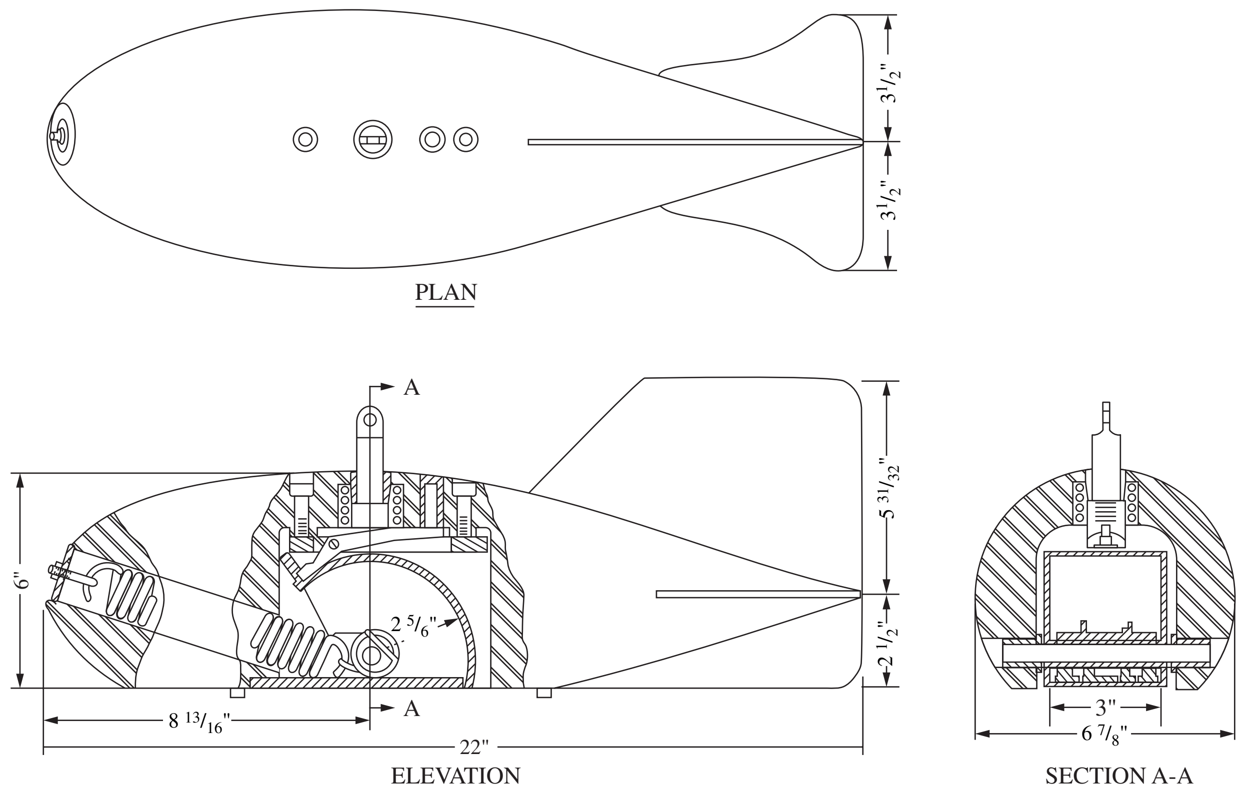

Figure 3.19 US BM-54 bed material sampler (Interagency Committee, 1963).

suspended-sediment discharge per unit width, g_{ss}, is given by

$$g_{ss} = \int_{\delta}^{d} CU dy = c_m q \qquad (3.2)$$

in which $d =$ the depth; $q =$ the water discharge per unit width; and $c_m =$ the suspended-sediment discharge concentration at the vertical where C and U were taken. The lower limit, δ, is rather indefinite, but it is usually visualized as being a few times the mean size of the bed sediment.

The mean concentration, $\overline{C}$, for a stream vertical is defined by $\overline{C} = 1/(d-a)\int_a^d C dy$, in which $a =$ the distance from the bed to the lowest sampling point; and d, y, and C are as previously defined. This concentration is readily obtained from a graph of point concentration, C, against position, y. If stream verticals in the cross section are equally spaced and close enough to represent the variation of concentration with width, the mean concentration for the cross section is the average of the concentration for the selected verticals.

The concentration and velocity profiles for a stream vertical can be used to determine the suspended-sediment discharge at the vertical. The product, CU, at the position, y, above the bed is plotted against y for a number of positions and a curve is drawn through the points. The area under the curve gives the suspended-sediment discharge, g_{ss}, per unit width over the depth, $d - a$.

The measured suspended-sediment discharge, G'_{ss}, is, by definition, the product of the measured suspended-sediment discharge concentration, $\overline{C}'_m$, and the total water discharge, Q, in the cross section. In scheme (1), the concentration is the average obtained for depth-integrated samples taken at stream verticals representative of areas of equal discharge. In scheme (2), the concentration is from a composite sample obtained from partial samples taken at equally spaced verticals in the stream cross section. The error in the suspended-sediment discharge, G'_{ss}, calculated in this manner varies with the fraction of the stream vertical, a/d, that is unsampled and with the shapes of the velocity and concentration profiles. For example, the error tends to be smallest in cases where the concentration gradient, dC/dy, in the unsampled zone is small. The concentration gradient is small for silt and clay particles or for small values of z, the exponent in the concentration profile, equation, Eq. 2.77, Chapter II, Section D. As the true error is difficult to estimate, corrections are seldom applied in the determination of the suspended-sediment discharge.

Water discharge and flow distribution in the cross section are based on velocity and depth observations at properly spaced stream verticals (Corbett, 1945). Centroids of areas of equal water discharge in the cross section are located from data from water discharge measurements. The water discharge in cubic feet per second for the individual areas, as represented by the selected stream verticals, is cumulated for the cross section. The cumulated discharge, expressed as a percentage of the total, is plotted against the lateral distance that each vertical is from a reference point.

