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Techniques of Water-Resources Investigations of the U.S. Geological Survey

Book 3, Applications of Hydraulics

Chapter C2

Field Methods for Measurement of Fluvial Sediment

By Thomas K. Edwards and G. Douglas Glysson

This manual is a revision of "Field Methods for Measurement of Fluvial Sediment," by Harold P. Guy and Vernon W. Norman, U.S. Geological Survey Techniques of Water-Resources Investigations, Book 3, Chapter C2, published in 1970.

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depth limit of the depth-integrating sampler, the observer should try to obtain a sample by altering the technique to collect the most representative sample possible. The best collection technique under these conditions would be to depth integrate 0.2 of the vertical depth (0.2*d*), or a 10-foot portion of the vertical. These samples then can be checked and verified by collecting a set of reference samples with a point-integrating sampler. By reducing the sampled depth during periods of high flow, the transit rate can be maintained at 0.4 V_m or less in the vertical, and a partial sample can be collected without overfilling the sample container, even under conditions of higher velocities that usually accompany increases in discharge.

Sampling Frequency, Sediment Quantity, Sample Integrity, and Identification

Sampling Frequency

When should suspended-sediment samples be taken? How close can samples be spaced in time and still be meaningful? How many extra samples are required during a flood period? These are some questions that must be answered because timing of sample observations is as important to record computations (see Porterfield, 1972) as is the technique for taking them. Answering such questions is relatively easy for those who compute and assemble the records because they have the historical record before them and can easily see what is needed. However, the field person frequently does not have this record and certainly cannot know what the conditions will be in the future.

Observers should be shown typical hydrographs or recorder charts of their stations or of nearby stations to help them understand the importance of timing their samples so that each sample yields maximum information. The desirable time distribution for samples depends on many factors, such as the season of the year, the runoff characteristics of the basin, the adequacy of coverage of previous events, and the accuracy of information desired or dictated by the purpose for which the data are collected.

For many streams, the largest concentrations and 70 to 90 percent of the annual sediment load occur during spring runoff; on other streams, the most important part of the sediment record may occur during the period of the summer thunderstorms or during winter storms. The frequency of suspended-sediment sampling should be much greater during these periods than during the low-flow periods. During some parts of these critical periods, hourly or more frequent sampling may be required to accurately define the trend of sediment concentration. During the remainder of the year, the sampling frequency can be stretched out to daily or even weekly sampling for adequate definition of concentration. Hurricane or thunderstorm events during the summer or fall require frequent samples during short periods of time. Streams having long periods of low or intermittent flow should be sampled frequently during each storm event because most of the annual sediment transport occurs during these few events.

During long periods of rather constant or gradually varying flow, most streams have concentrations and quantities of sediment that vary slowly and may, therefore, be adequately sampled every 2 or 3 days; in some streams, one sampling a week may be adequate. Several samplings a day may occasionally be needed to define the diurnal fluctuation in sediment concentration. Fluctuations in power generation and evapotranspiration can cause diurnal fluctuations. Sometimes diurnal temperature fluctuations result in a snow and ice freeze/thaw cycle causing an accompanying fall and rise in stage. Diurnal fluctuations also have been noted in sand-bed streams when water-temperature changes cause a change in flow regime and a drastic change in bed roughness (Simons and Richardson, 1965).

The temporal shape of the hydrograph is an indicator of how a stream should be sampled. Sampling twice a day may be sufficient on the rising stage if it takes a day or more for a stream to reach a peak rate of discharge. During the peak, samples every few hours may be needed. During the recession, sampling can be reduced gradually until normal sampling intervals are sufficient.

The sediment-concentration peak may occur at any time relative to the water discharge; it may coincide with the water-discharge peak or occur several days prior to or after it. Hydrographs for large rivers, especially in the Midwest, typically show water-discharge peaks occurring several days after a storm event. If the sediment concentration has its source locally, the sediment peak can occur a day or more prior to the water-discharge peak. In this case, the receding limb of the sediment-concentration curve will nearly coincide with the lagging water-discharge peak. In this event, intensive sampling logically should be done prior to the water-discharge peak. Detailed sampling of hydrograph peaks during the initial stages of a monitoring program will help determine when the sediment-sampling frequency should be increased and decreased in order to optimize the sediment-sampling effort relative to peak-flow conditions.

Intermittent and ephemeral streams usually have hydrograph traces in which the stage goes from a base flow or zero flow to the maximum stage in a matter of a few minutes or hours, and the person responsible for obtaining the samples frequently does not know when such an event is to occur. A sampling scheme should be designed to define the sediment discharge by taking samples during the rising stage, then the peak stage and the recession. Generally, adequate coverage of the peak is obtained if samples on the rising limb are four times as frequent as samples collected during the recession. For example, if the recession is best sampled on a bi-hourly basis, the rising limb should be sampled every one-half hour.

Elaborate and intensive sampling schedules are not required for each and all events on small streams that drain basins of rather uniform geologic and soil conditions because similar runoff conditions will yield similar concentrations of sediment for the different runoff events. Once a concentration pattern is established, samples collected once or twice daily may suffice, even during a storm period (Porterfield, 1972).

Streams draining basins with a wide variety of soils and geologic conditions and receiving uneven distributions of precipitation cannot be adequately sampled by a rigid, predetermined schedule. Sediment concentration in the stream depends not only on the time of year, but also on the source of the runoff in the basin. Thus, each storm or changing flow event should be covered as thoroughly as possible, in a manner similar to that described for intermittent and ephemeral streams.

The accuracy needed in the sediment information also dictates how often a stream should be sampled. The greater the required accuracy and the more complicated the flow system, the more frequently it will be necessary to obtain samples. This increase in sampling frequency—with the added costs of laboratory analysis—greatly increases the cost of obtaining the desired sediment information. Often, however, the record may actually cost less when adequate samples are collected than when correlation and other synthetic means must be used to compute segments of a record because of inadequate sampling.

Stream-sediment stations may be operated or sampled on a daily, weekly, monthly, or on an intermittent or miscellaneous schedule. Usually, those operated on a daily basis are considered adequate to yield the continuous record. One should be mindful that each sample at a specific station costs about the same amount of money, but the amount of additional information obtained often decreases with each succeeding sample after the first few samples are taken. Sometimes samples obtained on a monthly basis yield more information for the money than those from a daily station, although there is a danger that too little information may be of no value or may even be misleading. For a given kind of record, the optimum number of samples should be a balance between the cost of collecting additional samples and the cost of a less precise record.

The frequency of collection of bed-material samples depends upon the stability of the streambed at the sample site. In many cases, seasonal samples may be adequate to characterize the distribution among particles comprising the bed. However, samples should be obtained whenever possible during high-flow events in order to describe the composition of bed material as compared to its composition during periods of normal or low flow. Particularly important is the collection of bed-material samples following high flows that have inundated the flood plain and greatly altered the streambed configuration.

Sediment Quantity

Previous sections discussed the number of sampling verticals required at a station to obtain a reliable sediment-discharge measurement or a sample of the cross-sectional concentration. The number of cross-sectional samples required to define the mean concentration within specific limits also has been discussed. The requirements in terms of quantity of sediment for use in the laboratory to determine particle-size gradation may at times exceed the other requirements for concentration. The size range and quantity of sediment needed for the several kinds of sediment analyses in the laboratory are given in table 3. The desirable minimum quantity of sediment for exchange capacity and mineralogical analyses is based on the requirements for radioactive cesium techniques described by Beetem and others (1962).

To estimate visually the quantity of sediment entrained in a sample or series of sample bottles

Table 3. The desired quantity of suspended sediment required for various sediment analyses

[mm, millimeter; g, gram]

Analysis	Size range (mm)	Desirable minimum quantity of sediment (g)
Size:		
Sieves:		
Fine	0.062–0.5	0.07
Medium	0.25–2	.5
Coarse	1.0–16	20
Visual accumulation tube:		
Smallest	0.062–0.5	.05
Largest	0.062–2	5
Pipette	0.002–0.062	[1].8
Bottom withdrawal tube	0.002–0.062	[1].5
Exchange capacity:		
Fine	0.002	1
Medium	0.002–0.062	2
Coarse	0.062–2	10
Mineralogical:		
Fine	0.002	1
Medium	0.002–0.062	2
Coarse	0.062–2	5

[1] Double the quantities shown if both native and dispersed media are required.

requires considerable experience. It also is difficult to determine what portion of the total sample is sands (greater than 0.062 mm) because the proportion can be different from stream to stream and from time to time in the same stream. To aid in estimating such sediment quantities, it is helpful to have, in the office or laboratory, reference bottles with various known quantities and concentrations for visual inspection. The number of bottles of sample, the amount of sand, and sample concentration needed for a given kind of analysis are shown in figure 44 (G. Porterfield, written commun., 1968).

Although it is possible to conduct the laboratory operation for particle-size analysis in a manner that also will give the sediment concentration, it is best to obtain separate samples for size analysis and concentration analysis. Such "special" samples should be plainly labeled. Generally, it is desirable to instruct the observer to collect additional samples for particle-size analysis.

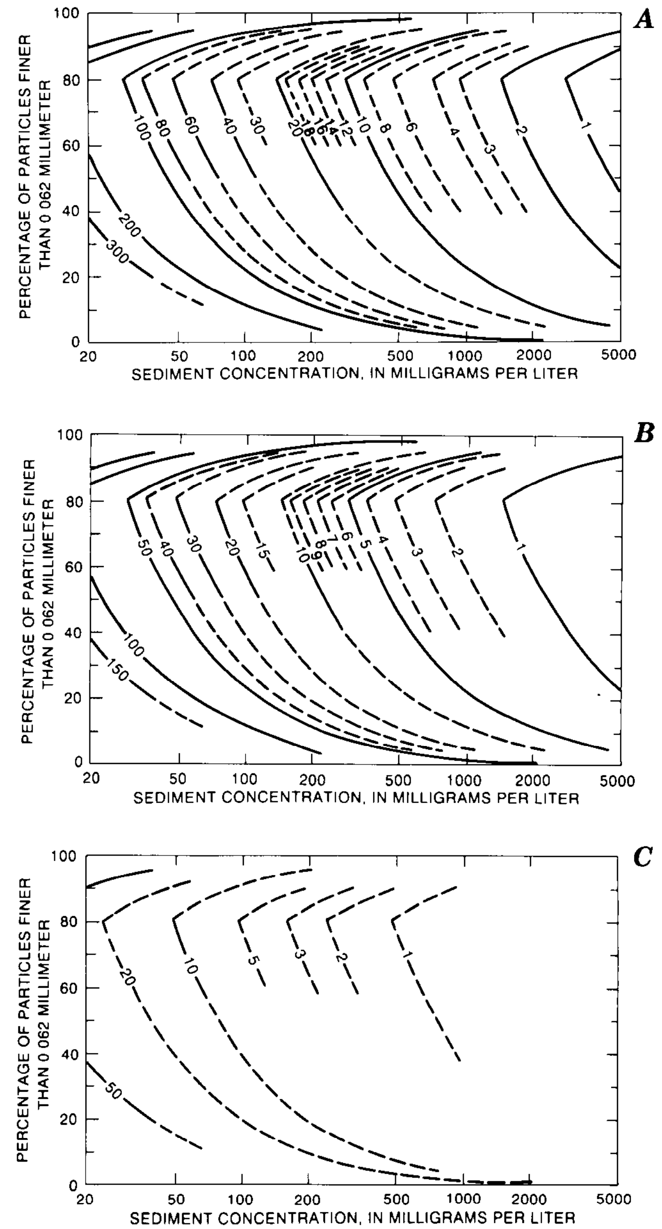


Figure 44. Minimum number of bottles containing optimum sample volume needed to yield sufficient sediment for size analysis (from Porterfield, 1972). *A*, Pint bottles each containing 400 milliliters with 1.0 gram of sediment. *B*, Quart bottles each containing 800 milliliters with 2.0 grams of sediment. *C*, Three-liter bottles each containing 2,400 milliliters with 3.0 grams of sediment.

Sample Integrity

Every sample taken by a field person should be, as previously indicated, the best sample possible considering the stream conditions, the available equipment, and the time available for sampling. Because sampling errors on sand-bed streams frequently occur in the dune regime where the nozzle of the sampler can accidentally pick up sand from the downstream side of a dune, each sample bottle must be inspected in the field immediately after removing it from the sampler. The cost of the field and laboratory work, to say nothing of the embarrassment of a bad record, is sufficient incentive to make this simple check and, if necessary, to collect another sample.

After the first bottle is taken, it can be checked by swirling the contents of the bottle, then holding the bottle where the sand on the bottom can be seen moving. A mental note is made of the quantity of sand contained in the bottle. The second and remaining bottles then can be examined and compared with the previous bottles. Any vertical or verticals where a bottle or bottles contain a significantly different quantity of medium and coarse sand should be carefully resampled. If the check sample also contains a noticeably different amount of sand in comparison to others in the set, retain both bottles and note that the high or low concentration of sand is consistent at the vertical or verticals in question. If the check sample contains a smaller or more representative amount of sand, or if the quantity of sand is different from the first but still not normal, it may be desirable to wait several minutes to take a third bottle on the assumption that the dune face would move beyond the sample vertical. This procedure is qualitative, however, and it must be noted that the extremely high errors are more likely to be detected by this method than are small errors.

