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AUTOMATIC COLLECTION OF SEDIMENT DATA

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ABSTRACT

The Federal Inter-Agency Sedimentation Project has included research of methods of automating the collection of suspended-sediment data. Several approaches have been investigated ranging from automatic sample collection to automatic sample analysis. To automate sample collection, several forms of pumping samplers have been developed. To automate sample analysis both direct and indirect methods have been studied. Analysis by indirect methods have included the influence of suspended sediment on conduction of electric currents and on radiation from acoustic, visible light, and gamma sources. Analysis by direct methods have included different techniques for measuring the bulk density of water-sediment-mixtures. Advantages and disadvantages of each approach are summarized, and suggestions for future research and development are offered. Experience indicates that, to facilitate data collection during the near future, one practical system consists of automatic sample collectors that supply samples to semiautomatic laboratory-based analyzers. For the more distant future, it would be desirable to develop a sample collector and sample analyzer combination suitable for continuous field operation.

Development of a sampler-analyzer combination has been hampered for lack of an instrument sensitive enough to detect sediment-mass concentrations of only a few milligrams per litre (mg/l). To be operated under adverse environmental conditions the instrument must be not only sensitive but also responsive to a wide range of concentrations. The required performance appears to exceed, by a considerable margin, state-of-the-art capabilities of the entire instrumentation field.

Transmission, recording, and processing of transducer-generated data have been advanced through both private and industrial research, and a comparable research effort may be required to improve sensors needed to measure directly suspended-sediment concentration. Pending development of improved sensors, the sensitivity of presently available sensors could be enhanced by connecting them to calibrated sediment concentrators.

INTRODUCTION

The objective of the Federal Inter-Agency Sedimentation Project is to seek solutions to sedimentation measurement problems that are of common concern to supporting agencies. To achieve this objective, equipment is developed, industrially produced equipment is evaluated, and both research and development are sponsored. To maintain a balanced program, the work of the project is reviewed and coordinated by members of the Technical Committee on Sedimentation, Water Resources Council. With the assistance of cooperating agencies, field tests are performed to supplement laboratory evaluations, then, at the conclusion of favorable tests, contracts are let for manufacture of custom items and stocks of the equipment are maintained for resale to governmental and educational institutions. Work on the project also includes providing calibration and some repair services.

Over the years the effort on the project has been devoted to the development of both manual and automatic equipment to facilitate the measurement of suspended-sediment discharged by streams. This effort has been motivated by a continuing need to expand data collection, to improve accuracy, and to reduce costs. Initially, laboratory experiments (U.S. Inter-Agency Committee on Water Resources (USIACWR), 1941a) were conducted to establish sampling criteria and to develop a diversified group of samplers needed for field-operation. Also, laboratory techniques and instruments were developed to analyze the collected samples (USIACWR, 1941b). The procedures for both sampling and analyzing require extensive manual labor, so automatic samplers have been developed to meet new economic and scientific requirements.

Successful application of automatic samplers requires several compromises. For any sampling procedure, accuracy and cost are of prime concern. Sampling manually, an operator can collect depth-integrated samples from several verticals within the cross section. The number of verticals can be increased to improve spatial representativeness but then sample collection requires additional time. If the stream's discharge or sediment concentration changes significantly during collection, the sample group represents only an approximation of instantaneous sediment discharge. The measurement of long-term sediment discharge requires repetitive sampling, but, with manual sampling, the high sampling frequency set by scientific requirements must usually be lowered to meet economic constraints set by operating budgets. A lower frequency results in a decrease in accuracy that becomes particularly severe for ephemeral streams.

The automatic samplers developed in this investigation are limited to sampling from one or perhaps two points in the cross section. Conversion of data from point samples to sediment discharge is analogous to converting gage height to water discharge. Water discharge is measured by partitioning the cross section, then measuring the velocity within each partition. The velocity data are integrated over the complete cross section to obtain instantaneous discharge. Instantaneous discharge is then related to gage height, a point property that can be conveniently monitored on a continuous basis. In a form similar to water discharge, sediment discharge can be stated as

$$Qs = \int_t \int_A C \; U \; dA \; dt$$

Both C, the point concentration, and U, the water velocity, are measured manually within each of several cross section zones, and the product CU is integrated over the cross sectional area to obtain the total instantaneous sediment discharge (USIACWR, 1963, and Task Comm. on Sed. Manual, 1969). This sediment discharge is then related both to the concentration of a sample collected with the automatic sampler and to the gage height. As with manual sampling, automatic sampling has both advantages and disadvantages. With automatic samplers, high sampling frequencies can be achieved at tolerable costs, and the equipment can sample many brief events that a manual sampling program would miss. Disadvantages stem largely from poor spatial integration imposed by point sampling. The correlation between point concentration and mean cross-section concentration contains a random component, the magnitude of which is site-dependent. The correlation and random component can only be evaluated by comparing manually collected samples with automatically collected samples. Automatic sampling techniques, then, must be viewed not as a replacement for manual sampling techniques but rather as a supplement.

The following report describes the automatic samplers. The report also outlines the capabilities of several types of instruments that have some potential for either laboratory analysis or on-site monitoring of sediment concentration. Sediment gage deficiencies are discussed, and remedial techniques are suggested. Guides for future equipment development and evaluation are presented. These guides include a description of system requirements and explain the need to adopt instrument test standards.

AUTOMATIC SAMPLERS

To facilitate automatic sampling, a number of automatic samplers have been developed that range in complexity from simple single-stage samplers to intricate automatic pumping samplers. The first single-stage sampler was developed in 1959 (USIACWR, 1961a). Designated the U-59, it requires no power and is designed to collect one sample during a rising stage. Only by making extensive field modifications, can samples be collected during a falling stage. To simplify field modifications, the project personnel developed the U-73, which can be set for either falling or rising stage operation by simply moving a link. Improved seals minimize the possibility of leaks that sometimes invalidated U-59 samples.

Several models were developed of battery-powered samplers capable of collecting and storing a number of samples. Two early models had sampling and storage capacities for 144 samples, but both samplers were large, heavy, difficult to assemble, and difficult to adjust. Later, another sampler was designed for greater portability, but its capacity was limited to only 48 samples. The latest model, designated the PS-69 (Beverage and Skinner, 1970a), contains the best features of each of the earlier models and was designed to achieve a balance between conflicting requirements, such as: large sample capacity, portability, versatility, simplicity, high sampling efficiency, and low power consumption. The PS-69 has a capacity of 72-quart samples and can be transported and reassembled easily. The electrical section contains a combination of compact solid-state timers, selected for their compact size, and power relays, selected for economy and durability.

The PS-69 will automatically cycle to pump and store a sample, but, for unattended operation, an automatic controller must be used to initiate each cycle. Several different controllers have been designed which may be used alone or in various combinations. The simplest controller is a clock that starts the sampler at intervals selected by the user. A modified version starts the sampler at either of two different intervals--a slow sampling rate, when stage is below a selected threshold, and a higher rate, when stage is above the threshold. To obtain the greatest amount of information from each sample, the controller must cycle the sampler only when water discharge or sediment concentration is changing. Three controllers respond to these changes. The Delta-Stage Switch activates the sampler only when the stage changes by a preset amount. Another device, the Proportional-Frequency Controller, (Beverage and Skinner, 1970b), provides sampling rates proportional to stream discharge. Discharge is electronically programmed in terms of gage height, transmitted to the instrument through rotation of a float-driven shaft. This controller permits compositing of samples if desired. Neither the Delta-Stage Switch nor the Proportional-Frequency Controller respond to changes in concentration. Some of man's activities, such as construction, mining, and roadbuilding, may cause brief increases in sediment concentration not associated with changes in either stage or water discharge. To sample these events, a third controller, termed the Turbidity Switch, may be used. It is a submersible optical sensor that responds to changes in turbidity by initiating a sampling cycle. Because the unit requires only a small amount of power it can operate continuously from the same batteries that power the pumping sampler.

The PS-69 has only one intake line, but, to improve the correlation between the concentration of pumped samples and the discharge-weighted concentration for the cross section, a dual-intake system may be used. The system consists of an electronic switch, two pneumatic valves, and a compressed-air source. When the controller signals, the switch cycles the sampler and, through the compressed air source, operates the valves. The sequence is programmed so that one sample is collected from each intake.

During the past few years, the demand for automatic samplers has increased. The demand has encouraged industry to develop several different types of small compact pumping samplers. As part of this investigation a battery-powered sampler was tested which employs a low-power peristaltic pump with a one-fourth-inch-diameter intake line (Model 1392, Instrumentation Specialties Co., Lincoln, Nebraska).[1] Pumping rates were adequate to transport suspended sediment through the intake lines; however, some of the coarse fraction deposited in the sample distributor system. The deposit caused cross-contamination of samples, with some having too low a concentration and some too high. As a result of the tests, the manufacturer is studying design changes to correct the problem. The sampler is smaller and lighter than any of the automatic samplers developed on the project and, with improvement, will fill a definite need in sediment sampling equipment.

AUTOMATIC SAMPLE ANALYSIS

The use of automatic samplers has resulted in an increase in the number of samples to be analyzed for concentration and for particle-size distribution. Traditional analytical methods are laboratory oriented and involve several manual operations, such as decanting, filtering, and

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[1] The use of brand names in this report is for identification purposes only and does not imply endorsement by the U.S. Geological Survey.

weighing small quantities of sediment. Through development of new techniques and evaluation of commercial equipment, a search is being conducted for an analysis technique that is adaptable to automation and that is accurate over the range of concentrations and particle sizes found in natural streams. The search has included studies of the response of sediment-water suspensions to various forms of radiant energy, to electrical currents, and to applied forces.

Radiant Energy

Sediment particles interact with radiant energy to produce both scattering and absorption. The interaction has been studied for two different forms of energy: acoustic and electromagnetic. Acoustic interactions were investigated by Flammer (1962), who, by calculation and experimentation, confirmed that within a sediment-water suspension similar relationships exist between the attenuation of ultrasonic energy and electromagnetic energy. At any single frequency the attenuation of either form of energy was affected by both particle size and concentration. Flammer showed that for idealized size distributions characterized by two parameters, both size parameters and concentration could be determined by measuring acoustic attenuation at three different frequencies. For either laboratory or field analysis, many problems have hampered application of the technique. Size distributions of suspended sediment are complex and would require measurements at perhaps as many as 10 different frequencies. Drift limited sensitivity and complicated the procedure for measuring background attenuation caused by dissolved constituents. Also, the method was subject to interference from even small amounts of air entrained while agitating the mixture to suspend the sediment particles. With modern ultrasonic transducers and with modern electronics, drift problems could be reduced, but not to levels required for monitoring most rivers. For automatic operation, elaborate equipment would be required to span the necessary frequency range.

Within the electromagnetic spectrum, the interaction of visible light with sediment has been studied. From several aspects, light-scattering techniques appear to have many attractive features. The method is sensitive to sediment concentrations as low as a few milligrams per litre, and, compared to other techniques, the components are simple and reliable. Certain experiments have shown that scattering correlates with one sediment parameter, such as total suspended mass; but in these experiments other parameters, such as particle shape and size, were not varied. The complexity of the technique is revealed by light-scattering theories, which show that the intensity and the spatial distribution of the scattered flux is a function of the index of refraction of the fluid, the index of refraction of the particles, the particle size, and the wave length of the light. In development of these theories, particles were assumed to be spherical and widely separated. In fluvial suspended-sediment samples, few particles are spherical; and generally the particles are spaced close enough to produce a complicated pattern of multiple scattering. Particles differ in chemical composition and consequently differ in specific gravity, polarization, and flourescence. At a field site all optical and mechanical properties of the particle population change with time, and the magnitude of the changes are site-dependent. The number of parameters that influence scattering are numerous, and their relative importance is best evaluated by field tests. To our knowledge, only marginal results have been published. At some sites optical measurements correlate to some extent with sediment concentration, but random errors frequently exceed 50 percent (Brown and Ritter, 1971). Research is continuing in an effort to improve optical response to mass concentration and particle-size distribution and to minimize response to other parameters, such as particle color and index of refraction. In most early studies, a white light was used to illuminate the suspension, and the scattered beam was measured at only one point. Currently under study is a new commercial technique, which employs laser illumination combined with four-point detection of the low-angle forward-scattered beam. A suspension is characterized by four parameters derived from the flux scattered through each of four different angles. Preliminary data have been encouraging enough to warrant additional laboratory tests.

For measurement of only particle-size, another commercial instrument (General Electric Prototron Particle Counter) was tested. The instrument illuminated the suspended particles with a laser. The beam rotated through a conical path, and the instrument detected the forward beam scattered through one fixed solid angle. Factory calibrations related the intensity of the scattered light to the size of the particle. An adjustable threshold circuit and a counter facilitated the collection and sorting of size data. Because the instrument was designed to detect individual particles, its lower concentration limit was essentially unbounded, but, to minimize multiple scattering, its upper concentration limit was small compared to concentration of stream samples. Even in clean tap water, the number of particles was so large as to saturate the instrument's counters. Instrument drift prevented a study of the effects of particle color and shape and complicated comparisons of particle-size data. The size distribution measured with the instrument was always much broader than distributions measured by either sedimentation or microscopic techniques. Broad distributions seem to have been caused by irregularly shaped particles, each of which scattered different amounts of light as it rotated in the fluid.

Dr. Richard H. Rust, of the University of Minnesota, evaluated a Millipore Corporation's system designed to analyze two-dimensional images. In his study the image consisted of sediment particles deposited on a transparent membrane filter. The image, magnified through a microscope, was sensed by a vidicon camera and displayed on a television monitor. Particle images which intersected the television raster lines were automatically counted and sized by a special data-processing unit. Distributions are presented as the number or percentage of particles larger than a stated optical diameter. With this system a complete particle-size analysis can be completed in a comparatively short time; 5 to 10 minutes is required to prepare the slide, and less than 1 minute is required to analyze the image. Unfortunately, difficulties stemming primarily from the wide range of particle sizes and the wide variability of particle shapes, have delayed adoption of this instrument for routine analysis of fluvial sediment samples. To avoid overlapping images, the maximum number of particles deposited on the slide was so limited as to be barely sufficient to satisfy statistical requirements. The basic instrument is expensive, and without expensive accessories, the instrument cannot resolve particles smaller than 0.5 micron. In many samples significant quantities of suspended sediment are composed of particles smaller than this limit. Particle-size data is historically given as a weight percentage finer than a given diameter. Conversion of the two-dimensional optical diameter to an equivalent fall diameter is another source of error; preliminary data indicate the conversion factors will contain random errors stemming from lack of data on particle thickness and shape. Other errors will enter when converting the "counts percentage coarser than" value into a "weight percentage finer than" value.

Gamma rays, another form of electromagnetic radiation, are scattered and attenuated by suspended particles. The attenuation coefficient is related to the suspension bulk density, which is, in turn, related to the mass concentration of sediment. As is true of light, the attenuation is also dependent upon other factors, such as the chemical composition of both fluid and sediment; consequently, dissolved solids always affect the measurements. Despite complications, the value of the technique has been demonstrated both in a variety of industrial processes and in sediment transport measurements closely supervised by Dr. J. R. McHenry of the Agricultural Research Sedimentation Laboratory at Oxford, Mississippi. In an attempt to more fully automate concentration measurements, Panametrics Incorporated, under sponsorship of the U.S. Atomic Energy Commission (now Energy Research and Development Administration), designed and built ten gamma-type sediment gages (Ziegler, Papadopoulos, and Sellers, 1967) for battery operation at remote unattended sites. The gamma radiation source, Cadmium 109, was selected to minimize undesirable effects of chemical composition. Temperature and long-term source strength variations were partially compensated by reference readings taken through distilled water contained within the gage. To meet requirements for safety, portability, and low power consumption, many technical compromises were necessary. Field tests showed that, despite refinements, design compromises combined with adverse environmental factors to cause excessive drift and numerous failures. Because of drift, high failure rates, high maintenance costs, and high assembly and installation costs, the test program was abandoned, but other types of equipment that employ the same principle are being studied. A laboratory instrument that combines size separation made by fall diameter techniques with concentration measurements made by X-ray attenuation techniques is being evaluated with the assistance of personnel at the Agricultural Research Service Laboratory at Chickasha, Oklahoma.

Electrical Conduction

Most fluvial sediment particles have a lower conductivity than the surrounding river water; therefore, the difference in conductivity between the water alone and the water-sediment mixture can be related to certain sediment parameters. Each utilizing conduction measurements, two different types of instruments have been studied. The instruments differ basically only in the volume of water through which the currents flow.

The first instrument studied was the Coulter Counter (USIACWR, 1964), in which the electric field is confined by an insulated orifice that bounds a volume of liquid of the same order of magnitude as the volume of a single sediment particle. The confined field enables the instrument to count and size individual particles as they are drawn through the field. In tests, the instrument was shown to be extremely accurate, but, because fluvial sediment particles have a wide range of sizes, the orifice frequently plugged. Plugging not only increased analysis time but also limited size measurements to particles larger than approximately 1 micron in diameter. Early models required a considerable amount of manual data reduction. New models include circuitry that performs all data reduction, but plugging is still a problem.

Hoping to eliminate the plugging problem, the investigation included sponsoring Killen (1969) in the development of a second form of a conductivity measuring instrument. Killen's device consisted of two orifices electrically connected in a bridge arrangement. The system included a hydrocyclone separator that diverted sediment to one leg of the bridge and relatively clear reference water to the other leg. The plugging problem was eliminated by using an orifice much larger than that used in the Coulter Counter. The orifice was so large that individual particles could not be sized; however, the instrument did respond to sediment volume concentrations equivalent to mass concentrations that ranged from 60 to 26,000 mg/l. Continuous hydrocyclone separation made the instrument insensitive to dissolved solids. Unfortunately, the separator could not divert particles smaller than about 8 microns. These fines divided between the two legs of the bridge, so their concentration could not be sensed. The insensitivity to fines was a rather serious limitation because streams often carry material that is a third to a half finer than 2 microns.

Applied Forces

Techniques for sample analysis may be classified as to the method of detecting sediment and the sediment parameter sensed. Discrete particle sensors respond to individual particles and include the Millipore instrument, the Coulter instrument, and the laser particle counter. The remaining instruments may be classified as concentration sensors. They respond to the concentration of groups of particles but are incapable of responding in a discrete fashion to each particle within the group. In this section we will consider field applications of concentration sensors most adaptable to unattended operation at field sites.

