6th International
NORTHERN RESEARCH BASINS Symposiums/Workshop
Michigan Technological University
January 26-30, 1986

SAMPLING SUSPENDED-SEDIMENT IN ICE-COVERED RIVERS

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ABSTRACT

Collecting water samples is a critical step in determining a river's suspended-sediment discharge. Samples usually are collected with depth-integrating samplers designed for use in free-surface flows. Unfortunately, a problem develops when the samplers are used in ice-covered rivers. Each sampling vertical spans a lower zone that extends from the river's bed to the bottom surface of the ice cap; this zone includes moving water and sediment. The upper zone is created when a hole is augered through the ice. This zone extends from the bottom surface of the ice-cap to the surface of the water standing in the hole. The upper zone includes only stagnant water that does not contribute to water or sediment discharge. However, when a depth integrator is lowered to sample the lower zone, some water from the upper zone flows into the sample container. Because this upper-zone water tends to be deficient in sand-size particles an error arises because the sediment concentration in the composite sample is less than the discharge-weighted concentration in the lower zone.

The sampling error depends on the grain-size distribution of the transported sediment and the depth of the upper zone. For sand-size particles, the sampling error, in percent, may be as large as 10 times the upper zone's depth in meters. For clay-size and silt-size particles, the sampling error probably is less than 1 or 2 percent.

A depth-integrating sampler can be lowered and raised through a sampling vertical by using two types of suspension rods. One type--straight shaft--holds the sampler in a horizontal position as the sampler is shifted through the two zones. The other type of rod, which is fitted with a manually-operated lever, holds the sampler in a vertical, tail-down position while it is moving through the upper zone. The operator then samples the lower zone after pulling the lever and rotating the sampler into a horizontal position. Regardless of which rod is used, water from the upper zone always dilutes the sample from the lower zone. Special procedures for controlling the sampling error introduced by dilution are discussed. If these procedures are followed, sampling errors associated with use of the two rods are equal.

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INTRODUCTION

In the northern United States, many rivers are covered with ice during the winter. Collecting suspended-sediment samples from these rivers involves an ice-drilling operation that creates an artificial zone of sediment stratification. When the drill (or chisel) breaks through the ice cover, sediment-bearing water wells up into the hole and then, after a few seconds, this flow stops.[a] Water standing in the hole begins to calm and sediment particles that were carried into the opening begin to settle and are swept away by the under-ice flow. Using present methods, a sampler on a wading rod is lowered through the ice hole and pushed down to the river bed. When the sampler touches bottom, the operator quickly reverses direction and proceeds to lift the sampler up through the opening. Normally, the sampler is lowered and raised at a steady speed and the entire traverse is completed with the sampler held in a horizontal position. The composite sample consists of a mixture of water and sediment from two zones: An upper zone that extends from the water surface to the bottom edge of the ice cap and a lower zone that extends from the under surface of the ice-cap down to the river bed (see fig. 1). Inflow from the upper zone creates an error in sediment concentration in the composite sample.

Interest in this "upper zone" error stemmed from an increase in winter-sampling activities which, in turn, spurred the development of a new device for raising and lowering suspended-sediment samplers. The device, termed the "tilting mechanism" (see fig. 2), was designed by Thomas Popowski of the U.S. Geological Survey. The tilting-mechanism has a labor-saving advantage: It enables operators to sample through small, 0.15-m-(meter) ice holes. By comparison, operators equipped with a sampler on a standard wading rod (see fig. 3) must drill or chisel 0.3-m diameter holes. The tilting mechanism is simple to use. The operator pushes down on the spring-loaded handle to pivot the DH-75Q[b] sampler into the vertical position. After lowering the sampler through an augered hole, the operator releases the handle and allows the spring to rotate the sampler into a horizonal position. After sampling the lower-zone by depth integration, the operator rotates the sampler back into a vertical position and then lifts the sampler up through the opening.

(a) At some sites, sampling verticals pass through several layers of ice interspersed with flowing water. This paper discusses sites where only a single, cap-layer of ice exists.

(b) DH-75Q samplers are supplied by the Federal Interagency Sedimentation Project, St. Anthony Falls Hydraulic Laboratory, 3rd Ave. S.E. and Hennepin Island, Minneapolis, MN 55414.

