SECTION 2

SAMPLING AND ANALYSIS

GAGES FOR MEASURING FLUVIAL-SEDIMENT CONCENTRATION

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ABSTRACT

Measuring sediment discharges in rivers is a crucial step not only in predicting life expectancies of reservoirs and scheduling channel-maintenance operations, but also in predicting movement of chemical pollutants, determining soil erosion rates, estimating influences of sediment on aquatic biota, and studying stability of hydraulic structures.

As a step toward improving measurement accuracy and reducing measurement costs, the Federal Interagency Sedimentation Project has studied four types of gages for in-situ measurements of sediment concentration. The gages measure sediment concentration by measuring (1) attenuation of gamma rays passing through river water, (2) vibrational frequencies of a U-shaped tube filled with water, (3) vibrational frequencies of a straight tube filled with water, and (4) buoyant forces on a submerged glass bulb.

Each gage has advantages and disadvantages that set it apart from the others. The vibrating U-tube gage and the buoyant force gage (plummet) appear best suited for most applications.

INTRODUCTION

The Federal Interagency Sedimentation Project (Project), established in 1939, has operated under the direction of two Federal agencies, the U.S. Geological Survey and the U.S. Army Corps of Engineers. Presently, other supporting agencies consist of the Agricultural Research Service, the Bureau of Reclamation, the U.S. Forest Service, the Bureau of Land Management, the Federal Highway Administration, and the Tennessee Valley Authority. Operating through the Subcommittee on Sedimentation, Interagency Advisory Committee on Water Data, the supporting agencies have established long-range goals for the Project. These goals include (1) developing, stocking, and calibrating sediment samplers, (2) developing strategies to improve sample representativeness, (3) developing laboratory procedures for analyzing physical properties of sediments and (4) developing instruments for automating sediment measurements. This paper compares four instruments developed to achieve the last goal--automated sediment measurements.

The ideal suspended-sediment gage would be small, lightweight, and inexpensive. It would scan the entire cross-section of a river to account for uneven sediment fluxes and it would repeat the scan every few minutes to account for temporal variability. It would collect sediment concentration and particle-size distribution data. It would be use at all sediment stations because it could be used for sediments ranging in size from clay to sand. Its calibration would be universal; readings would not have to be adjusted for local conditions. Measurement errors would be nonexistent.

Unfortunately, the ideal gage has not been built because of two major obstacles. The first is defining a stable property of sediment to serve as a measurement index. In contrast with chemical elements, which have precisely defined properties, sediment particles have broad ranges of shapes, sizes, colors, and densities. The second problem is sediment concentrations that are too low for many sensing methods. Concentrations less than a few milligrams per liter are significant for sedimentologic purposes, but are unmeasurable by all but the most sensitive instruments. Even with these instruments, it is difficult to obtain accurate measurements.

The desired properties of cross-section scanning and high sensitivity suggests the use of light and sound rays as a means of gaging sediment. Even though gages using light and sound are not of direct concern in this paper, they deserve comment because of their potential for future instrument development.

Measurements and visual observations indicate that opacity (turbidity) of a suspension increases with sediment concentration; consequently, measurement of turbidity has been and will continue to be a tantalizing method for determining sediment concentration. Studies, however, show measurement of turbidity as gaged by forward scattering or attenuation of light is strongly influenced by particle size and mildly influenced by particle shape and color. Measuring forward scattering as a ratio of side scattering has contributed little toward resolving the calibration problem. Studies conducted with light-emitting diodes (Skinner, 1984 and Szalona, 1984) show light attenuation correlates with particle surface areas, but even this relation is only approximate. Light attenuation is controlled by macroscopic features of particles such as their projected areas, but it is not influenced by features such as cracks, pits, and surface irregularities, which contribute to chemical reactions. Even the projected-area relation fails for particles smaller than a few wavelengths of the incident light. Measurement of turbidity by forward scattering or attenuation, however, are attractive sensing methods because both can easily detect sediment concentrations of only a few milligrams per liter.

The Project has also sponsored research on sound waves traveling through sediment suspensions. Dr. Gordon Flammer (1962) showed sound attenuation to be controlled by many of the same factors that control light attenuation. Flammer was able to obtain concentrations and size distributions by measuring sound attenuations through a range of frequencies. Unfortunately, efforts to apply the technique to routine analysis were hampered by low sensitivity and instabilities in the equipment. Sound attenuation is, however, a phenomenon that shows promise for complete cross-section scanning of sediment in rivers.

Completion of research reports on sound propagation coincided with the Project's involvement in a new sediment sensing technique based on the attenuation of gamma rays passing through sediment mixtures. This technique represents a landmark in terms of the large-scale efforts and diversity of talents directed to solving a sediment measuring problem. The instrument, termed the radioisotope gage, is the first of four instruments that are discussed and compared in this paper.

THE RADIOISOTOPE GAGE

In 1961 the Division of Isotopes Development, Atomic Energy Commission, joined the Subcommittee on Sedimentation to design and test a sediment concentration gage for in-situ field applications. Motivated by the desire to find peaceful applications for atomic energy, the Commission made important design decisions in cooperation with a commercial equipment designer (Ziegler and others, 1967). Because the gage was to contain radioactive material, health, safety, and portability dictated the use of a weak source capable of penetrating only a few inches of river water. This restricted the design to a gage that would be mounted on a fixed support in a cross-section. The gage was intended for use mainly in remote ephemeral streams in which concentrations fluctuated rapidly. However, it could be used in large, perennial rivers where concentrations were low and stable. For good overall application, the gage's range was from 0 to 50,000 mg/L (milligrams per liter). The gage was designed to record data at short intervals in order to document rapidly changing concentrations; however, high speed operation was accompanied by large random errors.

Electronic circuits and components in the gage were very advanced for 1966, the year of design completion. The sensing circuitry measured a beam of radiation emitted from a Cadmium 109 source plated onto the head of a small screw. This isotope was used because (1) its short half-life (470 days) minimized potential danger from vandalism or rupture of the protective housing and (2) its emitted radiation of 22 kev (kiloelectron volts) was attenuated equally by most chemical elements in sediments. Extraneous radiation at 87 kev was emitted that needed to be screened by a special detector because only slight attenuation of the extraneous radiation occurred in water and sediment. Pulses from the detector were counted with transistor circuits, which were a relatively new innovation. Shifts in water temperature and gradual weakening of the source were compensated by switching the radiation beam between sediment-free water in a reference cell and sediment-laden river water. At the end of the measuring interval, data were transmitted to a small shore-based unit and printed for retrieval every seven-days. The system operated from either 120-volt AC power or from four 6-volt automobile batteries.

Random errors in the collected data became the subject of much theoretical study. These errors, which were caused by fluctuations in the radio-active beam, increased with system operating speed. At the slow speed setting (15 minute data-collection interval) the standard deviation of the random errors was 0.5 percent; at the high speed setting (3 minute interval) it was 1.3 percent. These percentages applied at a concentration of 30,600 mg/L, a level selected arbitrarily for comparison. Much larger errors occurred at lower concentrations. For example, at 1,000 mg/L and at the slow-speed setting, the standard deviation was 16 percent; at the high speed setting it was 35 percent. At concentrations smaller than 200 mg/L, errors at both speeds exceeded 100 percent.

Field tests at most sites were hampered by many problems. Failure of the proportional detectors caused by gas leaks in the ionization chambers occurred frequently. Failures in the counting circuits were probably caused by lightning or switching transients. Failure of the water seals were traced to damaged radiation windows or microscopic leaks in the bronze castings that housed the underwater components. In most cases, defective gages had to be shipped to the Project office for diagnosis and repair, but obtaining parts and permission to ship the radioactive material across state boundaries caused delays.

Despite operational problems, Welch and Allen (1973), obtained data on eight storms. Instead of relying on theoretical computations, they determined the measurement errors by comparing the concentration determined by the gage with the concentrations determined from physical samples. During any given storm, errors were related to concentration ranges. The smallest standard error was $\pm$ 172 mg/L and occurred during a storm when concentrations were nearly steady; the maximum concentration for the storm was only twice the minimum. The largest standard error was $\pm$ 1884 mg/L and occurred during a storm when concentrations peaked; the maximum sediment concentration was 30 times the minimum. Minimum sediment concentrations were about 1,000 mg/L during all eight storms. The researchers concluded that the principle of measuring sediment concentration by nuclear techniques was sound and feasible but that high costs of instrument purchase and maintenance, poor reliability, and poor sensitivity to low sediment concentrations were serious obstacles to routine use. They also felt the short half-life of the radioactive sources contributed to both high maintenance costs and low calibration stability.

Even though the operational record was discouraging, it taught several lessons in designing and operating automatic gages. First, physical samples should be collected as a means of correcting for drift (long-term instabilities) in gage output. Corrections can be derived by comparing lab analysis with gage recordings. Second, gages should be based on simple principles and should be easy to install and operate. Many of the failures and delays stemmed from the complexity of the isotope gage. Third, gages should be built of modules that can be easily replaced. Field personnel cannot be expected to diagnose complex problems and make complicated repairs in the field.

VIBRATING U-TUBE

Several years after completing work on the radioisotope gage, the Sedimentation Project focused on concentration measurements using mechanical instead of nuclear instruments. Sediments (rock fragments in this case) differ in density but studies supporting the radioisotope gage indicated most of these differences are less that $\pm$ 50 kg/m^3 (kilograms per cubic meter). If these variations are neglected, control volumes of water-sediment mixtures can be weighed and the data converted to sediment concentrations. The weighing device (Skinner and Beverage, 1982) consists of a U-shaped metal tube. The tube ends are held stationary by a heavy support, but the curved section is free to vibrate under the influence of an amplifier and two electric solenoids connected to form a feedback loop. The vibrational frequency of the tube depends on the weight of the material it holds. If concentration in the tube increases, frequency decreases; conversely, if concentration decreases, frequency increases. At field sites, one end of the tube is connected to a river-water sampling pump. Every five minutes, the average vibrational period (reciprocal of frequency) is transmitted through a telephone line to a central computer which converts the data to concentration values.

Errors in measuring sediment concentrations with the U-tube stem chiefly from external vibration, dissolved solids, unsteady temperatures and flow rates, and debris on the walls. These potential errors are minimized in various ways. External vibration is blocked by hanging the U-tube from springs; a conductivity probe in the water provides data to correct errors caused by dissolved solids; thermistors mounted in the flow provide data to correct errors caused by temperature changes; flow rates are regulated with a constant-head tank; and debris on the walls is scrubbed away during maintenance visits. Other measurement errors are related to the size of the sediment grains flowing through the U-tube. The instrument loses sensitivity as particle size increases; for example, sand concentrations must be about 25 percent higher than clay concentrations to produce the same output signal. Particle-size effects have been detected in laboratory experiments but have not created significant errors in field-site operations. However, errors caused by temperature changes have been more of a problem. If temperature is stable or changes slowly, vibrational-period shifts can be predicted accurately and can be compensated. If, however, temperature changes rapidly, vibrational instabilities develop and persist for about nine minutes. During this interval, accurate corrections for vibrational shifts cannot be estimated. If water temperature changes again during the nine minute interval, a new instability develops. In ephemeral streams, water temperatures undergo large changes that may persist during entire runoff events. In these streams, U-tube gages are applicable only if sediment concentrations exceed 2,000 mg/L so as to mask errors caused by temperature.

Laboratory tests show that if temperatures and particle-size distributions remain stable, errors caused by frequency shifts from unknown sources are a function of sediment concentration and particle size. For concentrations less that 500 mg/L, expected errors for clay suspensions are $\pm$ 15 mg/L and for coarse-sand suspensions errors are $\pm$ 25 mg/L. For concentrations between 500 and 86,000 mg/L (the highest concentration tested), expected errors for clay suspensions are $\pm$ 3 percent and for coarse- sands suspensions, $\pm$ 12 percent.

In addition to laboratory tests, two field tests have been completed. The first field test was conducted on Willow Creek near Madison, Wisconsin in 1984 (Skinner and others, 1986). The vibrating tube and electronic circuits performed reliably, but a peristaltic pump for transferring samples from the river failed several times. Despite these problems, about 10 hours of continuous records and 17 samples were obtained during one storm. A statistical analysis indicated expected errors in the record were about $\pm$ 25 mg/L and were independent of true concentrations obtained from physical samples collected at the pump discharge. This error is the smallest likely to occur under field conditions because water temperatures in the tests were unusually stable--fluctuations were less than 1 ^{o}C (degrees Celsius) during the entire storm. Sediment concentrations in the physical samples ranged from 25 mg/L to 950 mg/L.

The second field test began in 1986 on the Toutle River near Mount St. Helens. The instrument was operated for three years by the Hydrologic Surveillance Section of the Cascades Volcano Observatory. After several months of continuous operation, the heavy-duty submersible pump had to be replaced, but, with this exception, the equipment operated continuously with only brief interrup-

tions. Verbal reports from operating personnel indicated errors of about $\pm$ 200 mg/L, which were obtained by comparing the sediment concentrations of several hundred pumped samples with vibrational frequency records. Concentrations ranged from 700 mg/L to 22,000 mg/L.

VIBRATING STRAIGHT TUBE

The vibrating U-tube has significant head loss in the flow path through the tube and is hampered by poor temperature-response characteristics. These factors contribute to another problem--high demand for electric power. Flow rates and instrument temperatures can be maintained at proper levels only by continuously running the river-sampling pump. As a result, the U-tube can be used only at sites served with electric power lines.

In an effort to achieve battery operation, the Project designed a gage that determines sediment concentration by measuring the influence of sediment concentration on the vibrational frequency of a straight rather than a curved tube (Skinner, 1989). The tube is mounted in a streamlined, watertight enclosure resembling a torpedo. The ends of the tube are open and clamped to the housing, but the center is free to vibrate under the influence of electric solenoids. Oscillations occur in the center with little or no movement at the ends. As with the U-tube, vibration rates are influenced by sediment concentrations. A pump is not required because the instrument is submerged and the pressure of the approaching flow maintains proper discharges through the tube.

Measurement errors are caused by temperature changes, dissolved solids, and debris on the tube walls. The gage is influenced only slightly by flow rates through the tube but, as if to offset this advantage, the gage is sensitive to depth of submergence. Reflected waves exert a strong influence on the gage when the housing is near the water surface or the channel bottom. Although the housing is heavy, about 50 Kg, it oscillates slightly in response to tube vibrations. These oscillations produce waves that radiate outward until reflected back by an obstacle. As the returning waves sweep over the housing, they either reinforce or partially cancel movement of the housing; the interaction depends on phasing between the motions. The reflected waves modulate the frequency at which the tube vibrates by altering the apparent stiffness of the tube's end supports. Reflected waves occurring in cables that suspend the instrument in the flow create particularly large errors.

Accuracy of the straight-tube instrument has been measured in a wooden tank in the laboratory as well as in a concrete lined diversion channel carrying flow from the Mississippi River at Minneapolis. Random errors in concentration measurements are about $\pm$ 1,000 mg/L. This value is nearly the same at all concentrations and is so large as to eliminate the straight-tube gage for routine field use; however, error reduction may be possible by using vibration resonators consisting of slender rods with weights fastened to their ends. Theoretically, a resonator fastened to each end of the tube will prevent vibrations from reaching the housing; however, this concept remains to be tested. Changing the tube walls is another problem because debris can be scrubbed free only if the instrument is above or slightly below the water surface.

PLUMMET

The plummet, a new experimental addition to automatic sediment gages, consists of a glass bulb suspended from a sensitive electronic balance by a thin wire. The bulb is suspended in the center of an upright section of pipe with an open top and a sealed bottom. When the pipe is pumped full of river water, sediment particles increase the density of the water-sediment mixture and thereby exert buoyant forces on the bulb. Concentration registers through its influence on the balance reading. The system functions much like a hydrometer (Orr and Dallavalle, 1959), but instead of manually collecting weight readings they are automatically recorded on an electronic data logger connected to the balance.

Operation of the plummet follows a simple pattern. After a water-sampling pump has filled the pipe, a recirculating pump mixes the suspension. The recirculating pump is then turned off and, after a 15 second delay to allow turbulent eddies to dissipate, the balance reading is recorded. Since the particles begin to settle as soon as the recirculating pump stops, the mixture density decreases and gradually approaches the density of sediment-free water. A temporal record of weights can be used to obtain not only total sediment concentrations but also coarse particle (sand size) concentrations. Timing constraints limit the size range of particles that can be analyzed. The plummet is submerged at 0.5 m (meters); therefore, particles smaller than about 60 μm (micrometers) fall too slowly to register before the next sample is pumped into the pipe.

Measurement errors are affected by particle size, dissolved solids, debris on the plummet surface, and temperature. The influence of particle size on measurement error is still under study; however, it is known that the shifts are small for distributions entirely within the clay-silt size range. Conductivity readings can be used to compensate for measurement errors caused by dissolved solids. Injections of a bleach solution retards bacterial growth and helps clean the bulb. Even though temperature interferes with the readings, the effects are small compared with those in the U- and straight-tube gages. Since the bulb is glass, expansion and contraction effects are slight. Even when temperature shifts occur rapidly, weight readings stabilize quickly and corrections can be computed from water-temperature readings. Random errors have been measured in laboratory experiments with particles smaller than 62 μm. For concentrations less than 1,000 mg/L, about half the random errors are less than $\pm$ 30 mg/L. To date, the plummet has been tested in the laboratory but not in the field.

CONCLUSIONS

Selecting an appropriate sediment concentration gage for a specific gaging application requires consideration of safety, accuracy, cost, reliability, and power. The radioisotope gage can be ruled out as a useful sediment concentration gage because of adverse features in all categories except power. Among the vibratory instruments, the straight-tube gage is too inaccurate for most applications. The U-tube gage has considerable potential, but its use is limited to sites having electric power. The plummet could be a useful sediment concentration gage because it is reasonably accurate and has good temperature-response characteristics.

REFERENCES

Flammer, G.H., 1962, Ultrasonic measurement of suspended sediment, Geological Survey bulletin 1141-A, U.S. Government Printing Office, p. 46.

Orr, Clyde, and Dallavalle, J.M., 1959, Sedimentation for Determination of Particle Size, Macmillan Co., N.Y. p. 60-66.

Skinner, J.V., 1984, Report FF measuring the surface area of sediment particles in a study of methods used in measurement and analysis of sediment loads in streams, U.S. Army Engineer District, St. Paul, p. 13-20.

Skinner, J.V., 1989, Report JJ, Model B sediment concentration gage: Factors influencing its readings and a formula for correcting its errors in a study of methods used in measurement and analysis of sediment loads in streams, U.S. Army Engineer District, St. Paul, p. 3-5.

Skinner, J.V., and Beverage, J.P., 1982, Report X, A fluid density gage for measuring suspended sediment concentration in a study of methods used in measurement and analysis of sediment loads in streams, U.S. Army Engineer District, St. Paul, p. 4-13.

Skinner, J.V., Beverage, J.P., and Goddard, G.L., 1986, Continuous measurement of suspended-sediment-concentration *in* Proceedings of the Fourth Federal Interagency Sedimentation Conference Subcommittee on Sedimentation, Interagency Advisory Committee on Water Data, v. 1, p. 29-39.

Szalona, J.J., 1984, Report CC, Test of an infrared light-emitting turbidimeter in a study of methods used in measurement and analysis of sediment loads in streams, U.S. Army Engineer District, St. Paul, p. 10-12.

Welch, N.H., and Allen, P.B., 1973, Field calibration and evaluation of a nuclear sediment gage, Water Resources Research, v. 9, no. 1, p. 154-158.

Ziegler, C.A., Papadopoulos, J., and Sellers, Bach, 1967, Radioisotope gage for monitoring suspended sediment in rivers and streams, International Journal of Applied Radiation and Isotopes, v. 18, p. 585-548.

MISSISSIPPI RIVER, CUBITS GAP, 2-D SEDIMENT STUDY

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ABSTRACT

A study was performed to evaluate several structural plans and channel modifications to reduce maintenance dredging in the Mississippi River from mile 0.0 to mile 4.0. During the spring high water in 1989, this reach experienced abnormally high shoaling rates. The study utilized the Corps TABS-2 suite of programs to analyze the complex hydrodynamic and sediment regimes that exist in this reach of the river. At the root of the 1989 problem was an increase in the flow distribution through Cubits Gap, one of several large distributaries in the Mississippi River Delta. This study evaluated this change and proposed solutions to return the flow to the previous distribution or mitigate its effects on the navigation channel. The study approach, verification procedures and results are presented and discussed as an example application for a complex numerical modeling problem.

INTRODUCTION

During the spring of 1989, Cubits gap, one of several large distributaries that form the Mississippi River Delta, experienced a large increase in flow over its historical capacity. Cubits gap is located at approximately mile 3.5 above the head of passes and some 23 miles above the Gulf outlet of the Mississippi River. The study area and vicinity are shown in Figure 1. The increase in flow diverted from the main navigation channel was troublesome in that it did not convey a proportionate amount of sediment with it. This resulted in a large shoal forming just downstream of the Gap. This shoal grew rapidly and encroached upon the navigation channel. At the peak of the depositional period, the shoal was growing at a rate of 20,000 cubic yards per day. This shoaling, in conjunction with normal shoaling experienced at high flows below this point on the river, created a serious challenge to keep the navigation channel open. The situation was further complicated when a Russian Freighter ran aground just below the Gap, enhancing shoaling and disturbing normal flow patterns which created additional navigational challenges in traversing this reach. At this point, the New Orleans District of the Corps of Engineers consulted with the Waterways Experiment Station (WES) Hydraulics Laboratory (HL) and asked that three solutions be evaluated.

PLANS EVALUATED

While three main plans were tested, there were several sub-features to one of the plans. The plans were; 1) to perform advance maintenance from mile 0.0 to 4.0 above the Head of Passes to a depth equivalent to -50 feet below the Mean Low Gulf (MLG). The project is typically maintained at an elevation of -48 MLG.

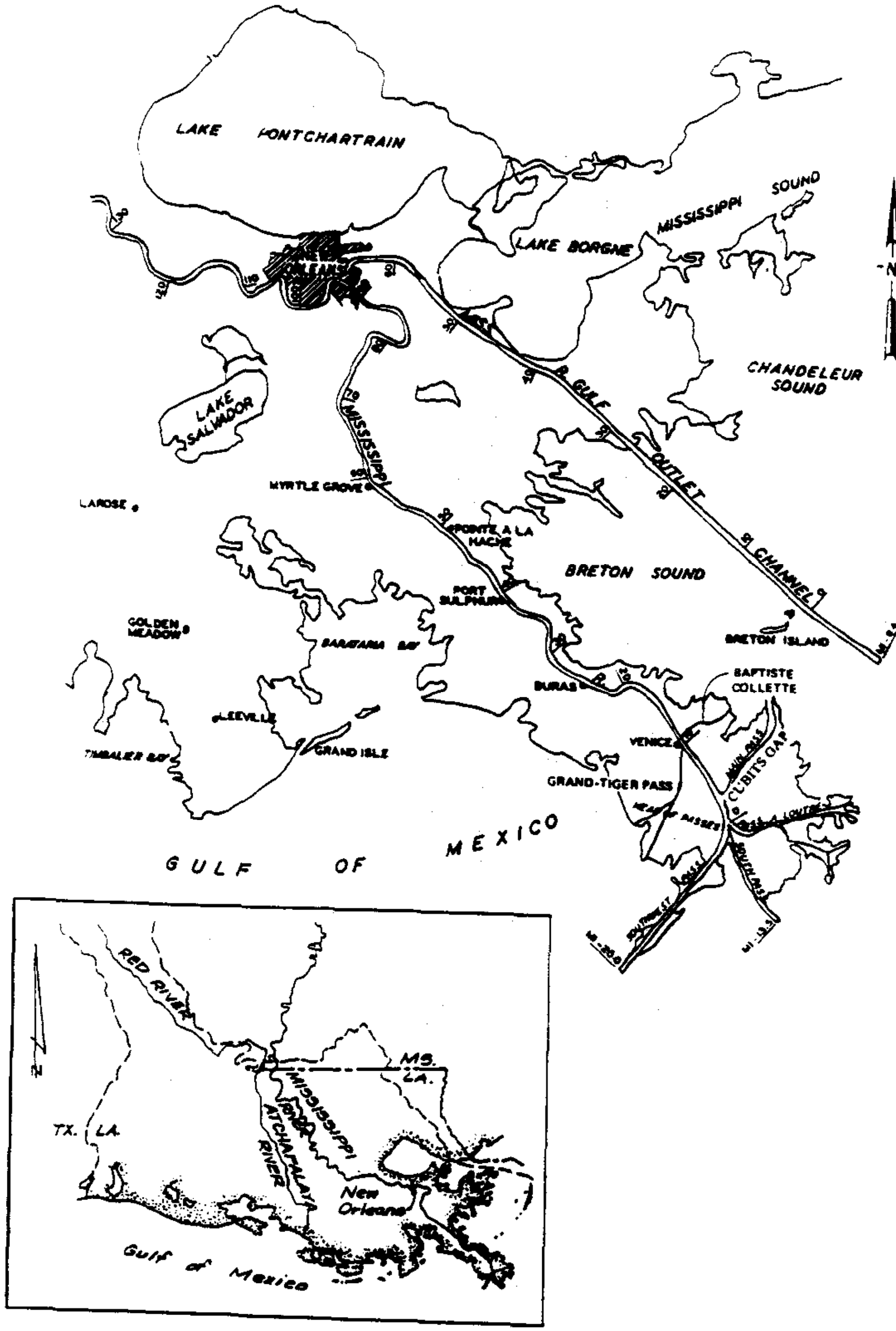

Figure 1. Location Map

2) Construct a sediment trap adjacent to the right descending edge of the channel. The trap would have a depth of -50 MLG, be 1000 feet wide and extend from mile 0.0 to mile 4.0 AHP. 3) Build a structural dike at Cubits gap to restore the percent of flow diverted to its historical level. For the dike plan, five geometries were evaluated. These consisted of upstream dikes angled at 90, 45 and 30 degrees normal to the flow in a downstream direction and a downstream headland structure parallel to the direction of flow. All plans tested are shown in Figure 2. The 90 and 45 Degree dike plans were rejected early on as they created circulation disturbances that extended into the navigation channel and did not seem to limit flow through the gap as desired. The 30 degree plan was refined by shortening the 2800 foot angle dike and removing the 800 foot headland dike, in various combinations. Their designations and features are tabulated below.

PLAN	CUBITS GAP DIKES	CHANNEL MODIFICATIONS
Existing Condition	None	None (-48 MLG)
Advance Maintenance	None	Deepen to -50 MLG
Sediment Trap	None	None, trap to -50 MLG
90 Degree Dike	90 Degree lateral Headland Dike	None
45 Degree Dike	45 Degree lateral Headland Dike	None
30 Degree Plan 1	30 degree lateral Headland Dike	None
30 Degree Plan 2	30 Degree lateral No Headland dike	None
30 Degree Plan 3	30 Degree lateral shortened-No Headland Dike	None

THE MODEL

The TABS-2 system of numerical models (Thomas and McAnally, 1985) was used to evaluate the various plans. Previously, a large mesh that represented the entire Delta was constructed and used to study various plans of improvement. (Richards and Trawle, 1988). This mesh was used to generate boundary conditions for a detailed inset mesh that featured the plan features and higher resolution near Cubits Gap. These meshes are shown in Figures 3 and 4, respectively. The TABS System includes the hydrodynamic code, RMA-2V which is a finite element, 2-dimensional, depth averaged code that solves the Reynolds form of the Navier-Stokes equations for turbulent flow. The sediment transport was calculated with the STUDH code, which used the Ackers-White (1973) procedure to

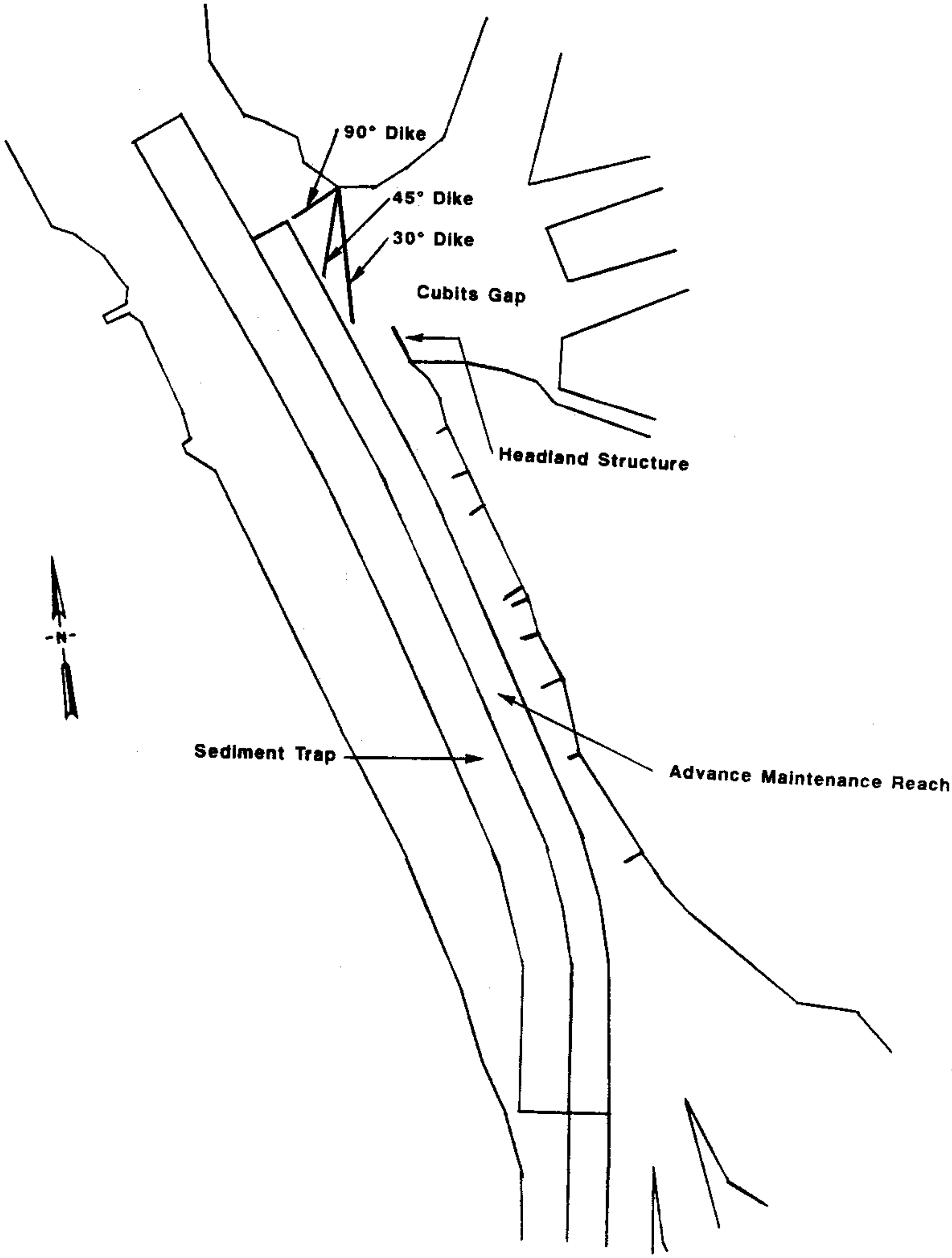

Figure 2. Schematic of All Tested Plans

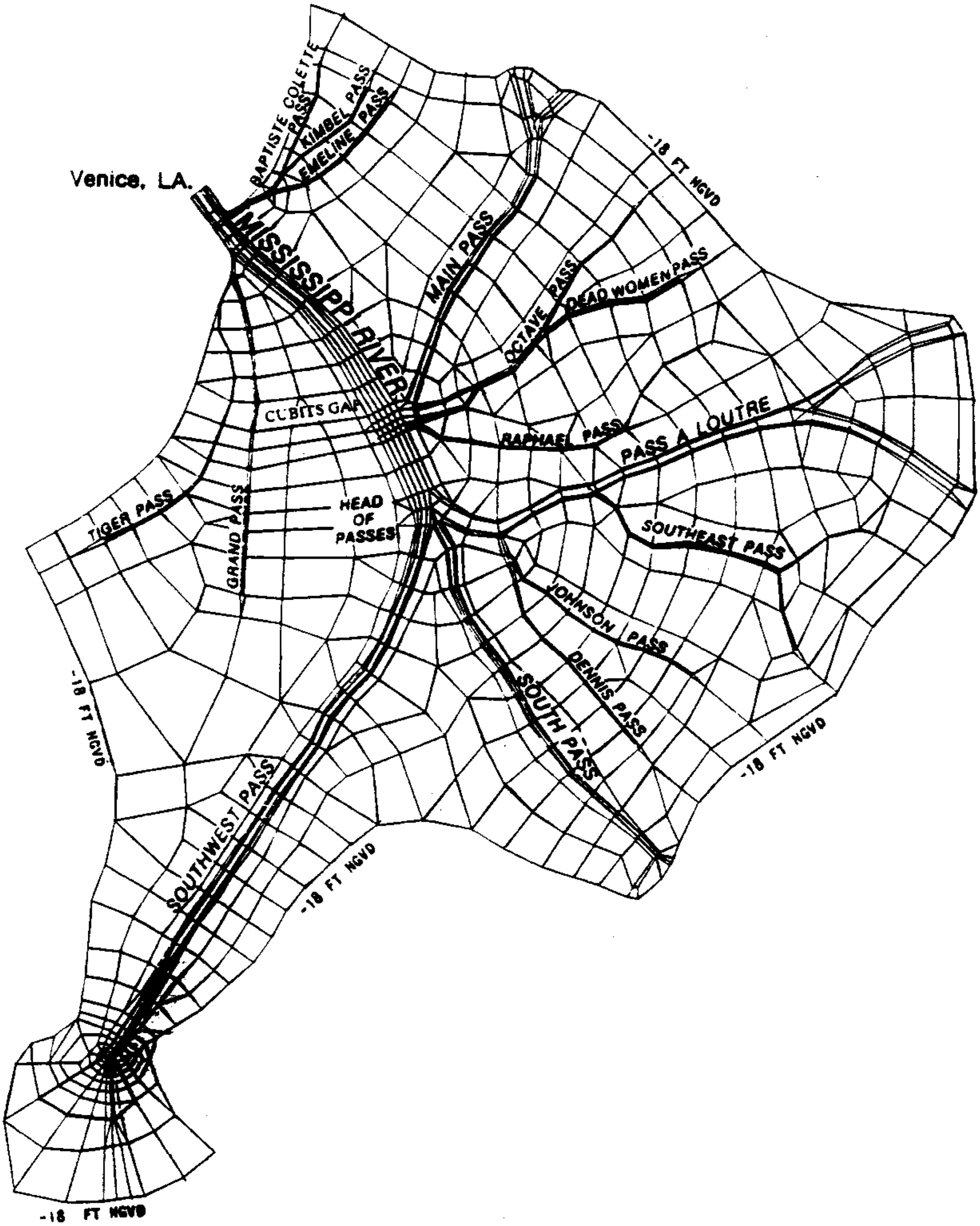

Figure 3. Full Delta Numerical Mesh

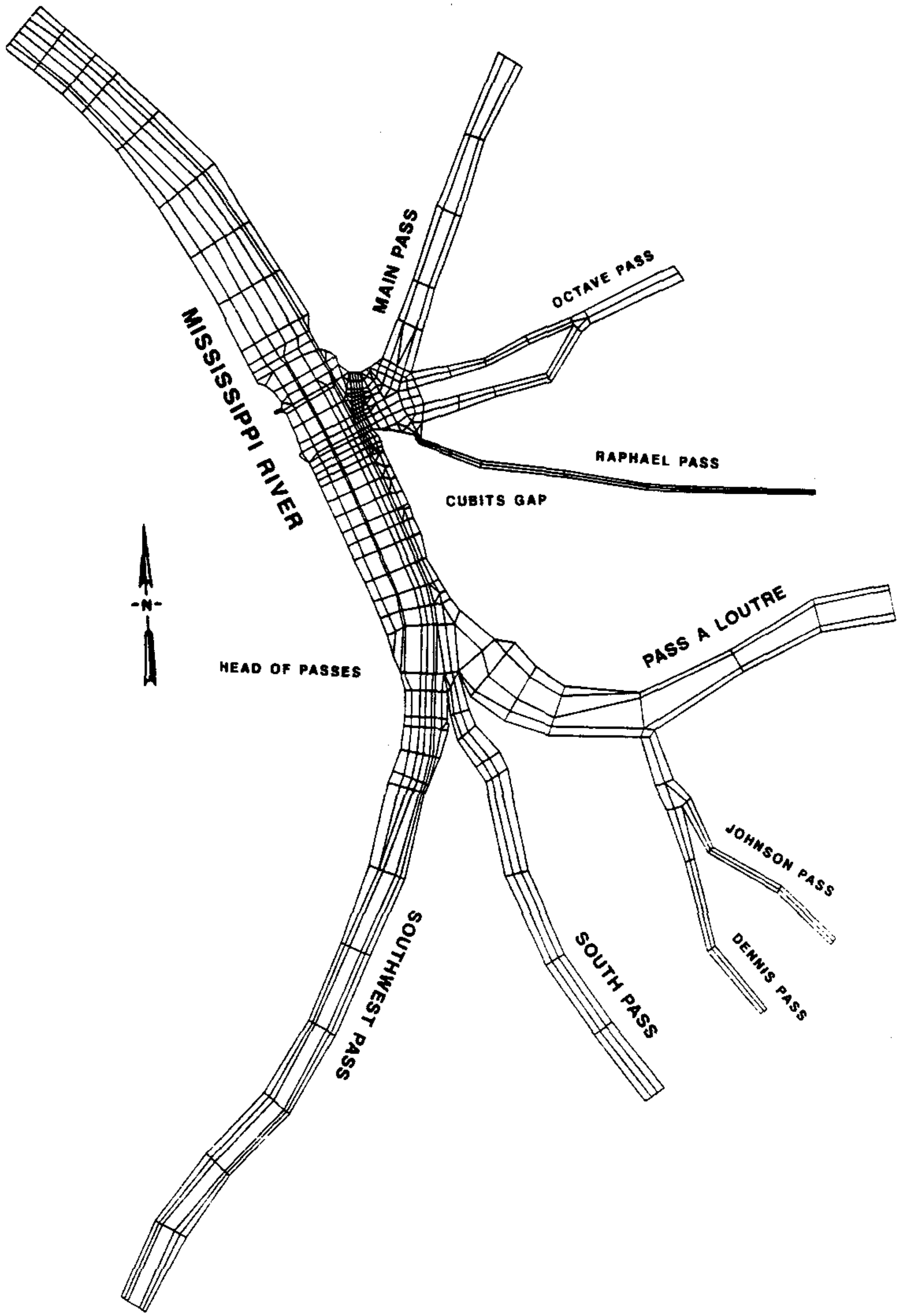

Figure 4. Cubits Gap Inset Numerical Mesh

calculate a sediment transport potential for the sands from which the actual transport is based on availability. Silts and Clays existed primarily as wash load in the study reach and were not included in the model analysis.

Verification

Both the hydrodynamic and sediment transport codes were verified by reproducing field measurements. The hydro code was initialized with the geometry and flows for May 2, 1989. Adjustments were made to the variable parameters until it accurately reproduced measured velocities in the main navigation channel and the sub-channels of Cubits Gap. The RMA-2V model was then used to reproduce the actual flood hydrograph of the Spring, 1989 observed flows from February 7th to May 4th. This became the input to the STUDH sediment transport code. The STUDH code, with RMA-2V hydro input and measured sediment data was run until the volume of deposition in the study reach duplicated that actually experienced during the time period corresponding to the flood hydrograph. This volumetric verification was within 2 percent of the measured values. Areal deposition was also checked where data were available and the model was found to be duplicating the measured data quite accurately. At this point the model was deemed verified and was used to evaluate the various plans.

Results

Both the Advance Maintenance and Sediment Trap Plans were found to induce shoaling beyond the volume experienced under existing conditions. Additionally, they provided little or no improvement in maintaining the authorized navigation channel. The 90 and 45 Degree dike plans were also rejected as not materially improving the hydrodynamic conditions in the vicinity of Cubits Gap. These plans were not further analyzed for sediment results. The 30 Degree Dike Plans all provided both less shoaling and longer periods of authorized navigation depth compared to the existing condition. These plans were also considerably cheaper than the channel modification plans on an annual basis. The volumetric results are shown in the tabulation below.

CONDITION	VOLUME OF SHOALING, CUBIC YARDS
Actual Dredged Volume Existing Condition	2,760,000
Model Verification	2,810,000
Advance Maintenance	3,880,000
Sediment Trap	4,280,000
30 Degree Dike Plan 1	1,350,000
30 Degree Dike Plan 2	1,950,000
30 Degree Dike Plan 3	2,310,000

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REFERENCES

Ackers, P. and White, W. R. 1973. (Nov) "Sediment Transport: New Approach and Analysis," Journal, Hydraulics Division, American Society of Civil Engineers. No. HY-11.

Richards, D. R. and Trawle, M. J., 1988. A Numerical Model Analysis of Mississippi River Passes Navigation Channel Improvements, Report 2, 45-Foot Channel Tests and Flow Diversion Schemes. Miscellaneous Paper HL-87-2, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Thomas, W. A., and McAnally, W. H., Jr. 1985 (AUG). "User's Manual for the Generalized Computer Program System: Open-Channel Flow and Sedimentation, TABS-2, Main Text and Appendices A through O," Instruction Report HL-85-1, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

SYSTEMATIC SAMPLING FOR SUSPENDED SEDIMENT

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ABSTRACT

Because of high costs or complex logistics, scientific populations cannot be measured entirely and must be sampled. Accepted scientific practice holds that sample selection be based on statistical principles to assure objectivity when estimating totals and variances. Probability sampling--obtaining samples with known probabilities--is the only method that assures these results. However, probability sampling is seldom combined with appropriate estimators to determine suspended sediment loads. Many current load-estimating methods, therefore, have unknown bias and variation making the estimates questionable.

Suspended sediment loads are often estimated by sampling concentration at fixed intervals. This type of sampling is promoted by the widespread use of pumping samplers which can be set to sample at regular intervals. Sampling intensity is sometimes increased during periods of high water discharge.

Randomly started systematic samples are probability samples, and estimates of totals from such samples are unbiased. These estimates tend to have low variance, but the variance cannot be *estimated,* and is not always reduced by increasing sample size. Systematic sampling of concentration distributes data evenly over time, so that most measurements are collected during low flows, and few during the brief high-flow periods when most sediment is transported.

Systematic sampling for estimating suspended sediment loads is investigated for a "complete" sediment record from the Mad River in northern California. The "true" total for the 31-day period is compared to expected estimates from systematic samples without random starts. Systematic sample variance is compared to three other finite sampling schemes and to estimates using the simple random sampling variance formula. The effects of changing systematic sample size are also studied.

If systematic sampling is used to estimate suspended sediment loads, the limitations of the method should be realized and correct estimating formulas used. The best use for systematic "sampling" is to define the sampled population for further sampling by more efficient finite sampling schemes.

INTRODUCTION

Fixed-Interval Sampling

Widespread use of pumping samplers promotes collection of suspended sediment data at regular time intervals. Although ease of data collection must be considered, the dictation of sampling method by technology (or logistical convenience) may result in distorted and misleading estimates and comparisons.

Sampling Suspended Sediment Data

Two factors should guide sampling of suspended sediment populations. One is the difficulty and cost of collecting and processing specimens, which dictates that samples be small. ("Specimen" refers to a bottle of water/sediment, and "sample" indicates a collection of specimens.) A second factor is that most sediment flux occurs during rare and brief periods of high flow. Such "sporadic" populations of suspended sediment are best sampled by emphasizing periods of high sediment flux. Fixed-interval samples do the opposite by spreading specimens evenly over the entire population.

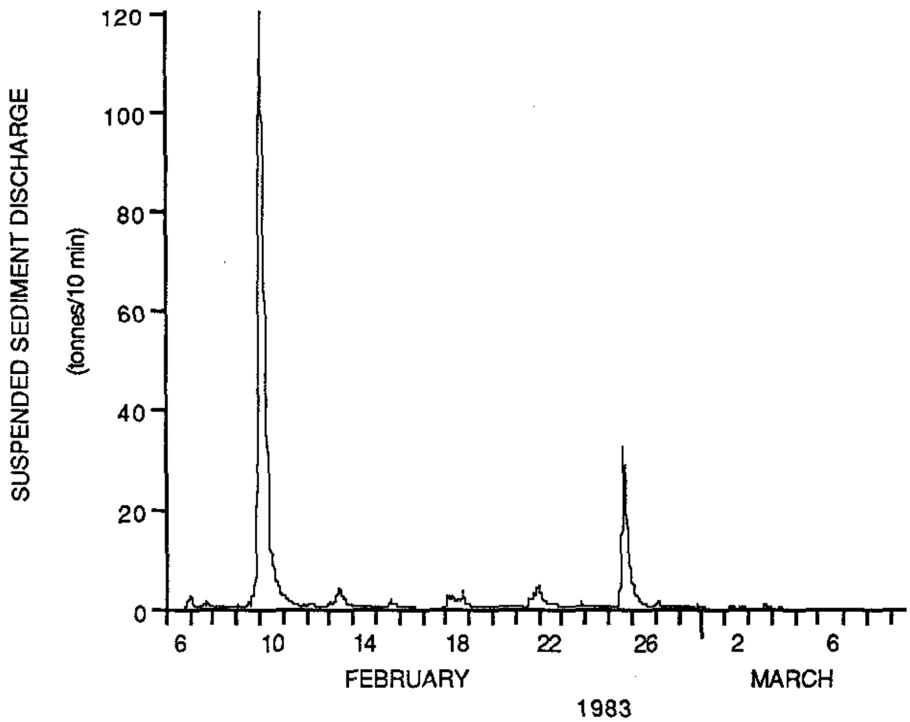

Figure 1- *Sedigraph of a 31-day period from water year 1983 at the North Fork of the Mad River near Korbel, California. Suspended sediment yields were calculated for 10-minute periods.*

Study Data

Data used in this study were taken from the North Fork of the Mad River near Korbel in northern California (Figure 1). Turbidity was continuously monitored for a 31-day period in 1983, and a good relationship found between turbidity and suspended sediment concentration. This relationship was used to predict the suspended sediment loads for 4450 10-minute intervals. This large finite data set is assumed to be the "true" population for sampling purposes; it was used for computing totals and variances for several sampling schemes and calculating the "true" suspended sediment load for the period.

