A STUDY OF METHODS USED IN

MEASUREMENT AND ANALYSIS OF SEDIMENT
LOADS IN STREAMS

FEDERAL INTER-AGENCY SEDIMENTATION PROJECT

REPORT W

TEST AND DESIGN OF AUTOMATIC FLUVIAL SUSPENDED-SEDIMENT SAMPLERS

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Geological Survey	**	Corps of Engineers
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REPORT W

TEST AND DESIGN OF AUTOMATIC FLUVIAL SUSPENDED-SEDIMENT SAMPLERS

By

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TABLE OF CONTENTS

Page

ILLUSTRATIONS

Figure

TABLES

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ABSTRACT

A laboratory test developed to evaluate suspended-sediment sampling efficiency was applied to five automatic pumping samplers. The test was designed to evaluate separately each of the basic parts of the typical sampling system: the intake, intake tubing, pump, and distributor. A commercial, uniformly graded sand (d_{50} = 200 microns) was used for the tests. All reference samples were collected at ambient stream velocity and were extracted through a nozzle aligned with the ambient streamlines. Test results showed the efficiency of projecting downstream-angled sampler intakes was nearly the same as for flush-mounted intakes (Rept. T, ICWR, 1966) oriented at right angles to the flume wall. To maintain sample representativeness, flow within the intake tube must have a Reynolds Number that exceeds 4,000 and have a mean velocity greater than twenty times the fall velocity of the largest particle in suspension. Within the mouth of the intake, the mean velocity should exceed the approach flow velocity.

INTRODUCTION

Sediment particles suspended in flowing water are acted upon by turbulence which generates spatial and temporal variations in sediment concentration. Even with "steady" flow conditions, the concentration will vary from point to point within a stream cross section, and at a given point the concentration will vary from moment to moment. The spatial and temporal variations complicate the task of sampling. To obtain an accurate sediment discharge for the entire stream cross section and to average short-term temporal variations, each sample must be collected for a sufficiently long duration (ASCE, 1975, p. 318-324). Furthermore, all samples must be collected isokinetically [1/] to minimize sampling errors at each sampling point. At the present time, the only practical way to meet all requirements is to manually collect the samples with a US-series sampler or its equivalent (ICWR, 1963; ASCE, 1975, Guy and Norman, 1970).

Manual sampling has several advantages and disadvantages. Properly conducted, the manual procedure is potentially the most accurate. The samplers are relatively simple to operate and are reliable. If equipment malfunctions occur, they can usually be corrected promptly at the site. A disadvantage stems from the fact that water discharge may vary significantly during an interval of several hours or even a few minutes. When the water discharge changes, turbulence and numerous other factors that determine the stream's ability to transport sediment also change. To chart accurately the history of a stream's sediment discharge, the sampling must be repeated through the rise and fall of the streamflow. If the flow changes unexpectedly or if the sites are remote, collecting

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1/ To sample isokinetically is to withdraw the suspension from the ambient flow without acceleration. The nozzle must face into the ambient flow and must sample at local instantaneous ambient flow velocity.

an accurate record is extremely difficult. To alleviate some of the problems, automatic samplers are being used at many sediment sampling stations to supplement a manual sampling program.

Compared to manual samplers, automatic samplers have several advantages and some disadvantages. Automatic samplers hold the promise of improved documentation of long-term changes with economic savings. They can be programmed to collect samples only during periods of significant stream change and thereby maximize the amount of information conveyed by each sample. On an ephemeral stream, they remain inactive until flow begins. On a perennial stream, the samplers can be programmed to collect samples periodically, and some samplers can be arranged to increase sampling frequency in response to changes in stage. Visits to the site are required only to obtain a manual check sample, to collect bottled samples, and to perform minor routine maintenance such as battery inspection. Disadvantages of automatic samplers include lack of spatial integration, lack of isokinetic sampling, and the complexity of the equipment. Although sampling from several points in the cross section is feasible, practical and economic considerations have limited sampling to one fixed point in the cross section. To be self-cleaning, the intakes [2/] must usually be misaligned with the flow. Equipment failures will go undetected and no data will be collected until the next service call. As with any piece of complicated equipment, diagnosis and repair of faulty components will frequently require the attention of a specialist with laboratory-based equipment.

2/ As used in this report both intakes and nozzles were short sections of pipe that opened into the flume flow. Misaligned with the flow, an intake collected non-isokinetic samples that were conveyed through an intake tube to an automatic sampler. Aligned with the flow, nozzles were operated to collect isokinetic samples for reference purposes.

Purpose and scope

The purpose of this investigation was to develop an evaluation procedure for automatic suspended-sediment samplers and to provide criteria by which the effectiveness of sampler design could be determined. The performance of any automatic sampler is affected by charteristics of the intake and of each component of the sampler. The procedure and criteria were applied to five different types of samplers. The hydraulic performance of intakes and important components were evaluated.

Acknowledgements

Acknowledgement is given Donald Benson, U.S. Army Corps of Engineers, who assisted with the tests and Florence Wright, U.S. Geological Survey, who typed the report. Many thoughtful, constructive suggestions and criticisms were offered by members of the Technical Committee of the Subcommittee on Sedimentation, Interagency Advisory Committee on Water Data, and by employees of their respective agencies.

TEST FACILITY

Flume

With minor alterations, an existing glass-sided flume (fig. 1) located at the St. Anthony Falls Hydraulic Laboratory, University of Minnesota, Minneapolis, Minn., was used for the tests. The flume bottom had zero slope and was made of smooth steel plates. Water from the Mississippi River passed through an elbow-type discharge meter, entered the head box, flowed over an elevator-type sediment feeder, passed through the flume, and then dropped into a sump connected to a waste-channel. The sediment feeder consisted of a rectangular cavity recessed into the flume bottom. Within the cavity was a platform coupled to a motor and hand crank, arranged to raise the platform so that the sediment load could be regulated. The sediment trap was located upstream of the tail section. Figure 1 also shows the final location of a vibrating sand feeder. This feeder had a 5-cm wide discharge trough. The sand fell from the trough onto a convex sheet-metal surface, which spread the sand evenly across the 30-cm width of the flume.

Intakes and nozzles

Several different sizes and shapes of debris-shedding intakes for automatic samplers have been evaluated previously (see Rept. T, ICWR, 1966). In that study, all intakes were mounted flush with the flume walls where, unfortunately, high concentration gradients complicated the selection of a point for collection of isokinetic reference samples. In the present study, the reference nozzles and sampler intakes (fig. 2) were extended a short distance from the wall where concentration gradients were lower and more easily measured. To simulate sampling of a natural stream where fibrous debris would lodge on obstructions, the intakes were angled 45° downstream. To minimize the angular acceleration of the sampled flow, the end of the intakes were cut parallel to the flume walls.

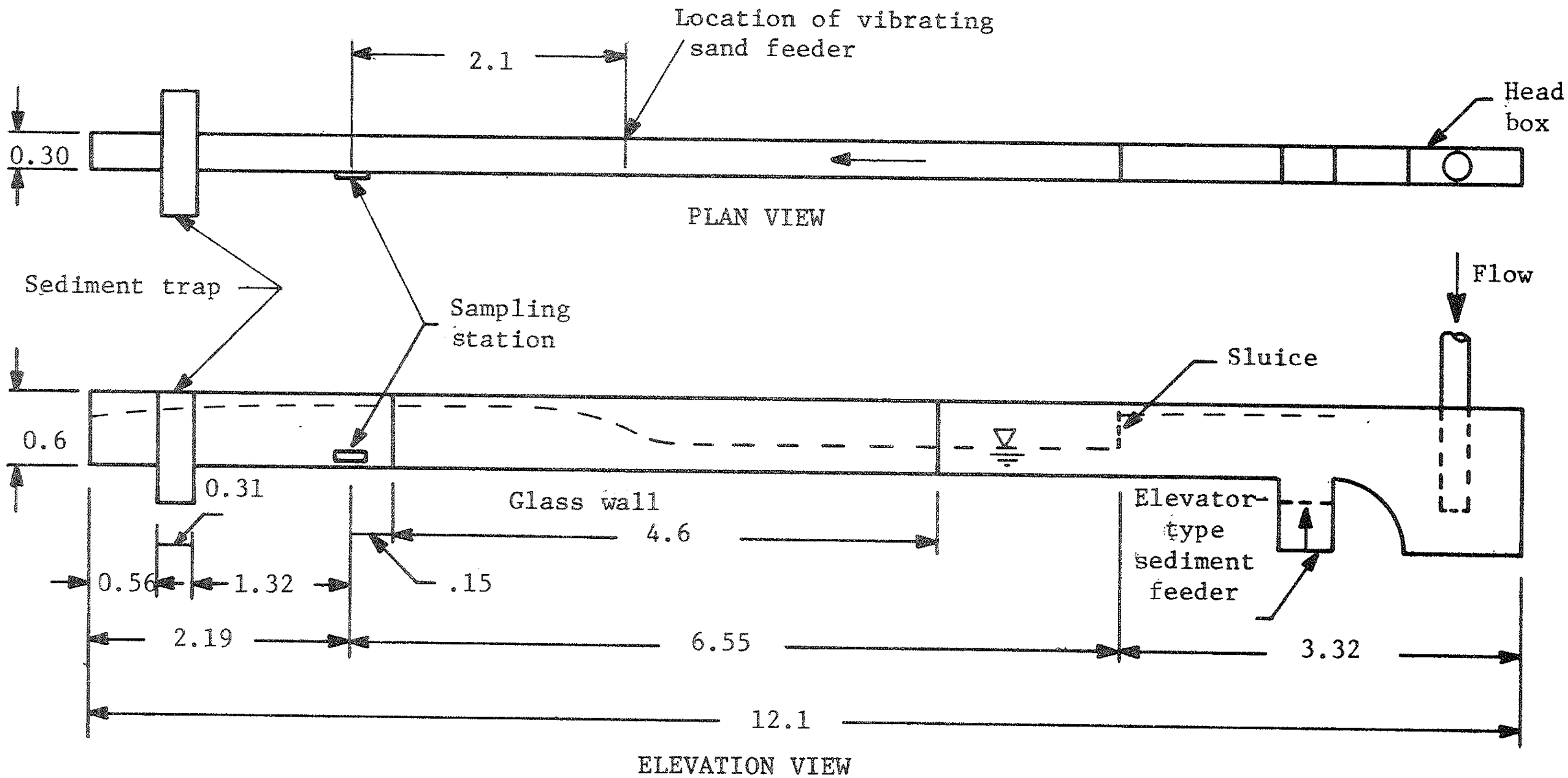

Figure 1.--Diagram of flume. All dimensions in meters.