Assuming all fluvial sediment has the density of quartz, which is 2.65, the bulk density of a mixture is related to sediment concentration. Bulk density has been measured by gamma attenuation, but it can also be measured in terms of the mixture's response to applied forces.

Arising from the steady force of gravity, the hydrostatic pressure within a liquid column has been measured and used to determine sediment concentration (USIACWR, 1961b). Unfortunately, use of the technique has been hampered by errors that stem from temperature effects and by errors from within the pressure transducer. At low concentrations, random errors could not be reduced to less than ± 25 mg/l.

More recently a special hydrometer was constructed and evaluated that also responded to small differences in density (Beverage and Skinner, 1974). The mixture was placed inside the hydrometer, which was then submerged in a water bath. The bath water, free of sediment, served as a density reference. To achieve maximum sensitivity over a wide concentration range, the hydrometer stem was tapered from top to bottom. Temperature sensitivity proved to be the largest source of error. With temperature variation limited to ± 1/2°C, concentration could be measured, but only within an error of ± 50 mg/l.

Currently a commercial bulk densimeter is being evaluated in which the steady force of gravity is replaced by the oscillating force of a spring. The spring is formed by a U-shaped tube fixed at its upper end and free to vibrate at its lower end. Vibration, induced electrically, is maintained by an amplifier connected to form a feedback loop. The elasticity of the tube, the mass of the tube, and the mass of the test suspension contained within the tube, all combine to determine vibration frequency, which can be monitored, then converted to sediment concentration. Through modifications in the electronics section, the instrument's range has been expanded, its long-term drift has been reduced, and its sensitivity has been increased. As with other bulk sensing techniques, errors arise from a number of different effects, and each effect becomes increasingly significant as mass concentration decreases. Within the test suspension, variations in temperature, in concentration of dissolved solids, in concentration of dissolved and suspended gas, all become significant at low concentrations less than a few hundred mg/l. Over short time intervals, random errors can probably be reduced to ± 50 to ± 100 mg/l.

LIMITATIONS AND CAPABILITIES OF CONCENTRATION ANALYSIS TECHNIQUES

Limitations and capabilities of concentration sensors can be assessed by comparing instrument characteristics and monitoring requirements. The techniques for sensing concentration cover a wide scope of technology that ranges from sophisticated gamma attenuation measurements to basic hydrostatic pressure measurements. Despite the scope of technology, random errors for all instruments are within the same order of magnitude. For pressure sensing techniques, random errors are ± 25 mg/l, and for the Panametric Gage, random errors are slightly less than ± 200 mg/l. Random errors for the other techniques are between these two values. Monitoring requirements are illustrated in Fig. 1, which summarizes the range in sediment concentration at each of 210 daily sediment stations reported by the U.S. Geological Survey for Water Year 1967 (U.S. Geol. Survey, 1971 and 1972). Two concentration values, C_{99} and C_9, determine each station's point. The parameters, chosen to eliminate extreme concentration values, were defined so that for the period of flow the concentration was less than C_x, x percent of the time. Comparison of instrument random errors with Fig. 1 shows that even the most sensitive instrument cannot accurately monitor the C_9 concentration levels of most rivers.

Despite lack of sensitivity the techniques do have some applications. Capabilities of the techniques depend primarily upon their ability to register high concentrations with greater accuracy. The one exception is optical scattering; field data show that errors generally increase with sediment concentration. Beverage and Skinner (1975) estimated that for streams whose daily mean concentration exceeds 10,000 mg/l for at least 1 day during the year, as much as 85 percent of the annual sediment discharge could be monitored by an instrument whose useful range extended down to only 1,000 mg/l. Useful range was arbitrarily defined to limit concentration errors to ± 10 percent. For periods when the concentration was less than 1,000 mg/l, laboratory sample analysis could be required to complete the record. A survey of historical data showed that, for annual discharge monitoring, about one-fourth of the stations are candidates for field-based gages and at most of these sites the sediment concentration would be above 1,000 mg/l for only short periods of time. Of present techniques, either hydrostatic pressure or the vibrating U-tube possesses the required sensitivity and range. Samples would have to be pumped from an intake to a region where the instrument could perform the measurement under controlled conditions. Experienced hydrologists would be required to perform hydraulic calibrations and to interpret results.

FUTURE EQUIPMENT DEVELOPMENT AND EVALUATION

To aid development of the optimum sensor, systematic instrument evaluation techniques and equipment design requirements would have to be established. The optimum sensor would be a single type of instrument with sensitivity and range adequate to permit continuous daily monitoring at any sediment station. The probability of building this sensor in the near future seems remote, but compromises can be considered. If the requirement for continuous monitoring is reduced to monitoring 90 percent of the time, Fig. 1 can be used in a variety of ways to estimate design requirements. For example, instead of a single type of instrument, three different types would allow a reasonable choice, depending on the expected concentration range. If the first was designed to monitor concentrations from 2 to 500 mg/l, the second from 10 to 5000 mg/l, and the third from 50 to 100,000 mg/l, then two-thirds of the stations could be monitored by one of the three instruments. A survey of the same stations was made to determine the following three particle-size distributions for suspended fluvial sediment:

	Percent less than indicated size in microns		
	4	62	250
Coarse	15%	50%	85%
Medium	45%	90%	100%
Fine	85%	100%	

The distributions were selected so that approximately 90 percent of the reported distributions were between those labeled coarse and those labeled fine. The concentration and size distribution data represent only a first step toward defining the problem and establishing test standards. Standards, framed in terms of fluvial monitoring requirements, would supplement presently used standards, such as glass beads, latex spheres, and formazin.

To help meet present needs, automation of present laboratory analysis techniques could be pursued. Equipment is being developed on this investigation to automate sample withdrawal in the pipette analysis. Also, Anderson and Zahn (1968) have automated one phase of the visual-accumulation-tube analysis. Automation of other phases of laboratory analysis combined with improvements in automatic sample collection would offer some short-term relief from the growing demands for data collection.

To help meet future needs, adaptations of present sensors should be studied. The following present techniques approach the required concentration range and are adaptable to automation: electronic sensor (liquid bridge), gamma attenuation, pressure difference, ultrasonic, and vibrating U-tube. Of these, the vibrating U-tube appears promising for modification and refinement, based not only on sensitivity but also on other factors, such as reliability, response speed, cost, and simplicity of the relationship between bulk density and sediment concentration.

Before any present techniques could be used for continuous daily monitoring, the lower limit of its useful range would have to be reduced by approximately two orders of magnitude. The probability of such a reduction seems small. An alternative would be to develop a field-based concentrator designed to separate suspended solids from the water. Only the concentrated sample would be routed to the instrument for measurement. Through proper metering, the measured concentration could be numerically scaled to stream concentration. To perform the separation, methods such as filtration, electrophoresis, chemical flocculation, and centrifugation would need to be investigated.

Each technique and instrument discussed has a restricted range of application for either laboratory or field use. Additional development is required, but considerable effort and time may be required to improve sensitivity, to increase range, and to minimize sources of interference. It is planned to continue development on this project, and other researchers, including those within industry, are encouraged to participate in the effort. The instrumentation industry has made rapid progress in development of data-handling systems, but development of the data-producing sensors, particularly those related to measurement of particulate matter in liquids, has lagged behind.

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REFERENCES

Anderson, R. F., and Zahn, C. H., 1968, Automatic Tracking Device for Visual Accumulation Tube Analysis, Omaha, Neb., Corps of Engineers, Department of the Army, Missouri River Division, Tech. Memorandum No. 1-68.

Beverage, J. P., and Skinner, J. V., 1970a, Operator's Manual PS-69 Pumping Sampler, Federal Inter-Agency Sedimentation Project, Minneapolis, Minn.

--------- 1970b, Operator's Manual for Proportional Frequency Controller, Federal Inter-Agency Sedimentation Project, Minneapolis, Minn.

--------- 1974, An Investigation of a Device for Measuring the Bulk Density of Water-Sediment Mixtures, Minneapolis, Minn., Federal Inter-Agency Sedimentation Project, Rept. U, 35 p.

--------- 1975, The Sensitivity of Suspended-Sediment Gages, Paper for Internatl. Seminar on Modern Developments in Hydrometry, Padova, Italy, Sept. 1975, Federal Inter-Agency Sedimentation Project, Minneapolis, Minn.

Brown, W. M., and Ritter, J. R., 1971, Sediment Transport and Turbidity in the Eel River Basin, California, Washington, D.C., U.S. Geol. Survey Water-Supply Paper 1986, fig. 31.

Flammer, G. H., 1962, Ultrasonic Measurement of Suspended Sediment, Washington, D.C., U.S. Geol. Survey Bull. 1141-A, 48 p.

Killen, J. M., 1969, A Feasibility Study of a Field Instrument for the Measurement of Suspended-Sediment Concentration, Minneapolis, Minn., University of Minn., St. Anthony Falls Hydraulic Laboratory, Project Rept. 109, 35 p.

Task Committee on Sedimentation Manual, 1969, Sediment Measurement Techniques: A. Fluvial Sediment, Jour. Hydraulics Division, Am. Soc. Civil Engineers, v. 95, No. HY5, p. 1477-1514.

U.S. Geological Survey, 1971 and 1972, Quality of Surface Water of the United States, Washington, D.C., U.S. Geol. Survey Water-Supply Papers 2011-2016, 5 vols., parts 1-16.

U.S. Inter-Agency Committee on Water Resources, 1941a, Laboratory Investigation of Suspended Sediment Samplers, Rept. 5 (Available from U.S. Army Corps of Engineers, St. Paul, Minn.).

--------- 1941b, Methods of Analyzing Samples, Rept. 4 (Available from U.S. Army Corps of Engineers, St. Paul, Minn.).

--------- 1961a, The Single-Stage Sampler for Suspended Sediment, Rept. 13 (Available from U.S. Army Corps of Engineers, St. Paul, Minn.

--------- 1961b, Investigations of Differential-Pressure Gages for Measuring Suspended-Sediment Concentrations, Rept. P (Available from U.S. Army Corps of Engineers, St. Paul, Minn.).

--------- 1963, Determination of Fluvial Sediment Discharge, Rept. 14 (Available from U.S. Army Corps of Engineers, St. Paul, Minn.).

--------- 1964, Electronic Sensing of Sediment, Rept. R (Available from U.S. Army Corps of Engineers, St. Paul, Minn.).

Ziegler, C. A., Papadopoulos, J., and Sellers, B., 1967, Radioisotope Gauge for Monitoring Suspended Sediment in Rivers and Streams, Internatl. Jour. Applied Radiation and Isotopes, v. 18, p. 585-593.

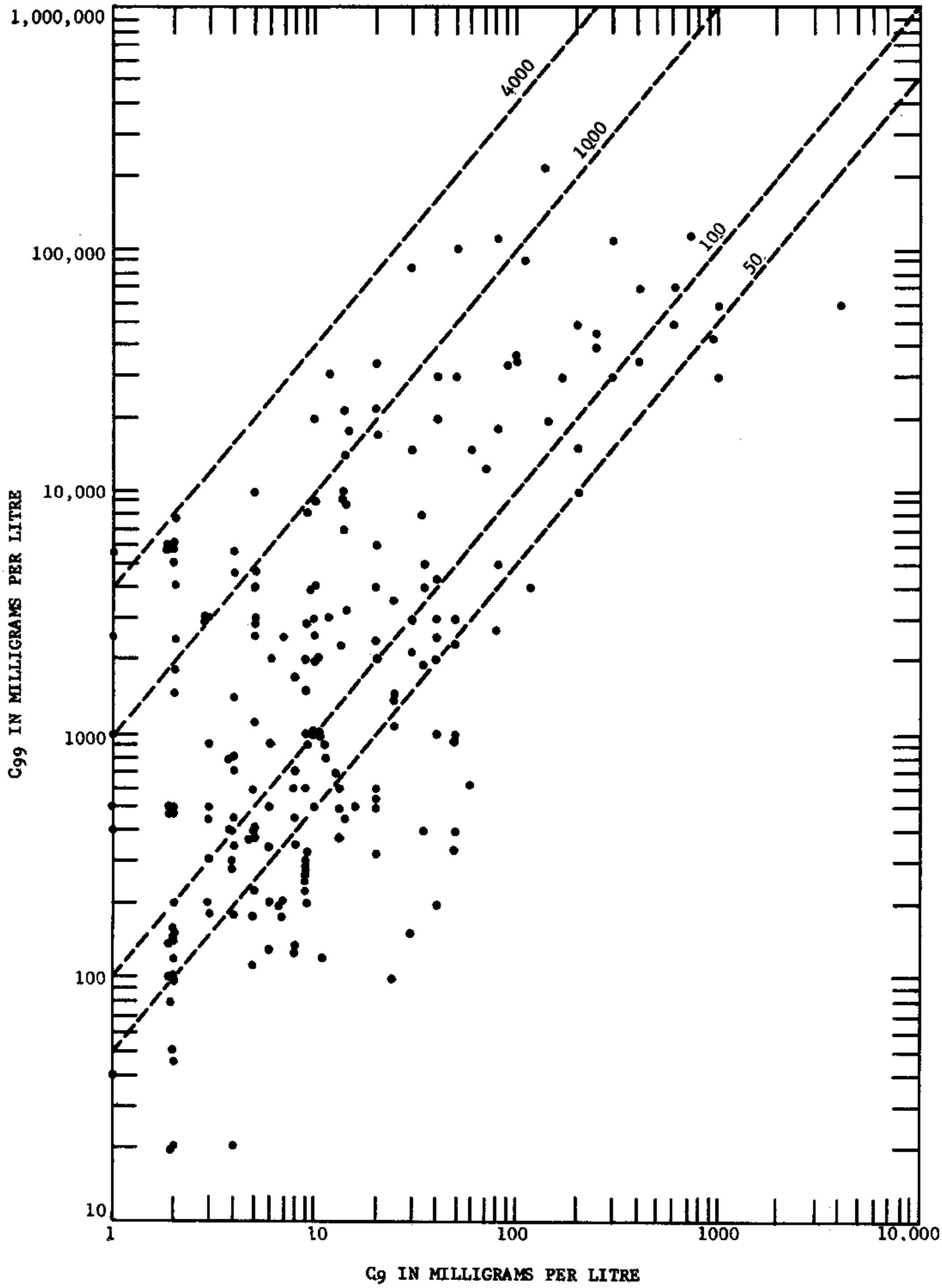

Figure 1.--Distribution of C9 vs C99 for 210 daily sediment stations. Each C9 and C99 refer to daily mean concentrations, at a single station, which are exceeded 91 and 1 percent of the time, respectively. Diagonal range lines refer to C99/C9 range ratios. Values computed from data reported for 1967 water year.

A TIME RELATED AUTOMATIC TOTAL-LOAD SEDIMENT SAMPLER

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ABSTRACT

A total-load, automatic, sediment sampler was developed and tested for use with small runoff measuring flumes. The system collects individual, total-load, sediment samples which provide periodic sediment concentration data during a runoff event. The system consists of two parts, the sampler and the collector. The sampler is a vertical slot that traverses on a horizontal rail through the flow at the flume's exit. The traverse speed is regulated by flow depth and aliquot size. The collector is a revolving table with a capacity of 18 2-liter (≃ 0.5 gal) bottles. Table rotation is regulated by a timer and a new bottle is filled with each traverse. The time of each traverse is recorded on the stage record. The system is powered by a 12-volt, DC battery charged by a solar generator, which allows using the system in remote areas where conventional electrical power is not available.

INTRODUCTION

Increased awareness of environmental protection has intensified the need for sedimentation-erosion data. Such data is needed to calibrate mathematical models of portions of the hydrologic and erosion cycle.

Historical procedures and instruments for measuring stream sediment load vary widely with some of them still in use. These methods vary with the stream size sampled. For rivers, depth-integrated or point samples have been obtained by individuals wading or with samplers suspended from cableways or bridges. The data can be greatly improved, in quality and quantity, if collected automatically at remote sites. In recent years, battery-operated pumping samplers have been extensively used to obtain point samples of suspended sediment. Pumping samplers are of limited value in many areas because they sample temporal, but not spatial, variability.

In sediment sampling of plots and small streams, collection basins have been used to sample the coarse sediment; finer sediments are sampled by fixed slots, Coshocton wheels, etc. Pumping samplers have also been used (Miller, 1969) and when equipped on a pivoting arm (Harrold, 1967), they can obtain proportionate samples from various positions in the flow depth.

All these samplers have serious limitations under certain circumstances. The wading and cable-suspended samplers do not sample the total load because they do not travel through the entire flow depth. Considerable effort is required in cleaning the tank of multislot divisors. In addition, obtaining a representative sample from the tank is difficult. Our automatic total-load sampler overcomes many limitations of these other samplers.

WALNUT GULCH TOTAL-LOAD SAMPLER

Figure 1 shows the logic used to control the operation of the Walnut Gulch sampler. The sampler operation is actuated from the flume's water-level recorder with a microswitch activated by a gear on the recorder (Figure 2). The start of a flow initiates the timing sequence. In the small ephemeral streams of the semiarid Southwest, the hydrographs are generally sharp-peaked and of very short duration. Therefore, we used a 3-min sample interval, although the sampler can accommodate other sampling intervals.

