tail water curve for a dam site and installations downstream.(34) No clear cut procedures are available at the present time on which to base such a prediction although many cases have occurred in which there has been degradation below hydraulic structures. The amount of degradation is dependent upon several factors which include the variation in size of bed material with depth, channel hydraulics, flow duration pattern, and the existence of downstream controls. Degradation may be limited in some cases only by the amount of storage behind a structure or the limiting slope for transport of the materials in the channel. In other cases it may be limited by the creation of bed armor. All present methods of computing degradation are affected by the empirical procedures for determining transport and limiting size of transportable materials.

Of particular concern in the western United States is the effect of irrigation wastes and return flows on a natural channel which is being used as a project wasteway or drain. This usually creates a different flow duration pattern than the one on which the channel was developed and a greatly increased "dominant discharge". Many such channels are changed from ephemeral to perennial (23) by injecting return flow from project wasteways or drains.

Research that will result in more reliable methods of sampling bed material, computing bed material transport, and determining limiting tractive forces will reflect directly into the accuracy in predicting degradation. More research is also needed to develop procedures for computing the channel degradation. Perhaps a correlation of records of actual degradation with empirical computations for determining bed material transport could be accomplished to devise procedures for predicting degradation below structures.

SEDIMENT CONTROL

In the development of Bureau of Reclamation projects, sediment studies based on sediment and water measurements are made to give the best estimate of sediment quantities involved. Then with the aid of model studies, the designer includes a sediment control device in his design. For the coarser bed sediments these sediment control devices have included curved guide walls, vortex tubes, and short tunnels.(35) For finer sediments a settling basin type of control is usually used in conjunction with mechanical or hydraulic sediment removal equipment. Two factors that influence the decision as to the type and extent of sediment control facilities included in the design of a diversion are: (1) the size and amount of sediment needing control and (2) the cost of sediment control versus benefits derived.

A typical study is that of Milburn Diversion Dam on the Middle Loup River in Nebraska.(36) A sediment study showed the diverted sediment load could be as much as 600 acre feet per year without sediment control. A hydraulic model study developed a short tunnel type of sediment control device, based upon which the designers recommended a diversion including a short tunnel and a settling basin for desired sediment removal. The short tunnel is very effective because it divides the water on a horizontal plane, allowing the water with only light suspended load to enter the canal, while the bedload and lower part of the suspended load pass through the short tunnel to the river channel downstream.

In those cases where excess sediment is carried into canals, various devices have been used to remove the coarse bed sediments. In the countries of India and Pakistan these are called excluders. Ralph L. Parshall (37) developed the vortex tube for removing sand from canals. His studies and later studies by Koonsman (38) indicated that to get good action in the vortex tube, a velocity near critical velocity $V = \sqrt{gd}$ was required. To overcome this difficulty of requiring such a high average stream velocity to get good action, an activator to work in conjunction with the vortex tube was developed in the Hydraulic Laboratory of the Bureau of Reclamation as a part of the model studies for Republic Diversion Dam. This activating vane is placed directly over the vortex tube with tapered upstream and downstream portions so that the velocity is increased as it approaches the vortex tube. The necessary drag force is thereby created on the channel bottom to create good vortex action in the tube keeping the bed material in suspension so it can be drawn off. Where the drag forces are insufficient, the vortex tube will fill with bed material and the tube will become ineffective as an excluding device. A typical design for a vortex tube with activator is shown on Figure 11. Many other types of sediment control devices on canals have been tried in this country and particularly in India and Pakistan. The success to which these work varies a great deal and depends upon the hydraulic characteristics of each case. The philosophy in this country has been to remove as much of the unwanted sediment load with the least amount of water loss. Research along this line of thinking is needed to improve the design and operation of our diversions and canal systems.

SUMMARY

In the foregoing discussion some of the sediment problems encountered by Bureau of Reclamation engineers in the planning, design, and maintenance of irrigation projects have been pointed out and some of the methods of solution have been indicated. The need for research in sediment hydraulics to improve and simplify present methods of acquiring basic data, computation, and design is apparent. There is a wealth of existing data available in the United States and abroad that could be combined with additional field and laboratory research to advance the science of sedimentology.

In some sections of the world, where irrigation developments are centuries old, sediment hydraulics has been and still is one of the major engineering problems. This points up the need for recognizing these problems early and developing corrective measures to reduce sediment problems before they become enormous.

The following is a summary of the phases of sediment hydraulics discussed herein where research is needed:

Sediment sampling--Improvement and simplification of present sampling equipment, procedures, and techniques will reduce the cost of a sediment sampling program and at the same time produce more representative data. Work is continually being done by such organizations as the Federal Inter-Agency River Basin Committee to improve sampling equipment. This work should be continued.

Bed material transport computations--The need for accurate and versatile methods of deriving unmeasured sediment transport is ever present. New formulas can be developed and present formulas improved so that they can be used with confidence within defined limitations. In developing any sediment transport formula, the point must be kept in mind that its usefulness depends upon the accuracy of the answers given when computing transport of natural streams.

Transport in nonalluvial streams--Existing bedload formulas are developed for alluvial-type channels with bed material of sand and fine gravel sizes. There are no such formulas for determining the transport in mountainous-type streams that are not strictly alluvial and have bed material ranging from sands to large boulders. Can a method of computation be developed to fit this case or should efforts be directed toward actual bedload sampling? If a bedload formula can be developed, how should a representative sample of the bed material existing under various river stages be obtained?

Total sediment transport--Because of the mechanical limitations of our present day sampling equipment and the early day developments of formulas to compute transport, we tend to think of sediment transport as segments rather than the overall total load. Total load and its size distribution is what must be determined in sediment studies. Inclusion of total sediment load figures in the published records would be a notable improvement and would be of much greater value to the sedimentologist.

Stable canals and channels--The need to define the influencing variables that create a stable condition in a canal or channel is one of the most urgent needs in the field of sediment hydraulics. Various formulas have been developed for computing stability but application of these formulas to a variety of field problems has indicated that further research is needed. Research along this line is being carried out by some organizations and agencies both in the field and in the laboratory.

Design for stability--The definition of the correct combination of variables that result in canal or channel stability will culminate in reliable methods for designing for stability. Although current design formulas and procedures appear to conflict or are based on a somewhat different approach it is hoped that continued investigations and research will reduce these differences and result in procedures that can be combined with definable field data to give more accurate solutions. The criteria for the type of channel control to use under different conditions and the limitations of these control works should also be improved and be more firmly established.

Aggradation and degradation--Very little progress has been made in developing methods for predicting channel aggradation and degradation. It is believed that a combination or correlation of records on actual happenings with sediment transport theories could provide some procedures for predicting aggradation and degradation. These procedures will, of course, still be limited in accuracy by the adequacy of the bedload formulas.