Table 3.1 Cumulative Percentage of Water Discharge in Cross Section

Number of Sampling Verticals (1)	Percentage of Cumulative Discharge at Centroids (2)											
2	25	75										
4	12	38	62	88								
6	8	25	42	58	75	92						
8	6	19	31	44	56	69	81	94				
10	5	15	25	35	45	55	65	75	85	95		
12	4	12	21	29	38	46	54	62	71	79	88	96

The cumulative percentage of water discharge in the cross section for each of a selected number of verticals is given in Table 3.1. Given the number of sampling verticals, the location of each vertical is determined from the percentage values from Table 3.1 and the plot of cumulated water discharge versus location in the cross section. For streams with rapidly changing stage-discharge relationships, a water discharge measurement usually is made to determine the centroids of the areas of equal water discharge prior to collection of the sediment samples.

Data on particle-size distribution are obtained from samples selected to be representative of a range of sediment discharge and runoff conditions. Data on specific gravity normally are limited to a few samples representative of a range of sediment discharge. Data for both determinations can be obtained from samples collected for concentration analysis or from samples collected specifically for each determination. The latter procedure adds to the field work because of the time required to collect additional samples. However, the laboratory analyses are greatly simplified if representative individual samples are available for "size," "concentration," and "specific gravity determination," as current laboratory equipment for splitting samples does not provide an acceptable degree of accuracy if sand particles are present in the sample.

In actual practice, the frequency of sampling with respect to runoff and the number of sampling verticals in the cross section depends upon the scope of the study and the accuracy required. At measuring sections where there is a minimum amount of variation in the concentration in the cross section, adequate data can be obtained by the routine collection of depth-integrated samples at one vertical, supplemented by the periodic collection of samples at a number of equally spaced verticals or at several verticals located at centroids of equal areas of water discharge. Determination of the suspended-sediment discharge in the stream cross section is often called a sediment discharge measurement. If the concentration in the cross section fluctuates erratically, the accuracy can be improved only by increasing the number of sampling verticals and the frequency of sediment discharge measurements.

The accuracy of a sediment discharge record depends upon the accuracy of the determination of both the concentration and the related water discharge. During flood periods, a desirable degree of accuracy can be obtained only by making concurrent water and sediment discharge measurements to define both the concentration and flow with respect to time. In addition, frequent reference samples at one stream vertical are required if rapid changes in concentration are to be recorded.

The type of field installations required for the collection of data to determine the suspended-sediment discharge depend primarily upon the size of the stream and accuracy of the record desired. For small streams, samples are collected by wading or from foot bridges with hand-operated samplers. For medium size rivers, samples are collected from cable or bridge measuring installations utilizing both depth or point-intergrating samplers, or both. At bridge measuring sections, a sampler and reel housed in a shelter attached to the side of a bridge is used if a record of daily concentration is to be obtained. Fig. 3.20(a) shows a typical bridge installation allowing a resident observer to collect frequent samples from the Bighorn River near Manderson, Wyo. A US D-49 sampler

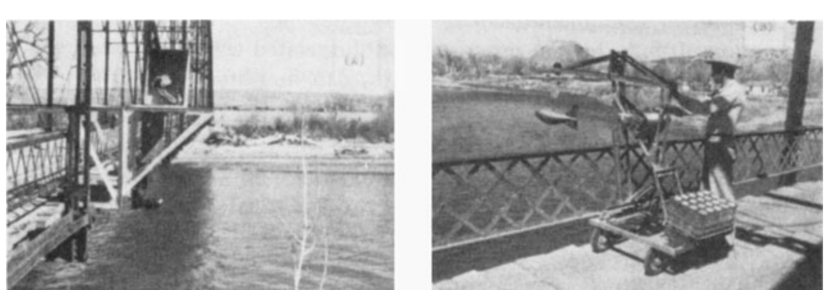

Figure 3.20 Equipment for collection of suspended-sediment samples: (A) US D-49 sampler installation near Manderson, Wyo.; (B) US D-49 sampler and four-wheel crane near Kane, Wyo. (Photographs by United States Geological Survey).

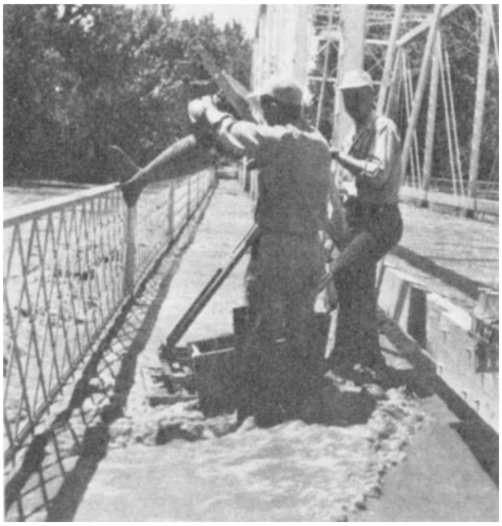

Figure 3.21 Equipment for collection of suspended-sediment samples, Solomon River at Beloit, Kansas: US P-46 sampler and four-wheel crane (Photograph by United States Geological Survey).