A more subtle error in sample concentration may occur when a bottle is overfilled. This error also results in too high a concentration, possibly caused by overfilling the sample bottle. Such a sample should be discarded and another sample obtained using an increased transit rate. If the transit rate or the nozzle must be changed to avoid overfilling during an EWI measurement, then it is best to discard any previous samples and resample in clean bottles. The computations required to make use of an EWI measurement having two transit rates are more costly and error prone than the minor expense of discarding samples.

Sample Identification

Although most of the information needed on sample bottles is indicated by figure 27, other information may be helpful in the laboratory and in records processing. The field person will need to keep the requirements for such processing in mind so that other explanatory notes can be recorded on the sample or inspection sheets (fig. 45). Such notes, some of which have been mentioned previously, may include:

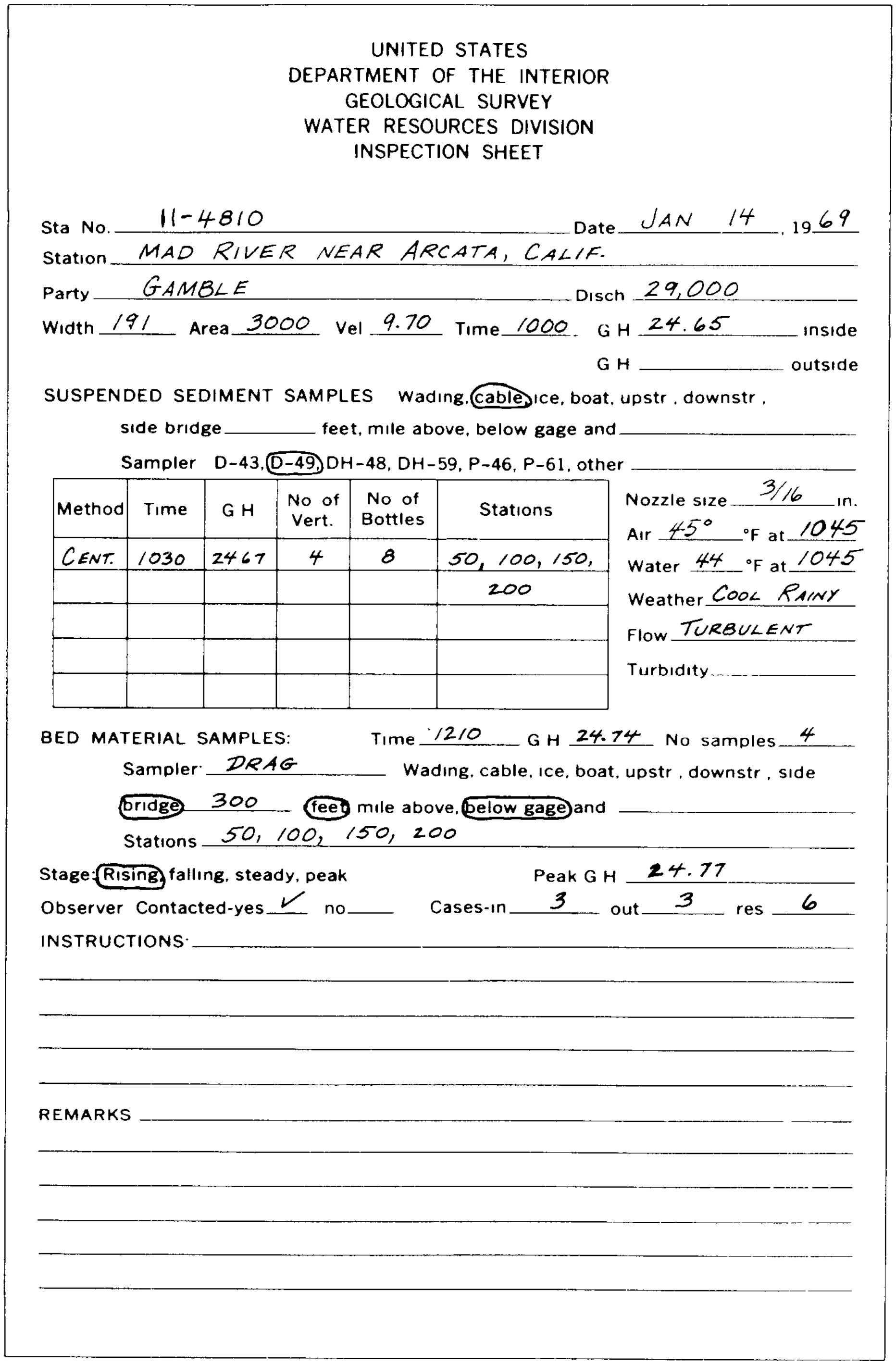
1. Time—Sometimes operations cross zone boundaries or the use of daylight time may cause confusion.
2. Method or location—Routine vertical, EDI, or EWI cross-section sample.
3. Stationing—Is it one location or sampling vertical, or is the sample an accumulation of several verticals at different locations?
4. Unusual sample conditions—Consistent sampling of sand at this location: surface sample or dip sample.
5. Variation of desired technique—Such as change of transit rate, change of sampling vertical location, depth somewhat beyond capacity of instrument, or transit rate may have exceeded 0.4 V_m.
6. Condition of stream—Such as boils noted on water surface, soft dune bed, swift smooth water, braided stream, sandbar in cross section, or slush ice present.
7. Location in the vertical—If a point sampler is used for one-way integration, mention which direction the sampler was moving, the depth dividing the integrated portions, and the total depth.
8. Gage height—Note if the inside or outside gage was used. Note any unusual conditions that may affect the reading.
9. Collector's name.

Sediment-Related Data

Water Temperature

Water-temperature data may seem unimportant in comparison with the sediment data. However, it has a growing list of uses besides the need to help evaluate the sediment-transport characteristics of the stream. The temperature or viscosity of the flow affects sediment suspension and deposition and may affect the roughness of a sand-bed stream.

The best or preferred method to obtain the correct water temperature is to submerge the thermometer while wading some distance out in the stream. The thermometer is held beneath the water for sufficient time (about one-half minute) to allow the temperature of the thermometer to equalize with the water temperature. The stem or the scale of the thermometer is raised out of the water and held so that the etched scale



UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY
WATER RESOURCES DIVISION
INSPECTION SHEET

Sta No. 11-4810 Date JAN 14, 1969

Station MAD RIVER NEAR ARCATA, CALIF.

Party GAMBLE Disch 29,000

Width 191 Area 3000 Vel 9.70 Time 1000 G H 24.65 inside

G H ____ outside

SUSPENDED SEDIMENT SAMPLES Wading, [✓ cable], ice, boat, upstr, downstr, side bridge ____ feet, mile above, below gage and ____

Sampler D-43, [✓ D-49], DH-48, DH-59, P-46, P-61, other ____

Method	Time	G H	No of Vert.	No of Bottles	Stations
CENT.	1030	2467	4	8	50, 100, 150,
					200

Nozzle size 3/16 in.

Air 45° °F at 1045

Water 44 °F at 1045

Weather COOL RAINY

Flow TURBULENT

Turbidity ____

BED MATERIAL SAMPLES: Time 1210 G H 24.74 No samples 4

Sampler DRAG Wading, cable, ice, boat, upstr, downstr, side [✓ bridge] 300 [✓ feet] mile above, [✓ below gage] and ____

Stations 50, 100, 150, 200

Stage: [✓ Rising], falling, steady, peak Peak G H 24.77

Observer Contacted-yes ✓ no ____ Cases-in 3 out 3 res 6

INSTRUCTIONS ____

REMARKS ____

Figure 45. Example of inspection sheet for use by field person to record the kinds of measurements made and the stream conditions observed during a visit to a sediment-measurement site.

on the stem is at right angles to the line of sight; the temperature then should be read to the nearest one-half degree. The bulb of the thermometer should always remain in the water until after the reading is obtained. The reading of a wet thermometer when exposed to the air may decrease several degrees in a matter of seconds because of evaporation, if the air is dry, or the wind is blowing. Be certain that the location in the stream where the temperature is taken is not affected by the inflow from a spring or tributary.

When it is not possible to wade out into a stream, the water temperature may be taken from a sample bottle. The thermometer should be inserted first into a bottle from near midstream to let the thermometer adjust to the approximate temperature. Then, immediately after removing the next bottle from the sampler, transfer the thermometer from the previous bottle and allow about 15 seconds for the temperature to stabilize. The thermometer should be read while the bulb of the thermometer is submerged. When removing the thermometer from a bottle, lift the thermometer about 2 inches from the bottom and shake slightly to remove sediment from the case of the thermometer. Most freshwaters freeze at 0°C; therefore, if a negative reading is obtained, an error is indicated. Brackish and brine waters freeze at temperatures somewhat less than 0°C, depending on the kind and concentration of ions present.

Stream Stage

As with temperature, stream-stage data may seem insignificant but in reality can be very important. The data may be used to construct missing gage-height records for periods of recorder failure or to verify time of sampling. Gage heights also may serve to indicate whether the observer actually obtained a sample at the time and in the manner indicated by available notes.

Remember that the gage height is defined as the water-surface elevation referred to some arbitrary gage datum. For the gage height to be considered correct, the observer or field person should always note which gage is read. The streamflow and sediment records are computed on the basis of the inside or recording gage. The observer is usually instructed to read only the outside or reference gage. Because of differences in location and the effect of velocity head, it is not expected that both gages will read the same at a given time, although some relation may exist between them as the stage changes (Buchanan and Somers, 1968; Carter and Davidian, 1968). The field person should record all stream-stage information on the inspection sheet (fig. 45).

The outside reference gage may be one of two types. The most common of those exposed continuously to the flowing stream are the staff gage and the slope gage. Under turbulent flow conditions, these exposed gages should be read by noting the average of several high and low readings made within a period of 10 or 15 seconds. It is necessary to make certain that the observers understand that the scale is divided into hundredths of a foot and not feet, inches, and fractions of an inch, and that they understand the divisions of the metric system if that is used. The other type of outside gage is the wire-weight gage or chain gage that is usually attached to a bridge railing. The weight from this type of gage is lowered so that its bottom breaks the water surface about one-half the time when there are water waves or ripples. For the wire-weight gage, the gage height is read on the scale of the drum at the pointer. For the chain gage, the reading is obtained by reference to the scale provided.

The inside gage height is usually referenced by tape from a float in a stilling well to a pointer. The stilling well is connected hydraulically to the flow of the stream. The inside reference gage should correspond to the gage height being recorded, but, as mentioned previously, it may vary somewhat from the outside gage. If the variance between inside and outside gages is unusually large and the inside gage is lagging the actual gage height of the stream, the intake should be flushed to remove any obstruction caused by sediment accumulation.

The field person should record the inside gage reading at least once each visit to ensure that the gage is working properly. Also, if the observer uses the outside gage, the field person should record the readings from both the outside and the inside gages.

Cold-Weather Sampling

Subfreezing temperatures can cause surface ice, frazil ice, and anchor ice to form on or in a stream and create many difficulties with regard to suspended-sediment sampling. The surface ice usually forms at the edges of the stream first and covers the midstream part last. If it is necessary to use surface ice for support to make holes for sampling, extreme caution should be exercised because the strength of such ice can be deceiving, especially if weakened during alternating freezing and warm periods. If these auger holes are to be reused later, a cover of wood or some other low-cost insulating material can be used to protect them from refreezing. However, it should be realized that covers of this type may be lost if the weather warms sufficiently for the ice to break up. In some cases (to avoid walking out on the ice or if a warming trend is expected), it may be possible to prevent loss by attaching the cover to a line or to the sampler cable to allow its easy removal. If the sampler cable is used for this purpose, however, the sampler should be secured to or removed from the sampler shelter to avoid its loss by falling through the open bottom of the shelter. Suspended-sediment samplers should never be used to break through seemingly thin ice by dropping the sampler more than 3 or 4 inches because the sampler and nozzle can be damaged by the force of the drop. If the ice will not break by the sheer weight or very gentle drop of the sampler, a hole must be opened by some other means.

If the ice is too thin to safely support a person's weight, it is best not to obtain a sample for 1 or more days because winter samples are generally low in sediment concentration and are, therefore, most certainly not worth the chance of an accident. When the spring breakup occurs, the large slabs of floating ice can easily cause damage to the sampler or the support equipment or injure the operator. Under these conditions, a surface sample may be all that can be obtained between cakes of floating ice. Every effort should be made to obtain such a surface sample because the sediment concentration can, and usually does, change considerably under such conditions.

Frazil ice is composed of the small ice crystals formed at the surface in the turbulent part of the stream. The crystals are formed in a variety of shapes, from slender needles to flat flakes. They do not freeze together because of the swift current, but may bunch together to form a soft mass. This kind of ice may partly or completely clog the intake nozzle of the sampler. Sampling may be best accomplished by moving the sampler swiftly through the layer of frazil ice and then using a normal transit rate to sample the relatively ice-free region below. Often when such ice obstructs the nozzle, it will remove itself when the sampler is brought out of the water, and the only indication that the sample is in error would be that the quantity of water in the bottle is significantly less than would be expected under normal circumstances.

