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Report NN
A Study of Methods Used in Measurement and Analysis of Sediment Load In Reservoirs
May 2000

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A Study of Methods Used in MEASUREMENT AND ANALYSIS OF SEDIMENT LOADS IN RESERVOIRS

May 2000

By

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Introduction

Before the construction of waterway projects on flood plains, sediment eroded from watersheds moved unhindered through river channels to resting places in estuaries, river deltas and along beaches. Subsequent to the construction of irrigation, flood control, and power projects, the transport paths are broken by reservoirs that serve not only as temporary storage basins for water but also as permanent sinks for sediment. Only small fractions of reservoir inflows are sediment; however, once deposited, sediment is difficult to dislodge. It fills storage space intended for water and thereby limits a reservoir's useful life. Sediment also contributes to a decline in aesthetic and recreational factors. Fine sediments diminish the penetration of sunlight, inhibit the photosynthetic processes, interfere with plant growth, and eventually lead to a decline of fish populations. Through its absorptive surfaces, sediment may act as a carrier and a sink for pollutants such as insecticides, fertilizers, toxic metals, bacteria, and viruses.

Measuring the quantities and properties of sediment carried in rivers is an important management tool for gauging the effectiveness of erosion control projects, predicting sediment deposition patterns in reservoirs, and estimating rates of storage depletion. This paper discusses equipment and techniques for measuring suspended-sediment discharge. Factors controlling equipment performance as well as maintenance, testing, and verification procedures for equipment are discussed. Major decisions involving the establishment of a sampling program are covered.

The scope of this paper covers not only sampling but also the mechanical analysis of sediment. Techniques for measuring grain-size distributions such as sieving and settling-rate methods as exemplified by the VA tube, pipette, and X-ray attenuation are discussed. Three common methods for measuring sediment concentration—evaporation, filtration, and wet-sieve-filtration—are explained and compared through precision and bias data.

Information in this paper centers mainly on concepts rather than procedural details. It is offered as an introduction to new personnel in the field of fluvial-sediment measurements. Readers are encouraged to expand their knowledge by studying the manuals and reports listed in the reference section. Questions on equipment procurement and operation should be addressed to the Chief, Federal Interagency Sedimentation Project (FISP), Waterways Experiment Station, 3909 Halls Ferry Road, Vicksburg, MS, 39180-6199. The FISP develops new equipment and also repairs, calibrates, and sells sediment samplers and analyzers.

General Concepts of Suspended-Sediment Sampling

Particles transported in rivers consist of both organic and inorganic material; however, this paper focuses on the inorganic component consisting of mineral fragments produced by the weathering of rocks. Sediment moves through a river channel in two modes: as bedload or suspended load. In bedload transport, large particles slide and roll along the river bottom in a series of jumps interrupted by periods of rest. Occasionally the particles are lifted into the flow, but their excursions cover short distances, usually less than a few particle diameters above the bottom. Suspended particles, most of which are smaller than a few millimeters, are entrained in the water and supported by upward components of turbulence or, in more tranquil flow, by forces of Brownian motion.

The size of suspended particles seldom exceeds 2000 micrometers. The lower limit extends down to clay-sized particles measuring only a few hundredths of a micrometer. As shown later, the lower size limit is, in a practical sense, operationally defined by the analysis technique used to measure grain sizes and concentrations.

Gradients in flow velocity and sediment distribution create many of the complexities in the design and use of sampling equipment. Flow velocity reaches a maximum near the water surface and decreases to a minimum near the streambed where roughness elements such as sand grains and sand waves retard velocities. Flow is slowed not only by the river's bed but also by its banks. As a result, gradients perpendicular to the flow are created with the maximum speeds usually occurring near the thalwag.

Superimposed on velocity profiles are gradients in sediment concentration. Fine particles, those smaller than about 62 micrometers, are often distributed in a nearly uniform fashion from water surface to bed and from bank to bank. Owing to their small sizes, fine particles settle slowly even in calm water. Turbulence easily overcomes the downward pull of gravity and disperses the particles throughout the cross section. At the coarse end of the size range, large particles are strongly influenced by gravity. Turbulence forces are able to lift large particles only a short distance above the bed; consequently, the population of these particles is comparatively sparse near the surface but dense near the bed. Each particle-size class is therefore linked to a particular sediment-concentration profile. This rather simplistic model of sediment profiles holds only if flow streamlines are parallel to one another and to the banks. If secondary currents are present, as they are in river bends, sediment gradients are more complex and less predictable.

Temporal variability or unsteadiness is another characteristic of suspended-sediment transport. Even at a fixed point in a cross section, sediment concentrations fluctuate over wide limits. In a laboratory test (FISP 1941) conducted in a closed recirculating flume, samples integrated for 20 seconds at a fixed point differed by more than 30 percent from one sample to the next. Fluctuations were larger for the coarse particles than for the fines. Only by increasing the integration time were fluctuations among samples damped through averaging.

Another property of sediment sampling concerns the manner of sample extraction. The concentration of a sample depends not only on the orientation of the sampling nozzle but also on the flow rate through its bore. Since the purpose of suspended-sediment sampling is to determine sediment flow rate (discharge) through a transect, the concentration of a sample must represent the concentration of the flow approaching the nozzle. A rational technique is to align the nozzle with the streamlines so that the intake faces directly upstream. This orientation minimizes disturbances because flow enters the intake without undergoing a change in direction.

For accurate sampling, nozzle alignment is important and also nozzle inflow velocity must match the approach velocity. Sacrifices in accuracy due to differences between the two velocities are given in Table 1.

Table 1. Concentration errors in percent for various relative sampling rates and sediment particle sizes.

Adopted from the FISP Report 5, "Laboratory Investigations of Suspended Sediment Samplers," 1941, St. Paul District, U.S. Army Corps of Engineers, St. Paul, MN. Relative rate is the flow velocity in a nozzle's entrance divided by the flow velocity a short distance upstream of the nozzle.

Relative Rate	0.45 mm sediment	0.15 mm sediment	0.06 mm sediment
0.4	45	30	5
0.6	19	14	3
0.8	7	5	1
1	0	0	0
1.2	-6	-4	-0.5
1.4	-9	-7	-1
1.6	-12	-9	-2

In the table, relative sampling rate is the flow velocity in the nozzle's entrance divided by the approach velocity a short distance upstream of the intake. For relative rates less than 1.0, the streamlines of flow diverge at the nozzle's entrance but the sediment particles, which are denser than water, cross the streamlines because particle momentum resists changes in vector velocity. Some of the water flow bypasses the nozzle but many of the particles move straight ahead, plunge into the nozzle and become part of the sample. Sediment concentration of the sample exceeds the concentration within the approaching flow. In this case, sampling errors are positive.

For relative rates greater than 1.0, the streamlines converge at the nozzle's entrance; however, some particles in this converging region move straight ahead and bypass the nozzle. Sediment concentration of the sample is less than that in the approaching flow. In this case, sampling errors are negative. As the table shows, each particle size fraction has a unique set of errors; furthermore, the errors diminish as particle size decreases.

With the nozzle oriented directly into the flow and with a perfect match between approach velocity and nozzle-intake velocity, sampling errors are zero. The combination of a perfect velocity match and an upstream-facing nozzle is known as isokinetic flow, a condition whereby water and particles enter the nozzle without undergoing changes in speed or direction.

The sediment discharged through a region surrounding a fixed point in a river cross section is the mathematical product of the sediment concentration at the point multiplied by the water discharge through the region. The size and extent of the region is a matter of judgment. Ideally, velocity and concentration gradients within the region approach uniform conditions. In practice, the region is chosen such that the gradients are small to minimize errors. In equation form, the discharge of suspended sediment through the region is given by $G_{ss} = CUA$, where C is the concentration of the isokinetic sample collected at a point in the region, U is the flow velocity through the region, and A is the area of the region.

Samplers for measuring sediment discharge have evolved along two lines. The Delft bottle sampler, named after the Delft Hydraulics Laboratory, consists of a sampling nozzle connected to the nose of a streamlined body that has a hollow interior and acts as a sediment trap. Water in the nozzle enters the body and then follows a serpentine path through a series of baffles before exiting through openings in the rear. Inside the body, the flow slows and drops its sediment load. Ideally, all incoming sediment is trapped in the body; but, in practice, the sampler's trap efficiency varies with flow velocity and particle size. In operation, the sampler is held at a sampling point for a measured time interval then the sampler is retrieved and emptied. Assuming perfect (100 percent) trap efficiency and an isokinetic inflow rate, the sediment discharged into the nozzle is the accumulated sediment weight divided by the sampling time interval. As an approximation, this sediment discharge is then applied to a region surrounding the nozzle. The Delft bottle has the advantage of measuring sediment discharge directly. Integration times can be quite long, and flow velocity readings are not required. A disadvantage is that correction factors for trap efficiencies are difficult to evaluate.