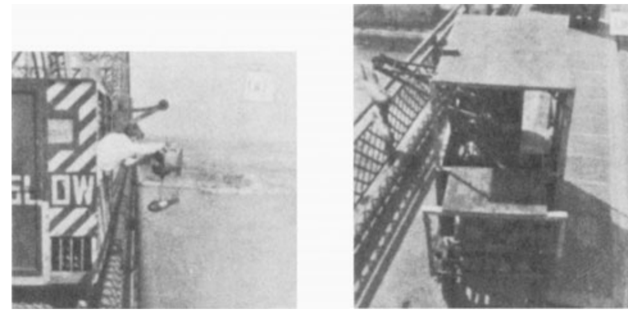

Figure 3.22 Equipment for collection of suspended-sediment samples, Mississippi River at St. Louis, Mo.; (A) US P-46 sampler with 100-lb sounding weight attached; (B) Power-operated car and crane assembly (Photographs by United States Geological Survey).

and four-wheel crane unit for the collection of samples at the sediment station on the Bighorn River near Kane, Wyo. is shown in Fig. 3.20(b). A 100-lb point-integrating sampler, as used in the Solomon River sediment investigations, is shown in Fig. 3.21. The valve in the sampler head is closed when the sampler touches the stream bed.

In large rivers, cable-suspended point-integrating samplers are used to collect both depth and point-integrated samples from bridges or boats. The equipment used at the sediment station on the Mississippi River at St. Louis, Mo., shown in Fig. 3.22, includes a power-operated car and crane assembly and US P-46 sampler. The 100-lb C-type stream gaging sounding weight, shown suspended below the sampler, was used to reduce the down-stream drift during flood runoff. The recent development of the US P-63 point-integrating sampler, weighing 200 lb, largely eliminates the need of using the C-type weight.

Total Sediment Discharge Measurement Direct observations of measurements of total sediment discharge, hereafter referred to as sediment discharge, cannot be made with existing sediment sampling equipment. Sediment discharge can be determined from direct observations of concentration, c_m, and particle size of suspended sediment, velocity distribution, stream depth, water temperature, and bed sediment size (Colby and Hembree, 1955) for selected segments of streams flowing in "sand bed channels."

In streams where the sediment load consists primarily of particles in the silt and clay range and the concentration distribution in the vertical section is essentially uniform, the suspended-sediment discharge is very nearly equal to the total sediment discharge.

In some streams, the sediment discharge can be measured in a contracted section of a channel where the velocity and turbulence are sufficient to suspend all the particles in transport. Such sections are sometimes called natural turbulence flumes. The United States Geological Survey (Serr, 1950; Colby, et al., 1953; Benedict and Matejka, 1953; Colby and Hembree, 1955) utilized natural turbulence flumes in the Niobrara River, Nebraska, and Fivemile Creek, Wyoming, to determine the sediment discharge. In each instance, the suspended-sediment discharge concentration, $\overline{C}'_m$, in the sampled depth was shown to be nearly representative of that for the total depth; thus, the observed concentration closely approximated the true discharge concentration.

In small streams, the sediment discharge can be measured if it is practicable to install an artificial turbulence flume. Fig. 3.23 is a photograph of this type of flume used on

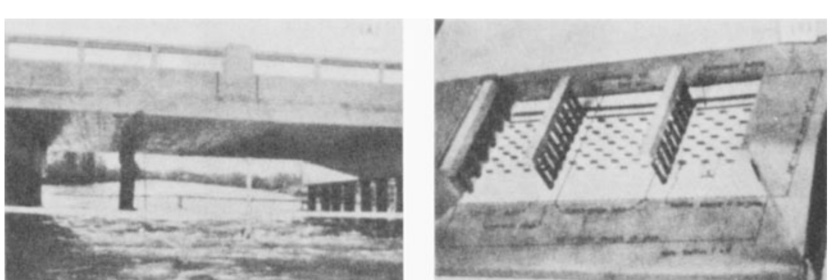

Figure 3.23 Turbulence flume, Middle Loup River near Dunning, Neb.: (A) view looking upstream towards turbulence flume, water discharge 350 cfs; (B) skeleton model of turbulence flume (Photographs by United States Geological Survey).

Figure 3.24 Streamflow and sediment measuring station, Pine Creek above Barry Placer Division near Idaho City, Idaho; broad-crested weir with rectangular flume for low stages; overfall structure for sediment sampling in foreground (Photograph by United States Geological Survey).

the Middle Loup River at Dunning, Neb., by the Geological Survey (Benedict, et al., 1955; Hubbell and Matejka, 1959). It consists of a series of baffles anchored to a concrete slab, the top of which is at average bed elevation for the stream at that cross section. The turbulence induced by the baffles is sufficient to transport in suspension almost the entire sediment load in the stream, thus enabling it to be sampled with a hand depth-integrating sampler.

The sediment discharge in small streams can also be measured at weirs or drops where it is practicable to collect samples by moving a depth-integrating sampler vertically through the nappe (Love and Benedict, 1948). A measuring station provided with a weir is shown in Fig. 3.24. It also may be measured on a continuous basis for individual storm periods by utilizing a modified weir and a splitting device similar or identical to that developed by the Tennessee Valley Authority (1961). In this type of installation, a continuous sample of the water-sediment mixture is taken by means of a series of splitting devices, in each of which a proportional part of the water and sediment passing that point is retained and the balance wasted. The accuracy of this type of sediment discharge measuring installation depends upon the accuracy with which the diverted flow represented the concentration of the total flow, the overall accuracy of the splitting device, and a related record of scour or fill in the weir pool, if any, for each runoff event.

A photograph of this type of installation on White Hollow Creek near Maynardville, Ten., is shown in Fig. 3.25. In this installation, the rate at which the actual sample was taken was shown to be 1/105,000 of the stream discharge.

The average annual sediment discharge of streams entering a reservoir can be obtained from reservoir sediment surveys if adequate information is available on sediment discharge from the reservoir. This method requires accurate topographic mapping of the deposits and measurements of the specific weight of the sediments deposited as discussed in Chapter III, Section B that follows.

Bed Load Discharge Measurement Direct field measurements of bed load have been made in Europe for only a few streams and for only short periods of time (Einstein, 1948). In the United States, several direct measurements of bed load movement under uniform flow conditions were made by the Soil Conservation Service in 1941. In these measurements, the sediment was accumulated in slot-traps placed across the channel and measured volumetrically or pumped into a weighing tank. Einstein (1944) points out that the volumetric method gives accurate results for small streams under uniform flow conditions.