Anchor ice is formed on the bottom of shallow streams by radiation of heat during the colder nighttime hours. Incoming radiation and the warmer temperatures during the day allow this ice to break loose from the bottom and float to the top to mix with the frazil ice. Sometimes, when the nozzle contains frazil or small pieces of anchor ice as the sampler is brought out of the water, a subfreezing air temperature will cause the ice to freeze tight in the nozzle. If the ice freezes tight to the nozzle or if the sample bottle freezes to the sampler casing, it will be necessary to heat the sampler, by using the heater in the field vehicle, soaking the sampler in a container of warm water, or heating the nozzle and sampler head with a small propane torch. Care must be taken when employing the torch method because the gaskets in the sampler head and plastic nozzles can be damaged by the open flame. Some of these problems can be avoided by the use of two samplers; while one is thawing, the other can be used to sample.

If the sampler or samplers are kept beneath the heater in the field vehicle while the observer drives to the station or from one station to another, the first one or two verticals can be more easily sampled. The observer should be advised and encouraged to remove the nozzle from the sampler and leave the sampler head in the open position after completing the sampling. This will allow the gasket, nozzle, and air vent to dry more completely and may avoid a frozen sampler nozzle or sampler head frozen shut on the next visit.

Aside from the problems with plugged sampler nozzles, a very cold sampler may cause freezing of water between the sample bottle and the inside of the sampler. This problem can be minimized by removing the bottle as quickly as possible from the sampler after the integration is complete; otherwise, it may be necessary to heat the sampler as described above. It also should be obvious that samples in glass bottles must be protected from freezing after the measurement and during transport to the laboratory. Freezing itself does not harm a sample for sediment analysis, but a broken bottle will obviously result in loss of the sample.

If an extensive sampling program is to be carried out during the winter months in areas of extreme cold, it is advisable for the investigator to obtain DH-75 and D-77 samplers. These samplers are designed to be used in freezing conditions, as previously discussed. Several sample bottles and nozzle and cap assemblies can be taken to the site, where they can be easily changed if nozzle or air-exhaust freezeups occur during sampling.

Bed-Material Sampling

Data on the size of material making up the streambed (across the entire channel, including flood plains) are essential for the study of the long-range changes in channel conditions and for computations of unmeasured or total load.

Materials Finer Than Medium Gravel

Selection of a suitable bed-material sampler is dependent on the size of bed material to be sampled, and on stream depth and velocity. When a stream can be waded, the most practical of the standard samplers is the BMH-53 or BMH-80 (figs. 15 and 17). When sampling from a boat, these samplers can be used to depths of about 4 feet.

In use, the BMH-53 is placed in a vertical position on the streambed with the piston extended to the open end of the cylinder. The cylinder then is pushed a full 8 inches into the bed while the piston is held at the bed surface. Complete filling of the cylinder will help ensure a minimum of disturbance of the top 1 or 2 inches when the sampler is raised through the flow. When coarse sand or gravel material is being sampled, it is often necessary to pull on the piston rod while pushing on the cylinder. By pulling on the piston, a partial vacuum is created above the sample, which helps draw the sample into the cylinder. The sampler then is withdrawn from the bed and held in an inclined position above the water with the cylinder end highest. For most purposes, only the upper inch of material nearest the surface of the streambed is desired or needed in an analysis. This is obtained by pushing on the piston while the sampler is still inclined until only 1 inch of material remains in the tube. Any excess material is removed by smoothing off the end of the cylinder with a spatula or a straight pencil. The material left in the sampler is ejected into a container (usually a paper or plastic carton). An experienced field person can composite samples from the entire cross section into just a few cartons. The inexperienced field person would do well to use a separate container for each vertical. Before storing the sampler, it should be rinsed by stroking the piston a few times in the stream to remove sediment particles from the cylinder and piston seal.

The BMH-80 is used in a manner similar to that of the BMH-53. The sampler is extended to the streambed with the bucket in the open position. After the sampler contacts the bed material, the field person should keep a firm downward pressure on the sampler while closing the sample bucket, thus trapping a shallow sample of the streambed. This sampling procedure should be repeated until the streambed has been representatively sampled.

If the stream is too deep or swift for the BMH-53 or BMH-80, the BMH-60 or the BM-54 can be used. The 30-pound BMH-60 is easiest to use when stream velocities are under 2 or 3 ft/s and depths are less than about 10 feet. To use the BMH-60, suspend the entire weight of the sampler by the hanger rod and cock the bucket in the open position with the allen wrench provided. The energy thus imparted to the spring and the sharp edge of the bucket make it obvious that one must keep hands away from the bucket opening at all times. If necessary, the safety yoke may be fastened around the hanger bar while opening and cocking the bucket. After the safety yoke is removed and fastened to the tail, the sampler then can be lowered by hand or by cable and reel to the surface of the streambed. Any jerking motions made while lowering the sampler that would cause the cable to slack may release the catch and allow the bucket to close prematurely. This can happen if the water surface is struck too hard. After the cocked sampler touches the streambed and tension is released on the line, the sampler should be lifted slowly from the bed so the bucket will scoop a sample.

To remove the sample from the bucket, a carton or container is positioned under the sampler, and the bucket is opened with the allen wrench. The sampler need not be held by the hanger bar during sample removal unless considerable material is clinging to the flat plate within the bucket cavity. If removal of such material is required, the bucket should be cocked in the open position and the sample brushed into the container with a stick or small brush. When moving the sampler between verticals and when storing it in the vehicle, the bucket should be in the closed position to avoid an accidental closing and to reduce the tension on the spring. If the bucket is closed for transport as suggested, a stick, a piece of tire, or similar material should be used to cushion the force of the bucket when it is closed because the closing force is sometimes great enough to break welded joints in the mechanism (J.V. Skinner, Federal Inter-Agency Sedimentation Project, written commun., 1985).

The 100-pound BM-54 is used when velocities are greater than 2 or 3 ft/s and depths are greater than 10 feet. The BM-54 sampling action, described previously, is similar to the BMH-60, except that the bucket opens front to back. It is used only with a cable-and-reel suspension and is rather awkward to handle when removing the sample. The techniques for taking a sample with the BM-54 are essentially the same as for the BMH-60. One important difference in operation is the use of a safety bar on the BM-54 to hold the bucket in an open position instead of the safety yoke as on the BMH-60. As noted earlier, the sampler should be stored with the bucket in a closed position and, if extended storage is anticipated, the tension on the spring should be further reduced.

A BM-54 can be used in extremely high velocities if a C-type weight is attached to the hanger bar above the sampler. If additional weights are required with the BM-54, extreme care should be taken to avoid bending and possibly breaking the hanger bar between the sampler and the C-type weight.

Personnel of F.I.S.P. have developed a heavy bed-material sampler (the BM-84, which weighs about 160 pounds). The P-61 point-integration sampler body is used to provide a large mass. The streamlined body configuration is fitted with a spring-driven sample scoop that is activated by a solenoid system similar to that used on point samplers. Otherwise, the sampler is similar to, and performs the same function as, the BM-54. The design is an attempt to cope with bed-material sampling problems encountered in the vicinity of Mount St. Helens volcano (J.V. Skinner, Federal Inter-Agency Sedimentation Project, oral commun., 1984). The weight of this configuration is increased by filling void space within the sampler body to increase the cross-sectional density of the sampler, thus increasing its stability in deep, high velocity conditions.

As previously discussed, other sampling equipment is available commercially—for example, the ponar sampler and core samplers, such as the vibra-core unit and gravity corer. These samplers can be very useful; however, careful planning of the proposed sampling project and analytical methods is essential to obtaining a representative sample and reliable data.

Materials Coarser Than Medium Gravel

Gravels in the 2- to 16-mm range can be analyzed by mechanical dry sieving; in order to obtain a representative particle-size distribution, the size of the sample to be collected must be increased with particle size. Large sediment sizes (>16 mm) are difficult both to collect and to analyze. The method now used for size determination of these very large particles involves a pebble count, in which at least 100 pebbles from a wadable streambed are manually collected and measured. A fixed grid pattern locating the sampling points can be paced, outlined by surveys, or designated by small floats. At the intersections of the fixed grid pattern, the pebble underlying the field person's toe is retrieved, and a measurement is made of the long, intermediate, or short diameters, or all three. The measurements are tabulated as to size interval, and the percentage of the total of each interval then is determined (Wolman, 1954).

Because the pebble-count method entails the measurement of the dimensions of randomly selected particles in the field, it is laborious and usually limits the number of particles counted. Too often this results in an inadequate sample of the population,

Another method for analyzing coarse particles involves the use of an instrument known as the Zeiss Particle Size Analyzer (Ritter and Helley, 1968). For the Zeiss technique, a photograph of the streambed is made during low flow with a 35-mm camera supported by a tripod about 2 meters above the streambed—the height depends on the size of the bed material. A reference scale, such as a steel tape or surveyor's rod, must appear near the center of the photograph to provide a size reference.

In the laboratory, particle diameters are registered cumulatively or individually on exponential or linear scales of size ranges (Guy, 1969). After the data are tabulated, the sizes registered on the counter of the particle-size analyzer must be multiplied by the reduction factor of the photograph, which is calculated from the reference scale in the photograph.

In nonwadable streams, a pipe dredge is useful in sampling these large particles. However, this method entails the use of equipment capable of handling extremely heavy loads and requires special attention to safety during operation.

Location and Number of Sampling Verticals

Bed-material samples are often collected in conjunction with a discharge measurement and (or) a set of suspended-sediment samples. If the discharge measurement and (or) the suspended samples are taken first, the bed-material samples should be collected at the same stations, but not necessarily from the same number of stations. By taking them at the same stationing points, any change in bed material or radical change in discharge across the stream that would affect the sediment-discharge computations can be accounted for by subdividing the stream cross section at one or between two of the common verticals.

To avoid collection of bed-material samples from an excessively disturbed streambed, it is best to obtain the bed-material samples prior to making other measurements, especially in wadable streams. Also, by taking the bed material first, radical changes across the section in bed-material size and water discharge can be used as a basis for choosing desirable verticals for other measurements.

Most results from bed-material samples will not be noticeably affected, but it should be remembered that the sample taken with the BMH-53 or other core sampler is different from that taken with the BMH-60, BMH-80, and the BM-54. The cross section of the BMH-53 or other core sampler is constant with depth so that each increment of sample with depth is equally represented by volume. The curved buckets of the BMH-80, BMH-60, and BM-54 do not sample equal volumes of material with depth; instead, the bottom one-half inch of the 2-inch-deep bucket contains only 15 percent of the total sample, whereas the upper one-half inch contains 33 percent of the sample.

The number and location of bed-material samples required at a cross section must be adequate to provide a representative statistical population. This population should include samples collected from the entire cross section. To obtain this population, the logical procedure is to use the results from a rather detailed set of 10 to 20 uniformly spaced bed-material samples taken from the cross section. Some studies may require that flood-plain deposits be represented in the bed-material sampling scheme to get a representative population.

Sample Inspection and Labeling

As samples are obtained across the stream, the field person should visually check and compare each sample with the previous samples to see if the material varies considerably in size from one location to the next. Samples of different sizes and (or) weight should not be composited. If a given sample does contain considerable coarser or finer material, another sample should be obtained about a foot from the original location. If, after two or three tries in the vicinity of the first sample, no appreciable difference is noted, the first sample should be retained. Small deposits of material that are coarser or finer than most of the bed material are not considered representative of the bed-material size for the stream cross section.

Proper labeling of bed-material samples is not only necessary for future identification but also provides important information useful in the laboratory analysis and the preparation of records. Information desired on each bed-material sample carton should include:

Station Name
Date
Time
Gage height
Water temperature
Stationing number
Bed form and flow conditions
Carton number of the set
Kind of sampler used
Purpose of sample or special instructions for analysis and computations
Initials of field person

Bedload Sampling Technique

The sediment moving in the unsampled zone (see fig. 1) comprises suspended sediment and bedload. Bedload is the sediment that moves by sliding, rolling, or bouncing along on or within a few grain diameters of the streambed.

Although many investigations have provided extensive knowledge in the areas of how bedload moves in a channel and how pressure-differential bedload samplers operate, a great deal more work in these areas is needed. The following paragraph, taken from Hubbell (1964, p. 2), is still appropriate:

> In the past, attempts have been made to determine the bedload discharge in three general ways: by direct measurement with some type of apparatus, by definition of physical relations from which the bedload could be estimated, and by quantitative measurements of the results of some sedimentation process such as erosion or deposition. Unfortunately, direct-measuring apparatus have been useful for only a very limited range of sediment and hydraulic conditions; the definition of physical relations has not been complete enough to estimate precisely the bedload discharge; and the quantitative measurements have supplied information only on the characteristics of the reach that was studied. As a result, no single apparatus or procedure, whether theoretical or empirical, has been universally accepted as completely adequate for the determination of bedload discharge over the wide range of sediment and hydraulic conditions in nature.