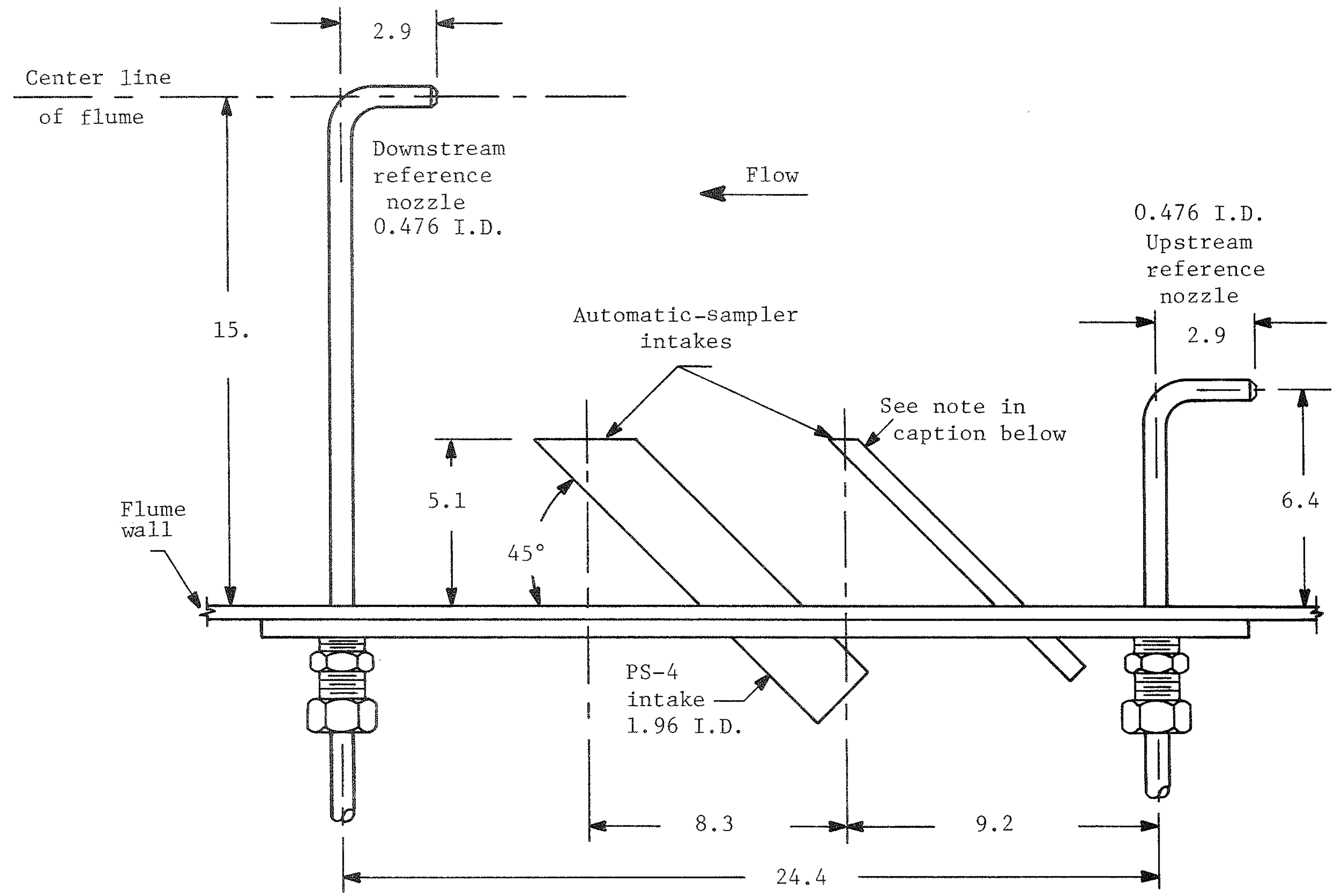

Figure 2.--Plan view of sampling station. All nozzles and intakes were centered on a horizontal plane 5.7-cm above flume floor. All dimensions in cm. Upstream sampler intake diameter (inside) matched intake tube: 0.476-cm ID for PS-1, and 0.754 for P-1A, PS-2, and PS-3.

The automatic samplers were not all designed to sample through the same diameter intake so alternate sizes were provided. A 1.96-cm I.D. intake was permanently mounted at the downstream position for the largest sampler. The upstream position was fitted with an intake that matched the I.D. of the intake tube for each of the remaining samplers. The intake tube, or simply tube, led from the sampler to the discharge end of the intake. Samplers were tested one at a time. The unused intake was plugged.

For collection of isokinetic reference samples one nozzle was mounted upstream and one downstream of the intakes. Each nozzle was held by a collet-type fitting so that it could be positioned and fixed at any desired distance from the flume wall.

Sediment

AGSCO (American Graded Sand Company) [3/] No. 4 silica sand was chosen because of its availability, chemical stability, and small variation in particle-size. As determined from a visual-accumulation-tube analysis, the median particle diameter was 200 microns and the geometric standard deviation was 1.13 (ASCE, 1975, p. 38). The particles were large enough to amplify errors caused by potentially deficient sampler pumping rates, yet small enough to be transported in suspension through a short reach of the flume. Because the particles were nearly uniform in size, the need to analyze samples by size fractions was eliminated.

TEST PROCEDURE

The concentration of a sample collected by an ideal sampler connected to an ideal intake and intake tube would be equal to the concentration of a sample collected isokinetically and concurrently from the stream in the immediate vicinity of the intake. The ideal sampler would have a 100-percent sampling efficiency.

3/ Trade names are included for information of the reader and do not constitute endorsement by the United States Government.

Practical sampling systems may suffer from errors that occur at the intake, within the tube, or within the sampler itself. Because the intake is misaligned with the flow, samples cannot be extracted isokinetically. If flow velocity within the intake tube is inadequate, some sediment that enters the tube may be deposited within the tube and fail to reach the sampler. If purging between successive samples is inadequate, the deposited sediment may appear in subsequent samples and create a "carry-over" error. Most pumping samplers contain conduits or channels that route each sample to an individual container. Deposition within the routing components will also create carry-over errors. Carry-over errors will cause the system sampling efficiency for a particular sample to depend upon antecedent conditions. The tests were designed to measure the efficiency of both the entire sampling system as a unit and also the individual components: intake, tube, pump, and distributor.

Two different types of antecedent stream conditions were simulated. In the ramp test, a series of samples were collected and analyzed as the flume sediment concentration increased slowly. In the step test, a situation was simulated whereby samples were collected alternately from high concentrations and from zero concentrations.

Position of samplers and intake tubes

To simulate the suction lift at a field site, the sampler under test was positioned on the next floor above the flume. The intake tube was routed through a floor opening directly above the intakes. To facilitate sediment transport during both backflushing and sampling, all slack tubing was pulled upward through the opening and was supported on an incline from the opening to the sampler. Small samplers were supported approximately 0.3-m (1 ft) above the floor. To insure comparability of test results all samplers were tested with a suction lift of 3.8-m (12.5 ft) and with an intake tube 6.7-m (22 ft) long, the standard length provided with many models.

Methods of injecting sediment

To minimize both gradients and variations in the concentration at the sampling station, several methods of introducing the sediment were tested. First, the elevator (fig. 1) was loaded with sediment. With a steady flume flow, the floor of the elevator was raised at a slow uniform rate to expose the sediment for transport. Unfortunately, turbulence and eddies developed at the elevator lip and rapidly scoured sediment from the cavity. At the sampling station, transport rates were uncontrollably high and erratic. A sluice was added to decrease flow velocity over the elevator; but because only a marginal improvement was noted, the elevator-feed method was abandoned. Next, the sluice was reinstalled and adjusted to establish a hydraulic jump. A vibrating sand feeder was positioned above the flow and between the jump transition and the sluice. By means of a large funnel, dry sediment was delivered to the sand feeder which steadily fed the sediment into the flow. Once set, feed rates varied by no more than 5 percent and could be set over a wide range. Unfortunately, sediment distribution across the flume was usually asymmetrical. Flow leaving the head-box contained a flow component which created a lateral concentration gradient at the sampling station. Screens installed at the inlet reduced the lateral gradient. In an additional attempt to increase turbulence and further reduce vertical gradients, blocks were glued to the flume floor but no significant improvement was noted. Tests showed the jump made no significant reduction in vertical gradients, so the final arrangement included only the sand feeder and screens. The sand feeder was relocated as shown on figure 1.

Intake calibration

During sampling operations, the sediment concentration within an intake would differ from the concentration within a reference nozzle because of differences in flow acceleration. To isolate the efficiency of the intake from the efficiency of the sampling tube and the sampler's distribution system, the intake was calibrated at the sampler pumping rate for a wide range of sediment concentrations. The objective was to empirically establish a correlation between paired samples - one collected isokinetically from the flow filament approaching the intake and the other withdrawn through the intake. To minimize residual temporal changes, the pairs were withdrawn concurrently; because nozzles and intakes were located in close proximity, the possibility of some mutual interference existed.

To minimize interference, a two-step procedure involving both reference nozzles was tested. First the upstream reference was positioned (fig. 2) to sample the filament approaching the automatic-sampler intake. Then with the intake plugged, several sets of paired samples were collected concurrently from the two reference nozzles and the paired set members were analytically related by a least-squares, first-order power series. Next, several sets of paired samples were collected through the appropriate automatic-sampler intake and the downstream reference nozzle. Approach concentrations computed from downstream reference samples and the power series were compared with intake samples. The wide separation of nozzles insured freedom from interference, but unfortunately it also created a large random variation in the correlation between paired concentration values. The variation could be averaged but only by collecting large numbers of replicate samples.

To minimize the random variation, a second procedure was tested in which the appropriate automatic-sampler intake and only the upstream reference nozzle was used. The intake tube was connected to an appropriate intake; then, with the sampler operating, the pumping rate was measured. Next, the intake was reconnected to a short tube adjusted to discharge at a rate equal to the pumping rate. Similarly, a tube attached to the upstream reference nozzle was adjusted to produce a flow velocity equal to the velocity as measured with a pitot tube just upstream of the reference. With both flume discharge and sediment injection rate held steady, one sample was collected from the nozzle and one from the intake. Each sample pair was collected simultaneously. Additional pairs were collected, each with a different sediment concentration. Table 1 illustrates the data and computations for one calibration test. Each reference sample concentration, labeled C_r, was paired with its corresponding intake-sample concentration, labeled C_s, to compute the least-squares equation, $C_s = 2.17\ C_r^{0.879}$ Compared to the first procedure, the second produced a better correlation coefficient and required fewer samples. Because of the reference nozzle's small size and small discharge, it was judged to produce negligible interference with the intake. The second procedure was used in all subsequent tests.