United States Army Engineers have made preliminary studies of bed load movement with portable samplers similar in design to some of the European models. Since 1945,

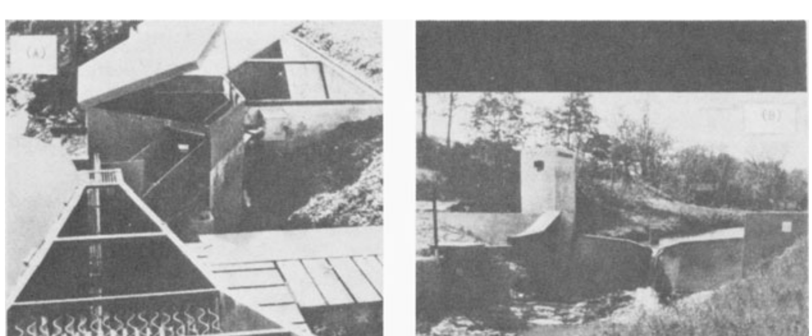

Figure 3.25 Streamflow and sediment measuring station, White Hollow Creek near Maynardville, Tenn.: (A) Flow splitting device with water-sediment storage tank; (B) Looking upstream—weir in immediate foreground, flow splitting device at left (Photographs by Tennessee Valley Authority).

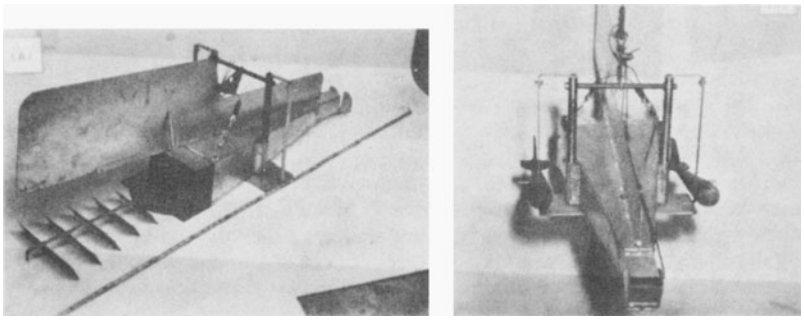

Figure 3.26 Experimental bed load sampler: (A) View of sampler with baffles removed; (B) View of sampler with sounding weights attached (Photographs by United States Army Engineer District, Little Rock, Ark.).

the experimental sampler shown in Fig. 3.26 has been used in the lower Arkansas River, where maximum depths of 60 ft and mean velocities of 14 fps are common occurrences. This sampler traps only that part of the sediment moving in a layer extending about 0.3 ft above the bed. The results from the sampler are uncertain when the bed is irregular, particularly when dunes or ripples are present. The sampler has been useful in obtaining qualitative information on sizes of sediment grains that may form a pavement and shield the bed from scour; it also has helped to obtain data for tractive force computations for deep flows, and information on when appreciable movement of the bed load begins. Information obtained also shows that "clay balls" that occasionally roll on the bed, clogged the entrance to the sampler. The samplers have not been used on a routine basis, as the investigations of bed load movement were entirely experimental in character (United States Corps of Engineers, 1958).

5. Records of Sediment Discharge

Records of sediment discharge are generally computed on a daily or annual basis. The method used for computing daily or annual values depends upon the data collected, the frequency of the field observations, and the size of the bed material in transport.

Suspended-Sediment Discharge Suspended-sediment discharge can be computed for any selected time interval. Where a relatively high degree of accuracy is desired, daily intervals generally are used. The suspended-sediment discharge in tons per day is the product of the daily mean concentration, the daily mean water discharge, and a conversion factor. Concentration generally is expressed in grams of sediment per liter of the water-sediment mixture or in parts per million by weight. Concentration in parts per million by weight is obtained by dividing the weight of the dry sediment by the weight of the water-sediment mixture. In the United States, present practice for computing a daily record is to plot concentrations from depth-integrated samples in parts per million or milligrams per liter directly on a chart (or a print of the chart) of the gage height against time (Benedict, 1948). A smooth concentration curve is then drawn through the plotted points. Daily mean concentrations are then read from the concentration graph. During periods of rapidly changing concentration and water discharge, the concentration and gage height graphs are subdivided into smaller than daily increments of time. Fig. 3.27 shows a typical concentration and gage-height graph for the Bighorn River near Manderson, Wyo.

At sediment stations where depth-integrated sediment samples are collected frequently from a fixed sampling installation, the concentration at this reference vertical is related to the concentration in the cross section determined from concurrent water and suspended-sediment discharge measurements. The frequency of these concurrent measurements to evaluate the concentration in the cross section depends upon the accuracy desired, the number of runoff events, and the characteristics of the stream channel at and above the measuring section. Frequent measurements, particularly during

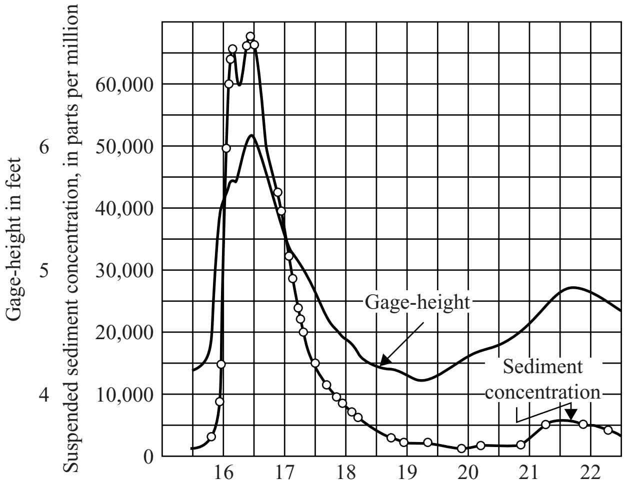

Figure 3.27 Graphs of suspended-sediment concentration and gage height, Bighorn River near Manderson, Wyo., April 16–22, 1952.