Despite these difficulties, the hydrologist often is called upon to provide estimates of bedload transport from measurements. The purpose of this section is not only to outline instructions governing the collection of bedload samples, but also to present a discussion of variations in bedload-discharge rate, the problems involved in collecting samples, and considerations in the design and development of a sampling program to define bedload movement.

Bedload discharge can be extremely variable. Variations can occur both spatially and temporally during steady-flow conditions, as well as with changes in stream discharge. In order to collect a sample that represents the mean bedload-discharge rate, all variations must be taken into account.

Even for constant flow conditions, the temporal variation of bedload transport rates at a given point in a cross section is quite large. When dunes are present, bedload discharges are zero, or near zero, in the troughs, increase progressively along the upstream side of the dune, and are maximum at the crest. Even in streams with gravel beds, the bedload appears to move in cycles or slugs (Emmett, 1981). These variations have been measured in the laboratory flume by Hubbell and others (1981) and in the field by Emmett (1975) and Carey (1985) (fig. 46).

Temporal variation in sampled bedload rates collected at steady-flow conditions at a single vertical are primarily dependent on the ratio of sampling time to the time it takes one dune, cycle, or slug to pass by

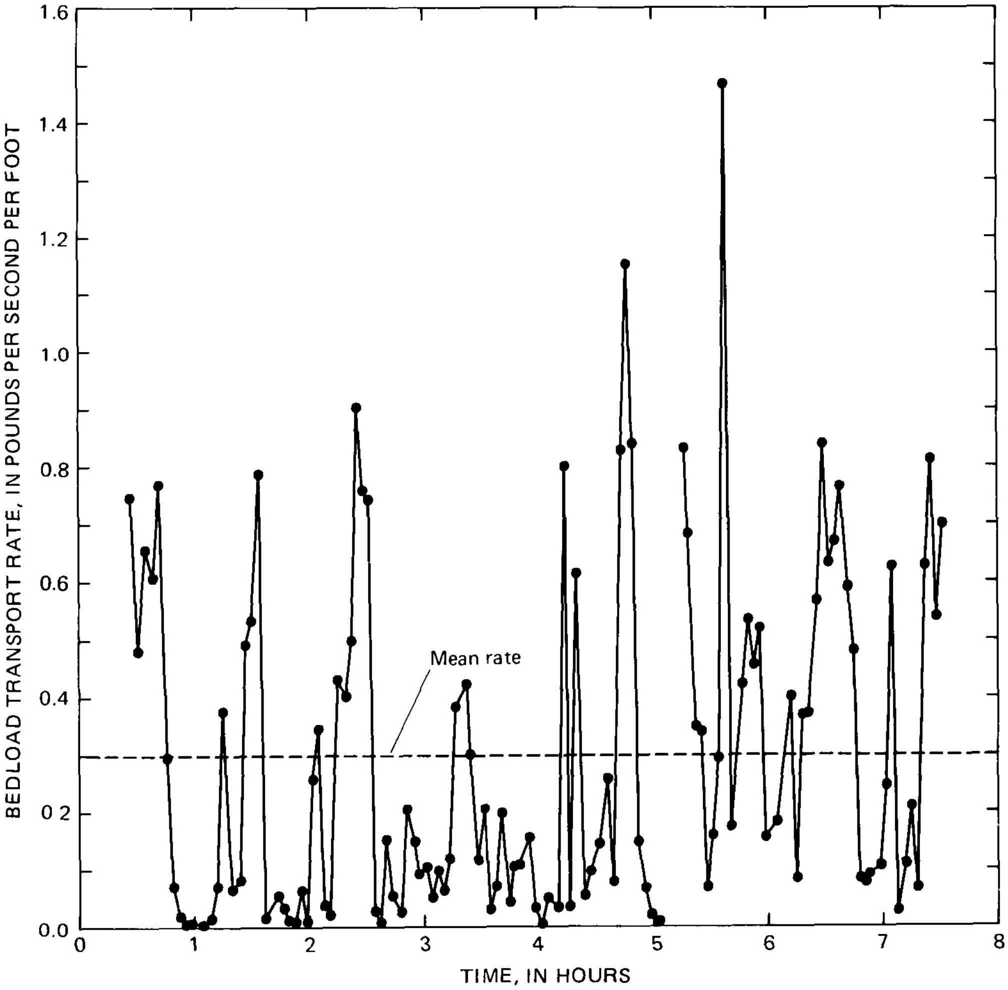


Figure 46. Temporal variation of bedload transport rates for 120 consecutive bedload samples from a stream with constant water discharge (Carey, 1985).

the sampling point. Obviously, if the sampling time were equal to the cycle period or several times greater than the cycle period, the temporal variation at a single sampling point would be small. However, as the sample time becomes less with respect to the cycle time, the temporal variation can become quite large.

Einstein (1937) and Hamamori (1962) both developed theoretical distributions to describe the temporal distribution of bedload transport rates at a vertical. Einstein based his distribution on the assumption that bedload particles move in a random series of steps and rests, with the particles generally resting a much longer period of time than they are moving. Hamamori's distribution was derived to define the temporal variation when dunes are present on the bed. Figure 47 shows a comparison of Einstein's and Hamamori's distributions. Einstein's T is defined as the nondimensional sampling time measured in terms of the average rest period. Einstein's T = 2 distribution (sample time equals the length of two average rest periods) and Hamamori's distribution are nearly identical. As T increases (sampling-time increases), the two theoretical distributions depart from one another, and Einstein's distribution indicates reduced variability.

The temporal variations in bedload transport rates measured by Carey (1985) at a single vertical in a sand-bed stream in Tennessee are shown in figure 46. The cumulative probability distribution of bedload discharges measured by Carey fit the theoretical distribution developed by Hamamori. As indicated in the figure, even for a constant flow condition, the rate determined from a sample taken from a single vertical at a point in time may differ considerably from the mean bedload discharge at that vertical. This extreme temporal variability in bedload transport rates has been known since at least 1931 (Hubbell, 1964).

The spatial or cross-channel variation in bedload discharge is usually significant. Typically, bedload transport rates vary from zero or small near banks through larger values toward midstream. The mean cross-channel distribution of bedload discharge may vary uniformly (fig. 48*A*), may be uniformly consistent (fig. 48*B*), may be erratic with varying tendencies (fig. 48*C*), or may be an unpredictable combination of varying tendencies (fig. 48*D*). Each river is likely to have a unique combination; adjacent reaches of the same river may have different configurations, and these configurations are likely to change

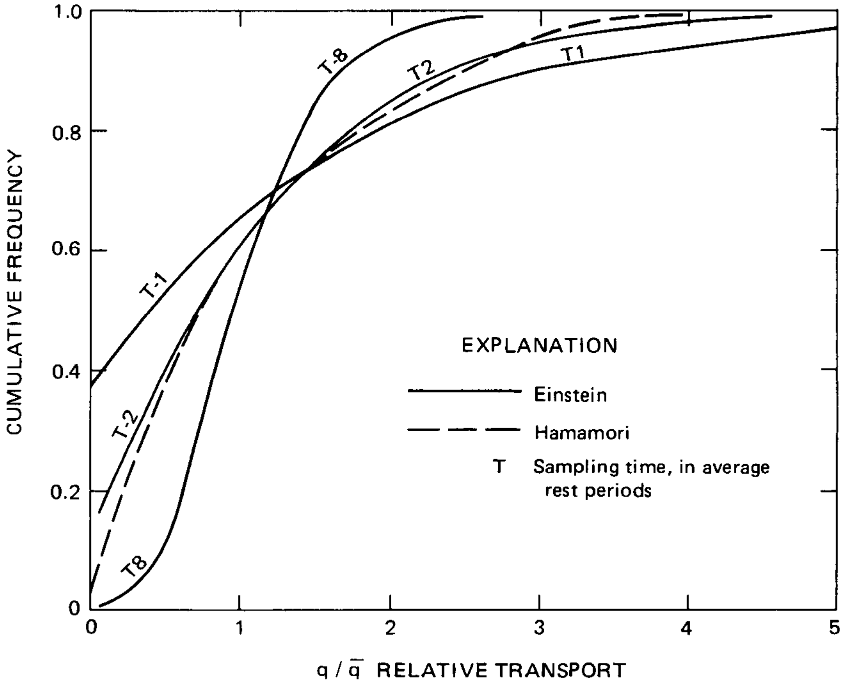


Figure 47. Comparison of cumulative probability distributions of bedload transport rates predicted by Einstein (1937) and Hamamori (1962) (D.G. McLean, University of British Columbia, written commun., 1986).

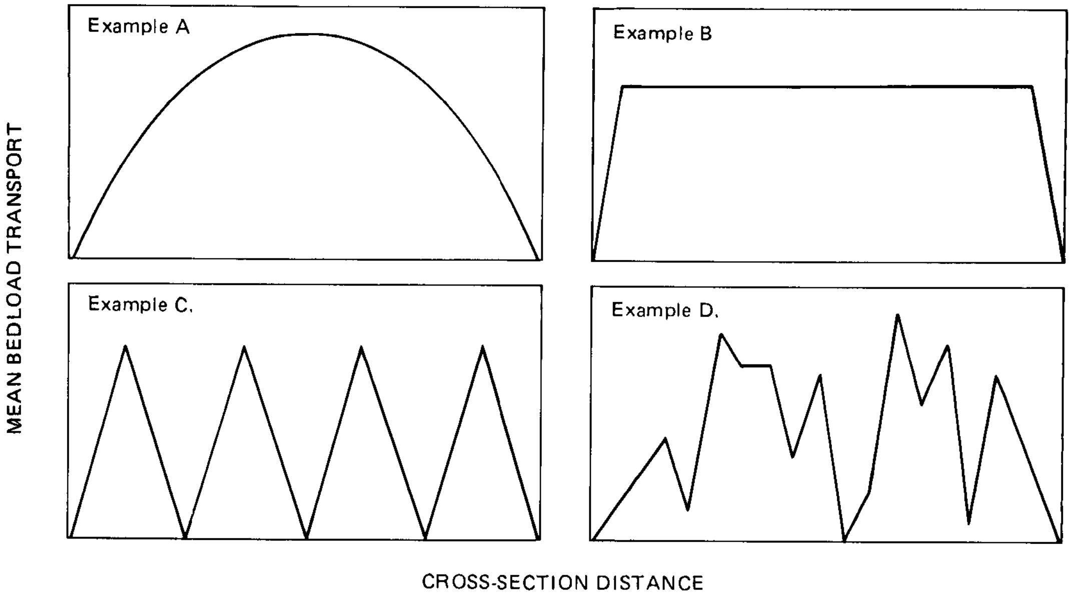


Figure 48. Examples of possible distribution of mean bedload transport rates in a cross section. *A*, Discharge varies uniformly. *B*, Discharge is uniformly consistent. *C*, Discharge is erratic with varying tendencies. *D*, Discharge is an unpredictable combination of varying tendencies.

with changing flow conditions (stages). There is little proven basis for predicting spatial variability.

The temporal and spatial variations in transport rates of bedload discharge that occur under steady-flow conditions are amplified when the stage changes rapidly. Because of these temporal and spatial variations, many samples have to be collected at many verticals in the cross section to ensure an accurate estimate of the mean bedload discharge. The samples also would have to be collected over a short enough period of time to avoid any change in transport rates due to changing stage. In most field sampling programs, the number of samples collected must represent and compromise between accuracy and economic or physical feasibility.

Another major problem encountered in bedload sampling is that of collecting a representative sample. To collect a representative sample, the sampler must (1) trap, during the sampling period, all bedload particles that would normally have passed through the width occupied by the sampler; and (2) reject all particles that normally would not have passed through the width during the same period. The degree to which this is accomplished is termed the "sampling efficiency," which is defined as the ratio of the mass of bedload collected to mass of bedload that would have passed through the sampler width in the same time period had the sampler not been there (Hubbell, 1964). For perfect representative sampling, the sampling efficiency should be 1.0 (or 100 percent) for all sizes of bedload particles in transport at the sampling point during the sampling period.

Currently, the most commonly used bedload sampler is the Helley-Smith sampler (see page 25 for discussion of recommended samplers). Over 3,000 of these samplers have been placed in use since the model was introduced in the early 1970's. It should be understood that the Helley-Smith is not a true bedload sampler because it collects some particles moving in suspension. As previously noted, bedload moves on or very near the streambed. Depending on the size of the unsampled zone, the Helley-Smith has the potential to collect a sample from the entire unsampled zone. Even if the Helley-Smith sampler has a sampling efficiency of 1.0, the total sediment discharge cannot necessarily be calculated by simply summing the measured suspended-sediment discharge and the measured bedload discharge. Figure 49 shows the percent error involved in computing total sediment discharge for a particular size range by summing the measured suspended-sediment discharge (Q_{sm}) and the bedload discharge measured with a Helley-Smith sampler (D) for that particular size range.