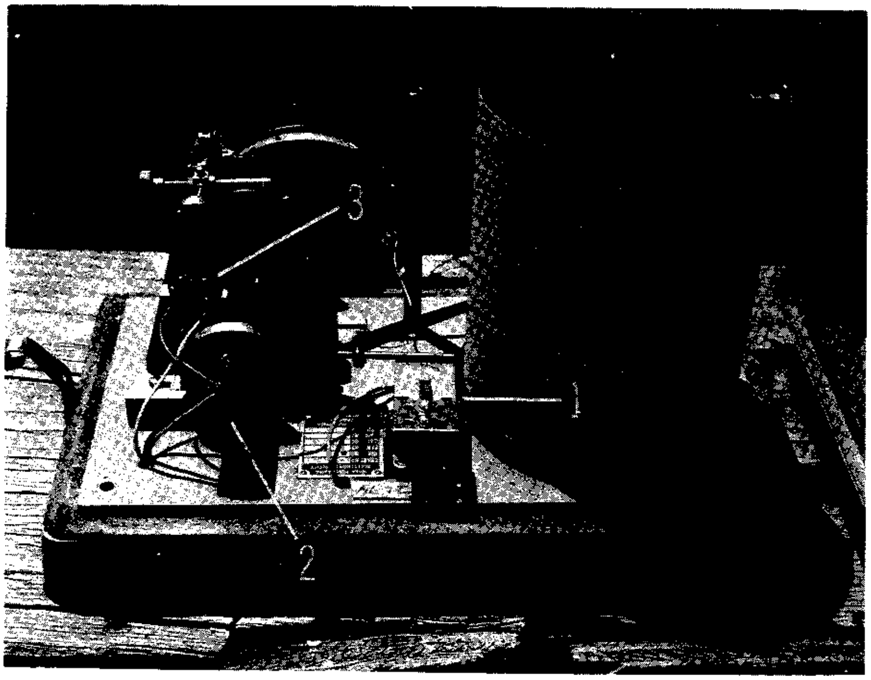
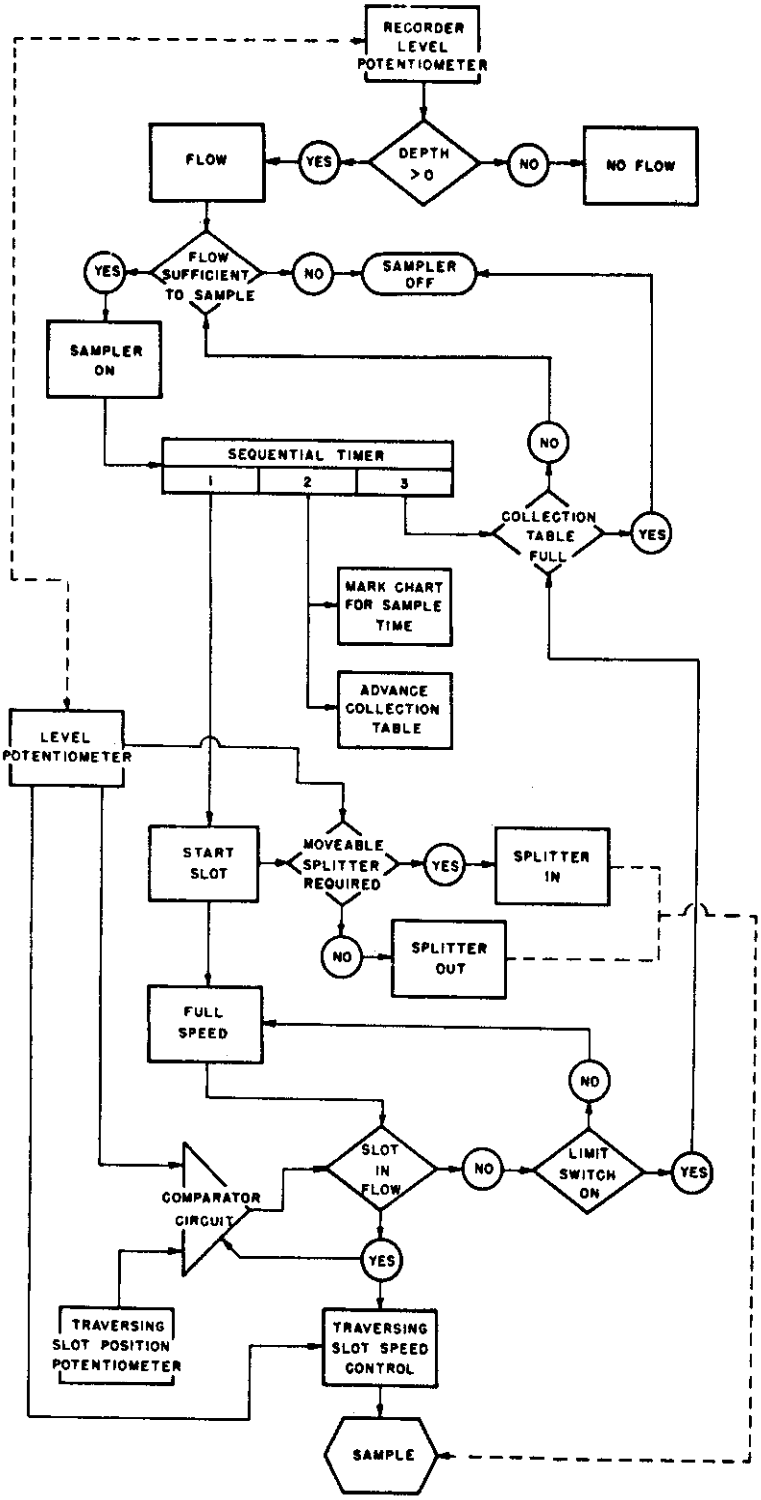


FIGURE 2. Water level recorder showing; 1) chart marking apparatus, 2) level potentiometer, and 3) OFF/ON microswitch.

FIGURE 1. Flow diagram of logic and controls used in sampling sequence.



The sampler was designed to obtain a water-sediment aliquot (particle sizes $\leq$ 12 mm) of the total flow at preset time intervals. Each sample is maintained separately for correlation with the hydrograph. In addition, the sampler was designed to operate automatically from a solar-charged DC battery.

The basic design (Figures 3 and 4) of the unit incorporates the traversing slot developed by Dendy (1973) and portions of the Chickasha sampler (Miller, 1969). The traversing slot has been mounted on an H-flume, a trapezoidal-throated flume (Replogle, 1971), and a supercritical flume in field applications. The sediment sample collection table of the Chickasha sampler is used for sample storage.

The traversing slot (1.3 cm (0.5 in) wide) (Figure 3), is chain driven and is normally in an out-of-flow position. The electronic circuitry causes the slot to move rapidly from this normal position to the edge of the flow, determined by comparing the water level position and traversing-slot position potentiometers. This rapid travel from the edges of the flow is a time- and power-conserving necessity. The speed of the slot in the flow is preset and determined from a depth-indicating potentiometer mounted on the water-level recorder. For a given depth, with the sample proportion of the discharge involved, the speed is set to collect an approximate 2-liter aliquot of the water-sediment mixture. After the slot has traversed the flow, it proceeds rapidly to the OFF position at either flume edge, out of the flow, and power to the drive motor is cut off by a switch at either end of the drive system. Sampling speeds range from 0.6 cm/sec (.25 in/sec) to 22 cm/sec (8.5 in/sec). The 10 preset speed/depth controls can be varied depending on the capacity of the flow-measuring structure. A complete sampling cycle is set for 3 min which includes: 1) a slot traverse, 2) mark sample time, 3) rotate collection table, and 4) determine if flow is sufficient to start another cycle (logic diagram in Figure 1).

The stationary slots or splitters receive the sample from the traversing slot and split the sample. These slots (1.3 cm (.5 in) wide) are evenly spaced below the flume exit (Figures 5 and 6). The center-to-center spacing between stationary slots is set to equal the exit width of the traversing slot which assures sampling of the total flow.

A fixed splitter installed in the drain tube from the stationary slots splits the sample; half is discharged back to the stream and half continues to the sample collector.

Samples are stored in a sample storage shelter located adjacent to the flume. The sample storage area must be provided so each sample can flow by gravity to its respective receptical. In applications by

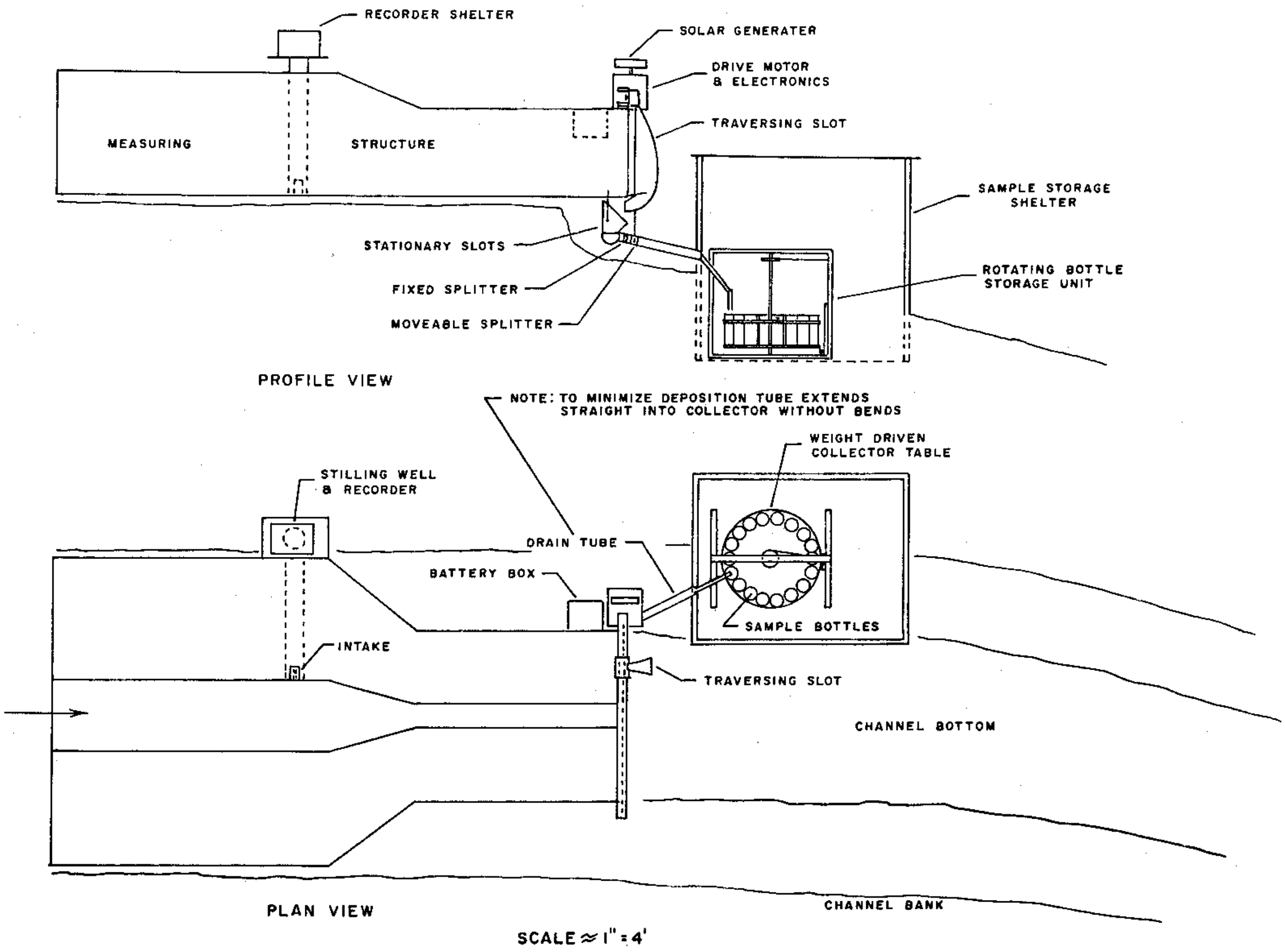


FIGURE 3. Plan and profile views of the sampler system adapted to a 2.2 m^3/sec (78 cfs) trapezoidal flume.

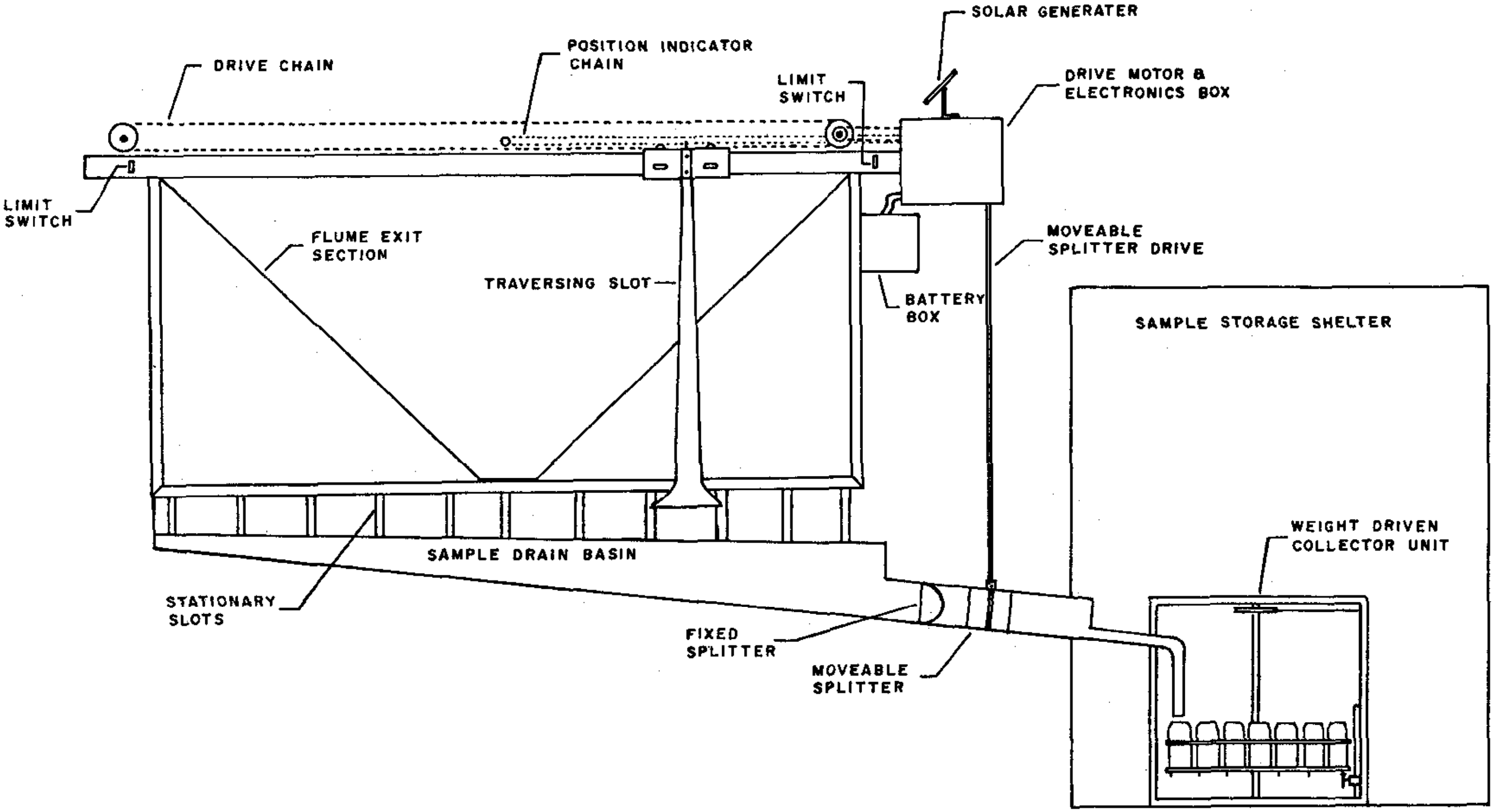


FIGURE 5. SCHEMATIC OF SAMPLER DETAILS LOOKING UPSTREAM INTO FLUME (NOT TO SCALE)

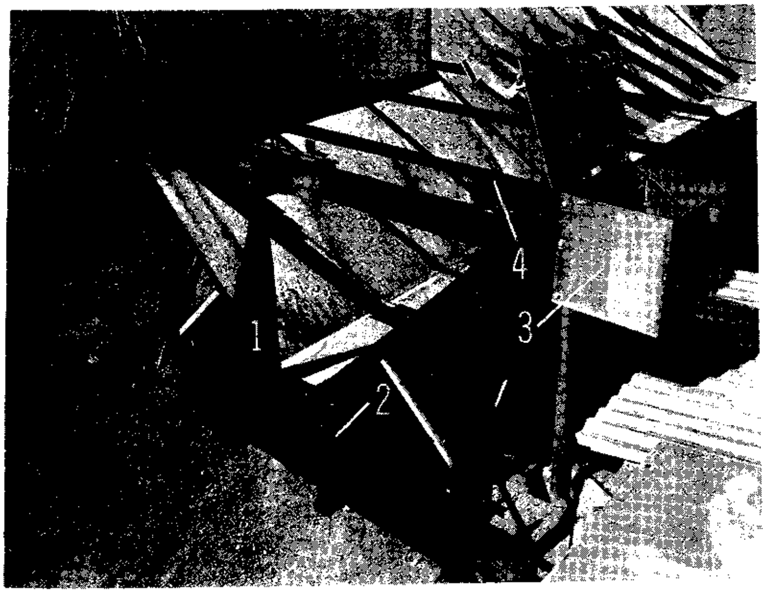
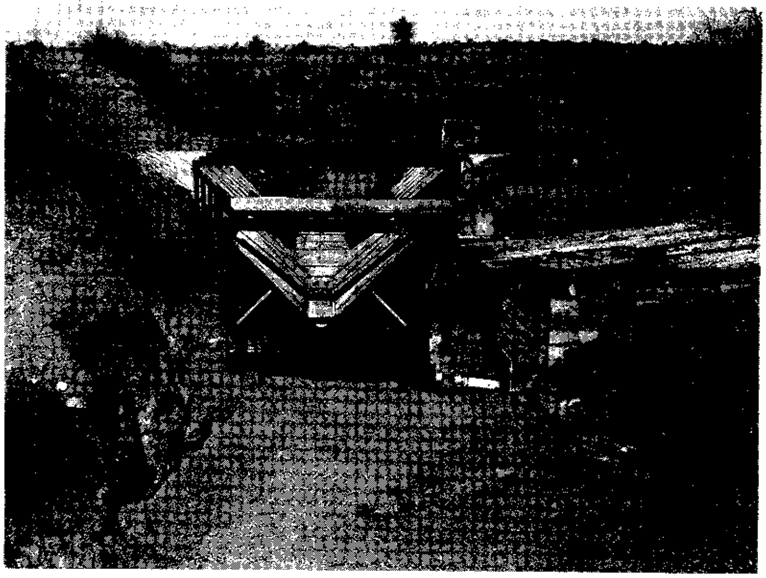


FIGURE 4. A closeup of the sampler system showing: 1) the traversing slot near the flume centerline, 2) the below flume splitters, 3) drive motor and electronic control box, and 4) chain drive mechanism.