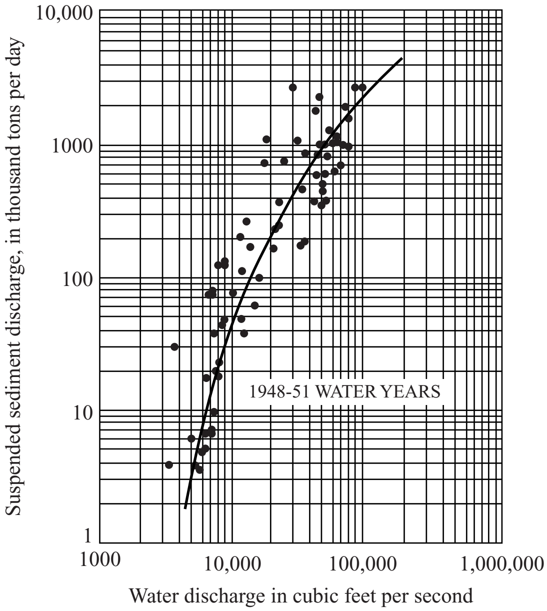

Figure 3.28 Suspended-sediment transport curve, Colorado River near Grand Canyon, Arizona.

periods of rapid increase in discharge, enhances the accuracy of the record.

In reconnaissance studies, a general relationship between suspended-sediment discharge or concentration and water discharge may be developed for a sediment station by plotting sediment discharge against water discharge for the period of record. The resulting curve is called the sediment transport curve. This approach is necessary when the interpolation of sediment concentration between infrequent measurements becomes impractical. If the sediment transport curve is a mean for a number of years of record, it can be used directly with a flow-duration curve (Searcy, 1959) to obtain an approximate amount of sediment passing the station for the period of record for which observations are available (United States Bureau of Reclamation, 1951). This amount of sediment is called the sediment yield (see Chapter IV) for the period involved. Fig. 3.28 shows suspended sediment transport curve for the Colorado River near Grand Canyon, Arizona, for the water years 1948–1951. The scatter in plotted values is typical for streams transporting sediment consisting of clay, silt, and sand-size particles. Transport curves for suspended clay-silt and sand fractions are shown in Fig. 3.29 (Colby, 1956). Transport curves can also be developed for daily values of suspended load and water discharge or for selected runoff events from comparable data. In a study of "load-discharge relationships" for 20 stations, Leopold and Maddock (1953) found that the concentration of suspended sediment generally increases with discharge. For some flood runoff events, Heidel (1956) shows that the progressive lag in the peak concentrations behind the peak flow alters the normal relationship between sediment discharge and water discharge.

The transport curve method for computing suspended-sediment discharge has particular merit for streams flowing on alluvial beds with a high percentage of the sediment discharge in the sand-size range. The silt and clay fraction of the total load, sometimes referred to as fine material load or wash load, is not functionally related to stream discharge or competence. Therefore, adequately-defined relationships cannot be developed for a sediment station where an appreciable fraction of the sediment discharge is composed of fine material load (wash load) (Witzig, 1944; and Johnson, 1944). However, where sufficient particle size data are available, sand transport curves can be developed to give a greater degree of accuracy for that fraction of the total load. Details of this procedure will be further treated in the following section.

Total Sediment Discharge In a study of the sediment discharge of the Niobrara River near Cody, Neb., Colby and Hembree (1955) developed a procedure for computing total sediment discharge based in part on Einstein's formulas and Geological Survey field data. This procedure that is discussed in Article 58 of Chapter II has been called the Modified Einstein procedure. It is based on field data including concentration, particle size of suspended sediment, stream velocity and depth, water temperature, and particle size of bed sediment for selected areas in a stream cross section.

Studies of sediment discharge of the Middle Loup River near Dunning, Neb., by Hubbell and Matejka (1959) confirm the results obtained in the Niobrara River study. Colby and Hubbell (1961) simplified the Modified Einstein computation procedure by the use of nomographs. Computations

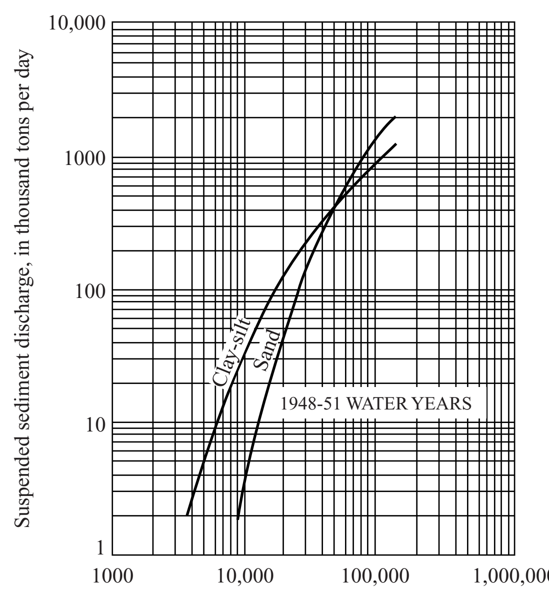

Figure 3.29 Suspended clay-silt and sand transport curves, Colorado River near Grand Canyon, Arizona.