In order to make bedload sampling practical, methods must be used that minimize the number of samples required to obtain a reasonable estimate of the mean cross-sectional bedload discharge. Field

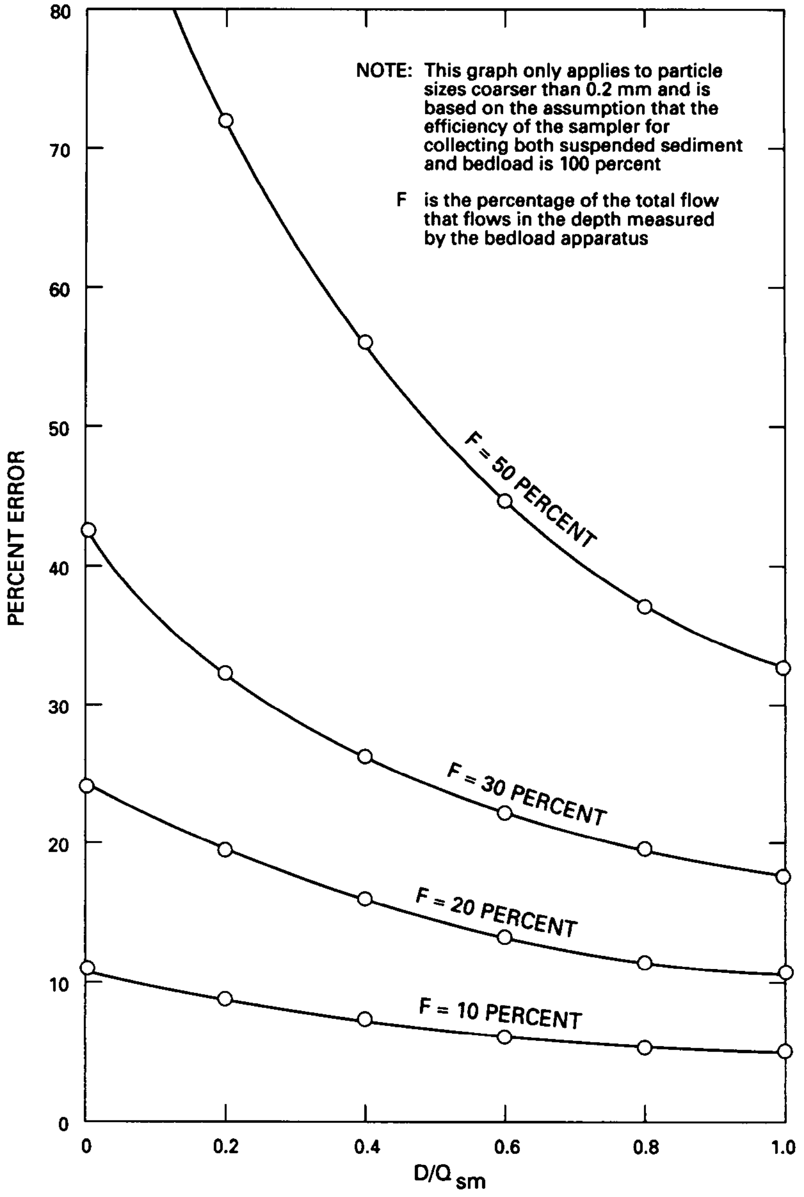


Figure 49. Percent error due to computing total sediment discharge of a size range by summing measured suspended-sediment discharge (Q_{sm}) and bedload discharge measured with a Helley-Smith sampler (D).

experience has shown that the collection of about 40 individual bedload transport rate measurements per cross-section sample is, in most cases, practical and economically feasible (Emmett, 1980a). The following general methods can be used to collect the samples.

(1) Starting at one bank and proceeding to the other, collect one sample per vertical at 20 evenly spaced verticals in the cross section, return to the bank, and repeat the process. We will refer to this method as the single equal-width-increment (SEWI) method (fig. 50). The time the sampler is left on the bottom should be equal for all verticals in a given cross section. The time the sampler is left on the bottom need not be the same for both cross sections collected. This procedure was first introduced by Emmett (1980a) and is widely used. The samples are collected at the midpoint of the evenly spaced increments. Samples collected in this manner can be composited for analytical purposes; however, a better understanding of the local bedload transport characteristics is gained if each vertical sample is analyzed individually.

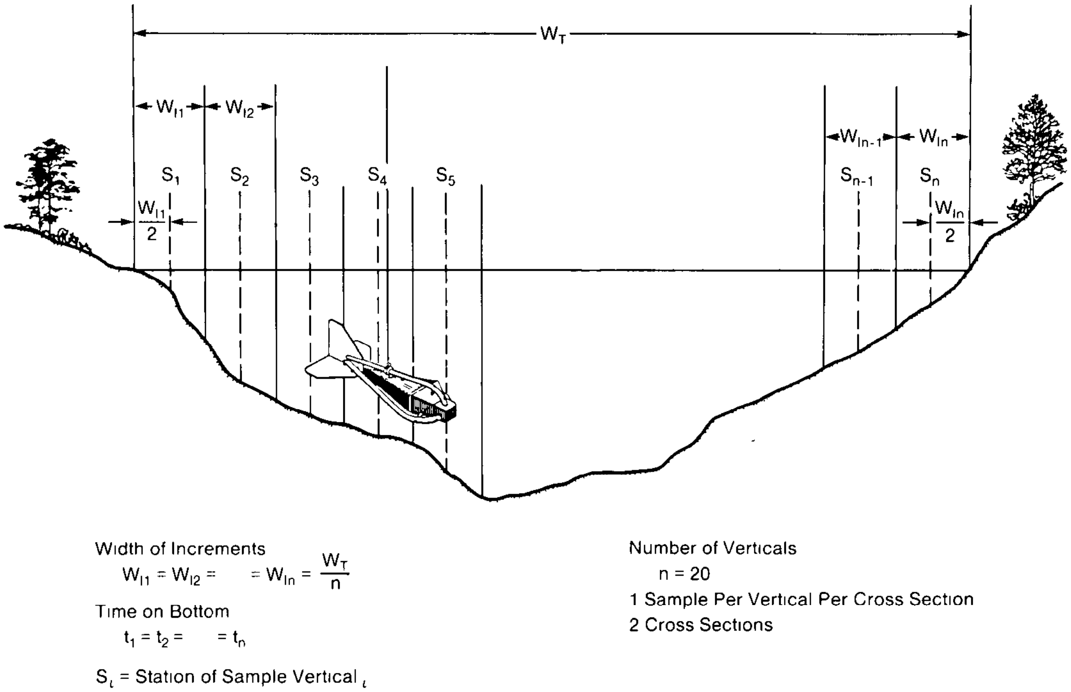
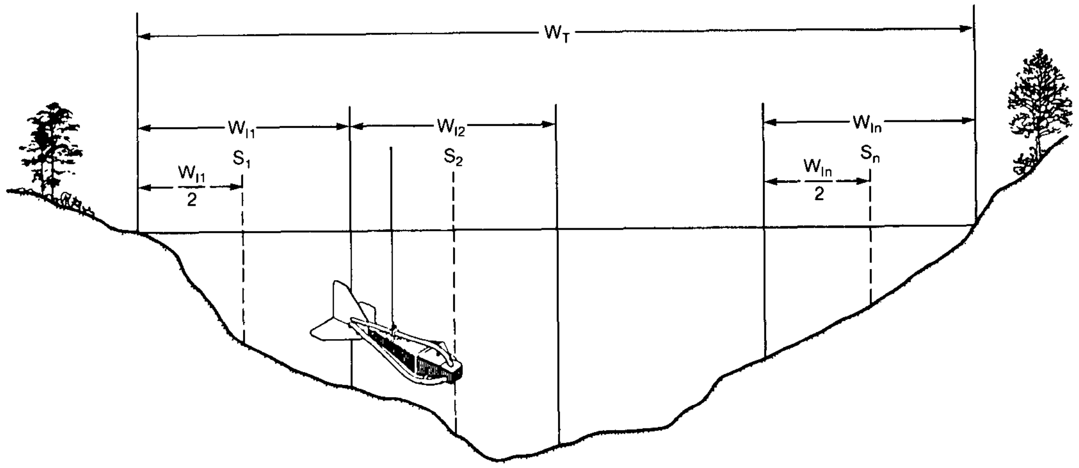


Figure 50. Single equal-width-increment bedload-sampling method.

(2) Starting at one bank and proceeding to the other, collect one sample at 4 or more evenly spaced verticals, return to the starting bank, and repeat the process multiple times until a total of 40 samples is collected. We will refer to this method as the multiple equal-width-increment (MEWI) method (fig. 51). If the sample collected at each vertical is bagged separately, the time the sampler is left on the bottom need not be equal at all verticals. If samples collected in a cross section are to be composited, sample times at each vertical in the cross section must be equal. As in the SEWI method, samples are collected at the midpoint of the evenly spaced increments.

(3) Starting at one bank and proceeding to the other, collect one sample from 4 or more unevenly spaced verticals, return to the starting bank, and repeat the process until a minimum of 40 samples is collected. We will refer to this method as the unequal-width-increment (UWI) method (fig. 52). This method requires some prior knowledge of the depths and velocities across the section. The selection of where to place the verticals in the UWI method depends, to a certain extent, on which method is to be used to calculate the bedload discharge. If the midsection method is used (see "Computation of Bedload-Discharge Measurements" section for explanation of calculation methods), the sampling verticals should be spaced unevenly in an attempt to delineate equal portions of the cross-section bedload discharge. To the extent possible, samples should be collected midway between breaks in the lateral bed slope and closer together in segments of high velocity and changing lateral bed slope. If the mean-section method is used to calculate the bedload discharge, sample verticals should be placed at the break points in the lateral cross-sectional distribution curve of mean bedload transport rate where the rate changes from one trend to another (that is, break in slope). At most sections, the lateral distribution in mean rates, once defined, can be related to velocity and lateral bed topography.

To quantify the approximate magnitude of sampling errors that could result from various sampling situations, Hubbell and Stevens (1986) developed a bedload transport simulation model. They used Hamamori's (1962) distribution to simulate temporal variations at the equally spaced sampling verticals and assumed that the sampler used had a 100-percent sampling efficiency. The results of test runs using two different spatial variations are shown in figure 53. In the first case, the lateral distribution of mean bedload transport rates is fairly uniform across the cross section and, in the second case, it is skewed. If these results were used to estimate maximum possible error for using the SEWI and MEWI methods, in the first



Width of Increments

$W_{I1} = W_{I2} = \quad = W_{In} = \frac{W_T}{n}$

Time on Bottom at $_i$

$t_1 \neq t_2 \neq \quad \neq t_n$

S_i = Station of Sample Vertical $_i$

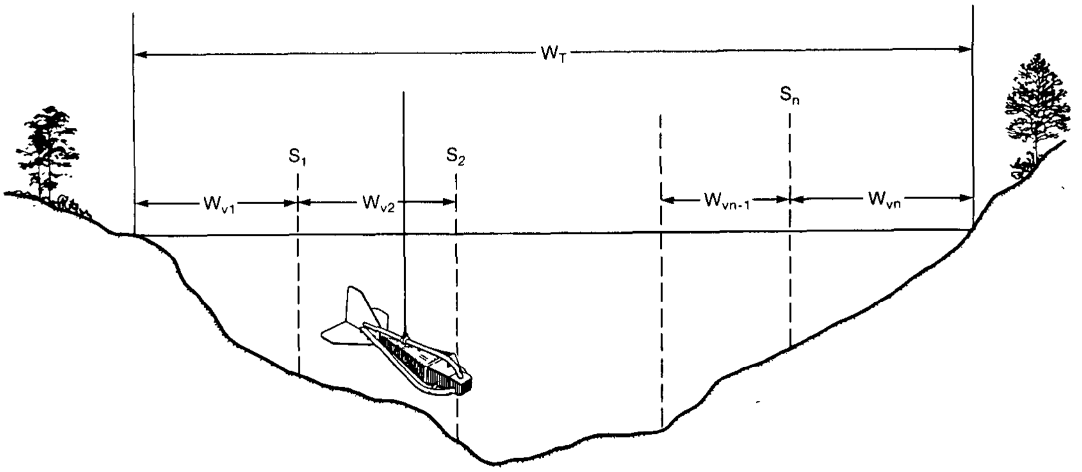
Number of Verticals

$n = 4\text{-}5$

1 Sample Per Vertical Per Cross Section

8-10 Cross Sections

Figure 51. Multiple equal-width-increment bedload-sampling method.



Width Between Sampled Verticals

$W_{v1} \neq W_{v2} \neq \quad \neq W_{vn}$

Time on Bottom

$t_1 \neq t_2 \neq \cdots \neq t_n$

S_i = Station of Sample Vertical $_i$

Number of Verticals

$n = 4\text{-}10$

1 Sample Per Vertical Per Cross Section

4-10 Cross Sections

Figure 52. Unequal-width-increment bedload-sampling method.