FIGURE 6. A view looking upstream showing the traversing slot in its normal position at the flume edge. The concrete block structure houses the sample collector table and spare bottles.



the Southwest Watershed Research Center, a storage area was excavated in the channel bank adjacent to the flow-measuring structure. The hole was protected with either a large culvert pipe, set vertically in the bank, or a cement-block structure. Because the ephemeral streams in the Southwest are normally dry, special care has not been taken to make water-tight storage areas which would be required in areas with perennial or intermittent streams.

The samples are collected on a rotating table which is patterned after the Chickasha sampler (Miller, 1969). The sample collector receptacle was modified to accommodate the larger sample bottles and the timing mechanism was replaced by the overall sampler control timer and logic mechanism (Figure 1).

Sampler Operation

The sampler operation is designed to obtain a relatively constant sample volume for laboratory analysis despite variations in stream discharge. Thus, because of the fixed slot sizes, the speed of the traversign slot must be varied to obtain this required volume. Experience with laboratory concentration determinations indicates that a 2-liter sample was sufficiently large.

A moveable splitter is needed on larger capacity flumes ot further reduce the amount of sample. If the flow discharge exceeds a predetermined amount, the moveable splitter, mounted in the drain tube, moves to the vertical center of the drain tube allowing half of the sample to continue to the collector table and the remainder to discharge into the stream.

Once the water-sediment aliquot passes these splits, it travels down the drain tube to the collector receptical. These bottles are placed in 18 numbered slots on a weight-driven, solenoid-controlled, round table. After each traverse, the table rotates one position, placing an empty bottle under the end of the drain tube. A time mark is made on the flow recording chart with a solenoid-activated pen after each sample is taken (Figure 2). This system continues at 3-min intervals until either all 18 bottles are filled or flow is insufficient for sampling.

Sampler Controls

Figure 7 shows the electronic controls involved in the sampling scheme. The main sampler controls consist of the sequential timer, level and position potentiometers, and the motor speed control. Additional details are being prepared and will be available upon request.

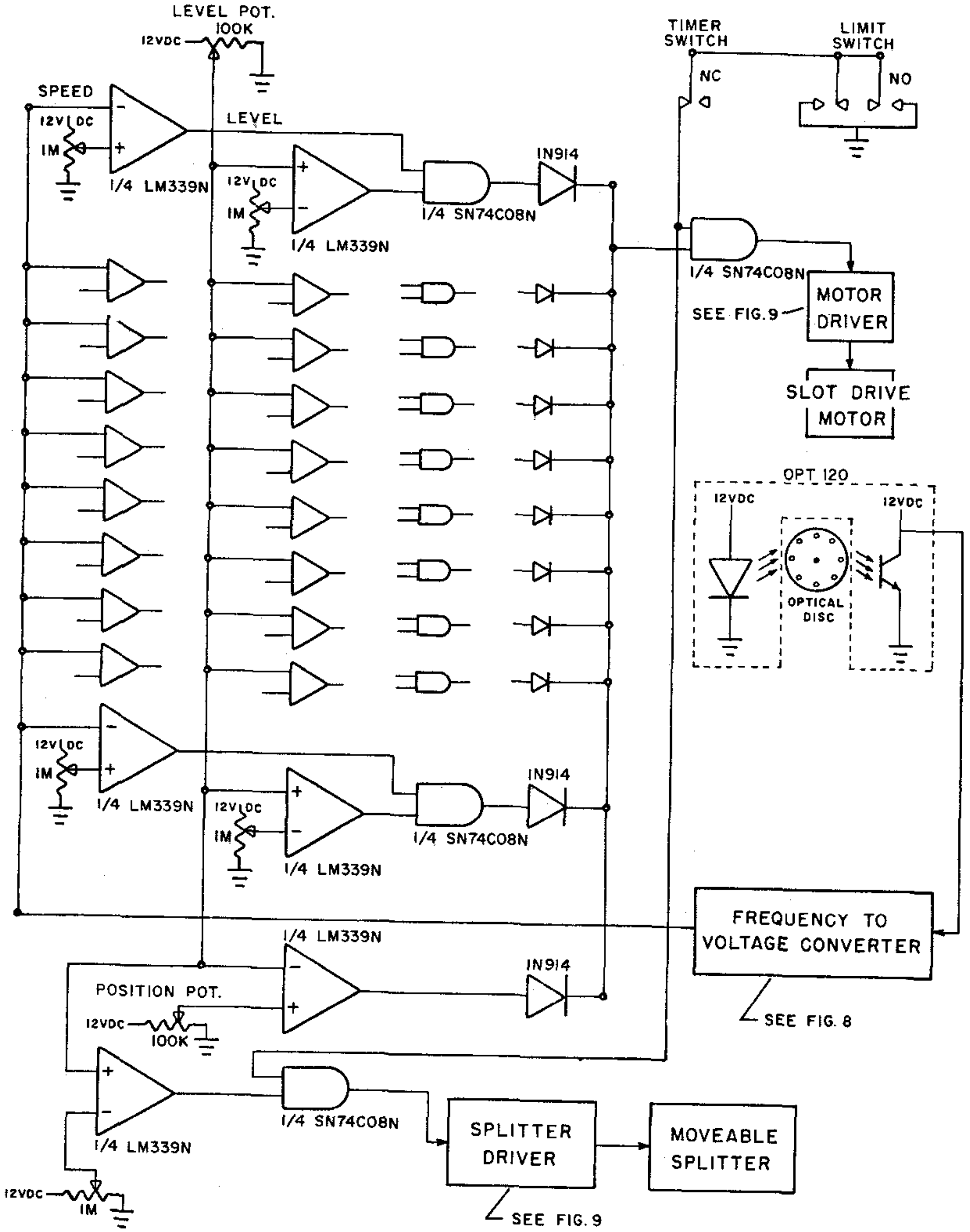


FIGURE 7. Electronic controls involved in the sample scheme.

The sequential timer is an electrical 12-VDC motor-type with detented, cam-activated switches. The first switch is on in the normally closed (NC) position with an OFF detent. This switch (No. 1 in Figure 1) allows the timer to make a complete 3-minute cycle after the sampler is turned on. The second and third switches are off in the normally open (NO) position with a 3-second ON detent. The second switch, (No. 2 in Figure 1) which controls the starting of the traversing slot, is activated approximately 5 seconds after the sequential timer is turned on. This switch overrides the motor speed-control, moving the traversing slot off the traverse limit switch. The third switch (No. 3 in Figure 1) is activated approximately 45 seconds after the sampler is turned on and controls both the marking of sample time on the water level recorder and the rotating of the collector table.

The level potentiometer is ganged with the water-level recorder so zero on the potentiometer equals zero flow on the water-level recorder (Figure 2). When the potentiometer is full-scale, water level on the recorder is maximum.

The traversing-slot position potentiometer is mounted near the edge of the flume exit. This position potentiometer is connected to the traversing slot so zero on the potentiometer is at the center line of the flume exit and the potentiometer maximum is at either edge of the exit.

The traversing slot potentiometer is turned by a small chain from the traversing slot to a sprocket mounted at the center of the flume exit to another sprocket mounted on the potentiometer. The position potentiometer is set to compensate for the ratio of water level at the recorder to flow width at the flume exit. During sample-taking, the output of the level potentiometer and position potentiometer are compared to determine the position of the traversing slot relative to the edge of the flow. If the position potentiometer output voltage is greater than that of the level potentiometer, the traversing slot is out of the flow and full power is applied to the motor-driven transistor circuit (Figure 8), driving the traversing slot at full speed either to the edge of the flow or to the traverse limit switch. When the outputs from the two potentiometers are equal or when the level is greater than the position output, the motor speed control is activated.

The speed control unit consists of 10 speed/level circuits. Each circuit has an adjustable speed potentiometer and a level potentiometer so various levels of speed and depth can be accommodated. The speed circuits incorporate the output of a frequency-to-voltage (FV) converter, the output of which is a function of motor speed (Figure 9). The FV unit is driven by an optical disk mounted on the rear of the traversing slot drive-motor shaft. If the FV output is less than a preselected amount, as adjusted for each of the speed potentiometers, power is applied to the motor. Conversely, if the FV output is greater than the preselected amount, no power is applied. This minimizes power

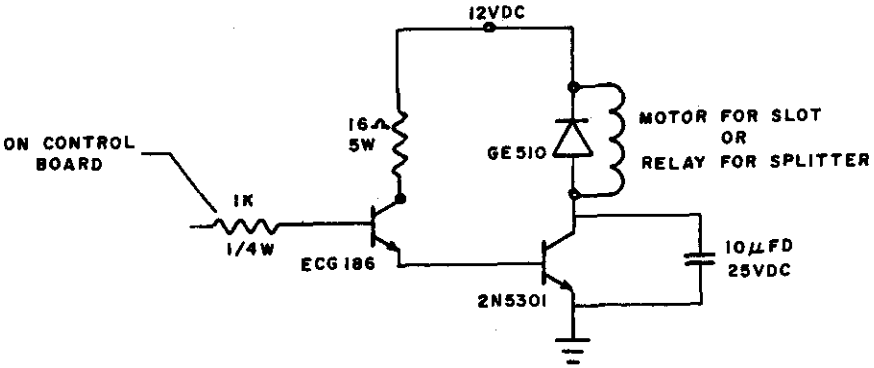


FIGURE 8. MOTOR OR SPLITTER DRIVER TRANSISTOR CIRCUIT

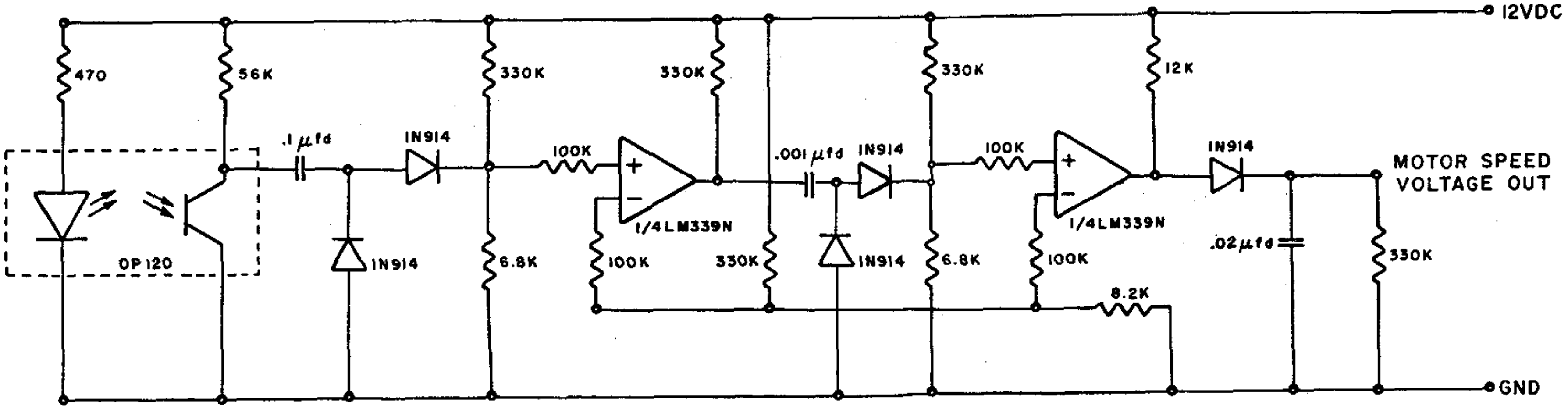


FIGURE 9. FREQUENCY TO VOLTAGE CONVERTER

loss through the motor drive transistor. The FV unit responds to conditions in excess of 1 MHz, so the motor speed is fairly constant. The level circuits use output from the recorder level potentiometer and compare this output to preselected outputs from the adjustable potentiometers of the level circuits. The particular traverse speed is selected by comparing the output from the level potentiometer of the recorder with the preselected level circuit potentiometers. For each of the 10 level circuits, there is a corresponding speed circuit. When the recorder level and the preset level agree, the appropriate speed circuit is used to power the traversing slot drive motor. The 10-speed adjustment potentiometers permit the "fitting" of water-level potentiometer output to the desired traverse motor speed; otherwise a special tapered level potentiometer would be required.

One of the 10 speed circuits is chosen by comparing the water level potentiometer with a series of preselected levels on the control board. The speed circuit selected by the control of the level circuits and a series of AND gates limits the routing of the output current of the gate to the holding AND gate. The holding AND gate input, when grounded by the limit switch, blocks the output of the control board and stops the traversing slot. Power for the moveable splitter is controlled by the holding AND gate and is activated only during the traverse time of the traversing slot (Figure 8).

The need for the moveable splitter in the sample drain line is determined by comparison of voltage output from the level recorder potentiometer and a separate preset level potentiometer.

Theoretically, the approximate power required to complete the filling of the 18 sample bottles is only 20% of the daily power produced by the 0.125 amp-hr/hr (average daylight) solar generator.

Table 1 is a condensed list of materials and their approximate cost for the construction of the complete sampler unit. These costs are based on using an FW-1 recorder with prices in the spring of 1975. The prices do not reflect any costs for the runoff measurement. Additional information, like model numbers, wiring details, etc., are being prepared and will be made available upon request.

The sampler's only application restriction is sufficient fall downstream to ensure that backwater and splash will not enter the below-flume splitters. Brush and debris problems can be controlled by installing small brushes vertically near each traverse limit switch so the traversing slot will rub across them and clean itself. Also, tilting the top of the slot away from the flume so debris would tend to ride up and off the slot will control debris buildup on the slot.

Table 1.

EQUIPMENT AND COSTS

Equipment	Cost (dollars)
Water Level Recorder & Electronics	311.00
Traversing Slot Drive Mechanism	116.00
Traversing Slot	100.00
Stationary Splitter	200.00
Position Indicator	39.00
Moveable Splitter with Motor	77.00
Sample Drain Tube	2.00
Collector Table & Drive	67.00
Collection Bottles	37.00
Sample House & Excavation	150.00
Control Board & Related Electronics	82.00
Sequential Timer	127.00
12 VDC Battery	44.00
Solar Generator	43.00
Total Sampler Cost	$1395.00*

*This total does not include any labor costs except that involved in assembling the traversing slot, stationary splitter, and moveable splitter.

REFERENCES

Brown, H. E., Hansen, E. A., and Champagne, N. E., Jr., 1970. A System for Measuring Total Sediment Yield from Small Watersheds, Water Resources Research, 6(3):818-826.

Dendy, F. E., 1973. Traversing-Slot Runoff Sampler for Small Watersheds, ARS-S-15, August.

Edwards, W. M., Bentz, W. W., and Harrold, L. L., 1969. Improvements in Automatic Sampling Equipment Used to Determine Extent of Pollution in Runoff from Agricultural Watersheds, ARS-41-151, May.

Harrold, L. L., Barrows, H. L., and Bentz, W. W., 1967. Automatic Sampling Technique to Determine Extent of Pollution in Runoff from Agricultural Watersheds, ARS-41-136, October.

Miller, G. E., Allen, P. B., Welch, N. H., and Rhoades, E. D., 1969. The Chickasha Sediment Sampler, ARS-41-150, June.

Replogle, J. A., 1971. Critical Depth Flumes for Determining Flow in Canals and Natural Channels, Trans. ASAE 14(3);428-433 & 436.

The Use of Color Infrared Photography For the Determination of Suspended Sediment Concentrations and Source Areas

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ABSTRACT

The concepts and special techniques for applying color infrared photography in sediment studies are presented. These techniques were developed and evaluated through a low elevation color infrared photography flight and concurrent water quality sampling conducted on 164 km (100 miles) of stream over the West Fork of the Madison River in southwestern Montana. The concentrations and sources of sediment produced during peak snowmelt runoff were determined by photo densitometric analysis coupled with specifically located ground control stations.

Excellent correlations were established by regression analysis of the ground truth variables including stream width to discharge and suspended sediment to turbidity. Photo density was correlated with suspended sediment and turbidity, both produced strong correlations which were signifinant at the 99% confidence level. These correlations made it possible to determine reliable estimates of sediment concentrations from the aerial photography where stream measurements were not obtained.

Sediment production estimates were made by using the concentration data linked with stream discharge as a function of stream width. The photoscale control markers were used to obtain stream widths from the aerial photography.

The photographic analysis indicated that the majority of the suspended sediment sources during the snowmelt runoff event were derived primarily from channel erosion. Additional interpretations which can be derived from photo analysis are also presented and discussed.

INTRODUCTION

Sediment production is one of the most serious water pollution problems of mountainous watersheds. Information is vitally needed about the source, magnitude, and consequence of accelerated sediment production, especially in relation to resource management activities. Watershed specialists have attempted to locate and quantify sediment production in many drainages; however, the problem of obtaining water resource data over large, inaccessible areas during short-term climatological events has been insurmountable by traditional methods. As a result, most of the sediment studies have been located at the confluences of relatively large watersheds.

Since 1966 accessibility and financial limitations have hampered efforts by watershed specialists to determine the amounts, sources, and distribution of suspended sediment in the West Fork of the Madison River in southwestern Montana. Public concern over the disproportionately high sediment contributions from the West Fork to the Madison River (a nationally famous trout stream), provided the impetus for additional studies. The objectives of these studies were to determine the sources of the high sediment concentrations and what effect the large array of land use activities have on sediment production.

Not only was accessibility a serious problem in the large watershed of 51,800 hectares (200 mi^2), but the extremely complex array of vegetation types, geologic formations and soils produced varying levels of natural erosion, stream channel types, and resultant sediment concentrations within the subdrainages involved. In conjunction with this variability was a variety of land use activities including grazing, timber harvest, road construction, wildlife and recreation. Under "traditional" water collection and analysis procedures, there were not enough people, funds, time or water bottles to meet the objectives of the water quality study.

It was evident that some type of remote sensing technique was needed to overcome these inventory and analysis difficulties, thus a color infrared photographic (CIR) flight was conducted concurrent with selected ground truth sampling. This flight was to provide a quantitative evaluation of the sources, concentrations and distribution of suspended sediment during the high elevation snowmelt runoff period, when sediment production was at its highest.

REMOTE SENSING CONCEPTS AND APPLICATION

There are many sensing devices which can be used to obtain images from the earth's surface. Sensors which can be used by aircraft include the human eye (visual reconnaissance), cameras, thermal and multispectral scanners in addition to radar and passive microwave sensing instruments (Keifer and Scherz, 1971). Airborne radiometers can be quite useful in determining surface temperatures of water, but it is the image-producing systems which appear to be the most useful for water quality studies (Scherz, 1971).