ESTIMATING LOADS WITH FIXED-INTERVAL DATA

Sediment rating curves are commonly used to estimate suspended sediment loads, regardless of the method of data collection. Rating curves model the logarithm of sediment response as a linear function of the logarithm of the simultaneous water discharge. This model can give highly biased estimates, especially for small streams (Walling, 1977a; 1977b; Walling and Webb, 1981). Ferguson (1986, 1987) suggested applying a correction for bias caused by the logarithmic transformation, but this method is not always satisfactory (Thomas, 1985; Walling and Webb, 1988). Thomas (1988) found that uncorrected and corrected rating-curve estimates using fixed-interval samples of 50 units from the Mad River data were biased. Also, a rating curve of the entire population gave an estimate of population total which was biased about the same as that for the samples. Therefore, rating curves are problematic, and should only be used where the hydrologist is certain that the model fits well.

Time series analysis requires fixed interval data to estimate total suspended load. Transfer function models have been used with fixed-interval data with good success (Gurnell and Fenn, 1984). Time series analysis accounts for the *serial correlation* usually present in closely spaced sequential data. Aside from the complexity of time series analyses, the generally sporadic nature of sediment flux makes it difficult to collect adequate information without frequent samples and consequent high cost. When such expenditures are justified, time series analyses provide information on patterns of sediment flux above that required for estimating suspended sediment loads.

Other techniques for estimating totals of *finite* populations are based on survey sampling theory. These methods are appropriate when the population is finite or when a reasonable finite *sampling population* (the population actually sampled) can be formed from the *target population* (the population of interest). A finite sampling population can be formed from a period of continuous sediment discharge by dividing the period into short equal-length time intervals. The interval length is chosen so that water discharge and sediment concentration measurements made at the midpoint reasonably represent the continuous sediment flux for each interval. This method uses fixed-interval "sampling" to form a finite sampled population from a continuous one.

Sample inferences apply to sampled and not target populations. Therefore, these populations must be similar in essential details, a condition usually based on judgement. The sampled and target populations of sediment flux are logically similar if the sample intervals are "short."

Survey sampling methods can often take advantage of any knowledge of the population to reduce sample size or variance. The fact that most sediment flux is delivered during periods of high water discharge can be used in several ways to obtain higher quality estimates with greater sampling efficiency.

SYSTEMATIC SAMPLING

In survey sampling theory, fixed-interval samples are called *systematic* samples. Consider a sequential population with $kn+c$ ($0 \leq c < k$) units. A systematic sample includes one of the first k units chosen at random, and every unit at intervals of k after the first. Each of the k possible samples is, in effect, a *cluster* of n or $n+1$ units that covers the population in a regular way. Systematic sampling is often used because it is easy to apply.

Clearly, composition of a systematic sample depends on which of the first k population units is selected at random and on population order. If the population is randomly ordered, each sample will be random. Such data can be treated as independent samples for estimation purposes. Suspended sediment discharges tend not to be random, however, at least when measured intervals are short enough to adequately define the process. Therefore, simple random sampling estimators should not be used with systematic samples of suspended sediment data unless serial correlation is negligible.

Randomly started systematic samples are probability samples (regardless of population order) and the estimates of totals are unbiased. If the ith suspended sediment load for the jth interval is given by y_{ij}, an unbiased estimator for total load during the sampled period is

$$\hat{Y} = k \sum_{i} y_{ij} \tag{1}$$

(Raj, 1968). Since each cluster covers the population evenly, these estimates tend to have low variance, but the variance cannot be estimated for the usual single-cluster systematic sample. Also, controlling the variance by changing sample size is dependent on the order of units in the population. In some cases increasing n actually *increases* the variance. Population order does not affect properties of the estimators for other forms of probability sampling in which larger sample sizes produce reduced variance.

SYSTEMATIC SAMPLES WITH AND WITHOUT RANDOM STARTS

Starting times for pumping sampler collection of concentration data usually depend on administrative and weather-related factors. In non-storm periods data collection intervals are long and starting times based on administrative convenience. Such data sets may be best from one statistical standpoint; long intervals can result in independence among the measurements so they can reasonably be treated as simple random samples for estimating totals and variances. However, during low flows, suspended sediment discharge is also low, and the contribution to the overall total and variance is small.

Sampling intervals can be shortened for higher flow periods, generally in response to existing or expected weather or stream conditions. It is reasonable to assume that storms from large frontal disturbances arrive at random times, but the interaction of work schedules and the logistics of getting to stations to start or change sampling programs may still produce nonrandom starts. Logistical and administrative restrictions are real, but they can be surmounted to ensure random starts for systematic samples. Pumping samplers not only have clocks to sample at preset intervals, but they also have time delays that can be used to initiate sampling at random times.

The sampled population is first specified by defining its units. Units are short time-intervals in the monitored period that can be characterized by one water discharge and suspended sediment measurement at mid-interval. Interval length depends on response time of the river; large rivers that react slowly to storm inputs might have units of several hours, while small flashy streams may have units of five to ten minutes. A criterion for suitable interval lengths is confidence that if *all* intervals could be measured, the resulting total would be the same as that for the continuous target population. It is best to err by selecting the intervals too short, especially since that does not greatly increase the sample size required.

In "ideal" systematic sampling the sampled population size, N, is determined by dividing the monitoring time by the sampling-unit duration. The sample size, n, is then chosen and k found by dividing N by n. If N is not an exact multiple of n, some samples are of size n and others are of size $n+1$. For sampling suspended sediment, however, n is usually set by the number of bottles in a pumping sampler and N by some vague limit imposed by costs of laboratory processing. Usually, no provision is made for samples of different size, so, implicitly, kn equals N exactly (i.e., $c=0$).

If an 18-hour period with 10-minute sampling units is to be sampled with a 24-bottle pumping sampler, there are 108 sampling units which cannot be divided evenly by 24. The sampling interval, k, can be chosen as 4 or 5 implying that N is 16 or 20 hours instead of the nominal 18. In either case, a value from 1 to k is chosen at random, and the first pumped sample taken at that time.

The effects of not randomizing over all possible starting times are shown for samples of size 62 (an average of 2 per day) for the Mad River data. Consider restricting starting times to any four-hour period in the k=71 (4450=71*62+48) starting times. There are 48 such four-hour periods from the beginning to eight hours into the record. Random samples in the four-hour periods give expected totals which are plotted against the first interval numbers of the periods (Figure 2). The expected values are generally biased, ranging from about 6750 to over 10,500 tonnes compared to the "true" load of 8307 tonnes.

In this case, if the samples were randomized within the four-hour period beginning at the 20th interval into the record, the expected total would be nearly unbiased. However, the shape of this curve and the point of crossing the true total are dependent on the ordering of units in the population, which is not known, even after the sample is collected. Generally, not enough is known about specific populations to ensure unbiased estimates of total loads using systematic sampling unless starting times are randomly selected over all possible samples.

VARIANCES FOR SEVERAL FINITE SAMPLING PLANS

Sampling plans should be chosen for performance characteristics as well as for ease of application. The performance of finite sampling schemes is measured primarily by bias and variance. Unbiased estimators produce distributions of estimates having expected values equal to the parameters being estimated. Most finite sampling schemes have little or no bias, so the main interest is in methods with minimum variance. Lower variance gives parameter estimates with smaller errors, better sensitivity for detecting differences, or reduced sample size. We now compare the variance of systematic sampling to several other finite sampling schemes suitable for measuring suspended sediment loads.

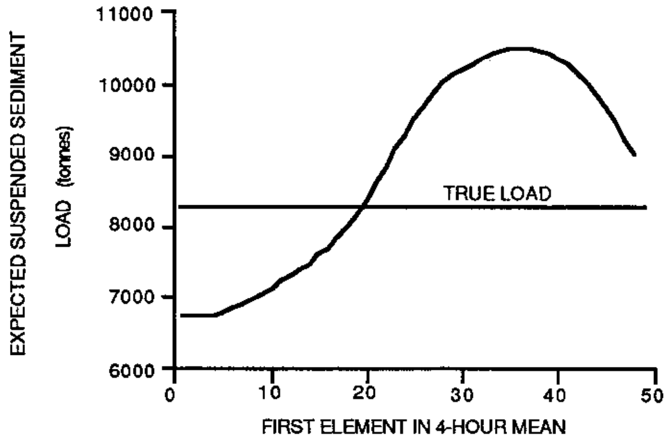

Figure 2 - *Expected suspended sediment loads for systematic samples of size 62 from the Mad River data. Values were computed by restricting random starts to 4-hour periods starting from the beginning to 8 hours into the record.*

There are formulas to calculate "true" variances for all finite sampling plans, but they depend on knowing the complete population. Since the entire Mad River sample population is known for the 31-day record, the "true" variance of systematic sampling can be calculated even though the variance cannot be *estimated* from a sample.

Systematic sampling was compared to simple random sampling (SRS), stratified random sampling (STRS), and selection at list time sampling (SALT), each sample having 62 observations (Figure 3). SRS was used as a benchmark method because it is the most fundamental finite sampling plan. SRS is not recommended for suspended sediment populations because, like systematic sampling, it does not emphasize periods that produce most sediment flux. Even though SRS estimates of the total and its variance are unbiased, its precision is inferior to that for systematic sampling for the Mad River population as measured by the standard error of the total. This result is expected since systematic samples always have at least some measurements during high-flow periods, while SRS measurements during those periods are due to chance.

Calculating "variance" from *systematic samples* using the *SRS variance formula* illustrates the effects of not using the correct estimators for given sampling schemes. The estimated standard error of systematic samples using SRS formulas averages about 3 times the true standard error, and is nearly equal to that for real SRS samples. Even though systematic sampling in this case is far superior to SRS, its variance is greatly overestimated by the SRS variance formula. This emphasizes the need to match sampling plans and estimators.

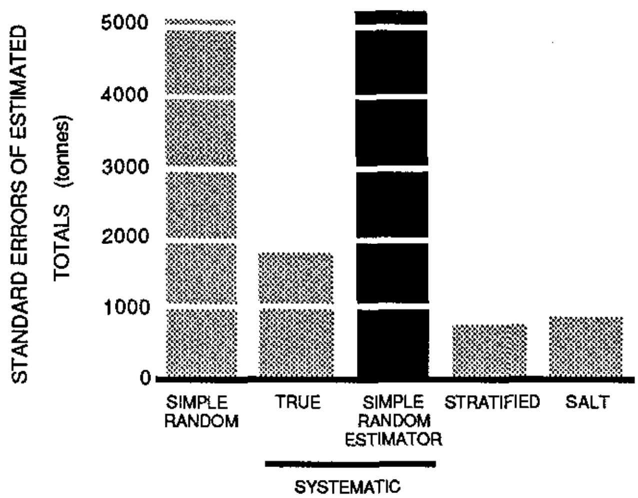

Figure 3 - *Comparison of sampling standard errors for five estimators of suspended sediment load for the Mad River data. All values are "true" standard errors calculated from the population for samples of size 62. The dark bar shows the mean standard error obtained from using the simple random sampling estimator with systematic samples.*

STRS is widely used to reduce variance. If populations can be divided into homogeneous strata and separate SRS samples are taken in each stratum, unbiased estimates having lower variance are usually obtained. The Mad River record was divided into 11 strata based on 3 stage classes separated at 1.2 and 1.8 meters. The 62 observations were optimally allocated to the strata by Neyman's method (Cochran, 1963). The results reduce the standard error of the total to 41% of that for systematic sampling.

The SALT sampling scheme also uses knowledge of population structure to reduce variance (Thomas, 1985). It is a variable probability scheme relying on a function of stage to make real-time decisions to enhance sampling probabilities during periods of high discharge. SALT samples of 62 specimens using a sediment rating curve of 100 water discharge/concentration pairs collected before the 31-day period give a standard error of estimate of about 845 tonnes. Again, this is an improvement over systematic sampling and is superior to SRS.

These comparisons are illustrative; the magnitudes, both relative and absolute, may not be uniform for all situations. This is especially true for the STRS and SALT schemes. The performance of those methods is heavily dependent on how the population is partitioned and how well sediment concentration can be predicted by stage. There are other ways to optimize both the STRS and SALT schemes, however, so these methods are likely to have lower variances than either systematic or SRS methods for most situations.

THE EFFECTS OF SAMPLE SIZE ON SYSTEMATIC SAMPLING VARIANCE

We now focus on the effects of changing sample size on the variance of systematic samples. As noted, the true variance of systematic sampling does not always respond as expected to changes in sample size. To see this for the Mad River data, the "true" sampling variances were plotted for 400 values of k (Figure 4). Values of k were used instead of n because k does not always divide N evenly so that n may not be unique, especially for large values of k. Lower values of k are essentially inversely proportional to those of n.

For these data, smaller values of k mean that the variance *generally* drops. Locally, however, reducing k can result in increased variance. For example,

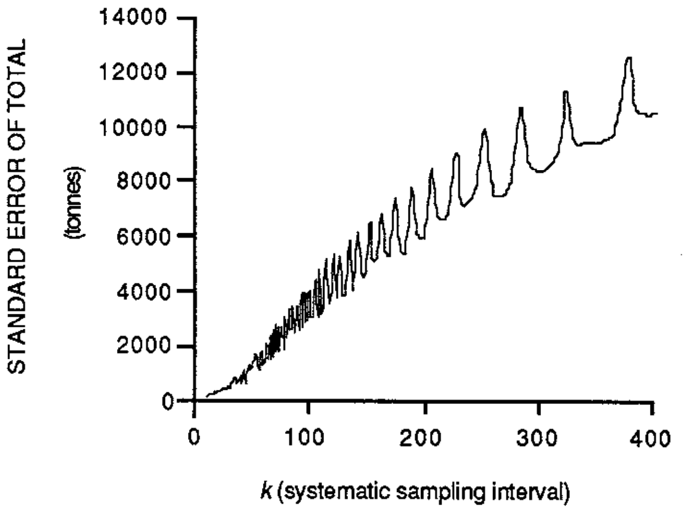

Figure 4 - *Standard errors for estimates of suspended sediment load using systematic sampling for sampling intervals,* k, *from 1 to 400 (*n *equals 4450 to 11). The "true" standard errors were calculated from the Mad River population.*

increasing the sample size 12 percent from 58 to 65 *increases* the standard error about 47 percent. The global pattern is expected; as k drops (and n increases), sampling variation must fall as n approaches the entire population (when $k=1$, $n=N$, and equation 1 is just the population total). Also, changes in the standard error are smaller as n becomes larger. Local behavior is more complex and depends on the interaction of the "grid" spacing of the systematic sample with the patterns in the particular record of suspended sediment flux. This behavior depends on the specific circumstances and cannot be predicted unless the complete population is known. Therefore, it is difficult to select the sample size for specified performance of general systematic schemes.

Some patterns of sequential populations produce more predictable relationships between systematic sample size and variance. If a population correlogram is concave upward, increased sample size always results in lower variance (Cochran, 1946). The correlogram for the Mad River data was concave upward over only part of its range, however, so this result does not hold (Figure 4).

A finite sampled population of sediment flux taken at short equal intervals from a continuous sedigraph is really a systematic "sample" of the target population. It has a logically similar total to the continuous target population, and the generally low variance of closely-spaced systematic samples supports using this method to define sampled populations. This kind of systematic sample can therefore be used to define the sampled population of suspended sediment discharge which can in turn be sampled by more efficient finite population schemes.

SUMMARY

Fixed-interval or systematic samples are widely used to collect data to estimate suspended sediment loads; a fact partly due to the convenience of pumping samplers. Systematic samples are inefficient, however, since evenly spaced sampling conflicts with the sporadic nature of suspended sediment populations. Several factors should guide the use of systematic sampling for estimating suspended sediment loads:

- Systematic samples with random starts give unbiased estimates of total loads.

- Variances of these estimates are generally low, but cannot be estimated from samples.

- Variances of systematic samples do not always drop with increased sample size.

- Stratified and variable probability sampling schemes are more efficient for sampling suspended sediment populations.

- Systematic "sampling" is best used for defining sampled populations for sampling by other finite population sampling schemes.

REFERENCES

Cochran, W.G., 1946, Relative accuracy of systematic and stratified random samples for a certain class of populations. Annals of Mathematical Statistics, 17, 164-177.

Cochran, W.G., 1963, Sampling techniques. Wiley and Sons, New York, pp. 413.

Ferguson, R.I., 1986, River loads underestimated by rating curves. Water Resour. Res., 22, 74-76.

Ferguson, R.I., 1987, Accuracy and precision of methods for estimating river loads. Earth Surf. Processes and Landforms, 12, 95-104.

Gurnell, A.M., and Fenn, C.R., 1984, Box-Jenkins transfer function models applied to suspended sediment concentration-discharge relationships in a proglacial stream. Arctic and Alpine Res., 16, 93-106.

Raj, D., 1968, Sampling Theory. McGraw-Hill, New York, pp. 302.

Thomas, R.B., 1985, Estimating total suspended yield with probability sampling. Water Resour. Res., 21, 1381-1388.

Thomas, R.B., 1988, Monitoring baseline suspended sediment in forested basins: the effects of sampling on suspended sediment rating curves. Hyd. Sciences Jour., 33, 499-514.

Walling, D.E., 1977a, Assessing the accuracy of suspended sediment rating curves for a small basin. Water Resour. Res., 13, 531-538.

Walling, D.E., 1977b, Limitations of the rating-curve technique for estimating suspended sediment loads, with particular reference to British rivers. In: Erosion and Solid Matter Transport in Inland Waters (Proc. Paris Symp., July 1977), 34-38. IAHS Publ. no. 122.

Walling, D.E., and Webb, B.W., 1981, The reliability of suspended sediment load data. In: Erosion and Transport Measurement (Proc. Florence Symp., June 1981), 177-194. IAHS Publ. no. 133.

Walling, D.E., and Webb, B.W., 1988, The reliability of rating-curve estimates of suspended sediment load: some further comments. In: Sediment Budgets (Proc. Porto Alegre Symp., December 1988), 337-350. IAHS Publ. no. 174.

ACQUIRING SOIL CONCENTRATION AND PARTICLE SIZE

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INTRODUCTION

Suspended sediment is the largest contributor by both volume and weight of nonpoint source (NPS) pollution in the United States (Ray, 1982). The EPA (1977) estimated that 81 percent of all basins in the U.S. are affected by NPS pollutants. Construction sites cause the most concentrated form of NPS pollution, increasing soil erosion from 2 to 4000 percent compared to pre-construction amounts (Wolman, 1967). Runoff from agricultural land does not contribute the most sediment per unit area, but because of the immense area involved (an estimated 194 million hectares in the United States), it produces more suspended sediment overall than any other source (Wischmeier, 1976).

Tollner and Hayes (1986) indicate that non-invasive particle sizing devices need to be developed to obtain proper modeling parameters for soil aggregates found in natural runoff. Rhoton and Meyer (1987) indicate that sediment size is of paramount importance in controlling sediment transport and deposition, but the time-consuming and expensive methods now employed for particle size determination in field runoff limit data availability. Cooper et al. (1984) indicate that new systems capable of nondestructively analyzing many samples rapidly would provide needed information about aggregate interaction in the soil erosion process.

Theory necessary for development of an alternative method for characterizing sediment concentration and particle size distribution was investigated. Appropriate theoretical concepts were implemented to design and develop the Vortical Particle Size Distribution System (VPSDS). Current technologies in opto-electronics, computer data acquisition, fluid dynamics, and natural resources engineering were incorporated in the final design.

OBJECTIVES

The objectives for this project were to:

1. develop methodology for determining particle size distribution and concentration parameters of soil-water mixtures occurring in nature,
2. construct necessary apparatus for implementing this methodology, and
3. evaluate performance and potential of this apparatus as an alternative method of particle size and concentration determination.

METHODOLOGY

According to work by Taylor (1950) and Cooke (1952) describing the fluid flow in swirl atomizers, soil particles move up the inclined surface of an inverted cone due to a secondary boundary layer flow. Since the tangential fluid velocity decreases as radial distance from the axis of rotation increases in a free vortex and the no-slip condition holds at the surface of the chamber, a pressure differential develops along the inner surface of the conical chamber. This promotes a secondary boundary layer flow upward perpendicular to the primary swirl. Due to the design of the VPSDS Vortex Chamber (VVC) and VPSDS Sensing Zone (VSZ), this secondary boundary flow forms a closed loop flow circuit within the VVC as shown in Figure 1. The VVC is similar in design to the swirl atomizer described by Taylor (1950) and Cooke (1952) with the axis of fluid rotation aligned with the gravitational vector (gR). Energy necessary for driving the secondary boundary layer flow circuit is supplied by the free vortex flow field, which receives its energy from the swirl mechanism located in the bottom of the chamber.

Soil particles in the bottom of the VVC move radially away from the axis of fluid rotation as a result of centrifugal force. As they come in contact with the inclined surface of the VVC, the secondary boundary layer flow circuit transports them upwards toward the discharge outlet of the VVC. If the potential and kinetic energies of a particle are overcome by the secondary flow, the particle will be discharged into the VSZ. If the boundary layer flow is not sufficient for particle transport, it returns to the bottom of the chamber where the process is repeated. This process allows particles with specific transport characteristics to be differentially transported into the VSZ.

VPSDS Sensing Zone (VSZ) Concepts

The tubing attached to the discharge outlet of the VVC is referred to as the VPSDS Sensing Zone. It serves two essential roles in the operation of the VPSDS. First, the parallel glass plates shown as the Sensing Zone in Figure 2 allow laser light to pass through the soil-water suspension in the VSZ. This facilitates electronic particle concentration measurement in the VSZ. Secondly, the VSZ provides a constant fluid head above the free vortex maintained inside the VVC. This prevents cavitation as impeller speed is increased.

Since the fluid in the VSZ is somewhat isolated from the swirling fluid flow in the VVC and is relatively static, it quickly dissipates velocity of particles discharged into the VSZ. Therefore the VSZ facilitates the closed loop secondary flow circuit which is the basis for operation of the VPSDS. As gravity and viscous drag reduce particle velocity, the particles move to the center of the VSZ where a low pressure core is maintained by the free vortex flow field inside the VVC. These particles are said to be in the "particle path transition zone" shown in Figure 1. Particles then move down the low pressure core and are forced back into the secondary boundary layer flow circuit. This process is maintained as long as impeller speed remains constant, providing a relatively stable supply of soil particles available for transport in the secondary boundary layer flow circuit.

Measurement Technique

Concentration of soil particles in the VSZ was monitored by passing a helium-neon laser beam through the suspension. The laser beam was split before entering the VSZ. The reference photodiode received laser light directly (unattenuated) from the splitting mirror, while the receptor photodiode received attenuated incident laser light that had passed through the VSZ. The reference and receptor photodiodes were connected to a logarithmic light detection circuit which had a voltage output

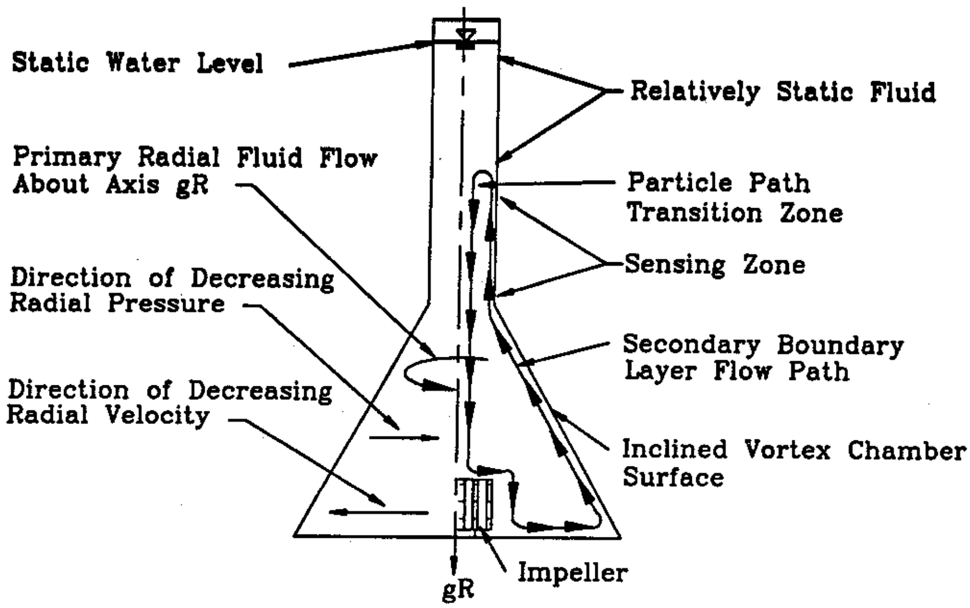

Figure 1. Conceptual flow paths in the VPSDS Vortex Chamber.

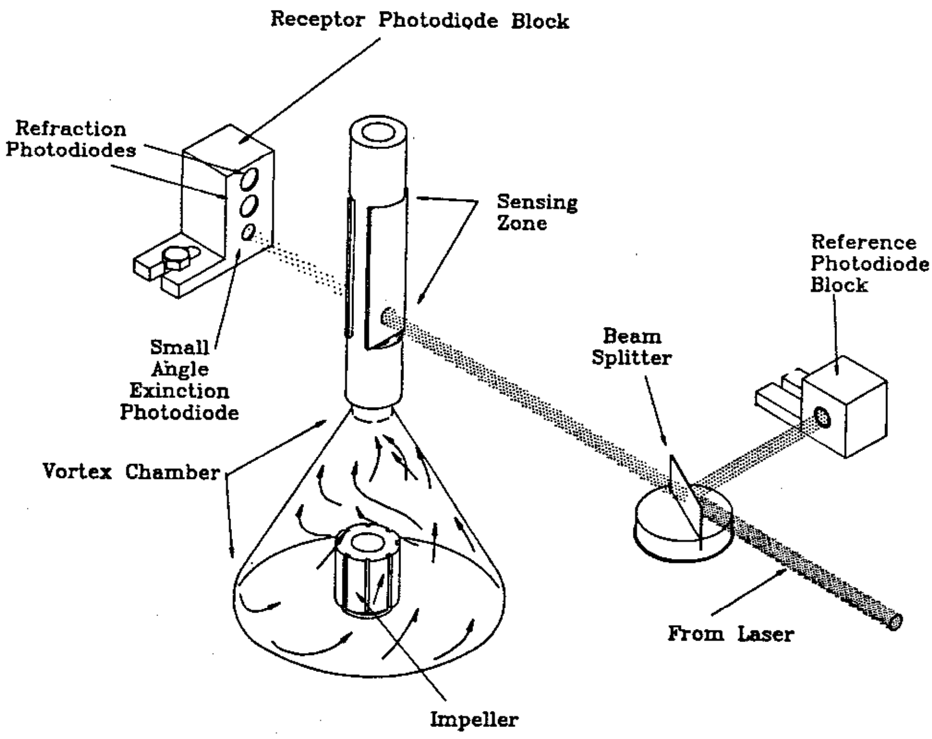

Figure 2. Three-dimensional view of laser light paths on upper base assembly of the VPSDS.

proportional to the logarithm of the input currents. This circuit measured light extinction. A Voltage Response Curve (VRC) was generated from the logarithmic light extinction circuit (LLEC) by increasing impeller speed. As impeller RPM increased, additional soil particles were discharged into the VSZ causing a proportional increase in voltage output from the LLEC. The VRC provides no direct information on the specific size of particles in the soil sample, but does provide a stepped relative size distribution of the sample.

APPARATUS

Mechanical design of the Vortical Particle Size Distribution System (VPSDS) was dictated by the VPSDS Vortex Chamber and the positioning of precise light detection systems. These constraints led to a prototype design that proved reliable in operation and delivered consistent data output. The VPSDS consisted of four basic sub-assemblies including (1) the lower base assembly, (2) the upper base assembly, (3) the VPSDS Vortex Chamber, and (4) the electronic circuitry module. The mechanical components of the VPSDS are shown in Figure 3 and will be briefly described.

The lower base assembly includes the drive motor, the motor support plate, the lower base plate, and the impeller assembly. A variable speed DC motor, with a maximum rotational speed of 2500 revolutions per minute (RPM), was regulated by analog signals originating from an IBM PC type digital to analog board. The motor controller was capable of maintaining shaft speed with no more than 2 percent variation at any selected output speed from 0 to 2500 RPM. A belt drive system was incorporated to power the impeller shaft.

The upper base assembly holds all light detection sensors and associated electronics. This unit provided a stable mounting surface for delicate light sensors. Assemblies included extinction photodiode assembly (receptor block), extinction reference block, adjustable mirror support block, beam splitter, laser with mirror end cap, adjustable mirror stem, and VPSDS circuitry enclosure. The photodiode blocks, mirror support block, beam splitter, and upper base plate were machined from aluminum. Two-dimensional adjustment capability allowed photodiode blocks to be accurately aligned with the laser beam. Three-dimensional direction control of the laser beam was achieved with an adjustable mirror mount. This facilitated targeting of the laser beam onto the small angle photodiode of the receptor block.

The class II helium-neon laser used on the VPSDS had a wavelength of 628.2 nanometers and a maximum output power of 0.9 milli-watts. Coherence of the laser was good due to the short travel distance (approximately 280 mm) of the upper base assembly. Laser light was directed onto the photodiodes using plano-convex lenses. They were mounted at a distance equal to their focal length from the photodiode's active surface. A mirror-type beam splitter with a 50:50 transmission to reflectivity ratio was used to split the laser light source.

The most important component of the VPSDS circuitry was the light extinction circuit. Currents from two separate photodiodes flow into the operational amplifier, which outputs a voltage proportional to the logarithm of the input currents. This voltage is proportional to the amount of light extinguished by soil particles. Matched photodiodes

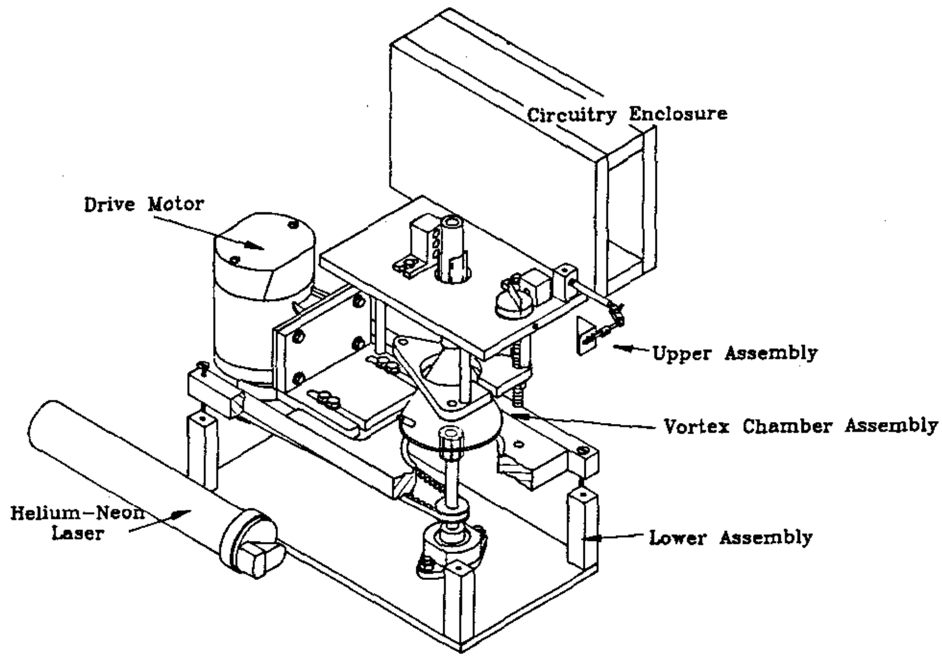

Figure 3. Exploded view of VPSDS sub-assemblies.

were selected such that voltage output magnitudes were essentially equal when identical amounts of light energy entered each photodiode. Two circuits measured the amount of light being refracted by soil particles in the VSZ. These circuits monitored only refracted light, since the incident laser beam was directed onto the small angle extinction photodiode of the receptor block as shown in Figure 2.

VPSDS DATA ACQUISITION AND CONTROL PROGRAM

Custom data acquisition and control programs were written to provide an interface that would allow inexperienced users to operate the VPSDS. Software incorporated pop-up menus and real-time display of incoming data and critical operating parameters of the VPSDS. Once a sample was positioned, automatic data collection proceeded via computer control.

An IBM XT compatible computer containing an analog to digital (A/D) and digital to analog converter (DAC) interface board was used to control the VPSDS. The interface board received incoming signals from refraction, light extinction, and the differential pressure circuits.

The control program used feedback information from the logarithmic light circuit to determine when particle concentration in the VSZ had stabilized between step speed increases of the impeller. Once particle concentration stabilized, samples were taken continuously for a time interval specified by the operator. At completion of the timed sampling interval, voltage values for each channel were averaged and stored in a data array. This resulted in 28 data points for each sample for impeller speeds ranging from 0 to 1920 RPM.

The data acquisition and control program recorded the Voltage Response Curve (VRC) from the logarithmic light extinction circuit. The VRCs indicated the relative concentration of particles in the VSZ as impeller speed was increased during the sampling procedure. Each additional increase in impeller speed allowed larger particles to be transported in the secondary flow circuit. Data were written to hard disk (and optionally to a floppy disk) for storage and subsequent graphical presentation.

DATA COLLECTION AND INITIAL RESULTS

Preliminary testing indicated that operational concepts of the VPSDS were valid. A prototype was constructed and specific tests were conducted to determine the operational capabilities of the system. Twenty three soil samples, with known physical properties, representing seven unified soil classifications, were tested using the VPSDS (Burcham, 1989). Presented here are two operational tests illustrating the VPSDS's ability to sense particle size and concentration.

A test to determine the VPSDS's response to particle size was designed by sieving a white sand into fractions containing particles <63 microns, 63 - 125 microns, 125 - 250 microns, 250 - 500 microns, and 500 - 710 microns. A sample of 0.5 grams from each size fraction was run in the VPSDS independently. Figure 4 illustrates the VRCs for each of these size fractions. Clearly the <63 micron particles are being transported and sensed in the VSZ at low impeller speeds. Note the step response for each subsequent increase in particle size. In fact the 500 - 710 micron particles are just beginning to be transported into the VSZ at maximum impeller speed. Additional tests showed that the VPSDS was able to differentiate 0.5 gram samples composed of three parts of <63 micron soil and a prepared sample containing two parts <63 micron soil and one part 63 - 125 micron soil (Burcham, 1989).

The VPSDS's ability to determine soil-water concentration was tested on a variety of soils types. Within a given unified soil class, concentration changes were detectable at any given impeller speed. Figure 5 illustrates the VPSDS's response to soil-water concentrations of 0.5, 0.3, and 0.1 grams per 225 milliliters of water. Results indicate that voltage at maximum impeller speed could be used to indicate soil-water concentration within a given soil type. Since clay content increases the voltage response throughout the VRC, this type of soil-water concentration determination is valid only within a specific soil type.

Standard Percent Finer Presentation

In order for the VPSDS to be successfully used as an alternative instrument for particle size and concentration determination, the VRCs must be transformed to a standard particle size presentation format. Two methods were developed to estimate percent finer information from VRCs. Each method approached the transformation of VRCs to standard percent finer formats from a different perspective. The Set Point Method (SPM) selected values from the VRC based on specific impeller speeds, while the Calibration Curve Method (CCM) attempted to incorporate other factors such as variable light extinction due to clay, particle shape, and particle density. The CCM accomplished this through the use of calibration curves which were generated for each of the seven unified soil classes tested.

To implement the SPM and CCM, the data acquisition and control program automatically estimated the unified soil classification of the sample based on stored VRCs. Once unified soil classification was determined, the VRC was used by both SPM and CCM percent finer estimation program modules. These two methods are described in detail in Burcham (1989) and summarized in Burcham and Hayes (1989).

Set Point and Calibration Curve Methods of percent finer estimation indicated that the VRCs generated by the VPSDS can produce particle size information in standard percent finer format. Tests by Burcham (1989) indicated that the SPM is reasonably accurate for particles larger than 50 microns. The CCM method was capable of estimating particle size down to 2 microns, but with the added complexity of the calibration process. Results with the CCM indicate that the VPSDS could be calibrated to estimate particle size on substances other than soil, ie., mining slurries, plastics, and powder technologies.

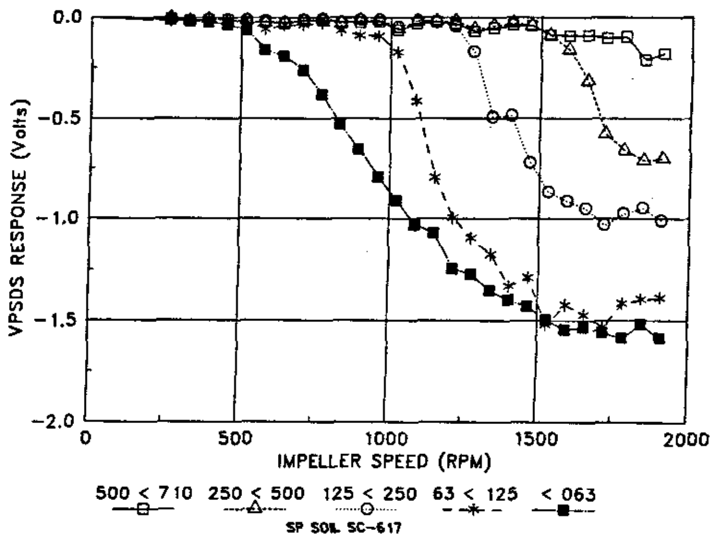

Figure 4. VPSDS response to particle sizes from 63 - 710 microns.

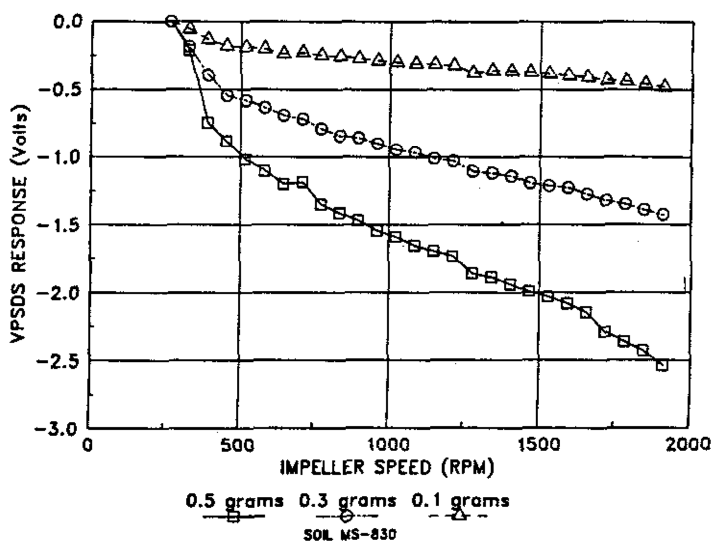

Figure 5. VPSDS response to soil-water concentration.

CONCLUSIONS

The ability of the VPSDS Vortex Chamber to differentially transport soil particles to the VPSDS Sensing Zone allows conventional sensor technologies to be incorporated for measuring the concentration and distribution of particle sizes in soil-water mixtures. The VPSDS was constructed using readily available hardware, therefore production cost should be relatively low. This will facilitate the adoption of VPSDS for on-site particle size analysis. Consecutive samples could be analyzed every 12 minutes with the prototype VPSDS. Further refinement will allow samples to be analyzed on a near real-time basis. Sample sizes of 0.5 grams or less are sufficient for analysis in the VPSDS.

Continued development and future testing will seek to quantify the transport capabilities of the VPSDS Vortex Chamber with respect to actual particle size, density, and shape factors. Increased sensitivity of the light detection circuitry, and optimized Vortex Chamber dimensions will improve the operational capability of the VPSDS. Initial test results indicate that the VPSDS is a viable instrument for determining particle size distribution and concentration parameters on soil-water mixtures.

REFERENCES

Burcham, T. N. 1989. Vortical particle size distribution system. Unpubl. Doctoral Dissertation, Clemson Univ. Library, Clemson, SC.

Burcham, T. N. and J. C. Hayes. 1989. Design concepts of the vortical particle size distribution system. Paper No. 892626, ASAE, St. Joseph, MI 49025.

Cooke, J. C. 1952. On Pohlhaussen's method with application to a swirl problem of Taylor. Jour. Aeronaut. Sci., 19:486-490.

Cooper, L. R., et al. 1984. Microtrac particle-size analyzer: an alternative particle size determination method for sediment and soils. Soil Science, 138:(1)-0038-075X/84/1382-0138.

Ray, B. R. 1982. An evaluation of suspended sediment response to bmp implementation in the broadway lake watershed, SC. Unpubl. Masters Thesis, Clemson Univ. Library, Clemson, S.C..

Rhoton, F. E. and L. D. Meyer. 1987. Sediment size distributions predicted for selected soils. Jour. of Soil & Water Cons., March-April, 42:(2).

Taylor, G. I. 1950. The boundary layer in the converging nozzle of a swirl atomizer. Quart. Jour. Mech. and Applied Math, 3:129-139.

Tollner, E. W. and J. C. Hayes. 1986. Measuring soil aggregate characteristics for water erosion research and engineering: a review. TRANS. of the ASAE, 29:(6) 1582-1589.

U.S. Environmental Protection Agency. 1977. National water quality inventory. 1977 Report to Congress, EPA 440/4-78-001, Wash., DC.

Wischmeier, W. H. 1976. Cropland erosion and sedimentation, control of water pollution from cropland. Vol. II, Report No. EPA-600/2-75-026b, June.

A SEDIMENT BUDGET OF THE LOWER FRASER RIVER

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ABSTRACT

A comprehensive sediment budget was developed for the lower 85 km of the Fraser River, British Columbia. The analysis involved comparing the bed material loads, dredging quantities and channel changes over the periods 1963 - 1974 and 1974 - 1984. The results of the budget were used to make preliminary estimates of the sediment outflows to the delta front and to assess the long term impacts of dredging on the regime of the river. The average annual total load of the Fraser River at Mission and Port Mann, at the upstream end of the study reach, was estimated to be 17.3 million tonnes/year. The average annual bed material load (sand coarser than 0.18 mm) was estimated to vary from 3.9 million tonnes/year between 1963 - 1974 to 2.4 million tonnes/year between 1974 - 1984. The net quantity of material removed from dredging exceeded the incoming bed material load by nearly a factor of two in the period 1974 - 1984. As a result, the river bed has been lowering at a rate of about 8 cm/year. The study demonstrates the usefulness of long term sediment measurement programs and the importance of integrating these programs with other data collection activities (monitoring dredging and hydrographic surveys).

INTRODUCTION

Purpose

This report describes the progress that has been made towards developing a comprehensive sediment budget for the Lower Fraser River (Figure 1). The study area extends 85 km from Mission City to the mouth of the river at Sand Heads and includes the main navigable portion of the river below New Westminster. The analysis provides a means for evaluating the relation between the incoming sediment loads, the past dredging activities and the channel changes that have taken place along the river over the last 20 years. These results will assist other agencies in planning and evaluating future dredging and river training programs on the river. A secondary objective of the study is to provide an estimate of the long term sediment outflow from the main channel to the delta front off Sand Heads. These estimates should assist in developing a better understanding of the likely impacts of continued dredging and river training activities on the long term stability of the delta front.

Description of the Study Area

The Fraser is the largest river in British Columbia draining an area over 234 000 square kilometres and travelling approximately 1 400 kilometres from its headwaters in Mount Robson Provincial Park to its mouth near Vancouver, British Columbia. In this report, the Lower Fraser River refers to the 165-kilometre reach between Hope and Sand Heads, the lighthouse marking the channel entrance at the estuary mouth.

Runoff in the basin is dominated by spring snowmelt and generally produces a bell-shaped hydrograph. Peak annual flows normally occur between the first of May and the end of June. Annual peaks at Hope, since 1912, have ranged from 5 130 m^3/s to 15 200 m^3/s with a mean of 8 770 m^3/s.

The tidal reach of the Fraser varies with flow. At low flows it extends to Sumas Mountain (km 98); for flows at Hope greater than 5 000 m^3/s, the tidal effects at Mission (km 85) become very small. At Port Mann (km 42) flows reverse until the flow at Hope exceeds 4 000 m^3/s (Ages and Woolard, 1976). Depending on flow and tide range, salt water from the Straight of Georgia can intrude some distance into the Fraser estuary. With low discharge flows and large tides the salt wedge may reach New Westminster (km 35), but for flows exceeding 5 000 m^3/s, it rarely extends beyond the Steveston Bend (km 10) (Beak, 1980).

The lower Fraser can be divided into three morphologic reaches. From Hope to Sumas Mountain, the river displays a wandering or anastomosed channel pattern with a gravel bed. The channel is frequently confined by bedrock outcrops and by rip-rap-protected embankments. Below Sumas Mountain, there is an abrupt transition to a single, sinuous, sand bed channel, frequently confined by Pleistocene uplands. The modern delta reach begins at New Westminster, where the river splits into three distributary channels.

Methodology

A sediment budget for any reach of the Lower Fraser River can be written as:

$$(1) \quad \Delta S_{CHAN} = S_{IN} - S_{OUT} - S_{DREDGE}$$

where:
- S_{OUT} = sediment outflow from the reach
- S_{IN} = sediment inflow to the reach
- S_{DREDGE} = the net mass of sediment dredged from the reach
- ΔS_{CHAN} = the net change in sediment stored within the channel

This equation shows that the long term channel change (ΔS_{CHAN}) will be determined by the loads coming into and exiting from the reach and the net effective dredging that has been carried out. The equation can be re-arranged to provide estimates of the past sediment outflows from a reach provided the inflows, net dredging quantities and past channel changes are all known:

$$(2) \quad S_{OUT} = S_{IN} - S_{DREDGE} - \Delta S_{CHAN}$$

The time period considered in this type of analysis is usually chosen to be in the order of years to decades, although shorter time periods could also be considered. Furthermore, the analysis must consider the size distribution of the channel sediments, the dredged materials and the incoming sediment load. As this analysis was applied only to the sediments that make up the bed material in the main stem of the river, the sediment budget is restricted to only the bed material load.