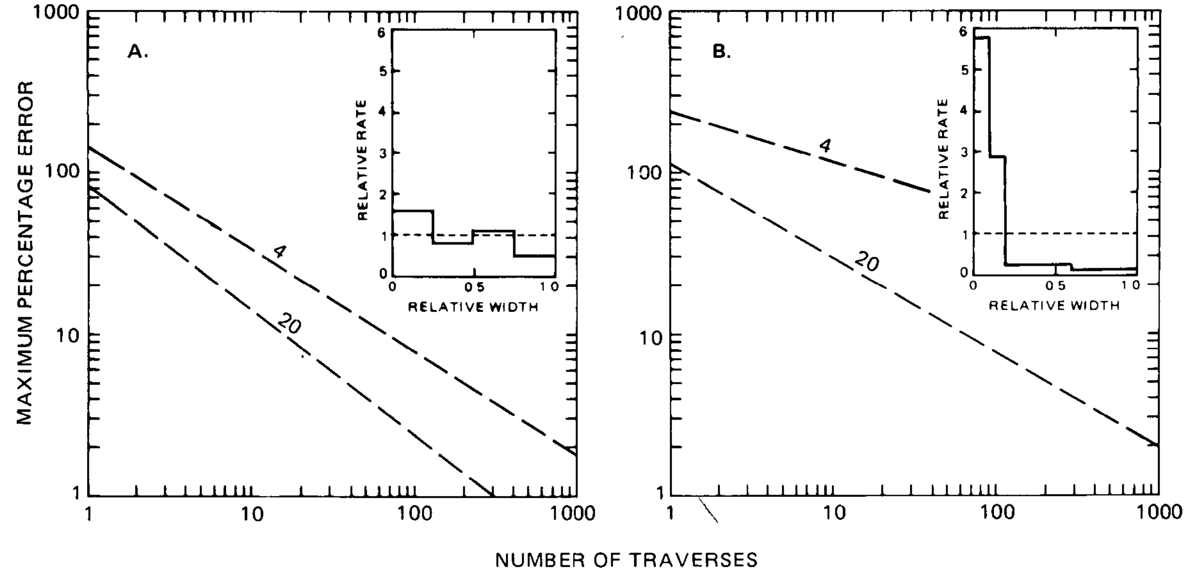


Figure 53. Variation in maximum probable errors with number of sampling traverses at 4 and 20 equally spaced verticals at cross sections with different bedload transport rates (modified from Hubbell and Stevens, 1986). *A*, Fairly uniform transport rates. *B*, Skewed transport rates.

case, the MEWI method would give a lower maximum possible error (35 percent) than would the SEWI method (50 percent). In the second case, however, using the SEWI method would result in a maximum error of 80 percent and using the MEWI method would result in a maximum error of 120 percent. The maximum probable error with the UWI method cannot be evaluated from figure 53.

From the previous discussion, it is obvious that no one method works best in all situations and that no one standard sampling protocol can be used at all stations. This should come as no surprise. There are two acceptable methods for collecting suspended-sediment samples (EWI and EDI). Both work equally as well as the other but are better suited to different stream conditions and cross-sectional sediment distributions. Likewise, a unique sampling protocol must be derived for each site at which bedload-discharge data are to be collected. Probably the best way to start sampling at a site is to do multiple sets of complete SEWI and MEWI or UWI measurements each time the site is visited and over as many flow ranges as possible. Unfortunately, human resources and budget restrictions, as well as hydrologic conditions, may prevent multiple or even single SEWI, MEWI, or UWI type cross-sectional measurements. If it is not possible or feasible to collect full SEWI, MEWI, and (or) UWI type samples, the approach listed below can be used as a minimum protocol to follow when first starting to collect bedload data at a site. Caution should be used, however, because the modified SEWI, MEWI, or UWI methods will not supply as much information as would the complete method. Therefore, more sets of samples may be needed to acquire sufficient knowledge of the cross section to design an efficient sampling protocol. (Note: The SEWI method helps define cross-sectional variations in bedload transport rates, whereas the MEWI and UWI methods are more effective in defining temporal variations at individual verticals.)

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

(2) Lower the sampler to the streambed and use a stopwatch to measure the time interval during which the sampler is on the streambed. The sampling-time interval should be the same for each vertical sampled

in the cross section. The time required to collect a proper sample can vary from 5 seconds or less to several hours or more. Generally, a sampling time that does not exceed 60 seconds is preferred. Because of the temporal variations in bedload transport rates, there is no easy way to determine the appropriate sampling time. Several test samples (as many as 10 or more collected sequentially at a vertical with a suspected high transport rate) may be needed in order to estimate the proper sampling-time interval to be used. The sample time should be short enough to allow for the collection of a sample from the section with the highest transport rate, without filling the sample bag more than about 40 percent full. The sample bag may be filled to 40 percent full with sediment coarser than the mesh size of the bag without reducing the hydraulic efficiency of the sampler (Druffel and others, 1976). Sediment that is approximately equal to the mesh size may clog the bag and cause a change in the sampling efficiency of the sampler.

(3) One sample should be collected at each vertical, starting at one bank and proceeding to the other. It is recommended that, during this initial data gathering stage, a minimum of one transect using the SEWI method be used. The samples should be placed in separate bags for individual analysis and labeled with the vertical's station number. They may be composited into one or several sample bags for a composite analysis, but if composited, no information on cross-sectional variability can be obtained from the data.

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

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

Station name/number
Date
Cross-section sample starting and ending times
Gage height at the start and end of sample collection
Total width of the cross section, including stations on both banks
Width between verticals (SEWI method)
Number of verticals sampled (SEWI method)
Station of verticals sampled (UWI or MEWI method)
Time sampler was on the bottom at each vertical
Type sampler used
Name of person collecting sample

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

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

Analysis of the first transect (SEWI method) will give some indication of the cross-sectional variability if individual verticals are analyzed separately. Analysis of the second set of transects (UWI or MEWI method) will give some indication of temporal variability. As stated before, the procedure described above should be considered the minimum to be followed when first collecting bedload data at a site. Additional samples and transects will help define the temporal and spatial variation at the site for all flow ranges. After a cross section has been sampled several times at different flow ranges using the above procedure, it should be possible to develop a sampling protocol that fits the site better.

Computation of Bedload-Discharge Measurements

The bedload transport rate at a sample vertical may be computed by the equation

$$R_i = \frac{KM_i}{t_i} \qquad (1)$$

where

R_i = bedload transport rate, as measured by bedload sampler, at vertical i, in tons per day per foot;

M_i = mass of the sample collected at vertical i, in grams;

t_i = time the sampler was on the bottom at vertical i, in seconds; and

K = a conversion factor used to convert grams per second per foot into tons per day per foot. It is computed as

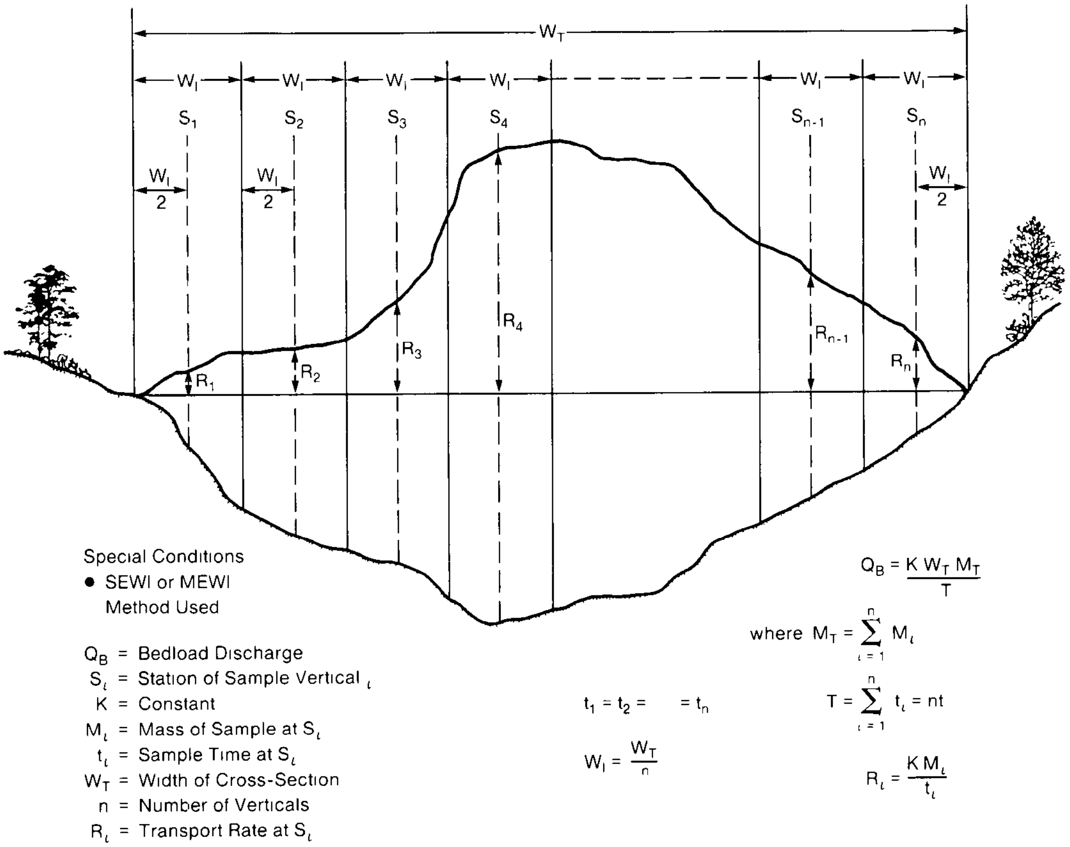
$$K = (86{,}400 \text{ seconds/day}) \frac{1 \text{ ton}}{(907{,}200 \text{ grams})} \frac{1 \text{ foot}}{(N_w)} \qquad (2)$$

where

N_w is the width of sampler nozzle in feet. (For a 3-inch nozzle, $K = 0.381$; for a 6-inch nozzle, $K = 0.190$.)

The cross-sectional bedload discharge measured by the Helley-Smith sampler may be computed using the total cross-section, midsection, or mean-section method. The simplest method of calculating bedload discharge from a sample collected with a Helley-Smith type bedload sampler is the total cross-section method (fig. 54). This method should only be used if the following three conditions are met:

1. The sample times (t_i) at each vertical are equal.
2. The verticals were evenly spaced across the cross section (that is, SEWI or MEWI method used).
3. The first sample was collected at one-half the sample width from the starting bank.



Special Conditions
- SEWI or MEWI Method Used

Q_B = Bedload Discharge
S_i = Station of Sample Vertical $_i$
K = Constant
M_i = Mass of Sample at S_i
t_i = Sample Time at S_i
W_T = Width of Cross-Section
n = Number of Verticals
R_i = Transport Rate at S_i

$$Q_B = \frac{K\,W_T\,M_T}{T}$$

where $M_T = \sum_{i=1}^{n} M_i$

$t_1 = t_2 = \quad = t_n$

$T = \sum_{i=1}^{n} t_i = nt$

$W_i = \frac{W_T}{n}$

$R_i = \frac{K\,M_i}{t_i}$

Figure 54. Total cross-section method for computing bedload discharge from samples collected with a Helley-Smith bedload sampler.

If these conditions are met, then

$$Q_B = K\frac{W_T}{t_T}M_T \qquad (3)$$

where

Q_B = bedload discharge, as measured by bedload sampler, in tons per day;

W_T = total width of steam from which samples were collected, in feet, and is equal to the increment width (W_i) times n (n = total number of vertical samples);

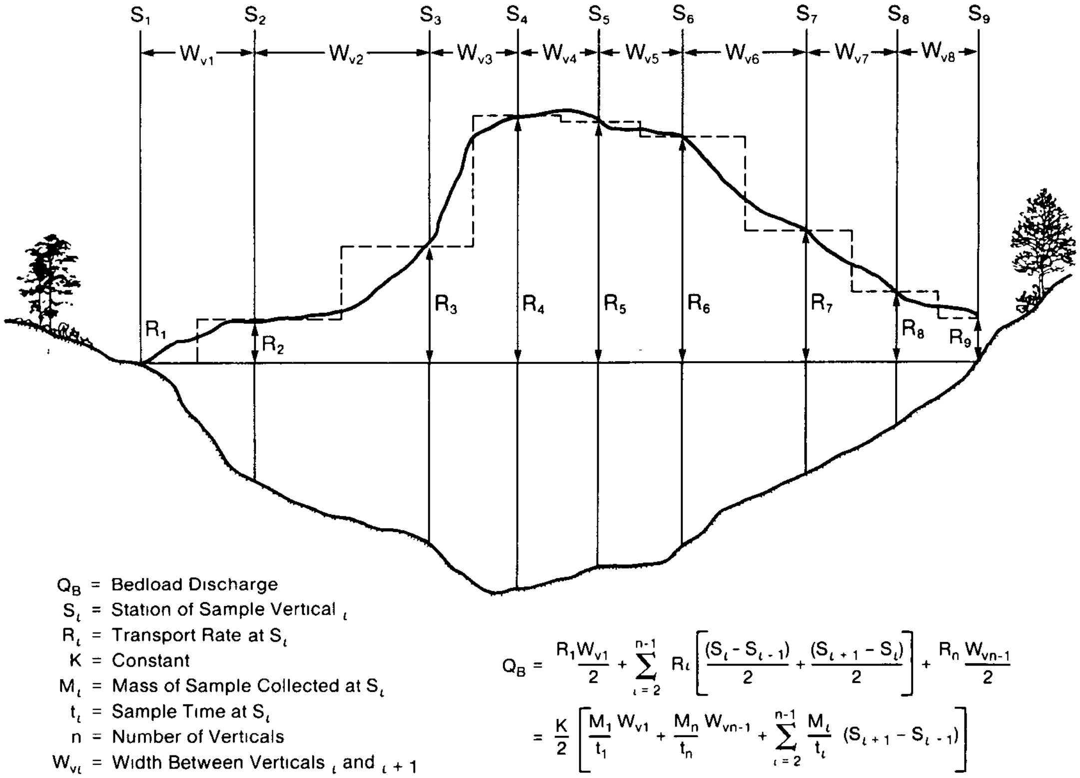
${}^tT$ = total time the sampler was on the bed, in seconds, computed by multiplying the individual sample time by n;

M_T = total mass of sample collected from all verticals sampled in the cross section, in grams; and

K = conversion factor as described in equation 2 above.