A type of image-producing system which appears to be the most suited for physical water quality studies is color infrared photography (CIR) or false-color film. This film is named because objects do not appear on transparencies of prints in the same color as they do to the human eye. The film is used with a "minus blue" (Wratten No. 12) filter which prevents blue light from exposing the film (Heller, 1970). Thus, only reflected green, red and infrared wave lengths (.6 to .9μm) reach the emulsion. The CIR film has a great ability to cut haze, which provides good resolution. One major disadvantage is that it has poor shadow penetration and needs uniform sky light conditions for consistent photo images. Thus, on heavy overcast days with variable sunlight reflection its use is limited for this purpose. Until recently there has been a lack of documented research for the specific application of CIR photography for the quantitative analysis of suspended sediment concentrations. Some investigators, however, have obtained preliminary results on some practical applications. Logan (1967) had been using CIR film for sediment detection purposes on National Forest land in southwestern Montana. By adapting a handmade microdensitometer, he found an apparent relationship between the photo density and the concentrations of sediment in the water. Clear water appeared dark blue as most of the energy was absorbed by the water. As the concentration of suspended sediment increased, there was more energy reflected, thus the image recorded on the film appeared in lighter tones of blue. Scherz (1971) reported that the energy from water targets which arrives at the camera using CIR film is a function of the suspended and dissolved material in the water, the material floating on the water, and the sum of energy that penetrates to the bottom and reflects back the images of the bottom. From the interpretation of reflectance curves he reported that the concentration of suspended solids appears to be correlated with the amount of light reflectance (Figure 1).

A suspended solids/density model was developed by Lillesand (1973), utilizing CIR photography, where a prediction of suspended solids concentration was determined from photodensitometric measurements. The model was developed from a relationship between image density, film exposure and scene reflectance. Their prediction equation as compared to observed suspended solids versus image density is shown in Figure 2.

Additional work by Lillesand, Scarpace and Clapp (1975) indicated that photodensitometric measurements, coupled with ground truth and analyzed with due regard for peripheral effects, can be used reliably to predict suspended solids in the mixing zone. Their research obtained more reliable and detailed information from densitometric analysis than by traditional surface measuring techniques.

Klooster and Scherz (1973) showed sample reflectance as a function of turbidity and related suspended solids (Figure 3). They concluded that using CIR photography in conjunction with densitometric analysis and ground truth provides a more complete and extensive quantitative evaluation of turbidity or suspended solids than conventional techniques. Turbidity, as an optical property, is related to light scattered from suspended material in the water (Klooster and Scherz, 1973). Since turbidity is what the aerial camera actually detects, it is important to establish a correlation of suspended sediment to turbidity and be aware of the relationship of the two for a particular stream.

Heller (1970) describes several quality control factors for applying densitometric analysis including: (1) physical factors such as ground luminance and reflectance, atmospheric scattering of light, angle of sun, and spectral quality of sunlight; (2) film, emulsion and filter properties; (3) camera and equipment factors such as image motion, etc. Heller also reported that, under clear weather, illumination drops off as latitude increases north or south from the equator by season of the year or by hours before and after local apparent noon. Thus, photographic flights for detailed quantitative analysis should be made within two hours of local apparent noon. If the investigator is to quantitatively analyze the film, variations in the optical density of the film against effective exposure should be determined through sensitometry techniques as explained by Dana (1971).

Another factor involving a very important peripheral effect is the surface reflection of energy due to the discontinuity in refractive index at the air-water interface. The percentage of the energy reflected at the interface is a strong function of angle (Pietch and Walker, 1971). Below 49° the percentage of energy reflected is small and constant (Figure 4). This can be adjusted in the photo analysis procedure. If sky light intensity is influenced by an overcast condition, this factor is not as significant in the photo analysis due to the uniformity of the light conditions. These and other spectral variability factors must be considered in planning aerial water quality surveys.

AERIAL PHOTOGRAPHY AND FIELD SAMPLING PROCEDURE

Photography

The author conducted the flight in June, 1971 on the Beaverhead National Forest, Northern Region of the U.S. Forest Service. A hand-held 70 mm Maurer P-2 camera fitted with a 6.8 cm (3-inch) lens and a Wratten 12, "minus blue" filter, was used with Kodak Aerochrome color infrared (type 2443) film. This camera system is described by Heller, et al., (1959). The film was loaded in three separate 15.5 m (50 feet) rolls. The photographs were taken vertically from the door of a helicopter, with a flying height of 91 meters (300 feet), which provided a 1:500 photo scale. Photo scale control was obtained by placing white 1.2 x 1.8 meter (4' x 6') markers at specified stream junctions prior to the flight. The photography was taken within 10 minutes of the actual field sampling.

The aerial flight was timed to coincide with the high elevation, snowmelt-generated peak runoff of the West Fork. Selection of the flight day also was closely coordinated with sky conditions. The flight was conducted two hours before and after local apparent noon. If sky conditions such as cloud shadows changed significantly, the helicopter would land and wait for favorable conditions. Figure 5 shows the hydrograph of the West Fork in relation to the flight. Over 161 kilometers (100 miles) of stream were flown with 46 meters (150 feet) of film taking intermittent photographs.

Field Sampling

In order to correlate the photo density with various water quality characteristics, 20 water sampling stations were established. These stations were stratified by hydrophysiographic units where sediment rating curves were expected to be different. These stations were also selected to provide the greatest variation in concentrations, differences in stream channels (materials and patterns), upstream management and elevation. All sampling was done concurrent with the flight.

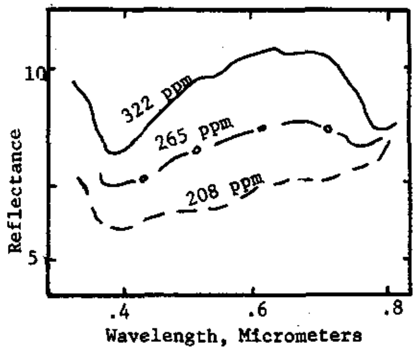

Figure 1. Change in reflection of steel mill discharge from Chicago area as a function of concentration of solids (Scherz, 1971).

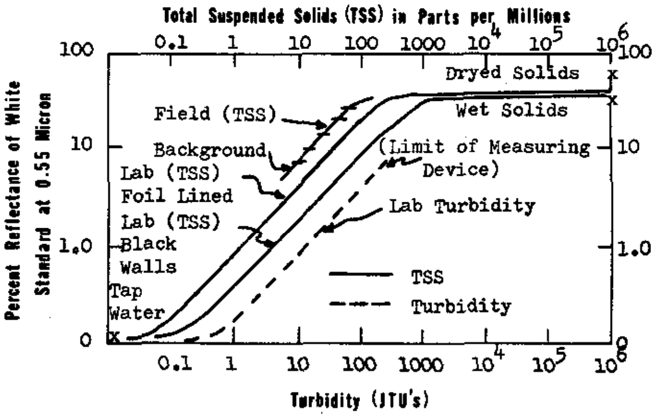

Figure 3. Reflectance vs. turbidity and suspended solids. Field reflectance was obtained from film. (Klooster and Scherz, 1973).

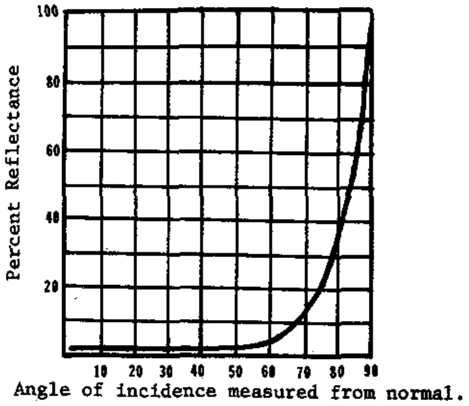

Figure 4. Percentage reflectance of air-water interface as function of angle of incidence, measured from normal direction (Pietch and Walker, 1971).

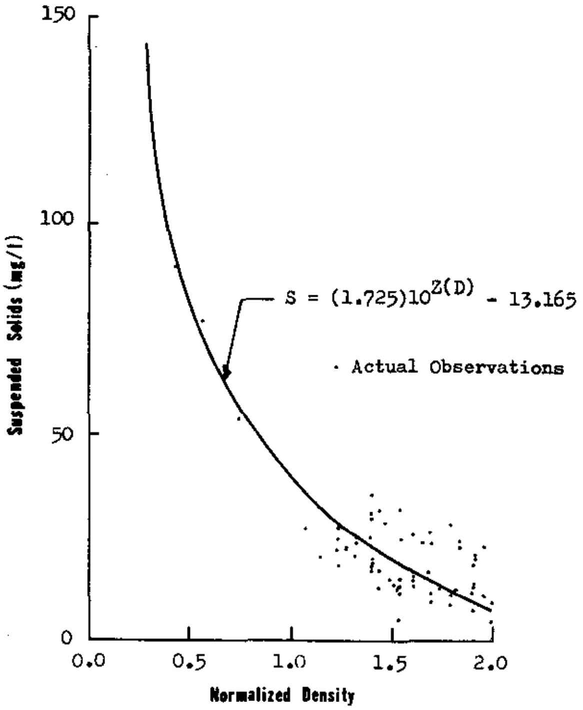

Figure 2. Suspended-solids/density model of red film layer (From Lillesand, Scarpace and Clapp, 1975).

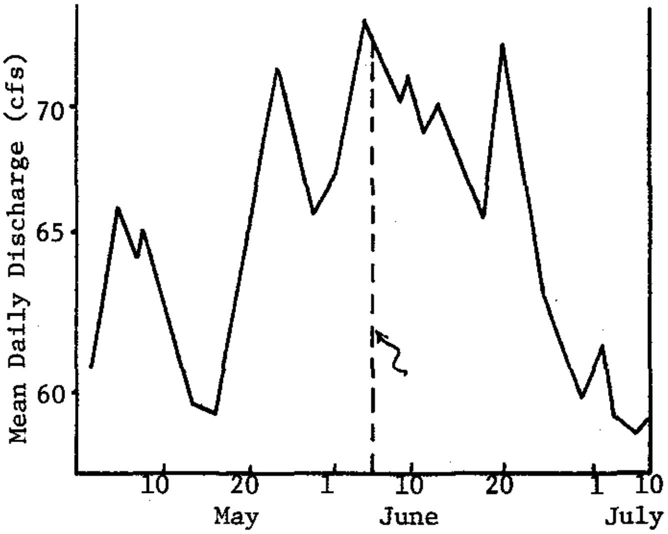

Figure 5. Hydrograph of the West Fork of the Madison River, Montana, 1971.

Suspended sediment samples were obtained using D. H. 48 and 59 depth-integrating hand samplers (Guy and Norman, 1970). The depth-integrating suspended sediment samples were averaged across the stream. Additional samples were obtained for turbidity, temperature, pH, and specific conductance. Stream discharge was measured at each site. These measurements were made to determine sediment production and to provide additional interpretation from stream velocity, depth, and width measurements.

The helicopter enabled ground truth data to be collected at inaccessible sites concurrent with the photographic flight. To speed up the photographic coverage of the watershed, field assistants provided ground truth data at a few accessible station locations as the helicopter approached.

DATA ANALYSIS AND RESULTS

Analysis

The water samples were analyzed for suspended sediment concentrations (mg/l) by the filtration procedure as described by Guy (1969). Turbidity (JTU) was determined with a Hach Model 2100 turbidimeter. Additional water analysis and stream measurements were obtained at the site during the flight.

The ground truth variables were analyzed by regression analysis. This analysis included the relationship of turbidity to suspended sediment and stream width to stream discharge.

After the CIR film was processed, the Pacific Southwest Forest and Range Experiment Station at Berkeley, California generously offered the use of their photometric data system's digital comparator microdensitometer and computer facility. This microdensitometer is described by Doverspike _et al_, (1965).

Optical densities were obtained by the microdensitometer on the 70 mm CIR film transparencies at the exact location where the water samples were obtained.

Density readings were obtained from the transparencies with clear, red, green and blue filters. Multiple regression analysis was used to determine which filter or filter combinations provided the best correlations with suspended sediment and turbidity variables with photo density.

The correlation coefficient, F-test, and standard of error estimates were obtained. Once the regression equations were developed for photo density to turbidity/suspended sediment, additional density readings were obtained where field data were not available. This was done to determine:

- Sources of sediment during the runoff event.
- Spatial distribution of sediment within the watershed.
- Concentrations of sediment by subdrainages as a function of stream discharge and channel type.

Results

The measured suspended sediment concentrations from the sampling stations varied from 22 mg/l to 660 mg/l. Turbidity levels varied from 15 JTU's to 202 JTU's.

Regression analysis of the ground truth variables produced the following correlations (Figures 6 and 7).

Variables	Correlation Coefficient $(r)^2$	Level of Significance
Suspended sediment/turbidity (JTU) (mg/l)	.92	99%
Stream width/stream discharge	.90	99%

A multiple regression analysis involving a linear relationship of photo density to suspended sediment and turbidity for clear (none), red, blue, and green filters indicated that the best correlation was obtained with the clear (no filter) density (Norick, 1973, personal communication).

Based on a plot of the X, Y variables for both sediment-density and turbidity-density, a curvilinear relationship appeared to be the most representative. A multiple regression analysis indicated a strong correlation of both turbidity and suspended sediment to photo density with the clear filter. The statistics summary is shown in Table 1. The regression equation for both turbidity and suspended sediment is shown in relation to the observed values (ground truth) (Figures 8 and 9).

Table 1. Statistics Summary of Regression Analysis of Photo Density to Turbidity and Suspended Sediment

	Turbidity (JTU)	Suspended Sediment (mg/l)
Correlation coefficient (r^2)	0.84	0.81
Standard error of estimate	18.6	71.5
F Value at the .01 level	36.2	28.9
$F_{.010}$ Test Significance	Highly Significant (99% level)	Highly Significant (99% level)

DISCUSSION

Variables in Photo Analysis

There are many spectral variables involved when taking direct photo density readings for quantitative analysis. The effects of many of the variables could not be evaluated in this study. They were, however, anticipated and isolated for later identity in the photography and ground control procedures. As discussed earlier high surface reflection occurred on many transparencies due to sun angle changes. However, this reflection

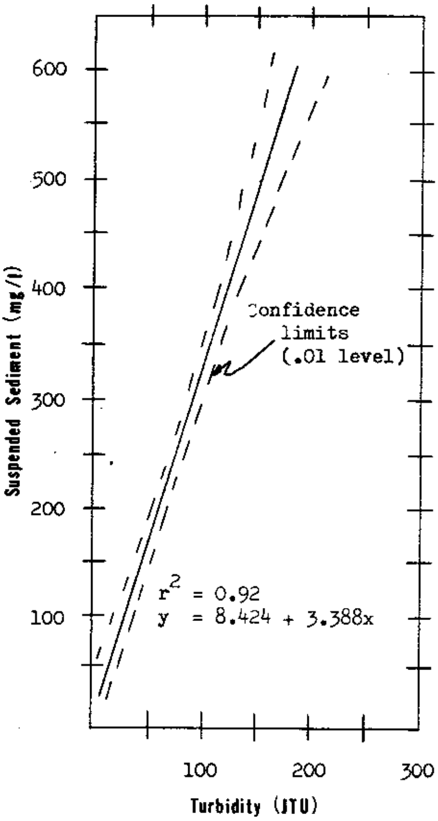

Figure 6. Linear regression of suspended sediment to turbidity.

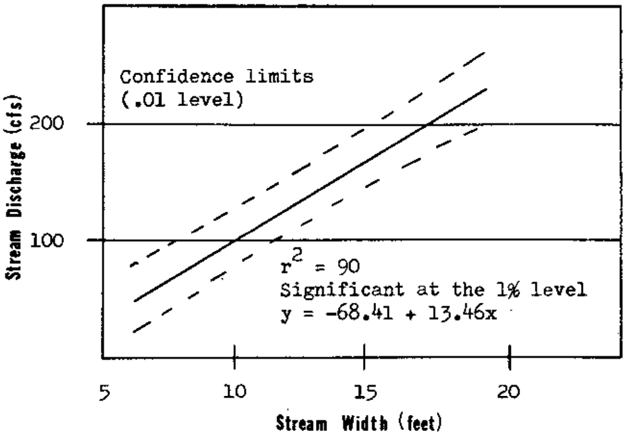

Figure 7. Regression of discharge as a function of width.

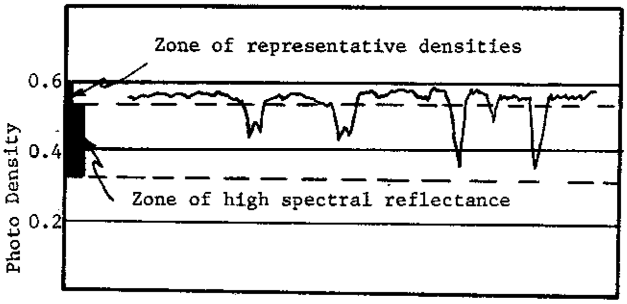

Figure 10. Chart trace of printout of microdensitometer readings indicating zone of representative densities and a zone of high spectral reflectance as a result of supercritical flow, sun angle, etc.

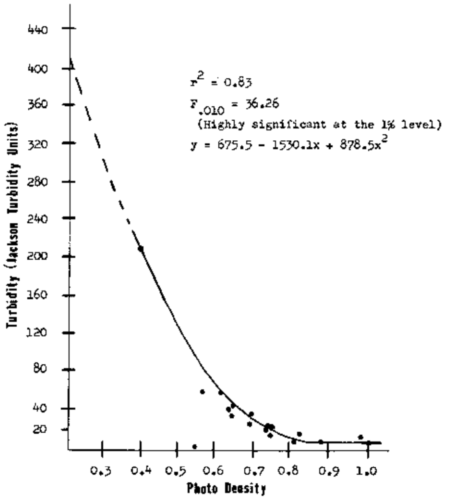

Figure 8. Curvilinear regression of turbidity to photo density.