The ramp test

The ramp test simulated operation during a period when sediment concentration gradually increased. Discharge from the upstream reference nozzle was adjusted to isokinetic conditions, the sediment feed rate was set and maintained constant, and then the test sampler was started. As samples flowed from the delivery point within the sampler, the discharge from the reference nozzle was collected. The delivery point was defined as the location within the sampler where flow entered the sample container. The sampler was allowed to complete its normal cycle. Then, without disturbing sediment that may have deposited within the sampler or intake tube, the feed rate was increased and the process repeated.

The weight of the water-sediment mixture for both the reference sample and the delivery-point sample was measured, then the water in both samples was carefully decanted. The sediment in each sample was dried and weighed. The dry weight in milligrams was divided by the mixture weight in grams and the quotient was multiplied by 1,000. The result was reported as concentration in mg/L (milligrams per liter). See table 2.

As shown in table 2, the concentration within the sampler intake, C_c, was computed from the correlation equation established in the intake-calibration test and the concentration of the reference sample, C_r. The percent efficiency expressed numerically the ability of the sampler to deliver a sample representative of the flow that entered the intake. Comparison of the trend of reference-sample concentrations shown in table 2 with those shown in table 6 and all succeeding ramp tests reveals that control of sediment feed rate improved with practice. Unfortunately, the limited supply of sand precluded a rerun of the first ramp test, but the efficiency (in percent) is believed to be reasonably accurate.

The step test

Table 3 illustrates data collected in the step test, designed to measure the sampling system's response to abrupt changes in stream concentration and to measure and detect the source of carry-over contamination. All parts of the sampler that contacted the sample were thoroughly cleaned, the tube was connected to the intake, and the sediment feed rate was set. Then a pair of samples were simultaneously collected: one from the reference nozzle and one from the delivery point within the sampler. Delivery-point sample concentration was labeled C_d. When the sampler completed its cycle, the tube was disconnected from the intake and immersed in a bucket of clear water. Then a delivery-point sample was pumped from the bucket. Any sediment collected (f, table 3) was directly attributable to carry-over contamination because the clear water was free of sediment. The sampler was then disassembled. The intake tube and sample distribution system were rinsed separately with clean water. Each batch of rinse-water was collected and the total quantity of sediment was weighed (d, table 3). The sampler component that yielded the bulk of the sediment was noted as "source of residue." The entire system was reassembled, the feed rate adjusted to a new value, and the process repeated.

The grouping of data in table 3 requires explanation. For each test, three lines of data are given. The first line is data collected from sediment-laden flume flow. The second line is data collected from the sediment-free source. The third line shows only the amount of residue. The lower case letters refer to values used in computing the various efficiencies in table 4.

Tables 1-4 pertain to the PS-1 sampler. In similar fashion, tables 5-8 pertain to the PS-1A sampler, tables 9-12 pertain to the PS-2 sampler, tables 13-16 pertain to the PS-3 sampler, and tables 17-20 pertain to the PS-4 sampler.

DESCRIPTIONS OF AUTOMATIC SAMPLERS

Table 21 shows mechanical, electrical, and hydraulic characteristics of each sampler.

PS-1 Sampler

Samples were collected by a peristaltic pump programmed to reverse rotation and thereby backflush the intake tube before and after each sample collection (see fig. 3). The sampler could be powered from 120-V a.c., an external 12-volt battery, or a self-contained rechargeable battery. The pump discharged each sample into a slightly inclined channel which routed the flow to the proper glass container.

PS-1A Sampler

Except for the higher-speed pump, this sampler was identical with the PS-1 (fig. 3).

PS-2 Sampler

An internal wet-cell battery provided power to all mechanical actuators and to an air pump which served to withdraw samples and purge the intake tube. The sampling cycle consisted of a purge-sample-purge sequence. The top of a container, termed the metering chamber (see fig. 4), was connected to an air pump and an intake tube; the bottom was connected through a pinch valve to a spout which routed samples to individual bottles. During the first purge, air was pumped through the intake tube to dislodge debris. Then the pressure in the metering chamber was reduced to allow the atmosphere to force a sample up the intake tube and into the chamber. When the chamber was full, a sensor operated a solenoid which routed compressed air into the chamber

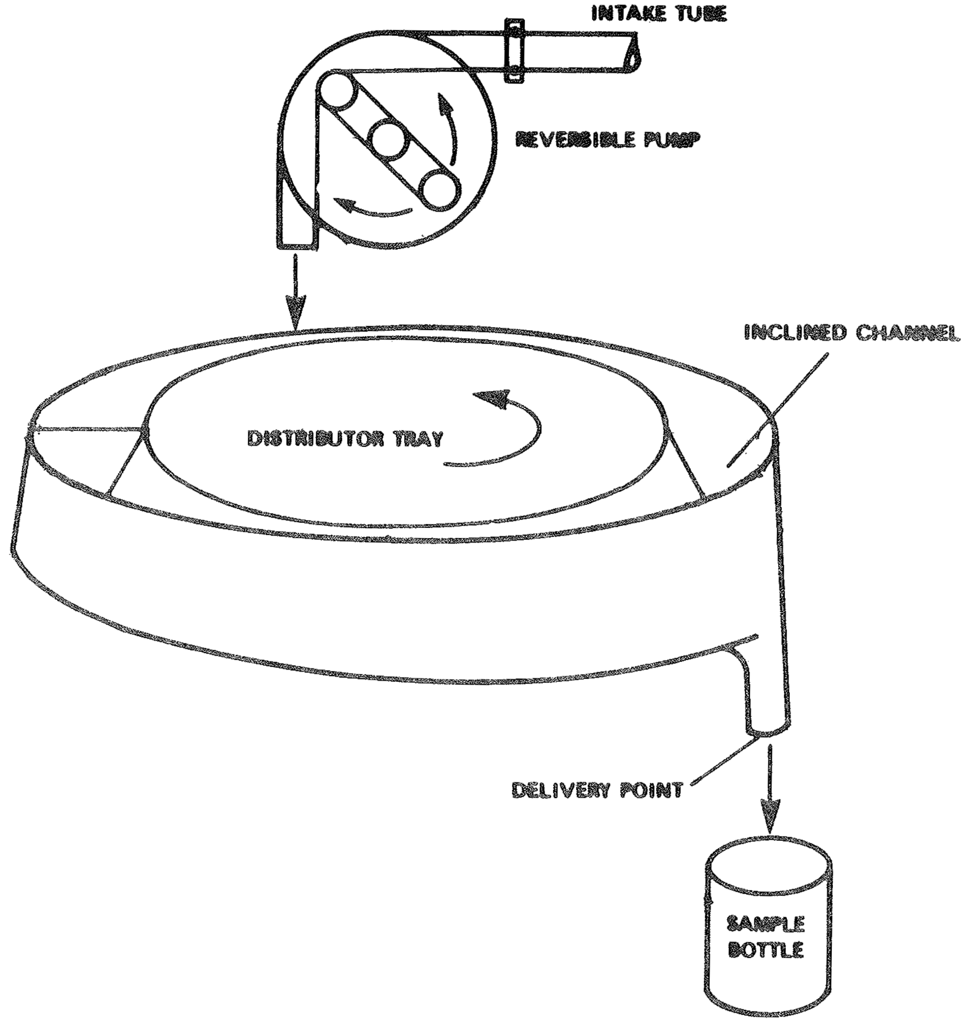

Figure 3.--Schematic diagram of PS-1 and PS-1A hydraulic systems.

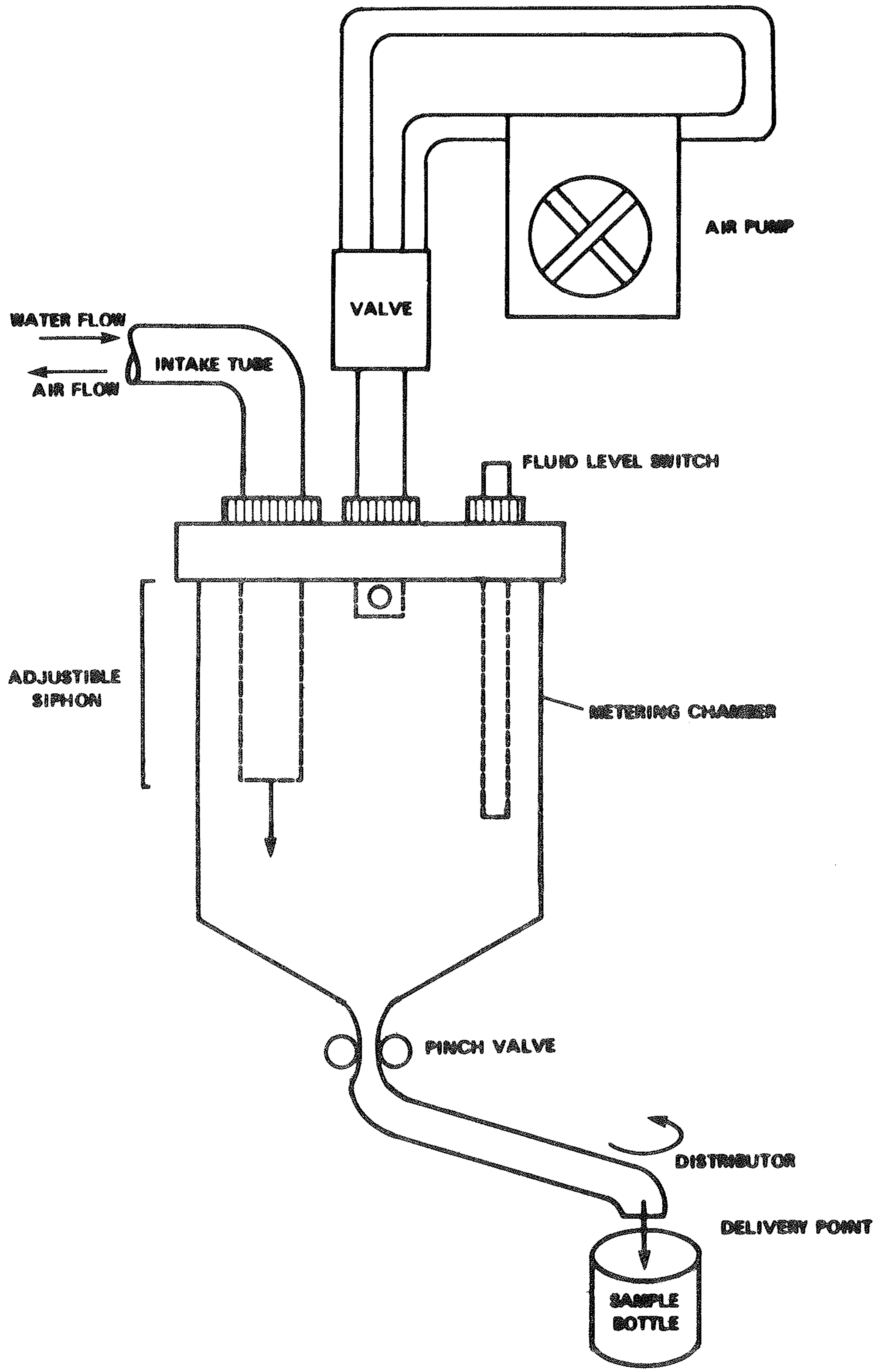

Figure 4.--Schematic diagram of PS-2 hydraulic system.