The other family of samplers is the US series developed at the Federal Interagency Sedimentation Project (FISP). These samplers consist of a streamlined body fitted with a nozzle and removable container that collects the sample. Guide vanes at the rear of each sampler keep its nozzle facing into the flow. Isokinetic inflow rates are maintained by a specially designed air exhaust, which automatically regulate pressures in the containers. Drawings of the samplers are shown in ASTM standard D-4411, "Sampling Fluvial Sediment in Motion" (ASTM 2000) and in the U.S. Geological Survey field methods report (Edwards and Glysson 1999).

The US samplers, which are used extensively within the United States, have the advantage of collecting and storing all water and sediment that enters the nozzles; trap efficiency is of no concern because none of the water and sediment escapes. Disadvantages are that current-meter measurements must be made concurrently with sampling. Also, integration times are limited to less than about a minute because inflow must be stopped before the container overfills.

Types of Suspended-Sediment Samplers

Several types of suspended-sediment samplers have been designed to overcome problems related to sampling errors, handling, and contamination of samples along with deployment of equipment at remote sites. Each type has limitations restricting its range of application. A few samplers are hybrids; but most can be classified as grab samplers, single-stage samplers, pumping samplers, rigid-container depth-integrators, rigid-container point-integrators, and flexible-container depth-integrators commonly referred to as bag samplers.

Grab samplers, sometimes called instantaneous samplers, consist of a container fitted with a valve that can be controlled by the operator. One style has a tube fitted at each end with spring-loaded stoppers. They are cocked open; the sampler is lowered to the desired depth; then a sample is trapped by dropping a sliding weight down the suspension line to trip the springs and seal the ends. Grab samplers are simple and reliable; however; they collect only short filaments of flow and therefore do a poor job of averaging temporal fluctuations. Another disadvantage is that samples must be poured from the sampler into other containers for storage or shipment. Pouring increases the risk of failing to transfer all particles and contaminating subsequent samples.

Single-stage samplers were developed to automate sampling of ephemeral streams too remote to reach during critical peak flow periods. A single-stage sampler consists of a bottle sealed to a pair of inverted “U” shaped tubes. The sampler is bolted to a post anchored near the center of a dry channel. When runoff begins and water rises above the lower tube, the bottle fills by siphoning while the displaced air exhausts through the upper tube. Filling automatically stops when water rises in the upper tube and increases backpressure in the bottle. The sample can be retrieved only after flow recedes. Several single-stage samplers can be mounted one above the other to repeat the sampling process through a complete runoff event. Compared to grab samplers, single-stage samplers collect long filaments of flow to average temporal fluctuations in concentration. The samplers are simple and inexpensive to make; however, each sample is collected at a fixed distance below the water surface; consequently, the samples fail to account for spatial variations in flow and concentration. The samplers occasionally malfunction when the seal around the bottle leaks causing water to flow from the intake down into the bottle and back out through the exhaust tube. The sample in the bottle is not representative because most of the sand-size particles entering the bottle accumulate on the bottom. Because the sample volume is fixed by the container’s size, the concentration increases until the bottle is completely filled with sediment.

Pumping samplers were developed to automate collection at remote sites and to improve temporal records of runoff events. The largest machines, US PS-69, have capacities of 72 samples; smaller models hold about two dozen samples. (The US PS-69 is no longer produced.) Combinations of floats and timers are used to initiate sample collection and control time intervals between sampling cycles. Despite the versatility of the samplers, they have several disadvantages. Battery failures detract from reliability; high costs of the samplers and their weatherproof enclosures limit applications; fixed-point samples correlate poorly with average

concentrations of sand-sized particles in cross sections; intake orientation violates isokinetic requirements because the nozzles must be shielded and mounted at right angles to the flow lines in order to deflect debris and prevent plugging.

Depth-integrating samplers conform to most of the principles of good sample collection practices. They have a streamlined body that encloses a plastic or glass sample container sealed to an upstream-facing nozzle and downstream-facing air exhaust tube. ASTM Standard D-4411 (ASTM 2000) gives physical and hydraulic properties of these samplers, which include the following models: US DH-48, US DH-59, US DH-76, US D-74, US DH-95, US D-95, and US D-77. All depth integrators are tested and adjusted (calibrated) under laboratory conditions to sample isokinetically at a fixed depth below the water surface. They automatically adjust their intake rates to closely match approach velocities in the range of approximately 1 ft/s to 7 ft/s (0.30 m/s to 0.83 m/s). Intake and approach velocities agree closely through the range of 2 ft/s to 4 ft/s (0.61 m/s to 1.22 m/s). Below 2 ft/s, intake rates are higher than approach velocities. In still water, intake flow is about 0.5 ft/s (0.15 m/s). For approach velocities faster than 4 ft/s, intake rates are 5% to 10% too low. Intake rates decrease by a few percent with falling temperatures that increase water viscosity. Details on intake characteristics for each class of sampler and for individual samplers within a class are available from the offices of the FISP, Waterways Experiment Station, 3909 Halls Ferry Road, Vicksburg, Mississippi, 39180-6199.

Depth-integrating (DI) samplers have several advantages. They are rugged and reliable because they have no moving parts. Also, they sample long filaments since the container, most of which is a pint or quart bottle, fill through a nozzle with a small bore, typically $^{3}/_{16}$ inch (4.763 mm) or $^{1}/_{4}$ inch (6.35 mm). Perhaps the most important advantage of DI samplers is that their inflow rate is nearly isokinetic even when they are being lowered or raised through flowing water. Because of this feature, DI samplers are used to collect discharge-weighted samples by lowering and hoisting the samplers at a uniform speed. A disadvantage is that only depths shallower than about 15 feet can be integrated with DI models because of the compressibility of air trapped in the sample containers.

Point-integrating (PI) samplers contain valves that operate through conductors in the suspension cables; therefore the PI samplers are more versatile than depth integrators. A point-integrating sampler (Figure 1) can be lowered to a desired depth before the valve is opened to start the sampling process.

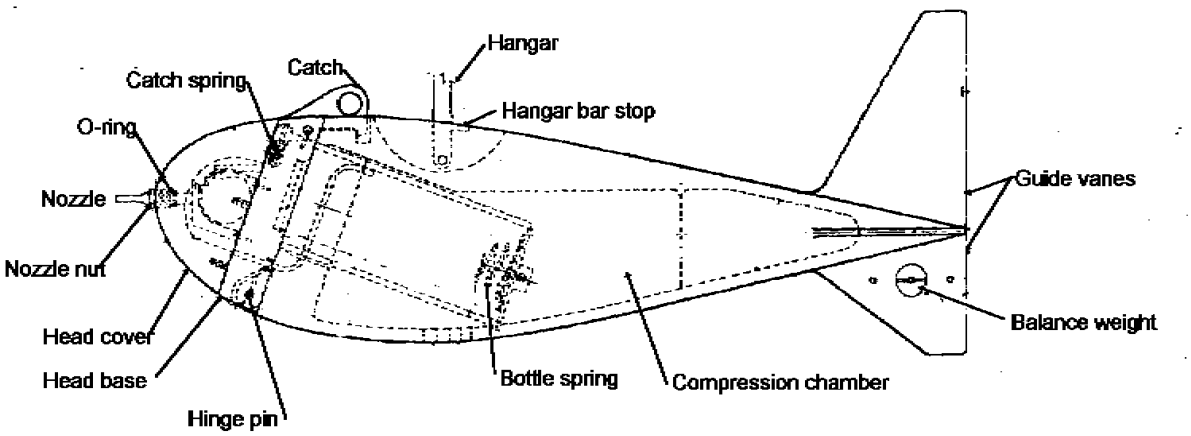

Figure 1. Point-integrating, suspended-sediment sampler.

At the proper time, the valve is closed and the sampler is hoisted for sample retrieval. The valve does more than open and close the intake; it also connects the bottle to a pressure-equalizing chamber in the tail of the sampler. Water enters this chamber through openings in the sampler's belly and forces trapped air into the sample bottle. This airflow insures that pressure inside the bottle matches the hydrostatic pressure outside the sampler near the nozzle's mouth. When electric power is applied, the valve rotates to seal off the compression chamber and, at the same time, opens the nozzle and air-exhaust tube. Flow can then enter the nozzle isokinetically from the instant the nozzle opens. Were it not for the equalizing chamber, flow would initially rush into the bottle owing to the difference between the bottle pressure and ambient pressure. Flow through the nozzle would greatly exceed the isokinetic rate, and some water would enter through the exhaust tube. A point integrator can be used to depth integrate by lifting or lowering the sampler through the flow with the valve held open. A disadvantage of point integrators is their complexity and need for frequent maintenance. The electric solenoid that turns the valve will corrode and fail if it is soaked in water. The valve sometimes bind if it becomes crusted with minerals or fine particles. A point integrator has a depth limit that is reached when hydrostatic pressures reach levels high enough to completely fill the compression chamber with water. Depth ratings depend upon the sampler type and the volume of its container. For example, a US P-61-A1 sampler with a pint bottle has a depth rating of 180 ft (54.9 m).