AVAILABLE DATA

Sediment Load

A comprehensive data collection program on the Lower Fraser was established by the Water Survey of Canada (WSC) at Hope, Agassiz, Mission and Port Mann. The program has included the measurement of suspended sediment, bed load and bed material. The initial planning and establishment of these stations was described in detail previously (WSC, 1970) and the history and evolution of the sediment network has been outlined by Zrymiak (1982) and Kellerhals (1984).

Based on 18 years of sediment data at Mission, the mean annual total sediment load is 17.3 million tonnes/year. This load is composed of approximately 35 percent sand (particles > 0.063 mm), 50 percent silt (0.004 - 0.063 mm) and 15 percent clay (< 0.004 mm).

A substantial effort was recently made to estimate the annual total load at Mission by grain size fraction using the discharge and sediment data (McLean and Church, 1986). A comparison between sediment transport measurements at Port Mann and Mission indicated that the annual loads agreed reasonably closely, which is not surprising since there are no major tributaries or sediment sinks between the two stations. A comparison of the size distributions of the loads also showed good agreement. Therefore, on this basis it appears that the annual loads measured at Mission provide reliable estimates of sediment inflows to the estuary.

Although some miscellaneous suspended sediment concentration measurements have been made in the estuary, these data are inadequate for estimating annual loads. This is because the unsteady nature of the tidal flows, and the effects of salinity intrusion greatly complicate any data collection program.

Channel Data

Complete hydrographic surveys of the 42 km reach between Port Mann and Sand Heads have been carried out on an annual basis for the last 30 years by Public Works Canada (PWC). These annual surveys have all been made during the low flow season usually between October - January when the bed is relatively inactive. Additional earlier surveys are also available at less frequent intervals with some soundings dating back to the 1880s. Hydrographic data upstream of Port Mann are available only for 1952, 1963 and 1984.

Dredging Data

PWC records of historical dredging volumes were reviewed and the methods, locations, disposal and grain size characteristics of the dredged sediments were assessed. Two types of dredging records are maintained; navigation dredging, dredging performed to maintain drafts in the 200 m wide navigation channel, and borrow dredging material removed for use in construction projects; it may or may not be from the navigation channel.

Bed Material Data

Bed material samples have been collected regularly at Mission and Port Mann by WSC using BM-54 samplers. Samples were also collected along the centre of the channel between Sand Heads and New Westminster by PWC in 1986. Comparison of the bed material samples collected between Mission and Sand Heads has shown that the composition of the river bed is fairly uniform. Using the criterion suggested by Einstein, (1950) a grain size of 0.18 mm was adopted in this study to represent the break between wash load and bed material load. Therefore, the bed material load was estimated on this basis.

SEDIMENT BUDGET RESULTS AND DISCUSSION

The sediment budget for the bed material load was computed for two time periods; 1963 to 1974 and 1974 to 1984. Figure 2 shows the estimated quantities of bed material load transported along the main stem as computed from the budget. An overall summary of the sediment budget for the two periods is shown in Table 1.

Table 1
Sediment Budget - Mission to Sand Heads

	1963-1974 10^6 t/year	1974-1983 10^6 t/year
average inflow of bed material (at Mission)	3.93	2.41
average net mainstem dredging	1.86	4.20
average net channel change	-1.16	-2.95
estimated losses to tributaries	0.47	0.25
average outflow of bed material (at Sand Heads)	2.76	0.91

A reliable check of the sediment budget results might be made by performing additional surveys and collecting sediment samples off the delta front near Sand Heads and estimating the long term sand accumulation that has taken place at the mouth of the river. However, due to the unsteady nature of flows in the estuary, this will be a difficult undertaking.

The budget shows that in response to the dredging program, the river has degraded. Figure 3 illustrates the overall net channel changes that have occurred between New Westminster and Sand Heads. This shows that the bed has lowered at a fairly consistent rate of 8 cm/year, or 2 m over the last 25 years. In the individual reaches (Figure 2) the mean bed levels have lowered on average by 2 m - 4 m (10 - 20 cm/year). However, in most reaches there is no consistent relation between rate of bed level change and dredging effort. For example, in the Sand Heads reach, the bed appears to have aggraded between 1974 - 1983 even though the dredging effort increased to near record levels. A similar pattern occurred at Steveston Cut where in recent years the dredging effort has nearly doubled while the bed level has remained virtually static.

The sediment budget analysis provides a good basis for illustrating how sedimentation processes have influenced the navigation improvements that have been achieved from the dredging program. The period between 1963 - 1974 extends before and after the construction of the Trifurcation Project at New Westminster. As a result, major channel adjustments were taking place during this time in response to these river training works. This period also includes some very large sediment inflow and runoff years such as 1972 and 1967. The analysis between 1974 - 1984 covers the period when increased dredging operations were carried out to increase the available drafts. This period was characterized by lower than average sediment inflow and runoff conditions. Therefore, the channel response during these two periods should be very different.

The analysis for the 1963 - 1974 period shows that the net dredging (20.5×10^6 t) comprised less than one half of the total bed material load (43.2×10^6 t) inflows at Mission. The resulting channel degradation (12.76×10^6 t) represented approximately 62% of the net dredging quantity. The estimated sediment outflow of bed material at Sand Heads amounted to 30.4×10^6 t over the period or about 2.8×10^6 t/year. This amount corresponds to 76% of the inflows at Mission which indicates the channel had a very high transport efficiency during this period.

The main features of the 1974 - 1984 analysis are the net dredging (46.1×10^6 t) exceeded the total bed material load at Mission (26.5×10^6 t) by 75%. The net channel degradation that occurred during this period (32.4×10^6 t) corresponds to about 70% of the net dredging quantity. The estimated outflow of bed material at Sand Heads was only about 40% of the load at Mission and about 45% of the estimated load immediately downstream of the Trifurcation. This indicates that the channel's transport capacity decreases substantially downstream of New Westminster and that without ongoing dredging this reach would have aggraded.

The higher transport efficiency during the 1963 - 1974 period may be due to two factors. First, although the sediment inflows were higher than average between 1963 - 1974 the peak flows were also persistently higher than the long term average. Therefore the capacity to flush the sediment out of the river was higher between 1963 - 1974 than between 1974 - 1984. Also the shallower depths and higher velocities in this earlier period would also increase the channel's transport capacity.

The results of the sediment budget analysis can be used to provide a first order estimate of the long term maintenance dredging requirements that would maintain the channel in equilibrium over a number of years. The analysis between 1974 - 1984 showed that the overall net trap efficiency of the main stem channel (for bed material load) amounted to nearly 60%. Assuming a long term inflow of 3.2×10^6 t/year this suggests that in the order of 2×10^6 t/year of sediment would have to be removed from the channel to maintain a long term equilibrium condition. However, this equilibrium condition would take a number of years to become established since channel adjustment and redistribution of sediment from the channel sides might continue for a number of years. Therefore, this figure represents a lower bound or end condition for the maintenance dredging requirements.

REFERENCES

Ages, A. and Woolard, A. 1976: The tides in the Fraser River estuary. Environment Canada, Institute of Ocean Sciences, Sidney, British Columbia. Report 76-5: 100 pp.

Beak Consultants Ltd. 1980: Proposed improvements to the Fraser River shipping channel, unpublished report to Public Works Canada, Vancouver, B.C.: 330 pp.

Einstein, H.A. 1950: The bed-load function in open channel flows. U.S. Dept. of Agriculture, Soil Conservation Service Tech. Bull. 1026: 70 pp.

Kellerhals, R. 1984: Review of sediment survey program, Lower Fraser River British Columbia. Consulting report to Sediment Survey Section, Water Resources Branch, Environment Canada, Vancouver, B.C.: 33pp.

McLean, D.G. and Church, M. 1986: A re-examination of sediment transport observations in the Lower Fraser River. Sediment Survey Section, Water Resources Branch, Environment Canada, Ottawa. Report IWD-HQ-WRB-86-62 56 pp and tables, figures.

Water Survey of Canada. 1970: Hydrometric and sediment survey, Lower Fraser River. Progress Report 1965-1968. Sediment Survey Section, Water Survey of Canada, Department of Energy, Mines and Resources, Ottawa: 133 pp.

Zrymiak, P. 1982. Sediment survey programs on the Fraser River, British Columbia. Internal report, Sediment Survey Section, Water Resources Branch, Environment Canada, Ottawa: 45 pp.

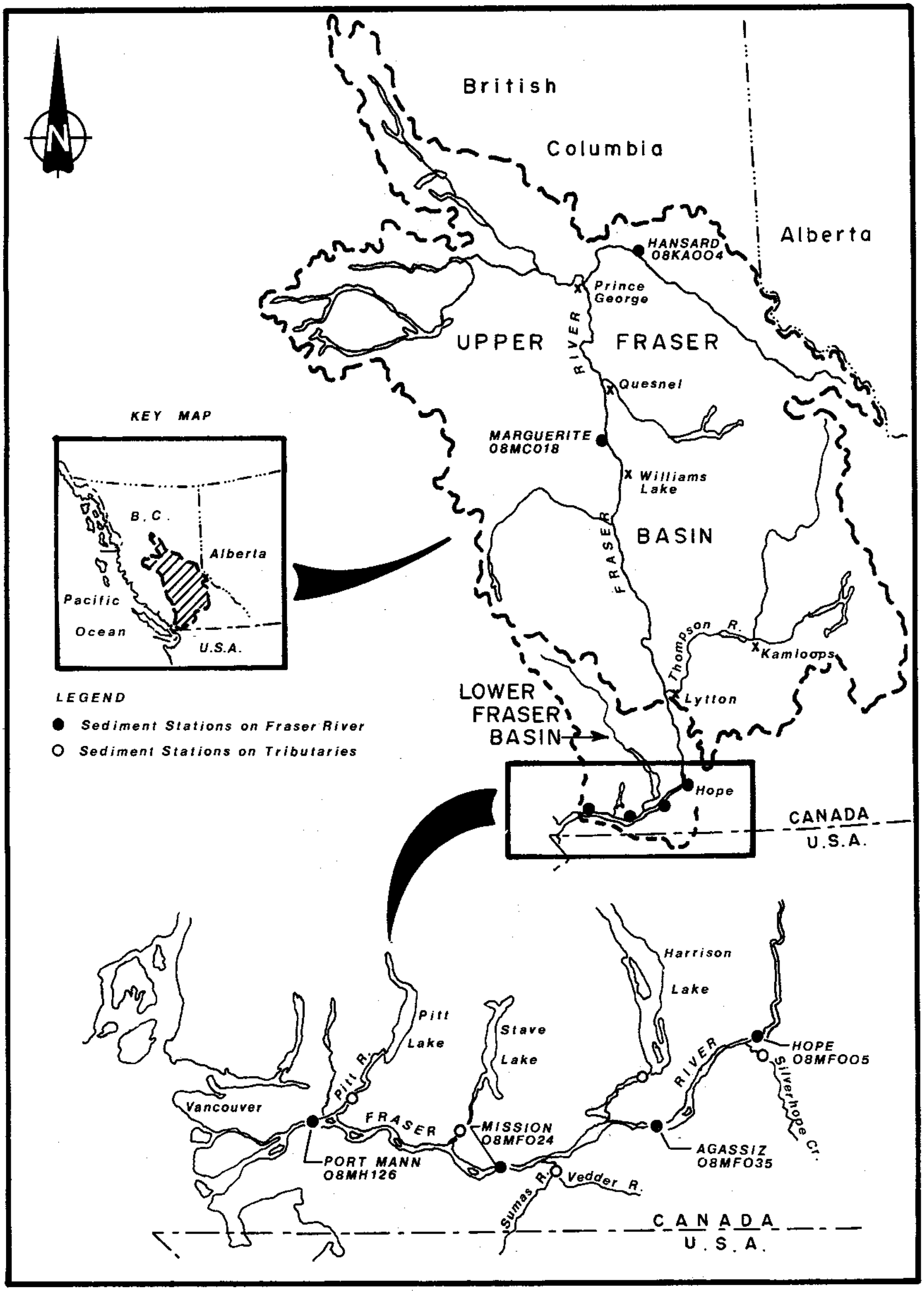

Figure I. The Fraser River Basin

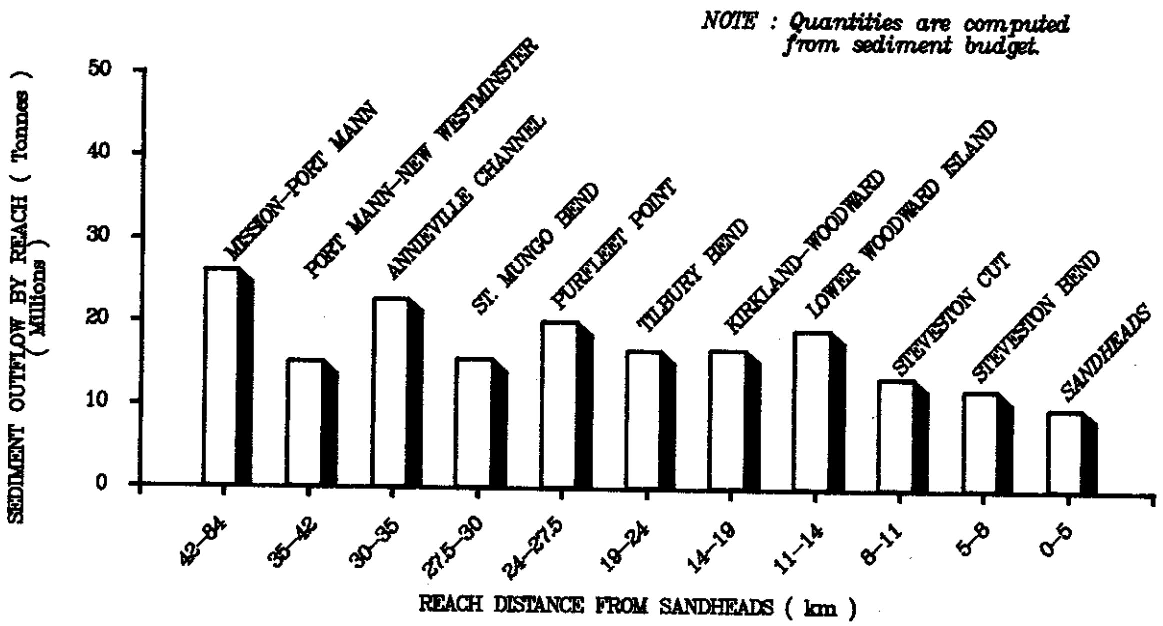

Figure 2. Total Bed Material Transport 1974 – 1984

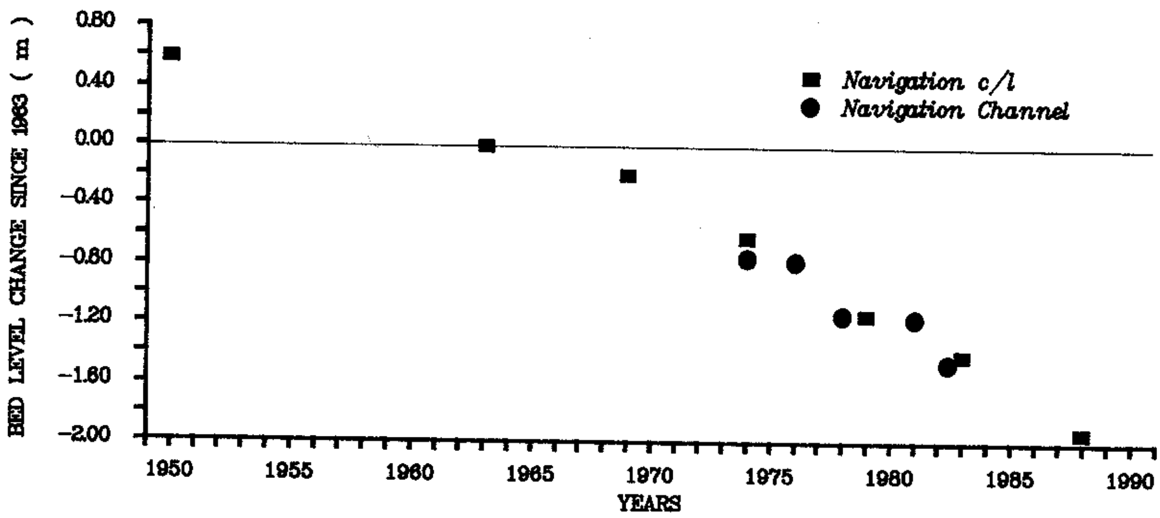

Figure 3. Average Channel Changes below New Westminster

CONTROLLING SEDIMENT COLLECTION WITH DATA LOGGERS

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ABSTRACT

The proliferation of commercial non-programmable data loggers in the past five years has done little to increase sediment sampling efficiency in remote locations. Recent advances in microelectronics have encouraged the development of commercial, low-power, programmable data loggers at reasonable cost. Although some facets of hydrologic data collection may lend themselves to fixed-time sampling intervals, sampling efficiency in many applications can be improved using a programmable data logger. For example, controlling the collection of suspended sediment with a probability sampling program may involve generating and sorting random numbers, testing input parameters, and activating a pumping sampler.

Commercial single-board data loggers are now available with high-level programming languages, such as BASIC. Modified BASIC commands that provide easy access to the data lines can simplify the programming required to control data collection. Low-power requirements, ease of programming, and the increased flexibility of connecting multiple sensors can improve data collection in remote locations. In most cases, the user must provide signal conditioning hardware between the sensors and the data logger. Environmentally sealed hand-held computers transported to the site and connected to the data loggers allow field personnel to update programs, transfer data files, view and plot data, and add observer records.

INTRODUCTION

Development of low-power commercial data loggers in the past five years has resulted in a larger selection of equipment for hydrologic data collection. Unfortunately, in spite of significant improvements in data logger hardware, high-level language programs are almost non-existent. In fact, most data loggers are not programmable, and those that are often use proprietary "assembly-like" languages that are difficult to use and modify. Commercial low-power single-board data loggers now offer high-level languages and access to microprocessor I/O (input/output) lines at considerable cost savings over non-programmable data loggers.

Early attempts to develop microprocessor-based systems demonstrated the potential of single-board data loggers to control sediment collection (Babbitt, 1987). Sampling algorithms provided a means to control the collection of samples in real-time, resulting in higher sampling rates during periods of interest. Technical limitations, such as assembly language programs and magnetic storage media, often discouraged potential users. By the mid- to late-1980s several commercial manufacturers of data loggers began to offer devices with a wide range of input sensor configurations, low-power requirements, and improved solid state memory. Most of these data loggers allowed only fixed-time sampling.

Another path of development utilized a programmable calculator interfaced to a pressure transducer and pumping sampler to control probability-based sampling for a study on cumulative effects in the Caspar Creek Experimental watersheds, near Ft. Bragg, California (Eads and Boolootian, 1985). Commercial products, such as the calculator used in the Caspar Creek study, often lack the robustness required in severe environmental conditions, and special precautions must be taken to protect the equipment.

Currently, four types of data loggers collect data from eight hydrologic studies in the Caspar Creek watersheds. Each study has unique requirements for interrogation intervals, sensor type, programmability, and data file structure. A large effort is expended in training field personnel to operate and maintain data loggers with dissimilar requirements. In addition to compatibility problems, the data loggers lack desirable and necessary features which would improve data collection. Replacement of existing data loggers with a single-board programmable data logger is under field evaluation. This paper describes the development of software and interface hardware for a single-board programmable data logger controlling the collection of suspended sediment samples and precipitation data.

SEDIMENT AND PRECIPITATION DATA COLLECTION

Sampling Methods

Suspended Sediment

Data for estimating suspended sediment loads are traditionally collected nonstatistically; that is, probabilities of collecting given samples are not known. This is partly why estimates made with these data give biased estimates of total load and variance (Walling and Webb, 1981). Algorithms that collect statistical samples to estimate sediment loads correct these deficiencies (Thomas, 1985; Thomas, personal communication, 1990). These methods use knowledge about sediment flux to improve sampling. One algorithm, called SALT (Selection At List Time), uses surrogate values calculated from discharge at 10-minute intervals that interact with preselected random numbers to enhance collecting sediment samples during high flow periods. Stratified sampling can also be used to obtain statistical samples with low variance by partitioning time into strata based on actual and expected changes in stage. Both schemes give unbiased estimates of total load and variance, but depend on sensing in-stream conditions to modify the sampling process.

Although both SALT and time-stratified sampling can be accomplished manually, remote study sites are well suited to automated data collection because of inherent problems of access and timing. In addition to controlling sediment collection, electronic data records reduce both labor and errors associated with keyboard entry and digitizing. Consider how an "intelligent" data logger connected to a stage sensor and a pumping sampler would collect data on suspended sediment under time-stratified sampling. Several sampling schedules with different sampling rates (i.e., bottles/hour) and stratum durations would be preselected for different in-stream conditions. In real-time at the start of each stratum, the data logger would determine in-stream conditions, choose the appropriate schedule, and randomly select the sampling times for the duration of the specified stratum. Then during the stratum period, the data logger would activate the pumping sampler at the selected times and store information needed for estimation. This process would be repeated for the period to be monitored and would require no human intervention until all of the bottles were filled.

Precipitation

Precipitation data are often collected at or near stream gauging stations. Programmable data loggers with multiple analog and digital I/O lines can combine data collection from several instruments. In small mountain streams, precipitation information can be used in addition to stage to refine the sampling algorithm. Tipping bucket rain gauges provide a digital output based on the number of "tips" occurring during a defined period. Tips are counted in the "background" while the data logger is in a low-power mode. The data file can be compressed in real-time by retaining only those periods that contain precipitation.

Hardware

The gauging station equipment that is used to control time-stratified sampling and precipitation data collection includes a tipping bucket rain gauge, modified stilling well, pumping sampler and intake boom, interface circuit, single-board data logger, and hand-held computer (fig. 1).

Single-Board Data Logger/Controller

Controlling data collection of suspended sediment with probability sampling encompasses several steps that are most efficiently handled by a programmable data logger. A pressure transducer is periodically interrogated to obtain an analog voltage, which is converted to a digital representation and applied to a calibration equation to measure stage. Stage is subsequently used to determine the appropriate sampling schedule and is also retained as the hydrograph record. The data logger controls the collection of sediment samples by providing a short duration switch closure to the pumping sampler through an interface circuit. Finally, the data logger must have sufficient on-board memory to store all records of interest for a period spanning regular maintenance intervals.

In addition to these general requirements listed above, the data logger should have low-power requirements, adequate A/D (analog-to-digital) resolution with multiple input channels, provide multiple digital I/O lines, and support a high-level language. A limited number of commercially available data loggers meet these requirements. Onset Computer Corporation's Tattletale Model 4A[1] was chosen for its ease of hardware development, low-power requirements, moderate cost, and suitability for a wide range of hydrologic studies. Onset's products require that the user provide signal conditioning circuitry, sampling programs, and physical packaging. The Model 4A does not include a display or keyboard. A computer, connected to the data logger with a serial cable and running communications software, provides a means to write and list programs and transfer files. A low-power display interfaced to the data logger can provide information to field personnel in situations where they may visit the field site but do not have a hand-held computer.

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[1]Trade names are used for information only and do not constitute endorsement by the U.S. Department of Agriculture.

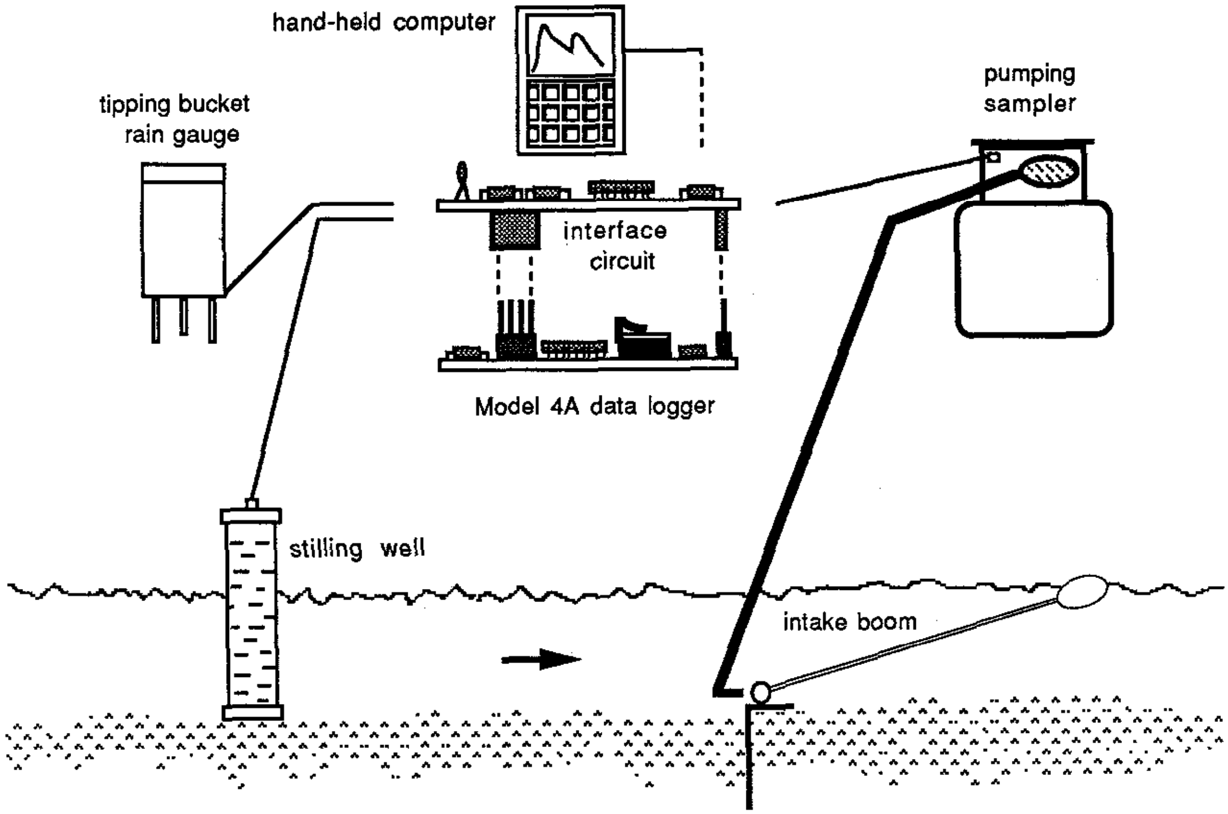

Figure 1. Gauging station equipment.

Stage Sensing

Solid state differential pressure transducers sense changing water depth by converting the mechanical flex of a silicon diaphragm to a proportional electrical signal while compensating for atmospheric pressure changes by venting the dry side of the diaphragm to the atmosphere. Because changes in voltage across the silicon piezoresistive bridge are small, the output signal must be amplified to the range of 0 to 5 volts. Amplification can take place within the sensor assembly or on an interface circuit board. Onset manufactures an interface circuit board, suitable for prototyping or for limited production, that provides connections to power, analog inputs, and digital I/O lines. To conserve power the data logger's A/D converter is active only during a small time window, and input devices must either have a fast settling time or invoke an assembly language subroutine to stabilize the signal before conversion is started. Input signals are converted ratiometrically to a 12-bit result and shifted left four bits, producing a 16-bit result in the range of 0 to 65,520 A/D units. Combined accuracy of most transducers is between 10 and 12 bits, so the additional bits of "precision" should be treated appropriately. The A/D value is applied to the pressure transducer's calibration equation to obtain a stage value in the appropriate units.

A modified stilling well, constructed of PVC pipe and geotextile filter fabric, can be anchored to the streambed. This design dampens wave pressure, blocks sediment entry, and maintains the pressure transducer in a fixed location. This simple installation greatly reduces the logistics associated with using traditional large-diameter stilling wells.

Sample Collection

The ISCO model 2700 sampler is a portable device designed to collect 24 discrete samples by pumping the water/sediment mixture from the stream to the sample bottles. Several sampling modes are possible with the model 2700. When the control unit is set to Flow Mode, as in the case of time-stratified sampling, the sampler waits for a short duration switch closure from an external controller before collecting each sample. The data logger provides the switch closure by setting a digital output line high and then low. An optical isolation circuit provides microprocessor protection and the required switch closure. The ISCO collects a preselected sample volume by counting the rotations of a peristaltic pump according to the settings made on the controller. The sampler intake is mounted on a depth-proportional intake boom anchored in the thalweg of the channel (Eads and Thomas, 1983). After each sample collection, the sampler's distributor arm is advanced to the next bottle, and the sampler then waits for the next signal.

Precipitation

Precipitation data are collected in the "background" by supplying a continuous 5 volt regulated source to a tipping bucket rain gauge and counting the number of tips as they occur. Background measurements are made with a BASIC "count" function that increments a variable for each square wave cycle appearing on a digital input during the measurement interval. Measurements are made while the program is in a "sleep" state.

Data Retrieval

Two methods are available for retrieving data files from the field: files can be transferred to a environmentally sealed hand-held computer, or a replacement data logger can be exchanged with the field data logger. Computer file transfer permits field personnel to enter observer records directly into the electronic file in real-time and to examine the data file on site. Plotting software permits a quick visual inspection of the data to determine whether plot traces look abnormal or values are out of range. This provides an opportunity to quickly replace defective sensors before additional data are lost. Onset offers communications software that simplifies data and program transfer with pop-up windows and limited selections that reduce training requirements for field personnel. Program updates are loaded to the data logger in the same manner that data are transferred.

Software

The Model 4A uses a version of BASIC that has been modified for the requirements of a low-power data logger and provides unique I/O commands that simplify interfacing requirements. Two methods of writing programs are available. TTBASIC provides an interactive environment where programs are developed on the data logger using a computer or terminal. TTBASIC supports 26 integer variables and one data array. Program editing is restricted to line replacement. Assembly language subroutines can be developed for unique applications that require special functions or increased speed.

Program logic for time-stratified sampling (fig. 2) demonstrates the flexibility of using a programmable data logger. Observer records provide additional information about site conditions that may affect the electronic record. For instance, differences between pressure transducer and staff plate readings may be used to adjust the electronic record. To determine the time to the first interrogation, or wake-up, a timer is set to check the real-time clock for the correct start time. Once a stratum is selected and started, sampling will continue until that stratum has been completed. When the stage drops below a minimum threshold, a new sampling schedule will not be initiated until the stage rises above the threshold. If the program selects a new sampling schedule that requires more bottles than are available in the sampler, the rate remains the same but the stratum length is shortened. At least two samples per stratum are required to compute variance. The data file contains all of the necessary information for analysis. Precipitation is stored as a separate record in the file to simplify data reduction. Finally, the display is refreshed and the timer is set for the next wake-up. The program is ended by pressing a switch on the interface circuit board that is connected to a port of the microprocessor. When the microprocessor detects an interrupt the program writes an ending record and halts.

The lack of floating point software can increase the complexity of programming when real numbers are needed, as in the case of time-stratified sampling. Generating random numbers between 0 and 1 in real-time and converting the result into integers in multiples of ten minutes is not a trivial task. An alternate solution is to generate random numbers on a computer and down-load the file to the data logger, but this does not make the most efficient use of the data logger.

SUMMARY

Low-cost single-board data loggers supporting high-level languages, such as BASIC, provide the flexibility to use sampling algorithms that range from simple applications, such as collecting precipitation data, to the more complex requirements that are needed for probability sampling. Onset's Model 4A requires two skills not normally needed when using data loggers: a basic understanding of analog and digital electronics and programming skills in BASIC. The expertise required in these two areas depends on the complexity of the intended application. For some sensors, such as non-amplified pressure transducers, the user must provide signal conditioning circuitry. But for single-ended sensors, the user may be required to only solder a few wires. The user must also provide a protective enclosure and the physical connections for the sensors and battery.

Currently, the only limitation of this technology is that Onset's data loggers do not support floating-point mathematics. In simple applications, this is not a problem. But, in cases requiring mathematical equations, programming expertise and code complexity are increased.

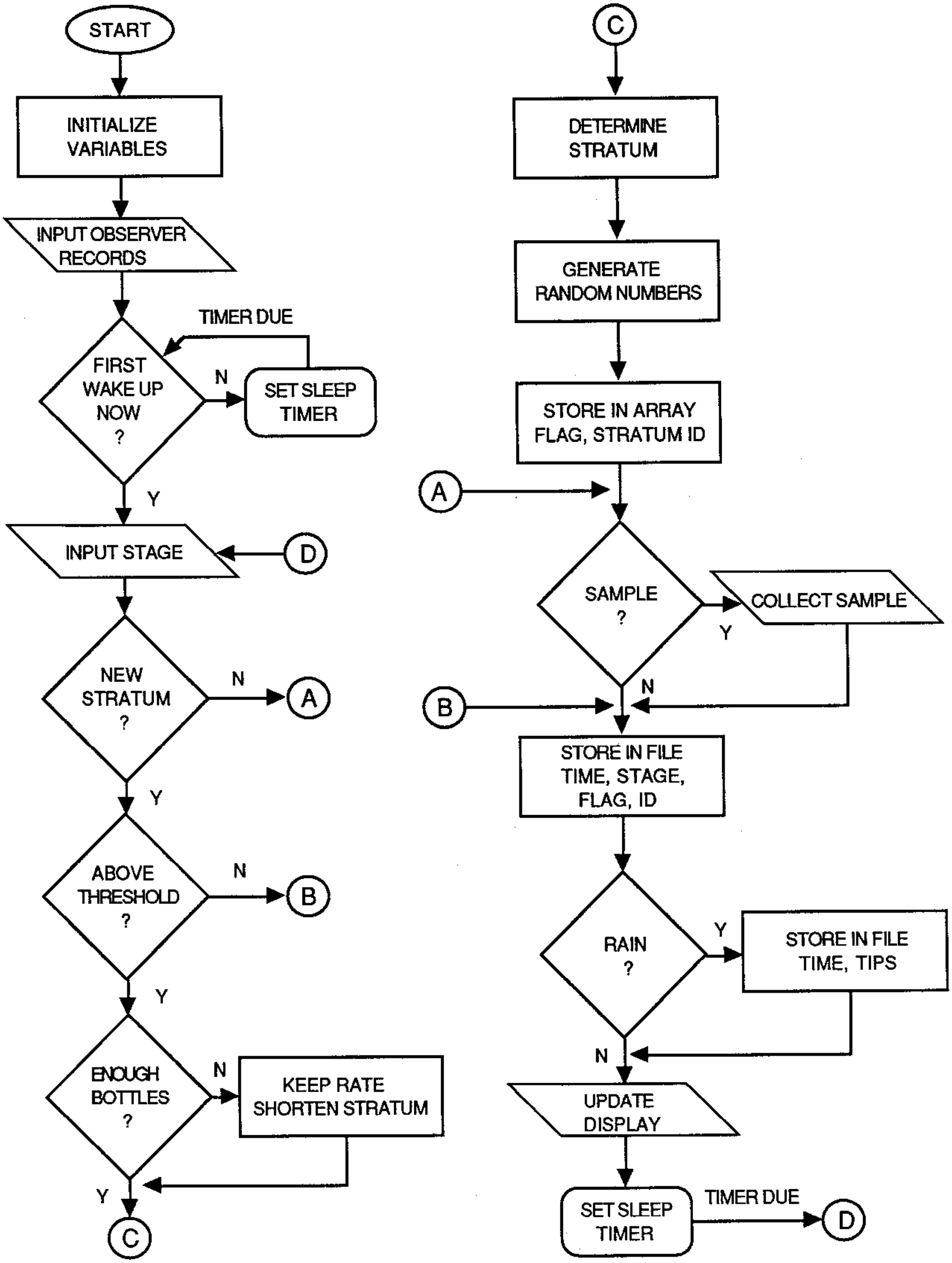

Figure 2. Program logic for time-stratified sampling. Letters inside circles indicate a continuation of the flow chart.

ACKNOWLEDGEMENTS

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REFERENCES

Babbitt, R. E., 1987, Improved streamflow and water quality monitoring using a microprocessor-based system. USDA Forest Service, Research Note INT-377.

Eads, R. E., and Boolootian, M. R., 1985, Controlling suspended sediment samplers by programmable calculator and interface circuitry. USDA Forest Service, Research Note PSW-376.

Eads, R. E., and Thomas, R. B., 1983, Evaluation of a depth proportional intake device for automatic pumping samplers. Water Resour. Bull. 19(2), 289-292.

Thomas, R. B., 1985, Estimating total suspended sediment yield with probability sampling. Water Resour. Res. 21(9), 1381-1388.

Walling, D. E., and Webb, B. W., 1981, The reliability of sediment load data, in Proceedings of the Florence Symposium, IAHS-AISH Publ. 133, 177-193.

EVOLUTION OF ONTARIO'S SEDIMENT MONITORING NETWORK

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ABSTRACT

The last 15 years has seen a varied evolution in Environment Canada's monitoring network for fluvial sediments in Ontario. The network has expanded from 9 to 130 stations as sampling strategies have shifted from continuous long term records to periodic short term records. These changes are in response to a combination of fiscal restraint and demands to increase the network in response to departmental interests in northern basins, in State of the Environment reporting and in addressing sediment quality problems. Overall in Ontario, sediment quality, not quantity is the primary concern. The primary strategy employed in our present network design is the reduction in the number of samples and the length of record at each station. There are now no continuous yearly sampled stations. On average, sampling has been reduced by 40 percent. By collecting only a few samples each year at any station, the network has been able to rapidly and economically expand. When properly managed, these programs can provide a data base adequate for most applications. A parallel evolution is occurring in the supporting data base and products as we respond to the changing user needs.

INTRODUCTION

While suspended sediments are by far the most significant component of the total load carried by Ontario rivers, the relative volumes of transported materials are small and generally only of local concern. Suspended sediment transport regimes in Ontario streams and rivers are characterized by a considerable range in annual loads from year to year (maximum loads can be 3-8 times the minimum annual loads). Consequently, 10 or more years of record are generally required to obtain reasonable estimates of mean and median loads (Dickinson and Green, 1987).

Seasonality is pronounced with most of the annual load being transported during the spring freshet period, with exact periods depending upon the location of the sampling site within a basin and where the basin is situated in the Province. Dickinson and Green (1987) and Smith (1983) have documented spring loads in the order of 60-85 percent of annual loads for rivers in southern Ontario. Loadings are very event oriented with just a relatively few days each year transporting a significant portion of the annual load.

These regime characteristics and the dominance of suspended sediment load shape the monitoring strategies employed to document sediment movement in Ontario waterways.

The Water Resources Branch of Environment Canada is the lead agency for monitoring streamflows and sediment transport in the Province. Field operations are carried out by the Branch under a joint federal-provincial agreement. Sediment sampling is undertaken by technicians as an adjunct to their hydrometric responsibilities and done by standardized methods and equipment. Sediment stations are always located at hydrometric stations in order to reduce costs and in order to provide necessary flow parameters for computing loads.

NETWORK ORIGINS

As elsewhere in Canada and the United States, Ontario's sediment monitoring program was developed as a direct extension of the hydrometric program i.e., the focus was on collecting detailed long term records to provide data for engineering applications. Sampling began in 1963 with one station and grew slowly to only 9 stations by 1970. Depending upon the station, sampling was done either all year round (a continuous program) or only during ice free periods (a seasonal program). These stations were all located in Southern Ontario (see Figure 1) near the population centres for the Province. Besides providing data for immediate practical problems, these stations were operated to provide an extensive data base for trend analyses (to document changes in the basin's physical state).

Over the next decade, 14 new stations were added, 5 miscellaneous stations in Northern Ontario in recognition of the need to provide even cursory data on sediment movement; and 9 continuous or seasonal stations in Southern Ontario. Some existing stations were discontinued, so by 1980, data in some form or other was being collected at 23 stations (Figure 1). Objectives remained mixed between baseline (long term) and project. This latter need saw, for example, a number of short term stations (1976, Figure 1), installed to provide design and environmental impact data for construction activities associated with the proposed international airport near Toronto, Ontario.

This period experienced the first systematic awareness that suspended sediments were an environmental agent as they acted as transporters and reservoirs for nutrients transported into the Great Lakes. The PLUARG (Pollution from Land Use Activities Reference Group) project of the late 1970's resulted in several new stations being activated on tributaries to Lakes Huron, Erie and Ontario.

At the end of 17 years of operation and up to 1979, the sediment monitoring program in Ontario produced data in various amounts and quality for 41 sites on 37 rivers. The program emphasized collection of data for clients - primarily for engineering applications.

NETWORK EVOLUTION: 1980-1990

This next decade experienced a change in philosophy, design, output and client services. The network developed gradually until 1987 when a rapid increase in network size and style occurred. Now as the program enters the 1990's, it is composed of 130 miscellaneous stations and a few seasonal ones (see Figure 2). Long term continuous sampling programs are no longer in operation. The focus is now short term, less detailed data sets. The reasons for this change are primarily threefold.

First, the limited resources available for monitoring programs, greatly restricted opportunities for increasing and otherwise altering the network. Even to maintain the level of network existing in the early 1980's, efforts had to be made to streamline the sampling strategies.

Second, today, quality not quantity is recognized as the sediment issue in Ontario (Conservation Management Systems, March 1986). Suspended sediments, and to a much lesser degree, bed transported sediments, preferentially carry many chemicals bound to their surfaces. The fine particles, typical of Ontario streams, are particularly effective transporters. These sediments for

EVOLUTION OF ONTARIO'S SEDIMENT MONITORING NETWORK

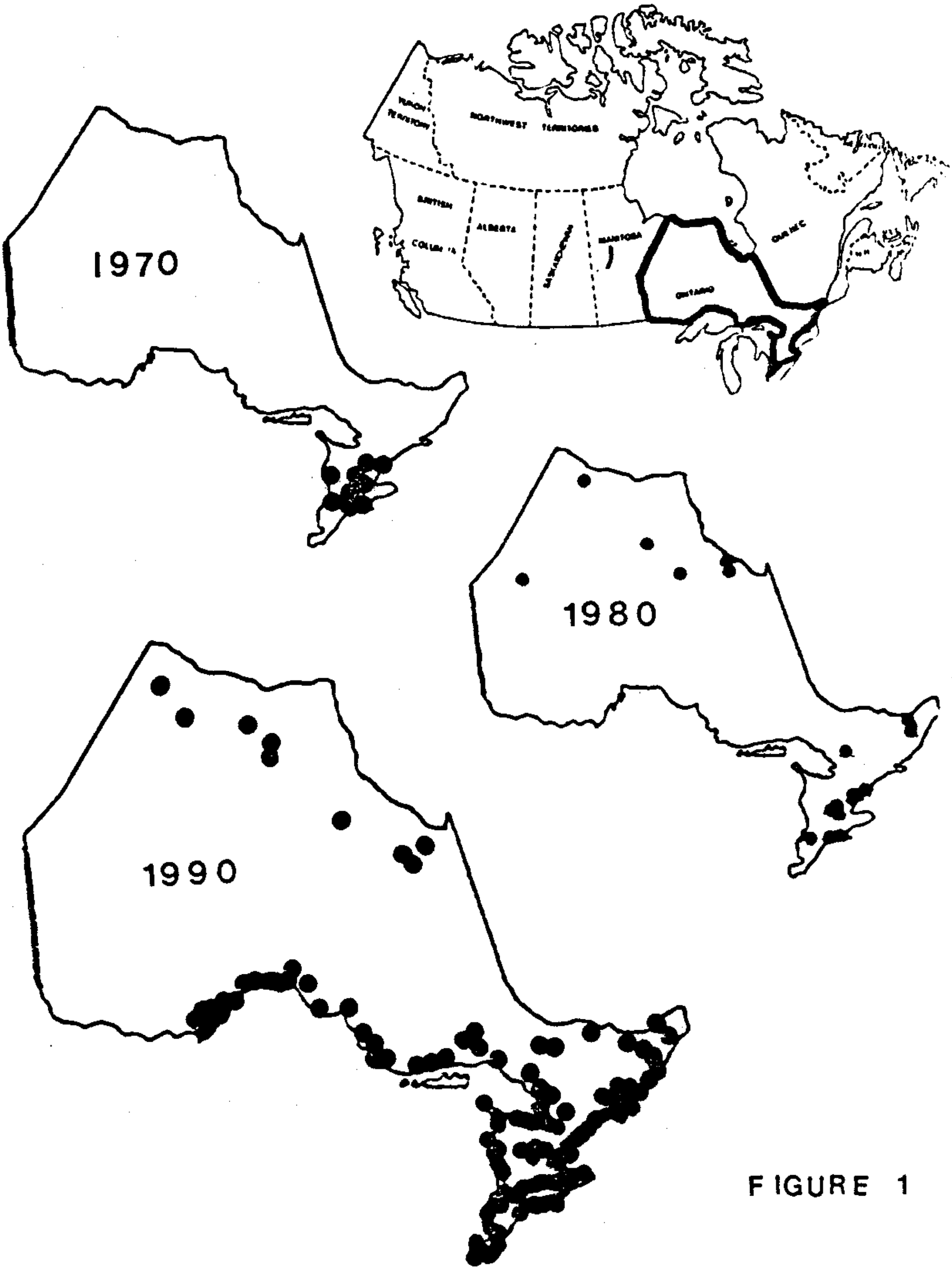

FIGURE 1

ONTARIO REGION
SEDIMENT NETWORK
HISTORICAL SUMMARY OF STATIONS

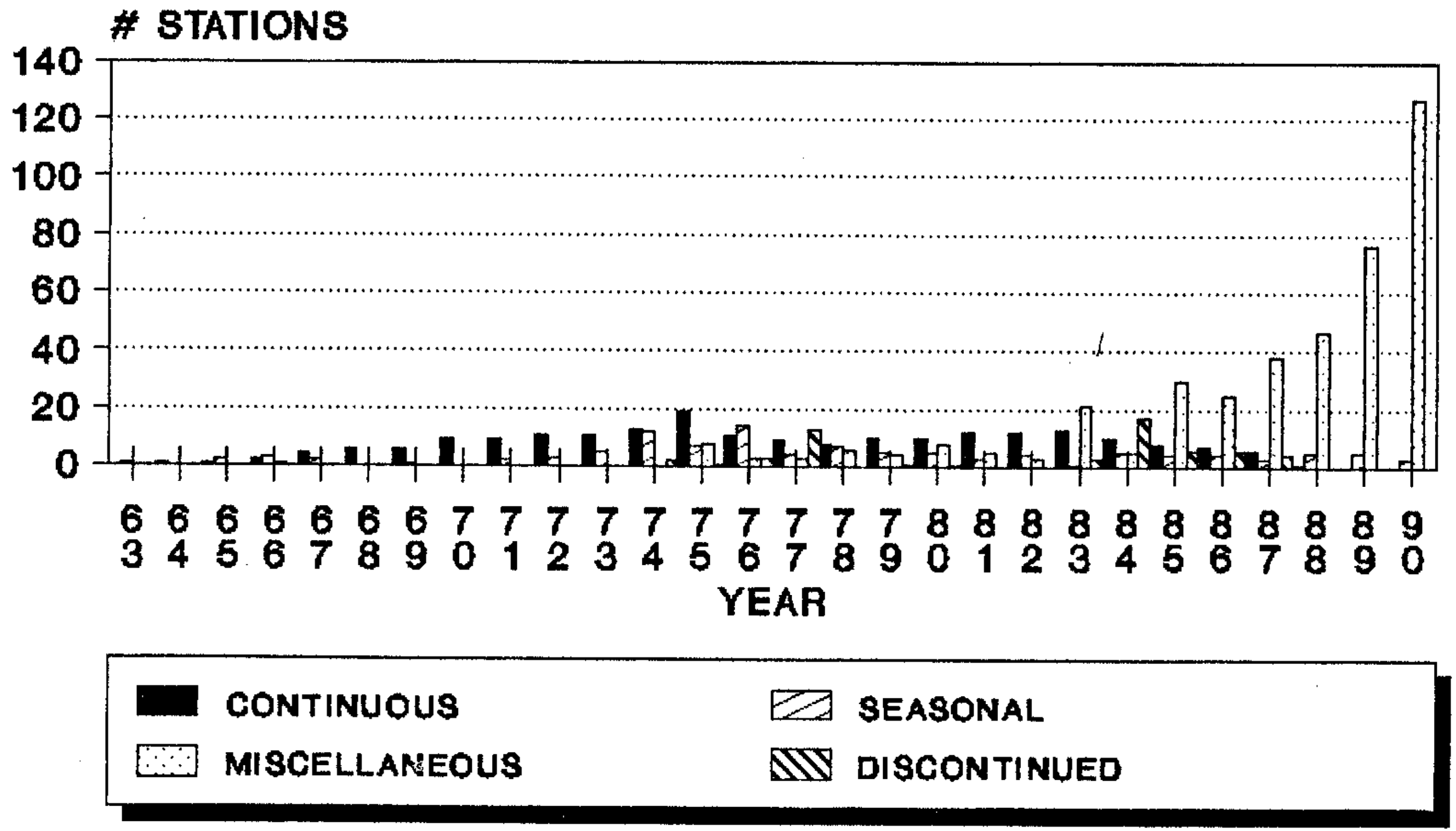

Figure 2

example, connect agriculturally drained areas that convey phosphorous, trace metals such as copper and lead, and some pesticides, to aquatic environments such as stream channels, wetlands and lakes. The presence of sediments also influences the phase in which contaminants are transported. In reponse to growing concerns, particularly those related to Great Lakes water quality, Federal & Provincial agencies in Ontario have taken initiatives such as Remedial Action Plans (RAP's) and the Soil and Water Environmental Enhancement Program (SWEEP). Each, along with the more regular tributary monitoring, will require sediment data to be integrated with other water related data and for assessments and decision making.