and expelled the contents of the sampling tube. The pinch valve then opened and allowed the contents of the chamber to flow through the distributor and into a sample bottle. Within the metering chamber, an adjustable siphon could be set to withdraw excess sample during the second purge.

PS-3 Sampler

The Chickasha sampler (fig. 5) was designed by personnel of the Agricultural Research Service at Chickasha, Oklahoma (Allen and others, 1976). The sampler was similar to the XPS-62 developed by personnel of the Federal Inter-Agency Sedimentation Project (Rept. Q, ICWR, 1962). Glass sample bottles were supported on the periphery of a circular tray 91-cm (3 ft) in diameter. Rotated by a weight and indexed by an escapement mechanism, the tray positioned a bottle directly under the funnel. The sampling cycle consisted of a waste-sample sequence. First, the initial discharge from the pump was wasted to establish an equilibrium in the intake tube, then the solenoid moved the diverter to direct the discharge into the funnel which drained into the sample bottle. Because the Chickasha sampler was constructed around an open framework, the sampler could be modified to meet custom requirements. For example the number, size, and shape of the sample containers could be varied, and the type and location of the pump could be changed. To minimize suction lift, the pump could be positioned near the stream. In the event of occasional submergence, the pump could be covered with an open-bottom container, a "diving bell."

PS-4 Sampler

The PS-69 (fig. 6) was specifically designed to sample fluvial sediment. Developed by personnel of the Federal Inter-Agency Sedimentation Project, the sampler holds 72 one-liter plastic containers. The containers are nested in a pull-out drawer. Constructed in an open framework, the sampler may be modified to meet a variety of requirements. However, its size limits its application to semi-permanent

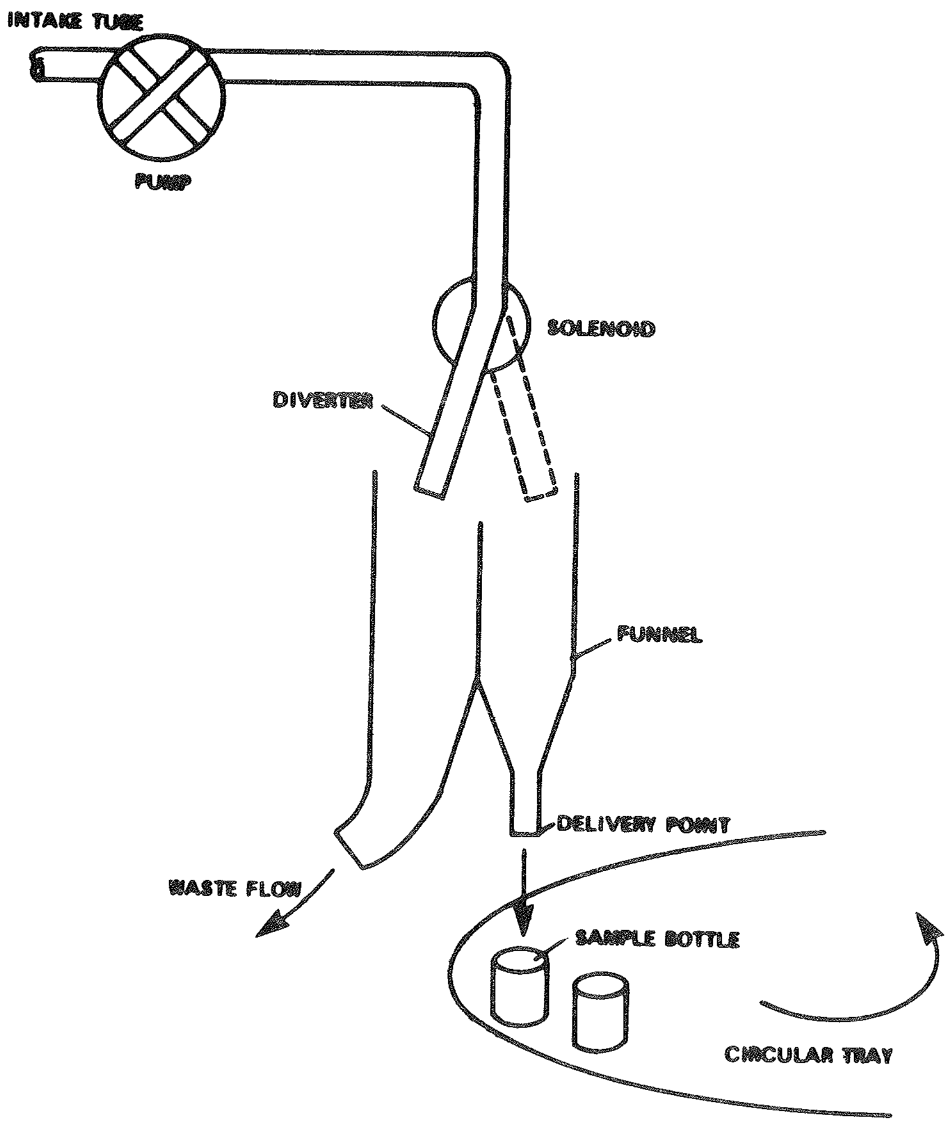

Figure 5.--Schematic diagram of PS-3 hydraulic system.

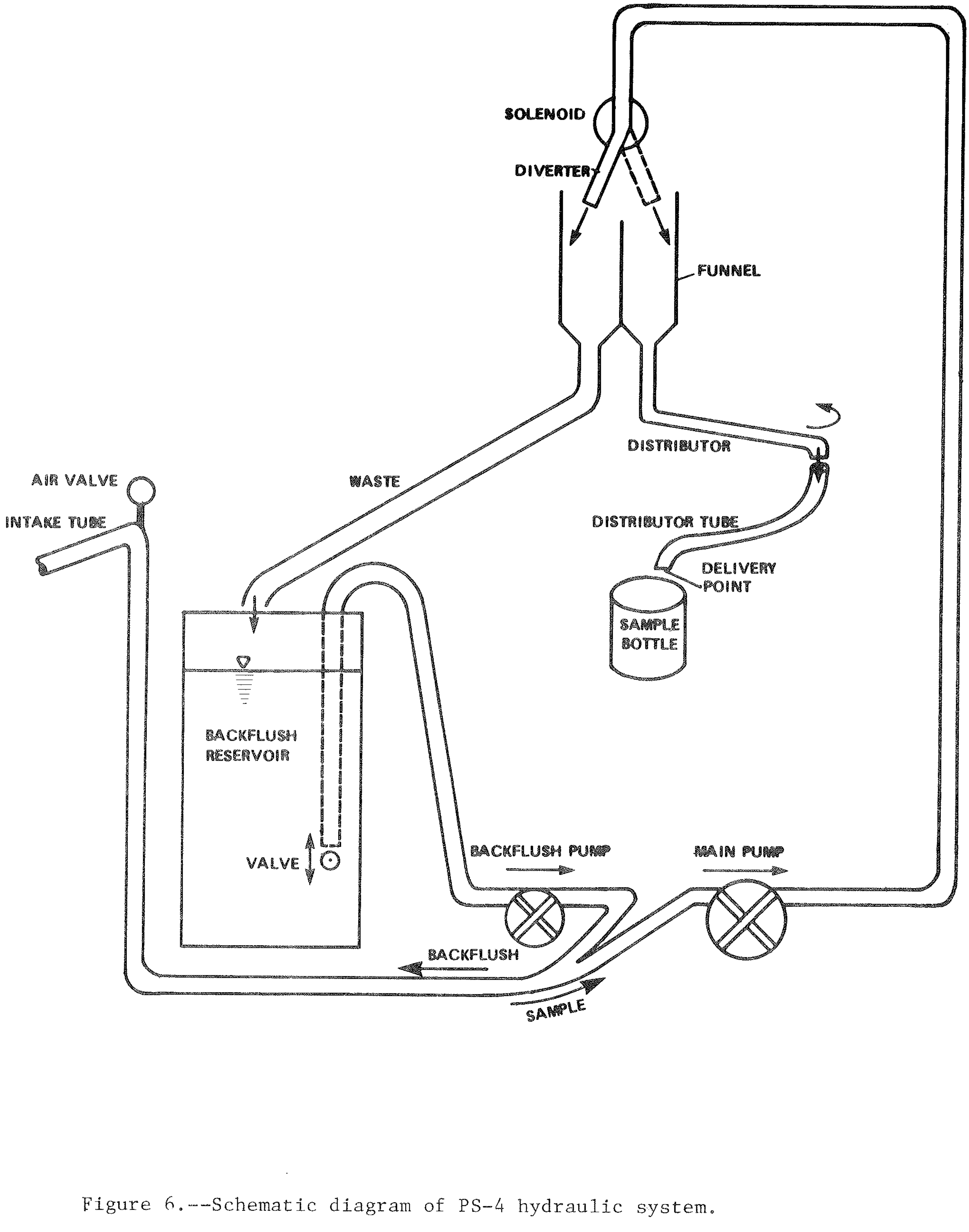

Figure 6.--Schematic diagram of PS-4 hydraulic system.

installations where a suitable shelter may be provided. The sampling pump is of the progressive-cavity type powered by a 1/3-hp, 36-volt motor. Three 12-volt automobile batteries are required for power.