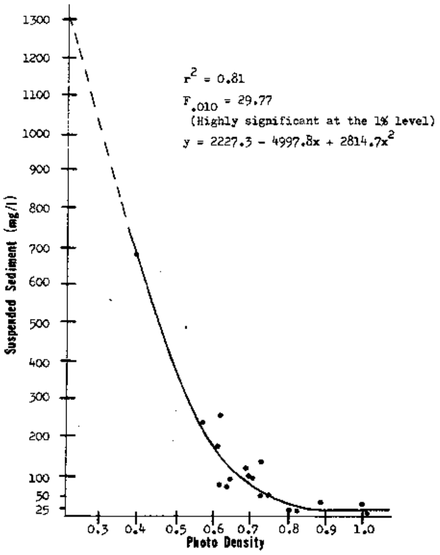

Figure 9. Curvilinear regression of suspended sediment to photo density.

only occurred on portions of the transparency, allowing the remaining areas to be analyzed. The microdensitometer produced abrupt "peaks" in these portions, quickly identifying the high reflections areas (Figure 10).

The ability to readily detect this reflection helps avoid unnecessary detailed microdensitometer anaysis. Reaches of steep gradient streams with super-critical flow also created very high surface reflectance. Thus, density readings were avoided in these reaches. As explained earlier, CIR has poor shadow penetration which directly affects optical density. When high cumulus clouds would create shadows, the helicopter had an added advantage over fixed wing aircraft by being able to land and wait for more consistent sky conditions. In some reaches, streamside vegetation caused shadows affecting photo density. Quantitative analysis from photo density could not be obtained in these areas.

Where stream depths were less than 0.3 of a foot combined with sediment concentrations of less than 20 mg/l bottom materials were reflected, causing unrealistic density readings. Since the .7 to 1.0 micrometer wave lengths are adsorbed by the first few inches of water there were penetration problems on these types of very shallow streams. It is the blue-forming layer of the CIR that captures the penetrating wave lengths (Kiefer and Scherz, 1971). Thus for future studies a filter combination eliminating the blue layer for density analysis of very shallow streams may provide a better representation. Most of the streams on the West Fork drainage had adequate depth and/or sufficient sediment concentrations to overcome this problem.

Over 98% of the total sediment production at the mouth of the West Fork is suspended load (Lisle, 1972). This factor and the fine texture of the material in suspension (silts and fine sands), contributed significantly to the high correlation of the suspended sediment/turbidity and to the good correlation of photo density (based on the reflective characteristic of sediment-laden waters) to suspended sediment concentration. These relationships will vary by streams and should be established concurrent with the photographic flights.

A regression equation may be regarded as a satisfactory predictor if the "F" value should exceed the selected percentage point of the F-distribution by a factor of four times the selected percentage point (Draper and Smith, 1966). The F values derived from Steel and Torrie (1960) for turbidity/density and sediment/density of 36.2 and 29.8, respectively, exceed the F value of 6.51 at the 99% level by over four times.

From this relationship density readings may be obtained to determine sediment concentrations throughout the watershed if the CIR transparencies are used with due regard to the spectoral variabilities involved. Thus, direct interpretations of sediment concentrations and turbidity can be made where field data was not obtained. This technique presents an approach to solving an age-old problem in sediment studies, that of obtaining ehough sample points within the watershed during a runoff event to determine sources and spatial distribution.

Not only is access limiting in wildland watersheds, but obtaining enough people, equipment, and dollars to determine source areas and distribution of sediment is not feasible (as evidenced by the lack of such data). With a densitometric analysis "thousands" of data points throughout the watershed become available to the interpreter as the runoff event is uniformly captured.

The total cost of this project, involving helicopter time, film, and film processing, field data collection and analysis, and the photo analysis was approximately $2,200, or $14/km ($22/mile).

Sediment Sources and Interpretations

Through the photo scale control stream widths can be measured by photo analysis. From the excellent correlation of the width to discharge reliable estimates of discharge can be obtained. Once discharge is determined the density readings to estimate suspended sediment concentrations can be combined to quantify total sediment production (tons/time/area) for various stream reaches.

To determine sediment source areas photo density readings were taken on headwater streams where problems in direct sediment introduction by overland flow, rilling and gullying were occurring. Very low density readings (indicating very high sediment concentrations) occurred on many headwater streams from these direct sources. The concentrations were reduced in a very short distance downstream due to the low stream discharge and the "depositional" type channels draining these areas. Thus, a low percentage of the introduced sediment appeared to be transported to the larger order streams. The low stream discharges from these headwater areas resulted in low sediment production compared to the total at the mouth of the West Fork during this snowmelt runoff period.

In many instances on both large and small streams incised in material of low "erosional resistance", density readings became progressively lower (higher concentrations of suspended sediment) with increasing width and associated discharge downstream. This increase as determined from density readings, would occur between contributing tributaries, indicating sediment sources were predominantly from channel erosion. This did not occur on stable channels incised in coarse angular material.

As the sediment concentrations were traced throughout the stream system, it was evident that during this runoff event the bulk of the total sediment production at the mouth of the West Fork was derived primarily from channel sources. The majority of the subdrainages appeared to owe the bulk of their sediment load to channel erosion processes. The sediment/discharge relationships of the various tributaries also provides some interpretation as to stream equilibrium conditions in relation to the downwasting rates of the various combinations of landtype within the subdrainages.

Another type of interpretation provided by the densitometric analysis was on the distribution of high concentrations of sediment from direct source areas. On one reach, density readings were obtained upstream, at the source, and within three meanders downstream of a very high unstable streambank. Although the average stream velocities in this reach exceeded 1.8 m/second (6 feet/second) and the material was composed of noncohesive fine sands, over 95% of the suspended load that was contributed from these areas was deposited within 400 yards downstream (Figure 11).

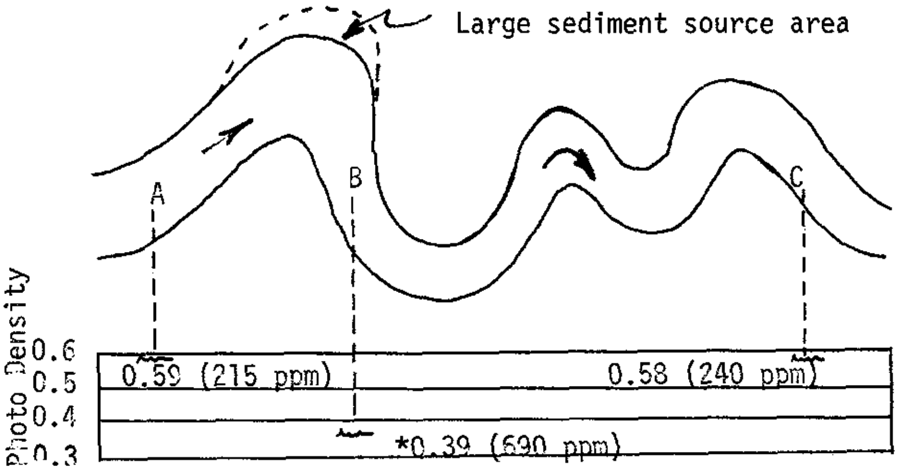

Figure 11. Sediment concentrations and distribution from direct source as determined by photo microdensitometer analysis and strip chart readout for respective stream points A, B and C. *Densities averaged across stream width at selected reach.

Due to the very high concentrations of the sands in suspension deposition occurred. The densitometric analysis provided the ability to determine downstream change in concentration from the sources. On-site field tests verified this interpretation of concurrent scour and deposition at this site. The net result is a prevalence of channel migration. Hydrodynamic studies conducted on the West Fork have shown that the stream is migrating at the mouth at the rate of 5 cm/year (2 inches/year) (Lisle, 1972).

A detailed analysis of the sediment study of the West Fork is beyond the scope of this paper; however, the CIR photography flight and analysis made it possible to pinpoint the sources and spatial distribution of sediment. The analysis also assisted in the water quality characterization of the various subdrainages within the West Fork watershed.

Application

Some of the more obvious advantages of using some form of remote sensing technique in sediment studies are:

1. Coverage of an entire stream system during short-term sediment producing events;
2. Establishment of permanent bench mark records for later detailed quantitative analysis and comparison;
3. Supplementation of detail and interpretation beyond limits of the human eye;
4. Minimum expenditure/unit area for data collection and analysis.

The use of photo analysis can also provide a key in the analysis of stream channel processes in a reach. Subsequent aerial photographs can also indicate rates of bar formations, channel widening, riffle-pool ratios, delta formations and other fluvial features.

Through proper interpretation and analysis of this data, answers can be provided to the following questions:

1. What are the sources and spatial distribution of sediment.
2. What are differences in the sediment producing characteristics between the various subdrainages for short-term hydro-meterological events.
3. What management criteria is needed to protect or enhance the physical water quality.

The use of CIR photography coupled with a well-planned network of ground truth data should provide a very reliable, fast and inexpensive means of obtaining water quality data in large remote areas. With proper attention to the controls necessary to minimize spectral variability in photographic procedures and microdensitometer analysis, reliable sediment concentrations may be obtained through photo analysis. The overall view provides a sound basis for determining sediment production within a watershed during runoff producing events.

Acknowledgment

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BIBLIOGRAPHY

Dana, Robert W., 1971. Calibration of Color Aerial Photography. Pacific Southwest Forest & Range Exp. Sta. U.S.F.S. Special Report

Draper, N. R. and H. Smith, 1966. John Wiley & Sons, New York. 407 pp.

Guy, Harold P., and Vernon E. Norman, 1970. Field Methods for Measurement of Fluvial Sediment. Book 3, Chap C2. Techniques of Water Resources Investigation of the U.S. Geol. Surv. Spt. of Docts. Wash, D. C.

Guy, Harold P., 1969. Laboratory Theory and Methods of Sediment Analysis. Book 5, Chap. C1. Techniques of Water Resources Investigation of the U.S. Geol. Surv. Spt. of Docts. Wash. D. C.

Heller, Robert C., Robert C. Aldrich and W. F. Bailey, 1959. Evaluation of Several Camera Systems for Sampling Forest Insect Damage at Low Altitude. Photogrammetric Engineering.

Heller, Robert C., 1970. Imaging with Photographic Sensors. Remote Sensing. National Academy Science, Washington, D. C. p 35-72.

Keifer, R. W. and J. Scherz, 1971. Aerial Photography for Water Resource Studies. Proceedings A.S.C.E. Vol. 97, No. SU.2.

Klooster, S., and J. Scherz, 1973. Water Quality Determination by Photographic Analysis. Report No. 21. University of Wisconsin, Madison.

Lillesand, T. M., 1973. Use of Aerial Photography to Quantitatively Estimate Water Quality Parameters in Surface Water Mixing Zones. PhD Thesis, University of Wisconsin.

Lillesand, T. M., F. L. Scarpace and J. L. Clapp. 1975. Water Quality in Mixing Zones. Photogrammetric Engineering and Remote Sensing. p. 285-298.

Lisle, Thomas E., 1972. Sediment Yield and Hydrodynamic Implications, West Fork of the Madison River, Montana. M. S. Thesis paper, University of Montana, Missoula, Montana.

Logan, Leon D., 1967. Remote Sensing of Physical Water Pollution on the Gallatin National Forest, U.S.F.S., Bozeman, Montana.

Norick, Nancy, 1973. Personal Communication on Statistical Analysis of West Fork Data. Statistician, Remote Sensing Unit, Pacific Southwest Forest and Range Exp. Sta. U.S.F.S., Berkeley, California.

Pietch, Kenneth R., and John E. Walker, 1971. Aerial Color Analysis of Water. "Journal Survey and Mapping Division". Proc. A.S.C.E. Vol. 97. No. SU.2.

Scherz, James P., 1971. Remote Sensing Considerations for Water Quality Monitoring. Proc. Seventh Int. Symp. on Remote Sensing of Environment. University of Michigan, Ann Arbor, Michigan.

Steel, R. G., and J. H. Torrie, 1960. Principles and Procedures of Statistics. McGraw-Hill Book Co. N.Y. 481 pp.

GAGING SEDIMENT-LADEN FLOWS WITH V-NOTCH WEIRS[1]

By K. E. Saxton, Hydraulic Engineer, USDA-ARS-Watershed Research Unit, Columbia, Missouri, and J. F. Ruff, Assistant Professor, Civil Engineering Department, Colorado State University, Fort Collins, Colorado.

ABSTRACT

Watersheds with areas of less than 1 mi^2 (2.59 km^2) often have streamflow with stages that rise and fall rapidly. These rapid stage changes prevent accurate field calibration of streamflow gaging stations by usual techniques; therefore, a reliable, precalibrated measuring device is necessary. Also, the streamflow from these small watersheds is often heavily laden with sediment (up to 200,000 ppm), and the alluvial stream channels change their cross section and slope upstream of the measuring device. These sloping and aggrading approach channels can change the streamgage calibration.

Broad-crested, V-notch weirs, developed by the U.S. Soil Conservation Service, have been used extensively. Recent evidence has shown that different approach channel slopes and shapes and sediment deposits cause significant deviations from the original calibrations. Model studies were conducted to define the effect of approach channel geometry and sediment deposits on the weir calibrations. A rigid-boundary model was used for the tests. Channel slopes were 0.0, 0.5, 1.0, 1.5, and 2.0 percent for several approach channel cross sections. The results provide improved calibrations for broad-crested, V-notch weirs for gaging sites in alluvial channels.

INTRODUCTION

Streamflow measurements are an important requirement of many research and design activities. These measurements have greater significance with the increased emphasis on environmental water quantity and quality. The economic, social, and scientific interpretations based on these streamflow measurements require that the measurements be accurate and reliable.

Numerous measurement techniques and instruments have been developed for a wide range of flow conditions and criteria, and each system has unique characteristics. Measurement of streamflow from small watersheds where maximum peak rates are expected to be 300 to 1,000 cfs (8.49 to 28.3

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cms) presents gaging requirements that are best met by precalibrated flumes or weirs because these watersheds often have rapidly varying, short-duration streamflow, where field calibration is difficult or impossible. Additional measurement problems exist because good accuracy is required throughout a wide range of flow rates, and the flow often contains significant amounts of trash and sediment which may interfere with the gaging device.

A broad-crested, V-notch weir was developed and tested by researchers of the U.S. Soil Conservation Service (SCS) for use as a precalibrated streamflow measuring device for small watersheds (Huff, 1938, 1941a, 1941b, 1942). The calibrations were developed using laboratory models with fixed-bed approach channels with geometric cross sections. These weirs have been used extensively, often with no further laboratory or field calibration verification. However, the weir calibrations are dependent on the approach channel conditions; thus, only when the laboratory condition is closely duplicated can the laboratory rating be reliably applied to field installations.

Although most hydraulic handbooks for flow measurements describe the required approach channel conditions for the weir ratings listed, few suggest the consequences if these conditions are not met. In many situations, appropriate approach channels cannot be constructed. And, often, properly constructed approach channels are later significantly modified by sediment deposition. In this article, we review the effect of approach channels on weir ratings, cite some maintenance difficulties of approach channels where sediment-laden flow is being measured, and present preliminary research results that indicate the potential effect of approach channels on the calibration of broad-crested, V-notch weirs.

DETERMINING WEIR CALIBRATIONS

The theoretical discharge of a sharp-crested, triangular weir is

$$Q = \frac{8}{15} (2g)^{1/2} \operatorname{Tan} \left(\frac{\theta}{2}\right) h^{5/2} \qquad (1)$$

where Q = discharge, $L^3 T^{-1}$
g = gravity constant, $L T^{-2}$
θ = internal weir angle
h = head above notch, L

The assumptions are: (1) no approach velocity, (2) parallel flow, (3) no energy loss within the approach reach, and (4) an energy coefficient of unity. Since these ideal conditions do not exist, a coefficient is incorporated with the constants of equation (1) to form a discharge coefficient, C_d, so that

$$Q = C_d h^{5/2} \qquad (2)$$

To precalibrate V-notch weirs, then, requires that the discharge coefficient, C_d, be determined for the entire flow range by laboratory models or other means. This coefficient is primarily dependent on the weir angle, weir cross section, and approach channel geometry. Usually, the coefficient is not constant through the full range of flow. The weir ratings are commonly expressed as graphs of C_d versus Q or as Q versus h (as shown later).

Field installations must closely simulate the laboratory setting to allow application of the laboratory-developed discharge coefficients, or some method must be used to modify these coefficients. For rectangular, thin-plate weirs with rectangular, level approach channels, Kindsvater and Carter (1959) developed modification criteria to estimate discharge coefficients for a variety of weir heights and approach channel widths. And for the SCS broad-crested V-notch weir, the calibrations were made dependent on the upstream cross section (which can be expressed as weir coefficients); but, again, only level channel slopes were considered (Holtan *et al.*, 1962).

THE BROAD-CRESTED, V-NOTCH WEIR

The broad-crested, V-notch weir developed by SCS researchers at Cornell University, the National Bureau of Standards, and the University of Minnesota was economical to construct, durable, and provided good accuracy throughout the flow range. The weir thickness was 16 in. (40.6 cm). The crest cross section had 6-in. (15.2 cm) wide sections sloping 3 horizontal to 1 vertical on the upstream and downstream side and a 4-in. (10.2 cm) wide horizontal section at the center. Weir section details are presented by Holtan *et al.* (1962), page 35.

Weirs with side slopes of 2, 3, 5, and 10 horizontal to 1 vertical were calibrated using the head 10 ft. (3.0 m) upstream of the weir. The approach channels for the weir calibrations had several sizes of rectangular or trapezoidal cross sections, a 0.0-percent grade, and bottom elevations 6 in. (15.2 cm) or more below that of the weir notch. These calibrations were first reported by Huff (1938, 1941a, 1941b, 1942); again by Harrold and Krimgold (1943); and later by Holtan *et al.* (1962).

Early field installations soon disclosed that sediment transported by the streamflow often deposited in the approach channel, which resulted in a channel gradient and an effective channel bottom at or above the weir notch elevation. Further testing was done on several modified approach channels for alleviating the deposition problem and head-discharge relationships were determined (Huff, 1942). Many of these tests showed significant deviations from the published ratings, irregular rating curves due to standing waves, and approach velocities near critical--but the summary reports were not widely disseminated.

The broad-crested, V-notch weir remains a useful stream-measuring device for numerous applications, both in the U.S. and in other nations. Usually, the field sites closely approximate those represented by the laboratory conditions; thus, the laboratory ratings are applicable. For cases of obvious approach channel deviations from the calibrated weir geometry or weir modifications, field calibration is necessary and accomplished; in other situations, field calibration is necessary, but is impossible or impractical. The only recourses here are either to accept the inaccuracy (usually of unknown magnitude) or to use a different measurement device, but suitable devices are often neither available nor practical. Thus, the broad-crested, V-notch weir continues to be used despite the difficulties of accurate ratings.