If any of the three conditions stated above are not met, then either the midsection or mean-section method should be used. Mathematically, the two methods, if used with no modifications, will produce identical answers. However, as indicated under the discussion of the UWI method, the placement of the sampling verticals with respect to breaks in the lateral cross-sectional distribution curve of mean bedload transport rate will somewhat dictate which method should be used. The midsection method (fig. 55) is computed using the following equation:

$$Q_B = \frac{R_1W_1}{2} + \sum_{i=2}^{n-1} R_i\left[\frac{(S_i - S_{i-1})}{2} + \frac{(S_{i+1} - S_i)}{2}\right] + \frac{R_nW_{n-1}}{2} \qquad (4)$$



Q_B = Bedload Discharge
S_ι = Station of Sample Vertical $_\iota$
R_ι = Transport Rate at S_ι
K = Constant
M_ι = Mass of Sample Collected at S_ι
t_ι = Sample Time at S_ι
n = Number of Verticals
$W_{v\iota}$ = Width Between Verticals $_\iota$ and $_{\iota+1}$

$$Q_B = R_1\frac{W_{v1}}{2} + \sum_{\iota=2}^{n-1} R_\iota\left[\frac{(S_\iota - S_{\iota-1})}{2} + \frac{(S_{\iota+1} - S_\iota)}{2}\right] + R_n\frac{W_{vn-1}}{2}$$

$$= \frac{K}{2}\left[\frac{M_1}{t_1}W_{v1} + \frac{M_n}{t_n}W_{vn-1} + \sum_{\iota=2}^{n-1}\frac{M_\iota}{t_\iota}(S_{\iota+1} - S_{\iota-1})\right]$$

Figure 55. Midsection method for computing bedload discharge from samples collected with a Helley-Smith bedload sampler.

where

W_i = width between sampling verticals i and $i+1$, in feet;

S_i = stations of the vertical (i) in the cross section measured from some arbitrary starting point, in feet; and

Q_B, n, R, and K have previously been defined,

You will note that equation 3 is very similar to the equation used to compute a surface-water discharge measurement. This method corresponds to the midpoint method currently used to compute surface-water discharge measurements (Buchanan and Somers, 1969). By combining equations 1 and 4 and rearranging terms:

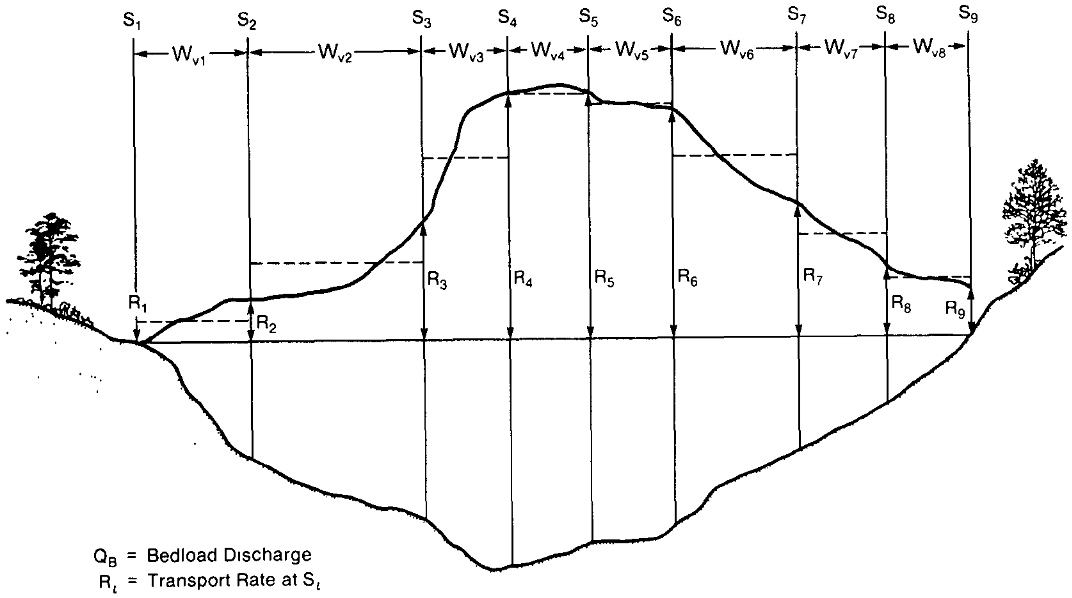
$$Q_B = \frac{K}{2}\left[\frac{M_1W_1}{t_1} + \frac{M_nW_{n-1}}{t_n} + \sum_{i=2}^{n-1}\frac{M_1}{t_i}(S_{i+1}-S_{i-1})\right] \qquad (5)$$

One advantage to using the midsection method is that the distance W_1 need not necessarily be equal to the distance between sampling verticals. At times, it may become apparent, due to local conditions, that a particular R_1 should not be applied over a width equal to halfway back to the last station and halfway forward to the next, but applied to some other width. This width, sometimes referred to as the effective width, is decided on by the user. Bridge piers, large boulders, abrupt changes in velocity or lateral bed topography, or other conditions that may obstruct or cause sudden changes to bedload transport rate will affect the selection of the effective width.

The third method, the mean-section method (fig. 56), is computed using the following equation:

$$Q_B = \sum_{i=1}^{n-1} W_i\,\frac{(R_i+R_{i+1})}{2}\,, \qquad (6)$$

which is equivalent to:



Q_B = Bedload Discharge
R_i = Transport Rate at S_i
K = Constant
M_i = Mass of Sample at S_i
t_i = Sample Time at S_i
n = Number of Verticals
S_i = Station of Sample Vertical $_i$
W_{vi} = Width Between Verticals $_i$ and $_{i+1}$

$$Q_B = \sum_{i=1}^{n-1} W_{vi}\,\frac{(R_i + R_{i+1})}{2} = \frac{K}{2}\sum_{i=1}^{n-1} W_{vi}\left(\frac{M_i}{t_i} + \frac{M_{i+1}}{t_{i+1}}\right)$$

Figure 56. Mean-section method for computing bedload discharge from samples collected with a Helley-Smith bedload sampler.

$$Q_B = \frac{K}{2}\sum_{i=1}^{n-1} W_1\left(\frac{M_i}{t_i} + \frac{M_{i+1}}{t_{i+1}}\right) \tag{7}$$

All the above terms are the same as used in the midsection method. This method averages the two adjoining rates and applies the average rate over the distance between them. For this reason, it is important to try to place the sampling verticals at points where the trends in lateral mean bedload transport rate change. Under most field conditions, this might be difficult.

For situations where the total cross-section method cannot be used, it is recommended that the midsection method be used. This recommendation is made because of its similarity to the surface-water discharge-measurement method, which most field personnel are familiar with, and because of the flexibility in using the effective width concept.

Collecting bedload samples will generate 40 or more samples, creating a potential problem regarding transportation and analyses of so many samples. Carey (1984) adapted a procedure for measuring the submerged weight of bedload samples in the field and converting that measurement to dry weight from a laboratory procedure used by Hubbell and others (1981). The method uses the basic equation

$$W_{ds} = \frac{SG_s}{SG_s - 1} W_{ss} \tag{8}$$

where

W_{ds} = dry weight of the sediment;
SG_s = specific gravity of the sediment; and
W_{ss} = submerged weight of the sediment.

Measurements for Total Sediment Discharge

Total sediment discharge is the mass of all sediment moving past a given cross section in a unit of time. It can be defined as the sum of the (1) measured and unmeasured sediment discharges, (2) suspended-sediment discharge and bedload discharge, or (3) fine-material discharge (sometimes referred to as the washload) and coarse-material or bed-material discharge.

There are some sand-bed streams with sections so turbulent that nearly all sediment particles moving through the reach are in suspension. Sampling the suspended sediment in such sections with a standard suspended-sediment sampler represents very nearly the total load. Several streams with turbulent reaches are described in Benedict and Matejka (1953). Further discussion concerning total-load measurement also can be found in Inter-Agency Report 14 (Federal Inter-Agency Sedimentation Project, 1963b, p. 105–115). Turbulence flumes or special weirs can be used to bring the total load into suspension. Total load can usually be sampled with suspended-sediment samplers to a high degree of accuracy where the streambed consists of an erosion resisting material such as bedrock or a very cohesive clay. In such situations, most, if not all, the sediment being discharged is in suspension (or the bed would contain a deposit of sand).

Benedict and Matejka (1953) and Gonzales and others (1969) have described some structures used for artificial suspension of sediment to enable total-load sampling. However, most total-load sampling is usually accomplished at the crest of a small weir, dam, culvert outlet, or other place where the sampler nozzle integrates throughout the full depth of flow from the surface to the top of the weir.

Where such conditions or structures are not present, the unmeasured load must be computed by various formulas. The unmeasured load can be approximated by use of a bedload formula such as that of Meyer-Peter and Muller (1948), Einstein (1950), Colby and Hembree (1955), or Chang and others (1965). However, these computational procedures can give widely varying answers. The Colby and Hembree (1955) method [modified from Einstein (1950)] determines the total load in terms of the amount transported for different particle-size ranges. Colby and Hubbell (1961) later simplified the modified Einstein method to include the use of four nomographs in lieu of a major computational step. The essential data required for the Colby and Hubbell technique at a particular time and location are listed here:

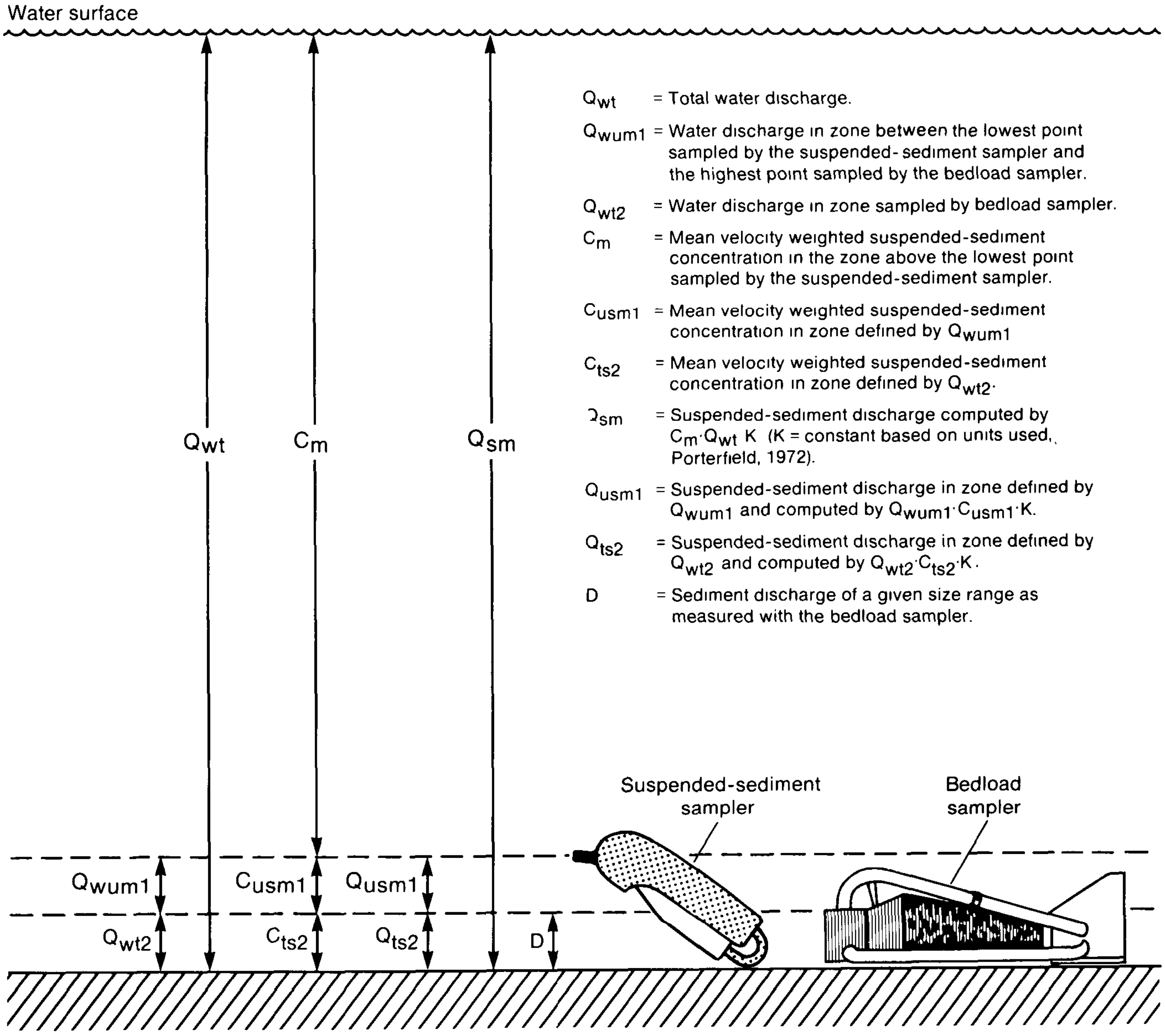
1. Stream width, average depth, and mean velocity.
2. Average concentration of suspended sediment from depth-integrated samples.
3. Size analyses of the suspended sediment included in the average concentration.
4. Average depth of the verticals where the suspended-sediment samples were collected.