Table 3.2 Maddock's Classification for Determining Bed Load

Concentration of Suspended Load, in Parts Per Million (1)	Type of Material Forming Channel of Stream (2)	Texture of Suspended Material (3)	Bed Load Discharge, in Terms of Suspended Sediment Discharge, as a Percentage (4)
Less than 1,000	Sand	Similar to bed material	25–150
Less than 1,000	Gravel, rock, or consolidated clay	Small amount of sand	5–12
1,000–7,500	Sand	Similar to bed material	10–35
1,000–7,500	Gravel, rock, or consolidated clay	25% sand or less	5–12
Over 7,500	Sand	Similar to bed material	5–15
Over 7,500	Gravel, rock, or consolidated clay	25% sand or less	2–8

have been further simplified by the Bureau of Reclamation (1959) and Army Engineers by the use of a digital computer procedure.

Schroeder and Hembree (1956, 1957), Laursen (1957), Fowler (1957), and Jordan (1965) have concluded that the Modified Einstein procedure, which was based on studies of sediment transport in shallow streams, gives reasonable results in larger streams flowing in natural sand bed channels. This conclusion is further confirmed by studies of the United States Bureau of Reclamation in the Lower Colorado River (1958). Colby (1964), in a study of "dominant measures of bed-material discharge," concluded that either the relation between bed material discharge per foot of stream width and mean water velocity, or the relation between stream power and shear stress, can be used as a basis for practical computations of bed material discharge. He further concluded that sediment transport curves based on the relationship between bed material discharge (0.1 mm–0.8 mm) per foot of width and mean water velocity are the most convenient to apply. Detailed discussion of this method for computing bed material discharge is presented in Chapter II.

Nordin and Beverage (1965), in a study of sediment transport in the Rio Grande, New Mexico, also concluded that a "sediment-transport curve" based on mean velocity and bed material discharge per unit of stream width provided a logical method for determining the total bed material discharge.

The Modified Einstein procedure or the sand-transport curve method provides a practical approach to determining the sediment discharge of streams flowing in channels consisting largely of sand. Frequency curves for water discharge or mean velocity per foot of width are used as appropriate. In streams where the coarse sediment load includes appreciable amounts of sand, gravel, and cobbles, the Meyer-Peter, Muller (Sheppard, 1960) formula has been used to compute that fraction of the load with a reasonable degree of success.

The average annual sediment discharge for long periods of time may be computed from reservoir surveys if adequate data on reservoir deposits and on sediment outflow are available. This procedure provides information on long-term sediment yields of drainage basins. The data, however, cannot usually be related to runoff events and therefore the procedure has limited use for determining sediment discharge.

Records of sediment discharge data published in the United States Geological Survey Water-Supply Papers have been limited largely to information on the suspended load. Practical methods for converting these data to total load vary in application. Stevens (1946) in a review of the data for the Colorado River basin, arbitrarily added a bed load correction of 15% to the suspended load to obtain total load.

Lane and Borland (1951) discuss the many factors to be considered in estimating the rate of bed load movement and conclude that it is not possible to develop a simple rule or formula that will give quantitative values for all streams. These conclusions have been summarized by Thomas Maddock, Jr. in Table 3.2.

The sand-transport curve method provides a procedure for converting daily values of suspended-sediment discharge to total sediment discharge for sand bed streams. Using a graphical procedure, correction coefficients can be computed from total sand transport determined from empirical graphs (Colby, 1964) and suspended sand transport based on field data, i.e., concentration and particle size of suspended sands, temperature, and mean velocity. For sand and gravel bed streams, the Meyer-Peter, Muller bed load formulas (Sheppard, 1960) are often used to compute the bed load discharge.

B. RESERVOIR DEPOSITS

6. General

This section discusses the field measurement techniques to determine the volume occupied by sediments deposited in

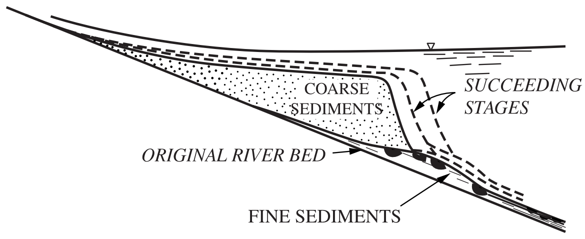

Figure 3.30 Profile of typical reservoir delta.

a reservoir. Also included are descriptions of some of the field equipment and office computational procedures used in the sediment volume determination. The process of applying the field measurement techniques, office procedures, and equipment results in a "reservoir sediment survey." The United States Army Corps of Engineers (1961) aptly defines a sediment survey as "a term applied to an individual reservoir sedimentation investigation, interpreted broadly to include office work, laboratory analyses of sediment samples, field measurements, and processing and analysis of data."

As a stream enters a reservoir, the flow depth increases and the velocity decreases. This causes a loss in the transporting capacity of the stream and the deposition of at least some of the waterborne sediments. Sediments carried into the reservoir may deposit throughout its full length. The pattern of deposition generally begins with the coarser sediments dropping in the reservoir headwaters area. This sedimentation process, described as aggradation, continues progressively until a delta is formed (see Chapter V, Section E). The finer sediment particles may be transported by density currents down to the dam, thus completing the depositional pattern. Fig. 3.30 shows a profile sketch of a typical reservoir delta (Bondurant, 1955). Aggradation in the stream channel can occur for long distances above the reservoir because of the reduction in velocity and sediment transporting capacity of the stream in this reach.

Sediment surveys determine not only the volumetric reduction in the reservoir but also furnish other valuable information and data. Such information includes how the sediment deposits are distributed in the reservoir and what change the stream channel has undergone owing to sediment transport and deposition. Field data collected during surveys are analyzed to include the specific weights of the deposits and their grain-size distribution, sediment yield rates of the drainage area, reservoir trap efficiencies, density currents, and other sedimentation features of lacustrine deposits.