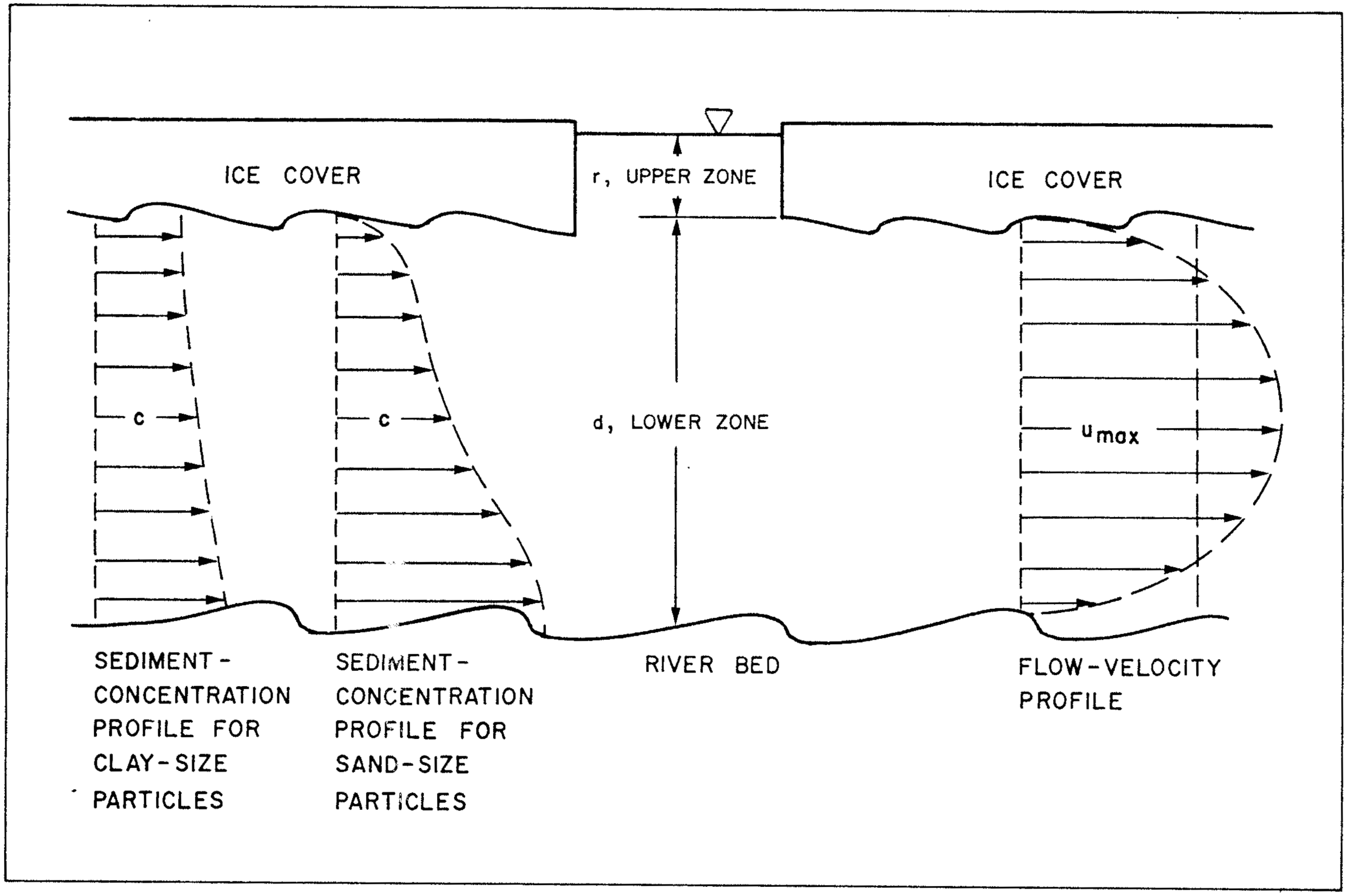

Figure 1.--Flow velocity and sediment-concentration profiles in an ice-covered river.