The sampling cycle consisted of a purge-waste-sample-waste sequence. The cycle starts when water is pumped from the backflush reservoir through the intake tube to the stream. At the end of this purge operation, water is pumped from the stream to replenish the reservoir and establish an equilibrium in the intake tube. After a preset time interval, a sample-splitter diverts the pump discharge into a funnel which, through a system of tubes, drains the sample into one of the bottles. The splitter then reroutes the flow to the reservoir. Pumping continues until the reservoir refills in preparation for the next cycle.

SAMPLER EVALUATION AND COMPARISON

The following evaluation is offered primarily as a basis for formulating suggestions and criteria for future design purposes. With one exception, the ramp-test efficiency was greater than the step-test efficiency. In the only exception, (PS-1), the two efficiencies were equal.

PS-1 Sampler

In the step test, 48 percent of the sediment that entered the intake was delivered to the distribution system within the sampler. Of this material, 18 percent was in the sample bottle, 71 percent was carried into the next (flush) container, and 11 percent remained behind as residue. Deposition within the inclined channel accounted for the low step-test efficiency. The glass sample containers used with the PS-1 sampler had a smooth interior and consequently were superior to plastic containers. The sample masses were quite consistent. With an average mass of 407 g (grams), the standard deviation was only 4 percent of the average.

PS-1A Sampler

The glass containers used with this sampler were satisfactory in all respects. Compared to the PS-1, the increased capacity of the high-speed pump served to raise the efficiency of the intake system to 100 percent. The quantitative data (tables 5-8), and visual observations through the transparent intake tube, confirmed that the suspension was traveling as a homogeneous mixture with no evidence of deposition. As shown by the step test, the pumping system responded very well to an increase in concentration. The average for six runs indicated that of the sediment delivered to the inclined channel, 47 percent was discharged on the first sampling cycle and 34 percent on the second cycle. The remaining 19 percent would have been discharged during some succeeding cycle. The only detrimental feature was the inclined channel tray. As with the PS-1, large quantities of material deposited in this channel would contaminate other samples during subsequent sampling cycles.

PS-2 Sampler

During the tests, the weir was positioned to retain the maximum sample, although 4 percent was automatically skimmed and discarded during the second purge. For sediments that settle rapidly, skimming a portion of the sample will result in undesired enrichment. The pressure-vacuum system proved very effective both in purging the system and in maintaining high flow velocities in the intake tube. (See tables 9-12). The relatively flat bottom in the metering chamber did trap and hold significant quantities of sediment. However, deposition was partially cancelled by carry-over contamination throughout most of the ramp test and resulted in an average efficiency of 78 percent. Step-test residues were collected to isolate the intake-tube efficiency which averaged 104 percent. The excess 4 percent was undoubtedly the result of siphoning during the purge cycle. Of the sediment delivered to the metering chamber, an average of 30 percent was delivered into the first sample container, 34 percent into the second (clear flush) container, and the remaining 36 percent was available for delivery on a subsequent sample.

PS-3 Sampler

Three different pumps were tested with the Chickasha sampler. The first two, of the flexible impeller type, were judged unsatisfactory because of limited suction-lift capabilities. The tabulated experimental data (tables 13-16) were collected with a small, commercially available peristaltic pump. Any peristaltic pump of similar capacity should give almost identical results. The sampler responded well to both a step increase and step decrease. The sampler was able to clear its hydraulic system of vestiges of previous samples and to transport, with modest loss in efficiency, a representative sample to the container. The distributor system contained essentially no plumbing and consequently retained only a negligible amount of sediment. Of the sediment transported to the sampler, 99 percent was discharged in the first sample and 1 percent in the second. Only a residual trace remained.

PS-4 Sampler

The purge and waste operations that preceded sample extraction proved effective in eliminating from the intake tube all traces of previous samples. (See tables 17-20.) The pumping rate was adequate to transport representative samples to the machine and the steep slopes in the distributor tubes provided efficient transport to the sample bottles. For each sample pumped, 99 percent of the sediment was delivered to the proper container. Slightly less than 1 percent was carried forward to the second sample and less than 1/10 percent remained as a residue in the splitter and distributor tubes.

In both the ramp and step tests the efficiency of the pumping system was approximately 107 percent. The excess 7 percent, being less than the standard deviation of 10 percent, was probably a result of random experimental errors.

Operating and physical characteristics

To provide a numerical system of comparison, data from table 21 was used to compute various figures-of-merit indices shown in table 22. Each figure-of-merit characterized, in numerical form, a salient physical or operating characteristic. Within any given category the index was defined so that the most desirable sampler had the highest numerical value. Furthermore, to permit comparison of samplers with different characteristics, each index was defined in terms of a single sample, for example the total power required per sample. The carry-over contamination index emphasizes sediment sampling efficiency by combining, with equal weight, the step-increase and step-decrease efficiencies.

The electrical index is the potential (minimum) energy required to lift a sample from the stream to the sampler divided by the measured electrical energy required to power the sampler through one complete sampling cycle. As defined, the index is a measure of overall electrical efficiency.

The electro-hydraulic index is proportional to the product of the electrical index and the sampling-tube efficiency. In design, a high electrical figure-of-merit could be achieved at the expense of sampling-tube efficiency by incorporating low pumping rates to reduce hydraulic losses. The electro-hydraulic index gives equal weight to the electrical index and sampling-tube efficiency.

The indices for floor area, volume, and weight are, respectively, the sample volume stored per unit of floor area, per unit of machine volume, and per unit of machine weight.

The dimensions are in a convenient, but not necessarily consistent, system of units; therefore, no direct interpretation should be made of individual numbers nor should comparisons be made from different categories. No great importance should be attached to figures-of-merit that differ by small amounts.

RECOMMENDATIONS

Future design

To establish design criteria, much can be learned by examining indices of the tested samplers. Table 22 shows that samplers which ranked low in carry-over contamination ranked high in several other indices. The converse was also true. The pattern illustrates the fact that with the current level of technology in materials and components, a designer can make a marked increase in one index, but only by making a marked decrease in one or more other indices. It appears possible to produce a sampler with a well-balanced design typified by the following range of indices: carry-over contamination, 80 to 100; electrical, 50 to 75; electro-hydraulic, 50 to 75; floor area, 50 to 75; volume, 75 to 100; weight, 50 to 75. Innovative designers may, through more radical changes, be able not only to meet all recommended minimums but exceed some of the suggested values.

When designing new samplers, consideration must be given to the following factors which augment the figures-of-merit:

(a) Storing separate samples is recommended over compositing them in one large container. With separate samples the group can be analyzed for trends and each sample can be correlated with water discharge. Faulty samples can be disregarded, and if desired the remainder can be composited mathematically.

(b) The required number of sample containers will depend upon the sampling frequency and the interval between service visits. Experience indicates that approximately twenty containers is the required minimum.

(c) Sampling duration would be sufficiently long to average short-term fluctuations in stream concentration. Bennett and Nordin (1973, p. 17-13) used a variability of 10 percent as a suitable criterion: that is, the sample volumes should be large enough to insure that the standard deviation of a group of successive samples all collected during steady stream conditions is no larger than 10 percent of the mean sample concentration.

(d) Sample volumes must be large enough to satisfy not only the sampling duration requirement, but also special analytical requirements. For only concentration and particle-size analysis, 350-ml is generally the minimum usable volume, but if individual samples must be split for other analyses the volume must be increased accordingly.

(e) Sample containers should be shaped to facilitate sample removal.

(f) For combined sediment and chemical analysis, the sampler intake, intake tube, and sample containers should be chemically inert.

(g) For biological analysis, provisions must be made for cooling the samples.

(h) At sites where evaporation, dust, or insects are a problem, containers should be covered.

(i) Unless the entire sampler can be submerged, the sample withdrawal system must be capable of lifting the sample far enough to span the extreme range of water stages. At most sites a pumping lift of six meters (20 ft) has proven to be adequate; but at a few sites where the stream flows through a deep canyon, the stage change and required lift may exceed twenty meters (66 ft).

(j) From the aspects of safety and universal use, a low-voltage battery supply is preferred over a 120-V a.c. system.

(k) Figure 7 shows that within the range of experimental reproducibility, the efficiency of the intakes used in this test were not significantly different from the intakes tested in Report T (ICWR, 1966).

(l) The step test is more rigorous than the ramp test and therefore should be used to evaluate modifications of existing samplers and new prototypes.

(m) The designer must strive to reduce the combined cost of equipment acquisition, installation, and maintenance. In addition to minimizing manufacturing cost, the designer should attempt to minimize or eliminate the required degree of operator training, the damage caused by freezing water, and the cost of ancillary shelters and heaters.

The designer must pay particular attention to the diameter of the intake tube and its relation to the capacity of the sampling pump. Within the intake tube, the flow rate must be adequate to insure efficient transport of the water-sediment mixture. For each of a variety of conditions, the minimum rate is difficult to establish precisely, but it may