7. Frequency of Surveys

The frequency of surveys generally depends upon the estimated rate of sediment accumulation in the reservoir. It follows then that reservoirs with high depositional rates are surveyed more often than those with low rates. Financing the cost of the survey is often a controlling factor in how frequently surveys are made. Considering that the cost of the survey is justified by the need to continue updating the reservoir capacity, a suggested guide to the frequency is a 5-yr to 10-yr interval depending upon the runoff inflow volume and magnitude of flows. Also, the frequency might be fixed by the period when the total reservoir capacity is reduced by some given percentage based upon the estimated sediment accumulation rate. Survey intervals can be influenced by special circumstances such as: (1) Following the occurrence of a major flood; or (2) timing the survey to update the capacity of a reservoir that has had its drainage area reduced by the construction of a dam upstream.

Some of the following suggested methods can be used as aids in determining how frequently sediment surveys should be made to ascertain the reservoir storage depletion: (1) Records obtained at sediment stations above the dam; (2) field observations of the reservoir area when the reservoir is drawn down (Murthy, 1971); (3) a check on the accuracy of the reservoir capacity curve when computing inflow-outflow volumes during operation studies; (4) reconnaissance measurements on a few index reservoir sediment ranges; and (5) when special problems associated with reservoir sediment deposition are indicated.

Guernsey Reservoir operated by the United States Bureau of Reclamation on the North Platte River, Wyoming, is cited as an example of scheduling surveys. The original total reservoir capacity in 1927 was 73,810 acre-ft. Knowing the reservoir was located on a heavily sediment-laden river, it followed that the capacity should be depleted at a high rate. This would, in turn, affect the reservoir operational plan including both power generation and irrigation. Partial or full-scale surveys were run eight times between the 1927 and the 1966 survey. The surveys were run at frequent intervals because of the need to provide current capacity data for efficient reservoir operation. The capacity was reduced to 45,228 acre-ft by 1966. Glendo Dam constructed on the North Platte River 16 miles upstream was closed in 1958. It reduced the drainage area above Guernsey Reservoir from 5,400 sq miles to about 700 sq miles. The 1957 Guernsey Reservoir survey was run to determine how the sediment accumulation rate was affected as the result of the closure of Glendo Dam. The total loss in reservoir capacity between 1927 and 1966 amounted to almost 39% or 0.97% annually, indicating a high sediment accumulation rate.

8. Equipment for Surveys

Establishing horizontal and vertical control using standard surveying procedures is a necessary first step in running an accurate sediment survey. The equipment used varies in type depending upon the size of the reservoir. Most reservoirs regardless of their size would require standard surveying equipment, e.g., transits, levels, plane tables and alidades, and stadia rods. Field books that contain data from prior surveys, a base map or aerial photograph, if available, are also necessary for making an adequate reservoir sediment survey. A dry reservoir could be surveyed with this equipment but other apparatus would be needed if sediment samples were to be obtained. For large reservoirs, it is usually more economical to delay the initial survey of the reservoir sediment ranges until the pool is at least partially filled so that much of the work can be done with sonic sounders. Where part or all of the reservoir basin is submerged, special equipment is needed including a boat or raft and auxiliary equipment, sonic sounding equipment, distance measuring instruments, and sampling equipment to determine the specific weight of deposited sediments.

With the advent of more sophisticated electronic instrumentation, survey equipment has been and is being developed to make field measurements and to prepare field data directly for computer processing. For example, direct readings of sounding depths and stationing location can now be stored on magnetic tape in the field for later processing by computer. Another example of such techniques is given in Engineering News Record (1966) which describes briefly an on-shore method of plotting the sounding boat positions using electronic equipment to measure distances and bearings. The author of this article subsequently developed a procedure that records the soundings of survey ranges to true scale on the sounder chart.

Boat or Raft and Auxiliary Equipment To run a survey of a partially or completely filled reservoir, a boat or raft is often necessary. The size of either vessel depends upon how large the reservoir is and other conditions, e.g., the physiographic setting of the lake. For small reservoirs, a shallow draft boat 14 ft long or longer would normally be adequate. Large reservoirs, correspondingly, would require larger boats and very often two boats are desirable, one to carry sounding equipment and the other to transport survey personnel. Selecting the size of a boat or raft, or both, is governed by the areal extent of the lake to be covered. For example, in very large reservoirs, such as Lake Mead, boats up to 45 ft long and barges up to 21 ft by 105 ft in plan dimension were used during the Lake Mead survey of 1963–1964 and the survey of 1948–1949 described by Smith, et al. (1960).

Rafts are generally more suitable than single boats for sediment sampling operations because of their stability. A suitable raft can be formed by two boats fastened together using planks or a platform as shown in Figs. 3.38 and 3.47. Launches 40 ft long or longer, equipped with booms for handling equipment, have proved adequate for surveys on very large lakes. In most cases the smaller lake vessels are propelled by an outboard motor. A set of oars is needed in case the motor fails or the water is too shallow to accommodate a motor.

Trailers, usually attached to a truck or other heavy vehicle, are required for transporting the large boats or rafts. Small lightweight boats can be transported satisfactorily on ordinary passenger cars by means of top racks. Two-way radios are generally required to maintain communication between shore parties and boat personnel.

Sounding Equipment Sonic sounders are currently (1973) used to run most sediment surveys of both small and large reservoirs. Manually operated sounding lines and sounding poles used in the past to survey small reservoirs are virtually outdated and replaced by modern sonic sounders.

A sonic sounder is very necessary where an extensive program is planned. It is a portable recording instrument designed to measure water depths by projecting a high energy acoustical signal downward, from just below the water surface, and receiving the signal reflected off the reservoir bottom. Measuring the depth of water depends on the speed of sound through the water. For known reservoir water temperature and salinity conditions, the speed of sound through water is governed so the time interval occurring between the projected and receiving signal relates directly to water depth. Through complex electronic and mechanical components, depths are continuously recorded on a chart as the boat transporting the sonic sounder traverses a predetermined course across the reservoir. Modern, although expensive, instrumentation also permits the recording of depths on magnetic tape for later direct processing into computer format.