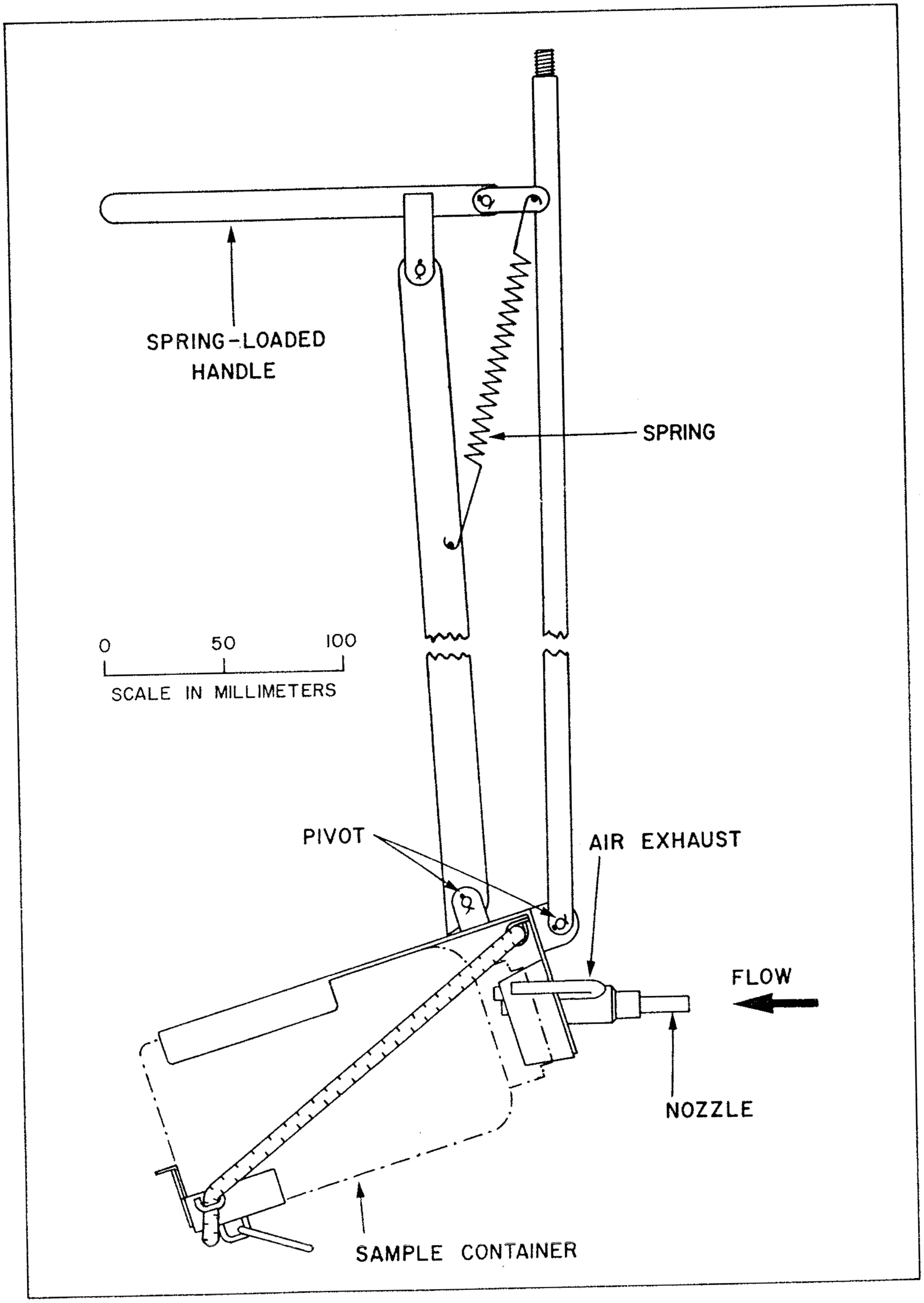

Figure 2.--Tilting mechanism developed by Thomas Popowski.