Deposition in reservoirs--Methods of predicting the distribution of the sediment that is to be deposited in a reservoir are still in need of improvement. A vast amount of data are available on existing reservoirs that could be sorted out and combined, perhaps by multiple correlation, to derive procedures or formulas for predicting how the sediment will deposit behind a structure.

Diversion structure design--The design of a diversion structure on a stream carrying unwanted sediments usually includes a sediment control device. The method employed to exclude the sediments can best be determined by a laboratory model study. Model study results, combined with the results of the prototype operation, will yield even better designs in the future.

Stabilizing canals below structures--The use of riprap below structures in canals is a common design practice to prevent or repair cases of erosion. The size and amount of riprap used are usually chosen on the basis of experience. Research which would assist in this field is needed.

Sediment exclusion from canals--Reducing the cost of cleaning canals is a goal towards which operating engineers on all irrigation projects are continually striving. Hydraulic sediment excluding devices are in use in some locations but for the most part canals are usually cleaned with mechanical equipment. Development of less costly means of keeping undesirable sediment out of canals would be very welcome research.

Design of canals in cohesive soils--The design of stable canals in earth materials to prevent scour necessitates the balancing of the scouring forces with the resistive forces. For noncohesive materials considerable information is available. There is a definite need to determine a correlation between some soils tests for cohesive materials with their resistance to scour by flowing water which can be used as a guide for designing canals in cohesive materials.

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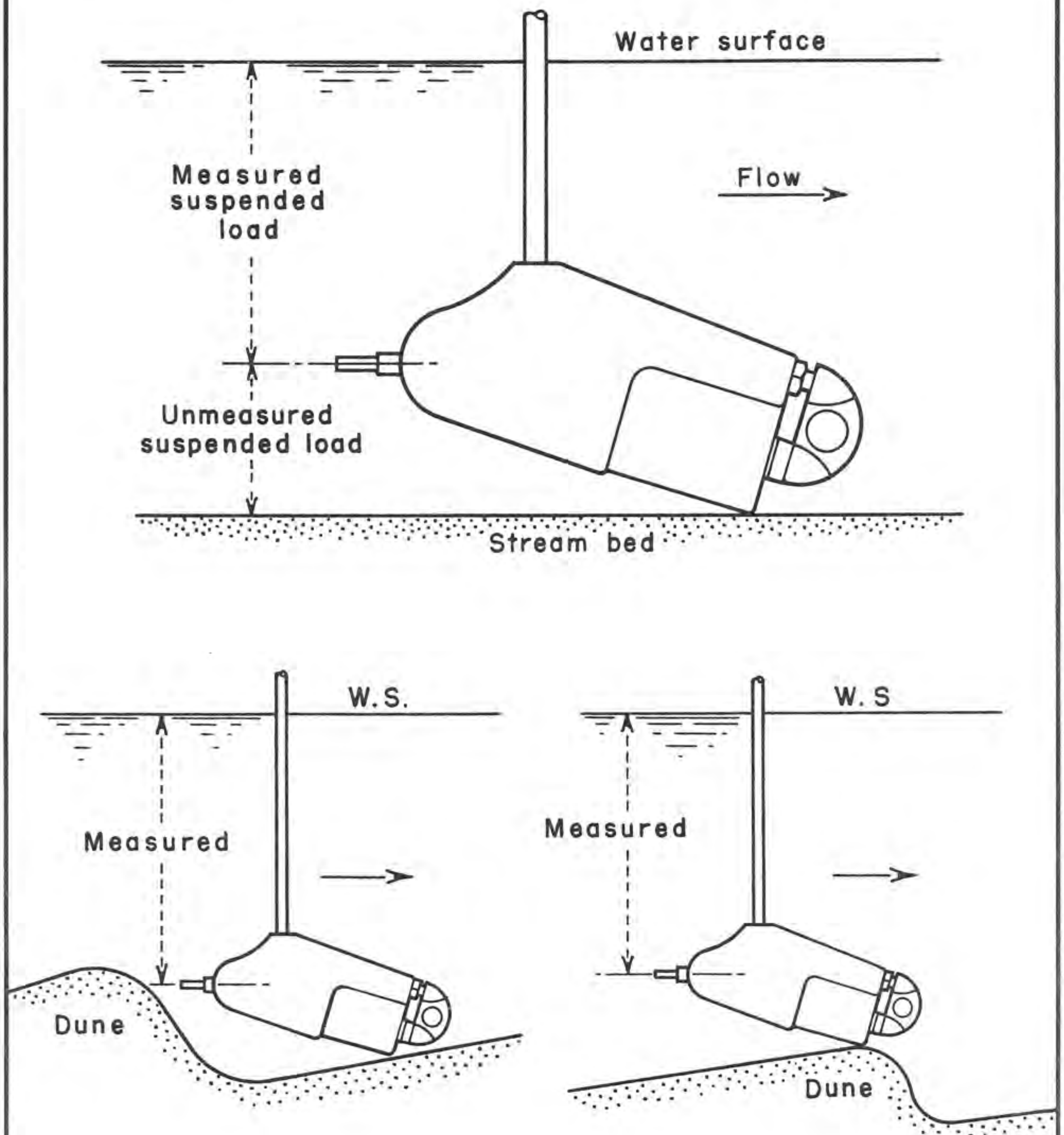
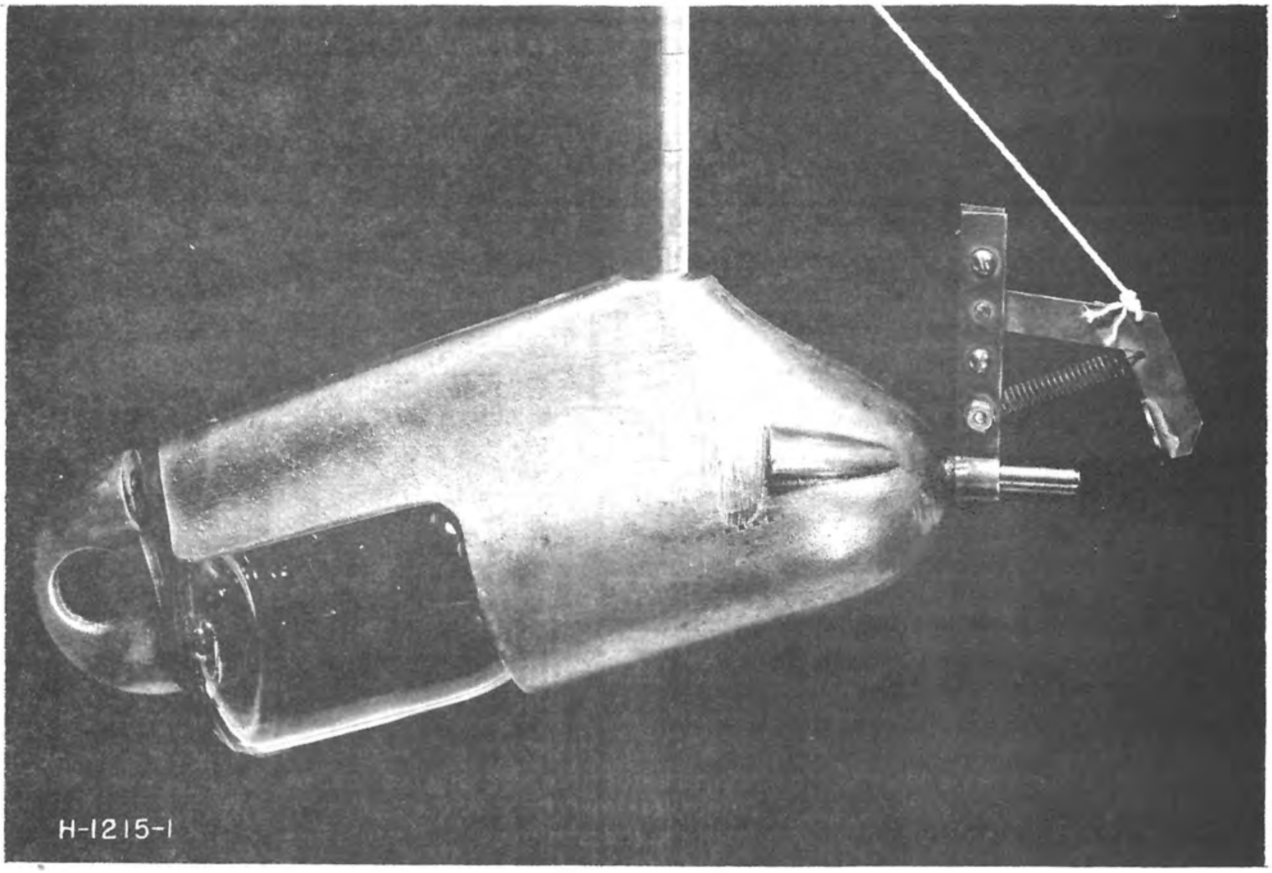
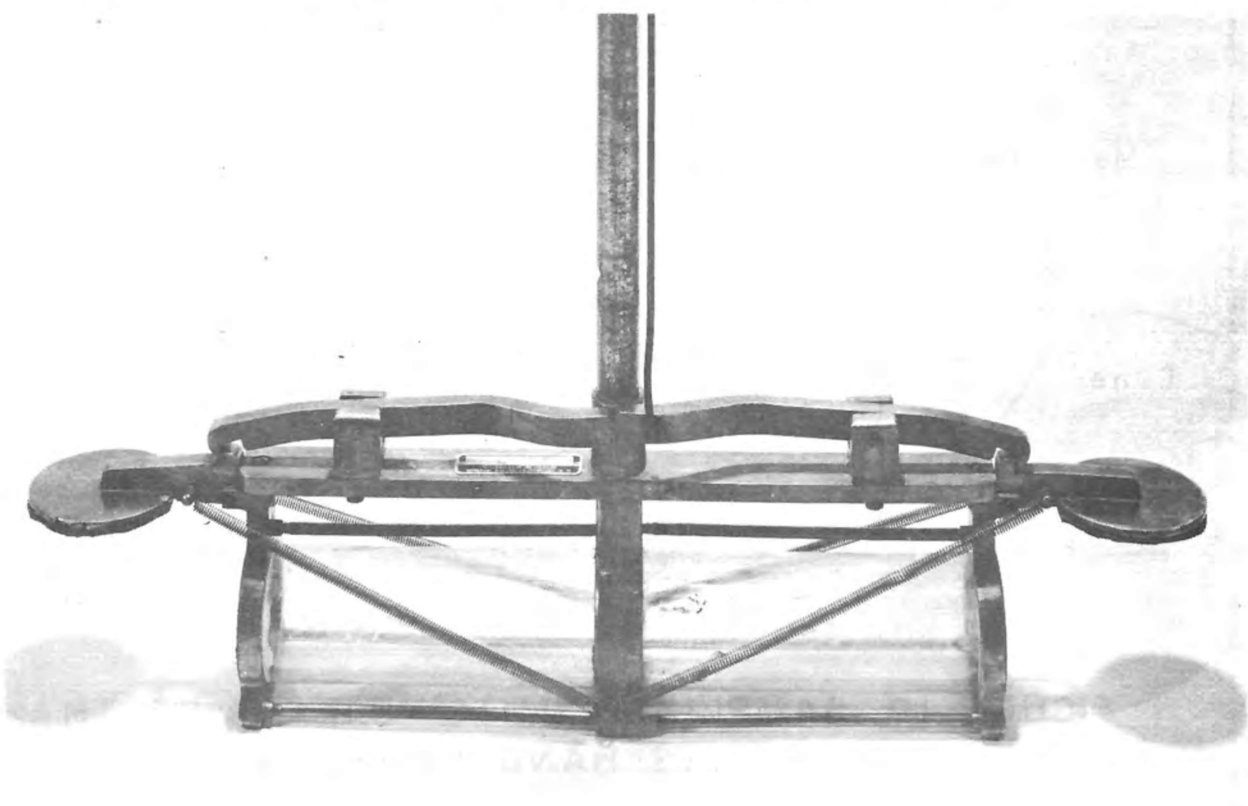