Third, Environment Canada now expects its data gathering programs to provide information to the Department on federal and national issues (those primarily related to environmental quality) as well as provide their traditional service to clients. These expectations are taking several forms, particularly the State of the Environment Reporting which, among other things, provides Canadians with information on the health and trends in the health of aquatic ecosystems. For data gathering agencies, this expectation requires, besides new skills, a broader awareness of, for example, sediment movement in the Province for better management of aquatic ecosystems.

These three factors: restraint, new focus and new expectations for information - presented a major challenge to the Branch's sediment monitoring activities. The response is structured around a miscellaneous sampling strategy, several information strategies and improved communications, particularly with clients. Therefore by 1990 or after 27 years of operation the sediment monitoring program in Ontario has produced data for 179 sites on 154 rivers.

THE MISCELLANEOUS STRATEGY

The concept of miscellaneous sampling is simple - collect a limited number of select samples sufficient to document the transport regime. Samples are obtained by single vertical depth integrating procedures. Approximately 25-40 samples are taken for each station. The implementation of this strategy has reduced sampling on average by 40 percent. The length of record has also been reduced significantly. Now record lengths of 7-12 years are acceptable. Studies of long term data sets (Smith, 1987; Binda, 1989) have shown that records of 23 years in length simply do not provide sufficient new information proportional to their cost.

The costs of a miscellaneous approach are quite inexpensive. Table 1 shows that for 1989 operations (5 seasonal, 75 miscellaneous) 11 miscellaneous stations can be operated for each seasonal one.

The management of this network sampling strategy is not so simple however. To be effective, greater control of sampling design is required. The technicians must carefully select the flows for which samples are required, and more care is required to track the field data using a concentration - discharge rating curve framework. One objective is to produce a sufficiently adequate rating relationship for the computation of sediment loads, and to document the seasonality in the data. Consequently, the field data collection must be designed to provide this information . An annual review process has been implemented to accomplish this task. (Day, 1987; McIlhinney 1986).

As a result of this approach, the data set for any sediment station is essentially unique. The total number of samples is entirely dependent upon the complexity of the concentration-discharge relationship, and the length of record on the representativity of the period of record.

TABLE 1
ACTUAL 1989 PROGRAM COSTS

Continuous Seasonal: (5 stations)

1.	Laboratory Costs (270 samples)[1]	= $ 4,950
2.	Salary to sample (technician)[2]	= 1,260
3.	Gauge reader sample pay	= 950
4.	Salary for computer, computations, approval	= 2,500
5.	Capital costs depreciation[3]	= 800
6.	Utilities, materials, supplies	= 1,000
	Total Cost	= $ 11,460
	Cost/station	= $ 2,290

Miscellaneous: (75 stations)

1.	Laboratory costs (20 samples)	= $ 5,180
2.	Salary to sample (techician)	= 1,035
3.	Transportation to lab of Sub-office samples	= 500
4.	Salary for SMP computations approval	= 4,200
5.	Utilities, material, supplies	= 200
6.	Capital cost depreciation	= 3,500
	Total Cost	= $ 14,615
	Cost/station	= $ 200

NOTES:

1. based on Laboratory Cost Study 1989, Ontario Region

2. based on EG-ESS-06 technician salary, 15 minutes/sample

3. based on sampler cost depreciation, $160/station

*

A further result of this approach is a shift to publishing instantaneous data, (Environment Canada, 1984) rather than the traditional daily values. New computer files have been developed and a massive effort to place all previous instantaneous data on computer files was required. Now clients have all the basic data available in a range of computer compatible forms. These instantaneous values are more relevant to environmental clients as they represent true instream conditions.

Also, new products are under development. For example, Ontario clients now have access to a combined sediment quality-quantity reference index designed to assist in the location of data sources, (Binda, 1987). Presently, a new user's guide (Dickinson, 1990) is being developed to help clients understand the available data types. Furthermore, a report on how to use and integrate sediment data is being drafted, again to assist new clients. The intent of these efforts is to increase the ease and effort required to locate and use these data. Increased awareness and marketing of products to clients is of paramount importance to maximizing benefits and the future success of this program.

CONCLUSIONS AND RECOMMENDATIONS

In conclusion, a program of sediment data collection has evolved from a long term, detailed, spatially limited, expensive network, to a network that is designed to respond to most data users needs and to the current environmental problems and issues. Results include: improved spatial coverage at similar costs, new data sets and a quicker response to today's needs which includes Federal Departmental concerns and new environmental clients.

With all but a few (12) tributaries to the Great Lakes unmonitored, the network of Ontario when managed efficiently, should provide data users and Federal-Provincial and International needs, with an accurate set of suspended sediment data.

It is recommended that continued refinement of data collection procedures, and data anaylses techniques be pursued to satisfy the growing need for accurate reliable sediment data, both for qualitative and quantitative purposes and programs.

LIST OF REFERENCES CITED

Binda, G.G. 1987, Sediment Data Reference Index for Ontario, Environment Canada, Inland Waters Directorate, Water Resources Branch, Ontario Region, 1987.

Binda, G.D. 1989, Sediment Station Analysis, Humber River near Elder Mills 02HC025, Sediment Survey Section, Environment Canada, Inland Waters Directorate, Water Resources Branch, Ontario Region, 1989.

Conservation Management Systems, Sediment Issues and Data Needs in Ontario; March 1986.

Day, T.J. 1987, Station Management Plan, Sediment Survey Section, Ottawa, Environment Canda, Ottawa, Canada, 1987.

Dickinson, W.T. and Green, D.R., 1987. Characteristics of Sediment Loads in Ontario Stream. Can. Journal Civ. Eng. 15 1067-1079 (1987).

Dickinson, W.T. 1990, Ontario Sediment Data - A User's Manual (Draft Report March 1990) Environment Canada, Inland Waters Directorate, Water Resources Branch, Ontario Region, 1990.

Environment Canada, Sediment Data, Ontario, 1984, Inland Waters Directorate, Water Resources Branch Water Survey of Canada, Ottawa, Canada, 1986.

McIlhinney, J. 1986, Station Review Plot Package, Sediment Survey Section, Environment Canada, Ottawa, Canada, 1986.

Smith, B.D. 1983. Ontario Region Miscellaneous Sediment Station Network Proposal, Sediment Surveys, Ontario Region, Environment Canada, Inland Waters Directorate, Water Resources Branch.

Smith, B.D. 1987 Sediment Station Analysis, Big Creek near Walsingham 02GC007, Sediment Survey Section Environment Canada, Inland Waters Directorate, Water Resources Branch, Ontario Region, 1987.

HYDROGRAPHIC SURVEYING IN CANADA'S SEDIMENT PROGRAM

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ABSTRACT

Technological developments are traced to show how they impacted upon the hydrographic surveying capability in Canada's sediment program. The importance of hydrographic data in providing a more complete understanding of sediment processes is highlighted through a number of studies. Innovative uses of hydrographic data ensures that hydrographic surveying will continue to be a valuable approach to addressing sediment concerns.

INTRODUCTION

History

Hydrographic surveying became an integral part of the sediment program in the 1960s with the initiation of two major related International Hydrological Decade (IHD) projects. The first dealt with measuring bed degradation downstream of the newly formed Lake Diefenbaker in Saskatchewan, and the second, dealt with monitoring sedimentation in the man-made lake. The conventional surveying methods that were used in these early years were both tedious and labour intensive and therefore these projects required a major program commitment. As a result, limited studies of this nature were initiated elsewhere in Canada.

In the 1970s technological advances made it possible to automate the data collection procedures and to greatly increase the program's surveying capabilities. This in turn led to numerous reservoir capacity surveys being initiated across Canada (Yuzyk, 1984). Other applications for the data: delta development, bed degradation, bed-load transport, hydraulic geometry, morphological studies, etc., resulted in the rapid increase in the number of studies being undertaken. To date there are 23 sites in Canada where hydrographic data have been collected by the sediment program to address a particular sediment concern (Figure 1).

Purpose and Scope

Technological developments in hydrographic surveying are traced to show how they impacted upon the type, extent and number of surveys that were undertaken. This paper reviews the findings from a number of these studies to show how they have contributed to our understanding of sediment processes. Some innovative applications for using hydrographic data to address sediment transport are briefly discussed.

HYDROGRAPHIC SURVEYING

Collection Methods

Initially, hydrographic surveying in the sediment program was manually oriented. A tag line, or triangulation by means of a transit, were used for

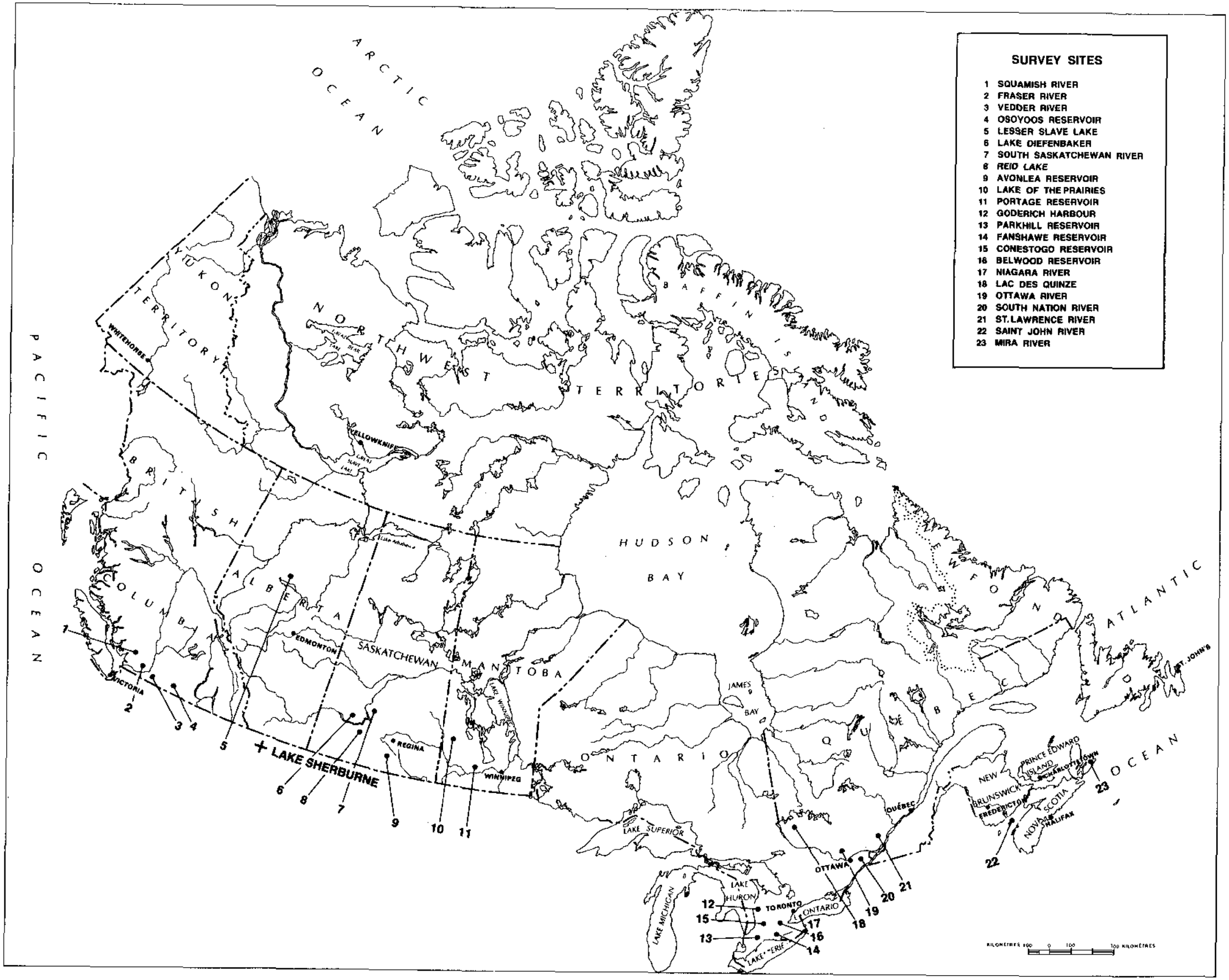

FIGURE 1: HYDROGRAPHIC SURVEY SITES ACROSS CANADA

positioning; and, a wading rod or weighted line were used for measuring depth. Thus, to survey a single cross section required a considerable amount of effort. During the 1960s relatively small reservoir surveys could take in the order of months to complete. A quantum leap in surveying capabilities was made with the introduction of the echo sounder for continuously recording depth, and dynamic electronic distant measuring equipment for more precise and quicker positioning. Even though these developments certainly improved surveying capabilities, compiling the data still proved to be a tedious task.

In the early 1970s a system's approach was adopted towards hydrographic surveying and the ability to collect, process and analyze large amounts of data quickly became a reality. A fully automated hydrographic data acquisition system - HYDAC-100 and computer driven hydrographic data reduction and analysis system - HYDRA were developed. Both these systems have been upgraded considerably over the years to account for technological advances. A second generation system (HYDAC-200) is currently in use.

HYDAC-200

A brief description of this system is provided in this paper, but for more details one should refer to Durette and Zrymiak (1978). The system is housed on a 10 metre, shallow-draft (0.3 m) water jet driven vessel, which is easily transported by trailer (Figure 2). The HYDAC-200 system is comprised of four sub-systems: positioning, depth-sounding, data processing and survey control, and data logging (Figure 3).

Positioning in the dynamic mode is achieved using a MRD-1 Tellurometer system. Two remotes are placed on shore in the most effective configuration for surveying. The master remains in the vessel and monitors the distance to the remotes. These units have an accuracy, in the dynamic mode, of ±1.0 metre over a maximum range of 100 km, assuming reasonable line-of-sight conditions.

Water depth is measured by means of a Krupp-Atlas Deso 10 depth sounder. It uses two transducers: a 210 kHz for low density deposits and a 33 kHz for detecting consolidated material. The sub-system is considered to be accurate to within 5 cm up to a depth of 100 metres.

The data processing and survey control sub-system monitors the various measuring instruments. It coordinates the data entry so that a data point (2 distances, depth, time, plus housekeeping characters) is capable of being collected every second under normal operating conditions.

Finally, the data logging sub-system is responsible for the storage of the data on magnetic field tape, as well as producing a hard copy printout for backup purposes and a quick visual check of the incoming data.

HYDRA

After the survey, the field tapes are brought to the office where they are dumped onto disk and data processing begins using the 377K memory mainframe computer (CYBER 730). The data are analyzed following a well defined set of procedures (Figure 4) in the HYDRA system (McIlhinney, 1987). Final products vary from simple cross-sectional plots to more elaborate colour contour and three-dimensional outputs. Numerous tabular outputs (e.g. capacity tables) can also be obtained.

FIGURE 2: Y.J. DURETTE SURVEY VESSEL

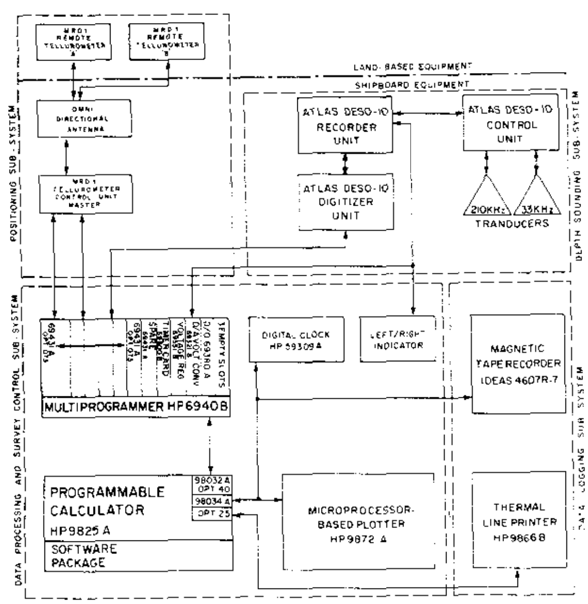

FIGURE 3: HYDAC-200
HYDROGRAPHIC DATA ACQUISITION SYSTEM

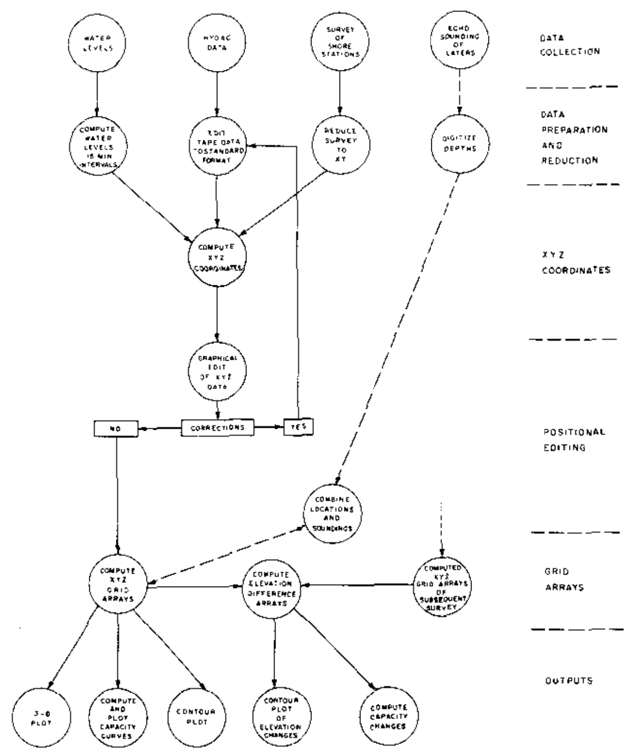

FIGURE 4: HYDRA
HYDROGRAPHIC DATA REDUCTION AND ANALYSIS SYSTEM

System Accuracy

Capacity studies undertaken over the years have shown that this system produces reliable results. For instance for Lake Sherburne (Montana), where sedimentation is negligible, the survey derived capacity was within 2% of the original (1924) topographically derived capacity.

To assess the repeatability of the system a square kilometre section of the Ottawa River was surveyed four times. The results show that the system is consistent, as the largest deviation for an individual survey from the mean (of all four surveys) was less than 1.5%.

INTERNATIONAL HYDROLOGICAL DECADE PROJECTS

Lake Diefenbaker, Saskatchewan (#6)

Filling of the 225 km-long Lake Diefenbaker, located in the semi-arid prairie region of southern Saskatchewan (Figure 5), began in 1964 and full supply level (FSL) reached in 1968. The reservoir has a design capacity of 9.4 million dam^3 (1 dam^3 = 1000 m^3), of which 4.0 million is live or useable storage. The South Saskatchewan River transports, on average, 8.0 million dam^3 of water and deposits 5.5 million tonnes of suspended sediment into the reservoir annually. Approximately 80% of the suspended sediment load is made up of fines (silt and clay). The reservoir is considered to have a 100% trapping efficiency.

To monitor sedimentation and delta formation 38 permanent cross sections were established along the full length of the reservoir (Figure 5). Surveying was initiated in 1966 and the latest survey completed in 1980. Most of the cross sections have been surveyed 3 to 4 times over this period. Other data that were collected during these surveys include: suspended sediment, bed material and temperature. Within the reservoir three large area surveys have been completed to provide more detailed information on the changes.

Based on a comprehensive analysis of these data, Yuzyk (1983) found that the sediment was being deposited over a 64 km-long section of the reservoir (Figure 6). The large drawdown (11 m), low original bed slope (0.00022) and narrow configuration determined this sedimentation pattern. The maximum deposition was measured to be ≈ 2 m (cross-sectional mean) at R-27. Volumetrically, these changes translate into an average 0.1% per year loss in total storage capacity, about half of this change affecting live storage.

Extensive bank erosion was an important factor in interpreting volumetric changes. Recession rates in the order of many m/yr are common along the length of the reservoir and contributes a considerable amount of sediment. Measured deposited densities of the sediment were found to be significantly lower than values calculated from the commonly used Lane and Koelzer method. These two factors were taken into account in deriving a good agreement (13%) between sediment station loading data and survey derived estimates.

The Lake Diefenbaker surveys have helped provide us with a more complete understanding of sedimentation patterns that occur in a reservoir. This knowledge has, in turn, been used in planning numerous other reservoir surveys. Much of the development and testing of the HYDAC is attributed to this project as well. The hydrographic data have also been used extensively to address many site specific concerns (e.g. water intakes, marinas, etc.).

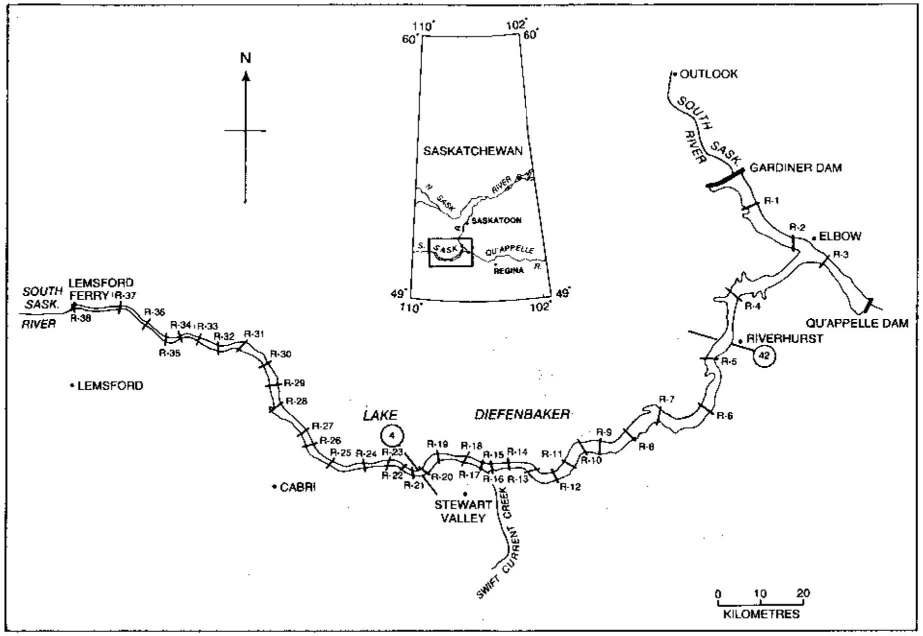

FIGURE 5: LAKE DIEFENBAKER RANGE LOCATION MAP

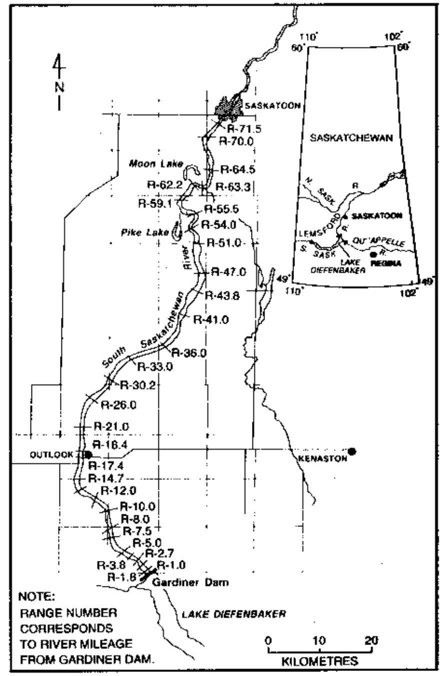

FIGURE 7: SOUTH SASKATCHEWAN RIVER RANGE LOCATION MAP

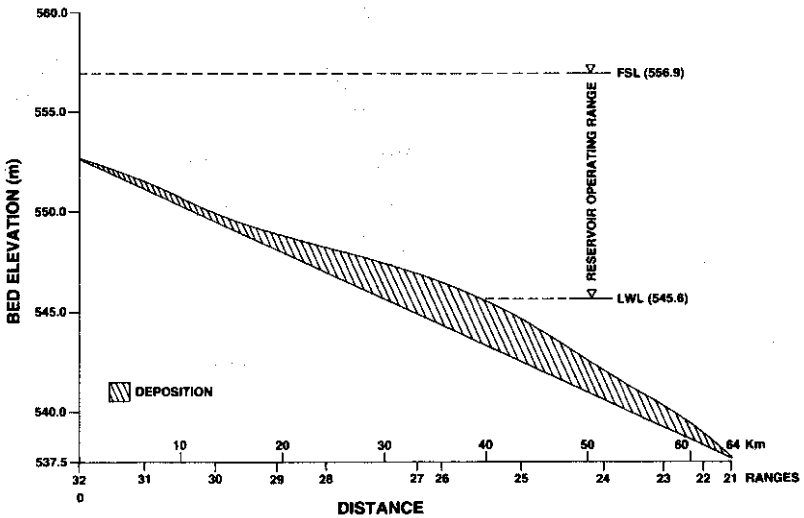

FIGURE 6: LAKE DIEFENBAKER LONGITUDINAL PROFILE

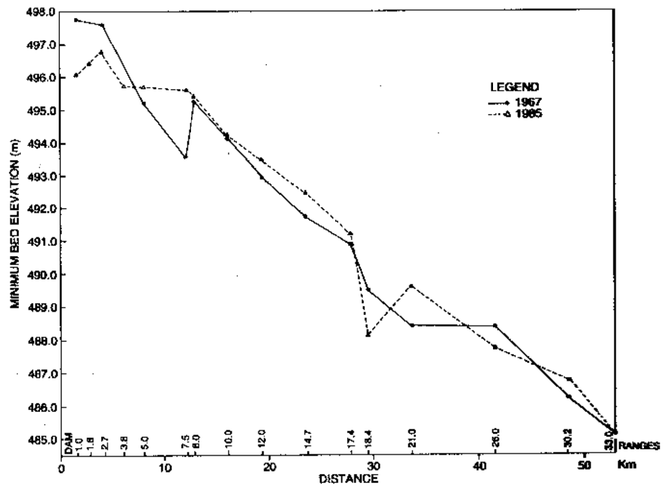

FIGURE 8: SOUTH SASKATCHEWAN RIVER LONGITUDINAL PROFILE

South Saskatchewan River, Saskatchewan (#7)

Regulation, due to Lake Diefenbaker, resulted in significant changes to both the flow and sediment regimes of the South Saskatchewan River. Based on station data collected at Saskatoon, post-reservoir peak discharge is 60% lower, while total annual flow is 30% lower than pre-reservoir conditions. Station data also showed that virtually 100% of the suspended sediment is being trapped in the reservoir. Initially, twenty-seven permanent cross sections were established between Gardiner Dam and Saskatoon to monitor the impact of these changes on channel morphology (Figure 7). These cross sections have been manually surveyed and bed-material data collected on an annual basis starting in 1967.

Up until 1980, surveys covered the reach from the dam to Saskatoon. Based on an evaluation conducted by Northwest Hydraulic Consultants Ltd. (1980) the survey area was reduced to extend only to Outlook and two new cross section (R-1.8 and R-3.8) were established to provide better definition of the changes that were primarily occurring near the dam. A slowing bed degradation rate has resulted in the survey interval being extended to 5 years.

According to Yuzyk (1987), bed degradation is apparent for the first 6 km below the dam then aggradation becomes the dominant process (Figure 8). The largest changes were measured at R-1.0 where the channel width has been reduced by 66% and the bed incised 1.7 m below the original bed level. The degradation rate slowed dramatically 5 years after dam closure. Bed armouring is a significant factor as the median grain size (D_{50}) was recorded to have increased from 0.24 mm (1968) to 2.50 mm (1985) at R-1.0. Low peak releases from the dam during the late 1970s and early 1980s also contributed to the low degradation rate.

This project provided a unique data set which has been used to evaluate HEC-6 capabilities (NHCL, 1980), and to develop and evaluate the MOBED flow model (Krishnappan, 1985). The information on degradation and armouring obtained from these surveys have made a significant contribution to our general understanding of these processes.

OTHER SURVEYS

Goderich Harbour (Lake Huron), Ontario (#12)

Area surveys were undertaken annually (1984-1988) on Goderich Harbour, located on the east side of Lake Huron, to determine the impact of a newly installed breakwater on sediment processes (Bishop and Zrymiak, 1990). The surveys show that the breakwater has not increased sedimentation in the Maitland River as was speculated. The restriction has, in fact, increased the velocity in the main channel so that some minor scouring is occurring. A salt mine located directly below the harbour has resulted in the subsidence of 0.5 m between 1984-1988, which certainly affected interpreting the results. Confidence in the survey results was instrumental in uncovering the subsidence problem. The continued impact of these changes will require further analyses.

Fraser River, British Columbia (#2)

The Fraser River has been a test site for a number of innovative applications of hydrographic data. The "Hydrographic Method" (Engel and Wiebe, 1979) was developed for computing bed-load transport rates based on tracking dune movement. Laboratory flume tests showed that this method calculates the bed-load discharge within 40% at the 95% confidence level. Field tests conducted in 1978 were inconclusive, as a low freshet resulted in too low a transport rate for measurement. These field tests still need to be repeated to verify this field approach to bed-load transport.

Mclean (1990) used an extensive amount of hydrographic data, collected from a 80-km gravel-bed reach of the Fraser River, to determine the bed-load transport rate. Channel changes were used to determine sediment transfer through the reach. This "macroscopic" approach was found to provide more meaningful results, when compared to short term bed-load sampling programs and estimates derived using bed-load equations.

CONCLUSIONS

The numerous surveys conducted over the years in Canada have helped to address a variety of sediment concerns, such as: reservoir sedimentation, bed degradation, etc. Sophisticated data collection (HYDAC) and reduction (HYDRA) systems have enabled more comprehensive, accurate information to be obtained in the last twenty years. This is in turn has helped provide us with a better understanding of depositional, erosional and armouring processes in a variety of hydraulic and morphologic settings. Innovative uses of hydrographic data to quantify bed-load transport and determine sediment budgets based on sediment transfer through a reach will ensure a growing need for hydrographic data in years to come.

REFERENCES

Bishop, C.T., and Zrymiak, P., 1990, Impact of the rubblemound breakwater at Goderich Harbour on coastal and fluvial processes. National Water Research Institute, Environment Canada.

Durette, Y.J., and Zrymiak, P., 1978, "HYDAC-100 - an automated system for hydrographic data acquisition and analysis". Technical Bulletin #105. Water Resources Branch, Environment Canada.

Engel, P., and Wiebe, K., 1979, A hydrographic method for bed load measurement. In: CSCE Fourth National Hydrotechnical Conference. Vancouver, British Columbia.

Krishnappan, B.G., 1985, Comparison of MOBED and HEC-6 river flow models. Can. J. Civ. Eng., Vol. 12, 464-471.

Mclean, D.G., 1990, The relationship between channel instability and sediment transport on the lower Fraser River. Doctor of Philosophy, University of British Columbia. Vancouver, British Columbia.

McIlhinney, J.P.L., 1987, Hydrographic data reduction and analysis system manual - HYDRA. Water Resources Branch, Environment Canada.

Northwest Hydraulic Consultants Limited, 1980, South Saskatachewan River, sedimentation studies - degradation. Water Resources Branch, Environment Canada.

Yuzyk, T.R., 1983, Lake Diefenbaker, Saskatchewan: a case study of reservoir sedimentation. Water Resources Branch, Environment Canada.

Yuzyk, T.R., 1984, Reservoir sedimentation studies in Canada. Water Resources Branch, Environment Canada.

Yuzyk, T.R., 1987, Bed degradation of the South Saskatchewan River below Lake Diefenbaker. Water Resources Branch, Environment Canada.

COMMENTS ON SAMPLING BEDLOAD IN SMALL RIVERS

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ABSTRACT

In most natural streams, bedload-transport rates are highly variable in time and space. The temporal and spatial scales at which significant transport-rate variations occur, and the time and effort often required to obtain even a few samples, make the sampling and measurement of bedload substantially different than measurements of streamflow and suspended-sediment load that are routinely undertaken at gaging stations. The accuracy of an estimate of the mean cross-sectional bedload discharge largely depends on the degree to which the temporal and spatial rate variations have been averaged by the sampling program adopted. Currently, no substantive guidelines for the design of bedload-sampling programs exist. Neither is a single sampling device universally accepted, or considered to be capable of adequately sampling all sizes of material transported as bedload under all flow conditions. Some factors influencing the choice and use of bedload samplers are discussed, and suggestions are made about the way in which sampling programs for streams less than about 30 meters wide may be designed.

INTRODUCTION

Bedload sampling involves three temporal elements: the **sampling time or sampling duration** (the length of time the sampler remains on the bed); the **sampling interval** (the length of time that elapses between consecutive samples); and the **sampling period** (the total time, or the sum of the sampling times and sampling intervals). In some situations, the sampling time may depend on the capacity of the sampler. In the case of cross-channel sampling, the sampling period is likely a consequence of the number of samples collected rather than the specified sampling time and sampling interval. A distinction is often made between **bedload-transport rates** (local, mean values); and **bedload discharge** (the total or a unit-width mean value). Strictly speaking, at-a-point and cross-channel bedload-sampling programs provide an estimate of the mean bedload-transport rate and mean bedload discharge. Only streamwide bedload traps provide measurements of bedload discharge.

Bedload is known to vary over a range of temporal and spatial scales. For example, Figure 1 illustrates the magnitude of the temporal and spatial variations that are typically encountered, under relatively constant flow conditions, in the East Fork River, Wyoming. Temporal variability in bedload-transport rates, which is independent of variations in flow conditions, arises from three principle sources (Gomez et al., 1989). First, variations may result from long- to intermediate-term changes in the rate at which sediment is supplied to or distributed within a channel or reach. Second, short-term, often quasi-cyclic, variations in bedload-transport rates may occur in response to the temporary exhaustion of the supply of transportable material, to the migration of bedforms or groups of particles, or to processes such as armoring. Third, instantaneous fluctuations in bedload-transport rates result from the inherently stochastic nature of the physical processes that govern the entrainment and transport of bedload. Spatial variability in bedload-transport rates results from downstream and cross-channel changes in the

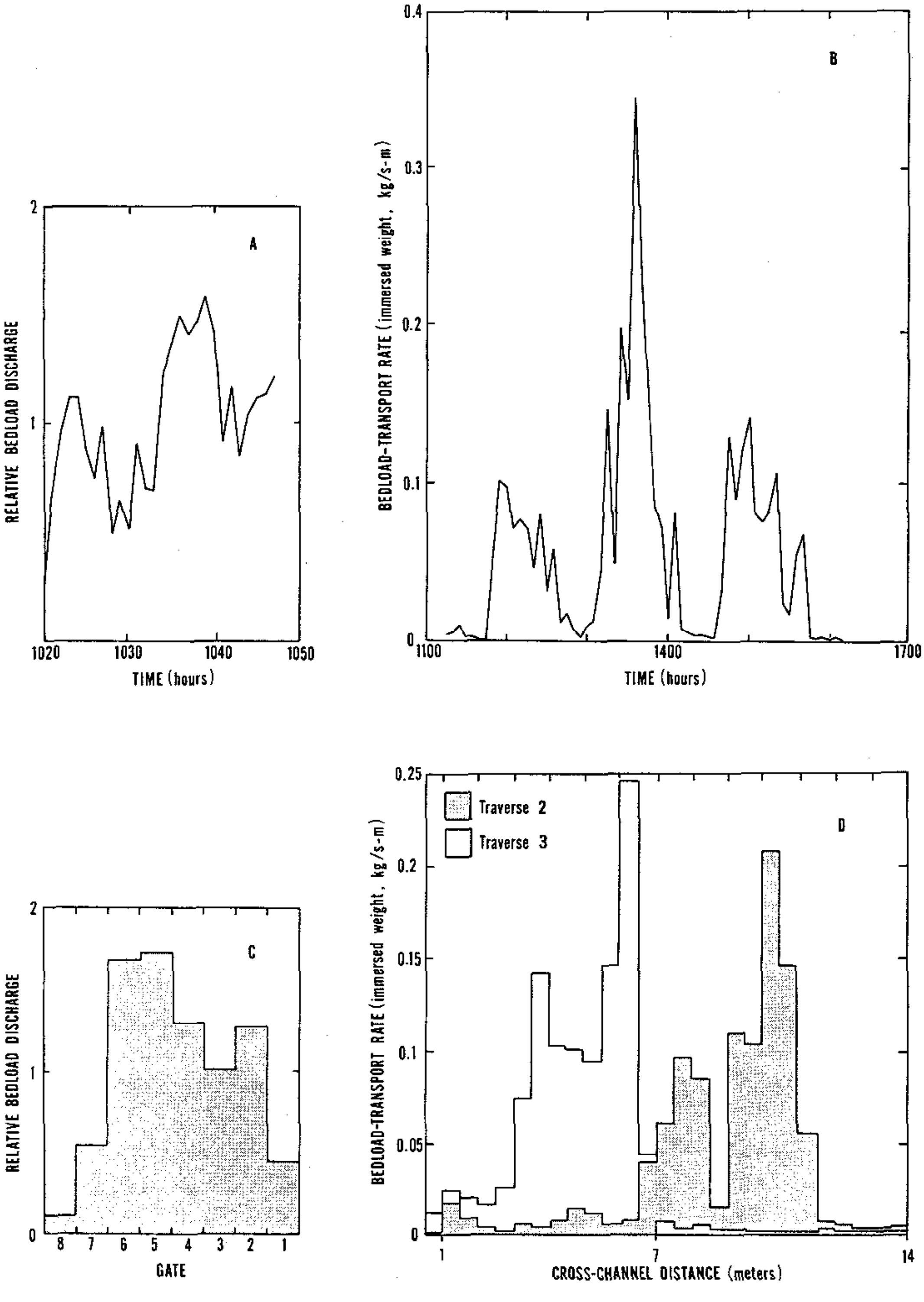

FIGURE 1. Temporal and spatial variations in bedload-transport and bedload discharge rates, East Fork River, Wyoming. A) Streamwide temporal variations in relative bedload discharge measured at the bedload trap, 27th May 1976. Measurement time = 60 s. Mean rate = 0.015 kg/s-m, immersed mass. B) At-a-point temporal variations in sampled bedload-transport rates, 5th June 1988. Sampling time = 30 s, sampling interval = 270 s. Mean transport rate = 0.057 kg/m-s. C) Spatial variations in relative bedload discharge measured at the bedload trap, 5th June 1976. Average of 30 measurements. Measurement time = 60 s. Mean rate = 0.057 kg/m-s. D) Spatial variations in sampled bedload-transport rates, 5th June 1988. Sampling time = 30 s. Mean transport rate: traverse 2 = 0.038 kg/m-s; traverse 3 = 0.036 kg/m-s.

transport field, that occur primarily in response to differences in the shear stress and to changes in the local relation between boundary shear stress and sediment transport (Dietrich and Whiting, 1989).

It has long been accepted that, in order to provide an accurate estimate of the mean bedload discharge, (1) at each sampling point, either a large number of short-duration samples must be collected or the sampling time must be long; and (2) samples must be obtained from a number of points across the section (Einstein, 1948; Hubbell, 1964). The accuracy of an estimate of the mean bedload discharge largely depends on the degree to which the actual temporal and spatial rate variations have been averaged by the sampling procedure that is adopted. Long- to intermediate-term temporal variability in bedload-transport rates may be difficult to document because of the lengthy sampling period required to establish its existence. The period of the briefest oscillation in bedload-transport rates that practicably may be identified is about the same as the duration of the sampling time. Short-term temporal variations in bedload-transport rates, that occur over time periods that range from the scale of the sampling time (seconds) to the sampling period (hours), and short-term cross-sectional variations are usually averaged.

One purpose of this paper is to indicate ways in which practical bedload-sampling programs may be designed to minimize the impact of temporal and spatial variability in bedload-transport rates on estimates of bedload discharge. Our comments are based on experience of sampling bedload in a wide variety of field situations, on the results of laboratory and field trials of various types of pressure-difference samplers, and on statistical analyses of the errors involved in sampling. In making these suggestions, we recognize that no one sampler design is adequate for all the various sizes of material and hydraulic and transport conditions encountered in natural streams. It is accepted that, at present (1991), the sampling efficiencies and characteristics of the many different types and configurations of samplers are imperfectly understood. Because this is the case, arguably it is unnecessary for any sampler to be designed with an efficiency of 100 percent (Einstein, 1948); data collected with any sampler may always subsequently be adjusted in the light of the best available estimates of the device's sampling efficiency (cf. Hudson, 1983). However, the degree to which any subsequent adjustment of the data will enhance its reliability depends not only on the completeness of the calibration but also on the manner in which the sampler was deployed. Currently, we consider that errors due to the imperfect design or calibration of any given sampler probably are small compared with those errors that are due to poor sampling techniques.

SAMPLER SELECTION

Pressure-difference samplers are commonly constructed to approximate specific hydraulic and sediment-trapping efficiencies and are often adequate to measure bedload. Pressure-difference samplers of the design developed by Helley and Smith (1971) are probably the most common sampling device in use today (1991). The Helley-Smith sampler has a nozzle with a short (88.9-mm-long), box-like entrance section attached to a slightly longer (114.3-mm-long) expansion section. The nozzle has 6.35-mm-thick walls, and a 76.2 by 76.2 mm entrance. The expansion section has a horizontal flare of 30° on each side and a vertical flare of 16° on the top (Helley and Smith, 1971, Figure 2, p. 5). A tapered sample bag about 500 mm long (surface area approximately 0.2 m^2), fabricated from non-wetting monofilament mesh, is attached to the rear of the nozzle. (Although 0.2-mm mesh was used in the original design, the most common mesh size is 0.25 mm.) Depending on construction details pertaining to the manner in which the mesh bag is attached to the sampler, the expansion section may have an exit-to-entrance ratio ranging from 3.2 to 3.7. Much of the literature describing the area ratio refers to a value of 3.22. This value reflects the bag attachment scheme of the original design (Helley and Smith, 1971, Figure 2). Other schemes tend to result in somewhat larger values for the area ratio. For the given nozzle geometry, flow separation occurs at an area ratio of about 2.0; nozzles with area ratios greater than about 2.0 have similar hydraulic characteristics. The Helley-Smith sampler has a hydraulic efficiency of approximately 1.54 (Druffel et al., 1976) and a putative, field-determined, sediment-trapping efficiency of 100 percent (Emmett, 1980). Laboratory studies (Hubbell et al., 1981 and 1986) indicate that the sediment-trapping efficiency is greater than 100 percent. The sampler may be mounted on a wading rod or attached to a weighted frame and suspended from a cable.