Bag samplers were developed to operate at depths beyond the range of conventional depth integrators. Depth limits were increased by replacing rigid bottles with pliable, thin-wall plastic bags that are purged of air by folding them into tight pleats. When the bag sampler is submerged, suction pressures on the outside of the bag combines with velocity head at the nozzle's entrance to open the bag and draw in the sample. Nozzle inflow rates are usually slower than isokinetic rates. In speeds slower than about 1.5 ft/s (0.46 m), inflow stops entirely. Samples must be poured from the bags into bottles for shipment and storage, but new bags can be used for each sample to minimize risks of cross contamination. All parts that contact sample water can be made of plastics to eliminate low-level metal contamination. Bag samplers are under

development and should be used only when conditions preclude the use of point or depth integrators of the US series.

Maintenance and Field Testing

Maintenance of sampling equipment is an essential part of a successful field program. Poorly maintained samplers not only fail at critical times and prevent collection of vital data but also contribute to the collection of erroneous data. Users should contact the FISP personnel for parts and assistance with maintenance; however, emergency repairs at field sites are sometimes necessary to insure collection of data during short-term runoff events. This section gives procedures for repairing and testing the US series of depth- and point-integrating samplers.

Depth Integrators

Mechanical Testing

Before sampling, users should inspect samplers for broken or damaged tail vanes, which can be repaired by a skilled machinist. After repair, the sampler's balance should be checked and, if necessary, adjusted. The only exceptions are the US DH-48, and US DH-81 samplers which fasten to rods and therefore have no critical balance points. Cable-suspended samplers hang from a pivot and therefore require careful adjustment. During manufacture, balance is adjusted by adding weights to the lower tail vane or by grinding metal from the trailing edge of the vanes. The same procedures can be used for rebalancing after major repairs. Occasionally, the original balance weights loosen and become lost. The number and location of weights varies among individual samplers; some have no weights, others have one or two.

During emergencies, an approximate balance adjustment can be made by sealing the air vent with tape and filling the bottle to about half capacity. Insert a drill rod into the nozzle hole to serve as a reference line. The rod must be of the same diameter as the nozzle opening, usually $^{3}/_{16}$ inch (4.76 mm), ¼ inch (6.35 mm), or $^{5}/_{16}$ inch (7.94mm). Rods of these exact diameters are available in most hardware stores. With the rod in place, submerge the sampler in still water then adjust balance weights until the rod is level as indicated with a small, lightweight plastic line level. While testing for balance, tilt the hangar bar forward to eliminate interference from the hangar bar stop located behind the hangar bar.

Hangar bar stops on cable-suspended samplers should be checked. The stop is a rectangular piece of metal tightly wedged in the hangar bar slot just behind the hangar bar pin. It allows the sampler to pivot into a nose-up position but prevents it from swinging nose down. When the sampler is submerged in flowing water, the hangar bar tilts forward and allows the sampler to swing free and level its nozzle. When the sampler is hoisted above the flow, the hangar bar stop prevents the sampler from tilting and spilling sample water through the nozzle.

The air exhaust tube should be periodically checked and cleared of obstructions. The tube is "U" shaped with one end facing downstream on the outside of the sampler and the other end opening into the mouth of the bottle. A thin, flexible spring such as a piece of automobile speedometer cable can be pushed through the tube to clear debris.

Nozzles should be inspected for damage such as dents or burrs at the entrances and bends in the projecting sections. Leading edges of brass nozzles become dented if the samplers swing against bridge piers or are carelessly handled in shipment or storage. Damaged nozzles should be replaced with new parts from the FISP. When ordering, specify the nozzle's bore diameter and the sampler model. Most nozzles are tapered from their discharge end, but the depth of taper varies among sampler types. Plastic nozzles eliminate problems of denting and low level contamination of samples when they contact metal parts; but unfortunately the nozzles sometimes break if struck with a sharp blow; or they bend if overtightened in the nozzle hole. They also bend if stored for long periods with weights resting against the projecting end or if left in direct sunlight for several days.

Plastic nozzles are color coded by sampler types according to Table 2, which gives the sampler model, nozzle color, and nozzle length. Except for the US D-77, US DH-95, and US D-95 the tail or body of each sampler holds a plastic screw that is dyed to match the nozzle color and thereby serves as a color code identifier.

Table 2. Nozzles used in suspended-sediment samplers.

Sampler model	Nozzle Color	Nozzle Length in Inches (mm)
US DH-48	Yellow	4 1/8 (105)
US DH-59	Red	4 1/8 (105)
US DH-76	Red	4 1/8 (105)
US DH-81	White	4 3/8 (111)
US DH-95	White	4 3/8 (111)
US D-74	Green	3 7/8 (98)
US D-77	White	4 3/8 (111)
US D-95	White	4 3/8 (111)

Hydraulic Testing

Hydraulic testing consists of two parts: checking for leaks around the bottle gasket and measuring hydraulic efficiency. Leaks usually arise from three sources: (1) using bottles with improper length or mouth diameter, (2) using samplers with a missing or broken bottle spring, and (3) using samplers with a missing bottle gasket. The following samplers have a flat, soft gasket that seals against the bottle and fit around the downstream end of the nozzle: US DH-48, US DH-59, US DH-76, and US D-74.

The pressure between the inside of a sample bottle and the water contacting the outside of the sampler is about one inch of head; consequently, bottle gaskets must withstand only low pressures. Leak tests need not be performed on every bottle but instead once at the beginning of a sampling session. Tests should be repeated if a problem arises such as persistent overfilling of containers. Inexperienced operators using samplers with hinged heads may wish to make a few leak tests to verify proper techniques in changing bottles. Occasionally the lip of a bottle catches on the metal boss in the center of the gasket. When this occurs, the bottle fails to seal or, in severe cases, it shatters when the head is latched. Operators should close the head slowly while guiding the bottle into position.

Pressurization is one method of testing for leaks. Insert the bottle, block the air exhaust with a finger, and then gently blow into a clean tube fitted over the nozzle. Escaping air indicates a leak. Its exact location can be found by cleaning and drying the mating parts and then applying a thin coat of petroleum jelly to the bottle lip. Bring the parts together by closing the head, or on a US DH-48, by swinging the bottle clamp into position. After a few seconds, remove the bottle and inspect the imprint left on the gasket. If the imprint forms only a partial circle, increase the contact pressure by stretching the spring at the base of the bottle cavity. Before sampling, thoroughly clean the bottle and gasket to avoid contamination. As a final check for leaks, seal the nozzle and air exhaust with small stoppers or tape the openings shut. Then submerge the sampler to a depth of about one foot in still water. After one minute, hoist the sampler and remove the bottle. If the volume of collected water exceeds 20 ml additional steps should be taken to improve the bottle seal.

Measuring hydraulic efficiency, the ratio of nozzle inflow velocity to stream velocity, is usually performed in a laboratory flume where test conditions can be controlled; however, the measurement can be approximated at a gauging station. The test should be run in a region where the flow lines are straight and the velocity is steady. Avoid testing in riverbends where secondary currents are strong or near obstructions such as bridge piers where turbulence intensity is high. The flow velocity is not critical; preferably, it should exceed 2 ft/s (0.60m/s) at the test point, which should be about 1.5 ft (0.46 m) below the surface. To start the test, lower the sampler until the bottom tail vane catches the flow and turns the sampler into position. While it is turning, take care to keep the nozzle above the flow. When the sampler is steady, lower it until the nozzle reaches the test point. As soon as the nozzle drops below the water activate a timer then, after a few seconds, hoist the sampler and stop the timer when the nozzle breaks the surface. A few trials may be necessary to determine the interval needed to fill the bottle to about half capacity. At the end of sampling, retrieve the sampler and, with a graduated cylinder, measure the accumulated water volume to the nearest 10 ml. Proceed immediately to measure the flow velocity at the test point with a current meter. Sampling efficiency, H, is computed from the following equations: for a $^{1}/_{8}$-inch nozzle, H = Q/2.41 VT; for a $^{3}/_{16}$-inch nozzle, H = Q/5.42 VT; for a ¼-inch nozzle, H = Q/9.65 VT; for a $^{5}/_{16}$-inch nozzle, H = Q/15.07 VT. In these equations, Q is the sample volume in ml, V is the flow velocity in ft/s as measured with the current meter, and T is the sampling interval in seconds. Although units in these equations are mixed, they are chosen to facilitate direct measurements with field and laboratory equipment. The measurement should be repeated

several times to average experimental errors. The optimum value for H is 1.00, but a value between 0.9 and 1.1 is acceptable.