The sonic sounding instrument consists of three units: (1) The recorder housed in a protective metal case includes the mechanical recording components and the electronic phasing, keying, and power circuitry; (2) the transmitting-receiving transducers can be mounted in the hull of the boat as shown in Fig. 3.31 or suspended over the side as shown in Fig. 3.32 (Rausch and Heinemann, 1968); and (3) a power source which may be either a wet cell battery or a generator-converter combination depending upon the size of vessel used. Transducers weighing less than 3 lb and much smaller in size than those shown in Figs. 3.31 and 3.32 are currently (1973) being manufactured. Necessary auxiliary components include a check bar to verify the sounder accuracy and a thermometer to measure the reservoir water temperatures. Usually the salinity content of fresh water reservoirs is negligible or constant for extended periods; however, if it is significant or variable, a conductance meter is needed to establish a correction factor for the speed of sound through water.

The depth of water is recorded continuously, at a rate of several hundred soundings per minute, on a chart that is moved at a uniform speed past the "printer" mechanism. Several chart paper speeds are available on some sounders to expand or contract the degree of individual sounding detail. The recorder paper is generally backed with a metallic coating. The printer mechanism causes an arc when the return echo is received and a print mark is burned into the paper representing the measured depth. Also recorded on this chart at selected intervals is the location of the sounding by a vertical fix line traced fully across the chart. The fix line actuated

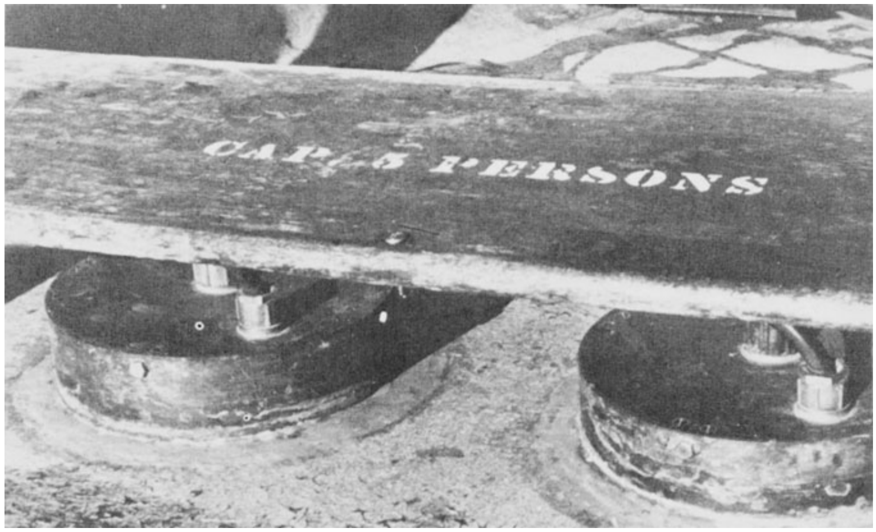

Figure 3.31 Transmitting and receiving transducers mounted in boat hull (Photograph by United States Bureau of Reclamation).

mechanically by either manual or automatic operation represents a known location along the sounding track. An example of a sonic sounding chart in Fig. 3.33 (Rausch and Heinemann, 1968) includes the appropriate notations of the water depths, fix distances, and reservoir bottom. The three lower recordings that decrease in intensity are echoes. These echoes or strays are generally the result of having the gain too high on the recorder.

Three additional comments on sonic sounder operation are considered pertinent. Firstly, the sonic wave projected from the transducer is emitted in the shape of a cone. The diameter of this cone enlarges with depth but is dependent upon the degree of power or "gain" setting of the recorder. At greater depths or lesser "gain" settings some of the sound wave is lost and does not return to the transducer. An important fact to acknowledge is that the highest reflecting point within the sound

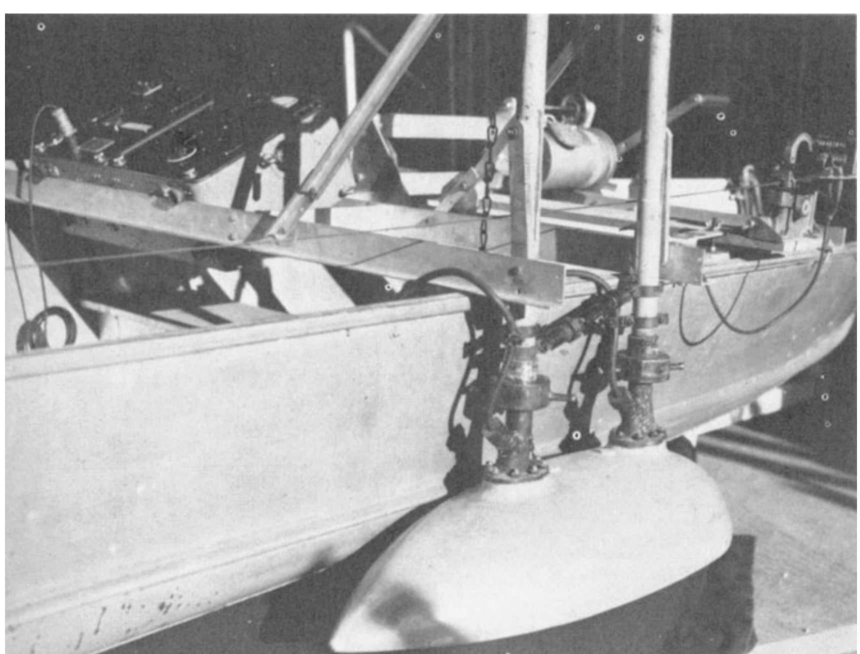

Figure 3.32 Transducer attached to side of boat (Photograph by United States Bureau of Reclamation).