Weirs cause hydraulic characteristics conducive to upstream sediment deposition. Streams carrying even moderate suspended sediment loads or those with mobile beds naturally assume some channel gradient and equilibrium cross section. If this results in a weir approach channel different from that represented in the laboratory, there may be significant rating shifts and inaccurate streamflow measurements. Streams carrying heavy bedloads, such as sandbed streams, or those with suspended loads greater than 50,000 to 100,000 ppm are particularly susceptible.

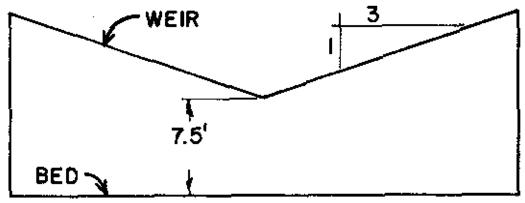
The sediment deposition in the approach channel may be dynamic during a flow event. These deposition changes may cause a variable rating shift that is difficult to document and assess. The deposit may become apparent only as the flow recedes, and only then if observers are tending the measurement station. Even with reasonable estimates for deposition depths, cross sections, and slopes during an event, no reliable method is available to adjust the weir rating.

RECENT WEIR TESTS

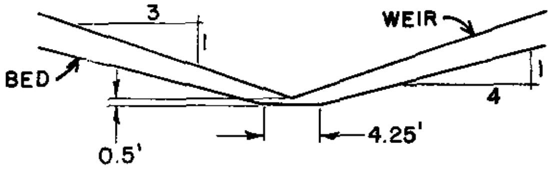
Model tests were conducted to further define approach channel effects on the calibrations of broad-crested, V-notch weirs. Fixed-bed models with a model-to-prototype ratio of 1 to 5 were installed in a 4 x 8 x 200 ft. (1.2 x 2.4 x 60.8 m) tilting flume. The weirs tested had side slopes of 2 and 3 horizontal to 1 vertical (127^o and 143^o internal weir angle, respectively). Head measurements were made 10 ft. (3.0 m) (prototype) upstream of the weir center line.

The approach channel cross sections tested are shown in Figure 1. Cross section 1 was the entire rectangular flume width. Cross section 2 was similar to the original weir calibration tests (Huff, 1938, 1941a, 1941b, 1942) and was used to verify similarity of results between the two test series. Cross sections 3 and 4 represent alluvial channels being gaged on research watersheds in western Iowa, near Treynor (Minshall and Spomer, 1965; Saxton et al., 1971).

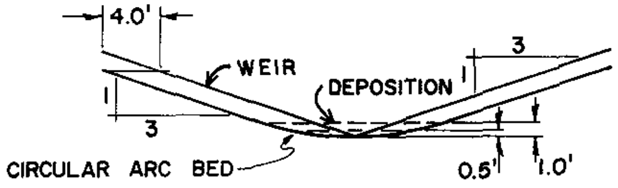
(1) RECTANGULAR CHANNEL



(2) 4:1 TRAPEZOIDAL CHANNEL



(3) 3:1 CIRCULAR BED CHANNEL



(4) 2:1 CIRCULAR BED CHANNEL

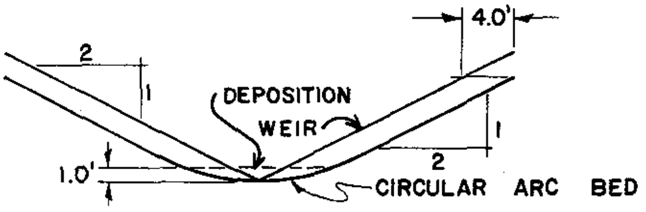


Figure 1.--Approach channel cross sections used in tests. All dimensions in prototype units (1 ft. = 0.30 m).

The effects of channel cross section at the 0.0-percent channel slope are demonstrated in Figure 2. As expected, the smaller channel cross sections caused increased flow rates due to increased approach velocities. These results compare well with those from the 1938 to 1941 tests reported by Holtan et al. (1962) which are shown as points on Figure 2.

Channel slopes of 0.0, 0.5, 1.0, 1.5, and 2.0 percent were tested for most cross sections by tilting the test flume. The rating curves in Figure 3 indicate the effects caused by channel slope. All curves are for the number 3 channel cross section (Figure 1). As expected, the channels with steeper slopes cause higher flow rates for a given head as a result of increased approach velocity. Some small irregularities in the rating curves for 1.0- and 1.5-percent slopes caused by standing waves at the measuring section were smoothed. Ratings for the 2.0-percent slope were omitted because of large irregularities caused by waves. The slope effects were not as large nor as irregular for the 4:1 trapezoid channel cross section (No. 2, Figure 1).

The effect of sediment deposition was tested by filling the channel bottom as shown by the dashed lines on cross sections 3 and 4 of Figure 1. Two deposit depths were tested for the number 3 cross section to represent 0.5 and 1.0 ft. (15.2 and 30.5 cm) depths (prototype) at the channel section 10 ft. (3.0 m) (prototype) upstream of the weir. The deposit depths were linearly reduced to zero at the weir notch and 30 ft. (9.0 m) (prototype) upstream.

The effect of deposition in the approach channel is demonstrated in Figure 4 for the 0.5 and 1.0 ft. (15.2 and 30.5 cm) (prototype) deposits in the number 3 cross section. For the 1.0-percent channel slope, the discharge for specified heads was significantly reduced by the deposit, but the effects were not consistent throughout the flow range. Deposits in the channels with less slope caused less discharge change and the results were more consistent.

Representative discharge values are given in table 1 to aid in assessing the effects of channel slope and deposition as shown by the preliminary results of figures 3 and 4. The values for 1.0-percent slope seem to provide a disproportionate discharge increase. If the discharge ratings for the 1.0- and 1.5-percent channel slopes are representative of field site situations, discharge measurements based on ratings of 0.0-percent slope may be more than 100 percent in error throughout the flow range. However, the laboratory model is probably smoother than most field sites; thus the expected error would be somewhat less, but further comparisons with field data are needed for verification.

The 1.0-ft. (30.5 cm) deposition resulted in less discharge decrease than the 0.5-ft. (15.2 cm) deposition at heads less than about 2.5 ft. (76 cm). Observations in the flume showed that the deeper deposit caused high velocities between the weir and 10 ft. (3.0 m) (prototype) upstream. An alluvial stream bed would probably not maintain this situation for any length of time.

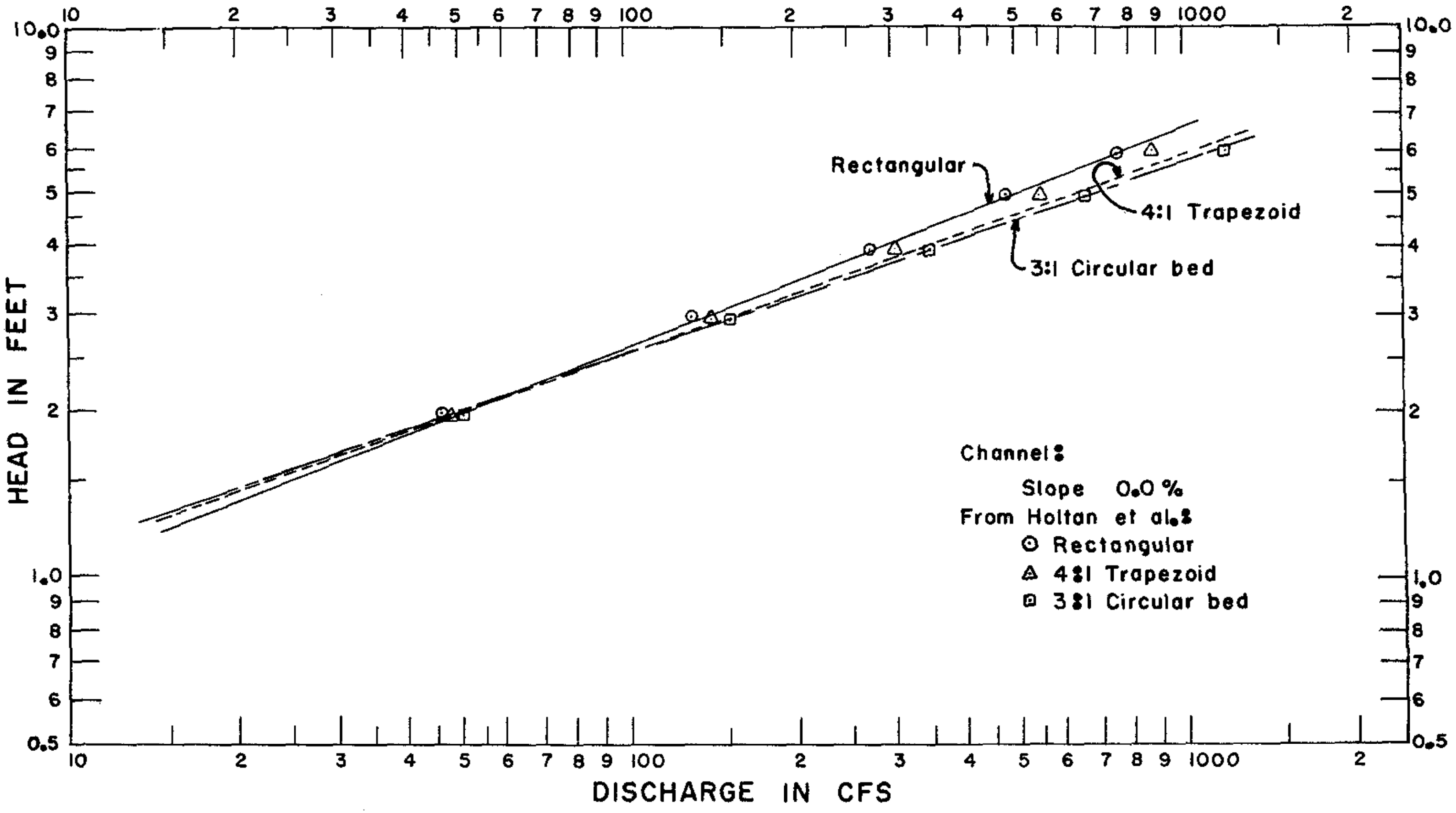


Figure 2.--The effect of approach channel cross sections on the 3-to-1 V-notch weir rating (1 ft. = 0.30 m, 1 cfs = 0.028 cms).

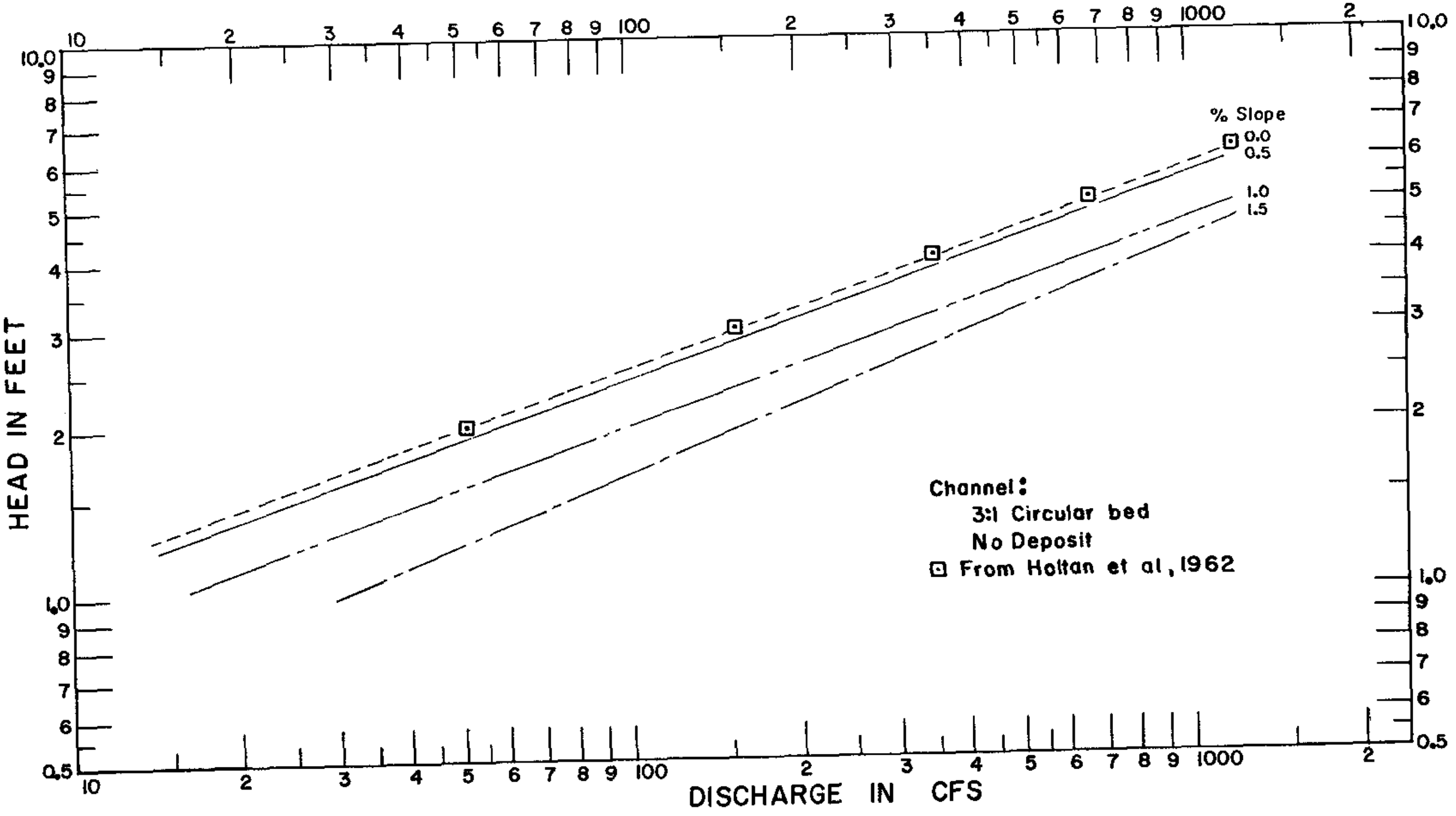


Figure 3.--The effect of approach channel slope on the 3-to-1 V-notch weir rating (1 ft. = 0.30 m, 1 cfs = 0.028 cms).

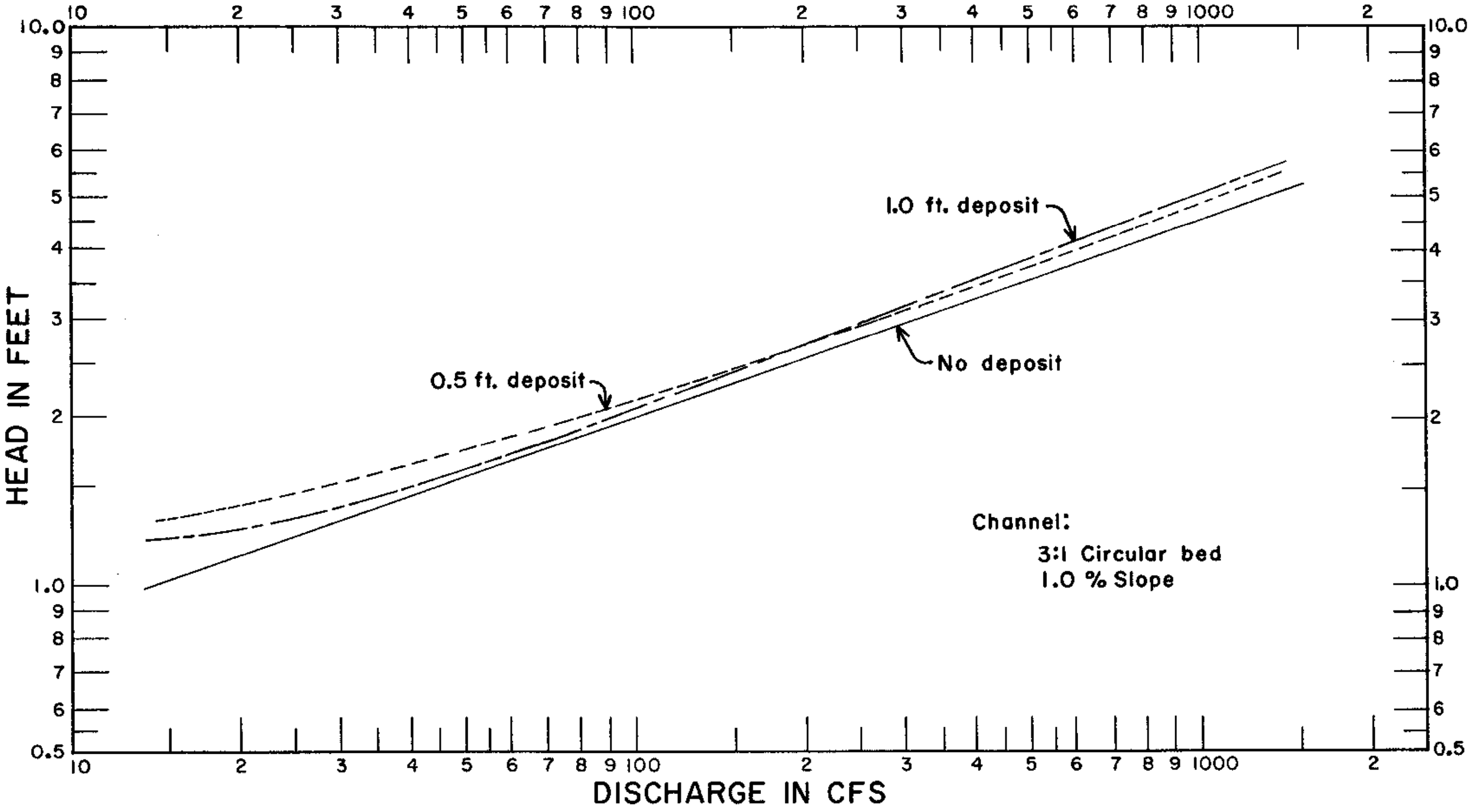


Figure 4.--The effect of deposition in the approach channels on the 3-to-1 V-notch weir rating (1 ft. = 0.30 m, 1 cfs = 0.028 cms).

Table 1--Representative discharge values for the effects of approach channel slope and deposition (1 ft.=0.30 m, 1 cfs=0.028 cms).