Point Integrators

Mechanical Testing

Despite their rugged appearance, point integrators contain parts that wear and corrode. Point integrators contain several moving parts and therefore require more maintenance than depth integrators. As with depth integrators, point integrators should be inspected for external damage especially to tail vanes and the nozzle. After major repairs, refer to the depth-integrator section for balance adjustments.

The nozzle for point integrators is blue in color (brass nozzles are also available) and has a $^{3}/_{16}$-inch diameter, straight-bore holes. Taper for inflow adjustment is cut into the end of the water passageway in the head base. A damaged nozzle should be replaced along with a new "O" ring that fits around the nozzle and down into the threaded hole for the nozzle nut as shown in Figure 1. The hinge pin holding the head to the body and the pin passing through the hangar bar should be cleaned every six months. The pin must form a good electrical contact because it carries electric current from the valve solenoid.

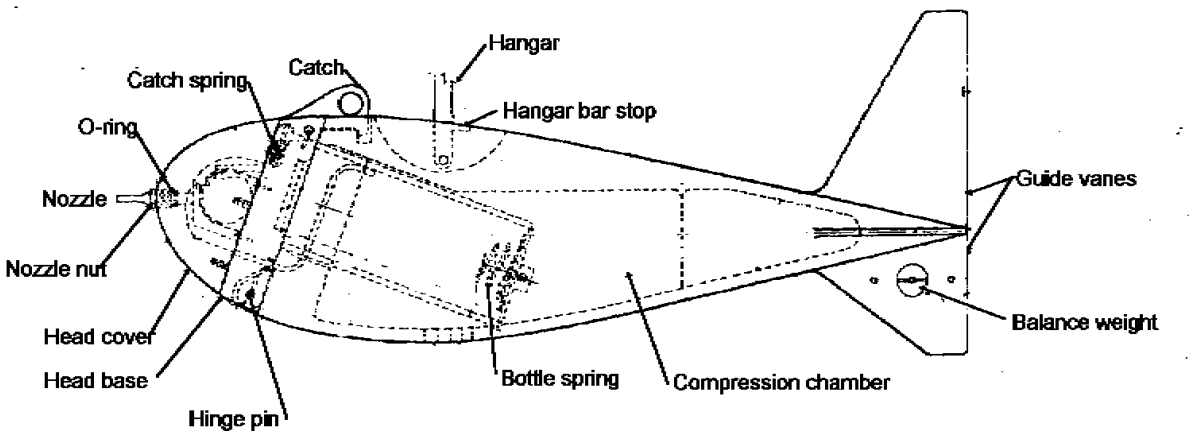

Figure 1. Point-integrating, suspended-sediment sampler.

The small gasket in the body near the hinge should be inspected before each sampling session. This gasket seals to the head base and routes air from the compression chamber into the head cavity. If the gasket is missing, water leaks into the head and corrodes the solenoid. Spare gaskets should be ordered from the FISP but, in an emergency, a temporary replacement can be made by cutting a $^{3}/_{8}$-inch (9.5 mm) length from a ½-inch (12.7 mm) OD by ¼-inch (6.4 mm) ID rubber tube. When the head is closed, the gasket must center on the small hole in the head base.

To check alignment, lightly coat the gasket with petroleum jelly, then close and immediately reopen the head. Inspect the imprint left on the mating surface. Poor alignment with the head cover hole indicates the head was transferred from another sampler. Heads should not be interchanged because, during manufacture, each head is machined to fit its matching body. On samplers made after about 1994, a matching serial number is stamped on the head cover, the head base and the body.

The seal between the bottle and bottle gasket can be checked after opening the valve by applying 48 volts of direct current from a FISP battery pack (US RBP-95) or a set of six-volt or twelve-volt batteries. When power is applied, the valve should snap open to form a straight passageway from the nozzle to the bottle. This can be confirmed by opening the head and sighting through the nozzle. If the valve fails to open, it may be binding on a dry mineral scale deposited during storage. Sometimes the valve can be freed by applying power and striking the head with a soft mallet, but be careful to avoid hitting the nozzle. Once the valve has opened, insert a bottle, close the head, and then seal the air exhaust with a finger while blowing into a clean tube fitted over the nozzle. If air escapes, refer to the leak test procedures for depth integrators.

If the valve refuses to open, water has probably corroded parts inside the head. The following actions cause leaks into the head cavity and must be avoided:

(a) Submerging the sampler without a nozzle allows water to enter the head cavity through the gap between the head cover and valve body.

(b) Submerging the sampler without a nozzle "O" ring lets water leak past the nozzle nut.

(c) Submerging the sampler without a sample bottle lets water flows through the air-exhaust hole and into the head.

(d) Tipping the sampler nose down with the bottle filled to capacity and with the valve in the pressure-equalizing (closed) position lets water flows through the air-exhaust hole and into the head. A tilt of more than about 10 degrees creates a problem.

(e) Failing to properly tighten the nozzle and nozzle nut lets water leak past the "O" ring. The nozzle should be only handtight since overtightening causes plastic inserts in some valves to shift and rub against the valve plugs. The nozzle nut can be tightened with a wrench but overtightening buckles the "O" ring and creates leaks.

(f) Submerging the sampler with a missing or deformed compression chamber gasket lets water enter the air hole.

(g) Pouring rinse water over the bottle gasket with the valve in the power off condition lets water leak into the vent hole. If rinsing is required, lower the sampler and fill the bottle to about half capacity. Retrieve the sampler and then, with power applied, tip the sampler forward to allow water to drain and rinse the nozzle bore. It is essential to keep

power on during this procedure. Because the head is vulnerable to leaks when the valve is in the pressure-equalizing (power off) position, it is important to keep the power supply fully charged and to periodically clean the reel connectors and hinge pins.

Even with a well-maintained sampler, slow leaks occur around the valve since a small clearance is needed to reduce friction. The torque applied to the valve is low because of the safe, low-voltage supply and the electrical resistance in the suspension cable that carries power to the solenoid. After a sampling session, the head should be drained by removing the nozzle nut along with the nozzle and its "O" ring and then tipping the head so trapped water can drain out through the opening. Before placing the sampler in storage, open the head as described in the next section and dry the internal parts.

The gasket between the head and head cover plate is frequently blamed for leaks; however, it is seldom at fault. If a replacement is needed, it should be ordered from the FISP because the gasket thickness is critical. A gasket of the improper thickness creates a misalignment between the nozzle and nozzle nut. When reinstalling a new gasket, be sure to position it so the pressure-equalizing hole is open. Do not use gasket cement.

The first step in dismantling the valve is to remove the nozzle nut and nozzle (Figure 1). After removing the head assembly from the body, remove the six cap screws holding the head cover to the head base. Lay the head assembly on a bench and lift off the head cover to expose the valve mechanism shown in Figure 2.