FIGURE I – SAMPLING LIMITS - D.H.- 48 DEPTH INTEGRATING HAND SAMPLER



A. DH-48 Sampler with nozzle adaptor for point sampling.



B. Plastic Tube Sampler for sampling close to hard stream bottoms and for large sediment.

Figure 2. Samplers adapted for special conditions.

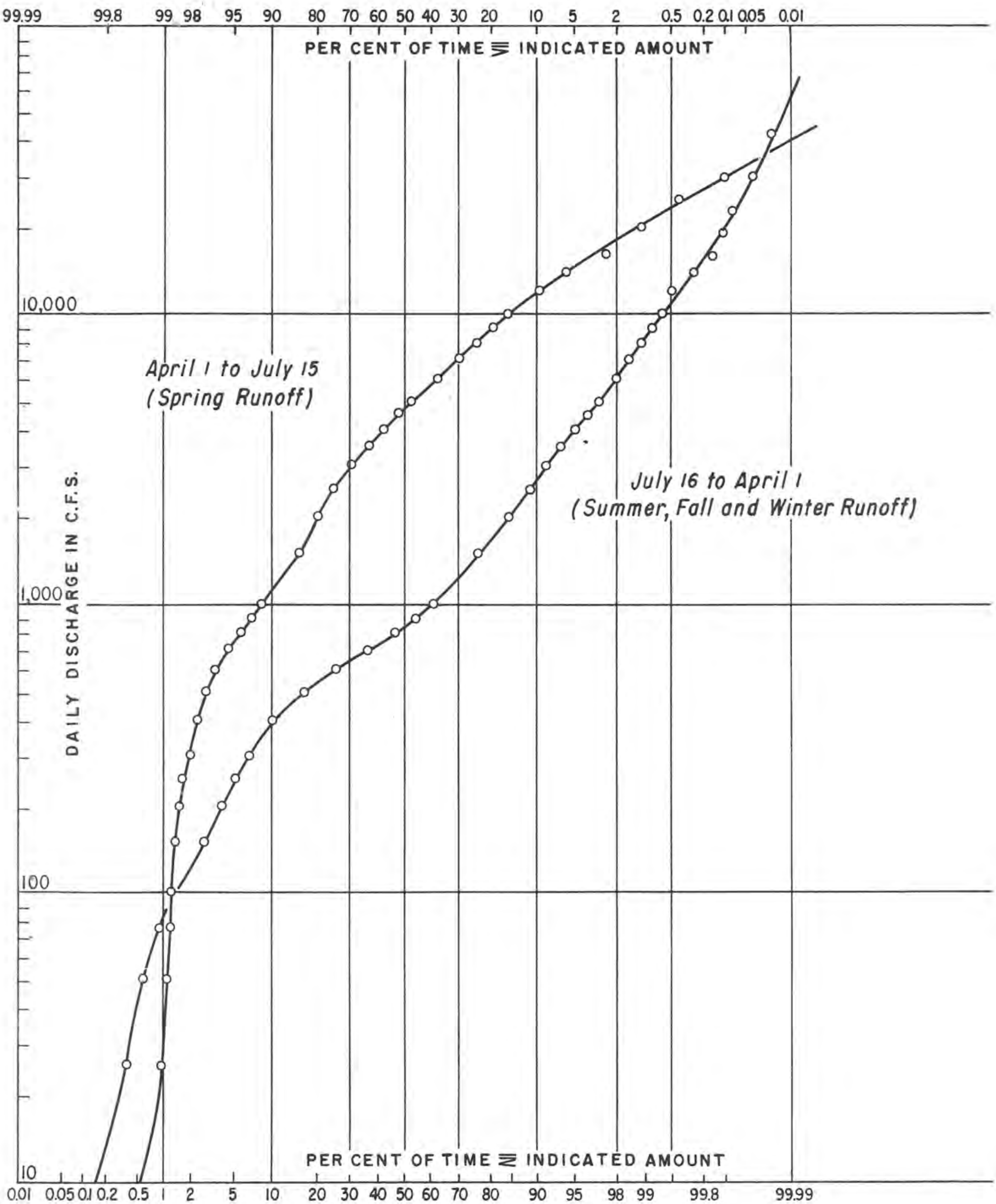


Figure 3 - Seasonal Flow-Duration Curves, San Juan River, Bluff, Utah

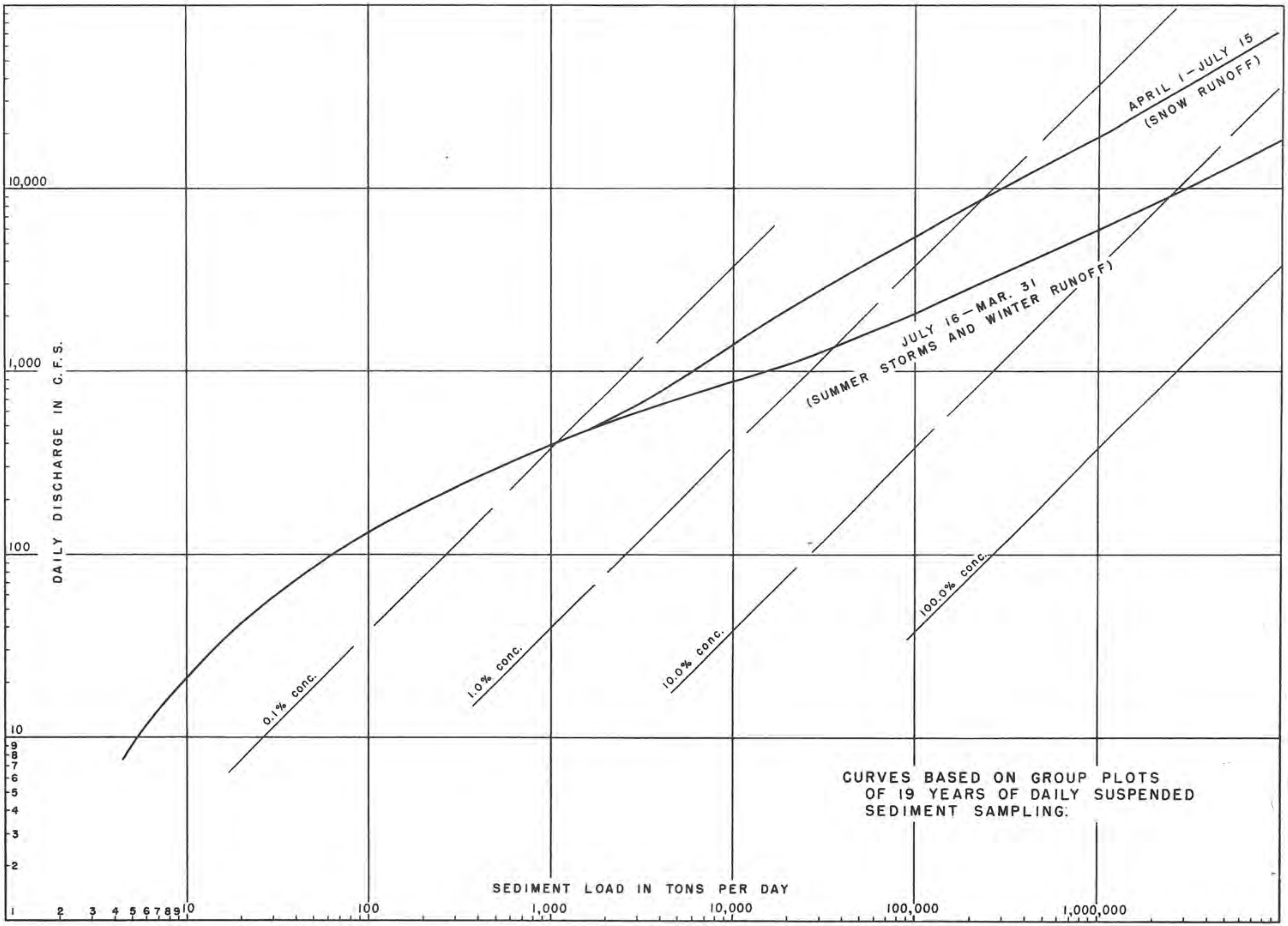


Figure 4 – Seasonal Suspended Sediment-Rating Curves,
San Juan River, Bluff, Utah