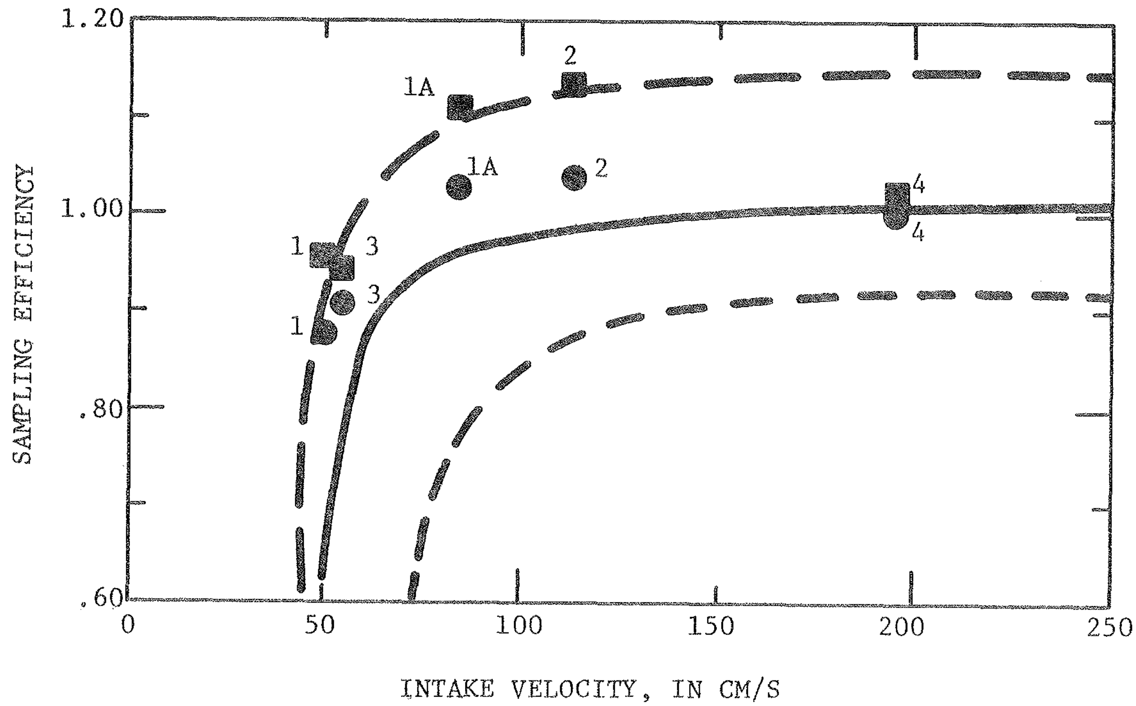

Figure 7--Plot of sampling efficiency versus intake velocity for the entire range of concentrations tested (circles) and for concentrations less than 2,500-2,800 ppm (squares). Numbers refer to automatic sampler code. Curves are from Rept. T (ICWR, 1966) for flush-mounted intakes tested with 0.19-mm sand, 3.7 ft/s (1.1 m/s) flume velocity, and concentrations of 2,500 ppm or less. The dashed curves are envelopes that indicate the scatter in Rept. T data (p. 49), and the solid curve is the average curve shown in Rept. T (fig. 12, p. 36).

be estimated from the minimum required Reynolds number and from the fall velocity of individual sediment particles. Tests outlined in this report indicate a Reynolds number as low as 2,000 may be satisfactory, but to provide a margin of safety the minimum should be 4,000 to 5,000. Good efficiencies were obtained in the range of 5,000 to 7,000. Above 7,000 the added efficiency probably does not warrant the increased head loss and power demands. These estimates are based primarily on transport of AGSCO No. 4 sand which had a high settling rate, and therefore simulated worst-case conditions.

Another simple and reasonably reliable flow-rate criterion is the ratio of the mean velocity in the intake tube divided by the settling velocity of the largest particle to be transported. Early estimates set this ratio at a minimum of 17 in horizontal conduits (Fed. Interagency Work Group, 1972, p. III-20) and these tests confirmed the estimate. For example, the PS-3 with a ratio of 18.4 had an intake-tube efficiency of 88 percent. PS-1A with the high-speed pump had a ratio of 28 and an efficiency very near 100 percent. To provide for a margin of safety in design, the ratio should be no less than 20.

A change in the nature of the sediment being sampled will affect the pumping requirements. Gilbert and Durand (ASCE, 1975, p. 272) observed that the sediment tranport rate increased when the sediment size gradation was broadened.

Sedimentation Engineering (ASCE, 1975, p. 254-256) summarizes generalized equations for sediment transport in pipes. The critical velocity ratio ascribed to Newitt and others divides homogenous and heterogenous pipe flows: for AGSCO No. 4 sand, $V_H/w = 56$, where V_H is the critical flow velocity and w is the particle fall velocity. For sampling purposes, this ratio seems too high. Transport would be efficient but pumping head loss would be excessive. An equation ascribed to Spells yields a velocity ratio of 15 for the AGSCO sand. For sampling purposes, Spells' equation appears more realistic. The disparity between the two estimates indicates the need for additional studies.

Sampler modification

Of the samplers tested, each was deficient in one or more aspects. As an alternative to complete redesign which would be costly and lengthy, each sampler could be improved through modification or limited redesign. The following suggested modifications will increase some figures-of-merit and decrease others toward the balanced design concept.

To increase the carry-over contamination index, the pumping rate of PS-1 must be increased and the sample distribution systems of PS-1, PS-1A, and PS-2 must be redesigned. To maintain the contamination index at a high value yet provide latitude to improve other indices, the PS-4 pump should be replaced with a smaller, more efficient unit; and the diameter of the intake tube should be decreased to maintain a sufficiently high flow velocity.

To meet the electrical and electro-hydraulic objective the total lift capabilities of PS-1, PS-2, and PS-3 should be increased. On both PS-1 and PS-1A, the peristaltic pump should be mounted so that, as an option, it can be easily detached and relocated near the stream. Through relocation, the high-pressure discharge capability of the peristaltic pump could be more fully utilized. The pump and motor must be enclosed to permit operation during stream flows high enough to submerge the units. To increase its total lift, the PS-2 would probably have to be equipped with an auxiliary pump. As mentioned previously, the PS-4 should be equipped with a smaller pump.

The floor-area index of the PS-3 could be improved by rearranging the bottles into a more compact array; two or three concentric circles or possibly a two-level arrangement. To access all bottles, a new distributor system must be designed.

The volume index of PS-1, PS-2, and PS-3 could be lowered without a significant sacrifice in portability. At many sites, volume is not of prime concern; however, for manhole installation the overall height could be increased to accommodate modifications previously mentioned. PS-3 would again benefit from a more compact bottle arrangement. The height of PS-4 could be reduced slightly, but more importantly the volume per sample and sampling duration could be nearly doubled through use of taller containers.

The weight index of PS-3 could be greatly increased by substituting lightweight aluminum for the heavy steel used in the frame.

CONCLUSIONS

1. The step-test procedure was adequate to define deficiencies in all samplers tested.

2. All samplers tested could be improved through modification.

3. Three conditions for representative samples can be stated:
    a) The mean velocity within the mouth of the intake should exceed the approach flow velocity.
    b) Flow in the intake tube should have a Reynolds number that exceeds 4,000.
    c) Mean velocity in the intake tube should exceed 20 times the fall velocity of the largest particle in suspension.

4. The efficiency of projecting, downstream-angled sampler intakes was nearly the same as flush-mounted intakes oriented at right angles to the flume wall.

The preferred procedure for testing future samplers or modifications of existing designs is the step test. This test is simple and easily adapted to any sampler. By first sampling flow with a known sediment concentration and then sampling clear water, the amount of carry-over contamination can be determined. Also, by disassembling the sampler and flushing the separate parts, sites of deposition may be located.

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Sampler PS-1 Date January 24, 1977

Intake tube I.D. 6.35 mm. Total length 6.7 m.
Elevation, intake to sample containers 3.8 m.
Water temperature 4° C.
Test sediment AGSCO No. 4.
Intake tube flow rate 15.7 ml/s.

Upstream Reference nozzle I.D. 4.76 mm.			Automatic sampler Intake I.D. 4.76 mm.		
Sample Mass, g	Sediment Mass, g	C_r Conc, mg/L	Sample Mass, g	Sediment Mass, g	C_s Conc, mg/L
522	0.2393	458	427	0.1955	457
573	.2591	452	450	.2004	445
524	.4258	812	413	.3363	814
589	.5052	857	459	.3906	850
577	.4986	864	452	.3818	844
592	1.3256	2239	473	.9102	1924
588	1.4540	2472	465	1.0007	2152
596	2.6091	4378	473	1.6166	3417
591	2.3745	4018	459	1.5043	3277
578	2.2190	3839	461	1.3597	2949
576	2.2228	3859	460	1.3810	3002
582	2.2654	3892	459	1.3858	3019

Computations

Curve fit: $C_s = f(C_r) = 2.17\ C_r^{0.879}$ Correlation coef. 0.999

Mean velocity in intake tube 49.5 cm/s. Reynolds No. 2000

Sediment D_{90} fall velocity 3 cm/s.

Ratio of mean velocity in intake tube to D_{90} fall velocity 17

Table 1.--PS-1 intake calibration data.

Sampler PS-1 Date January 26, 1977

C_r, Conc. at Reference Nozzle, mg/L	C_c, Computed Conc. at Sampler Intake (1), mg/L	C_d, Conc. at Sampler Delivery Point (2), mg/L	Efficiency Percent (3)
4491	3552	1902	54
4704	3700	2094	57
4825	3784	2092	55
4788	3758	2780	74
3474	2834	1578	56
874	841	983	117
1014	959	532	55
1472	1331	717	54

(1) $C_c = 217\ C_r^{0.879}$

Mean 65

Standard Deviation 22

(2) At discharge side of pump

(3) Efficiency in percent = $(100C_d)/C_c$

Table 2.--Ramp-test data for PS-1.

Sampler PS-1 Date January 27, 1977

Test No.	C_r, Conc. at Reference Nozzle, mg/L	C_c, Computed Conc. at Sampler Intake (1), mg/L	Sampler Delivery-Point Sample: Gross Sample Mass, g	Sediment Mass, g	C_d, mg/L	Residue Mass, g
1	1084	1017 (b)	424 (g)	0.0288 (e)	68 (a)	
	0	0	385	.0487 (f)	126 (c)	
						0.0234 (d)
2	1759	1557	415	.0246	59	
	0	0	416	.1372	329	
						.0084
3	3749	3030	405	.0666	164	
	0	0	405	.5239	1293	
						.0251
4	3576	2907	405	.0443	109	
	0	0	425	.5712	1344	
						.0142
5	4176	3332	404	.1801	445	
	0	0	418	.7667	1834	
						.0693
6	3671	2974	409	.2110	516	
	0	0	374	.3534	944	
						.1851
		Gross Sample Mean	407			
		Standard Deviation	15			

(1) $C_c = 2.17\ C_r^{\ 0.879}$

Source of Residue - Inclined channel

Table 3.--Step-test data for PS-1. Each test consists of a suspended-sediment sample (first line), a clear-water sample (second line), and a system flushing residue (third line). Lower-case letters reference values used in table 4.

Sampler PS-1 Date January 1977

Test No.	C_c, mg/L	Sampler Delivery: Efficiency for Step Increase, Percent (1)	Efficiency for Step Decrease, Percent (2)	Efficiency of Sampling Tube, Percent (3)
1	1017	7	88	23
2	1557	4	79	26
3	3030	5	57	50
4	2907	4	54	53
5	3332	13	45	75
6	2974	17	68	62
		Mean 8 Ideal ≐ 100	Mean 65 Ideal ≐ 100	Mean 48 Ideal ≐ 100

(1) 100 a/b

(2) $100\ (1 - \frac{c}{b})$

(3) $\left[\frac{e + f + d}{gb}\right] \times 10^8$

Table 4.--Computed efficiencies based on step-test data in table 3.