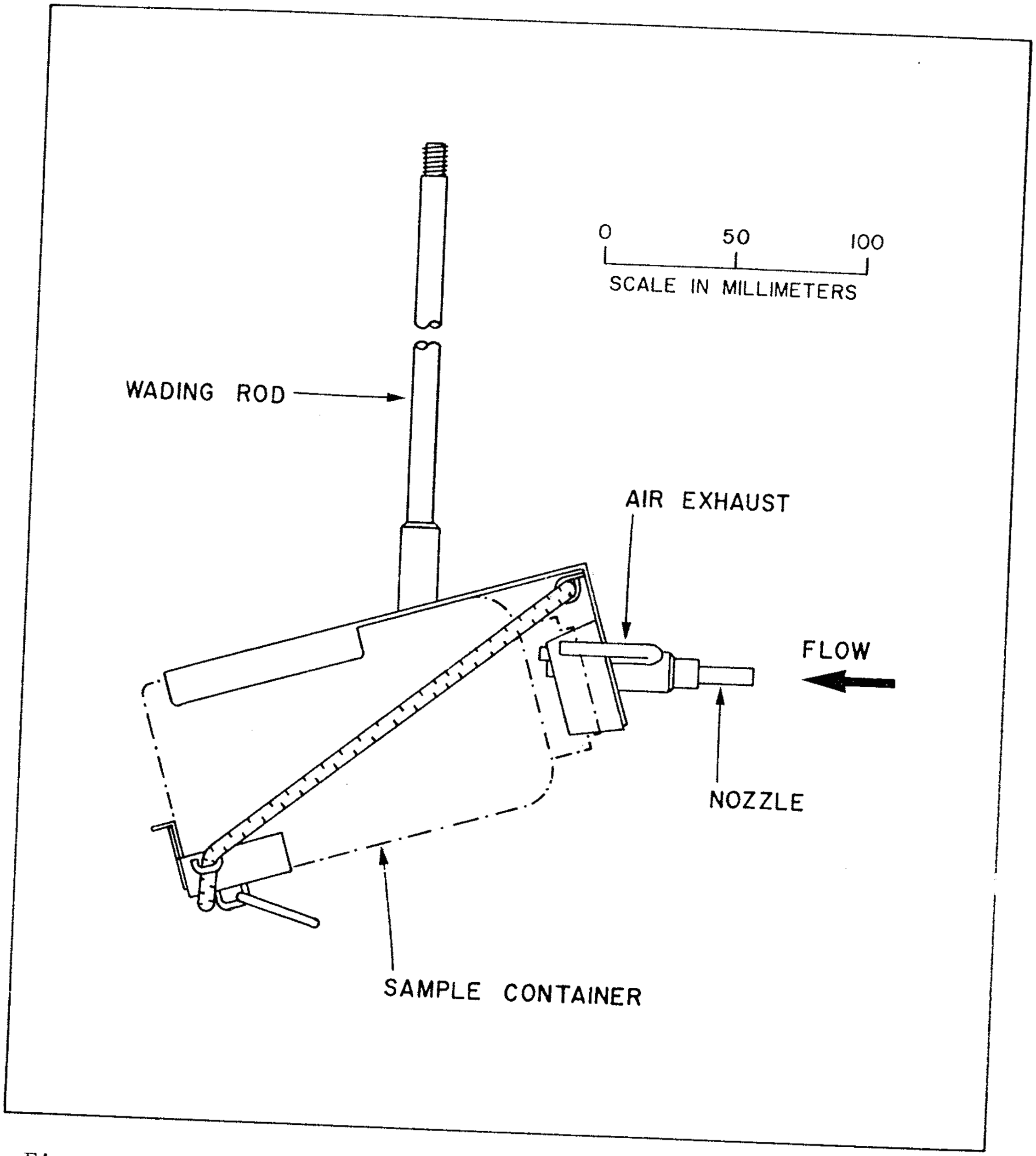

Figure 3.--US DH-75Q depth-integrating suspended-sediment sampler fastened to a wading rod.

The study described in this paper compares sampling errors associated with two methods of moving a DH-75Q sampler through the upper zone. In one method, the sampler is fastened to the tilting mechanism and the sampler's nozzle is held vertically; in the other method, the sampler is fastened to a wading rod which holds the nozzle horizontally. Before comparing these errors, a brief review of some equations and concepts pertaining to movement of water and sediment under ice is presented.