Station: Bluff, Utah Period: April 1 to July 15 River: San Juan

1 % limits	2 % interval	3 % mid ord	4 Q_w	5 Q_s	6 2 x 4 Q_w disch	7 2 x 5 Q_s disch
0.00-0.02	0.02	0.01	40,000	3,500,000	8.0	700
0.02-0.1	0.08	0.06	32,000	2,400,000	25.6	1,920
0.1 -0.5	0.4	0.3	25,000	1,550,000	101.2	6,200
0.5 -1.5	1.0	1.0	20,700	1,130,000	207.0	11,300
1.5 -5.0	3.5	3.25	16,300	740,000	570.5	20,450
5-15	10	10	11,700	400,000	1,170.0	40,000
15-25	10	20	8,900	245,000	890.0	24,500
25-35	10	30	7,000	157,000	700.0	15,700
35-45	10	40	5,650	107,000	565.0	10,700
45-55	10	50	4,720	79,000	472.0	7,900
55-65	10	60	3,750	52,000	375.0	5,200
65-75	10	70	2,940	33,500	294.0	3,350
75-85	10	80	1,950	17,000	195.0	1,700
85-95	10	90	1,100	7,000	110.0	700
95-98.5	3.5	96.75	540	2,100	18.9	74
98.5-99.5	1.0	99.0	25	12	0.3	
99.5-99.9	0.4	99.7	8	5		
99.9-99.98	0.08	99.94	2	2		
99.98-100	0.02	99.99	0	0		
				TOTAL	5,702.5	150,394

Q_wP.D. = 5,702.5 D.D. x 106 x 1.9835 = 1,200,000 (AF)/period
Q_sP.D. = 150,394 D.D. x 106 = 15,950,000 tons/period
20 percent correction for bedload = 3,200,000 tons/period
Total sediment discharge = 19,150,000 tons/period

D.D. = daily discharge
P.D. = period discharge
D.A. = drainage area 23,000
62.5 = lb/cubic foot
1,361 = tons/acre foot

Sediment

P.D. $\dfrac{19,150,000}{1,361}$ $\dfrac{\text{tons/period}}{\text{tons/(AF)}}$ = 14,070 (AF)/period

Yield $\dfrac{19,150,000}{1,361 \times 23,000}$ $\dfrac{\text{tons/period}}{\text{tons/(AF)} \times \text{D.A.}}$ = 0.612 (AF)/sq mi

Concentration $\dfrac{15,950,000 \times 100}{1,200,000 \times 1,361}$ $\dfrac{Q_s\text{P.D.} \times 100}{Q_w\text{P.D.} \times 1,361}$ = 0.977 percent

Runoff

Rate $\dfrac{1,200,000}{23,000}$ $\dfrac{Q_w\text{P.D.}}{\text{D.A.}}$ = 52.17 (AF)/sq mi

Figure 5.--Sediment Load for San Juan River at Bluff, Utah, Spring Runoff Period

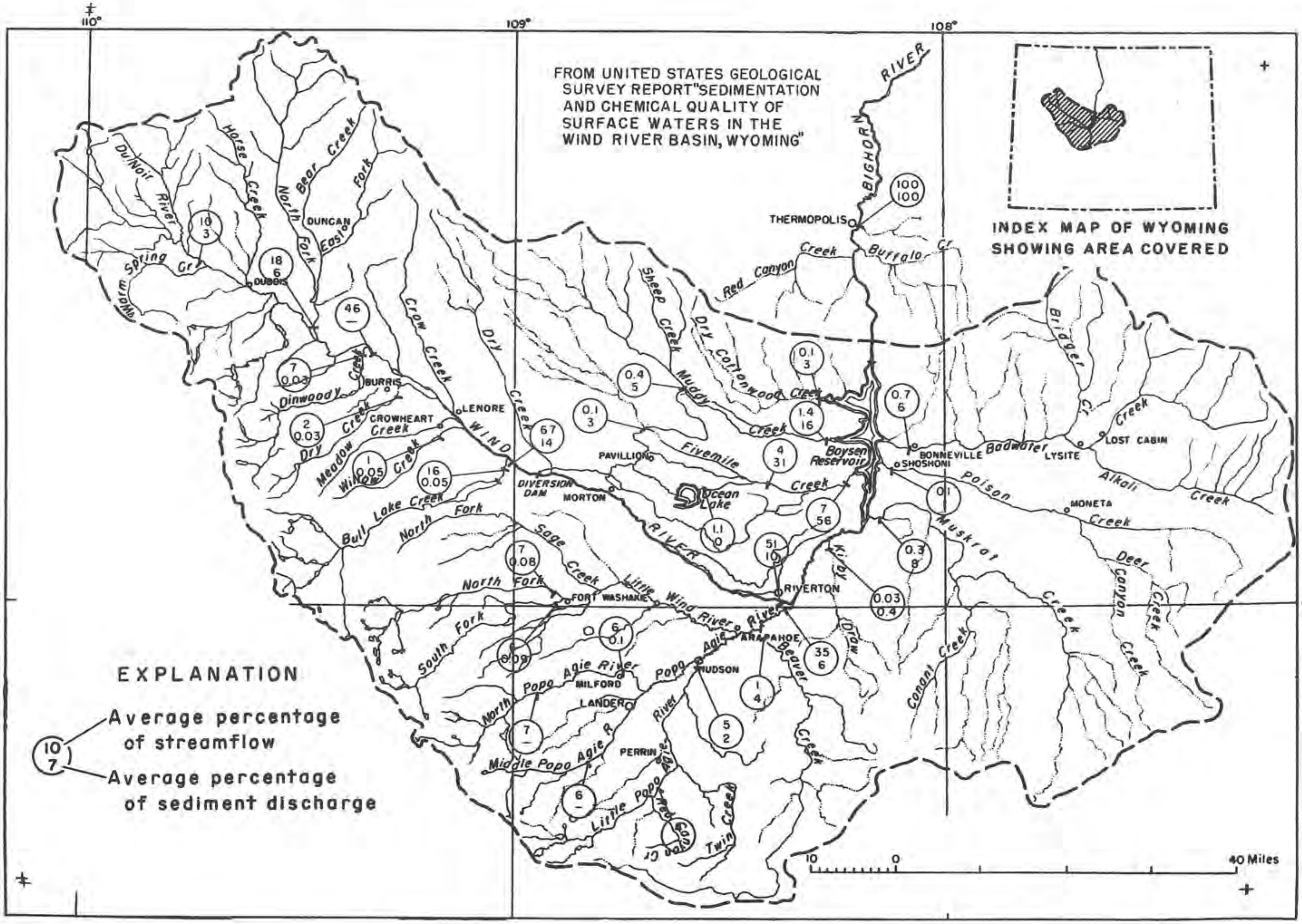


FIGURE 6 APPROXIMATE AVERAGE SEDIMENT DISCHARGE AND STREAMFLOW IN PERCENTAGE OF SEDIMENT DISCHARGE AND STREAMFLOW AT THERMOPOLIS