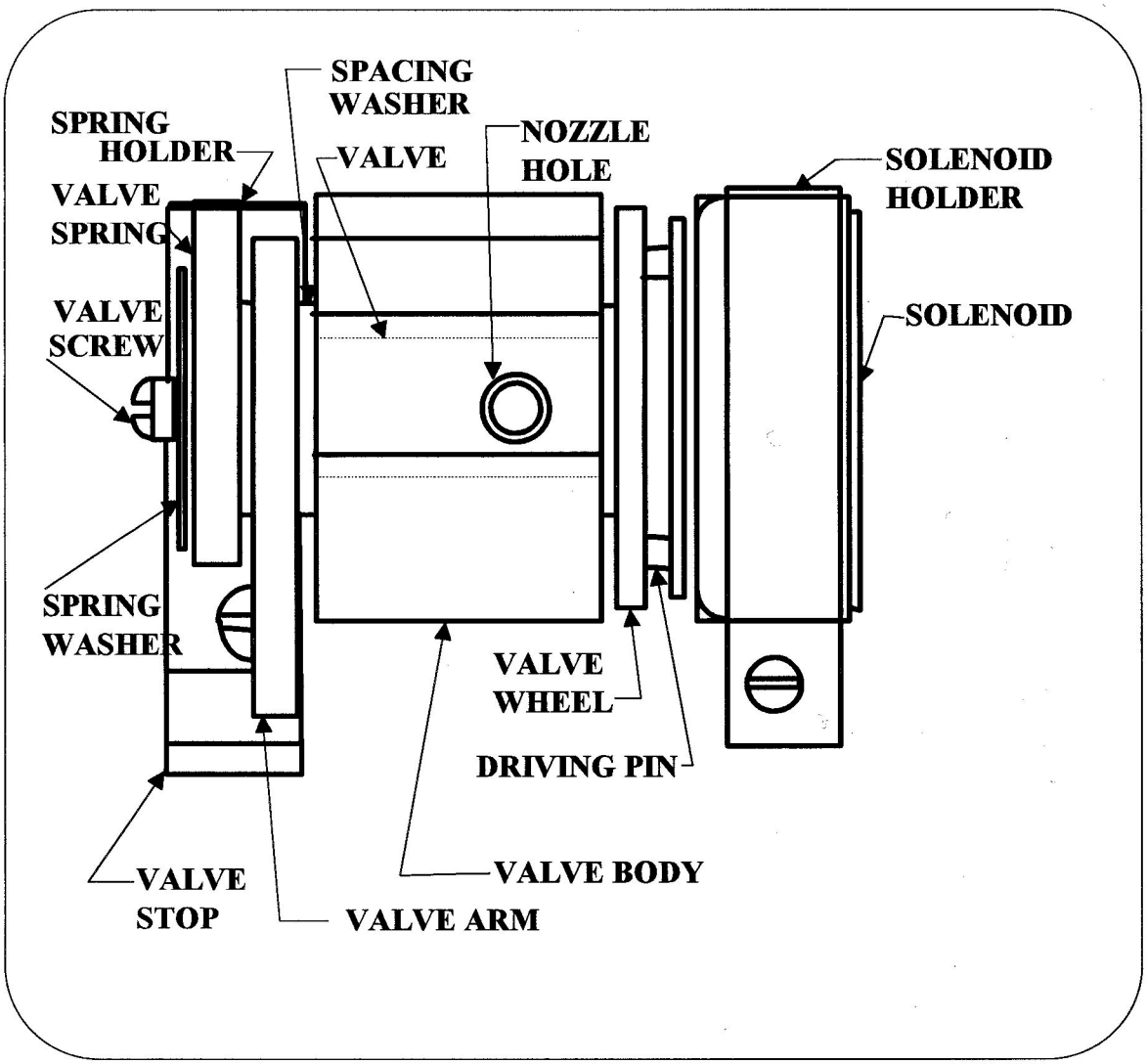

Figure 2. Valve mechanism for a point-integrating, suspended-sediment sampler.

Before dismantling the assembly, mark the position of all mating parts. Remove the screw in the end of the valve plug then remove the spring washer and spring boss. Note the position of the valve relative to the end of the valve plug. On some samplers, the mating surfaces are identified by punch marks. Mark the position of the solenoid relative to its holder. Since the solenoid's position is critical, make alignment marks with a scribe or sharp tool. Loosen the solenoid holder and remove the solenoid to expose the end of the valve. The valve plug can now be pulled from the valve body. Scale and dirt can be removed from the valve surfaces with fine-grade steel wool. Household abrasive cleansers should not be used since the particles become imbedded in the brass body and may cause the valve to bind. With the solenoid free of the other parts, it can be tested by applying 48 volts of direct current between its wire lead to its metal shell. The armature should rotate 45 degrees and then when power is removed it should return to its starting position. If the armature fails to turn, corrosion has probably damaged the windings or ball bearings. Repairs can be made only by replacing the solenoid.

To assemble the valve, reverse the above procedure. First, identify the top and bottom of the valve plug. The top, which faces the nozzle opening, has two closely-spaced holes; the bottom has four. Wind the spring about a half revolution and install it so that the spring tightens when the valve arm moves to the sampling position. After replacing the spring washer and valve screw, check the axial clearance of the valve by pulling and pushing on the washer under the screw. The movement should be almost imperceptible, only a few thousandths of an inch. Excessive movement indicates the spacing washer surrounding the valve plug is either missing or has fallen out of position during assembly. Press the valve arm down against the valve stop while sighting through the nozzle hole. The passageway must be completely open. Slight misalignment can be corrected by shifting the valve stop, but this is seldom necessary. When all parts are in place, set the head cover back on the gasket and head cover then insert the cap screws. Before tightening the screws, number them in sequence in a clockwise direction then torque them in the sequence 1-4-6-3-5-2. Make several passes while increasing the torque each time. The final torque should be 100 pound-inches to 125 pound-inches, but the exact torque is not as important as having all screws tightened uniformly.

Electrical Testing

The electric circuit for a point integrator starts at the power source, which may be a group of batteries or a special unit (the US RBP-95) available from the FISP. Electric current flows from the source to the brush and slip-ring assembly on the cable reel. Current enters the center conductor of the suspension cable and flows down to a special cable clamp fastened to the sampler's hangar bar. Current flows from the suspension cable to the wire leading to the solenoid. After flowing through the solenoid winding, current enters the solenoid's metal shell and flows through the solenoid clamp to the sampler's head. The path continues across the hinge pin to the sampler's body and across the hangar bar pin to the hangar bar and finally into the outer braid of the cable which leads back to the source. A break or high-resistance connection at any point in the circuit prevents the solenoid from operating.

A portion of the circuit with several connections is the section starting at the solenoid clamp and ending at the cable's outer braid. To improve reliability, samplers can be wired with a special coaxial cable available from the FISP. The cable lets current flow directly from the solenoid frame to the braid on the suspension cable without passing through the head, body, hinge pin and hangar bar pin. All samplers produced since about 1993 are fitted with this two-conductor cable. The ground (outer braid) on the sampler cable should be connected to the outer braid on the suspension wire. The center conductor on the sampler cable should be connected to the center conductor on the suspension wire.

Any direct current power supply in the 48-volt to 56-volt range will operate a point integrator. One style, the US BP-76, which is still used but no longer produced, delivers a 48-volt pulse to turn the solenoid. Voltage then drops to 12 volts to hold the solenoid in position. Although the unit conserves power, it malfunctions if the sampler's circuit is even momentarily broken by poor contacts at the hangar bar or the reel's slip ring. A more reliable power unit, the US RBP-95, is

rechargeable and maintains 48 volts through the entire sampling cycle. The unit is available from the FISP.

Hydraulic testing

The hydraulic efficiency of point integrators supplied by the FISP is adjusted as part of the inspection and test routine. A sampler remains in calibration unless its valve becomes misaligned or its air passageways become blocked. Hydraulic adjustment consists of taper reaming the passageway leading from the bottle to the downstream end of the valve plug. The reamed section lies entirely within the head base and valve body. After machining, the hole diameter in the head base is about $^{5}/_{16}$ inch, noticeably larger than the $^{3}/_{16}$-inch hole through the nozzle. If the entire passageway has a uniform diameter of $^{3}/_{16}$ inch, the sampler was probably supplied by a vendor who failed to make the necessary adjustments. Deficiencies can be corrected by arranging with the FISP for laboratory testing.

Although hydraulic efficiency measurements are seldom made at a field station, users wishing to do so should refer to the procedure described for depth integrators; the procedure is similar for both types. After lowering the point sampler to the test point, apply power to open the valve, then after a few seconds hoist the sampler and measure the accumulated volume. A few trials are usually necessary to adjust the interval to fill the container to about half capacity. The formula for computing hydraulic efficiency is given in the depth integrator section. Use the formula for $^{3}/_{16}$-inch nozzles.

Laboratory tests verify that a US P-61-A1 sampler can be calibrated in a flowing-water flume or in a tow tank where the sampler is pulled at a controlled speed through still water. Tow tank testing can be approximated on a boat moving at a steady speed through a lake or reservoir. The sampler and current meter must be lowered to a test point off the forward beam to avoid turbulence and eddies produced by the hull.

Sampling Protocol

Selecting a sampling site is one of the early steps in organizing a field program. Suspended-sediment discharge is the mathematical product of concentration and water discharge; therefore, a site near a gauging station provides ready access to discharge data. If possible, avoid sites near confluences. Stations upstream of river junctions are exposed to interference from backwater flows; those downstream of confluences usually have strong lateral gradients owing to slow mixing in the converging flows. Cross sections shallow enough to wade even during peak flows can be sampled with US DH-48 hand samplers, but many rivers are too deep and fast for wading and, therefore, must be sampled from cableways or bridges. The upstream side of a bridge is favored over the downstream side because of better visibility and freedom from eddies. Floating debris such as brush and tree trunks can be seen before they snag samplers and current meters. High turbulence and reverse eddies downstream of the piers are avoided.

Data on sediment discharge through a cross section can be collected by point or depth integration. The method should be selected early in the program. In point integration, the cross section is divided by vertical lines spaced across the channel. Samples are then collected at several elevations along each vertical. In essence, the cross section is divided into a series of rectangular panels and one sample is collected within each panel. Each concentration value is then multiplied by its related water discharge to obtain sediment discharge. Finally, sediment discharges at each section are added to obtain the total suspended-sediment discharge through the cross section.

Point integration sampling is rarely used owing to the high cost in time and labor. Each sample must be accompanied by a velocity measurement and each sample must be analyzed separately. However, point integration must be used if a cross section is to be mapped for concentrations or sediment discharges.