In the United States, the original Helley-Smith sampler, with 0.25-mm mesh sample bag, or samplers with geometrically scaled-up or scaled-down versions of the nozzle (cf. Emmett, 1976; Gomez, 1983) have been used extensively during the last 20 years. Geometrically scaled versions of the Helley-Smith sampler nozzle appear to roughly preserve the hydraulic and sediment-trapping efficiencies of the original design (Druffel et al., 1976; Hubbell et al., 1981 and 1986). A modified version of the Helley-Smith sampler was tentatively recommended for general use by the Technical Committee of the Federal Inter-Agency Sedimentation Project (FISP). This nozzle has a 76.2 by 76.2-mm entrance, an area ratio of 1.4, an estimated hydraulic efficiency of 1.35 and a reported sediment-trapping efficiency of about 100 percent (Hubbell et al., 1981 and 1986). A larger, modified version of the FISP sampler, which has a 304.8-mm-wide by 152.4-mm-high entrance and an area ratio of 1.4, has been primarily used to sample coarse gravel bedload (Childers et al., 1989). This sampler apparently has a roughly similar sediment-trapping efficiency to the FISP-recommended sampler (Hubbell et al., 1981 and 1986).

It is assumed that appropriate measures will be taken to ensure the proper use of a sampler in the prevailing flow conditions. If the sampler is operated from a cable, it should be suspended in a tail-down attitude and attached to a stayline to minimize cross-stream and downstream drift. This attitude discourages gouging by the nozzle during placement, scooping on retrieval, and unintentional dumping of the sample. The frame should be adequately weighted and should incorporate a tail assembly to help align the sampler in the flow direction. The physical conditions in the channel should permit the sampler to lie in firm contact with the bed surface and to be maintained in a stable position. In the absence of a complete calibration for any sampler, a principal factor influencing the choice of sampler is the particle size of the bedload. To minimize the chance of particles obstructing the nozzle, it is desirable that the nozzle entrance be at least twice the size of the largest particle likely to be in motion.

Probably in the interests of maintaining consistency in sampling programs within the United States, pressure-difference type samplers used routinely in the field have been restricted to: (a) exact copies of the FISP-recommended sampler or the modified version; and (b) carefully constructed copies or geometrically scaled versions of the original Helley-Smith sampler.

Subsidiary factors that may affect sampler performance include the size of the sample bag and the size of the mesh (Johnson et al., 1977; Beschta, 1981). The sample bag should not be filled to more than about 40 percent capacity (Druffel et al., 1976). Thus, in the case of the 76.2 by 76.2-mm Helley-Smith sampler and a bedload-transport rate of about 2 kg/s-m - immersed mass, the sampling time should not exceed 30 s. Larger sample-collecting bags probably may be used without adversely affecting sampler performance. A coarse mesh may prevent fine sediment and organic debris from clogging the sample bag. However, care should be taken to select a mesh size that minimizes both clogging and the loss of fine fractions of the bedload through the mesh.

SAMPLING PROCEDURES

Much bedload data from the United States have been obtained from rivers less than 30 m wide (cf. Williams and Rosgen, 1989). In this paper, discussion is limited to sampling procedures applicable to single-thread channels less than 30 m wide. It is not impossible to obtain representative estimates of bedload discharge from other rivers but, at present (1991), logistical constraints probably make it difficult to do so on a routine basis. At-a-point sampling emphasizes temporal aspects of bedload and provides insight into transport processes. Cross-channel sampling emphasizes spatial aspects of bedload and provides insight into at-a-section behavior. Reliable estimates of bedload discharge are dependent on good at-a-point knowledge across the full width of the channel.

At-a-Point Sampling

In theory, any number of random at-a-point samples may be used to provide an estimate of the mean bedload-transport rate prevailing at a given point, providing that a probability level is specified. A truly random sequence of bedload samples is almost impossible to obtain in the field. Thus, most at-a-point samples that are collected are sequential and probably are serially correlated. With steady-flow conditions, two factors, the number of samples and the length of the sampling time, exert an influence on the variance associated with an estimate of the mean bedload-transport rate. Under conditions where coherent bedforms exist, the variance for a specified number of samples may be large if the sampling time is short in comparison to the length of time that it takes a bedform to migrate past the sampling point. The variance of estimates of the mean transport rate also may be large when only a small number of samples is used to define the mean value. For any given transport condition, lengthening the sampling time reduces the variance of estimates of the mean bedload-transport rate. However, in most instances the sampling time is limited by the sampler capacity. A reliable estimate of the mean bedload-transport rate may be obtained from about 21 sequential samples, provided at least one entire bedform passes the sampling point (Gomez et al., In Press). Where the sampling time is short (about 30 s), ordinarily an adequate degree of independence between the samples may be maintained by ensuring that the sampling interval is relatively long (more than 300 s). The sampling period ideally should be long enough to document the passage of multiple bedforms past the sampling point. The effects of non-stationarity may be minimized by ensuring that the sampling interval does not coincide with the period of the bedforms. When the above criteria are met, an estimate of the observed mean relative bedload-transport rate should fall within ±50 percent of the true mean relative rate, at the 99 percent confidence level. (The relative transport rate is the measured rate divided by the mean rate.) However, between 50 and 100 samples are required to define the complete distribution of at-a-point bedload-transport rates (Gomez et al., In Press).

Cross-Channel Sampling

Hubbell (1987) investigated errors in the mean cross-channel bedload discharge derived from averaging rates from different numbers of equally spaced sampling points with different lateral distributions of transport rates. In general, errors decrease as the number of sampling points across the channel increases. Emmett (1980) suggested that about 20 equally spaced sampling points were required to ensure that zones of maximum and minimum transport are adequately sampled. However, because temporal as well as spatial variations in bedload-transport rates affect an estimate of the mean bedload discharge derived by averaging all sampled rates, Emmett (1980) suggested that two 20-position traverses were required to accommodate spatial and temporal variability. Conversely, Hubbell (1987) argued that sampling should be undertaken repetitively to define acceptably accurate mean rates only at those points required to determine the lateral distribution of mean rates.

There is a dearth of knowledge concerning the factors that control spatial variability in bedload-transport rates, and there is no means of predetermining unequivocally which points must be sampled to determine the lateral distribution of mean rates. Thus, it appears prudent to sample as many locations as possible, although, there often may be no reason to exceed 20 sampling points per traverse. Also, where two-dimensional dunes are present, it is reasonable to assume that lateral rate variations will occur gradually. In general, for the small streams considered in this paper, it seems unnecessary to sample at less than 0.5-m intervals and undesirable to sample at greater than 2 to 3-m intervals.

Because of temporal variability at each cross-channel location, one or two traverses ordinarily may not provide information about the cross-sectional distribution of mean bedload-transport rates. Also, generally the average of rates from a single traverse may be insufficient to provide an acceptable estimate of the mean bedload discharge. Carey and Hubbell (1986) advised that little reliance can be placed on any mean value derived from fewer than five random at-a-point bedload samples. Although this conclusion does not directly apply to the problem of cross-section sampling, it would appear appropriate if the mean bedload discharge is computed by averaging samples using at-a-pont rates from a minimum of five traverses. This procedure seems reasonable as, in reality, even though the time at which the first point is sampled may be predetermined, the time that it takes to sample each point and move on to the next varies. In consequence, the time taken to complete each traverse and return to the initial sampling point varies, and the likelihood of any point being sampled at regular intervals is small. Thus, the phasing of rate sequences between adjacent points probably will be random. Samples should preferably be collected at regularly spaced intervals across the section unless the lateral distribution of mean rates is known. In this case, the sampling verticals may be irregularly spaced. More (greater than 5) samples may be collected at verticals where the mean at-a-point rates is high than in locations where it is low. The suggested number of samples per traverse and number of traverses generally will generate more samples than routinely are collected at present (1991). However, the number of samples may be constrained by hydrological and logistical practicalities.

Logistical Considerations

Most sampling programs represent a compromise between logistical constraints and accuracy. A number of factors, including the time and cost involved in implementing a sampling program, influence how many samples practicably may be obtained with the available resources. Variations in the flow conditions also profoundly affect bedload-discharge rates. Usually there is a finite time period available to collect samples that realistically may be used to characterize the bedload-discharge rate associated with specific flow conditions. The flow conditions ideally should remain constant throughout the sampling period. It often takes one person 5 or more minutes to collect and store a bedload sample and move on to the next sampling point.

Flow conditions that change rapidly and logistical constraints may prohibit the establishment of a comprehensive sampling program. In such circumstances it may only be possible to define the mean bedload-transport rate at a limited number of sampling points across the channel. This information can then be used to estimate the lateral distribution of mean rates from which a cross-section mean can be determined.

DATA ANALYSIS

Until such time as sampling procedures are formalized, it is desirable that at-a-point and cross-sectional means be specified. Every individual sample should be weighed and sieved because subsequent adjustments of the data may depend on the particle-size distribution and the weight of individual samples. Where this is not practical, and the flow conditions remain relatively constant throughout the sampling period, samples obtained from the same point on different traverses may be weighed individually and then composited for size analysis. Samples should be composited by traverse only as a last resort.

SUMMARY

Understanding the bedload-transport process depends not only on knowledge gained from detailed research projects designed to investigate specific problems, but also on data that routinely are collected. Satisfactory estimates of mean bedload discharge may be obtained only by sampling according to an individually planned effort designed to account for the unique situations encountered at individual sites. For the determination of bedload discharge, it is desirable to establish rigorous, standardized procedures that are flexible enough to apply to as wide a range of conditions as possible. Because the collection of bedload data is costly, all data obtained should be salvageable regardless of future changes in ideas and policy. Thus, our suggestions err on the conservative side. In the future, it is possible that the procedures we advocate will be relaxed.

For the present:

1) only exact copies of the FISP-recommended or modified nozzle, or carefully made copies and geometrically scaled versions of the original Helley-Smith nozzle should be selected for field use.
2) a principal factor determining which type and size of sampler to use is the size of the bedload. In the absence of unequivocal information to the contrary, the FISP-recommended and the Helley-Smith samplers probably may be considered to be interchangeable in field use. A sampler with a wide entrance may be used to sample coarse gravel bedload. In all sampling situations, care should be taken to ensure that sampler efficiency is not impaired because the sample bag becomes clogged.
3) rivers less than about 30 m wide should be sampled at not less than 0.5-m and not greater than 2 to 3-m intervals. Sampling should preferably be undertaken at equally spaced points across the channel unless the lateral distribution of mean at-a-point rates is known.
4) multiple traverses are preferred to compute the cross-channel mean bedload discharge and fewer than two traverses are considered unsatisfactory.
5) where the flow conditions change rapidly or logistical constraints prohibit more detailed sampling, emphasis may be placed on collecting samples at a limited number of (regularly spaced) points across the channel.

6) each sample should be bagged and weighed and its particle-size distribution be determined.

REFERENCES

Beschta, R. L., 1981, Increased bag size improves Helley-Smith bedload sampler for use in streams with high sand and organic matter transport, Internatl. Assoc. Sci. Hydrol. Publ., 133, 17-25.

Carey, W. P., and Hubbell, D. W., 1986, Probability distributions for bedload transport, 4th Fed. Inter-Agency Sed. Conf., Proc., 2, 131-140.

Childers, Dallas, Huanjing, Gao, Gangyan, Zhou, 1989, Field comparison of bedload samplers from the United States of America and the Peoples Republic of China, 4th Internatl. Symp. River Sedment., Proc., 2, 1309-1316.

Dietrich, W. E., and Whiting, P. J., 1989, Boundary shear stress and sediment transport in river meanders of sand and gravel, in: River Meandering, Ikeda, Syunsuke and Parker, Gary (eds), Am. Geophys. Union, Washington, D.C., 1-50.

Druffel, Leroy, Emmett, W. W., Schneider, V. R., and Skinner, J. V., 1976, Laboratory calibration of the Helley-Smith bedload sediment sampler, U. S. Geol. Survey Open-File Rept. 76-752, 63 p.

Einstein, H. A., 1948, Determination of rates of bedload movement, 1st Fed. Inter-Agency Sed. Conf., Proc., 75-93.

Emmett, W. W., 1976, Bedload transport in two large, gravel-bed rivers, Idaho and Washington, 3rd Fed. Inter-Agency Sed. Conf., Proc., 1100-1115.

Emmett, W. W., 1980, A field calibration of the sediment-trapping characteristics of the Helley-Smith bedload sampler, U. S. Geol. Survey Prof. Paper 1139, 44 p.

Gomez, Basil, 1983, Temporal variations in bedload transport rates: the effect of progressive bed armouring, Earth Surface Processes and Landforms, 8, 41-54.

Gomez, Basil, Naff, R. L., and Hubbell, D. W., 1989, Temporal variations in bedload transport rates associated with the migration of bedforms, Earth Surface Processes and Landforms, 14, 135-156.

Gomez, Basil, Hubbell, D. W., and Stevens, H. H., In Press, At-a-point bedload sampling in the presence of dunes, Water Resources Res.

Helley, E. J., and Smith, Winchell, 1971, Development and calibration of a pressure-difference bedload sampler, U. S. Geol Survey Open-File Rept, 18 p.

Hubbell, D. W., 1964, Apparatus and techniques for measuring bedload, U. S. Geol. Survey Water-Supply Pap. 1748, 74 p.

Hubbell, D. W., 1987, Bedload sampling and analysis, in: Gravel-Bed Rivers, Thorne, C. R., Bathurst, J. C., and Hey, R. D. (eds), Wiley, New York, 89-118.

Hubbell, D. W., Stevens, H. H., Skinner, J. V., and Beverage, J. P., 1981, Recent refinements in calibrating bedload samplers, in: Water Forum '81, Am. Soc. Civ. Engrs., New York, 1, 128-140.

Hubbell, D. W., Stevens, H. H., Skinner, J. V., and Beverage, J. P., 1986, Characteristics and use of Helley-Smith type bedload samplers, U. S. Geol. Survey Open-File Rept. 86-415W.

Hudson, H. R., 1983, Evaluation of selected bedload formulae in a steep gravel-bed river, Can. Soc. Civ. Engrs., 6th Hydrotech. Conf., Proc., 1, 331-356.

Johnson, C. W., Engleman, R. L., Smith, J. P., and Hanson, C. L., 1977, Helley-Smith bedload samplers, J. Hydr. Div., Am. Soc. Civ. Engrs., 103, 1217-1221.

Williams, G. P., and Rosgen, D. L., 1989, Measured total sediment loads (suspended loads and bedloads) for 93 United States streams, U. S. Geol. Survey Open-File Rept. 89-67, 128 p.

ANALYZING SEDIMENT TRANSPORT DATA: ALBERTA RIVERS

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ABSTRACT

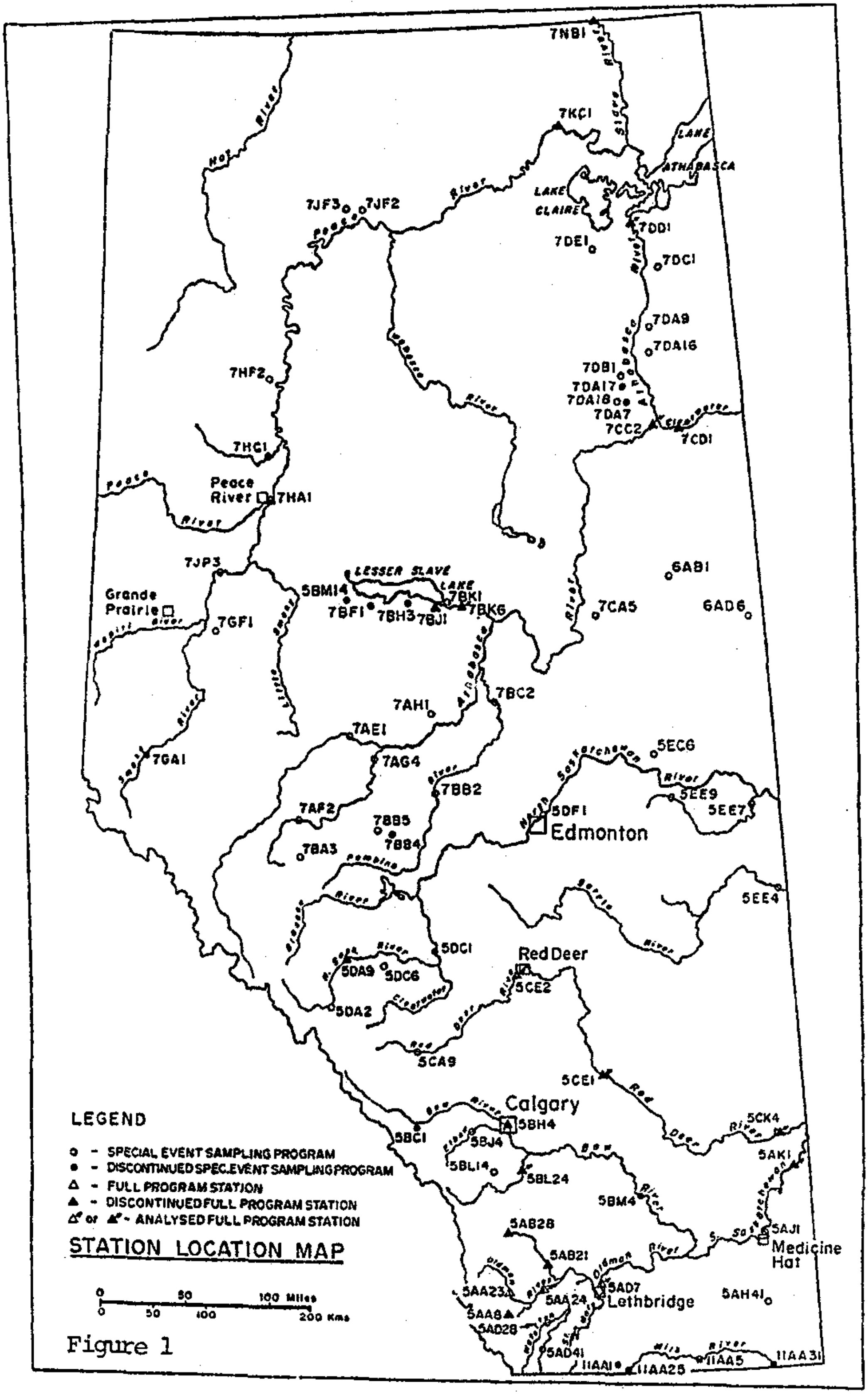
The analysis and interpretation of suspended sediment transport is an important management strategy for the Water Survey of Canada. There are several reasons for this strategy. First, government restraint has lead to the need to manage data collection programs more effectively and evaluating station records can assist in making objective decisions on station life. Second, the emergence of environmental quality issues is leading to the need for interpreted data, which is preferred by environmental consultants. Third, Environment Canada now expects its data collection programs to provide information for policy and management decisions of national consequence. For a traditional data service organization, these demands for an understanding of the data have posed a major challenge. The strategy developed by Water Survey of Canada managers is based upon a systematic approach to interpreting sediment data using internal and external expertise and to developing recognized custom-tailored products. To communicate with clients, workshops are held.

INTRODUCTION

The Alberta District of the Water Survey of Canada began to implement this current strategy first in response to internal management concerns for the information content of their long term sediment data collection programs. Many of these stations had been operational for 20 to 30 years and the concern was whether or not sufficient data were now available to meet expected user needs.

The District faces similar challenges as it moves to address the demands of environmental quality concerns and the departmental need to report on the quality of the aquatic environment. Canada's State-of-the-Environment Reporting initiative requires input on the characteristics and health of river systems -- a need that is far removed from the traditional design philosophy of Alberta's sediment network. Now there is a greater need, for example, to understand how sediment is transported through, or deposited within, a basin and how it interacts with and affects water quality.

The Alberta sediment network today is a loose array of 61 active stations, generally established for project purposes such as engineering design. A modest baseline network documenting general transport characteristics at a site is part of this network. There are also 132 discontinued stations in the province. The distribution of both types is shown in Figure 1. Presently, Water Survey of Canada does not have a network strategy in place to address the concern for transport of sediments through a basin: nor is its network managed in such a way to enable proper documentation of regional characteristics.



LEGEND
o - SPECIAL EVENT SAMPLING PROGRAM
• - DISCONTINUED SPEC. EVENT SAMPLING PROGRAM
Δ - FULL PROGRAM STATION
▲ - DISCONTINUED FULL PROGRAM STATION
ANALYSED FULL PROGRAM STATION
STATION LOCATION MAP
0 50 100 Miles
0 50 100 200 Kms
Peace River
Grande Prairie
Edmonton
Red Deer
Calgary
Medicine Hat
Lethbridge
LESSER SLAVE LAKE
LAKE CLAIRE
LAKE ATHABASCA
7NB1
7KC1
7JF3
7JF2
7DD1
7DE1
7DC1
7DA9
7DA16
7DB1
7DA17
7DA18
7DA7
7CC2
7CD1
7HF2
7HC1
7HA1
7JP3
5BM14
7BF1
7BH3
7BJ1
7BK1
7BK6
7GF1
6AB1
7CA5
6AD6
7BC2
7AH1
7AE1
7AG4
7GA1
5EC6
7BB2
5EE9
5EE7
7AF2
5DF1
7BB5
7BB4
7BA3
5EE4
5DC1
5DA9
5DC6
5CE2
5DA2
5CA9
5CE1
5BH4
5CK4
5BC1
5BJ4
5BL14
5BL24
5AK1
5BM4
5AB28
5AJ1
5AB21
5AD7
5AA23
5AA24
5AH41
5AA8
5AD28
5AD41
11AA1
11AA25
11AA5
11AA31

Figure 1

The present network style, therefore, reflects its traditional client focus and today's resource constrained programs - there is little opportunity to establish new stations without closing others, and sediment data collection is not a priority. The challenge for Water Survey of Canada staff is to maximize the information content of the existing data base (both active and discontinued stations).

DATA ANALYSIS STRATEGY

The strategy developed for the Alberta District focuses on four elements: (1) an annual data review for active stations (see Herrington et al. this conference for more details of procedure) now being implemented for operational management needs, can provide a range of summary statistics on suspended sediment transport. (It is planned to complete this process for all discontinued sites as time allows, to provide a broader base of first level analyzed data); (2) single station analysis reports for reviewing long term data sets or for stations when interpreted data is required for project applications; (3) basin analysis reports to assess the capability of existing stations to document transport through the basin; (4) regional analysis studies which attempt to generalize existing transport data to show temporal and spatial patterns.

The emphasis presently is to implement the annual review process as it allows staff to manage the field programs more effectively. However, a number of single and basin analysis reports have been prepared and a regional study is just now being completed. The objectives, approaches and results of these reports are reviewed below.

STATION ANALYSIS REPORTS (SAR)

Our approach to evaluating the 'completeness' of a sediment data set is based upon the use of simple standard techniques:

- evaluation of how well samples have covered seasonal and annual flow ranges during the period of record - both rating curves and flow duration curves are used.

- judgement on the representativity of the period of record versus the longer flow record (if available) - frequency analysis on daily maximum and annual flow volumes are used.

- the presence of trends in the data are roughly screened using a double mass curve and visual inspections of the flow history at the station.

- effects of record length in summary statistics of the suspended load are determined using standard error of mean plots (vs record length).

These techniques permit both rigorous and subjective evaluations to be made. The reports also contain a series of plots and tables which document various transport regime characteristics, the significance of events, and the strength of concentration-discharge relationships on various time scales. All supporting sediment data such as transported and bed material particle sizes are summarized and interpreted as much as possible.

A summary of four SAR's is given in Table 1 a. In each case the data analyses have indicated that more than sufficient data are available to document the character of the suspended sediment transport regime for any anticipated engineering and environmental application. With the exception of the site on the Oldman River at Brocket, all stations are now operated on an event basis only - samples will be taken only during previously unsampled high flows. The Brocket site will be maintained until the Three Rivers dam on the Oldman River (upstream) is completed.

BASIN ANALYSIS REPORT (BAR)

Many of today's needs for sediment data and information relate to its source, transfer, fate and effects within a basin. Concerns for sediment associated contaminate transport require an understanding of how sediment is moved through a basin, its travel and residence times, where it is stored, how and for how long, and how it effects aquatic ecosystems. For a sediment network designed to provide transport data only for specific sites addressing the 'basin' concern is difficult.

In the past, the District has operated several stations within one basin or along a river channel. Program objectives included: obtaining data on sediment sources (e.g., Red Deer River; HYDROCON, 1987); obtaining data for a range of engineering and land-use concerns (Lesser Slave Lake Basin, HARDY BBT, 1989); the collection of sediment data for a channel response to altered flow regimes (Milk River basin, Spitzer, 1987) (see Table 1 b.). In reviewing these activities, the authors, while documenting some successes, generally determined that improvements in network operational management were required (to ensure good sampling of flow ranges, complementary period and lengths of record); and that sediment stations alone, even when well coordinated, are insufficient to thoroughly document the passage of sediment through a basin. In the future, data monitoring will have to be complemented by source studies, volumetic channel surveys for storage calculations, etc. (see Table 1 c.).

The information from these basin approaches, even if based upon site specific data, can be used effectively to document the general nature of suspended sediment transport characteristics through a basin. Ashmore (1986) in his assessment of the Saskatchewan River basin, the upper portion of which covers much of southern Alberta, has done this effectively. He shows how sediment regimes change across the basin from the foothills to the prairies. Such overviews provide important background for basin scale problems such as climate change and toxic transport.

Currently the District is reviewing its data for the Athabasca River basin to evaluate its adequacy to meet the expected study needs and for compliance monitoring for possible contaminants from the proposed pulp and paper mills (Carson, 1989).

REGIONAL ANALYSIS REPORTS (RAR)

Hudson and Niekus (1990) (see Table 1 c.) have investigated approaches to regionalize suspended sediment loads to demonstrate temporal and spatial variations. Data from both federal and provincial sources are being used in this first effort to develop a provincial scale interpretation. The limitations of a rigorous approach, linking loads to basin parameters for example, are painfully obvious--there are only sufficient data for larger rivers and only infrequently are they spatially sufficient to describe a basin.

COMMUNICATIONS

The Alberta District has chosen three strategies to communicate its analytical products to clients and to respond to the need for interpreted data. First, all reports prepared by or for the branch are distributed throughout the Province. These reports have been given a distinctive format to aid in recognition. Also, access is given upon request to our annual data review files. Second, a user workshop (Yuzyk and Chapin, 1988) was held to discuss the future of sediment work in Alberta and to show the Branch's products. Third, custom-tailored reports are being designed to aid the environmental client base to understand how sediment data and information can be applied.

SUMMARY

The data analysis strategy implemented by the Alberta District is successfully addressing the need to understand the data for operational management concerns, for meeting the changing needs of its client base, and for responding to Environment Canada's interest in reporting on the health of aquatic systems. A range of initiations have been developed and a number of analytical procedures and products are already completed. The success of this strategy can be related to the development of a systematic approach, the careful use of contract expertise, the willingness to look ahead, and to make changes.

TABLE 1

a. Station Analysis Report Summary

Station Name	Station Objective	Length of Record Years	Decision	Author
Highwood River	To determine suspended sediment characteristics	12	Terminate; sample high flows only.	Day and Spitzer (1985)
Oldman River @ Brocket	Reservoir evaluation	25	To continue to operate station due to political concerns	Day and Spitzer (1985)
Oldman River @ Lethbridge	Engineering evaluations	19	" " "	Cashman and Spitzer (1990)
South Saskatchewan River @ Hwy. 41	Reservoir Sedimentation	21	Terminate; sample high flows only.	Cashman and Spitzer (1989)

b. Basin Analysis Report Summary

Basin	Objective of Review	No. of Stations	Author
Red Deer River	To evaluate the sediment transport regime; to determine a sediment budget; determine reservoir effects; and determine the adequacy of existing sediment bases.	3	HYDROCON Engineering (Continental) Ltd.
Saskatchewan River	To present a summary and analysis of the suspended sediment data collected at WSC stations in the Saskatchewan River Basin.	112	Ashmore (1986)
Lesser Slave Lake	To review the available sediment data and its usefulness to potential applications to engineering, environmental, and water quality projects; to determine a sediment balance in and out of Lesser Slave Lake.	7	HARDY BBT (1989)
Lower Athabasca	To provide a summary of the sediment regime as well as to provide an insight into the sources and fates of these sediments.	15	Carson (1989)
Milk River	To determine the usefulness of a limited amount of suspended sediment data and to make this available in readily-usable formats.	7	Spitzer (1988)

c. Interpretative Reports

Title	Objective	Author
An Interpretative Study of the Upper Oldman River Sediment Regime	To examine sediment sources and controls, to relate these to long term sediment regime at a downstream station and to evaluate existing approaches and to develop technology	Hudson and Askin (1987)
Regionalization of Fluvial Suspended Sediment Loads in Alberta	To design a regional synthesis of sediment transport and related data in Alberta	Hudson and Niekus (1990)

REFERENCES

Ashmore, P. E., 1986, Suspended Sediment Transport in the Saskatchewan River Basin. Water Resources Branch, Environment Canada, Ottawa.

Cashman, M. A. and Spitzer, M. O., 1989, Sediment Station Analysis: South Saskatchewan River at Highway No. 41 - 05AK001. Water Resources Branch, Environment Canada, Calgary.

Cashman, M. A. and Spitzer, M. O., 1990, Sediment Station Analysis: Oldman River near Lethbridge - 05AD007. Water Resources Branch, Environment Canada, Calgary.

Carson, M. A., 1990, Evaluation of Sediment Transport Data for the Lower Athabasca River Basin, Alberta. For Water Resources Branch, Environment Canada, Calgary.

Day, T. J. and Spitzer, M. O., 1985, Sediment Station Analysis: Highwood River near the Mouth: 05BL024. Water Resources Branch, Environment Canada, Ottawa.

Day, T. J. and Spitzer, M. O., 1985, Sediment Station Analysis: Oldman River near Brocket: 05AA024. Water Resources Branch, Environment Canada, Ottawa.

HARDY B.B.T. Limited, 1989, Sediment Transport Analysis: Lesser Slave Lake Basin. Water Resources Branch, Environment Canada, Calgary.

HARDY B.B.T. Limited, 1988, K. Factor Analysis: Red Deer River at Drumheller: 05CE001. Water Resources Branch, Environment Canada, Calgary.

Herrington, R., Day, T. J. and Yuzyk, T. R., 1991, A Management Strategy for Sediment Stations, Water Resources Branch, Environment Canada, Ottawa, Fifth Federal Interagency Sedimentation Conference.

Hudson, H. R. and Askin, R. W., 1987, An Interpretative Study of the Upper Oldman River Sediment Regime. Water Resources Branch, Environment Canada, Calgary.

Hudson, H. R. and Niekus, F., 1990, Regionalization of Fluvial Suspended Sediment Loads in Alberta. Water Resources Branch, Environment Canada, Calgary.

HYDROCON Engineering (Continental) Ltd., 1987, Sediment Station Analyses: Red Deer River - at Red Deer (05CL002) - at Drumheller (05CE001) - near Bindloss (05CK004). Water Resources Branch, Environment Canada, Calgary.

Northwest Hydraulics Consultants Limited, 1986, The Use and Publication of Hydraulic and Morphologic Data for Canadian Rivers. Water Resources Branch, Environment Canada, Ottawa.

Spitzer, M. O., 1988, Sediment Data Milk River Basin. Water Resources Branch, Environment Canada, Calgary.

Yuzyk, T. R. and Chapin, N.F.R., 1989, Proceedings of the Alberta Sediment Issues Workshop. Water Resources Branch, Environment Canada, Calgary.

BED MATERIAL SAMPLING: ISSUES AND ANSWERS

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ABSTRACT

Several issues regarding areal sampling of gravel-bed streams have been raised in this paper. It was found that the inconsistent bias towards coarser particles does not allow for direct comparison between areal samples. The limitations of the modified cube model in describing a natural sediment deposit was examined. The necessary exponent for converting an areal to an equivalent volumetric sample for both unimodal and bimodal sediment mixture was determined from experiments. A simple model for calculating the approximate minimum depth required for a volumetric sample was described. The depth predicted from this model is in good agreement with that measured from experiments.

INTRODUCTION

The bed material of gravel-bed streams is typically stratified in terms of particle size. Usually, three distinct layers can be identified. The uppermost bed layer is often referred to as pavement because it contains a significantly higher percentage of large stones than does the underlying layers. Directly below the uppermost stratum is the second layer which is referred to as the subpavement. This layer possesses a greater percentage of fines than both of the other two layers. The thickness of both the pavement and the subpavement layers is close to the size of the largest particle. The rest of the bed material in the stream is in the third or bottom layer. This bottom layer does not have a predetermined thickness and its material is similar in size to that of the subpavement but not as rich in fines (Diplas, 1991).

It is important to be able to analyze each of these distinct layers separately. The composition of the pavement layer determines the frictional characteristics and stability of the channel boundary. The material, especially the fine content, of the subpavement strongly influences the quality of fish habitat (Shirazi and Seim, 1981). The vast majority of the bed material found in a gravel bed stream is in the bottom layer.

Traditionally, volumetric sampling has been the standard sampling procedure. It consists of the removal of a predetermined volume of material which is subjected to sieve analysis. The results are interpreted as a frequency distribution by weight. The volume that is removed and analyzed must be large enough to be independent of the dimensions of the individual grain sizes to obtain an unbiased sample. While this technique is appropriate for sampling the bottom layer, it cannot be employed for the upper two layers where the depths and thus the volumes are dependent upon the size of the particles (Kellerhals and Bray, 1971). Instead, a surface oriented sampling technique is needed to sample the top two layers. The size distribution obtained from such a sample, however, tends to be biased in favor of the coarser particles (Diplas and Sutherland, 1988). For comparison purposes, a common base should be used when interpreting the results from different sampling methods. Typically, the size distribution of areal samples is converted into the size distribution that would have resulted from an equivalent volumetric sample.

Several issues related to sampling of bed material are addressed in this paper. They include the unsuitability of using surface samples as a basis of comparing deposits; the analysis of material obtained from both unimodal and bimodal samples, and some implications of using the cube model, that was first introduced by Kellerhals and Bray (1971), to describe areal sampling. The dependence of the formula used in the conversion of an areal sample on the depth of the areal sample is examined. Also the minimum depth of bed material that is necessary to render a sample volumetric is addressed.

COMPARISON BETWEEN AREAL SAMPLES

It has been clearly demonstrated that areal samples cannot be directly compared with volumetric samples (Kellerhals and Bray, 1971; Kellerhals and Church, 1977). Before any such comparison takes place, the size distribution obtained from a surface oriented sampling technique should first be converted into the size distribution that would have been obtained from a volumetric sample had there been no stratification of the bed material. Due to perceived uncertainties about the appropriate formula for converting areal into equivalent volumetric samples, some researchers have resorted to comparing areal samples directly to other areal samples (Little and Mayer, 1976; Wilcock and Southard, 1988; Kunhle, 1989).

The following expression has been suggested for the conversion of an areal sample into an equivalent volumetric sample:

$$p(V\text{-}W)_i = C\ p(A\text{-}W)_i \bar{D}_i^{\,x} \qquad (1)$$

(Kellerhals and Bray, 1971)

where $p(V\text{-}W)_i$ and $p(A\text{-}W)_i$ are percentages of the size fraction i obtained from volume-by-weight (volumetric) and area-by-weight (areal) procedures

respectively, $\bar{D}_i$ is the geometric mean diameter of the same size fraction i, and C is a constant that is unique to the sample. The value of the exponent x depends upon the method used to obtain the areal sample (Diplas, 1989). Laboratory tests have indicated that for a wax areal sample the exponent approximately equals -0.47 (Proffitt, 1980; Diplas and Sutherland, 1988). It

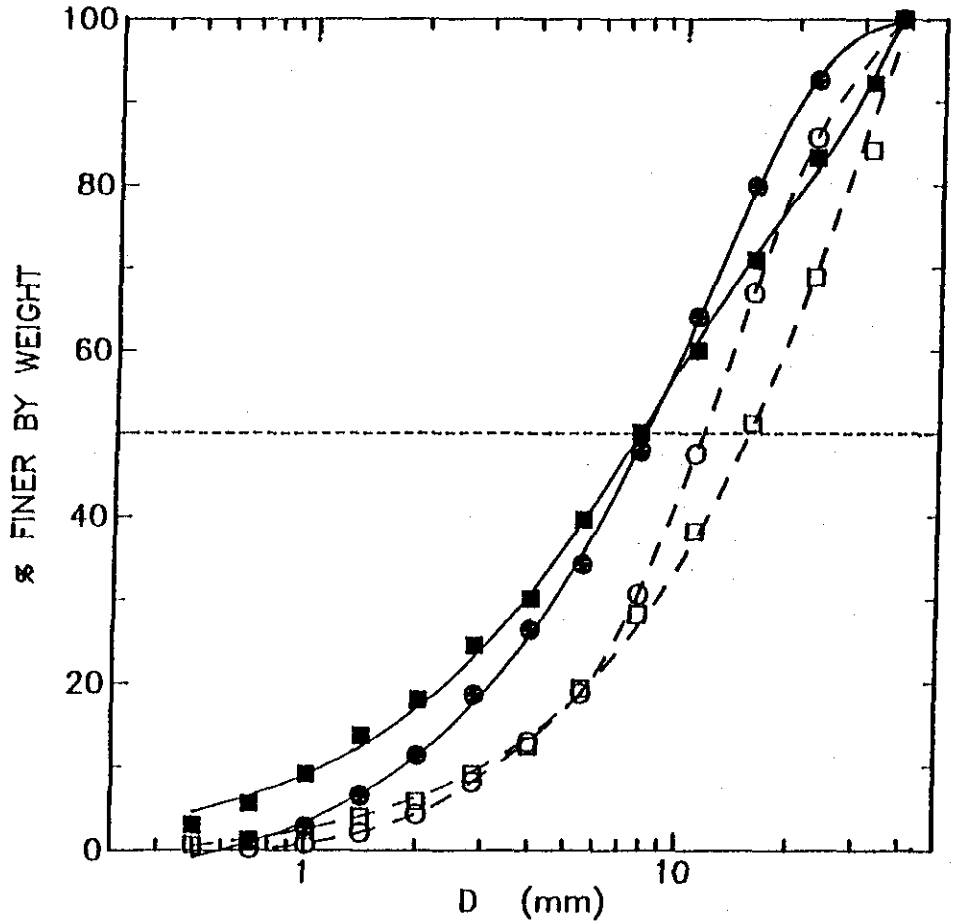

Figure 1. Areal and volumetric samples of two different gravel mixtures. Solid symbols represent volumetric samples and open symbols represent areal samples.

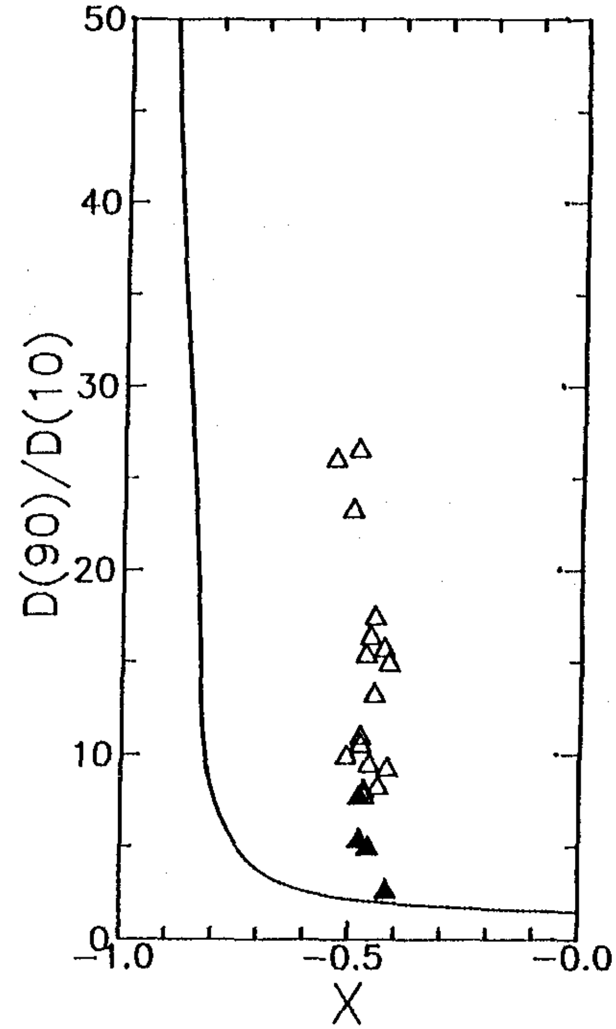

Figure 2. Mean diameter of the larger mode of bimodal mix over the smaller or (D_{90}/D_{10} for unimodal) versus the required exponent. △ from Proffitt (1980), ▲ present experiments. Solid line represents the results of the cube model for different cube ratios.

is important to realize that due to the exponent, equation 1 is nonlinear. In addition, it has been generally accepted that volumetric samples are unbiased while areal samples are biased in favor of the coarser particles. Equation 1 shows that this bias or distortion is nonlinear, thus areal samples are not directly comparable among themselves.

To further demonstrate the incompatibility of areal samples, the results of areal and volumetric sampling of two different unstratified sediment mixtures are plotted in figure 1 (Proffitt, 1980). As shown in this figure, the median sizes of the wax areal samples are 12.5mm and 11mm, while the median sizes of the corresponding volumetric samples are approximately identical (8mm).

LIMITATIONS OF THE CUBE MODEL

The cube model that was developed by Kellerhals and Bray (1971), for simulating alluvial gravel deposits did not account for any voids. For the conversion formula (Eq. 1) this model indicates an exponent of -1, which has been shown to over correct the areal sample's natural bias towards the larger grain sizes by indicating a higher percentage of finer particles than is actually present (Diplas and Sutherland, 1988). This model was modified by Diplas and Sutherland (1988) to include voids in order to better represent actual gravel deposits. These voids allow additional smaller particles that are not on the surface of the deposit to be part of the sample as long as they are directly below a void of the exact same size. Using a two to one ratio of the large cube to the small cube this refined model indicates that an exponent of -0.42 is required for the conversion, a result which is very close to the experimentally determined values. However, the exponent depends upon the cube ratios as shown in figure 2. For small values of the cube ratio the exponent x appears to be sensitive to slight variations, while for very large ratios it asymptotes towards -1 (Fig. 2). The cube model is restricted insofar as that smaller cubes which are not directly beneath a void of the exact same or larger size will not be included in the areal sample. Actual sediment deposits contain particles that are more ellipsoid in shape and are not stacked nearly upon each other like the cubes. As it was indicated from the present experiments, wax flows through the increased number of voids in the surface and adheres to the particles below. Because wax can penetrate the small surface voids, it causes particles that are larger than the voids to become part of the sample. By removing more finer particles from below the surface than is suggested by the modified cube model, the exponent maintains a fairly constant value of -0.4 to -0.5. This was shown to be true in laboratory experiments for both gravel unimodal sediments (Proffitt, 1980) and for bimodal sediments in the present study.

MINIMUM DEPTH OF A VOLUMETRIC SAMPLE

As previously mentioned, the basic premise behind a volumetric sample is that it is large enough so that it does not favor any particular size range. There has been very little specification on how deep a sample must be taken in order to be unbiased. Without a minimum depth criterion volumetric samples could be too small, which leads to inaccurate results, or too large, which results in sieving of excessive amounts of sediment. To resolve this problem, a series of areal samples were taken in succession to remove thin layers of material

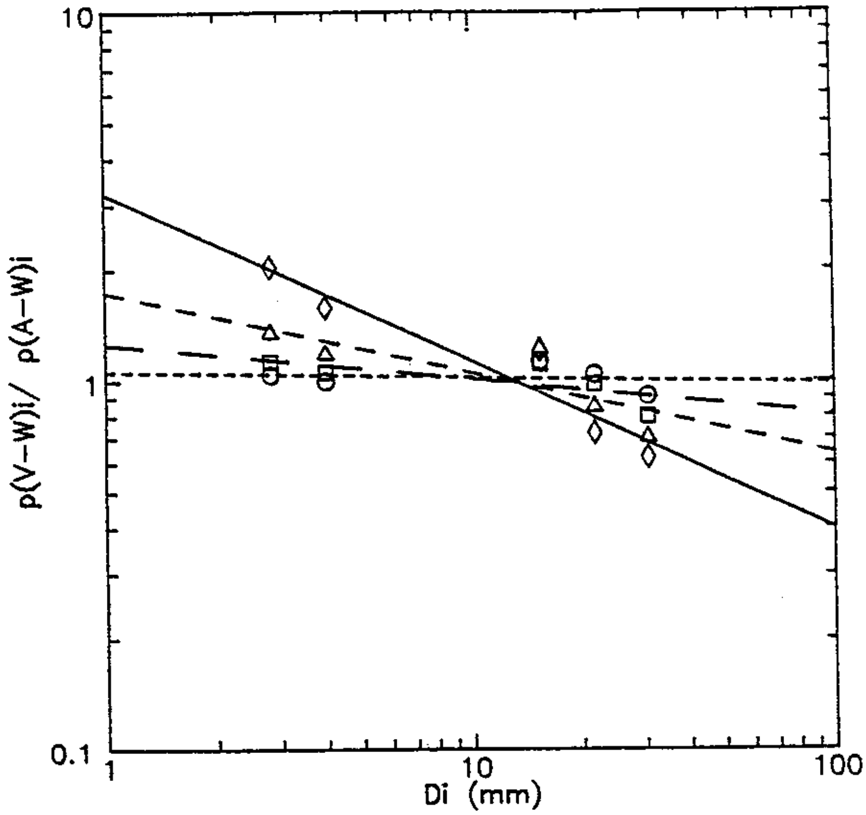

Figure 3. Results of consecutive areal samples of a known bimodal mixture.