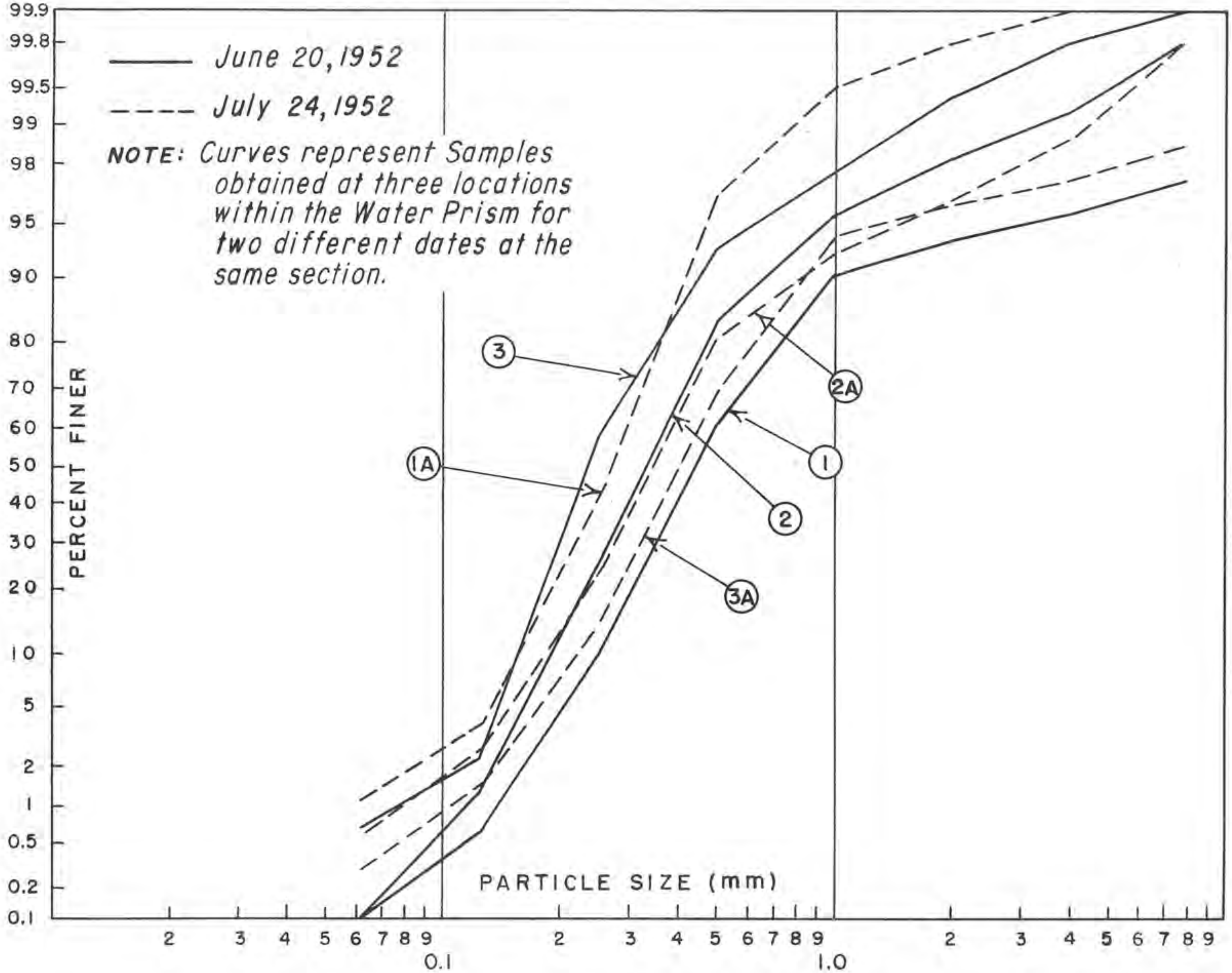


Figure 7 - Bed Material Size Analysis Curves, Middle Rio Grande River, Bernalillo Study Reach, Section F