In depth integration, the cross-section is again divided by vertical lines spaced across the channel. One sample is collected at each vertical by lowering a depth-integrating sampler through the flow at a steady rate. When the sampler contacts the channel bottom, traversing is immediately reversed and the sampler is hoisted at a steady rate back to the surface. In depths greater than about 15 feet, the maximum rating for most D-series samplers, samples must be collected with a point integrator. A vertical is divided horizontally into segments and each segment is sampled separately. The point integrator is lowered to the top of a segment, and then the valve is opened and held open as the sampler is lowered at a steady rate to the bottom of the segment. In this mode, the point sampler is used as a depth integrator. Segments of thirty feet or less can be sampled in this manner. Lowering and hoisting rates must be carefully controlled as explained later.

Operator judgment plays a vital role in obtaining accurate data. All samplers are deficient to some degree in that they deviate from perfect isokinetic inflow rates; however, inflow errors and concentration errors are seldom equal to one another. For example, Table 1 shows an inflow rate forty percent higher than isokinetic causes a concentration error of only nine percent for coarse

particles. When a sampler is used for depth integration, it moves through velocity and concentration gradients that introduce additional errors. The sample now becomes a composite of many smaller samples each collected within a particular depth zone. If one zone is oversampled (intake exceeds isokinetic), it dilutes samples from the other zones. Therefore, the weighting factor for the oversampled zone exceeds its proper value. Another type of error arises when a sampler's direction of travel is reversed from lowering to raising. As a sampler is lowered, water impinging against the bottom surface produces uplift opposing the pull of gravity. The combination of uplift and frontal drag pushes the sampler downstream; but when the traverse direction is reversed, flow striking the sampler's top surface produces a downward thrust. In seeking a new force equilibrium, the sampler swings upstream and in so doing, oversamples the zone, which is usually near the river's bed. Using a sampler as heavy as possible and using a cable as small as strength and safety permits, helps reduce the upstream motion. The cable normally used with US P-61-A1 point integrator is $^1/_8$ inch in diameter and of the Ellsworth design. It can be obtained from the Hydrologic Instrumentation Facility operated by the U.S. Geological Survey. A substitute cable may be used if its electrical resistance is less than 100 ohms per 1,000 feet of length.

The maximum volume of a sample must be carefully regulated to maintain isokinetic inflow. A sampler bottle should not be filled above the lower edge of the nozzle. If the water surface rises above the nozzle, (a) backpressure reduces the inflow rate and (b) part of the sample drains away when the sample is hoisted above the river. Drainage increases sample concentration because sediment carried in with the flow remains trapped in the bottle. Maximum volume rating is set to provide a margin of safety against spillage if the sampler pitches up and down during retrieval. Most sample containers can be filled to about $^2/_3$ capacity without risking inflow-rate reduction or loss due to drainage. The fraction varies slightly among sampler types.

A sampler's transit rate must be slow enough to maintain a continuous balance between air pressure inside the bottle and hydrostatic pressure near the nozzle's entrance. Furthermore, the compression caused by lowering the sampler must be compensated entirely by inflow through the nozzle. If the lowering rate exceeds a critical speed, the growth of hydrostatic pressure not only increases inflow through the nozzle but may also force water into the air-exhaust passageway. The adverse flow direction at the exhaust introduces errors by violating principles of isokinetic inflow.

Maximum transit rates are set by compression at the river surface, by slow velocities near the river bottom and by turbulence at the nozzle's entrance. At the surface, pressure rises abruptly from atmospheric to hydrostatic as the sampler enters the water. The maximum lowering rate at the surface is given by the expression ASh/V, where A is the nozzle area in square feet, S is the flow velocity at the surface in ft/s, h is atmospheric pressure head in feet (34 feet at sea level), and V is the volume of air trapped in the bottle in cubic feet. In depths shallower than about 15 feet (4.6 m), transit rates, in most cases, are limited by slow velocities near the bottom. The third limiting factor, turbulence at the nozzle's entrance, occurs when the lifting or lowering rate exceeds 0.4 of the mean stream velocity. As an aid in determining transit rates for various depths

and types of samplers, Edwards and Glysson (1999) show the construction of special charts. Maximum depth ratings are given in the FISP Memo 94.04 available through the FISP office.

Nozzles are supplied with a range of bore diameters ranging from 3/16-inch to 5/16-inch in diameter. Nozzles with 5/16-inch bores are used only on D-77 samplers that have large (3-liter) containers. The 3/16-inch and 1/4-inch diameters give best results. The 1/8-inch nozzles plug easily and have erratic inflow rates. They should be used only when low hoisting power imposes limits on transit rates (FISP no longer supplies 1/8-inch nozzles).

After selecting the appropriate sampler, users can focus on choosing locations for the sampling verticals. The equal-discharge-increment (EDI) method or the equal-width-increment (EWI) method is ordinarily used. The EDI procedure yields a discharge-weighted, suspended-sediment concentration for the entire cross section. The first step in choosing verticals is to plot cumulative water discharge against distance across the section. The chart's origin, corresponding to a discharge of zero and a distance of zero, matches the starting point on one bank. Cumulative water discharge is then plotted against distance from the starting point. The last point, total discharge for the entire section, is plotted opposite the distance to the opposite bank. This chart is then used to determine the boundaries of panels dividing the cross section into sections of equal discharge. The chosen number of panels usually ranges from three to five. A vertical is then positioned within each panel at its centroid of flow—a location such that half the panel's discharge is to the left of the vertical and half to the right. Verticals are then sampled by depth integration at transit rates yielding sample volumes that are equal for all verticals. Meeting the equal-volume requirement usually requires transit rates that differ from one vertical to the next. Practical considerations demand some tolerance on volumes: variations less than ±10 percent from the group mean are usually acceptable. If the samples meet this criteria, they can be composited (poured together) prior to making a laboratory analysis. Compositing helps lower costs by reducing laboratory work, but compositing should not be attempted if sample volumes differ significantly. In this case, samples should be analyzed separately then the discharge through each panel computed as the product of sample concentration for the vertical multiplied by the water discharge through the panel. Total cross section discharge is obtained by adding discharges for all panels. Additional details on EDI measurements are given in ASTM Standard D-4411 and in Edwards and Glysson (1999). EDI measurements have a disadvantage in that data on lateral distribution of water discharge must be collected and charted before sampling can begin. Recharting is necessary because the appropriate location of the verticals varies with water discharge.

The EWI procedure, like the EDI procedure, yields a discharge-weighted concentration for the cross section. As its name implies, the EWI method is based on sampling verticals that are equally spaced across the section. The EWI procedure differs from the EDI in that with the EWI method the same transit rate is used at all verticals. An optimum transit rate is determined for the region of maximum discharge, then this rate is used at all other verticals. Since depths and flow velocities differ among the verticals, sample volumes also differ from one vertical to the next. However, because the volumes are discharge weighted, all samples can be composited before analysis. About twenty verticals are sampled if the cross section has considerable variability in

depths and velocities, but the number can be reduced to about ten if velocities and depths are nearly uniform. For unusually wide sections, a preliminary survey should include intensive sampling at twenty or more verticals. After analyzing the samples separately, an assessment can be made of the accuracy lost by reducing the number of verticals used in subsequent measurements.

Duplicate sample sets should be collected if data on grain size and concentration are required. Each sample should be labeled according to its set and its sampling vertical. For example, the mark 5A indicates a sample collected at vertical number five and a member of set A scheduled for particle-size measurements. About 10 percent of all samples for concentration should be collected in duplicate as a means of verifying quality control in the laboratory.

An advantage of the EWI method is that water discharge need not be measured and plotted before sampling begins. A disadvantage is that transit-rate limits must sometimes be exceeded near the banks where flow velocities are slower than at verticals near the center. Another disadvantage is that data on cross-channel variability is not obtained if the samples are composited.

Sampling trips should be scheduled to include peak flows and times when flows or concentrations are expected to change rapidly. For economic reasons, local observers are sometimes employed to collect daily samples but only at one or two verticals. Observer samples are then compared with a complete set of discharge-weighted samples collected by EDI or EWI procedures. Correlation coefficients are then developed and applied to the observer's samples. At sites too remote for observer sampling, pumping samplers or single stage samplers may be used.

All sample bottles must be marked at the conclusion of a sampling session for identification at the laboratory. The water level in each bottle should be marked with a grease pencil so that laboratory personnel can check for leakage and evaporation. Each bottle should be marked with the following information: river name, personnel's initials, sampling technique (EWI or EDI), time and date of collection, gauge height, water discharge and temperature, sampling station number, and set identification letter for duplicate samples.

Samples should be packed in sturdy shipping containers for transport to the laboratory. Insulation should be used if there is danger of freezing which not only breaks bottles but precipitates carbonate minerals. Packing must also comply with requirements set by the carrier. U.S. Post Office regulations call for containers with enough absorbent material to hold all water released if the sample bottles are accidentally broken. Each container should be packed with a log showing the following information: condition of sample bottles, total number of bottles collected in the cross section, personnel's initials, stage, comments on unusual hydrologic conditions, type of analysis requested (concentration or grain size), instructions for compositing, and identification of duplicate samples. Edwards and Glysson (1999) present additional details on sediment discharge calculations and forms for logging data.