Sampler PS-1A Date January 31, 1977

Intake tube I.D. 9.53 mm. Total length 6.0 m.
Elevation, intake to sample containers 3.8 m.
Water temperature 4° C.
Test sediment AGSCO No. 4.
Intake tube flow rate 60 ml/s.

Upstream Reference nozzle I.D. 4.76 mm.			Automatic sampler Intake I.D. 7.54 mm.		
Sample Mass, g	Sediment Mass, g	C_r Conc, mg/L	Sample Mass, g	Sediment Mass, g	C_s Conc, mg/L
269	0.1866	694	767	0.6430	838
263	.2572	978	769	.8569	1114
280	.3143	1123	796	1.0514	1321
252	.3545	1407	743	1.1714	1577
262	.4555	1739	770	1.4519	1886
260	.5381	2070	754	1.6145	2141
272	.7296	2682	787	2.1419	2722
258	.9210	3570	764	2.6479	3466
266	1.1459	4308	783	2.7565	3520
274	1.1482	4191	787	2.8736	3651
271	1.0489	3870	773	3.0408	3934
279	1.1796	4228	798	2.8899	3621

Computations

Curve fit: $C_s = f(C_r) = 4.09\ C_r^{0.819}$ Correlation coef. 0.995

Mean velocity in intake tube 84 cm/s. Reynolds No. 5200

Sediment D_{90} fall velocity 3 cm/s.

Ratio of mean velocity in intake tube to D_{90} fall velocity 28

Table 5.--PS-1A intake calibration data.

Sampler PS-1A   Date January 31, 1977

C_r, Conc. at Reference Nozzle, mg/L	C_c, Computed Conc. at Sampler Intake (1), mg/L	C_d, Conc. at Sampler Delivery Point (2), mg/L	Efficiency Percent (3)
518	687	514	75
995	1174	1131	96
1932	2024	1988	98
3117	2996	2800	93
3355	3183	3140	99
4090	3744	3738	100
4144	3784	3302	87
4399	3974	3748	94
4160	3796	3817	101
3932	3625	3545	98
2294	2330	2866	123
716	896	919	103

(1) $C_c = 4.09\ C_r^{0.819}$

Mean 97

Standard Deviation 11

(2) At discharge side of pump

(3) Efficiency in percent = $(100C_d)/C_c$

Table 6.--Ramp-test data for PS-1A.

Sampler PS-1A Date February 1, 1977

Test No.	C_r, Conc. at Reference Nozzle, mg/L	C_c, Computed Conc. at Sampler Intake (1), mg/L	Sampler Delivery-Point Sample: Gross Sample Mass, g	Sediment Mass, g	C_d, mg/L	Residue Mass, g
1	756	938 (b)	401 (g)	0.2713 (e)	677 (a)	
	0	0	421	.0670 (f)	159 (c)	
						0.0669 (d)
2	948	1129	396	.1429	361	
	0	0	408	.1599	392	
						.0991
3	1295	1458	394	.2810	714	
	0	0	416	.2415	581	
						.0761
4	4191	3820	392	.6519	1663	
	0	0	412	.4533	1100	
						.3146
5	3885	3589	389	.6320	1625	
	0	0	413	.6225	1507	
						.0813
6	3724	3467	386	.5323	1379	
	0	0	412	.4304	1045	
						.4483
		Gross Sample Mean	403			
		Standard Deviation	12			

(1) $C_c = 4.09\ C_r^{0.819}$

Source of Residue - Inclined channel

Table 7.--Step-test data for PS-1A. Each test consists of a suspended-sediment sample (first line), a clear-water sample (second line), and a system flushing residue (third line). Lower-case letters reference values used in table 8.

Sampler PS-1A Date February 1977

Test No.	C_c, mg/L	Sampler Delivery: Efficiency for Step Increase, Percent (1)	Efficiency for Step Decrease, Percent (2)	Efficiency of Sampling Tube, Percent (3)
1	938	72	83	108
2	1129	32	65	90
3	1458	49	60	104
4	3820	44	71	95
5	3589	45	58	96
6	3467	40	70	105
		Mean 47 Ideal = 100	Mean 68 Ideal = 100	Mean 100 Ideal = 100

(1) $100\ a/b$

(2) $100\ (1 - \frac{c}{b})$

(3) $\left[\frac{e + f + d}{gb}\right] \times 10^8$

Table 8.--Computed efficiencies based on step-test data in table 7.

Sampler PS-2 Date February 2, 1977

Intake tube I.D. 9.53 mm. Total length 7 m.
Elevation, intake to sample containers 6 m.
Water temperature 4° C.
Test sediment AGSCO No. 4.
Intake tube flow rate 81 ml/s.

Upstream Reference nozzle I.D. 4.76 mm.			Automatic sampler Intake I.D. 7.54 mm.		
Sample Mass, g	Sediment Mass, g	C_r Conc, mg/L	Sample Mass, g	Sediment Mass, g	C_s Conc, mg/L
221	0.2530	1145	817	1.0522	1288
216	.1285	594	810	.6011	742
211	.2098	994	799	.9080	1136
217	.2559	1179	807	1.0707	1327
222	.2593	1168	825	1.1594	1405
214	.6002	2803	803	2.2728	2830
220	.7098	3226	821	2.5851	3148
221	.7429	3362	832	2.4880	2990
226	.7303	3231	832	2.6106	3137
221	.9904	4481	834	3.3538	4021
223	.9409	4219	827	3.2568	3938
228	.9857	4323	849	3.4071	4013

Computations

Curve fit: C_s $f(C_r) = 3.58\ C_r^{0.837}$ Correlation coef. 0.999

Mean velocity in intake tube 115 cm/s. Reynolds No. 7000

Sediment D_{90} fall velocity 3 cm/s.

Ratio of mean velocity in intake tube to D_{90} fall velocity 38

Table 9.--PS-2 intake calibration data.

Sampler PS-2 Date February 3, 1977

C_r, Conc. at Reference Nozzle, mg/L	C_c, Computed Conc. at Sampler Intake (1), mg/L	C_d, Conc. at Sampler Delivery Point (2), mg/L	Efficiency Percent (3)
550	717	279	39
811	994	527	53
1188	1370	877	64
1032	1217	1058	87
1482	1650	1415	86
1783	1927	1483	77
1867	2003	2040	102
2244	2337	2293	98
4038	3829	2959	77
4047	3836	3600	94
4721	4366	4046	93
4479	4177	2783	67

(1) $C_c = 3.58\ C_r^{0.837}$

Mean 78

Standard Deviation 19

(2) At discharge side of spout

(3) Efficiency in percent = $(100C_d)/C_c$

Table 10.--Ramp-test data for PS-2.

Sampler PS-2 Date February 3, 1977

Test No.	C_r, Conc. at Reference Nozzle, mg/L	C_c, Computed Conc. at Sampler Intake (1), mg/L	Sampler Delivery-Point Sample: Gross Sample Mass, g	Sampler Delivery-Point Sample: Sediment Mass, g	Sampler Delivery-Point Sample: C_d, mg/L	Residue Mass, g
1	838	1021 (b)	481 (g)	0.1922 (e)	399 (a)	
	0	0	482	.1879 (f)	390 (c)	
						0.1742 (d)
2	1367	1541	481	.2298	478	
	0	0	481	.1956	406	
						.2686
3	2357	2436	482	.3919	813	
	0	0	481	.5058	1052	
						.4607
4	4651	4311	479	.5984	1249	
	0	0	480	.7828	1631	
						.7986
5	4661	4319	482	.5813	1206	
	0	0	481	.6541	1360	
						.7360
6	4512	4203	479	.5790	1209	
	0	0	480	.7118	1483	
						.7500
	Gross Sample Mean		481			
	Standard Deviation		1			

(1) $C_c = 3.58\ C_r^{0.837}$

Source of Residue - Metering chamber

Table 11.--Step-test data for PS-2. Each test consists of a suspended-sediment sample (first line), a clear-water sample (second line), and a system flushing residue (third line). Lower-case letters reference values used in table 12.

Sampler PS-2 Date February 1977

Test No.	C_c, mg/L	Sampler Delivery: Efficiency for Step Increase, Percent (1)	Efficiency for Step Decrease, Percent (2)	Efficiency of Sampling Tube, Percent (3)
1	1021	39	62	113
2	1541	31	74	94
3	2436	33	57	116
4	4311	29	62	106
5	4319	28	69	95
6	4203	29	65	101
		Mean 32 Ideal = 100	Mean 65 Ideal = 100	Mean 104 Ideal = 100

(1) 100 a/b

(2) $100\ (1 - \frac{c}{b})$

(3) $\left[\frac{e + f + d}{gb}\right] \times 10^8$

Sample enrichment caused by siphoning during second purge elevated the efficiency by 4%.

Table 12.--Computed efficiencies based on step-test data in table 11.

Sampler PS-3 Date February 7, 1977

Intake tube I.D. 9.53 mm. Total length 6.7 m.
Elevation, intake to sample containers 6.1 m.
Water temperature 4° C.
Test sediment AGSCO No. 4.
Intake tube flow rate 40 ml/s.

Upstream Reference nozzle I.D. 4.76 mm.			Automatic sampler Intake I.D. 7.54 mm.		
Sample Mass, g	Sediment Mass, g	C_r Conc, mg/L	Sample Mass, g	Sediment Mass, g	C_s Conc, mg/L
312	0.1843	590	838	0.5524	659
308	.2484	806	818	.6221	760
294	.2502	851	785	.6710	855
323	.3451	1068	856	.8492	992
314	.3362	1071	846	.8731	1032
311	.4236	1362	832	1.0995	1322
317	.6108	1927	850	1.4584	1716
324	.7774	2399	852	1.7692	2077
316	.8573	2713	848	2.0095	2370
331	1.1322	3421	868	2.4547	2828
311	1.1362	3653	825	2.3573	2857
343	1.6407	4783	910	3.2172	3535

Computations

Curve fit: $C_s = f(C_r) = 2.88\, C_r^{0.844}$ Correlation coef. 0.998

Mean velocity in intake tube 55 cm/s. Reynolds No. 3400

Sediment D_{90} fall velocity 3 cm/s.

Ratio of mean velocity in intake tube to D_{90} fall velocity 18

Waste before sample extraction = 0.74 liters.

Table 13.--PS-3 (Chickasha sampler with peristaltic pump) intake calibration data.