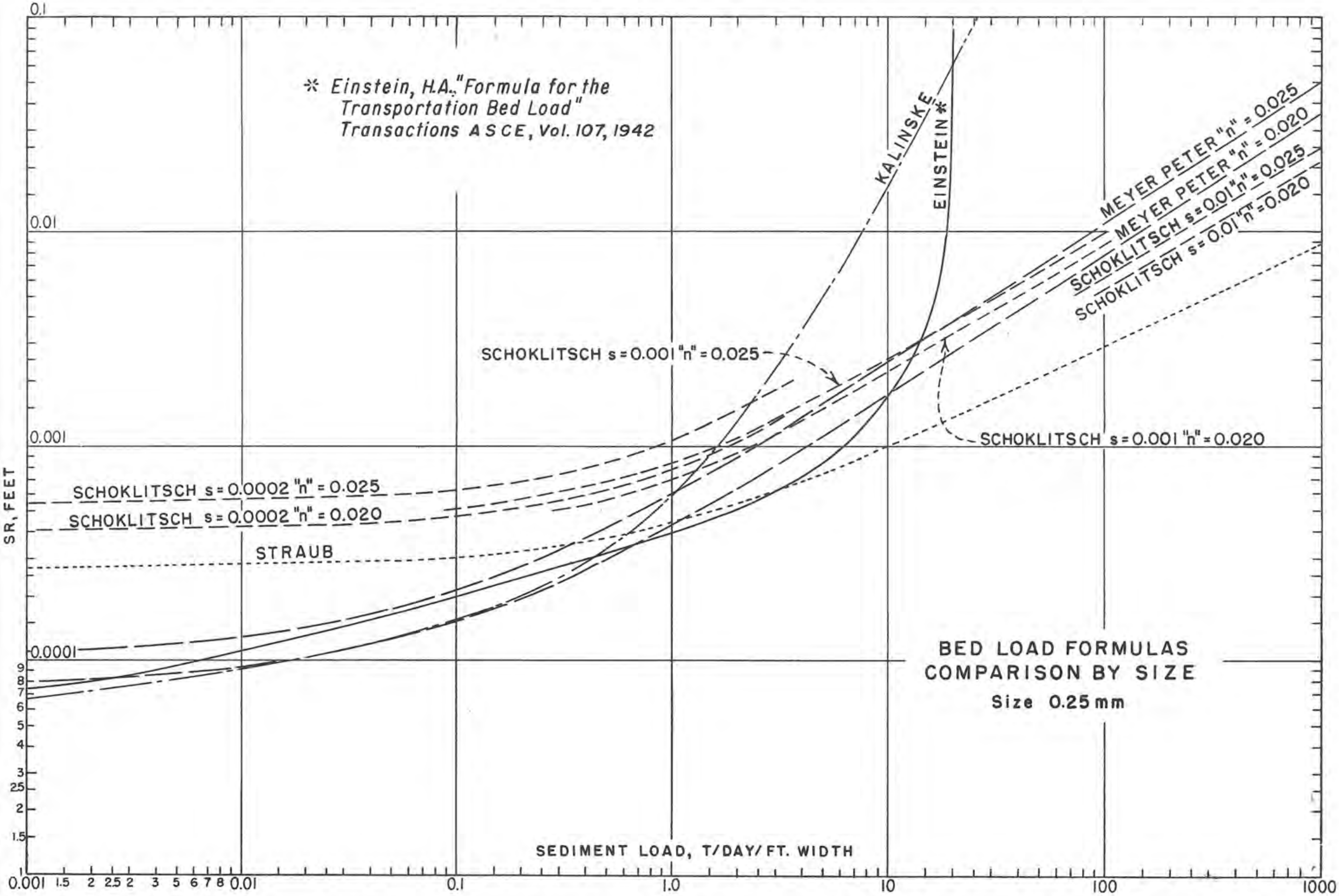


Figure 8 - Showing Variation of Transport as computed from various Formulas

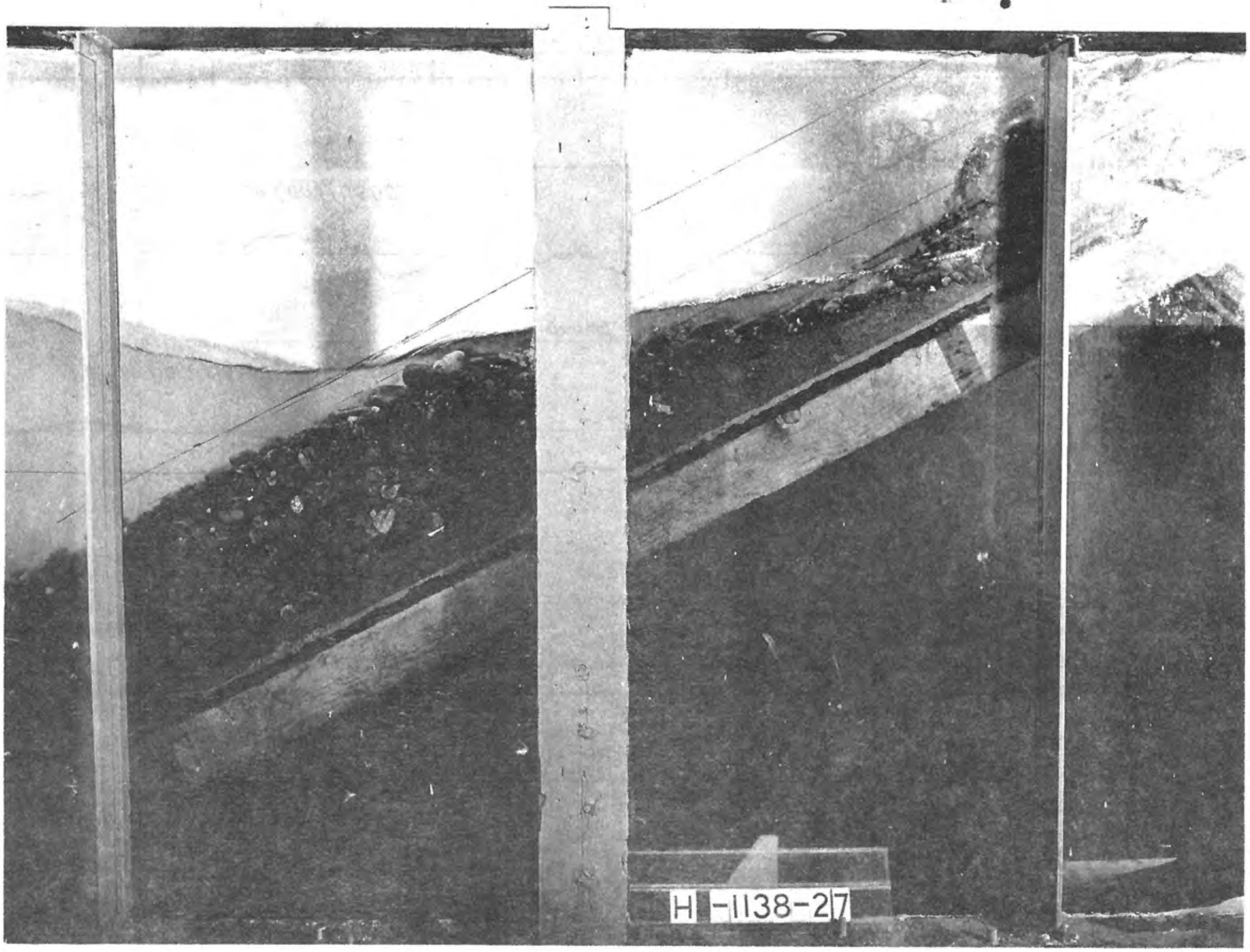


Figure 9. Beaching slope of 5.14 to 1 developed on pit run gravel from Kennewick Main Canal, Yakima Project Washington, after being subjected to 0-43 foot high waves at a frequency of 42 per minute for 19 hours.