FLOW-VELOCITY PROFILES

The flow-velocity profile (fig. 1) for an ice-covered river is influenced by roughness in the bed-forms and undulations in the bottom of the ice layer. Larsen (1969) mathematically described velocity profiles by dividing under-ice flow into two sections. For the lower section, which extends from the river bed up to about mid-depth, he presented the equation

$$U = A \log_e (By), \quad (1)$$

where U is flow-velocity and y is distance <u>above the bed</u>; A and B are constants. For the upper section, which extends from the underside of the ice down to about mid-depth, Larsen again used equation (1) but substituted new values for A and B. His equation for the upper section gives U at a distance "y" units <u>below the underside of the ice</u>. Many of the profiles Larsen measured in the field show a high degree of symmetry: Within each vertical, the maximum velocity U_{max} (fig. 1) occurred at mid-depth and the profile for the upper section was a mirror image of the profile for the lower section. The following equation fits most of his symmetrical profiles:

$$U = A \log_e (250y)$$

where y is in meters (m) and U is in meters per second (m/s). For any chosen vertical, "A" is picked so that U_{max} obtained from the equation matches U_{max} obtained from the experimental data.

Some velocity profiles are not symmetrical because the retarding influences of the bed and ice are different. For example, Rantz and others (1982) show a velocity profile in which U_{max} occurs at about 0.4 of the total depth. The exact shape of an asymmetrical profile can best be determined by plotting current-meter readings taken at several depths in the flow.

SEDIMENT-CONCENTRATION PROFILES

Sediment-concentration profiles (fig. 1) are invariably asymmetrical: Concentrations near the bed are almost always greater than concentrations near the bottom surface of the ice. To be more precise, we should think of each particle-size class as having its own concentration profile. For example, if we start at the bed and move up through the flow, the concentration of clay-size and silt-size particles decreases slightly. By comparison, the concentration of sand-size particles decreases much faster.

Ismail (1952) cited the following equation for sediment-concentration profiles in a rectangular conduit:

$$\log_e (C/C_a) = (W/E_S)(y - a). \qquad (2)$$

In this equation, C is concentration at an elevation "y" units above the conduit floor, C_a is a reference concentration at an elevation "a" units above the floor, W is the velocity of the sediment particles falling in still water, and E_S is a turbulent transfer coefficient for the particles. Ismail's equation is an approximation because he assumed E_S was independent of "y."

Hsu and others (1980) studied concentration profiles in a round pipe and described each profile with two equations. One equation fit the lower half of the profile and the other fit the upper half. Hsu's "lower-half" equation is

$$C = C_o e^{Z}, \qquad (3)$$

where $Z = Wy/Ay_o$, C_o is the concentration at the center of the pipe, C is the concentration at a distance "y" units below the pipe's center, W is the settling velocity of the sediment particles in still water, A is a constant that includes certain hydraulic properties of the flow, and y_o is the radius of the pipe. Hsu's "upper-half" equation is

$$C = C_o e^{-Z}, \qquad (4)$$

where the exponent Z is the same as in equation 3. However in equation 4, C is the concentration "y" units above the pipe's center.

Ismail and Hsu studied movement in conduits with smooth-surfaces and simple cross-sectional shapes. Their equations only approximate profiles in rivers which have rough beds, rough ice covers, and irregular cross-sectional shapes; however, their equations show that several concentration profiles exist at river verticals. Each computed profile applies only to particles in a narrow fall-velocity range characterized by "W."

Sampling and analyzing data for several sediment-concentration profiles is a tedious process. Fortunately, isokinetic sampling combined with depth integration eliminates some of the work. In isokinetic sampling, a filament of water maintains a uniform speed and a uniform direction as the filament leaves the river and enters a sampler's nozzle. At the nozzle entrance, the streamlines remain straight and parallel. Neither the water nor the particles are acted upon by accelerative forces; consequently, the inflow process occurs without altering the sediment concentration (U.S. Inter-Agency Report, 1941). An ideal suspended-sediment sampler operates isokinetically at all times. If the sampler is lowered into flowing water with the nozzle facing upstream, the sampler quickly adjusts its sampling rate to match the local flow velocity.