Sampler PS-3 Date February 7, 1977

C_r, Conc. at Reference Nozzle, mg/L	C_c, Computed Conc. at Sampler Intake (1), mg/L	C_d, Conc. at Sampler Delivery Point (2), mg/L	Efficiency Percent (3)
814	802	758	95
816	804	766	95
948	912	804	88
1310	1196	1092	91
1130	1057	1097	104
1727	1509	1359	90
2089	1771	1627	92
2784	2254	1956	87
3914	3001	2311	77
4011	3063	3009	98
4177	3169	2982	94
4618	3448	2961	86

(1) $C_c = 2.88\ C_r^{0.844}$

Mean 91

Standard Deviation 7

(2) At discharge of sample splitter

(3) Efficiency in percent = $(100C_d)/C_c$

Table 14.--Ramp-test for PS-3.

Sampler PS-3 Date February 7, 1977

Test No.	C_r, Conc. at Reference Nozzle, mg/L	C_c, Computed Conc. at Sampler Intake (1), mg/L	Sampler Delivery-Point Sample: Gross Sample Mass, g	Sediment Mass, g	C_d, mg/L	Residue Mass, g
1	1211	1120 (b)	914 (g)	0.9256 (e)	1012 (a)	
	0	0	934	.0055 (f)	6 (c)	
						0.0002 (d)
2	1771	1541	917	1.4088	1536	
	0	0	932	.0066	7	
						.0002
3	2224	1866	918	1.0557	1150	
	0	0	947	.0066	7	
						.0007
4	2629	2148	932	1.8544	1990	
	0	0	903	.0111	12	
						.0006
5	3580	2784	930	2.3271	2502	
	0	0	932	.0104	11	
						.0006
6	3499	2731	921	2.2428	2435	
	0	0	941	.0224	24	
						.0014
	Gross Sample Mean		927			
	Standard Deviation		12			

(1) $C_c = 2.88\ C_r^{0.844}$

Source of Residue - Sample splitter

Table 15.--Step-test data for PS-3. Each test consists of a suspended-sediment sample (first line), a clear-water sample (second line), and a system flushing residue (third line). Lower-case letters reference values used in table 16.

Sampler PS-3 Date February 1977

Test No.	C_c, mg/L	Sampler Delivery: Efficiency for Step Increase, Percent (1)	Sampler Delivery: Efficiency for Step Decrease, Percent (2)	Sampler Delivery: Efficiency of Sampling Tube, Percent (3)
1	1120	90	99	91
2	1541	100	100	100
3	1866	62	100	62
4	2148	93	99	93
5	2784	90	100	90
6	2731	89	99	90
		Mean 87 Ideal = 100	Mean 99 Ideal = 100	Mean 88 Ideal = 100

(1) $100\ a/b$

(2) $100\ (1 - \frac{c}{b})$

(3) $\left[\frac{e + f + d}{gb}\right] \times 10^8$

Table 16.--Computed efficiencies based on step-test data in table 15.

Sampler PS-4 Date February 16, 1977

Intake tube I.D. 19.1 mm. Total length 6.7 m.
Elevation, intake to sample containers 4.1 m.
Water temperature 2° C.
Test sediment AGSCO No. 4.
Intake tube flow rate 560 ml/s.

Upstream Reference nozzle I.D. 4.76 mm.			Automatic sampler Intake I.D. 19.6 mm.		
Sample Mass, g	Sediment Mass, g	C_r Conc, mg/L	Sample Mass, g	Sediment Mass, g	C_s Conc, mg/L
519	0.1823	351	7930	3.1891	402
720	.3194	444	8354	3.6502	437
765	.4638	606	8454	3.6501	432
783	.5389	688	9168	6.4616	705
707	.6257	885	7949	7.5927	955
608	.8373	1377	7968	12.2656	1539
716	.9842	1374	7945	11.2385	1414
718	1.4016	1952	7930	15.9197	2008
720	2.1581	2997	8450	23.1286	2737
684	2.1086	3083	7158	21.3585	2984
691	2.1221	3071	7434	22.9456	3087
656	2.1040	3207	7855	23.7826	3028

Computations

Curve fit: $C_s = f(C_r) = 1.07\ C_r^{0.989}$ Correlation coef. 0.988

Mean velocity in intake tube 195 cm/s. Reynolds No. 24,000

Sediment D_{90} fall velocity 3 cm/s.

Ratio of mean velocity in intake tube to D_{90} fall velocity 65

Sample extraction preceded by 10.6 liters stored in backflush container.

Table 17.--PS-4 (PS-69 sampler with 1/3-hp motor) intake calibration data.

Sampler PS-4 Date February 16, 1977

C_r, Conc. at Reference Nozzle, mg/L	C_c, Computed Conc. at Sampler Intake (1), mg/L	C_d, Conc. at Sampler Delivery Point (2), mg/L	Efficiency Percent (3)
463	466	516	111
389	392	443	113
424	427	501	117
527	530	575	108
745	746	778	104
737	738	765	104
543	546	647	118
892	892	974	109
1343	1337	1513	113
1825	1811	1627	90
2662	2632	2554	97
2975	2938	2854	97

(1) $C_c = 1.07\ C_r^{0.989}$

Mean 107

Standard Deviation 9

(2) At discharge end of tubes that lead to individual sample bottles

(3) Efficiency in percent = $(100C_d)/C_c$

Table 18.--Ramp-test data for PS-4.

Sampler PS-4 Date February 17, 1977

			Sampler Delivery-Point Sample			
Test No.	C_r, Conc. at Reference Nozzle mg/L	C_c, Computed Conc. at Sampler Intake (1), mg/L	Gross Sample Mass, g	Sediment Mass, g	C_d, mg/L	Residue Mass, g
1	756	757 (b)	613 (g)	0.5594 (e)	913 (a)	
	0	0	601	.0075 (f)	12 (c)	
						0.0002 (d)
2	1209	1205	613	.7408	1208	
	0	0	641	.0053	8	
						.0009
3	1134	1131	631	.7601	1205	
	0	0	657	.0095	14	
						.0003
4	1500	1492	643	.9854	1533	
	0	0	663	.0058	8	
						.0002
5	2089	2071	636	1.5168	2385	
	0	0	638	.0148	23	
						.0007
6	2121	2102	613	1.2193	1989	
	0	0	641	.0076	12	
						.0004
	Gross Sample Mean		633			
	Standard Deviation		19			

(1) $C_c = 1.07\ C_r^{\ 0.989}$

Source of Residue - Funnel and tubes

Table 19.--Step-test data for PS-4. Each test consists of a suspended-sediment sample (first line), a clear-water sample (second line), and a system flushing residue (third line). Lower-case letters reference values used in table 20.

Sampler PS-4 Date February 1977

Test No.	C_c, mg/L	Sampler Delivery: Efficiency for Step Increase, Percent (1)	Efficiency for Step Decrease, Percent (2)	Efficiency of Sampling Tube, Percent (3)
1	757	121	98	122
2	1205	100	99	101
3	1131	107	99	108
4	1492	103	99	103
5	2071	115	99	116
6	2102	95	99	95
		Mean 107	Mean 99	Mean 108
		Ideal = 100	Ideal = 100	Ideal = 100

(1) $100\ a/b$

(2) $100\left(1 - \frac{c}{b}\right)$

(3) $\left[\frac{e + f + d}{gb}\right] \times 10^8$

Table 20.--Computed efficiencies based on step-test data in table 19.

	UNIT	SYM-BOL	SAMPLER				
			PS-1	PS-1A	PS-2	PS-3	PS-4
1. Required floor area	m^2	a	0.20	0.20	0.20	1.06	1.33
2. Height	m	h	.54	.54	.52	1.12	1.85
3. Weight, including batteries	kg	w	18	18	19	106	126
4. Sampling sequence:							
Air purge, sample, water purge.	–	–	x	x	x		
Presample waste, sample, postsample waste.	–	–				x	
Water purge, presample waste, sample, and postsample waste.							x
5. Number of sample containers	–	n	28	28	24	28	72
6. Nominal sample container volume	ml	v	500	500	500	500	1000
7. Sample volume reproducibility (Standard deviation/mean) 100	%	–	4	3	.2	1	3
8. Suitability of container for coarse sediment extraction & cleaning	–	–	good	good	poor	good	good
9. Power source (b = battery, c = converter)	–	–	b/c	b/c	b	b	b/c
10. Supply voltage	volts	–	12	12	12	12	36

Table 21.--Characteristics of tested samplers.

	UNIT	SYM-BOL	SAMPLER				
			PS-1	PS-1A	PS-2	PS-3	PS-4
11. Energy demand per sample cycle	kW-s	E	.7	1.2	3.7	1.3	24
12. Recommended maximum.							
Suction lift 1/	m	-	7.9	7.9	7.0	7.0	6.7
Total lift 2/	m	l	7.9	7.9	7.0	10	15
Tubing length	m	-	6.7	6.7	7.0	20	17
13. Computed efficiencies in percent:							
Ramp test	%	-	65	97	78	91	107
Step increase	%	e_i	8	47	32	87	107
Step decrease	%	e_d	65	68	35	99	99
Sampling tube for step test	%	e_t	48	100	104	88	108
14. Contains provisions for cooling samples	-	-	yes	yes	yes	no	no
15. Includes weather-tight enclosure	-	-	yes	yes	yes	no	no
16. Portable	-	-	yes	yes	yes	no	no

1/ Suction lift is the distance from the stream surface to the suction side of the pump.

2/ Total lift is the distance from the stream surface to the sampler. The pumps on PS-3 and PS-4 can be operated away from their samplers.

Table 21.--Characteristics of tested samplers--Continued.

	Defining Equation 1/	PS-1	PS-1A	PS-2	PS-3	PS-4
1. Carry-over contamination	$e_i e_d \, 10^{-2}$	5	32	11	86	106
2. Electrical	$\frac{vl}{E} \, 10$	56	33	10	73	6
3. Electrohydraulic	$\frac{vle_t}{E} \, 10^{-1}$	27	33	10	64	7
4. Floor Area	$\frac{nv}{a} \, 10^{-3}$	70	70	60	13	54
5. Volume	$\frac{nv}{ah} \, 10^{-3}$	130	130	115	12	29
6. Weight	$\frac{nv}{w} \, 10^{-1}$	78	78	63	13	57

1/ Symbols are defined in table 21.

Table 22.--Tabulation of various figures-of-merit describing tested samplers. These indices are compounded in such a way that the highest rating is most desirable.