5. Size analyses of the bed material.
6. Water temperature.

Stevens (1985) has developed two computer programs for the computation of total sediment discharge by the modified Einstein procedure. One program is written in FORTRAN 77 for use on the PRIME computer; the other is in BASIC and can be used on most microcomputers.

Hubbell (1964) gives the following formula for determining the total sediment discharge of a given size range from the measured suspended-sediment discharge and the discharge measured with any type of bedload apparatus (see fig. 57).

$$Q_T = \frac{Q_D}{eff} + Q_{sm} + Q_{usm1} - FQ_{sm} + (1 - E/e)Q_{ts2} \quad (9)$$



Q_{wt} = Total water discharge.

Q_{wum1} = Water discharge in zone between the lowest point sampled by the suspended-sediment sampler and the highest point sampled by the bedload sampler.

Q_{wt2} = Water discharge in zone sampled by bedload sampler.

C_m = Mean velocity weighted suspended-sediment concentration in the zone above the lowest point sampled by the suspended-sediment sampler.

C_{usm1} = Mean velocity weighted suspended-sediment concentration in zone defined by Q_{wum1}

C_{ts2} = Mean velocity weighted suspended-sediment concentration in zone defined by Q_{wt2}.

Q_{sm} = Suspended-sediment discharge computed by $C_m \cdot Q_{wt}$ K (K = constant based on units used, Porterfield, 1972).

Q_{usm1} = Suspended-sediment discharge in zone defined by Q_{wum1} and computed by $Q_{wum1} \cdot C_{usm1} \cdot K$.

Q_{ts2} = Suspended-sediment discharge in zone defined by Q_{wt2} and computed by $Q_{wt2} \cdot C_{ts2} \cdot K$.

D = Sediment discharge of a given size range as measured with the bedload sampler.

Figure 57. Zones sampled by suspended-sediment and bedload samplers and the unmeasured zone.

where

Q_T = total sediment discharge of the size range,

Q_D = discharge of the size range as measured with the bedload apparatus. If the apparatus measures more than the bedload discharge, as does the Helley-Smith, Q_D includes some of the suspended-sediment discharge,

e = efficiency of the bedload apparatus in measuring bedload discharge of the size range,

Q_{sm} = measured suspended-sediment discharge of the size range,

Q_{usm1} = unmeasured suspended-sediment discharge of the size range in the depth between the lowest point measured by the suspended-sediment sampler and the highest point measured by the bedload apparatus,

F = the fraction of the total depth represented by the flow in the depth measured by the bedload apparatus,

E = the efficiency of the bedload apparatus in measuring the suspended-sediment discharge of the size range transported through the vertical sampled by the apparatus, and

Q_{ts2} = total suspended-sediment discharge of the size range through the depth measured by the bedload apparatus.

A more detailed explanation of how to compute the total sediment discharge from measured suspended-sediment discharge and bedload discharge measured with a bedload measuring apparatus is given by Hubbell (1964, p. 7–9). If the efficiency of the bedload sampler is 100 percent for both bedload and suspended-sediment load and if the bedload sampler samples the entire unsampled zone, then the above equation is much simpler.

Reservoir-Trap Efficiency

The efficiency with which a reservoir traps sediment depends mostly on its size with respect to the rate of inflow. Other factors may include the reservoir shape, its operation, the water quality, and the size and kind of inflowing sediment. Except for small detentions with bottom outlets, all of the sand-sized and much of the silt-sized particles would be expected to be trapped. An evaluation of reservoir-trap efficiency must involve measurements of the quantity and size characteristics of the sediment entering and leaving the reservoir (Mundorff, 1964, 1966). Sometimes measurements of sediment accumulation in the reservoir plus the sediment output are used as a practical method of evaluating the sediment yield of the drainage basin.

Inflow Measurements

On many reservoirs, trap efficiency cannot be evaluated in sufficient detail from measurements of accumulation and sediment outflow. For such reservoirs, it is necessary to measure the sediment discharge and particle size entering the reservoirs. This measurement requires that stations be operated daily or continuously on streams feeding into the reservoir. Trap efficiency on a storm-event basis can be determined if several samples adequately define the concentration of the inflow and outflow hydrographs. For small detention reservoirs, it may be difficult or impractical to measure the inflow on a daily basis. If a continuous record is not possible, the objective should be to obtain observations sufficient to define the conditions for several inflow hydrographs so that a storm-event sediment rating curve can be constructed for use in estimating the sediment moved by the unsampled storms (Guy, 1965).

If it is impractical to obtain sufficient data to define the sediment content of several storm events, the least data for practical analysis should include 10 or 15 observations per year so that an instantaneous sediment rating curve can be constructed (Miller, 1951). It is expected that the instantaneous curve will yield less accurate results than the storm-event curve, which in turn will be less accurate than the continuous record. Each of the rating-curve methods may require data for a range of conditions so that adjustments can be determined for the effect of time of year, antecedent conditions, storm intensity, and possibly for the storm location in the basin (Colby, 1956; Jones, 1966).

As for most new sediment stations, particle-size analysis should be made on several of the inflow observations during the first year. These particle-size analyses will form a data base, which may make it possible to reduce the number of analyses required in future years.

Outflow Measurements

The outflow from a reservoir is drastically different from the inflow because of the attenuating effect of the flow through the reservoir or because of possible willful control in the release of water (Carter and Godfrey, 1960; Mitchell, 1962). Logically, the smaller reservoirs, which are likely to have fixed outlets and the poorest trap efficiencies, require the most thorough outflow measurement schedules. If an inflow-outflow relation for sediment discharge can be constructed, such a relation may change considerably in the direction of greater sediment output (lower trap efficiency) as the reservoir fills with sediment.

Normally, the particle size of sediment outflow is expected to be finer than for the inflow; and, therefore, the concentration of outflowing sediment should not fluctuate as rapidly as that of the inflow. The normal slowly changing outflow concentration may not occur if the outflow is from the vicinity of the interface involving a density current.

A desirable sampling schedule for outflow may vary from once a week for the large reservoir to several observations during a storm event for a small reservoir. The need for outflow particle-size data also will depend on the scale of the stream and reservoir system, the trap efficiency, and how well the inflow is defined. With respect to quality control, if the trap efficiency of a reservoir is expected to be more than 95 percent and if the sediment inflow can only be measured to the nearest 10 or 15 percent of its expected true value, it is not necessary to measure the sediment outflow in great detail unless there is a need to accurately define the amount of sediment in the flow downstream from the reservoir.

Sediment Accumulation

The small reservoir or detention basin can be used—if trap efficiency can be estimated or measured—to provide a measure of the average annual sediment yield of a drainage basin. This method is useful in very small basins where the inflow is difficult to measure and where the amount of water-inflow and sediment-concentration data is not important.

For small catchment basins or reservoirs on ephemeral streams (those that are dry most of the time), the determination of sediment accumulation involves a detailed survey of the reservoir from which stage-capacity curves can be developed—usually 1-foot contours for the lower parts of the reservoirs and 2- to 5-foot contours for the upper parts, depending on the terrain and size of the reservoir (Peterson, 1962). The accretion of sediment then can be measured either by monumented range lines in the reservoir or by resurvey for a new stage-capacity curve.

For reservoirs not dry part of the time, the sediment accumulation is usually measured by sounding on several monumented range lines spaced to provide a representative indication of the sediment accumulation between measurements. Methods for reservoir surveys are described by Heinemann (1961), Porterfield and Dunnam (1964), and Vanoni (1975). A summary of reservoir sediment deposition surveys made in the United States through 1975 was compiled by Dendy and Champion (1978). The period from 1976 to 1980 has been covered by the Inter-Agency Advisory Committee on Water Data's Subcommittee on Sediment (1983).

In order to convert the measurements of sediment volume found in reservoirs to the usual expression of mass of sediment yield, it is necessary that the sedimentation surveys of reservoirs include information on the volume-mass of sediment. Heinemann (1964) reports that this was accomplished in Sebetha Lake, Kansas, using a gamma probe and a piston sampler. From his data, obtained at 41 locations, he found that the best equation for predicting volume-mass is

$$V_M = 1.688d - 0.888c + 98.8 \tag{10}$$

where

V_M = the dry unit volume-mass, in pounds per cubic foot;

d = the depth of sample from the top of the deposit; and

c = the percentage of clay smaller than 0.002 mm.

On the basis of 1,316 reservoir deposit samples, Lara and Pemberton (1965) found the unit volume-mass to vary according to changes in reservoir operation and to the fraction of clay, silt, and sand. The Office of Water Data Coordination (1978) reported that refinements based on reservoir operation, sediment size, and compaction could be made to the estimates made by Lara and Pemberton (1965) and Lane and Koelzer (1943). The following formula, along with factors listed in table 4, may be used to estimate dry unit volume-mass:

$$V_M = V_{tc}P_c + V_{tm}P_m + V_{ts}P_s \tag{11}$$

where

V_M = dry unit volume-mass, in pounds per cubic foot;

V_t = dry unit volume-mass as computed in equation 12, in pounds per cubic foot;

c = clay-size material;

m = silt-size material;

s = sand-size material;

P = percent of total sample, by weight, in size class (clay, silt, sand); and

$$V_t = V_i + 0.43K\left[\frac{T}{T-1}(\log T) - 1\right] \qquad (12)$$

where

V_i = initial unit volume-mass, in pounds per cubic foot from table 4;

K = Lane and Koelzer (1943) factors from table 4, in pounds per cubic foot; and

T = time after deposition, in years.

Table 4. Initial dry unit volume-mass (V_1) and K factors for computing dry unit volume-mass of sediment deposits in pounds per cubic foot (Office of Water Data Coordination, 1978)

	V_1			K		
Type of reservoir operation	**Clay**	**Silt**	**Sand**	**Clay**	**Silt**	**Sand**
1. Sediment submerged.........	26	70	97	16	5.7	0
2. Moderate to considerable annual drawdown..............	35	71	97	8.4	1.8	0
3. Normally empty................	40	72	97	0	0	0
4. River sediment..................	60	73	97	0	0	0

OTHER SEDIMENT DATA-COLLECTION CONSIDERATIONS

In retrospect, it must be emphasized that field methods for fluvial-sediment measurements must be coordinated with methods for other hydrologic and environmental measurements. With the ever-increasing requirements of a thorough data-acquisition system, together with advances in technology, it must be expected that methods will continue to change in the future. For example, because there is a foreseeable need for increasing water-pollution surveillance studies with respect to stream-quality standards, it is apparent that a continuous recording of some indicator of sediment conditions is badly needed at a large number of sites. Consequently, the F.I.S.P. has undertaken the development of sensors and automatic pumping-type samplers with a view toward continuously recording the concentration of sediment that moves in streams. The development of such automatic equipment is likely to enhance rather than detract from the need for conventional manual observations.

The authors sincerely hope that the material regarding the equipment and techniques for sampling presented herein will stimulate the ongoing development of better equipment and techniques for the future and, at the same time, help to standardize and make more efficient the day-to-day operations.

The opportunity certainly exists at the field level for many innovations for improving the end product or the sediment record. Some field people, for example, may like to carry a copy of the station stage-discharge rating curve, on which all particle-size analyses are recorded, showing date and kind of sample for each measuring site. As communications and river forecasting become more sophisticated, it may be possible to have better dialogue between the office and the field people or local observers, who are trying to obtain the maximum information at many sampling sites. Such communication is especially critical during periods of flooding, when timely data are most important.

In addition to increasing coordination of sediment-data activities with other related measurements, it is important to stress that adequate notes be obtained (including pictures) so that those involved in the laboratory analysis of the samples, those responsible for preparing the record, and especially those responsible for interpreting the data can properly read what happened at the sample site. The amount of new information to be obtained from data interpretation is seriously affected by the quality of the information with respect to timing and representativeness of the sediment measurements.

The authors further emphasize the need for a concerted and continuing effort with respect to safety in the measurement program. Aside from the hazards of highway driving, the work usually involves the use of heavy equipment during floods or other unusual natural events, often in darkness and under unpleasant weather conditions. Even though the hazards of working from highway bridges and cableways are mostly self-evident, there are many opportunities for the unusual to happen and, therefore, a great deal of effort must be expended to ensure safety. Such effort, of course, must be increased when it is necessary to accomplish the work in a limited amount of time and with a reduced work force.

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