If we visualize a sampling vertical as horizontal layers stacked one above the other, we can discover some properties of depth-integrated samples. For convenience, assume all layers have the same thickness. As the sampler moves downward through the layers at a uniform speed, the sampling nozzle spends a fixed time-interval in each and every layer. Because flow always enters the nozzle at isokinetic rates, each layer makes a velocity-weighted contribution to the water-sediment mixture accumulating in the sample container. Furthermore, each layer contributes sediment from all particle-size fractions (or W fractions) moving within the layer. After the sampler cuts through all layers and touches the river bottom, the downward traverse is stopped and an upward traverse is started immediately. All layers are sampled again before the nozzle finally breaks through the water surface. The sample has now been integrated with respect to both depth and flow velocity. The mass of sediment in the sample is a fraction of the sediment discharged through the entire vertical. Furthermore, the volume of water in the sample is a fraction of the water discharged through the entire vertical. These two fractions are equal; consequently the discharge of sediment at the vertical can be obtained by multiplying the concentration of sediment in the sample by the water discharge computed from current-meter readings. Water discharge is expressed on a "unit-width" basis so the sediment discharge at the vertical must also be expressed on this same "unit-width" basis.

The DH-75Q samples isokinetically but only if the following conditions are met: (a) the intake end of the nozzle must face directly into the approaching flow, (b) the speed of the approaching flow must be greater than about 0.3 m/s, (c) the pressure of the air inside the sample bottle must be slightly lower than the hydrostatic pressure at the intake end of the nozzle, and (d) the discharge end of the nozzle must be above the water surface inside the sample container. Conditions (c) and (d) and their relationship to the sampler's maximum traversing speed and the sampler's maximum operating depth are discussed in U.S. Inter-Agency Report No. 6 (1952).

INFLOW TO THE DH-75Q SAMPLER

Let us now return to the sampling vertical shown on figure 1. This vertical presents a problem when we attempt to sample it with a DH-75Q. The main problem centers on the stagnant water in the upper zone labeled "r." This zone should contribute nothing to the depth-integrated sample but, in reality, some inflow does occur. The rate of inflow to the DH-75Q is strongly influenced by the sampler's orientation. Two orientations--nozzle facing the horizon and nozzle facing straight up--are of primary concern.

Inflow rates to a DH-75Q with its nozzle facing the horizon were measured in a laboratory experiment. A stopwatch was started and at the same time the sampler was quickly submerged in a barrel of still water and then held stationary with the intake end of the nozzle at a depth of 0.3 meters. After a few seconds, the sampler was quickly lifted and the watch was clicked off when the nozzle broke the water surface. Elapsed time and the volume of water in the sample container were recorded. An analysis of data collected in several tests showed that the inflow occurred in two stages. During the first 3 seconds the sampler consistently collected about 30 mL of water. After 3 seconds, the inflow rate became erratic. In some trials, the inflow stopped because surface tension trapped and held water in the air-exhaust tube; however, in the remaining trials, the inflow stabilized at about 6 mL/s as water entered through the nozzle and air vented through the exhaust tube. In another series of runs, the sampler was submerged and then held stationary at a depth of 0.45 meters. During the first 3 seconds, the sampler collected about 35 mL of water. After 3 seconds, the inflow either stopped or stabilized at about 6 mL/s.

When the DH-75Q was plunged into still water with the nozzle facing up, inflow again occurred in two stages. The first stage was marked by a rapid inrush that lasted for about 3 1/2 seconds. When held at a depth of 0.3 meters, the sampler always collected about 45 mL of water. The second stage of inflow was accompanied by an intermittent-bubbling action. First, an air bubble rose through the bore of the nozzle. This action lowered the pressure inside the bottle and allowed water to flow in through the air-exhaust tube and enter the sample container. When the bubble sprang free of the nozzle, the air pressure increased and stopped the inflow. A fraction of a second later, a new bubble formed in the nozzle and then the cycle repeated. The average inflow rate was between 6mL/s and 8 mL/s.