—◇— Layer 1, x=-0.45
— △ —Layer 1 and 2, x=-0.22
—□— —Layer 1,2 and 3, x=-0.10
- - -○- -Layer 1,2,3 and 4, x=-0.02

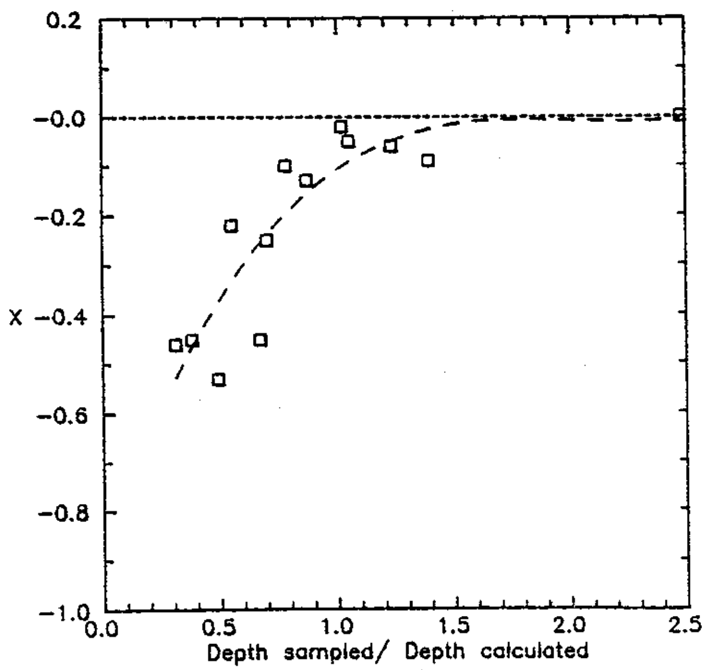

Figure 4: Depth sampled , d_s, over volumetric depth, d_c, versus required exponent.

from a known gravel mix. This was done by placing the gravel mix in a box with 40cm x 40cm surface and 20cm depth where it was sampled areally using wax in a 30cm x 30cm frame. With the increase in total depth, the cumulative sample gradually became volumetric. This result is shown in figure 3, where, as the depth of the sampled sediment increases, the $p(V\text{-}W)_i/p(A\text{-}W)_i$ ratio approaches one and the exponent approaches zero, indicating that the total of the consecutive areal samples has become equivalent to the actual mix. Different mixes, both unimodal and bimodal, were sampled in this manner. While all of the initial layers required an exponent of between the expected -0.4 to -0.5, they became volumetric at different depths.

The depth at which an areal sample becomes volumetric is dependent upon the makeup of the given mix. Mixes with larger particles obviously require deeper depths than for mixes with smaller particles. The minimum depth where a sample becomes volumetric should be achieved when an integral number of particles for each size range is reached. The particles in a gravel combination can be represented by the sieve diameters which are all multiples of the square root of two. By using the least common multiple of the two largest sieve sizes, a depth can be determined that would be an integral multiple of all of the size ranges. Laboratory tests in the present study have suggested that by rounding these two largest sieve sizes down to the nearest even whole number, the minimum depth where the sample becomes volumetric can be approximated. For example, if the two largest sieve sizes of appreciable percentage sampled were the #3 (6.7mm) and the #4 (4.75mm) then the depth below the original sample surface would be about 12mm. The dimensions are rounded down to the nearest even number because most sampled sediment particles can nest together, reducing the required depth. The expected result of the exponent approaching zero as the sampled depth nears the calculated volumetric depth is shown in figure 4 for various mixes.

Several researchers (Proffitt, 1980; Diplas and Sutherland, 1988, et. al.) determined experimentally that the exponent is fairly constant at -0.4 to -0.5 for areal samples with an average depth of D_{60} to D_{75}. The present study confirms this finding as true up to a depth in excess of D_{90}. In most cases, wax will not penetrate a sample much beyond D_{75}, but for very unimodal samples, where voids are especially large, wax can penetrate much deeper. If the excess voids in a unimodal sample cause the areal sample to be very deep then care must be taken to assure that the sample is not already volumetric. This is shown in figure 5, where the mix has a geometric standard deviation of only 1.4. The necessary depth to be volumetric was determined, based on the present model, to be about 8mm. The first areal sample, however, reached an average depth of 11mm below the surface. Figure 5 shows that the percentages of the areal sample are practically identical to the percentages of the actual mix. If a conversion formula were used on the areal sample, then erroneous findings would result.

CONCLUSIONS

The bed material in gravel-bed streams consists of three distinct layers. The sediment in each layer statistically constitutes different population and therefore, should be sampled separately. A surface-oriented technique should be used to sample the pavement and subpavement layers, while the bottom layer can be sampled volumetrically. Areal samples are not directly comparable among themselves, due to t..e nonlinear bias towards the coarser particles that is exhibited by them. The exponent x in the conversion formula (Eq. 1) based

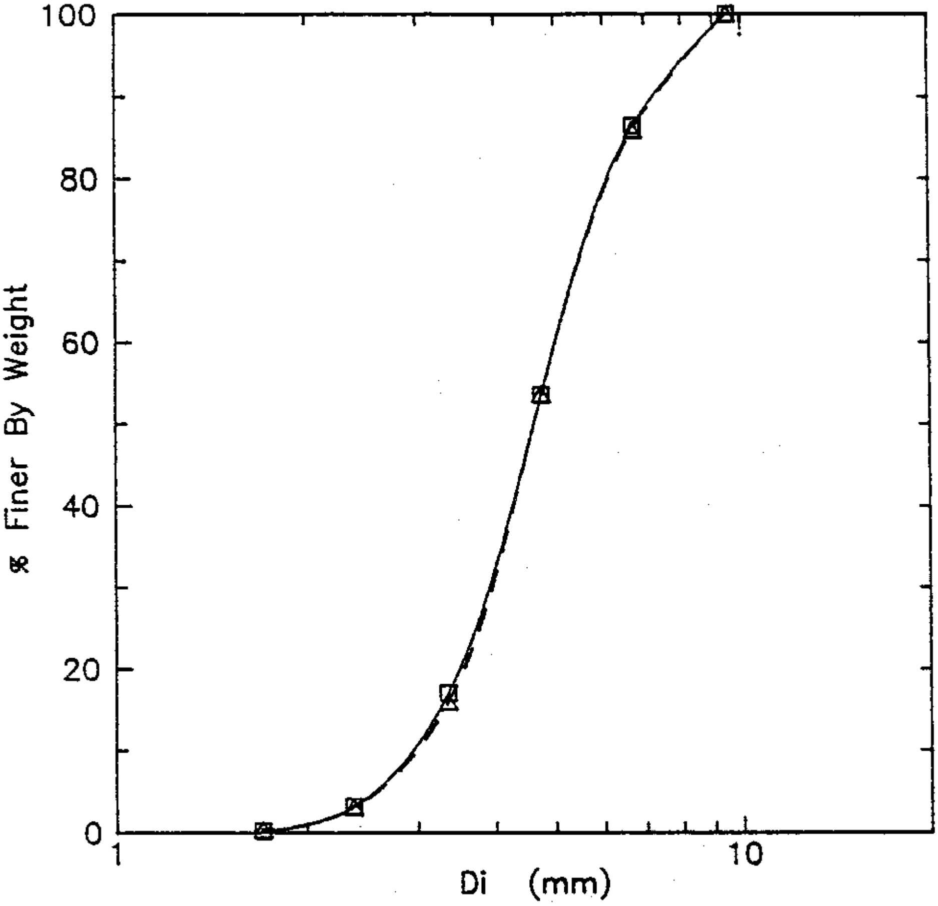

Figure 5. Areal and corresponding volumetric samples of a well sorted gravel mixture. Squares represent the volumetric sample and triangles represent the areal sample.

on the modified cube model is not constant, but depends on the relative size of the cubes. Experiments indicate that wax samples of both unimodal and bimodal natural sediment tend to include higher amounts of finer particles, compared to the cube model, resulting in a fairly constant exponent ($-0.4 < x < -0.5$) in Eq. 1. As the depth of the sampled material increases, the exponent x approaches zero, indicating a volumetric sample. The minimum depth required to obtain a volumetric sample is approximately equal to the least common multiple of the largest sieve sizes representing the bed material.

ACKNOWLEDGEMENTS

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REFERENCES

Diplas, P., 1989, Areal sampling techniques. Proceedings of the International Symposium on Sediment Transport Modeling, New Orleans, LA., 380-385.

Diplas, P., 1991, Interaction of find sediment with coarse gravel matrix. Fifth Federal Interagency Sediment Conference, Las Vegas, NE.

Diplas, P., and Sutherland, A.J., 1988, Sampling techniques of gravel sized sediments. J. Hydr. Eng. ASCE 114(5), 484-501.

Kellerhals, R., and Bray, D.I., 1971, Sampling procedures for coarse fluvial sediments. J. Hydr. Div. ASCE 103(HY8), 1165-1180.

Kellerhals, R., and Church, M., 1977, Stability of channel beds by armoring. J. Hydr. Div. ASCE 103(HY7), 826-827

Kuhnle, R.A., 1989, Bed-surface size changes in gravel-bed channels. J. Hydr. Eng. ASCE 115(6), 731-743.

Little, W.C., and Mayer, P.G., 1976, Stability of channel beds by armoring. J. Hydr. Div. ASCE 102(11), 1647-1661.

Proffitt, G.T., 1980, Selective transport and amouring of non-uniform alluvial sediments. Thesis presented to the University of Canterbury, at Christchurch, New Zealand, in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

Shirazi, M.A., and Seim, W.K., 1981, Stream system evaluation with emphasis on spawning habitat for salmonids. Water Resources Res., 17(3), 592-594.

Wilcock, P.R., and Southard, J.B., 1988, Experimental study of incipient motion in mixed-size sediments. Water Resour. Res., 24(7), 1137-1151.

A STUDY ON THE MEASURING METHOD OF BEDLOAD

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ABSTRACT

By means of the theoretical analysis, the simulating calculations and the comparative analysis of field data, the method of the distribution of meassuring verticals across the section according to the equal bedload transport rate has been demonstrated. Such a method can make the measuring errors to the minimun.

The quantitative analysis of the number of measuring verticals, the sampling duration and the required repeating sampling times have been conducted. And a practical application of the principle that the required repeating sampling times can be determined by the corresponding bedload transport rate has been presented. This method can give a clear concept to the existing different viewpoints about the method of the bedload measurement.

INTRODUCTION

For bedload movement. There is intensive pulsation on time distribution and there is nonuniform violence on width distribution. In order to eliminate the pulsation error and to control the transverse variation, the measuring method including multivertical and repeating sampling (three times) has been conducted, but only a few study is made for its reasonableness. In America, two viewpoints are existed. One suggests 20 verticals assigned, by order foreward and backward for each, and the other suggests 4 verticals assigned, repeating 10~20 times for each verticals. Which one will conform with the pratice, the following views are prepared and discussed.

THEORATICAL DEMONSTRATION

The transportation of bedload depends on the flow condition, composition of bed material and the location of the sediment, and these are all random, so the statistic method becomes a major theoratical research to study the moving law of bedload.

Poisson distribution suggested by Han Qiwei, is widely praticable with strict and reasonable derivation, being a theoretical foundation for the following discussed problems.

a.Error of transport rate at point

Han Qiwei established a Poisson distribution for the transport rate as $M[\xi w]$ and $D[\xi w]$ are mathmetical expected value and variance of sediment weight (w) with a width b of instrument entrance in a period t respectively, then the coefficient of variance for homogeneous sediment is obtained as follows

$$C_V=\frac{\sqrt{D[\xi_{\hat{q}}]}}{M[\xi_{\hat{q}}]}=\sqrt{\frac{\pi\gamma_S D^3}{6bt\overline{q}}}=\sqrt{\frac{1}{\overline{W}_n}} \qquad (1)$$

in which γ_s, is unit weight of sediment; D is grain diameter of sediment; q is time average transport rate; $\overline{W}_n$ is average number of grains entering into the sampler equal to $\left(\frac{6bt\hat{q}}{\pi\gamma_S D^3}\right)$

If the sediment is heterogeneous, and taking the equivelent grain diameter $D_0=\sum_{L=1}^{L_m}D_L^3R_{b,L}$, then,

$$C_V=\sqrt{\frac{\pi\gamma_S D_0^3}{6bt\overline{q}}}=\sqrt{\frac{1}{\overline{W}_n}} \qquad (2)$$

in which $\overline{W}_n=\frac{6bt\overline{q}}{\pi\gamma_S D_0^3}$. After the comparison of equation (1) and (2), it is found that if the grain size distribution is unchanged and the equivelent grain disameter is taken, the coefficient of variance for heterogeneous sediment is consistent in format with that for homogeneous.

If repeating sampling is taken and the sediment is homogeneous, or heterogeneous sediment of definite grain size distribution, C_v or the relative errors for both are also the same.

It is known that as for the homogeneous sediment and the heterogeneous sediment with definit grain size distribution, if the total sampling time is the same, the reault of a single sampling or repeating samplings are the same. Thus a theoretical basis is provided for simplifying the operation procedures, such as in practical work, reducing the unmber of repeating samplings and prolonging the sampling duration t as the intensity of transport rate is appropriate.

For cobble river bed with heterogeneous sediment,

$$C_V=\frac{\sqrt{D[\xi_{\hat{q}}]}}{M[\xi_{\hat{q}}]}=\sqrt{\sum_{L=1}^{L_m}R_{b,L}\left(\frac{R_{b,L}}{R_{1,L}}-1\right)+\frac{\pi\gamma_S D_0^3}{6bt\overline{q}}} \qquad (3)$$

For $\sum_{L=1}^{L_m}R_{b,L}=1$, $\sum_{L=1}^{L_m}R_{1,L}=1$, $\sum_{L=1}^{L_m}\frac{R^2_{b,L}}{R_{1,L}}\geqslant 1$, is proved.

When grain size of bed material is in random variation, comparing with the bed material with definite grain size distribution, the coefficient of variance will be greater. If the duration of sampling is sufficient long, the second term in right hand of equation (3) compared with the first term can be neglected. If the sampling duration is further prolonged, there will be no effect. If the sampling is repeated m_1 times within the time t, and each sampling duration $t_1=t/m$ then,

$$C_V=\sqrt{\frac{1}{m}\sum_{L=1}^{L_m}R_{b,L}\left(\frac{R_{b,L}}{R_{1,L}}-1\right)+\frac{\pi\gamma_S D_0^3}{6bt\overline{q}}} \qquad (4)$$

It is known that when grain size distribution is in random variation, and the total duration are the same, the coefficient of variance for repeating samplings is smaller than that for single sampling.

For equation (1), $\bar{q}$, D and bare given as definite values, then the trend relation that C_v inversely varies to the duration t can be displayed. As for easy comparison,the percentage of the difference between two adjacent C_v as the ordinate, (i=1, 2···, m), time t as abscissa, the relation is shown in Fig.1. From this figure, it is shown that as t is greater than 100s, if still increased, the reduction of C_v is slow. As from Fig.1, the equation (4) is resolved and assuming $\sum_{L=1}^{Lm} R_{b.L}\left(\frac{R_{b,L}}{R_{1,L}}-1\right)$ as a definite value,t being 100s,

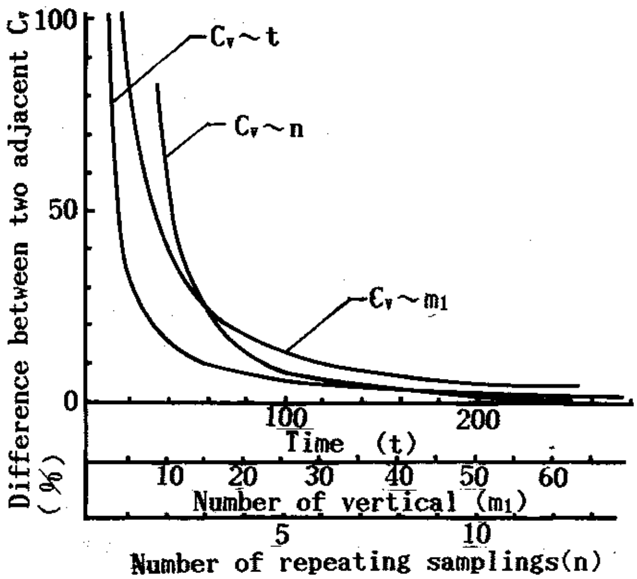

Fig.1 Relation between C and sampling duration time t, number of verticals m_1, number of repeating samplins n

the relation between the number of repeating samplings and C_v can be derived, Taking $\left[\frac{C_{v(i-1)}}{C_{vi}}-1\right]\%$ as ordinate and the number of samplings as abscissa as shown in Fig.1. It is shown that if the number of repeating samplings more than 5, there will be no significant reduction on C_v. If 1% is taken as a control index, 4 repeating samplings is sufficient. The theorectical data and pratical value are well comformed.

b. Error of transport rate in cross section

The verticals of measuring bedload arranged in cross-section is m_1 verticals, j indicates serial No.; $\xi\hat{q}_j$ is ransport rate for each vertical; b_j is the representative width for each vertical; B is the total width. then, $B=\sum_{j=1}^{m_1} b_j$,

the transpoot rate in cross-section is $\xi_{\hat{q}}=\sum_{j=1}^{m_1}\frac{b_j}{B}\xi_{\hat{q}j}$

As the transport rate for each point is independent each other, the coefficient of variance is [1]

$$C_v=\frac{\sqrt{D[\xi_{\hat{q}}]}}{M[\xi_{\hat{q}}]}=\sqrt{\sum_{j=1}^{m_1}\left(\frac{b_j}{B}\right)^2\frac{\bar{q}_j^2}{\bar{q}^2}(u_j-1)+\frac{\pi\gamma_s D_{0j}^3}{6bt_j\bar{q}_j}} \qquad (5)$$

in which $\overline{q} = \sum_{j=1}^{m_1} \frac{b_j}{B}\overline{q_j}$ ($\bar{q}_j$ is time mean transport rate)

$$u_j=\begin{cases}\sum_{L=1}^{L_m} \frac{R^2_{bL,j}}{R_{1,L,j}} & \text{(Heterogeneous sedinent for bed material grain size distribution is random variable)} \\ 1 \end{cases} \quad (6)$$

$$D_{0j}=\begin{cases}\left(\sum_{L=1}^{L_m} R_{bL,j}D^3_{L,j}\right)^{1/3} \\ D_j\end{cases} \quad (7)$$

As for a certain vertical, the greater the b_j, $\bar{q}_j$, the greater the error of cross-sectional transport rate. Assuming q_j is a definit value, the verticals are uniformly distributed in cross-section, the trend of C_v related to the number of verticals is shown in Fig.1.
In natural stream, uniform distribution is not existed. According to equation (5), if the product of b_j/B and $\bar{q}_i/\bar{q}$ is made to be minimum, the distribution of vertical will be the most ideal. If the transport rate distribution is changed accross the cross-section, the uniform distribution can not be used. According to the variation, the verticals should be adjusted, and C_v should be made to meet the specified requirement. Extending to the fieldwork, the distribution of verticals can be base on the method of equal transport rate (each partial section in a cross-section).

c. According to the propagation equation of random error, the square of relative mean square error is

$$S^2_{\bar{q}} = \frac{1}{\bar{q}^2}(S^2_{q_1}q^2_1+S^2_{q_2}q^2_2+\cdots\cdots+S^2_{q_n}q^2_n) \quad (8)$$

As if, the relative mean square errors and weights of each partial section are equal,

$$q^2_1+q^2_2+\cdots\cdots+q^2_n>N\bar{q}^2_i=\frac{\bar{q}^2}{N}. \quad (9)$$

After substitution, the following equaition is proved

$$\frac{S^2_{\bar{q}_i}}{N} < S^2_{\bar{q}} < \frac{S^2_{\bar{q}_i}}{N\left(\frac{\bar{q}_i}{q_1}\right)} \quad (10)$$

in which $S_{\bar{q}}$ is the relative mean square error of transport rate in crosssection, S_{qi}, is the average relative mean square error of transport rate in partial section; q_1 is the greatest term of q_i.
It is shown that the error of equal transpert rate distribution ($\frac{S^2_{\bar{q}_i}}{N}$) is the minimum.

SIMULATING COMPUTATION

Base on the measured data, plotting a diagram for transverse distribution of transport rate in vertical accross the crosssection and smoothing the curve, the crosssectional transport rates are computed for uniform distribution of vertical and equal transport rate distribution of vertical. The above method is called simulating computation as shown in Fig.2. As comparing two distributions, if the number of verticals are the same, and smaller than ten, the error for equal transport rate distribution is much smaller than that for uniform distribution. As for different peak patterns, the error for single peak is smaller than that for double peaks.

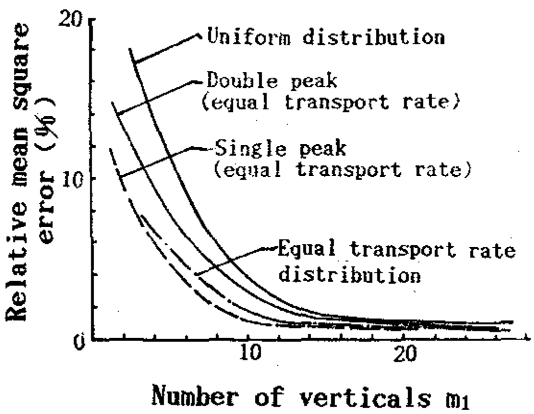

Fig.2 Relation between simulating number of verticals and relative mean square error

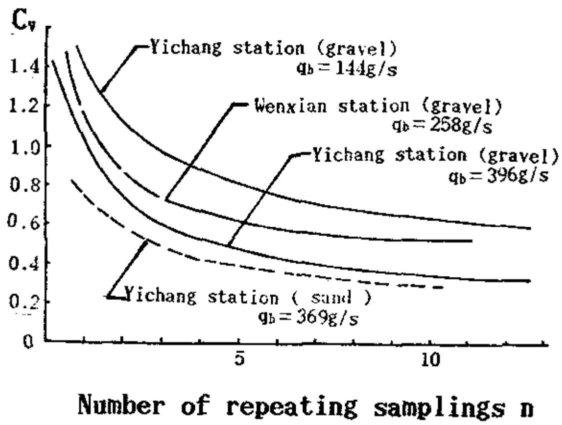

Fig.3 Relation between number of repating samplings n and observed C_v.

DEMONSTRATION GIVEN BY MEASURING DATA

The measuring data including the duration of measuring point, number of repeating samplings and the verticals distribution are being demonstnated.

a. Duration of measuring point and number of repeating sampings

It is proved by the measuring data that pulsation error of transpert rate for bedload expressed as normal skew, and the intensity of pulsation and coefficient variation are decreased with the increase of transport rate.
The experiment of Yichang and Wenxian stations in 1973 are shown in Fig. 3, conforming to trend of the curve in Fig.1.

b. Distirbation of verticals

The distribution of bed load accross the crosssection is not uniform and always concentrated in some so called "bedload strip" forming violent strip in the crosssection. Thus, the transport rate in violent strip should be considered, otherwise a large error will be occured.

The analysis of gravel bedload measurement at Zhutuo station in 1982 has been made in 1983[2]. According to these data analysed, for uniform distribution, the error can not be reduced to meet the requirement. Only the way is the improving the precision of measurement in violent strip.

The principle of equal transport rate has been extended to be a distribution principle in which close distribution in violent strip and sparse distribution in weak strip. The increase of the number of repeating samplings is according to the ratio of partial transport rate, so the number of repeating samplings in violent strip is more and that in weak strip is less even only taking once for each vertical. Three kinds of test and varification are made on some precise measurements for Zhutuo station and Cuntan station on Changjiang river as follows:

1. The range of violent strip is definite, the number of repeating samplings (4~5) on verticals in this range is unchanged; and taking a single sampling (The first sampling) on the verticals in weak strip. The statistical results are compared with the original results shown in Table 1.

2. The mean partial transport rate in vertical is obtained by averaging all partial vertical transport rates in crosssection, the range, in which the partial transport rate of the verticals is greater than the mean partial transport rate will be considered as violent strip. The rest procedure is the same as 1.

3. The range, in which the partial transport rate is greater than 50% of mean partial transport rate is determined as violent strip. The rest procedure is the same as above paragraph. The results are tabulated as Table 1. By the sampling statistics, the relative mean square errors of these methods are all smaller than 10%; the max, systematic error is 2.4%; max random error is -12.9%; the error for Zhuduo station of which the transverse distribution is single peak type is smaller than the error for Cantan station with double peak type. It is consistent with the result of Fig.2. If 4 repeating samplings of 4 verticals (definite) are taken in violent strip and a single sampling on the next two verticals (duration time>180s) for Zhutuo station, and the result is compared with the original result of precision measurement, the relative mean square error is 3.9%; systematic error is -0.7%; max random error is -7.8%. then 9—16 original verticals have been reduced to 6 verticals, so the extended method is a good pratical method which verticals are less and the results are precise.

Table.1 Statistical errors of three kinds of sampling

Station		Zhutuo	Cuntan	Mean
First method	relative mean square error (%)	2.1	9.5	6.2
	systematic error (%)	0.9	-0.9	0.2
	number of verticals in violent strip	4	7	4—7
	number of verticals in weak strip	5—13	10—11	5—13
	total verticals	9—16	17—18	9—18
Second method	relative mean square error (%)	6.7	9.6	8.0
	number of vertioals in violent strip	2—4	4—6	2—6
	number of verticals in weak strip	6—14	11—13	6—14
	tolal verticals	9—16	17—18	9—18
Third method	relative mean square error (%)	4.0	4.5	4.2
	systematic error (%)	1.6	-1.1	0.6
	number of verticals in violent strip	2—5	8—9	2—9
	number of verticals in weak strip	4—13	8—9	4—13
	tolal verticals	9—16	17—18	9—18

CONCLUSION

1. The intensity of pulsation on bedload is strong. In order to have a representative bedload transport rate, the duration time for each sampling will not be less thaw 150s. As for the whole crosssection. The grain size distribation of bed material is varied at all time, but for a small block or for instantaneous sampling for a vertical, it can be considered as unchanged. If the tolal duration time is same, the results for a single sampling and for repeating samplings are the same. Base on the above printiple, generally a single sampling of which the duration time is 240s can be adopted for the measurement instead of the repeating samplings. If the volume of sampler comtainer is limited, the duration time can not meet the requirement and the grain size distribution of bed material is varied rapidly, the repeating sampling method should be used and the number of repetitation is always to be 4. Both theoretical computation and measured data prove that much more repeating samplings does not have significant effect for the elimination of pulsation error.

2. The method of the distribution of measuring verticals accross the section according to the equal bedload transport rate can make the measuring errors to the minimum. When the single peak is presented in transverse distribution of transport rate per unit width, 8～12 verticals can be arranged; when it is double peak, 11～16 verticals should be arranged. If the requirement of precision is lowered the reduced number of verticals can be approximately found in Fig.2. But in pratical applicalion, it is so difficult to distribute the verticals according to the equal transport rate, application of close distribution in violent strip and sparse distribution in weak strip is an extended principle of equal transport rate method.

3. The uniform distribution method can not be adopted. Although distibuting more than 20 verticals can reduce some measusing error, it is only equivelent to 12 verticals for equal transport rate method.

ACKNOWLEDGEMENT

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REFERENCES

[1]. Han Qiwei and He Mingmin, 1984. Statistic Theory of Sediment.
[2]. Su Yifan, 1983. Primary Analysis on Measuring Method of Gravel Bedload.

DEVELOPMENT OF A PORTABLE SAND TRAP

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ABSTRACT

Traps are commonly utilized to measure sediment transport rates and collect samples of the transported material in rivers. In contrast, traps are under-utilized in the coastal zone despite an analogous quasi-steady state current which transports sand-sized material alongshore. The streamer trap, a portable net-type sand trap developed for use in the coastal zone, was evaluated for hydraulic and sand-trapping efficiencies in a series of laboratory and field experiments. The Helley-Smith sampler, a popular riverine sediment sampler, was also evaluated for comparison. Results indicate that the streamer trap has near-optimum hydraulic and sediment-trapping efficiencies both in the laboratory and field, whereas the Helley-Smith sampler has a much higher sand-trapping efficiency than reported in the literature.

INTRODUCTION

Sediment transport by water is a complex phenomenon that is little understood despite more than 200 years of intense study by engineers and scientists. The streamer trap, a portable net-type sand trap consisting of a vertical array of cylindrical mesh bags mounted on a frame (Figure 1), was developed to measure rates of sand transport in the surf zone, the region extending from the wave breaker line to the shore. Each mesh bag is attached to a nozzle into which sediment-laden water flows; the bag and nozzle together form the streamer element, first developed by Katori (1982), which "streams" into the water column with the flow. Kraus (1987) mounted the elements in a vertical array to measure the distribution of sand transport through the water column. Through accurate measurement of transported sand, and associated waves and currents, sediment transport models can be developed.

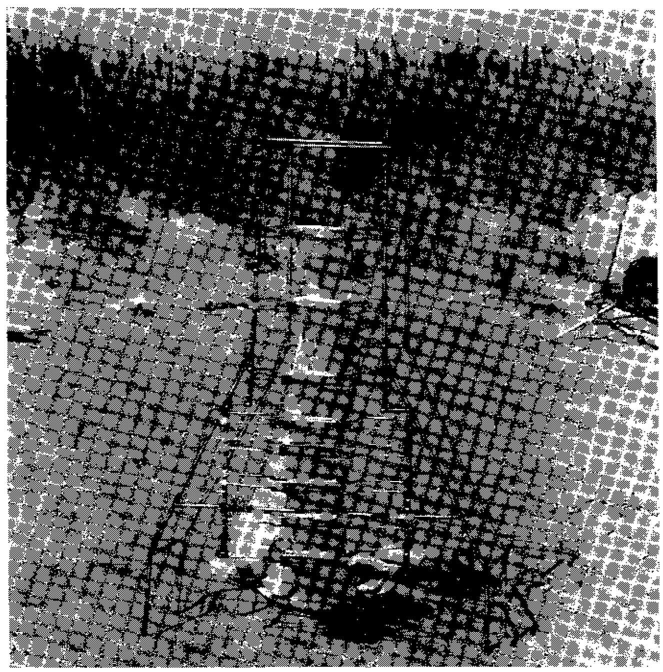

Figure 1. Streamer trap

Two laboratory experiments and several field tests were conducted to define and improve upon the hydraulic and sand-trapping characteristics of various streamer trap nozzles. The Helley-Smith (H-S) sampler, a popular portable net-type riverine sediment trap previously examined in the laboratory and field (Helley and Smith 1971, Druffel et al. 1976, Emmett 1980) was evaluated for comparison. The streamer trap has also been deployed in the United States in several major field data collection projects (Kraus and Dean 1987; Kraus, Gingerich and Rosati 1989; Rosati, Gingerich, and Kraus 1990).

The laboratory experiments were conducted in an 18.3-m long uni-directional flow tank to simulate the quasi-steady state longshore current that occurs in the surf zone during oblique wave approach. The first experiment measured the hydraulic efficiencies of 23 streamer trap nozzles and the H-S sampler (Rosati and Kraus 1988). From this experiment, selected streamer trap nozzles and the H-S sampler were further evaluated in a sand-trapping experiment (Rosati and Kraus 1989). Sand-trapping efficiencies of the H-S sampler and three streamer trap nozzles with favorable laboratory performance were then inter-compared through a series of field tests.

HYDRAULIC LABORATORY EXPERIMENT

The uni-directional flow tank employed for the hydraulic and sand-trapping experiments had a cross-section of 0.76 by 0.76 m and a maximum water discharge of 0.2 m^3/sec. For the hydraulic tests, the bottom of a 10-m long test section was lined with plastic grass mat carpet (1.3 cm in height) to create a uniform roughness. Hydraulic efficiency tests were conducted to evaluate the degree to which the measurement devices disturbed the flow field. Hydraulic efficiency is defined as,

$$E_h = \frac{1}{N} \sum_{i=1}^{N} \frac{V_{ti}}{V_{ai}} \tag{1}$$

where V_{ti} is the flow speed at point i in the nozzle mouth, measured at N locations, and V_{ai} is the ambient flow speed at the same location in the tank without the trap. Water speed was measured at points distributed uniformly across the area of the nozzle (3, 4, or 9 points, depending on nozzle size and geometry). The standard deviation in efficiency was computed from corresponding pairs of point measurements. Ideally, $E_h = 1.0$, indicating that the flow field at the nozzle opening is identical to the ambient (without nozzle) flow field. The H-S sampler operates on a pressure-difference principle, in which an exit-to-entrance area ratio greater than unity results in a hydraulic efficiency previously established as 1.54 (Druffel et al. 1976).

A specific procedure was followed in all hydraulic efficiency tests to ensure that ambient and flow conditions with the trap in place varied less than 5 percent. Separate tests were performed with nozzles configured three ways in the flow. A single nozzle was either positioned at mid-depth, for which the flow was ascertained to be almost uniform over the area occupied by the nozzle (midflow tests), or with the nozzle resting on the mat, for which the flow speed increased steeply from near-zero at the mat surface in classical log-law manner (bottom-flow tests). A third type of test consisted of nozzles positioned at both the bottom-flow and mid-depth locations (two-streamer tests). Tests of 117 combinations of nozzle type, elevation of nozzle in the water column, and flow condition were conducted. Streamer element parameters examined included nozzle height and width (varied between 2.5- by 15-cm and 25- by 20-cm), presence or absence of a hood, presence or absence of a bottom lip (only evaluated in bottom-flow tests), and streamer length (varied between 0.36 and 2.0 m).

Hydraulic testing was conducted by evaluating each nozzle for mid-range and high-range flow conditions (midflow speed V_{mid} = 43 and 74 cm/sec). From these initial evaluations using two flow conditions, four nozzles were identified for further testing over additional flow speeds (V_{mid} = 22 and 59 cm/sec): two streamer trap nozzles with hydraulic efficiencies close to unity, (1) a 2.5- by 15-cm nozzle with 5.1-cm hood later used in the SUPERDUCK field data collection project (Rosati, Gingerich, and Kraus in press) (hereafter referred to as the SUPERDUCK (SD) nozzle), and (2) a 5.1- by 5.1-cm nozzle with 5.1-cm hood, hereafter referred to as the CUBE (C) nozzle; (3) the 9- by 15-cm nozzle previously used in the DUCK85 field data collection project (Kraus, Gingerich, and Rosati 1989), hereafter referred to as the DUCK85 (D85) nozzle; and (4) the H-S sampler for comparison.

Figure 2 presents the bottom-flow hydraulic efficiencies and standard deviations for the SD, D85, C, and H-S nozzles at the four flow conditions. Lengths of vertical lines at each point represent one standard deviation about the mean. Table 1 summarizes the average hydraulic efficiency for each nozzle for each testing condition (bottom-flow, midflow, or two streamers). The maximum standard deviation for a nozzle for a flow speed during a particular testing condition was chosen as a conservative representative value. The average hydraulic efficiency of the H-S nozzle over the range of flow conditions (E_h = 1.30) confirms a previously-reported average hydraulic efficiency for the sampler equal to 1.54 for flow speeds ranging from 94 to 113 cm/sec (Druffel et al. 1976). The C nozzle had an average hydraulic efficiency closest to optimum (E_h = 0.94), and the D85 and SD nozzles had average hydraulic efficiencies near optimum (E_h = 0.88 and 0.90, respectively).

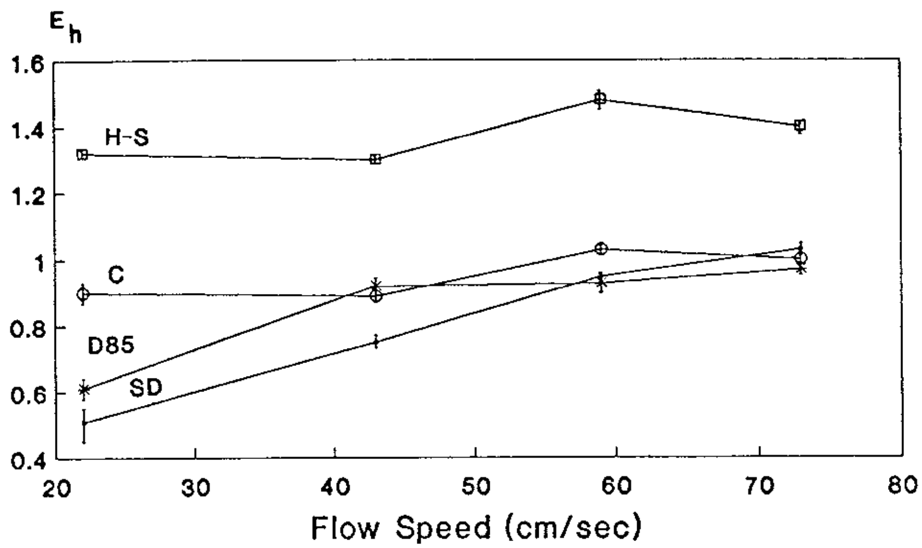

Figure 2. Bottom-flow hydraulic efficiency

Table 1. Average Hydraulic Efficiencies and Standard Deviations

Testing Condition	DUCK85 (D85)	SUPERDUCK (SD)	CUBE (C)	Helley-Smith (H-S)
Bottom-Flow	0.86 ± 0.03	0.81 ± 0.03	0.96 ± 0.03	1.38 ± 0.03
Midflow	0.92 ± 0.02	1.02 ± 0.01	0.93 ± 0.02	1.23 ± 0.02
Two Streamers	0.88 ± 0.04	0.87 ± 0.03	0.95 ± 0.06	-----------

SAND-TRAPPING LABORATORY EXPERIMENT

The purpose of the second set of experiments was to quantify the sand-trapping efficiency of nozzles with previously determined near-optimal hydraulic efficiencies over a range of flow speeds and bedforms representative of the surf zone. Sand-trapping efficiency E_s is defined as the ratio of the trap-predicted sand transport flux to the ambient sand transport flux that occurs for the same flow condition without the trap, with flux defined as,

$$F = \frac{S}{\Delta w \Delta h \Delta t} \tag{2}$$

where S is the dry weight of transported sand (g), Δh and Δw are representative height and width dimensions, respectively (cm), and Δt is the sampling time interval (sec). After evaluating several alternatives, a pit bedload sampler, consisting of a 6.1-m long catchment section divided into three basins, was installed at the down-flow end of the flow tank to measure ambient sand transport. Large sheets of monofilament sieve cloth identical to the streamer cloth were secured to the bottom of the basins, and ambient sand transport rates were determined from the quantity of sand collected in the cloths over a sampling interval. The flow tank was also modified to include a 6.1-m-long sand transport test section that was 15.2-cm deep. Quartz sand with a median grain size of 0.23 mm was placed in the test section.

Separate procedures were developed for the pit sampler and trap tests to accurately simulate the sheet-flow mode of sediment transport in the surf zone, produced by waves and longshore current. Specific steps followed in each procedure are detailed by Rosati and Kraus (1989). In general, flow parameters were first defined for a particular testing condition, then sand transport was measured from a flat sand bed either with the pit sampler cloths or a trap in place for a nominal 5-min testing period. Sand collected was weighed in a drip-free wet condition, which has been shown to be linearly correlated with the dry weight for sand-sized material (Kraus and Nakashima 1986).

It was empirically determined that sand transport within 5 cm of the bed accounted for at least 96 percent of the total transport in the laboratory. Integrating through the water column to obtain a total rate introduced error as great as 100 percent. Therefore, for determining E_s, it was assumed that nozzles positioned above the bed (measuring suspended sand transport only) had sand-trapping efficiencies equal to their hydraulic efficiencies, and E_s was determined only for streamers resting on the bed. Sand fluxes were calculated using 5 cm as the vertical distance of significant sand transport for both pit sampler (control) and nozzle evaluation tests.

A total of 101 nozzle and pit sampler sand-trapping efficiency tests were conducted over a period of 40 laboratory work days. Nozzle performance during testing was qualitatively observed. The D85 bottom nozzle began scouring around its outer edges immediately after testing began, and the scour increased during the test until sand began passing under the nozzle toward the end of the test. The SD bottom nozzle occasionally scoured around its outer edges for part or all of a 5-min test, and sand would either pass around or under the outer edges. The H-S sampler behaved as a vacuum cleaner or jet pump, creating turbulence and large longitudinal eddies such that sand to the rear of the sampler moved upstream and into the nozzle at the higher flow speeds. The H-S sampler thus dug into the bed and buried itself. Qualitatively, the C nozzle appeared to function optimally, and the moving sheet of sand and small bedforms entered unhindered into the nozzle. Nozzles designed with both long and short, and straight and curved bottom lips tended to enhance scour rather than reduce it. Power relationships that use the midflow speed minus an experimentally-determined threshold flow speed V_* as the independent variable were fit to the sand flux data. A relationship was not developed for the H-S sampler as testing was discontinued after two measurements due to the unrealistic sand-trapping characteristics of the device. The empirical data and power relationships developed are presented in Figure 3.

The curve labeled "Pit-Sampler" in Figure 3 represents the control fluxes to which the nozzle transport fluxes should, in principle, be calibrated. However, although the C nozzle sand transport fluxes are comparable to the pit sampler transport fluxes at lower midflow speeds, as much as 45 percent higher values of flux were obtained with the C nozzle at higher speeds. Many possible reasons for this discrepancy were evaluated and eliminated, and it was concluded that the pit sampler was deficient in measuring ambient transport rates at higher flow speeds. Therefore, fluxes measured with the bottom C nozzle were used as a standard measure of the ambient sand transport rate. Values of E_s for the SD and D85 nozzles were calculated with the C nozzle flux substituted for the ambient sand transport flux.

All nozzles were fully tested in the 60 to 66 cm/sec range of midflow speeds, which resulted in a flat-bed sand transport condition most like the mode of sand transport occurring in the surf zone. Therefore, values of E_s for the SD and D85 nozzles were calculated by integrating relationships describing the measurements from 60 to 66 cm/sec to obtain the area under each curve, and

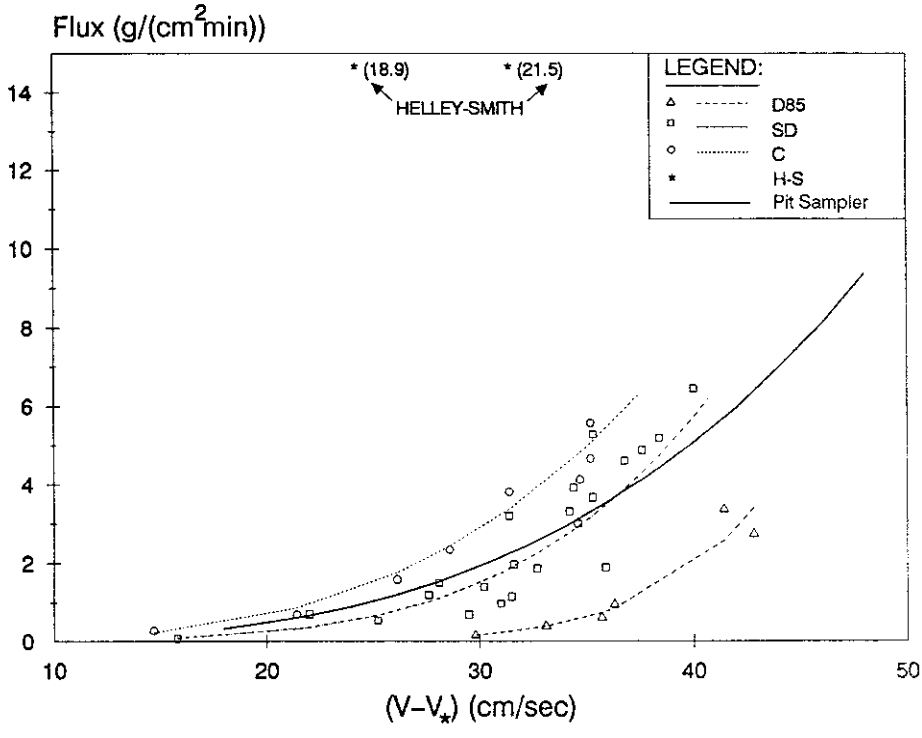

Figure 3. Summary of sand flux data and empirical relations

dividing the SD- and D85-related areas by the C-related area. Areas below upper and lower 95-percent confidence limits were also calculated to obtain a corresponding standard deviation (Table 2). Values of standard deviation for the near-bed tests are high, in part due to variability in bedforms and scour at the nozzle base. Sand fluxes obtained with a particular nozzle type should be divided by the corresponding value of E_s to obtain an estimate of the true sand flux. Near-bed E_s for the H-S was estimated (Figure 3) at 1,000 percent, higher than the 150 to 175 percent stated in the literature for sand-sized material (Helley and Smith 1971, Emmett 1980).

Table 2. Sand-Trapping Efficiencies and Standard Deviations

Nozzle Type	Near-Bed E_s	Midflow E_s ($=E_h$)
DUCK85 (D85)	0.13 +/- 0.50	0.92 +/- 0.02
Superduck (SD)	0.68 +/- 0.51	1.02 +/- 0.01
Cube (C)	1.00 (by definition)	1.00 +/- 0.02
Helley-Smith (H-S)	10.00	-------------

FIELD COMPARISONS

The streamer trap has performed successfully in three major field data collection projects as well as in several smaller field projects. During these data collection projects, tests were conducted to evaluate the behavior of the streamer trap in the prototype and compare the trap with other measurement apparatus such as the H-S sampler and Optical Backscatter Sensors (OBS).

Consistency Tests

During the DUCK85 and SUPERDUCK field data collection projects, two traps were placed in close proximity to each other (within 1 m in the alongshore and on-offshore directions) such that the traps would measure transport under similar longshore flow and wave regimes. These measurements were called "consistency tests," and the purpose was to quantify the reliability and reproducibility of the trap. The consistency test data were analyzed in two ways; a comparison of the shape of the vertical flux profile (either linear, exponential, or power dependence on flow speed), and calculation of a "consistency ratio," a comparison of total rates measured by the two closely-spaced traps. For the D85 nozzles, it was determined that 9 out of 10 vertical flux profiles had the same type of shape, and vertical flux profiles measured with the SD nozzles had similar shapes for 5 out of 7 consistency tests. D85 nozzles had consistency ratios, a ratio of the lower transport rate density divided by the higher value, between 0.5 and 0.9, whereas consistency ratios ranged from 0.5 to 1.0 for the SD nozzle. These favorable comparisons indicate that behavior of the streamer trap with the SD and D85 nozzles is consistent, and the trap provides reproducible measurements of the transport rate.

Comparison with OBS

Sand transport rates were measured simultaneously with a streamer trap (SD nozzles) and seven OBS's mounted on the same trap frame at the Great Lakes '88 field data collection project conducted on Lake Michigan at Ludington, Michigan. Comparison of results indicated favorable agreement between trap (adjusted with E_s presented in Table 2) and OBS measurements through the water column, with a squared correlation coefficient equal to 0.62 (Rosati et al. in press). Larger values of OBS-predicted sand flux at higher flow rates corresponded to lower values of streamer trap measurements. This difference between measurement methods may be explained by short-term reversals in particle direction that would be "double-counted" by the OBS. The streamer trap has no such bias because material does not enter the streamer nozzle if flow is not directed into it.