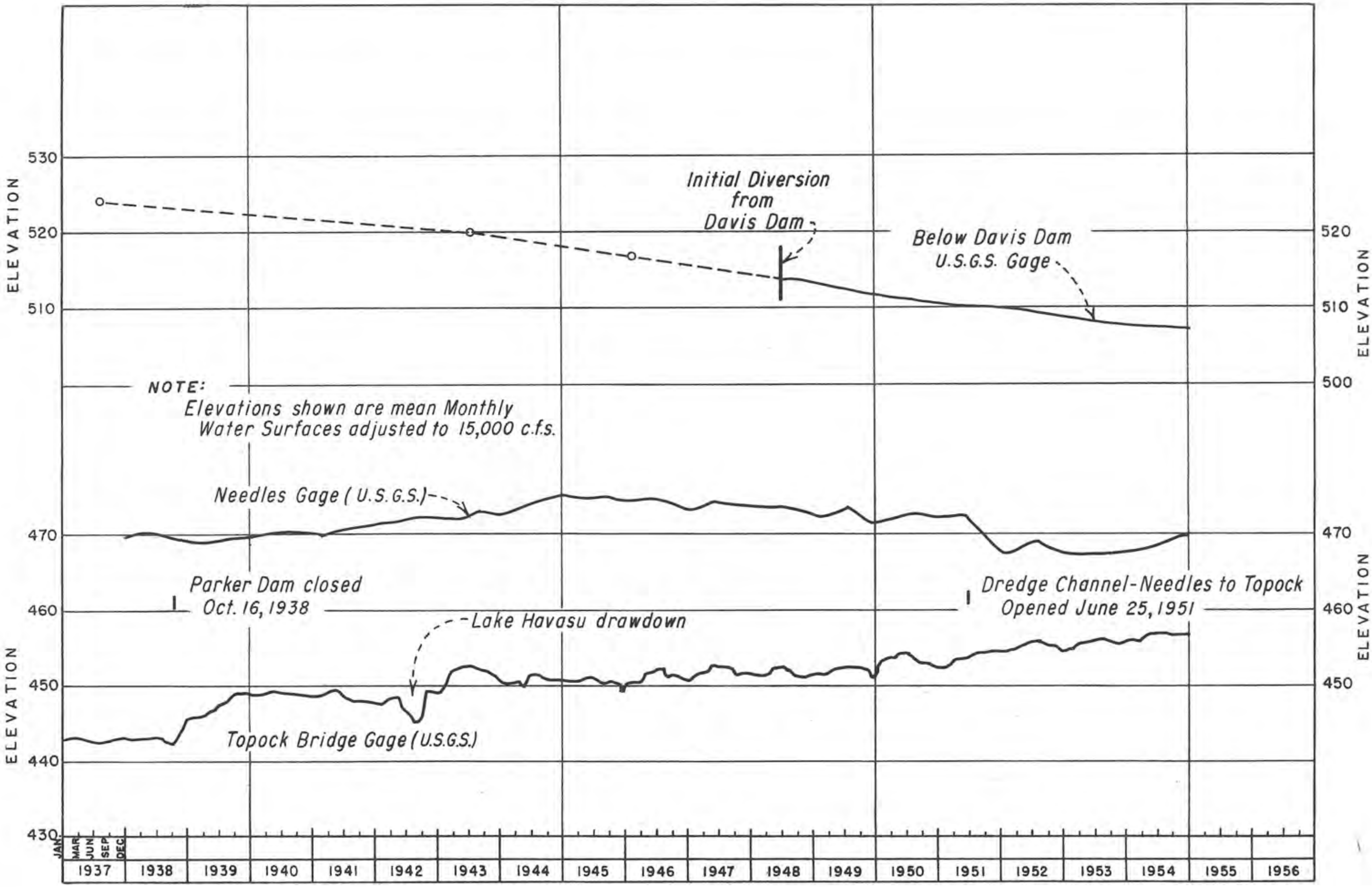
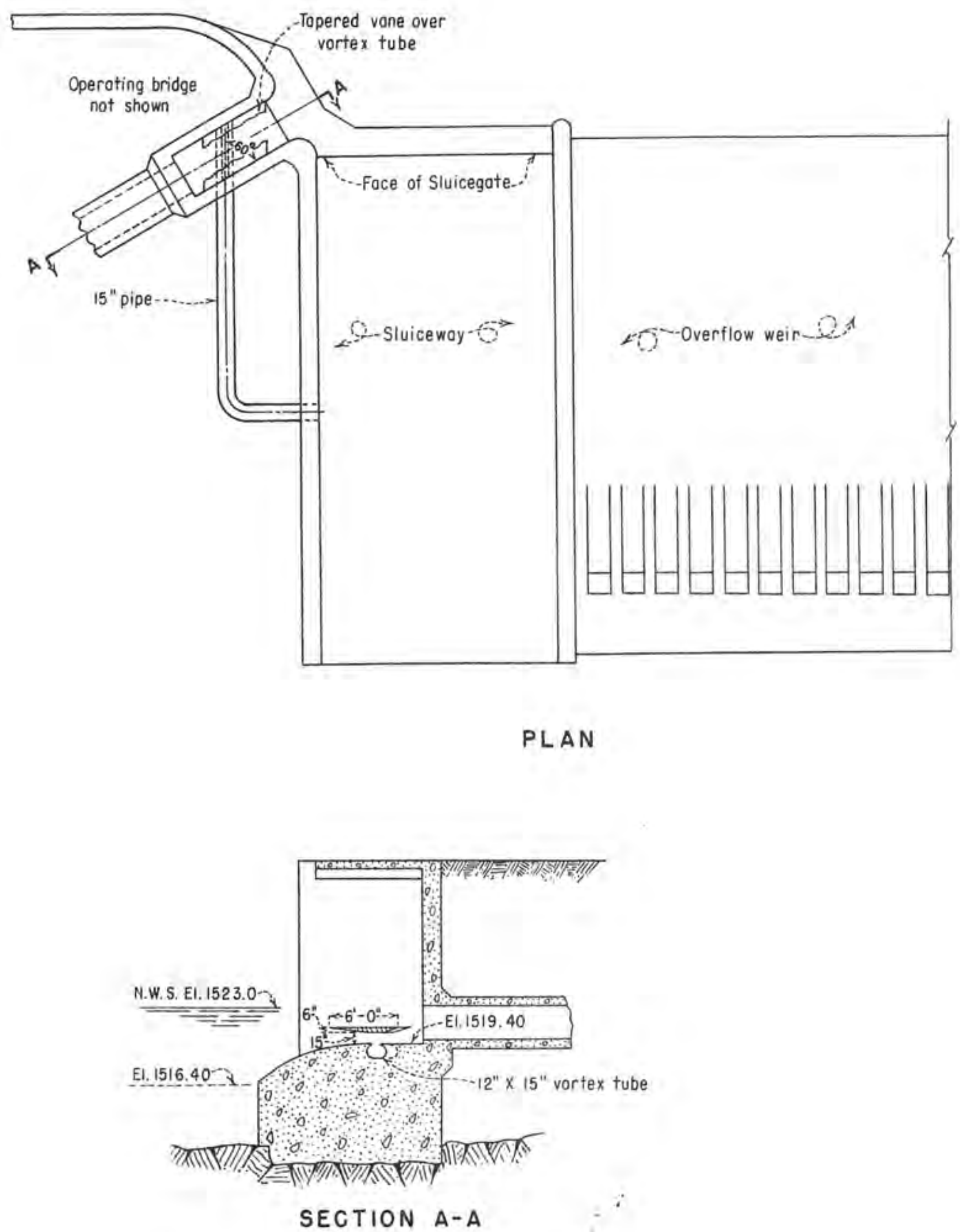


Figure 10 – Change in Water Surface Elevations due to Aggradation and Degradation between Davis Dam and Lake Havasu



HYDRAULIC MODEL STUDIES

REPUBLIC DIVERSION DAM

RECOMMENDED DESIGN-HARDY HEADWORKS

MODEL SCALE 1:15

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Figure 11 - Vortex Tube with Activating Vane for Sediment Exclusion