In summary, "still-water" inflow occurs in two stages. The first stage, which lasts only a few seconds, is accompanied by rapid inflow through both the air exhaust and the nozzle. Cumulative volumes are consistent from run to run, and are altered to only a slight degree by shifting the nozzle's orientation. Cumulative volume depends on depth-of-submergence: Both factors increase together. At the end of the first stage, the air pressure inside the container is nearly equal to the water pressure outside the container. The second stage, which lasts until the bottle is completely full, is an erratic process. The inflow rate is not consistent from run-to-run and the rate depends on the nozzle's orientation: shifting the nozzle from a horizontal position to a vertical position increases the inflow rate, but shifting the depth of submergence does not alter the inflow rate.

MAGNITUDE OF THE SAMPLING ERROR

The error in sampling an ice-covered river depends on the flow velocity and sediment-concentration profiles under the ice, the sediment concentration within the augered hole, and the depth of the upper zone. An analysis of the sampling error is based on the following assumptions:

1. The water in the augered hole is motionless and free of sediment particles.
2. When the sampler reaches depth "r" (fig. 1) during the downward traverse, the accumulated volume is governed by the first stage of filling; furthermore, we assume this accumulated volume is governed by Boyle's Law.
3. The DH-75Q samples isokinetically while it is being lowered and raised through the under-ice flow.
4. No water enters the sample bottle while the sampler is being lifted through the augered hole.

The water that enters the sampler when it reaches depth "r" is calculated from the second assumption. Because air inside the container is compressed isothermally, the following form of Boyle's Law applies:

$$P_{at}V_c = P_rV_r. \qquad (5)$$

In this equation;

P_{at} = atmospheric pressure (101. x 10^3 pascals),

V_c = volume of sample container (1.06 x 10^{-3} M^3),

P_r = absolute hydrostatic pressure (in pascals) at a depth of "r" meters and

V_r = volume (in cubic meters) of air inside the sample container at depth "r".

The absolute pressure at depth "r" is

$$P_r = 101. \times 10^3 + (9.71 \times 10^3)(r) \qquad (6)$$

Let V_i designate the volume of inflow in cubic meters. Solving equation 5 for V_r and substituting the relationship into the equation $V_i = V_c - V_r$ we obtain

$$V_i = V_c - (P_{at}\ V_c/P_r) = V_c[1-(P_{at}/P_r)] \qquad (7)$$

Substituting equation (6) into equation (7) and then substituting

1.06×10^{-3} for V_c, we obtain

$$V_i = (0.0103\ r)/(101. + 9.71\ r) \tag{8}$$

Let us now write an expression for the concentration of an isokinetic, depth-integrated sample collected entirely under the ice. Being undiluted by inflow from the upper zone, this sample has a sediment concentration equal to the discharge-weighted concentration through the zone "d" on figure 1. Denoting this concentration as C_T, we write

$$C_T = M_s/V, \tag{9}$$

where M_S is the mass of sediment in the sample and V is the volume of water in the sample.

Let us now consider the concentration of a sample collected by lowering a DH-75Q through the zone "r" and then traversing zone "d" at the same transit rate used to collect the sample with the concentration C_T (see equation 9). When the operation is complete, the composite sample contains inflow of volume V_i. According to the first assumption, this volume of water is free of sediment; consequently, concentration of the composite sample is

$$C_r = M_s/(V + V_i) \tag{10}$$

The sampling error E is related to the difference between C_T and C_r. Expressing E as a percentage error, we obtain

$$E = 100\ (C_T - C_r)/C_T \tag{11}$$

After substituting equation 9 and equation 10 into equation 11 and then simplifying the result, we obtain

$$E = 100[V_i/(V + V_i)] \tag{12}$$

Numerical values for E can now be evaluated from equation 8 and equation 12. For example, assume r is 0.25 meters. From equation 8, we obtain

$$V_i = 2.5 \times 10^{-5} \text{ cubic meters.}$$

The maximum volume collected in zone "d" is set by V_i, and by the requirement that the water surface in the container lie below the ends of the nozzle and air-exhaust tube. To satisfy this water-surface requirement, the volume of the composite sample must be less than 0.93×10^{-3} cubic meters; therefore the maximum value for V in equation 9 is $0.93 \times 10^{-3} - 2.5 \times 10^{-5} = 90.5 \times 10^{-5}$. Values for Q and V_i are now substituted into equation 12 to obtain E = 3 percent. The third row of table 1 shows results of our computation. The other rows in the table show accumulated volumes and sampling errors for several other values of r. Notice that each E value bears a simple relationship to its corresponding r value--E is approximately equal to r multiplied by 10.