Sediment-Concentration Measurements

Sediment samples arriving at a laboratory for analysis should be inspected for breakage, leakage, and evaporation. Water levels should be compared with the marks placed at the completion of sampling. Differences should be noted and corrections applied later in the calculations.

Most laboratories have computer-logging programs that track samples through the analysis procedures. The logging procedure consists of measuring gross weights, transcribing sample-identification data into electronic form, and measuring the sample's specific conductance which is used as a quality control check on samples collected by observers. Samples are then sorted according to the type of analysis to be performed. Most laboratories will have a backlog, so incoming samples must usually be stored for a time, but storage periods should not exceed about 60 days to avoid excessive growth of algae and mold. Storage areas should be cool and dark to slow biological growth.

When the samples are scheduled for analysis—the type of concentration procedure—the laboratory chooses either evaporation or filtration. Selections are based on the degree of settling that occurred in storage and the estimated level of concentration. The analysis method imposes an operational definition on the term "sediment." Whereas the classical definition mentions particles derived from rocks or biological material, a more pragmatic definition is the material separated from the sampled mixture in the course of making the analysis.

Dimensional units for concentration have changed since the inception of sediment measurements. Early definitions centered on the units of parts per million (ppm) taken as the weight of dry sediment multiplied by one million and this product divided by the weight of the water-sediment mixture. Recent usage centers on the units of milligrams per liter (mg/L), the mass of dry sediment in milligrams divided by the volume in liters of the water sediment mixture. In practice, concentrations are measured in parts per million and then converted to mg/L with tables by Guy (1969) and in ASTM Standard D-3977 (ASTM 2000). The two systems of units are almost equal for concentrations less than 8,000 ppm.

Quality assurance and quality control of procedures have grown in importance during recent years. Modern practices specify that about five percent of all data should be on blank samples, reference samples or duplicate runs. Blanks are samples of distilled water tested to verify not only the precision of balances and consistency of tare weights but also the purity of the laboratory water supply. A reference sample is prepared by adding distilled water to a known amount of sediment and comparing it with the amount recovered. Nondestructive tests such as dry sieving and X-ray analysis for grain sizes should be repeated on about 5 percent of the samples. Part of the quality assurance program is to periodically check laboratory equipment. Balances are checked daily using weights traceable to the National Bureau of Standards; conductance meters are checked with standard solutions; tare weights of crucibles and weighing dishes are measured at each use and oven thermometers are checked every few months at two temperatures, usually 80 °C and 110 °C.

Evaporation Method

In the evaporation method, sediment is separated by allowing it to settle during storage. When the sample is ready, most of the water is carefully removed without disturbing the sediment layer. A "J" shaped tube with one end connected to a vacuum is pressed against the bottom of the sample bottle. The tube's open end faces upward away from the sediment deposit. Water is slowly vacuumed away until only about 40 ml to 70 ml remains. The water surface is then marked on the wall of the bottle before the mixture is transferred to an evaporating dish. Water is evaporated away in a temperature-controlled oven, and then the dish is cooled in a desiccator and weighed.

The sediment weight is corrected for dissolved solids by filling the sample bottle to the water-level mark and measuring the liquid volume with a graduated cylinder. A measured portion of the water withdrawn with the "J" tube is heated to dryness and the residue of dissolved solids is weighed. This weight is used to determine a correction factor for the amount of dissolved solids in the dried sediment. Details for these steps are given in ASTM D-3977.

Sediment concentration is computed by dividing the corrected weight of dry sediment by the weight of the original sample recorded during login and then multiplying this ratio by one million. Conversion of ppm to mg/l can be made with the equation:

$$C_1 = C/(1\text{-}622x10^{-9}\ C)$$

where

C_1 is sediment concentration in mg/L and
C is sediment concentration in ppm

The precision and bias of the evaporation method was measured with assistance from ten analysis laboratories. These data were then used to compute S_T, the overall standard deviation of pooled data from all laboratories, and S_O, the standard deviation for single operators. Bias, which is a comparison of sediment added to sediment recovered, includes errors not only in laboratory measurements such as drying and weighing but in transferring sediment from the shipping bottles as well as small losses which probably occur because of sample dissolution. Table 3 gives values for S_T, S_O and bias for the evaporation method.

Table 3. Precision and bias of the evaporation method.

Concentration, mg/L	S_T	S_O	Bias, percent
10	2.5	2.3	-10
1,000	36.8	15.9	-2.4
10,000	532	360	0.3

Filtration Method

In the filtration method, water is separated by trapping the sediment on a filter. A sample qualifies for filtration if its sand concentration is less than about 10,000 mg/L and its clay concentration is less than about 200 mg/L. Filter plugging occurs if concentrations are higher than these levels.

Filter types, sizes, and retention ratings strongly influence results. Type 934-AH filters, which consist of a mat of borosilicate glass fibers, have been selected as a compromise between particle-retention efficiency and filtration rates. Also, this type of filter is thermally and chemically stable and is inexpensive. Its retention rating is 1.5 micrometers; however, it retains some particles smaller than this size and passes a few that are larger. The retention rating is not a precise cutoff owing to the filter's construction, which consists of a mat of randomly oriented fibers forming openings of irregular, non-circular shapes. The filter's retention shifts to smaller sizes as filtering proceeds and a layer of particles accumulates. The thickness of the layer depends on the filter's diameter and the amount of sediment in the sample. Filters with 24-mm diameters are recommended; however, filters as large as 42 mm may be used if plugging is a problem. Each filter is washed and then placed in a crucible that is connected to a vacuum pump to increase flow rates. The sample is rinsed into the crucible then, after all water has passed the crucible and its contents are dried at 105 °C. The crucible and sediment are then cooled in a dessicator and weighed. Sediment weight is obtained by subtracting the tare weight of the crucible and filter. As the last step, concentration is calculated in ppm and then converted to mg/l.

Compared to the evaporation method, filtration is simpler and faster because dissolved-solids corrections are not required. Precision and bias of the filtration method was measured at ten laboratories as explained in the evaporation section. Table 4 gives values for S_T, S_O, and bias for three concentrations.

Table 4. Precision and bias of the filtration method.

Concentration, mg/L	S_T	S_O	Bias, percent
10	2.6	2	-20
100	5.3	5.1	-9
1,000	20.4	14.1	-3.9

Wet-Sieve-Filtration Method

The wet-sieve-filtration method is used if two concentrations are required: one for coarse particles, those retained on a 63-micrometer sieve, and one for fine particles, those passing through the sieve. The method is also used when large samples of several liters are collected but only small volumes, a liter or less, can be shipped back to the laboratory. The volume of the large sample is measured then it is poured through a 63-micrometer sieve. The mixture passing

through the sieve is split by withdrawing an aliquot from a churn-type splitter. This aliquot along with all material retained on the sieve is then shipped to the sediment laboratory.

Samples of a liter or less can be analyzed by the method by first wet sieving and then analyzing all material passing the sieve; the aliquot extraction step is not used. If desired, the filtration phase can be replaced by evaporation. Details on the wet-sieve-filtration method are given in the ASTM Standard D-3977.

Precision and bias measurements were made on samples of coarse and fine particles composited in the proportions of 1 part coarse to 10 parts fine. Table 5 shows results obtained from ten laboratories.

Table 5. Precision and bias of the wet-sieve-filtration method.

Mixture Number	Particle-sieve diameter, micrometers	Spiked concentration, mg/L	S_T	S_O	Bias, percent
1	>62 (sand)	1	2.8	2.4	240
1	<62 (fines)	10	4.3	2.9	-13
2	>62 (sand)	9	5.9	1.9	-44
2	<62 (fines)	91	15.2	11	-13
3	>62 (sand)	91	12.3	5.9	18
3	<62 (fines)	909	87.2	61	-8

Bias values in Table 5 were partially influenced by normal imperfections in wet sieving. Fine particles inadvertently retained on the sieve acted to bias the concentration of fines toward negative values (material lost) and the sands concentration toward positive values (material gained).

A comparison of methods shows the wet-sieve-filtration method has a comparatively large bias and therefore should be used only when dictated by needs for sample splitting. Compared to the filtration method, the evaporation method has a smaller bias for concentrations less than 1,000 mg/L. Unfortunately, the improvement in accuracy is gained through and expenditure of additional labor.

Grain-Size Analysis

Much of the sediment carried into reservoirs is deposited when the river currents slow, spread and become too weak to support particles in suspension. The size of the particles is an important factor in determining the shape and location of the deposits. Measuring the size of particles is straightforward for those with simple, regular shapes such as cubes or spheres. Sediment particles, on the other hand, have irregular shapes produced by weathering and fracturing. Some resemble spheres with rough and pitted surfaces. Some resemble rods; others are flat and platelike.