Comparison with H-S

Three comparison tests were conducted with a H-S sampler located approximately 0.5 m shoreward of a SD trap in a narrow surf zone. The H-S sampler was observed to fill very quickly (removed after 2.5-min rather than the typical 5-min data collection period due to excessive filling of the sampler bag), with similar "self-burying" characteristics as occurred in the laboratory tests. Fluxes obtained with the bedload SD nozzle (adjusted with E_s) were compared with H-S fluxes (not adjusted with E_s), with the H-S predicting transport up to 5.4 times that measured with the SD nozzle, and averaging 3.3 times the SD nozzle flux. The comparatively higher H-S measurements and observations of the sampler in the field corroborate laboratory results.

CONCLUSIONS

This laboratory and field study was conducted to evaluate and improve upon the hydraulic and sand-trapping characteristics of the streamer trap nozzle for use in the nearshore zone. Measurements were also made with the Helley-Smith sampler and Optical Backscatter Sensors for comparison. Values of hydraulic and sand-trapping efficiency were obtained for various streamer trap nozzles and used to adjust field-measured transport rates. Qualitative comparisons of trap performance in the field indicate that trap-measured transport rates are reproducible. Preliminary results indicate a favorable comparison between the SD trap and measurements made with Optical Backscatter Sensors.

The pressure-difference Helley-Smith sampler had similar values of hydraulic efficiency as reported in the literature. A sand-trapping efficiency of 10.0 was calculated for two measurements made in the laboratory, and three comparisons with a SD trap in the field indicated an average sand-trapping efficiency of 3.3. Considering the high values of efficiency and "self-burying" behavior of the Helley-Smith sampler in the laboratory and field, this device and other pressure-difference traps are not recommended for use in measuring bedload transport in the nearshore zone and rivers where sand-sized particles are present. This conclusion supports Emmett's (1980) recommendation that the Helley-Smith sampler not be used for material finer than 0.25 mm. Our findings further indicate that the suitability of the Helley-Smith sampler for measuring transport of any size particles is questionable.

Based on results of this study, it is concluded that the streamer trap is an accurate and reliable apparatus for measuring rates and vertical distributions of sand transport. The trap is recommended for use in low to moderate unidirectional flow regimes, as occur in rivers and the coastal nearshore zone.

ACKNOWLEDGMENTS

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REFERENCES

Druffel, L., Emmett, W. W., Schneider, V. R., and Skinner, J. V., 1976, "Laboratory Hydraulic Calibration of the Helley-Smith Bedload Sediment Sampler," U.S. Geological Survey Open-File Report 76-752, U.S. Government Printing Office, Washington, DC.

Emmett, W. W., 1980, "A Field Calibration of the Sediment-Trapping Characteristics of the Helley-Smith Bedload Sampler," U.S. Geological Survey Professional Paper 1139, U.S. Government Printing Office, Washington, DC.

Helley, E. J., and Smith, W., 1971, "Development and Calibration of a Pressure-Difference Bedload Sampler," U.S. Geological Survey Open-File Report No. 73-108, Menlo Park, CA.

Katori, S., 1982, "Measurement of Sediment Transport by Streamer Trap," Report of the 6th Cooperative Field Investigation, Nearshore Environment Research Center, Report No. 16, TR-81-2, Tokyo, Japan, 138-141 (in Japanese).

Kraus, N. C., 1987, "Applications of Traps for Obtaining Point Measurements of Sediment Transport Rates in the Surf Zone," Journal of Coastal Research, Vol. 3, No. 2, 139-152.

Kraus, N. C., and Dean, J. L., 1987, "Longshore Sand Transport Rate Distribution Measured by Trap," Proceedings, Coastal Sediments '87, American Society of Civil Engineers, 881-896.

Kraus, N. C., Gingerich, K. J., and Rosati, J. D., 1989, "DUCK85 Surf Zone Sand Transport Experiment," Technical Report CERC-89-5, U.S. Army Engineer Waterways Experiment Station, Coastal Engineering Research Center, Vicksburg, MS.

Kraus, N. C., and Nakashima, L., 1986, "Field Method of Determining Rapidly the Dry Weight of Wet Sand Samples," Journal of Sedimentary Petrology, Vol. 56, No. 4, 550-551.

Rosati, J. D., Gingerich, K. J., and Kraus, N. C., in press, "SUPERDUCK Surf Zone Sand Transport Experiment," Technical Report, U.S. Army Engineer Waterways Experiment Station, Coastal Engineering Research Center, Vicksburg, MS.

Rosati, J. D. and Kraus, N. C., 1988, "Hydraulic Test of the Streamer Sediment Trap," Journal of Hydraulics Division, Vol. 114, No. 12, 1527-1532.

Rosati, J. D. and Kraus, N. C., 1989, "Development of a Portable Sand Trap for Use in the Nearshore," Technical Report CERC-89-11, U.S. Army Engineer Waterways Experiment Station, Coastal Engineering Research Center, Vicksburg, MS.

Rosati, J. D., Kraus, N. C., Gingerich, K. J., Smith, J. M., and Beach, R. A., in press, "Distributions of Longshore Transport Measured in Lake Michigan," Proceedings, Coastal Sediments '91, American Society of Civil Engineers.

A FLUME STUDY EXAMINING SILT FENCES

Tom Munson [1]

ABSTRACT: The use of silt fence, as well as various other alternative sediment controls is a common practice in the coal mining areas of Utah to control erosion and sedimentation of streams. Through the use of a flume, site-specific data has been collected to assess the filtering efficiency and water quality changes attributed to various silt fence fabrics using site-specific mine soils. This paper discussess the results of this study. **KEY TERMS:** Silt fence, filtering efficiency, sediment control.

INTRODUCTION

The use of silt fences to control sedimentation of streams and erosion of disturbed soils is a common practice in the coal mining areas of Utah. The water quality regulations promulgated by state and federal government provide the basis and need for the use of alternative sediment controls (i.e., silt fences) in meeting the requirements of those regulations.

The coal mines in Utah have many small disturbed areas isolated from the major mine complex, calling for sediment control. The cost of constructing sediment ponds for these small areas, usually less than two acres, is prohibitive when these areas can effectively be treated by less costly alternative measures, i.e., silt fence. The effectiveness of silt fence, its installation, the materials used, and its longevity are all closely examined by the regulators and the coal operators.

This paper attempts to take a closer look at the filter efficiency of three silt fence fabrics and their ability to filter a clayey soil and a sandy soil taken from two Utah mine sites. A flume was employed to simulate variables, such as slope of the ditch, and provide a means of analyzing different fabrics. Water quality data (Total Suspended Solids) was taken before, during, and after each run to determine filtering efficiencies, and water quality comparisons.

Soils Description

Two site-specific mine site soils were used during the testing of three silt fence fabrics. One soil (DCM-1) was a sandy soil and the other

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(AM-1) was a clayey soil. DCM-1 was taken from the Deer Creek Mine facility in Central Utah. It is 56 percent coarse sand, 42 percent fine sand, and 2 percent gravel. AM-1 was taken from the proposed Alton mine site in Southern Utah. It is 63 percent clay, 24 percent silt, and 13 percent very fine sand.

These two soils were chosen to examine the effects of sand vs. clay on the filtering efficiency of the three fabrics used.

Silt Fence Fabric Description

Three different fabrics were chosen to represent the most commonly used silt fence fabrics. They were Marifi 700X, AMXCO SF-55 and AMXCO SF-26. All three fabrics are woven drainage fabric. The AMXCO SF-26 and SF-55 are loose weave, whereas, the Marifi 700X is a heat bonded weave.

The following table shows other pertinent specifications.

Table 1. Silt Fence Specifications

	SF-26	SF-55	700X
Weight of fabric	2.5 oz/SY.	5.5 oz/SY.	6.5 oz/SY
Thickness	6 mils	25 mils	19 mils
Equivalent opening size (U.S. Std. Sieve Size)	70-100	20	70-100

Manufacturers list many other specifications regarding fabrics but due to the lack of comparison between laboratory tests given by different manufacturers and their applicability to the actual study of site-specific field conditions, the results are not given.

Test Procedure

The test procedure chosen was fashioned after the Virginia Highway and Transportation Research Council's laboratory procedure for measuring filtering efficiencies of silt fences. The procedure is spelled out in a publication entitled "Evaluation of Filter Fabrics For Use as Silt Fences" by David C. Wyant, Research Scientist. The procedure outlined below mimics the test used by Mr. Wyant.

1. Apparatus

   a. A flume 48 in. (1.2 m) long by 32 in. (0.8 m) wide by 12 in. (0.3 m) high with a gutter attached to one side.

b. Two 20-gal. (0.08 m ^{3}) containers.

c. A stirring paddle to agitate sample.

d. Stopwatch.

e. A DH-48 integrated water sampler.

2. Procedure

a. Stretch a sample of the fabric 39 in. (1.0 m) long by 12 in. (0.3 m) wide across the flume opening 32 in. (0.8 m) wide and fasten securely in place to assure that all the sediment-laden water passes through the sample. Note: The flume opening is the standard length of a straw bale.

b. Elevate the flume to an 8 percent slope.

c. Prewet the fabric by passing 50 litres of untreated, fairly sediment-free water through it.

d. Mix 150 grams of minus 10 material of the soil chosen in 50 litres
of the untreated water placed in one of the 20 gal. (0.08 m ^{3}) containers. Thoroughly agitate the solution with a stirring paddle to obtain a uniform mix.

e. After uniformly mixing the solution, quickly dump the solution behind the fabric sample in the flume. Start the time at dumping.

f. Rinse the mixing container with 1 to 2 litres of the filtrate and dump into the flume.

g. Time the flow of water through the fabric until the water level drops to a point 10.5 in. (0.27 m) behind the fabric. At this point the flow has essentially ceased.

h. Collect filtrate samples at 5 min., 55 min., and 1 hr. 35 min. for suspended soilds analysis.

i. Collect all filtrate in a second mixing container.

j. At the completion of the test, agitate the collected filtrate until the mixture is uniformly mixed. Obtain a depth integrated, suspended solids sample from the mixture during agitation.

k. Process all suspended solids samples by test #209C, "Total Suspended Solids Dried at 103-105° C" Standard Methods for the Examination of Water and Wastewater, 11985, 16th ed. (APHA, AWWA, WPCF).[2]

1. Calculate the filtering efficiency (FE) of the fabric as follows:

$$FE\ (\%) = \frac{SS_{BF} - SS_{AF}}{SS_{BF}} \times 100 \qquad (1)$$

where SS_{BF} and SS_{AF} are the suspended solids values before filtration and after filtration, respectively.

Results

The results are graphically represented on Figures A-2 through A-5. The Total Suspended solids values for before filtration and after filtration are shown on Figure A-2 for the Alton Mine and on Figure A-3 for the Deer Creek Mine. The filtering efficiencies of the three silt fence fabrics for the Alton Mine are shown on Figure A-4 and for the Deer Creek Mine on Figure A-5. A total of seven runs were completed for each mine site; two runs for SF-55 and SF-26 for each mine site soil (SCM-1 and AM-1) and three runs for 700X for each mine site soil.

The graphically presented results show filtering efficiencies of greater than 90 percent on four runs (10, 12, 13 and 14) for the Deer Creek soils, and on one run (7) for the Alton Mine soils. Generally speaking, the filtering efficiencies for the AM-1 soils were in the 80 percent range for the 700X fabric and SF-55, but reached as high as 93.5 percent filtering efficiency for SF-26. It must be noted that the variability between the initial suspended solids data directly affects the filtering efficiency results. This is demonstrated by comparing the data from run number 3 and number 5 on the silt fence fabric 700X using the same soil. Run number 3 had an initial suspended solids reading of 380 mg/l and a final reading of 76 mg/l. Run number 5 had an initial reading of 512 mg/l and a final reading of 53 mg/l. The respective efficiencies were 80.0 and 89.6 percent.

Surveying the final results, the filtering efficiencies for the two soils can be used to draw some generalized conclusions. First, the initial suspended solids data was extremely variable between runs on the same soil type. Initial suspended solids values ranged from 380 mg/l to 735 mg/l for the Alton Mine soils with a mean value of 595 mg/l. For the Deer Creek soils, initial suspended solids values ranged from 212 mg/l to 522 mg/l with a mean Equivalent Opening size (E.O.S.) of the fabric affected the final composite suspended solids data in some runs, but not all. SF-55 had the lowest E.O.S. (20 U.S. Std. SIEVE), and therefore it was generally expected to see lower filtering efficiency values. This was not the case with the AM-1 soils because the initial suspended solids data for SF-55 runs were generally high, bringing up the filtering efficiencies values. It was interesting to note, for both soil types, the final composite suspended solids values for SF-55 were as high or higher than the SF-26 and 700X values. This can be attributed to the

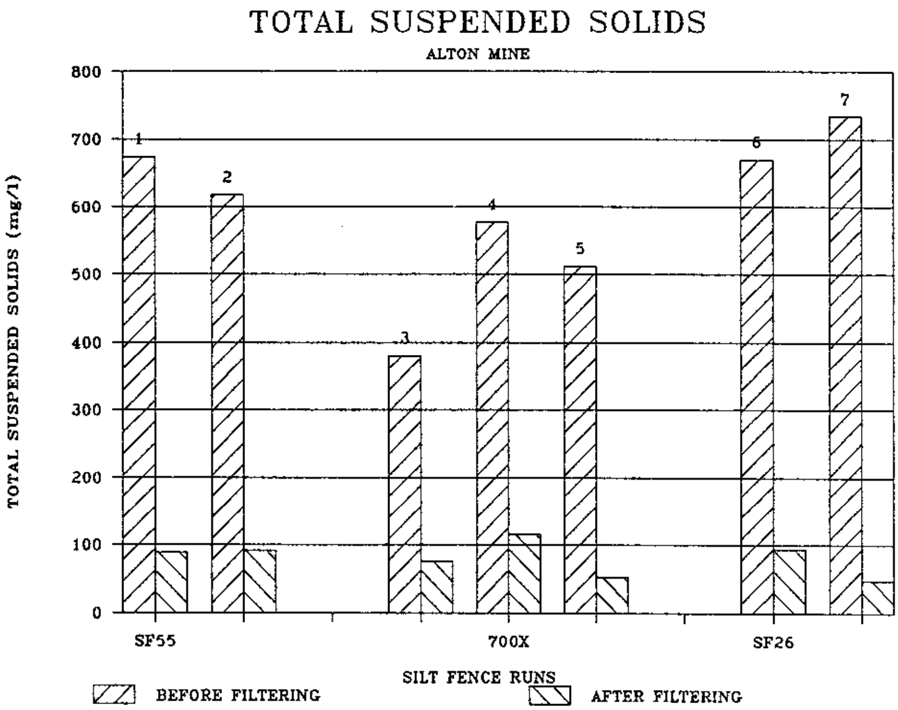

FIGURE A-2. T.S.S. VALUES ALTON MINE

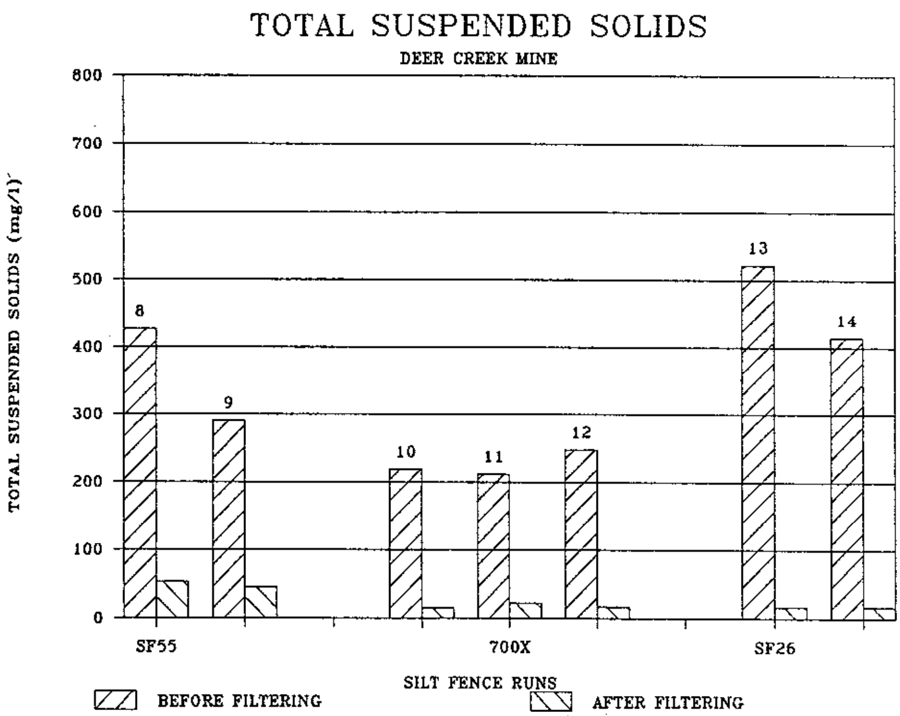

FIGURE A-3. T.S.S. VALUES DEER CR. MINE

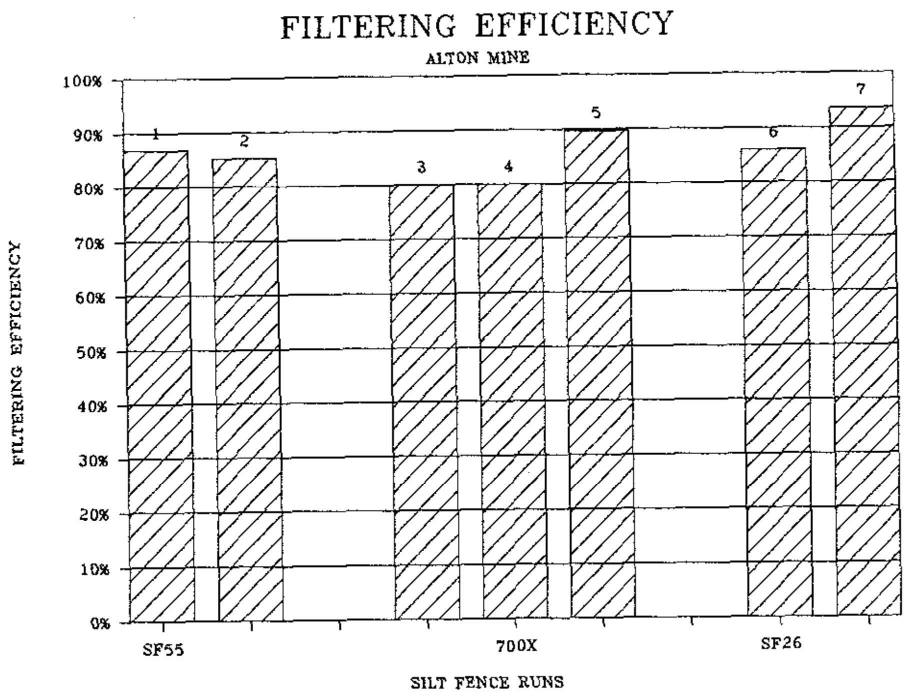

FIGURE A-4. FILTERING EFFICIENCY ALTON MINE

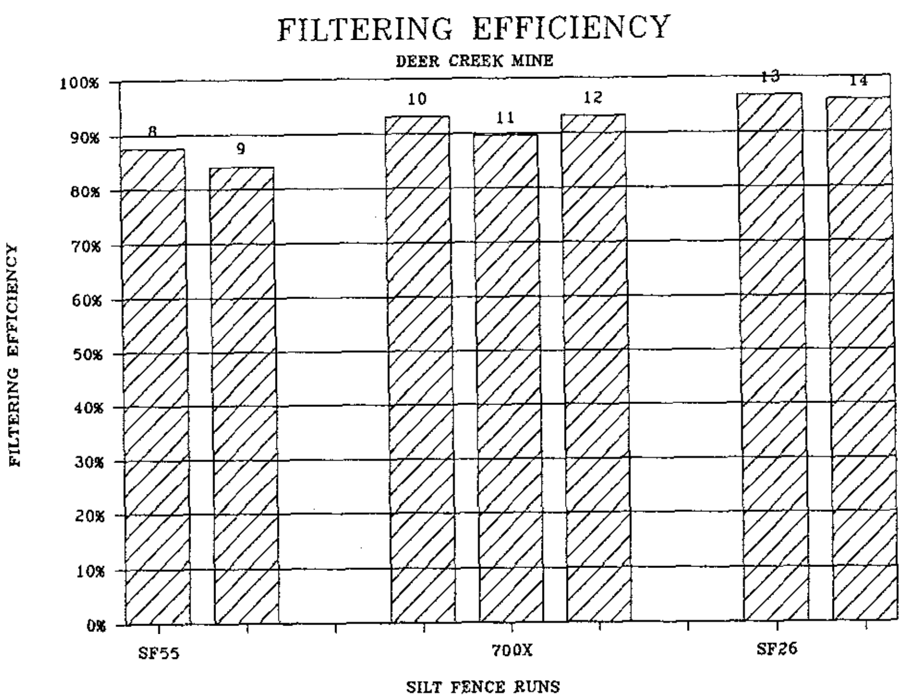

FIGURE A-5. FILTERING EFFICIENCY DEER CR. MINE

E.O.S. of the fabric. The cricial data observation comes when one looks at the final composite suspended solids values corresponding to soil type. Filtering efficiency values are misleading because of the variability of initial suspended solids data.

Therefore, in conclusion, when water quality is a crucial issue, it is possible that water quality impacts from using silt fences for sediment control can be calculated by looking at a specific soil type, calculating initial suspended solids values for that soil type, and determining the final composite suspended solids results based on flume studies. If threshold values of suspended solids are crucial to the survivability of certain sensititve aquatic organisms, then the highest values expected can be predicted based on initial filtrate flow through the silt fence. as seen from Figure A-6. Since the head of water behind the silt fence is the driving force, initial filtrate values (3 mins.) from the silt fence runs ranged from half again as high to seven times as high as the final composite values of suspended solids (see Figure A-6). This is an important observation when determining impact during a storm event. Within one hour after a flume run was started, suspended solids dropped to values significantly less than the final composite reading. Not only is the settling velocity for various particles sizes a factor, but the silt fence openings become clogged with fines, increasing filtering ability as well as significantly decreasing the flow. A plot of filtrate values for various flume runs overtime, using silt fence SF-26 and each soil type is shown on Figure A-6, demonstrating this effect. An interesting point is noted when looking at this figure. The final composite values for total suspended solids were higher and approached the initial 3-5 minute values for the clayey Alton Mine soils, but generally, the final composite values for the sandy Deer Creek Mine soils were as low and stayed as low as the 55 minute values. This indicates the influence the fine particles (, #200 U. S. Std. SIEVE) had on the final composite values for the clayey soils. A percentage of the fine particles, that pass through the fabrics, remain in suspension and can be considered a potential impact to water quality when clayey soils are filtered.

LITERATURE CITED

1. D. C. Wyant, "Evaluation of Filter Fabrics for Use as Silt Fences". Virginia Highway and Transportation Research Council, June, 1980.

2. Standard Methods for the Examination of Water and Wastewater, 1985, 16th ed., (APHA, AWWA, WPCR.)

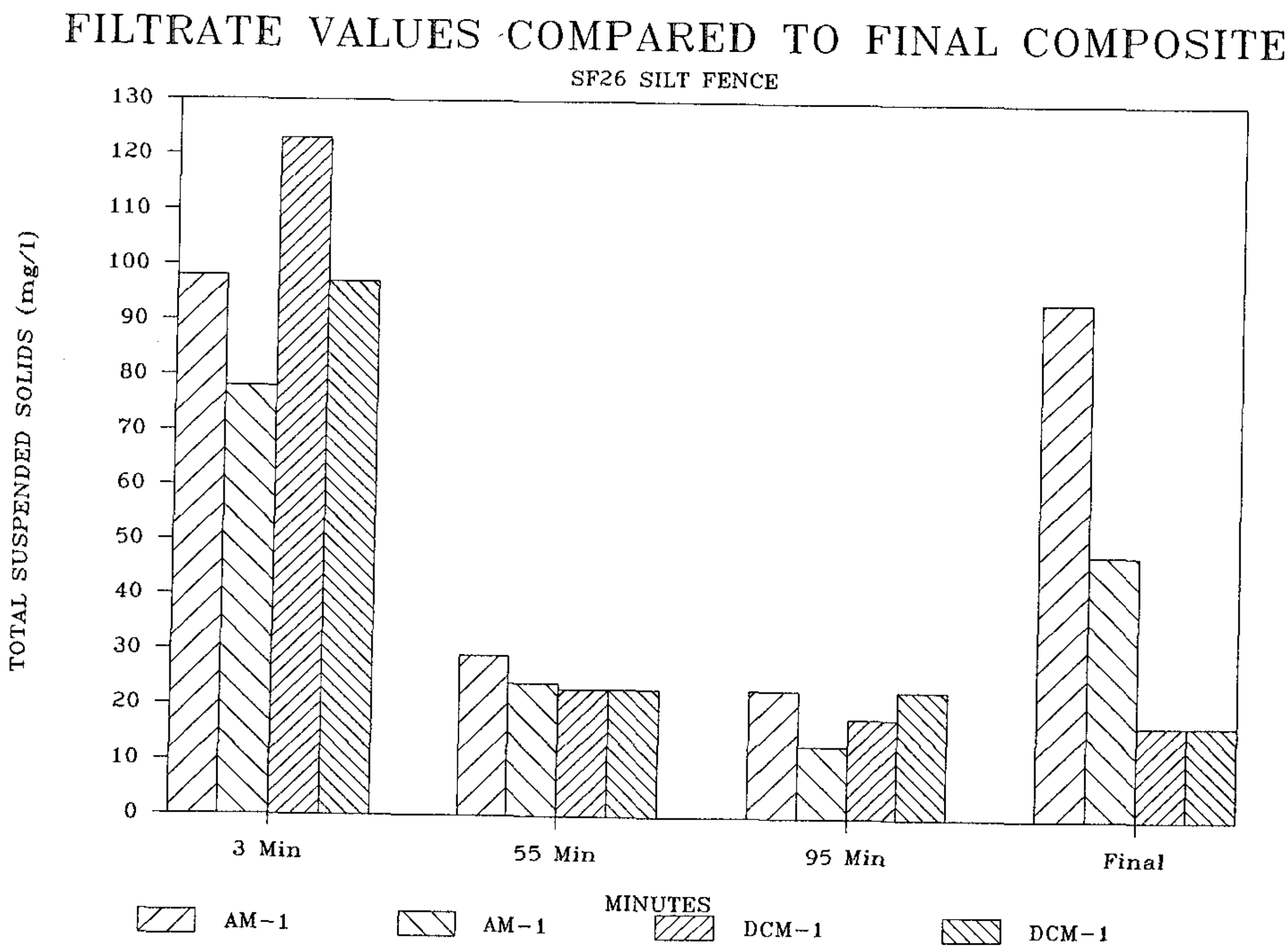

FIGURE A-6. A PLOT OF FILTRATE VALUES OVERTIME FOR SF-26

MEASUREMENT OF SCOUR AT SELECTED BRIDGES IN NEW YORK

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ABSTRACT

The U.S. Geological Survey (USGS), in cooperation with the New York State Department of Transportation, collected bridge-scour data at 77 sites throughout New York, excluding Long Island. This report is part of a 6-year study to evaluate data-collection methods and predictive equations for local scour at bridges. Methods are similar to the "limited approach" developed by the USGS in cooperation with the Federal Highway Administration.

One to 2 feet of local scour was found at many sites at the start of the study. At a few sites, the scour has exposed spread footings that were buried during construction. Twelve high-flow measurements, including two flows with a recurrence interval exceeding 5 years, did not indicate any new scour beyond the existing holes. Flows with recurrence intervals greater than 5 years may be necessary to trigger scour in streams with coarse bed material.

Sonar and geophysical techniques were evaluated at a few sites for their effectiveness in bridge-scour investigations. A transducer inside a 100-pound sounding weight provided an alternative method of measuring water depth, although moving the unit across the bridge was cumbersome. Another method used a transducer, installed on a bridge pier, and a data logger that recorded changes in streambed elevation automatically at selected time intervals. Geophysical techniques applied to gravel and cobble streambeds did not detect any backfilled scour holes, possibly because (1) deep holes did not exist, (2) resolution of the equipment (1 to 2 feet) could not detect a slightly deepened hole, or (3) the deepened hole was backfilled with the same type of bed material that lined the existing hole.

INTRODUCTION

Approximately 500,000 bridges in the United States are built over water and are subject to scour, the most common cause of bridge failure. Accurate estimates of potential scour are needed to design, construct, and maintain bridges. The added cost of making a bridge resistant to scour is usually small compared to the cost of bridge failure (Federal Highway Administration, 1988).

Floods in June 1972 damaged 182 bridges along New York State roads and many bridges on county roads. Scour and debris were the primary causes of damage (Highway Research Record, 1973). Damages from floods in April 1987 ranged from abutment washouts of short, single-span bridges over small streams to the catastrophic collapse of the five-span, multilane New York State Thruway bridge over Schoharie Creek that claimed 10 lives (Zembrzuski and Evans, 1989). Floods in June 1989, in western New York, damaged several bridges.

In 1988, the USGS, in cooperation with the New York State Department of Transportation (NYSDOT), began a 6-year study of bridge scour in New York through methods similar to those used in its national bridge-scour program in other States. The objectives were to (1) compile a statewide data base, (2) evaluate data-collection methods and predictive equations for local scour, and (3) identify the types of channels and bridges that are vulnerable to scour. This report describes the techniques used to collect bridge-scour data at 77 sites and presents the criteria for site selection, methods of data collection, and types of equipment used. It describes, in general terms, the extent of scour measured during the first year and discusses the limitations of certain procedures and equipment. It also presents a comparison of conventional methods of data collection with sonar and geophysical techniques.

TYPES OF BRIDGE SCOUR

Scour is the erosive action of flowing water that removes material from the streambed (Federal Highway Administration, 1988), and *scour depth* is the depth to which material is removed below a stated datum. Scour is a natural phenomenon that occurs in alluvial streams; it also can occur in any stream that contains erodible bed material.

Three types of scour can occur at a bridge: general scour, constriction or contraction scour, and local scour. *General scour* is the progressive degradation of the streambed from natural or man-induced processes in a channel over many years. *Constriction scour* is streambed erosion caused by increased flow velocities near a bridge that results from the decreased flow area formed by the bridge, approach embankments, and piers. *Local scour* is streambed erosion caused by local disturbances in the flow, such as vortices and eddies in the vicinity of piers. A general practice in bridge design is to estimate the depth of each type of scour separately, then sum the estimated depths to obtain the total scour depth. Local scour may produce greater scour depths than the other types of scour and is the primary focus of this study (Richardson and others, 1988).

The depth and extent of scour is determined by the following factors, described by Richardson and others (1988); Raudkivi and Ettema (1983 and 1985); Klingeman (1973); and Blodgett (1984):

1. Velocity, depth, and angle of approach flow
2. Size and gradation of bed material
3. Bridge geometry
4. Presence of debris or ice
5. Duration of high flow
6. Channel geometry
7. Total number of high flows
8. Channel morphology

The flow pattern and vortex system induced by a pier are shown in figure 1. These vortices result from the pileup of water at the upstream face and subsequent acceleration of the flow around the nose of the pier.

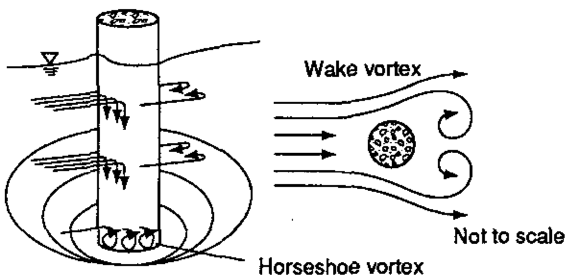


Figure 1.

Flow pattern and vortex system induced by a pier. (Modified from Richardson and others, 1988.)

Two types of local scour are "clear-water" scour and "live-bed" scour. Clear-water scour occurs when bed material upstream of the scour hole is motionless and cannot replace material removed by scour, and scour depth increases if the scour mechanism is able to remove material from the hole. Live-bed scour occurs when bed material upstream of the scour hole is moving, and scour depth increases only if the removal rate of material from the hole exceeds the transport rate of material into the hole.

MEASUREMENT OF SCOUR

The dynamic processes of a stream can cause the streambed to degrade and then aggrade during the course of a flood. Scour holes may develop and fill before the stream returns to normal levels. The interface between the backfilled material and the scour hole can be measured by geophysical techniques if the two layers have differing electrical or seismic-reflection properties (Gorin and Haeni, 1989).

Turbulence during floods in New York has caused 150-lb weights to skip along the water surface; this downstream movement caused errors in the depth measurement. Although corrections can be applied to compensate for most of this type of error, the exact location of the weight is always uncertain (Rantz and others, 1982; Coon and Futrell, 1986; Beverage, 1987). The use of mobile and fixed sonar instruments to measure scour depth is being studied. The mobile technique is similar to the method used by the USGS in Arkansas (Southard, 1989), where a graphic recorder plots a vertical cross section of the streambed while a transducer, submerged 1 to 3 ft, is moved across the stream. A fixed sonar installation automatically records streambed elevation at the base of a bridge pier.

Reconnaissance

An extensive literature search provided many articles on scour. Field data were sparse, but USGS and NYSDOT files provided some information related to scour. Stage-discharge ratings for USGS gaging stations were analyzed to determine channel stability near the bridge. Many rating curves at a station may indicate bed-material movement. Data from crest-stage gages and partial-record sites were also reviewed, and stations in areas of erodible bed material (sand, gravel, or recent alluvium) were identified (fig. 2). Stations on streams with drainage areas greater than 100 mi^2 and a potential for scour also were identified. Factors that affect scour potential include erodible bed material, high stream velocity, and any documented scour nearby. Bridges with a medium or high scour-susceptibility rating in NYSDOT's bridge-inventory file were reviewed, and bridges scheduled for immediate scour countermeasures (riprap, concrete-filled bags, etc.) were excluded. The NYSDOT scour-susceptibility rating of 950 State bridges with piers over water (Steve G. Georgopoulos, NYSDOT, written commun., 1989) indicated the following distribution:

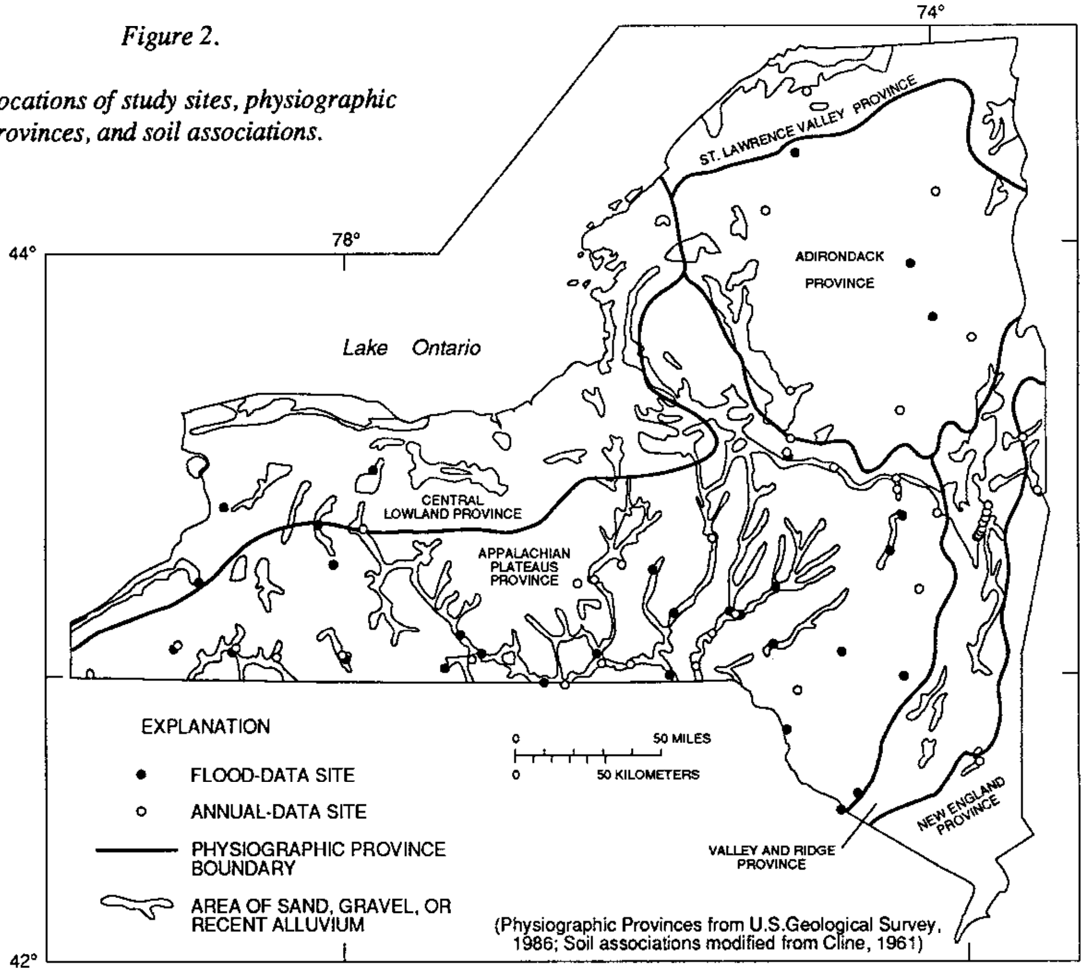
Susceptibility rating	Number of bridges	Percentage of total
High	43	4
Medium	102	11
Low	805	85

Site selection

The locations of bridge sites studied are shown in figure 2. A total of 77 bridge sites were selected--31 for flood-data collection and 46 for annual-data collection. The network represents six physiographic provinces in upstate New York and includes a wide range of basin characteristics and bridge designs. Drainage areas range from 30 mi^2 to more than 8,000 mi^2. Few gaging stations met the selection criteria in the Central Lowland, St. Lawrence Valley, and New England physiographic provinces. All bridges were constructed between 1902 and 1989.

Figure 2.

Locations of study sites, physiographic provinces, and soil associations.



Sites identified from reconnaissance were visited for evidence of scour. A checklist developed by the USGS to standardize the selection process is depicted in figure 3. If a bridge did not meet the selection criteria, the next two bridges upstream and downstream of the site were visited.

Study sites were divided into two categories: flood-data sites and annual-data sites. Flood-data sites represent locations where data are to be collected during high flows; data from these sites can be used later to determine what types of channels and bridges are vulnerable to scour and to evaluate local scour equations. Annual-data sites provide an inexpensive method of expanding the data base; at these sites the streambed elevation along the upstream side of the bridge is measured annually. Priority was given to sites near USGS gaging stations along streams that contain erodible bed material or appeared unstable from review of USGS rating curves and NYSDOT files.

The site-selection criteria were as follows:

a. Site is at or near a USGS stream-gaging station to facilitate data collection.

b. Drainage basin exceeds 100 mi^2. Smaller basins generally contain single-span bridges (no piers), and the short duration of high flows limits the scour mechanism and the ability to collect flood data.

c. Streambed contains an ample supply of bed material prone to scour. Piers on bedrock or protected by riprap are excluded.

d. Pier nose is square, round, or sharp.
e. Network represents a wide range of basin characteristics.
f. Pier is in the main channel.
g. Channel is uniform upstream and downstream from bridge.
h. Flow-angle approaching pier is 10 degrees or less.
i. Scour is evident (although having a few sites with no scour is acceptable).
j. Bridge does not encroach upon main channel.
k. Pier does not constrict cross-sectional flow area by more than 10 percent.
l. Nearest reservoir is at least 10 mi upstream from the site.
m. Quantity of debris or ice is minimal.
n. Water depth at a few piers always exceeds 5 ft.
o. Boat access is available on large streams (to facilitate data collection).
p. Information on site construction, inspection, and maintenance is available.

Additional criteria for flood-data sites are:
a. Scour hole is accessible from upstream side of bridge.
b. Distance from bridge deck to streambed is less than 80 ft, preferably less than 40 ft.
c. Bridge is wide enough to provide safe working space for a two-person crew and measuring equipment, and does not interfere with operation of equipment.
d. Telemetry is available or observer is nearby to provide flood-alert information.

Rating Item	+	0	-
Is bridge accessible at high flow? Yes (+); No (-)			
Is streambed composed of bedrock or clay? No (+); Yes (-)			
Distance from bridge deck to streambed (in feet)? Less than 40 (+); 40 to 80 (0); more than 80 (-)			
Is sustained high flow likely during a flood? Yes (+); No (-)			
Can scour be measured safely at this bridge? Yes (+); No(-)			/////
Are there any other factors that would prevent scour from being measured at this site? No (+); Yes (-)			/////
Is scour likely to occur at one or more piers? Yes (+); No (0)			/////
Is scour likely to occur at more than one pier? Yes (+); No (0)			/////
Is scour likely to occur at one or more bridge abutments? Yes (+); No (0)			/////
Can pier be reached by a sounding weight lowered from the bridge? Yes (+); No (0)			/////
Does the bridge constrict high flows significantly? Yes (+); No (0)			/////
Shape of pier nose: square or round (+); sharp (0)			/////
Angle at which flow approaches piers (in degrees): 0 to 5 (+); more than 5 (0)			/////
Are pier footings exposed? No (+); Yes or don't know (0)			/////
Has riprap been placed around one or more piers? No (+); Yes or don't know (0)			/////
Is debris lodged on one or more piers? No (+); Yes (0)			/////
Is a gaging station located nearby (within view of the bridge)? Yes (+); No (0)			/////
Is boat access available nearby? Yes (+); No (0)			/////
Does the bridge have trusses? No (+); Yes (0)			/////
Will a traffic lane need to be closed to make measurements? No (+); Yes (0)			/////
Totals (+, 0, and -)			

Figure 3.--Sample checklist for bridge-site selection.

Data Collection

Data collection began in May 1989 at 77 bridges in New York (fig. 2); high-flow data are being collected at 31 bridges, and annual cross-section data at the remaining 46. Methods are similar to the "limited approach" developed by the USGS in cooperation with the Federal Highway Administration, whereby discharge, velocity, streambed elevation, and bed-material data are collected through equipment and procedures compatible with the Survey's stream-gaging program (Jarrett and Boyle, 1986). This approach is being used in the USGS's national bridge-scour program and in similar studies in other States; scour data collected in these studies may supplement data collected in New York. In addition, geophysical and sonar techniques are being used at a few sites to evaluate their effectiveness.

Flood Data.--This information is used to identify changes in streambed elevation, velocity distribution around piers, and bed-material characteristics. Data are used to determine the types of channels and bridges vulnerable to scour and to evaluate local scour equations.

Reference points were established at four cross sections per site--the upstream and downstream bridge railings, the approach section (one bridge-width upstream), and the exit section (one bridge-width downstream). The water-surface-and streambed-elevations at each cross section are calculated from the reference-point elevation.

Copies of bridge plans, drill logs, maintenance and inspection sheets, and fathometer surveys were obtained from NYSDOT. Dimensions of the piers and footings were recorded from bridge plans or site inspections. Channel-roughness coefficients were estimated at each cross section.

Recurrence intervals of the 2-year (mean annual) and 5-year floods were estimated from guidelines outlined by U.S. Water Resources Council (1981) or multiple regression analyses (Zembrzuski and Dunn, 1979). Flood data are to be collected whenever streamflow exceeds the mean-annual recurrence interval. Post-flood data are to be collected if the flow exceeds a 5-year recurrence interval. Intervals were based on studies of sand, gravel, and cobble streambeds in which thresholds for particle motion were exceeded during flows of these magnitudes (Culbertson and others, 1967; Norman, 1975; Andrews, 1979; Andrews, 1984; and Sidle, 1988).

Bed-material samples were collected at the water's edge near the bridge. A variation of the grid-sampling technique (International Organization for Standardization, 1989) is used because the streambeds are armored. The intermediate axis of each stone is measured every 0.5 ft along a 50-ft tape. The frequency of each size interval is the percentage, by number, of the 100 stones in the original sample that fall in the interval. A USGS bedload sampler is to be used at streams that could experience live-bed scour at high flow to determine the size of the bed material in motion (Helley and Smith, 1971).

The size distribution of the subsurface material is estimated from a 5- to 10-lb bulk sample collected after removal of the armor layer. The frequency of each size interval is expressed as the percentage, by mass, of the original sample that falls within the interval. The relations among differing methods of sampling that have been established for densely packed cubes in random arrangement indicate that the grid sample (by number) frequency is equivalent to the bulk sample (by mass) frequency (International Organization for Standardization, 1989). Core borings are to be taken at selected sites for comparison with data collected by grid and bulk sampling methods.

Baseline cross sections were measured at each reference point at the beginning of the study to determine the extent of scour. Streambed elevations are to be compared with (1) those shown on bridge plans, (2) previous measurements at the site, and (3) data collected during the study. About 20 soundings were used to define each cross section, and additional soundings within one "pier width" of each pier were used to define the streambed at the upstream and downstream sides of the pier. The cross sections at the approach- and exit sections are used to measure general scour; those at the bridge are used to measure constriction scour; and soundings near the pier are used to determine local scour.

Whenever discharge at a site exceeds the mean-annual flood, the following procedures are to be used:

1. Make a standard discharge measurement at the upstream side of the bridge.
2. Measure gage heights at the approach section, upstream and downstream sides of the bridge, and exit section before and after the discharge measurement.
3. Make depth soundings at the upstream and downstream sides of the bridge by the standard depth measurement with a sounding weight or the mobile-sonar technique. If the standard method is used, make the soundings about 1 ft apart within one "pier width" of the pier, and remove the velocity meter to reduce drag.
4. Photograph the stream to document the hydraulic conditions, particularly the state of flow, direction of flow approaching bridge, presence of debris, eddies, water-surface pileup, and drawdown.
5. Evaluate bedload-transport conditions with a bedload sampler or by listening for the sound of rocks striking the bridge or other rocks.
6. Measure water temperature.
7. Make depth soundings and measure gage height at both sides of the bridge after the flow recedes if the recurrence interval of the flood exceeds 5 years to determine whether changes in streambed elevation have occurred.