Table I.--Computed sampling errors for several ice-cover thicknesses.

r, depth of upper zone, in meters	V_i, accumulated upper-zone volume, in milliliters	E, sampling-error, in percent
0	0	0
.10	10	1
.25	25	3
.50	49	5
.75	71	8
1.00	93	10
1.50	133	14
2.00	171	18

The sampling errors in table 1 are upper-limits because the analysis is based on the assumption that sediment-free water fills the upper-zone. At most field-sampling sites, clay-size and silt-size particles will be suspended in this upper zone; consequently, errors in field samples will be less than the errors listed in the table. It is important that we use a sampling procedure consistent with constraints incorporated in the mathematical development.

SUGGESTED SAMPLING PROCEDURES

Sampling errors depend on two critical factors in the sampling procedure. The first factor is the time spent in lowering the sampler to the depth r. A trial and error process is probably the simplest way of determining the correct traversing speed for this upper zone. After drilling the hole, measure the depth r (fig. 1) and then lower the sampler to this depth with a smooth, steady motion. Now lift the sampler from the water as quickly as possible and measure (or estimate) the volume of water in the container. If this volume is significantly larger than V_i (table 1), shorten the lowering time; conversely, if the volume is less than V_i, lengthen lowering time. Be sure to empty the bottle after each run.

After determining the correct upper-zone speed, we turn to the second critical factor--the time spent in lowering and raising the sampler through the entire sampling vertical. Start with an empty container and lower the sampler to the depth "r." If the tilting mechanism is used, immediately rotate the sampler into the horizontal position then, without pausing, lower the sampler at a uniform speed until it touches the river bottom. When contact is made, immediately reverse direction and steadily raise the sampler back to the depth "r." Without hesitating, rotate the sampler into a vertical position and quickly lift it through the ice hole. If a wading rod is used, follow the same procedure but hold the sampler level throughout the entire traverse. At the end of this round-trip integration, the water level in the sample container should lie a few millimeters below the nozzle when the sampler rests in a horizontal position. If the water level is too high, discard the sample then repeat the process at a higher transit rate. Conversely, if the water level is too low, use at a slower transit rate. After the optimum rate has been established, place a clean container in the DH-75 sampler and then collect a sample for laboratory analysis.

The sampling errors in table 1 are based on an optimum transit rate for each vertical in a transect. The optimum rate usually differs from one vertical to another, so a problem arises in sampling a transect by the EWI (equal-width-increment) method (National Handbook of Recommended Methods of Water Data Acquisition, 1978). This method requires that the same transit rate be used at all verticals in a transect. Fortunately, the EDI (equal-discharge increment) method circumvents this transit-rate problem. The EDI method, (ibid, 1978) allows different transit rates at different verticals; however, the location of the verticals must be carefully selected. A transect must first be divided into segments having equal water discharge, then a sampling vertical is situated at or near the center of each segment.

SUMMARY AND CONCLUSIONS

On an ice-covered river, each sampling vertical spans two zones. The upper zone consists of still water standing in the ice hole; the lower zone consists of sediment-bearing water flowing under the ice. A sampling error is caused by inflow that occurs as a depth-integrated sampler is lowered through the upper zone. If this zone contains no sediment, the sampling error (in percent) is approximately 10 times the upper zone's thickness in meters. The sampler may be lowered through the upper zone with the nozzle held in a horizontal position (wading rod suspension) or it may be lowered with the nozzle held in a vertical position (tilting mechanism). Technique is an important factor in controlling sampling errors for incorrect transit rates can lead to large, unpredictable errors. Optimum transit rates vary from vertical to vertical; consequently, the EDI (equal-discharge increment) method is the most accurate way of sampling a transect for sediment discharge.

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