Designating the size of an irregular particle involves the concept of an equivalent sphere that can be assigned in several ways. For example, on a volume-equivalence basis, a particle is assigned the diameter of a sphere such that the two have equal volumes. Sizes can also be assigned on the basis of processes or instruments used in the measurements. For example, particles sized by mechanical sieving are assigned diameters equal to the width of the square opening in the sieve fabric.

Every sizing method has shortcomings and inaccuracies. For example, long, rod-shaped particles can turn upright and pass through sieve openings only slightly larger than the particle's waist (smallest) dimension. These particles are then assigned a diameter that is unrealistically small. Other rod-shaped particles may be retained on the sieve and therefore classed in a different size category. Measuring sediment particles with optical instruments is a field of on-going research. Several instruments have been proposed, but the results have generally been unsatisfactory because of interference from a particle's color, index of refraction, and orientation relative to the optical beam. A beam striking a platelike particle with its broad surface illuminated registers the particle as having a large diameter. The same particle turned to expose its thinnest dimension registers as having a small diameter.

Agreement among most sizing methods is poor; therefore, it is important to avoid changing methods or instruments without first evaluating potential discrepancies. In sediment studies, equivalence is usually based on settling rates in still water. Unfortunately, technical difficulties in settling-rate measurements limit the method to particles smaller than about 2 mm. Particles larger than this limit are usually sized by sieving.

Dry sieving is rarely used to process suspended-sediment samples but is frequently used with sedimentation techniques for analyzing bed-material samples. The test is usually run with a group of sieves with openings that differ by a common multiple such as $\sqrt{2}$. The sieves are stacked with the coarsest sieve on top and the finest next to the bottom over a closed pan. After placing the sample on the top sieve, the stack is placed in a vibratory shaker specially designed for the purpose. The stack is vibrated for about 10 minutes during which time the particles settle through stack until they reach a screen too small for passage. At the end of the process, the contents in the pan and on each sieve are weighted separately. Sediment in the pan is sometimes analyzed in greater detail by using a sedimentation technique. When two or more techniques are used on one sample, accurate records of weights are necessary in order to combine results into

one data set of cumulative percent-finer values. For accurate sieving, loading limits must be observed. Particles on each sieve must be spread thin enough to give each particle an opportunity to contact the screen and pass through the openings. A limit of about 35 grams of sediment and a vibrating time of 10 minutes applies to eight-inch diameter sieves.

Particles fine enough to pass through 2-mm sieve openings but coarse enough to be retained on a 53-micrometer opening can be analyzed with a visual-accumulation-tube-size analyzer (VATSA). The VATSA is no longer produced by FISP. The apparatus consists of a special glass tube with a funnel and a release clamp at the top. The bottom end of the tube makes a smooth transition to a small-bore section. The tube mounts upright in a special stand that supports an eyepiece opposite the small bore. The eyepiece can be raised and lowered with the aid of a crank and screw connected to a marker pen on a recording chart.

To start the analysis, the tube is filled with distilled water, the pen is zeroed on the chart, the top clamp is closed, and the sample is poured into the funnel. After stirring the sample for a few seconds, the clamp is opened to allow the particles to settle through the column. When the clamp opens it starts a motor that slowly turns a drum holding the chart. As the particles settle, the operator cranks the eyepiece up to track the top surface of the sediment accumulating in the small-bore section. After all particles have settled, the percent-finer data is read from the chart. Particle sizes determined in the VATSA are termed “fall diameters” which are based on fall velocities of equivalent spheres. Test conditions such as water temperature are standardized to insure consistent results. The cumulative height of sediment in the small-bore section should be between 0.5 inches and 5.0 inches for accurate readings. Tubes are available with small-bore diameters ranging from 2.1 mm to 7.0 mm. If cumulative height is beyond optimum limits, the sample can be removed and analyzed in a different tube. When analysis is complete, the sample is removed, dried and then weighed in order to merge the data with other size analysis methods. Details on assembling and operating a VATSA are given in FISP (1958).

Two types of initial conditions are used in particle sizing by sedimentation. In the VATSA, all particles start from a thin layer above the clamp at the top of the tube. This initial condition is termed stratified system. In the pipet, bottom-withdrawal tube, and X-ray methods, which are explained later, the particles are initially scattered and dispersed throughout the sedimentation column. This initial condition is termed a dispersed system. Because mathematical procedures for reducing raw data from the two systems are different, users are urged to consult the references for complete information.

The pipet method is used on particles smaller than 62 micrometers. The lower limit extends into the clay-size range; however, most tests are terminated at 2 micrometers. The sample is mixed with distilled water in a column the size of a 1-liter, graduated cylinder. The optimum quantity of sediment is 2 grams to 5 grams; however, with a sacrifice in accuracy, smaller quantities can be analyzed in 250-ml cylinders. Dispersing agents are added to prevent flocculation during the settling process, which lasts a few hours.

The analysis starts by dispersing the particles with a stirring and churning action. When mixing stops, the particles begin to settle at rates, which according to theory, are free of interference from other particles and the container walls. Immediately after stirring stops, the first withdrawal is made with a volumetric pipet. This subsample contains all size fractions in the sample at their initial concentrations. After a prescribed time delay, another sample is withdrawn at a predetermined depth. This second sample is deficient in particles larger than a critical diameter that is based on Stokes' Law for spheres settling in fluids. The Stokes equation reduces to $D_c = K\sqrt{x/t}$ for a given particle density, liquid density and liquid viscosity. The cutoff diameter is D_c, the withdrawal depth is x, and the withdrawal time is t. Withdrawals are usually made at critical diameters of 32, 16, 8, 4, and 2 micrometers. Tables for sampling depths and times are given in the manual by Guy (1969). Each withdrawal, which is made under controlled conditions, is dried and weighed. These weights are then plotted against critical diameters to obtain a percent-finer size distribution.

The bottom-withdrawal (BW) tube is used on sediment quantities too small to analyze with the pipet procedure. Samples in the range of 0.5 grams to 1.8 grams can be analyzed by the BW method, which like the pipet, is based on the theory of particles settling in a dispersed system. Fall velocity is related to fall diameter through an equivalence based on experimental measurements for sand-size particles and on Stokes' Law for clay- and silt-sized particles. The equipment is simple and inexpensive. It consists of a 1-inch diameter tube 48 inches long. The lower end is constricted to form a short ¼-inch section that is sealed with a short rubber tube and a pinch clamp. The sediment is placed in the tube that has been filled with distilled water to a depth of 1.0 m. The contents are mixed by inverting the tube several times, and then the tube is hooked into clamps that hold it upright as settling proceeds. Samples of known volume are drained at prescribed intervals from the lower end by opening the clamp and catching the mixture in an evaporating dish. After all withdrawals have been made and dried, the weights are plotted against withdrawal times to form an Oden curve. A series of tangent lines are drawn to the Oden curve and extended to intersect the vertical axis where percent-finer values are read.

Accuracy of the BW method was evaluated using batches of small, glass spheres large enough to measure with a microscope. Their fall velocities were measured experimentally. Individual analyses of size classes were within ±20 percent of the correct value in about half the tests. Details are given in FISP (1953).

The newest addition to the particle-measurement field is an instrument that measures attenuation of X-rays transmitted through sediment suspensions. A test mixture is homogenized by pumping it through a measuring cell having its bottom end aligned with a collimated radiation beam. The analysis starts when the pump is turned off and the particles begin to settle. The intensity of the beam, which is monitored continuously, grows as particles settle and the concentration of sediment in the radiation path decreases. To speed the analysis of fine, slow-settling particles, the sedimentation column is lowered through the beam to measure concentration gradients near the top. As settling proceeds, the instrument automatically plots a graph of cumulative percent-finer data opposite particle fall diameters. The instrument's size range is from 0.18 micrometers to 50 micrometers. The principle sources of interference are air bubbles and organic particles in

the column. Compared to water and sediment, air absorbs few X-rays and therefore causes abrupt shifts in the attenuation record. Organic material rises and causes particles to move upward instead of settling.

Compared to a pipet analysis, the X-ray method usually indicates from five to ten percent more material is finer than a given diameter. The reason for this bias is uncertain: it may stem from a reduction of fall rates caused by the cell walls or from particle-to-particle interactions.

The instrument's main advantage is speed: it completes an analysis in a fraction of the time required with a pipet or BW tube. Also, the instrument's reproducibility is superior to that of the other methods. Even though X-ray instruments are more costly than pipet apparatus, their speed offsets the higher investment. The X-ray method has been accepted as an alternate method of size analysis as announced in the FISP Memo 96.01, dated April 15, 1996. The memo requires that all size data be identified by the analysis method used and that duplicate analysis be made on at least 10 percent of the samples to evaluate differences between the X-ray method and the pipet or BW tube.

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