Annual Data.--This information is used to expand the data base along the upstream side of a bridge. The streambed elevation is measured annually in relation to a reference point established on the upstream side of each bridge. Dimensions of the piers and footings are determined from bridge plans or site inspections.

Supplemental Data.--Since 1984, NYSDOT bridge-inspection procedures require recording of scour depth every 2 years, and diving inspections at bridges in deep water every 5 years. This information, along with data from bridge plans and USGS measurements, are to be analyzed to determine long-term changes in streambed elevation.

Equipment.--Standard USGS streamflow-measuring equipment is used to collect most of the scour data. This equipment includes a bridge crane, velocity meter, and sounding weight (50 to 100 lb); descriptions are given in Rantz (1982). Fathometers mounted on boats, floats, and piers have been used to measure scour (Norman, 1975; Hopkins and others, 1980; and Skinner, 1986). In this study, sonar and geophysical equipment is being tested for ease of operation, safety, and accuracy. The equipment must be reliable, simple, and practical.

Four types of geophysical equipment are being used to analyze scour: ground-penetrating radar, tuned transducer, color fathometer, and black-and-white fathometer; descriptions are given in Gorin and Haeni (1989). The radar system, with dual 80 MHz (megahertz) antennae, is floated in water 5 to 20 ft deep. The output is recorded on magnetic tape and a graphic recorder. The tuned transducer operates from a boat at a frequency of 3 to 14 kHz. The output is recorded with equipment similar to the radar system. The color fathometer, operating at 20 to 100 kHz, digitizes reflected seismic signals and assigns a color for every 6-decibel change in the acoustic impedence of the reflected signals. The output is recorded on cassette tape and displayed on a color monitor. A black-and-white fathometer, operating at a frequency of 200 kHz, can distinguish only between a hard and soft streambed. This system provides a rapid and accurate depth measurement and is used with the other geophysical equipment to verify the water depth. Output from the fathometer is plotted on a graphic recorder.

The mobile sonar system is identical to the black-and-white fathometer except that the transducer is mounted in a 100-lb sounding weight instead of a boat (fig. 4A). The design of the sounding weight enables the transducer to remain horizontal in the water.

A sonar unit (fig. 4B) attached to a bridge pier is being evaluated. This system was chosen because the analog output can be transmitted to a data logger as far as 300 ft away; other systems with digital or graphic output were not compatible with a data logger and must be within 100 ft of the transducer. The force of waterborne ice and debris can severely damage or destroy this equipment; therefore a shield was designed to protect the transducer and microprocessor (fig. 4C). Newer models allow the microprocessor to be placed out of water. The data logger activates the unit at preselected time intervals and transmits the data by satellite telemetry.

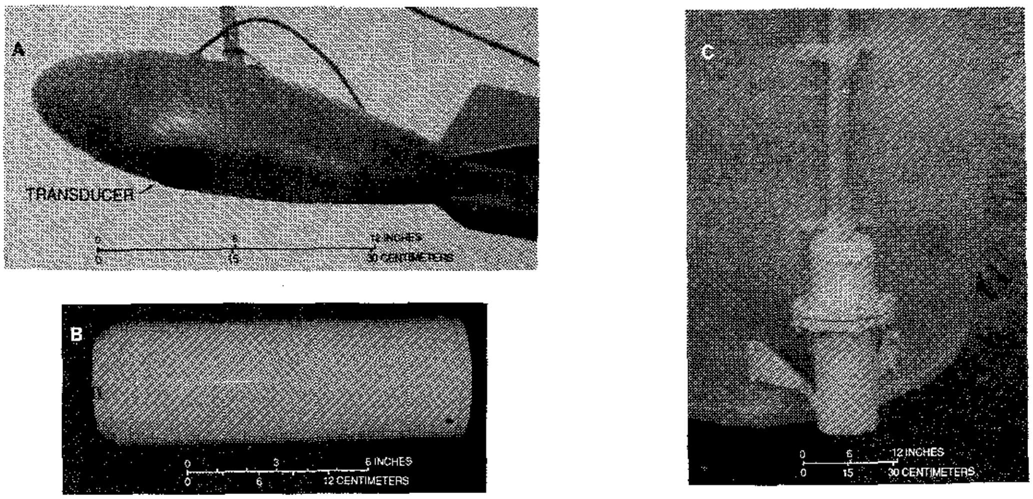


Figure 4.--Sonar equipment. A. Transducer in 100-lb weight. B. Sonar unit used at fixed installation. C. Protective shield for sonar unit, mounted onto bridge pier.

Observed Scour at Selected Sites.--One to 2 ft of local scour was found at many sites at the start of the study. At a few sites, the scour has exposed spread footings that bridge plans show to have been buried during construction. Many of these holes were caused by clear-water scour during a previous flood or floods. Twelve high-flow measurements, including two flows with a recurrence interval exceeding 5 years, show no additional scour since the initial observation. These results agree with Sidle (1988) that scouring of coarse material is triggered by flows with recurrence intervals greater than 5 years.

One objective of the study is to evaluate the accuracy, safety, and ease of operation of the procedures and equipment. Stream velocity and depth are difficult to measure near piers in deep, swift streams, especially when debris is present, and heavy weights (100 to 150 lb) are not always adequate to stabilize the equipment. When mobile- and fixed-sonar installations are used to measure water depth, air or sediment entrained in the flow may interfere with the signal. Also, even though the mobile equipment can be brought to a site rather than installed permanently, moving it across the bridge and recording data have been found cumbersome. Fixed installations, by contrast, can automatically record streambed elevation at selected time intervals but must be extremely rugged. A plot of the output from the data logger is shown in figure 5. Signal scatter, due to wide reflections from cobbles, increases as the signal ground loses contact with water (gage height 4.0 ft), and spikes or "lost signals" occur when the transducer is exposed to air (gage height 3.0 ft). This equipment has been tested for 1 year, in which the peak flow had a recurrence interval less than the mean-annual flood, and no scour was observed.

Geophysical techniques were applied to gravel and cobble streambeds but did not reveal any backfilled scour holes. Probable reasons are that: (1) deep holes did not exist, (2) resolution of equipment (1 to 2 ft) did not permit detection of slightly deepened holes, (3) the deepened scour hole was backfilled with the same type of bed material that lined the existing hole. The usefulness of geophysical techniques depends on the characteristics of the site. The equipment is sophisticated and requires a high degree of skill for effective operation and interpretation. Many objects can interfere with the signal; for example, buried pipes, rocks, backfill from construction, and side echos. The most useful results are likely to be from streams that undergo live-bed scour.

The number of years of available record and hydrologic conditions during the sampling period may limit the amount of data collected in some basins. If scour countermeasures are installed at some sites by NYSDOT before the project is completed, results will be affected.

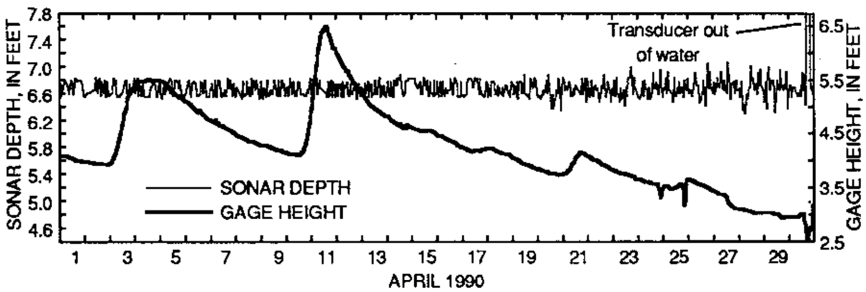


Figure 5. Sonar and gage-height output from data logger.

SUMMARY

Scour data are being collected at 77 bridges in New York, excluding Long Island. Bridges near USGS gaging stations on streams with erodible bed material were selected in six physiographic provinces. High-flow data are being collected at 31 bridges, and annual data at the remaining 46 bridges. The conventional method of data collection by a sounding weight is being compared with sonar and geophysical techniques for ease of operation, safety, and accuracy. Cross sections measured at the beginning of the study are to be compared with bridge plans, previous measurements, and data collected during the remaining years of the project to determine the extent of scour in New York.

One to 2 ft of local scour was found at many sites at the start of the study. At a few sites, the scour has exposed spread footings that bridge plans show to have been buried during construction. Twelve high-flow measurements, including two flows with a recurrence interval exceeding 5 years, did not show any new scour. Present scour holes and the coarse bed material indicate clear-water scour to be more common than live-bed scour.

Geophysical techniques were applied to gravel and cobble streambeds but did not reveal any backfilled scour holes. The effectiveness of these techniques depends on local conditions, and the methods and equipment require a high degree of skill for effective operation and interpretation. Streams with fine bed material probably provide more useful results than those with coarse material.

A fathometer provided quick and accurate depth measurements. The mobile method was cumbersome, and the fixed installation required extensive protection. A fixed installation designed to record streambed elevation automatically at selected time intervals is expected to provide useful information during floods. Further study is needed to determine how well these units operate amid flood turbulence, debris, sediment, and ice.

REFERENCES

Andrews, E.D., 1979, Scour and fill in a stream channel, East Fork river, western Wyoming: U.S. Geological Survey Professional Paper 1117, 49 p.

_____ 1984, Bed material entrainment and hydraulic geometry of gravel-bed rivers in Colorado: Geological Society of America Bulletin, v. 95, no. 3, p. 371-378.

Beverage, J.P., 1987, Determining true depth of samplers suspended in deep, swift rivers: Federal Interagency Sedimentation Project, 56 p.

Blodgett, J.C., 1984, Effect of bridge piers on streamflow and channel geometry: Transportation Research Record 950, p. 172-183.

Cline, M.G., 1961, Soils and soil associations of New York: New York State College of Agriculture at Cornell University, Cornell Extension Bulletin 930, 64 p.

Coon, W. F, and Futrell, I. C., 1986, Evaluation of wetline depth-correction methods for cable-suspended current meters: U.S. Geological Survey Water-Resources Investigations Report 85-4329, 30 p.

Copp, H. D., Johnson, J. P., and McIntosh, J. L., 1988, Prediction methods for local scour at intermediate bridge piers, in 67th annual conference proceedings: Washington, D.C., U.S. Research Board, 24 p.

Culbertson, D.M, Young, L.E., and Brice, J.C.,1967, Scour and fill in alluvial channels: U.S. Geological Survey Open-File Report, 58 p.

Federal Highway Administration, 1988, Interim procedures for evaluating scour at bridges: Federal Highway Administration, 64 p.

Gorin, S.R., and Haeni, F.P., 1989, Use of surface-geophysical methods to assess riverbed scour at bridge piers: U.S. Geological Survey Water-Resources Investigations Report 88-4212, 33 p.

Helley, E.J., and Smith, W., 1971, Development and calibration of a pressure-difference bedload sampler: U.S. Geological Survey Open-File Report, 18 p.

Highway Research Record, 1973, Highways and the catastrophic floods of 1972: Highway Research Board, 65 p.

Hopkins, G. R., Vance, R. W., and Kasraie, B., 1980, Scour around bridge piers: Federal Highway Administration Report FHWA-RD-79-103, 131 p.

International Organization for Standardization, 1989, Liquid flow measurement in open channels--sampling and analysis of gravel-bed material: ISO Report 9195, 9 p.

Jarrett, R. D., and Boyle, J. M., 1986, Pilot study for collection of bridge-scour data: U.S. Geological Survey Water-Resources Investigations Report 86-4030, 89 p.

Klingeman, P.C., 1973, Hydrologic evaluations in bridge pier scour designs: Journal of the Hydraulics Division, Proceedings of the American Society of Civil Engineers, v. 99, no. HY12, p. 2175-2184.

Norman, V. W., 1975, Scour at selected bridge sites in Alaska: U.S. Geological Survey Water-Resources Investigations Report 32-75, 160 p.

Rantz, S.E., and others, 1982, Measurement and computation of streamflow--vol.1, measurement of stage and discharge: U.S. Geological Survey Water-Supply Paper 2175, 284 p.

Raudkivi, A.J., and Ettema, R., 1985, Scour at cylindrical bridge piers in armored beds: Journal of Hydraulic Engineering, v. 111, no. 4, p. 713-731.

_____ 1983, Clear-water scour at cylindrical piers: Journal of Hydraulic Engineering, v. 109, no. 3, p. 338-350.

Richardson, E.V., Simons, D.B., Julien, P.Y., 1988, Highways in the river environment: Fort Collins, Colorado State University, p. 69-115.

Sidle, R.C., 1988, Bed load transport regime of a small forest stream: Water Resources Research, v. 24, no. 2, p. 207-218.

Skinner, J.V., 1986, Measurement of scour-depth near bridge piers: U.S. Geological Survey Water-Resources Investigations Report 85-4106, 33 p.

Southard, R.E., 1989, A mobile scour monitoring system for use at bridges, *in* Proceedings of the Bridge Scour Symposium: McLean, Va., Federal Highway Administration, 8 p.

U.S. Geological Survey, 1986, National water summary 1985--Hydrologic events and surface-water resources, New York: U.S. Geological Survey Water-Supply Paper 2300, p. 347-354.

U.S. Water Resources Council, 1981, Guidelines for determining flood frequency: Hydrology Subcommittee Bulletin 17B, 28 p.

Zembrzuski, T. J., and Evans M. L., 1989, Flood of April 4-5, 1987, in southeastern New York, with flood profiles of Schoharie creek: U.S. Geological Survey Water-Resources Investigations Report 89-4084, 43 p.

Zembrzuski, T. J., and Dunn, B., 1979, Techniques for estimating magnitude and frequency of floods on rural, unregulated streams in New York State excluding Long Island: U.S. Geological Survey Water-Resources Investigations Report 79-83, 66 p.

A BRIDGE SCOUR MEASUREMENT DATA BASE SYSTEM

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ABSTRACT

Obtaining field measurements of bridge scour data is an objective in projects ongoing in more than 20 states in the United States. A Bridge Scour Data Base System is being developed to support preparation, compilation, and analysis of bridge scour measurement data. The program will be portable to microcomputers, engineering workstations, minicomputers, and mainframes. The program will enable users to interactively store, retrieve, select, update, and display bridge scour and associated data. Interactive processing will use full-screen menus and form fill-ins, including prompts, help information, and default values. The program will have an option to compute estimated scour from selected equations and to display estimated with observed scour depths. The data base system is designed to store all of the essential information from a detailed scour measurement. The structure of the data base system provides four categories for each data set: site data; scour measurement data; flood event data; and channel geometry data. Site data are location, site description, datum, and bridge data. This Bridge Scour Data Base System is an important element in attaining the goal of reduced risk from scour processes at bridges.

INTRODUCTION

Scour and channel instability account for more than 90 percent of bridge failures over waterways. Scour processes have been extensively researched using laboratory model studies. This research has provided valuable data and understanding. However, scour predictions based on model results vary considerably, probably due to dynamic dissimilarity and other factors not duplicated in most laboratory models. It has long been recognized that field measurements of bridge scour are needed to broaden our ability to understand and predict bridge scour. Significant historic scour data exist in the files of hydrologic data collection agencies such as the U.S. Geological Survey (USGS) . Field measurements of local scour have been compiled by Froelich (1988) and by Zhuravljov (1978). These data sets contain valuable information, but most do not contain information on all of the factors known to affect scour. Catastrophic bridge failures, such as the failure of the New York Throughway Bridge over Schoharie Creek in April 1987 have led to new scour inspection practices and the broadest and most intensive bridge scour data-collection efforts to date in the United States. Scour data is now being collected (at different levels of effort) in more than 20 states by the USGS in cooperation with State highway agencies. A computer data base system is needed to support preparation, compilation, and analysis of bridge scour measurement data. This paper describes a Bridge Scour Data Base System (BSDBS) being developed to support these needs.

The BSDBS will support preparation of bridge scour data sets by providing a complete, formatted list and description of the data elements . The utility of data sets will be enhanced by the use of a uniform, portable data base system and by the periodic compilation of data entered into the system and by redistribution to those conducting scour investigations and research. The BSDBS is being developed by the USGS National Scour Study, in cooperation with the Federal Highway Administration.

CHARACTERISTICS AND CAPABILITIES

The basic functions of the BSDBS are data archival and retrieval. The principal features are portability and ease of use. The program is being written in Fortran and will be portable to microcomputers, engineering workstations, minicomputers, and mainframes. The program enables users to interactively store, retrieve, select, update, and display bridge scour and associated data. User interaction will feature full-screen menus and form fill-ins, including prompts, help information, and default values. The data are stored in an unformatted, direct-access file with several types of pointer systems and chaining for rapid access to the data and for efficient management of disk space after data editing and deletion. The data-management functions of the program enables a user to add, delete, or modify data sets. Elements within data sets can be selected and modified or copied from one data set to another. Data sets can be added interactively or from an ASCII file. Search and selection of data sets are based on criteria of data element values or value ranges. Search criteria include: equal to, less than, greater than, not, and, and or. For example, a user may select sites based on State, a range of latitude and longitude, pier type, etc. Data elements that can be used for search criteria are noted in Table 1 with a (#) symbol. Data sets in the data base that satisfy search criteria are added to a buffer for further processing. Graphic capabilities include plotting the location of selected sites on an outline map of the United States. Hydrograph and cross-sectional data also can be plotted. Information from selected records can be exported to ASCII files or viewed interactively. Formats for exported information can be default or user defined. Output can then be read by separate programs for statistical analysis, mapping, or other purposes.

The BSDBS will have an option to compute estimated scour from selected equations and to display estimated with observed scour depths. A limited number of equations are included for estimating local pier scour, local abutment scour and contraction scour. The initial list of equations is tentative and will be supplemented as additional field data becomes available and improved equations are developed. The program includes the following local pier scour equations: (1) the Colorado State University equation (HEC-18, 1990); (2) the Froelich equation (Froelich, 1988); (3) the Neill (1964) equation of the Laursen and Toch (1956) design curve. The program includes the local abutment scour equation by Froelich (1989). For contraction scour, the program includes Laursen's 1960 equation for a long contraction and Laursen's 1980 equation for a relief bridge with no bed-material transport. These equations are based primarily on laboratory data with the exception of Froelich's 1988 pier scour equation. The equations should only be applied to streams characteristic of the conditions for which the equations were developed. Some sites will not be represented by any of the equations.

An important consideration when comparing observed with computed scour depths is that these equations were developed generally for bridge design. Thus, the criterion for developing the equations was generally conservativism, requiring most of the data be enveloped, rather than accuracy. Froelich's pier and abutment scour equations are an exception because best-fit regression was used for their initial computation. However, Froelich's final equations include a factor of safety to envelop most of the data. In developing new equations, the goal of accuracy, rather than conservatism should be investigated. Designers could then apply risk analysis to determine a factor of safety based on equation accuracy, average daily traffic, etc.

STRUCTURE AND ELEMENTS OF DATA SET

The structure and elements of a data set in the BSDBS are shown in Table 1. Each data set has four categories: site data; scour measurement data; flood data; and channel-geometry data. Site data are location, site description, datum, and bridge data. Scour measurement data are defined for local pier scour, local abutment scour, contraction scour, and general scour. Flood event data are peak stage and discharge, hydrograph, and debris data. Channel-geometry data include coordinate reference information, 3-dimensional channel geometry data, and time-of-measurement data. For each site there might be several sets of channel-geometry data and/or data on several floods. For each flood event there can be several sets of scour measurement data. The BSDBS is designed to store all of the essential information from a detailed scour measurement; however ,most data sets contain only the information collected in the more common limited-detail measurements. Descriptions of all elements in Table 1 is beyond the scope of this paper.

Table 1.– Bridge Scour Data Base System data structure and elements
(# – data elements which may be used in search criteria)

I. SITE DATA

LOCATION DATA

Stream Name #
Highway / Road
State #
County
City
Latitude #
Longitude #
USGS Gaging Station Number #

SITE DESCRIPTION

This is a text field to describe features such as levees, upstream meanders, bridges upstream or downstream, scour or bank protection works, nearby confluences, etc.

ELEVATION DATA

Datum Type: local / gage / msl
Difference: local datum to msl
Descriptions: bench or reference marks

STREAM DATA

Drainage area #
Stream slope in vicinity #
Curvature through study reach, degrees:
straight (<5) / medium (6-20) / high (>20)
Flow Impact : none / left bank / right bank
Channel Roughness: table of [depth and Manning's "n" or Chezy's "C"]
Geomorphic Factors that affect stream stability: / stream size/ flow habit/ bed material/ valley or other setting/ flood plain/ natural levees/ apparent incision/ channel boundaries/ tree cover on banks/ degree of sinuosity/ degree of braiding/ degree of anabranching/ variability of width and development of bars *(Note: from HEC-20, 1990)*
Stage of channel evolution: premodified / constructed / degradation / threshold / aggradation / restabilized
Bed material measurements: table [Sample no., date, type sampler, sample depth, no. of samples, D95, D84, D50, D16, sigma, density, cohesion, composite or representative]
Observed armoring: high / medium / low

BRIDGE DATA

Bridge inspection number (BIN) #
Bridge plans on file: y / n
Bridge length
Low chord elevation
High centerline elevation
Skew of alignment to flood flows
Spur dikes: none / eliptical / straight / other
Dual bridges: y / n
continuous abutments: y / n
distance between centerlines
distance between upstream pier faces
Number of piers
Description of pier numbering

ABUTMENT DATA

Cross section station of upstream left abutment
Cross section station of upstream right abutment
Left abutment is: [N,S,E,W,NE,NW,SE,SW]
Abutment type #
Abutment slope: [1:1,2:1,...]
Embankment slope
Right embankment length
Left embankment length
Abutment skew to flow
Distance from abutment to channel bank: left abutment / right abutment
Wingwalls: y / n
angle (90=parallel to abutment)

PIER DATA

(pier refers to pier and pile bent unless specified)

Pier number
Cross section (X) station of pier at nose
Profile (Y) station of pier at nose
Highway station of pier
Type: single pier / pile bent #
If Pile Bent:
number of piles
spacing between piles

Pier width #
Pier shape (nose): cylinder / square / round / sharp / elliptic (2:1, 3:1) / lenticular (2:1, 3:1) #
Pier shape factor
Pier length
Pier skewness to flood flow #
Pier protection: none / riprap / other #
Foundation: poured footing / piles #
Footing (or pile cap) data:
- top elevation
- bottom elevation
- width
- shape: square / round / square with rounded corners / other

Pile tip elevation
Pier notes: (note special material or shape characteristics)
Pier diagram: table [coordinates to draw pier in front profile]

II. SCOUR MEASUREMENT DATA

PIER SCOUR DATA

Date and time of measurement
Pier number
Local pier scour depth #
Scour hole side slope
Scour hole top width
Approach flow velocity #
Approach flow depth #
Sediment transport: clear water / live bed / unknown #
Bed material in scour hole: cohesive / non-cohesive / unknown #
Sand Bed Form: riffle / dune / transition (flat) / antidune #
if Dune, then:
- local scour during dune trough
- local scour during dune crest

Bed material:
- D50.p #
- sigma.p (SQRT(D84/D16)) #
- density.p #

Comments

ABUTMENT SCOUR DATA

Date and time of measurement
Abutment: left / right
Local abutment scour depth #
Approach flow velocity #
Approach flow depth #
Sediment transport: clear water / live bed / unknown #
Bed material in scour hole: cohesive / non-cohesive / unknown #
Sand Bed Form: riffle / dune / transition (flat) / antidune #
if Dune, then:
- local scour during dune trough
- local scour during dune crest

Bed material:
- D50.a #
- sigma.a #
- density.a #

Comments

CONTRACTION SCOUR DATA

Date and time of measured scoured geometry
Date and time of measured pre-scoured geometry
Contraction scour depth #
Channel contraction ratio #
Eccentricity
Bridge pier contraction ratio (due to piers)
Approach flow velocity #
Approach flow depth #
Sediment transport: clear water / live bed / unknown #
Bed material in scour hole: cohesive / non-cohesive / unknown #
Sand Bed Form: riffle / dune / transition (flat) / antidune #
if Dune, then:
- local scour during dune trough
- local scour during dune crest

Bed material:
- D50.a #
- sigma.a #
- density.a #

Comments

GENERAL SCOUR DATA

Date and time of measured scoured geometry
Date and time of measured pre-scoured geometry:
Average general scour depth over cross section #
Maximum general scour depth in cross section
Approach flow velocity #
Approach flow depth #
Comments

III. FLOOD EVENT DATA

PEAK DISCHARGE AND STAGE DATA

Peak discharge, date, and time
Peak stage, date, and time:
Water temperature, date and time
Event probability

HYDROGRAPH DATA

(tabular data)

Discharge hydrograph
Stage hydrograph
Suspended-sediment hydrograph
Bed-load hydrograph

DEBRIS DATA

Description: (extent and location of debris; floating or submerged; may refer to photos on file)
Table - [Stage and percent of opening obstructed]

IV. CHANNEL GEOMETRY DATA

Reference Points:
- Upstream left abutment: x, y
- Upstream right abutment: x, y
- Other points: x, y, description

Channel Geometry:
- Date measured
- Stage of measurement
- ID
- Description
- Time-[start time and end time]
- Y-[start y and end y]
- Z-[specify whether z is depth or elevation data]
- Array data [X, Z, (Y, t)]

OPERATION

The BSDBS features full-screen menus and form fill-ins, providing prompts, help information, and data element limits and defaults. For any particular screen, prompts can be issued in one of three formats: (1) menu selection for processing options; (2) form fill-ins in which a form is written on the screen and responses are made at highlighted locations; or (3) a table format to input or update values in rows and columns. When updating existing information, the heading and the previous or default values can be displayed so that only those elements in the set that need to be changed will have to be entered. Extensive help functions are an integral feature of the program. A window near the bottom of the screen provides general instructions for processing the particular screen. Additional help can be obtained by selecting help or limits from the command line at the bottom of the screen. Thus, beginning users can obtain detailed descriptions of data elements, of the data base operation, and of the equations in the analysis option. Graphics are used for the description of some of the data elements.

SUMMARY

A Bridge Scour Data Base system (BSDBS) is being developed to support preparation, compilation, and analysis of bridge scour measurement data. The primary functions of the BSDBS are data archival and retrieval. Data base elements include the essential information for a detailed scour measurement. Data base elements are categorized as site data, scour measurement data, flood event data, or channel

geometry data. Users may store, modify, and retrieve bridge scour data. An analysis option enables users to compute estimated scour depths for selected data sets from user-specified equations. User interaction is with full-screen menus and fill-ins with help options. Preparation and compilation of data sets are supported by a uniform and complete list and description of bridge scour data set elements and by the availability of a uniform, portable data base system specifically for this data. The USGS or the Federal Highway Administration periodically compile and redistribute data entered into the system by those conducting scour investigations and research. The BSDBS is an important element in attaining the goal of reduced risk from scour processes at bridges.

REFERENCES

Froehlich, D.C. 1989. Local scour at bridge abutments: American Society of Civil Engineers. Proceedings of the National Conference on Hydraulic Engineering, New Orleans, Louisiana. p. 13-18.

_____ 1988. Analysis of onsite measurements of scour at piers: American Society of Civil Engineers. Proceedings of the National Conference on Hydraulic Engineering, Colorado Springs, Colorado. p. 534-539.

Jones, J.S. 1983. Comparison of prediction equations for bridge pier and abutment scour: TRB 950, Second Bridge Engineering Conference. vol. 2 TRB, NRC, Washington, D.C.

Laursen, E.M. and Toch, Arthur. 1956. Scour around bridge piers and abutments: Bulletin no. 4, Iowa Research Board. 60 p.

Melville, B.W. and Sutherland, A.J. 1988. Design method for local scour at bridge piers: American Society of Civil Engineers. Journal of Hydraulic Engineering. v. 114, no. 10, p. 1210-1226.

Neill, C.R. 1964. River-bed scour, a review of bridge engineers: Canadian Good Roads Association. Technical publication no. 23. Ottawa, Canada. 37 p.

Zhuravljov, M.M. 1978. New method of estimation of local scour due to bridge piers and its substantiation: Trans. 109. Ministry of Transport Construction, State All Union Scientific Research Institute on Roads, 20 p.

Lumb, Alan M., John L. Kittle, Jr., and Kathleen M. Flynn. 1990. Users manual for ANNIE, a computer program for interactive hydrologic analyses and data management: Water Resources Investigations Report 89-4080, U.S. Geological Survey, Reston, Virgina.

Matthai, Howard, F. 1967. Measurement of peak discharge at width contractions by indirect methods: U.S.Geological Survey Techniques of Water-Resources Investigations, Book 3, Chapter A4, 44 p.

Simon, Andrew and Outlaw, G.S. 1989. Evaluation, modeling, and mapping of potential bridge-scour, west Tennessee. Proceedings of the Bridge Scour Symposium, Federal Highway Administration, McLean Virginia.

U.S. Federal Highway Administration. 1990. Evaluating scour at bridges: Hydraulic Engineering Circular no. 18, 97 p. (in preparation)

_____ 1990. Stream stability at highway structures: Hydraulic Engineering Circular no. 20, 195 p. (in preparation)

SOME FUNDAMENTAL PROBLEMS IN SUSPENDED SEDIMENT MEASUREMENT

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ABSTRACT

This paper disccusses some of the fundamental problems in suspended sediment measurement, i.e. criteria in classification of the basic sediment gauging stations, improvement of techniques for suspened Sediment measurement for enhancing the accuracy, indirect method of determining sediment transport in the unsampled zone, sediment measurement in hyperconcentrated flow and evaluation of the accuracy of the sediment measurement etc. Contusions drawn from the study has been adopted in the revised edition of the Chinese National Standard for Suspended Sediment measurement.

INTRODUCTION

The new standard of measurement of suspended sediment is being edited in China according to the research results and experience obtained at home and abroad and suitting for the conditions and development levels in been developed, some problems are quite complicated and lack of experience, and need further studies.

CLASSIFYING REQUIRMENTS OF THE SEDIMENT MEASUREMENT

Network for measurement of sediment transport

The sediment measurement network in China, is based on the discharge network and is determined by same planning methods. When the basin area is more than 3000－5000KM^2, number of stations is dtermined by the Linear principles－increasing rate of sediment load along the river and the interpolating accuracy, and the stations can be called the controling stations on large river. when the basin area is less than 3000－5000KM^2, the number of stations is determined by the zoning principles－the hydrological sub－zone area class, the increasing rate of the sediment transport module and the geographical interpolating requirments, and the stations can be called the river. The total of 1600 sediment station plays an important role in the observation and research.

Sediment measurement

Large a mount of observed data has been got from the sediment network for about fourty years and provides basis for exploitation of water resources and construction work. It has been shown in practice that, if the measuring contents, methods and accuracy requirments at different station are not been classfied, the needs in practice can not very well be satisfied.

Classifying the sediment stations into three kinds and setting different requirements for different purposes and needs

The first kind of stations: At stations on the major sediment laden river that play an important part in the researches of the sediment yield, the design construction, planning and management of key projects and the channel regulation or in the studies of fluvial process, the suspended sediment discharge and concentration and the suspended sediment and bed meterial size distribution should be measured.At some stations, the river crossection and the total sediment load should be measured according to the needs, the accuracy required should be higher than of others, and the measurement should be done also in whole year.

The second kind of stations:At some common controling stations and some important representative stations, the suspended sediment discharge and concentration, the size distribution in most stations and the bed material in accordance with the needs should be measured, at the same time, the accuracy required is usually less than of the first kind of stations.

The third kind of stations:At the common representative stations and the riverlet stations, the sediment concentration, the size distribution at some stations, should be observed and the accuracy required should be less than for taking measurements at some stations can be determiled by needs.

The classifing requirement above have been defined particularly and systematically in the new standard.

IMPROVING ON THE CONVENTIONAL MEASURING TECHNOLOGY

Controling the systematic error strictly

In the suspended sediment measuremet, the systematic error can easily take place and any mainly exist in the bed material load.The systematic error mainly comes from the instruments, the sampling methods at verticals, the processing of samples and so on.Although the horizontal trap type sampler has been widely used in China for many years, its use has been restricted in the new standard because this type sampler with the volume of 2000ml migth have 4.5% systematic deviation less than the standard sampler based on the experiments at 16 stations on the Yangtze River and the Yellow River.

The testing of accuracy of the sampling method on verticals: The systematic errors of the average sediment consentration sampled with different methods are analysed according to the data on 626 verticals sampled with the seven-point method or five-point method at 34 stations of the Yangtze River and based on the data on 306 verticals sampled with the eight-point method at 10stations of the Yellow River.

The approximate true values of the average sediment concentration in a vertical can be calculated with:

$$C_t = \frac{\sum_{1}^{n} \frac{1}{2}(C_i V_i + C_{i+1} V_{i+1})(\eta_i - \eta_{i+1}) + \int_0^{\eta_b} C \cdot V d\eta}{\sum_{1}^{n} \frac{1}{2}(V_i + V_{i+1})(\eta_i - \eta_{i+1}) + \int_0^{\eta_b} V d\eta} \qquad (1)$$

in which: C_t is the approximate true value of the average sediment concentration in the vertical(kg/m^3);C_i,V_i are the sediment concentration and velocity respectively at the point i;η_b and η_i are the relative water depth at the lowest point and at the point i from the bottom, C and V in the integral formular are respectively ditermined by the exponential formulae of the sediment concentration and the velocity distribution:

$$C = C_a e^{-k\eta} \qquad (2)$$

$$V = V_0 \eta^m \qquad (3)$$

in which: Vo and Ca are respectively the evlosity at the surface and the sediment concentation at the reference point at the bottom;m and k are respectively the exponents of the velocity distribution and the sediment concentration distribution; η is the relative depth from the bottom.

The parameters in the formulae (2) and (3) are calculated by the regression analysis of the measured data on each vertical,and the each fitted curve must go though the lowest measursed point.The integral parts of formulae (1) are calculated by the numerical integration.

$$\text{relative error} \quad \delta_i = \frac{C_i}{C_t} - 1 \qquad (4)$$

$$\text{systematic error} \quad e_t = \frac{1}{n} \sum \delta_i \qquad (5)$$

in which: C_i is the average sediment concentration sampled with certain method on the vetical i.

The synthetical systematic error of the average sediment concentration on the vertical with different sampling method for different size classes are shown in following table:

error(%) / particle class / sampling method	synthetical systematic error at ten stations of the Yellow River (%)			synthetical systematic error at 24 stations of the Yangtze River (%)		
	total suspened sediment	d>0.025mm	d>0.05mm	total suspeded sediment	d>0.05mm	d>0.1mm
One-point (0.5d)	-1.96	-7.57	-15.9	-0.16	-2.70	-10.75
One-point (0.6d)	4.53	5.60	-0.74	2.41	3.05	-1.74
two-point (0.2d, 0.8d)	-0.66	-1.41	-2.84	-0.02	-0.95	-5.81
three-point (0.2d,0.6d,0.8d)	1.05	0.85	-2.43	0.77	0.31	-4.28
five-point(lowest point 0.1d near bottom)	-1.42	-2.35	-3.79	-1.42	-4.49	-7.05
five-point(lowest point 0.05d near bottom)	-0.12	0	1.15	-0.03	-0.22	-0.76
five-point(lowest point 0.01d near bottom)				1.53	4.75	6.08
2:1:1 mixing method	-2.02	-4.52	-7.62	-0.79	-3.21	-10.02
2:2:1 mixing method	-0.72	-2.49	-6.25	-0.15	-1.96	-8.36
1:1:1 mixing method	4.20	6.75	3.97	1.60	2.18	-0.75
1:1 mixing method	4.07	7.33	6.32	1.20	2.02	-0.26

note:The fixed proportional mixing method is a sampling method in a vertical whose sample is obtained according to volumetric propertion of samples taken at relative depth 0.2, 0.6 and 0.8 or at 0.2 and 0.8.

The average sediment concentration measured with depth-integration method in the vertical is 1.25% less than those measured with the seven-point method according to the comparative testing at Gaocun and Tongguan stations of the Yellow River.

Consequently, in the new stadnard, the of one-point mthod and fixed proportional mixing method must be resticted, the position of the lowest point of the five-point method, the condition of use and the operational technology of the depth-intergralion method have to be defined, respectively.

Sample processing: The fitering, replacement and baking methods have also many factors which may introduce systematic error such as the loss in decantation the soluble material in the stream, the leak of filting paper, the moisture absorption of sand bag, the selection of sediment density and so on. These factors should be properly controlled.

Simplify the measuring method and improve the accuracy of controlling the variation of sediment discharge in the process of flow

The cross-sectional average sediment concentration can be determined by the sediment discharge method on the following formulae:

$$\bar{C}=\frac{\sum_{1}^{n} C_{mi} V_{mi} d_{mi} b_i}{\sum_{1}^{n} V_{mi} d_{mi} b_i} \qquad (6)$$

in which: $\bar{C}$ is the cross-sectional average sediment concentration; Cmi and Vmi are the sediment concentration and velocity on the vertical respectively; dmi and bi respectively represent the average depth and the surface wedth of increment i.

With the above method, the accuracy may be higher, but the method is laborious and time consuming, furthermore, this method can hardly be used in the flood period. For many years, the method of increasing number of sampling by taking index samples has been adopted to conrtol the process, and relation between the index and cross-sectional sediment concentration has been taken to convert the index sediment concentration into the sectional ones. In this method, the data quanlity is influenced greatly because, sometimes, error of the index sample may be too large. In order to solve this problem, simplifid method fitting for the principle of the formula (6) should be taken to directly measure the sectional average sediment concentration and grain size distrbution.

The simplified methods include (1) ETR method; (2) EDI method; (3) EAT mehod. The EAT method is a whole sectional mixing method with the equal area increment and the equal sampling duration. The cross-sectional average sediment concentration cna be got by sampling at verticals in the center of the equal area incrcment, selecting the same sampling method and duration, using nozzles with same intake diameter, mixing the samples on whole section.

If the arca increments are not equal, the ratio of the area increment to the total area can be used as the weighted cofficient to distribute the sampling duration on each vertical, the sampling method on each vertical is determined by the given duratin and by the same method, consequently, the samples are mixed and the cross-sectional average sediment concentration can be obtained.

The cross-sectional average grain size distribution suitable for the weighted principle of the sediment discharge increment can be obtained by particle size analysis of the whole mixing sample suitable for the weighted principle of the discharge increment.

In the first and second kinds of network in China, there is a tendency that the whole cross-sectional mixing method would replace the index sample method to directly measure the cross-sectional average sediment concentration and particle size distribution and to improve the quality and accuracy of sediment measurememt in controling the variation of sediment discharge in a flow process.

Solve the tehnologic problems of measuring sediment with cable way

Measurement of sediment with cable way is used at about 40% stations in China, In past years, it was unable to measure the cross-sectional average sediment concentration with cable in the flood period. Though the late experiment and resarch, great improvement has been achieved in the sampling method and measuring instrument with cable. Now, with the new-type time-integrated instrument and the whole cross-sectional mixing method, it only takes 0.5-1.0 hour to sample in 5-7 verticals over a cross-section with a top width of 200-300 m. The standardization of the sediment measuring instrument series and its attaching equipment are further needed.

SOLVE THE PROBLEM OF UNMEASURED ZONE FOR DIFFERENT PURPOSES

Suspedned sediment measurement (to provide the suspended sediment data)

Beacuse of the instrument limitation, the unmeasured zone (near the bottom) exists in the suspended sediment measurement, and there are two kinds of methods in the world to deal with this problem. We have an opinion that, for the purpose of determining the cross-sectional average sediment concentration and size distribution, corrections are usually not needed if the following methods are used to determine the average sediment concentration on verticals in whole water depth according to data analysis:

two-point method: $$C_m = (V_{0.2}C_{0.2} + V_{0.8}C_{0.8})/(V_{0.2} + V_{0.8}) \qquad (7)$$

three-point method: $$C_m = (V_{0.2}C_{0.2} + V_{0.6}C_{0.6} + V_{0.8}C_{0.8})/(V_{0.2} + V_{0.6} + V_{0.8}) \qquad (8)$$

five-point method: $$C_m = \frac{1}{10v_m}(V_{0.0}C_{0.0} + 3V_{0.2}C_{0.2} + 3V_{0.6}C_{0.6} + 2V_{0.8}C_{0.8} + V_{1.0}C_{1.0}) \qquad (9)$$

The mixing method on the vertical: sampling on ratio of durations, mixing on vertical, is carried out according to following table:

sampling method	Position(relative depth from the surface)	sampling duration at each point (s)
two-point	0.2, 0.8	0.5t 0.5t
three-piont	0.2, 0.6, 0.8	t/3, t/3, t/3
five-point	surface, 0.2, 0.6, 0.8, bottom	0.1t, 0.3t, 0.3t, 0.2t, 0.1t
note: t is the total sampling duration on each vertical		

Depth integration method; The intake nozzle should be lowered to a depth less than 5% relative depth to the bottom.

Total sediment load measurement(to provide the total sediment load data)

When th indirect method is used to measure the total sediment discharge on a sandy bed, bed material samples should be taken at same time with the masurement of suspended sediment discharge. According to the measured discharage, measured suspended sediment discharge, cross-sectional average particle size distribution of suspended sediment and material and so on, the total sediment discharge for different size group can be calculated by the modified Einstein procedure or procedures proposed by Lin Binwen et al. The calculating accuracy of this method needs to be verified further and the data processing method needs to be studied too.

SEDIMENT MEASUREMENT METHOD SHOULD BE DIFFERENT IN HEAVILY SEDIMENT LADEN STREAMS

Simplifing the measurement method

Under the condition of hyper-concentrated flow, the cross-sectional sediment distribution is fairly uniform. According to the date analysis on verticals of six tributaries in the middle Yellow River, the sediment concentration and particle size distrbution at each point on the vertical is basically the same, and the ratio of sediment concentrations at the bottom and surface is in average 0.93. On the cross-section, the sediment concentration on any vertical can represent the average cross-sectional sediment concentration and the maximum error is less than ±5%. For this reason, the sampling method may be simplified greatly, and depth-integrated sampling or one-point sampling at 0.5 depth on one vertical near the maincurrent may meet the needs.

Some additional items should be measured

The rheological characteristics of the hyper-concentrated current is that of non-newtonian, and its movement and sediment transportating characteritcs are naturally different from that of common sediment carrying flow, and is of great difference in different region. For this reason, rheological properties of the sediment laden mixture should be added to the measurement of hyperconcentrated flow.

Additionally, the special phenomena of the debris flow, the plugging of flow or the phenomena sometimes described as bottom turned over and so on , may usually take place in the heavily sediment landen streams, and observation of these phenomena is of importance for the studies of sediment transport characteristics of the hyper-concentrated flow.

EXAMINATION AND EVALUATION METHODS FOR THE MEASURED DATA ARE NEEDED

Determining by experiment every kind of error based on classification of sources of error

Errors of the suspended sediment measuring mainly come from instrument, sampling method on vertical, fluctuation of sediment concentration, number of sampling verticals, sample processing, particle size analysis and so on. Except for the ssediment fluctuating error, every term of errors may have two kinds of errors — the systematic error and random error.

The instrumental error can be determined by comparation of the instrument

with the standard ones. Error introbuced by sampling method in a vertical can be determined by the data analysis in the vertical with seven-point or eight-point methods. The sdeiment fluctuation error can be dtermined by analysis of the fluctuations of sediment concentration measured continuously by some automatic recording apparatus. Error induced by insufficient number of verticals can be dtermined by the experiment data analysis on more than 30 verticals and so on.
Error control

When the cross-sectional average sediment concentration is dtermined by the sediment discharge measurement, according to the data analysis, the limit of allowable error of the sampling method and number of verticals is shown in following table:

kind of station	relative statdard deviation of the sampling method on vertical(%)	relative standard deviation of number of sampling verticals (%)	systematic error of sampling method on vertical (%)		systematic error of number on verticals (%)	
			total suspended sediment	bed materal	total suspended sediment	bed materal
the first-kind	6.0	2.0	±1.0	±5.0	±1.0	±2.0
the second-kind	8.0	3.0	±1.5		±1.5	
the third-kind	10.0	5.0	±3.0		±3.0	

Every term of the random uncertainty (95% confidence level) and controlling index for systematic error are shown in following table:

kind of error / kind of station	instrument's error Eyq (%)		error of sample prosessing Ecl(%)		error of sampling duration C_I (%)		error of sampling method on vertical C_{II} (%)		error of number of sampling verticals C_{III} (%)	
	X'	Se	X'	Se	X'	Se	X'	Se	X'	Se
the first	10	1.0	4.2	-2.0	6.6	——	12.0	±1.0	4.0	±1.0
the second	16	1.5	4.2	-3.0	〃	——	16.0	±1.5	6.0	±1.5
the third	20	3.0	4.2	-4.0	〃		20.0	±3.0	10.0	±3.0

Notes: X' is the random uncertainty (%)
Se is the systematic error (%)

Evaluate the total random uncertainty and systematic error of the average cross-sectional sediment concentration

The total random uncerainty:

$$X'_C = [X'_{III} + \frac{1}{m+1}(X'^2_{YQ} + X'^2_{ECl} + X'^2_{CI} + X'^2_{CII})^{1/2}] \qquad (10)$$

The total systematic error is the algebraic sum of every term of systematic error.

REFERENCES

Ma Xiufeng et al, The principles of sediment notwork design and the data transposition mehtod, proceedings of hydrologic network planning in arid atea, March 1988
Zhao Boliang et al, Experiments and studyes on suspended sediment measuring methods, the Yellow River. No.1 1989
Wang Yunhui et al, The correction used in measurement of suspended sediment by point-integration method, sediment research, No.2 1984
Long Yiqian, Mannel on operitional methods for the measurement of sediment transport, W.M.O, NO.686, 1989
The groups of the bereau of water concervacy, The ministry of water resources and electric power, China. The handbook of hydrometry, No.1 1975
Qian Ning, Efficient of depth integration method on suspended sediment sampling, Joural of geophysic science, Oct, 1952
Qian ning & Wan Zhaouui, Errors in determination of suspended sediment discharge by point-intergrated method, Sediment research, No.2 Vol.1 1956
Liu Bingwen et al, Application and modification of the method of total sediment discharge, March 1987
Qian Ning & Wan Zhao hui, Mechanics of sediment transport, scientific publishing house, 1983
Zhao Boliang et al, Analysis of the verical distribution of high sediment concentrations in the Yellow River and studies of methods of observation, proceedings of IAHS, 1982