Head ft.	Discharge, cfs.						
	Slope, %[1]				Deposition, ft.[2]		
	0.0	0.5	1.0	1.5	0.0	0.5	1.0
2	51	58	100	160	100	81	91
3	160	180	320	440	320	280	260
4	370	420	700	890	700	610	550
5	700	790	1300	1500	1300	1050	980

[1] Circular bed channel; no deposition; values read from figure 3.

[2] Circular bed channel; 1.0% slope; deposition depth 10 ft. (3.0 m) (prototype) upstream of weir; values read from figure 4.

The test results presented in Figures 2, 3, 4, and Table 1 are samples from a large group of data. These data will be combined with those previously obtained and the results generalized for predicting weir discharge ratings for likely conditions in alluvial channels. These relationships will not provide adequate answers for situations where extreme amounts of bedload or suspended sediments are deposited in the weir approaches. They will, however, provide guidelines for predicting the head-discharge relationship for V-notch weirs installed at many alluvial streamgaging sites.

SUMMARY

Broad-crested, V-notch weirs have many characteristics that make them desirable for streamflow measurements where expected peak flow rates range from 300 to 1,000 cfs (8.4 to 28.0 cms). A weir developed by the U.S. Soil Conservation Service is often used. This weir was originally calibrated with varying approach channel cross sections but with the channel bottom level and at least 0.5 ft. (15.2 cm) below the weir notch. For alluvial streams carrying sediment, the approach channels establish a slope, and the channel bottom at the weir is usually near the notch elevation. Because the weir head-discharge relationships are dependent on approach channel conditions, any deviation from the original calibration conditions causes a rating change.

Recent model tests have been conducted to determine the effect of approach channel slope and cross section and of deposition on the ratings of these broad-crested, V-notch weirs. These laboratory results provide improved predictions for the head-discharge relationships of these weirs for many common field sites.

REFERENCES

Harrold, L. L., and Krimgold, D. B., 1943, Devices for Measuring Rates and Amounts of Runoff, USDA, Soil Conservation Service, SCS-TP-51.

Holtan, H. N., Minshall, N. E., and Harrold, L. L., 1962, Field Manual for Research in Agricultural Hydrology, Agriculture Handbook 224, USDA, Agricultural Research Service.

Huff, A. N., 1938, Tests of 16-inch Weir and Comparison with 30-inch Weir, Report No. 1, Cornell University, Section of Watershed and Hydrologic Studies.

Huff, A. N., 1941a, Calibration of 2:1 V-notch Measuring Weirs, St. Anthony Falls Hydraulic Laboratory, Minneapolis, Minnesota, Report No. MN-R-3-6.

Huff, A. N., 1941b, Calibration of 3:1 V-notch Measuring Weirs, St. Anthony Falls Hydraulic Laboratory, Minneapolis, Minnesota, Report No. MN-R-3-8.

Huff, A. N., 1942, Calibration of 3:1 and 5:1 V-notch Measuring Weirs, Supplement to Calibration of 2:1 V-notch Measuring Weirs, St. Anthony Falls Hydraulic Laboratory, Minneapolis, Minnesota, Report No. MN-R-3-7.

Kindsvater, C. E., and Carter, R. W., 1959, Discharge Characteristics of Rectangular Thin-plate Weirs, Transactions of the American Society of Civil Engineers, 124, 772-822.

Minshall, N. E., and Spomer, R. G., 1965, New Type Weir Construction for Small Watersheds, Proceedings of the American Society of Civil Engineers, 91(IR1), 11-15.

Saxton, K. E., Spomer, R. G., and Kramer, L. A., 1971, Hydrology and Erosion of Loessial Watersheds, Proceedings of the American Society of Civil Engineers, 97(HY11), 1835-1851.

TEN YEARS OF EXPERIENCE WITH AUTOMATIC PUMPING-SEDIMENT SAMPLERS

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ABSTRACT

The U. S. Geological Survey has used pumping-sediment samplers to study the sediment transport characteristics of small streams in Maryland for the last 10 years. Four different samplers developed by the Federal Inter-Agency Sedimentation Project were used to sample suspended sediment on five streams with drainage areas ranging from 1.2 to 54.6 square kilometres (0.47 to 21.1 square miles). A PS-62 sampler has been in continuous operation since its installation in 1966. The sampler provided satisfactory coverage for 139 of 220 storms between 1966 and 1975. Installation of a streamlined intake structure, commercial electrical power, and in-line battery chargers increased the reliability of the sampler from 32 percent in 1969 to 84 percent in 1973. It is estimated that the latest version of pumping samplers, the PS-69, would provide reliable service during 90 percent of the storms if the installation were properly designed and maintained.

INTRODUCTION

Assessing sediment problems related to residential and highway construction, agriculture, mining, and other activities, may require extensive sediment sampling programs. These activities generally have the greatest impact on small drainage basins, in which it is impractical and often impossible to obtain sufficient basic data through hand sampling. On remote or flashy streams there is often insufficient time for personnel to collect the samples needed to define the temporal variation in sediment concentration. Pumping samplers have been used successfully by the U. S. Geological Survey to study the effects of urban development on the sediment transport characteristics of small streams in Maryland. This paper summarizes the operation of these samplers and presents some ways of obtaining reliable service from them.

Pumping samplers were operated at five sites in the headwaters of the Rock Creek and Anacostia River basins near Washington, D. C., between 1966 and 1975. Drainage areas upstream from the sites ranged from 1.2 to 54.6 km^2 (square kilometres) or 0.47 to 21.1 mi^2 (square miles). In order to define the seasonal variation of sediment discharge, it was necessary to operate the samplers on a year-round basis.

Long-term climatic records indicate that precipitation averages about 1,070 mm/yr (millimetres per year) or 42 in/yr (inches per year) and is evenly distributed throughout the year. Average monthly precipitation ranges from 71 mm (2.8 in) in February to 124 mm (4.9 in) in August. Much of the summer precipitation comes in short, high intensity rainfalls from convective storms, where as winter precipitation generally comes in low intensity rains from frontal storms. Winters are cold enough to cause freeze-related problems with sampler operations, but are generally not cold enough to cause the streams to ice over for extended periods. Normal minimum temperatures are above freezing except in December, January, and February.

The physiographic and soil conditions of the study area are generally suitable for suspended sediment sampling with pumping samplers. The size distribution of sediment averages 21 percent sand, 45 percent silt, and 34 percent clay. This distribution closely approximates that of the silt loam and silty clay loam soils typical of the drainage basins. Channel slope and roughness and bed-material particle size are such that most of the sediment is transported in suspension. In one basin, the unmeasured bedload was computed as being 5 and 12 percent of the suspended load, using the Meyer-Peter Muller and Schoklitsch bedload formulas, respectively.

DESCRIPTION OF SEDIMENT SAMPLER INSTALLATIONS

Most of the different types of pumping-sediment samplers developed by the Federal Inter-Agency Sedimentation Project were used at the Maryland sites. These included PS-62, PS-66, PS-67, and PS-69 samplers (fig 1). Although numerous changes and improvements were designed into each newer version of sampler, the basic operating sequence remained essentially as follows: (1) Sampler accepts a signal from trigger mechanism, which initiates one sampling cycle. The trigger mechanism can be a time-clock switch, change-of-stage switch, proportional frequency controller, or any other device that provides an electrical impulse to the sampler (Federal Inter-Agency Sedimentation Project, 1974). The Pennsylvania District of the U. S. Geological Survey has used a turbidimeter to trigger a PS-69 sampler (J. F. Truhlar, written commun., 1975). (2) Intake line is reverse-flushed from a reservoir by gravity or pump to clear the intake of debris and prime the pump. (3) Pump draws water from stream to refill flushing reservoir. (4) Part of water-sediment mixture is diverted or trapped for storage in individual sample bottles. (5) Sample-event marker records time of sampling on stage recorder or a separate recording device. (6) Sampler advances to next bottle position and resets to accept the next signal from the trigger mechanism.

A general description of each of the five sampler installations in Maryland is given in the following section to illustrate the basic differences between the samplers and the type of installations required for each.

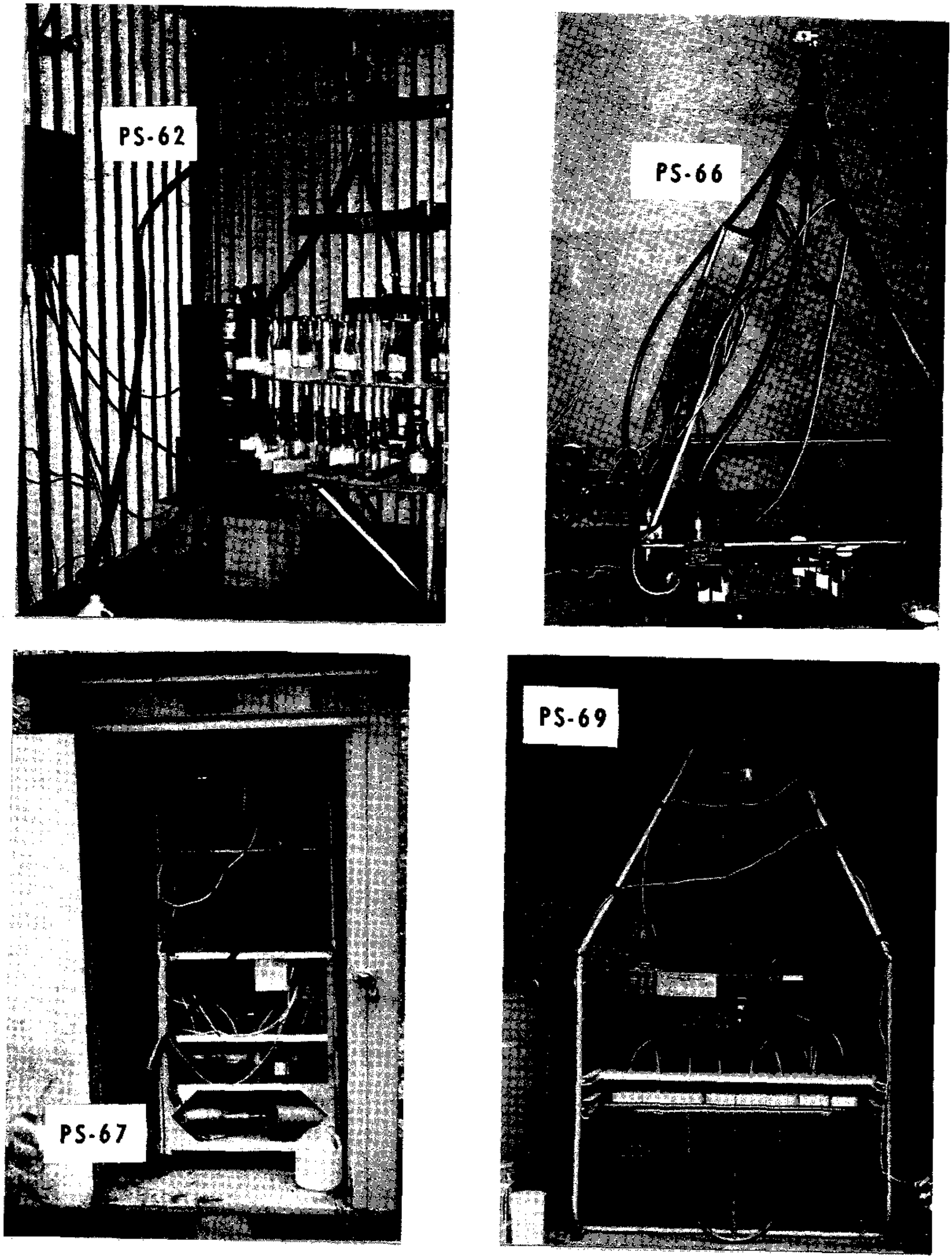

Figure 1. General view of four different automatic pumping samplers used to collect suspended-sediment samples.

PS-62

A PS-62 sampler is located on a stream draining 54.6 km^2 (21.1 mi^2). The sampler (144-bottle capacity) is powered by three 12-volt storage batteries and is housed in a 2.4- x 3.0-m (metre) or 8.0- x 10.0-ft (foot) steel shelter. Several intakes are built into a reinforced concrete retaining wall at the stream bank (fig. 2a). The lower intake, 0.3 m (1 ft) above the bed, is used most of the time. Commercial electrical power is used to heat the house and to charge the storage batteries. The digital recorder feeler-arm assembly, which is usually used with a binary decimal transmitter for telemetering gage heights from remote sites, is used to trigger the sediment sampler. When the stage exceeds a specified level, contacts on the feeler-arm assembly close to initiate a sample cycle each time the recorder punches. This single component eliminates the need for a float switch, sample-event marker, and a separate timing mechanism, that are standard equipment with the PS-62 sampler.

PS-66

A PS-66 sampler is located at the outfall of a multiple-purpose reservoir (fig. 2b). The sampler has the same capacity and power requirements of the PS-62 sampler. The shelter and intake structure are the same as previously described. Commercial electricity is available. This site could be sampled manually, but, because of access problems, baseflow sample needs, and sampling priorities within the immediate area, a pumping sampler is used to collect samples. A time clock triggers once-daily samples during base flow periods and two or four samples per day during periods of high runoff. This variable sampling frequency is built into the logic circuit of the sampler and is adjustable, depending on the user's requirements.

PS-67

Two PS-67 pumping samplers were installed on small streams draining areas undergoing extensive urban development. The 48-bottle-capacity samplers are powered by three 12-volt storage batteries and are housed in 1.2- x 1.2-m (4.0- x 4.0-ft) steel shelters. The shelters have 25-mm (1-in) marine plywood floors and are supported by 2 tiers of 200- x 250-mm (8- x 10-in) pressure-treated timbers. Only battery power is available at each site.

One sampler is located at the outlet of a stream enclosure (fig. 2c). The drainage area is 1.2 km^2 (0.47 mi^2). Stage recording equipment and the sampler intake are mounted on the headwall of the enclosure. Samples are triggered by a change-in-stage switch on the back of the digital recorder. The mechanism consists of a fixed reed switch, which closes to trigger one sample cycle as magnets attached to the float wheel rotate past the switch. Magnets are spaced to trigger the sampler each time the stage rises or falls 76 mm (0.25 ft). A stop-pin in the stilling well prevents the recorder float from falling

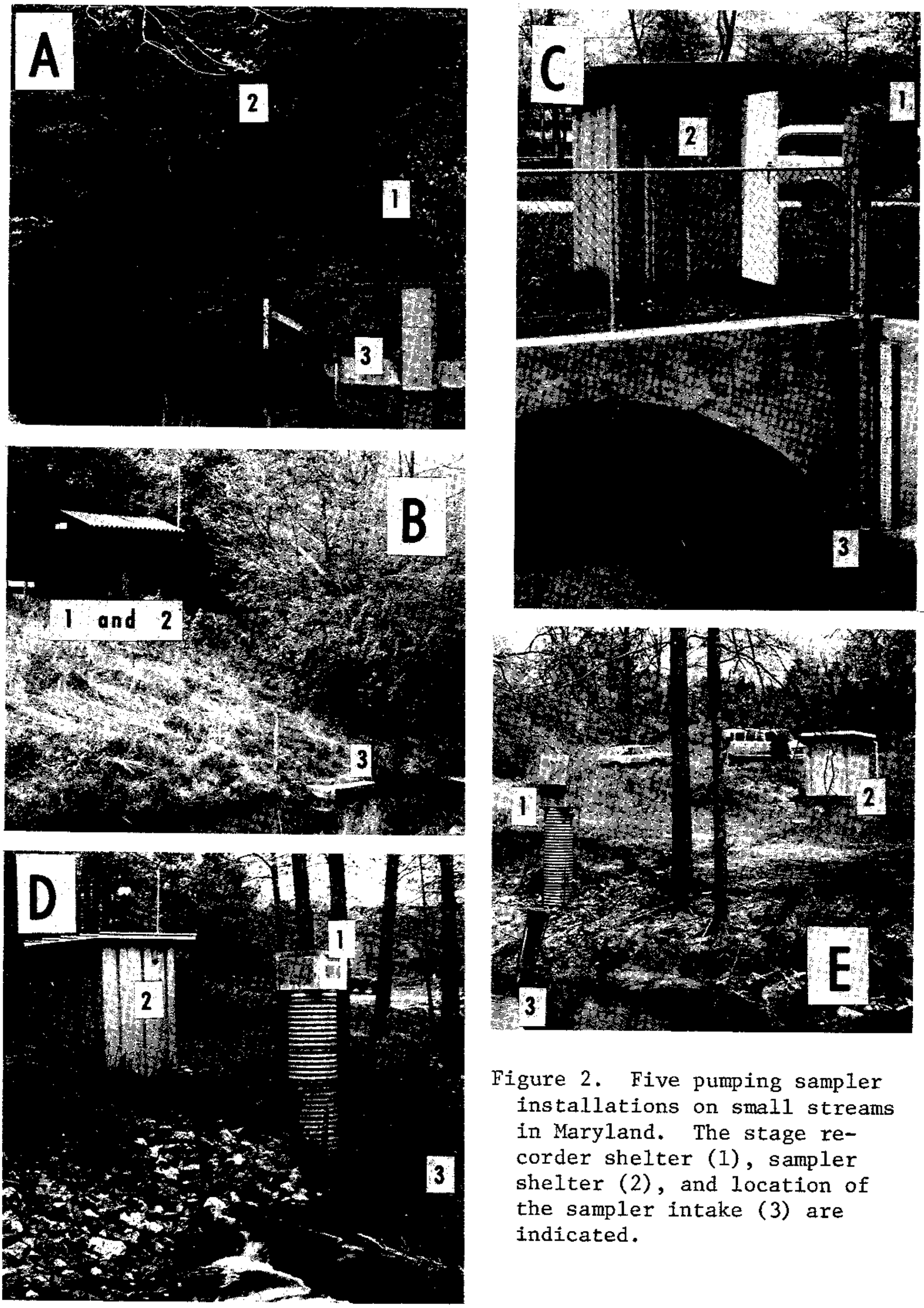

Figure 2. Five pumping sampler installations on small streams in Maryland. The stage recorder shelter (1), sampler shelter (2), and location of the sampler intake (3) are indicated.

below the sampler intake level, eliminating the need for a float switch. A memory-latch circuit in the sampler stores a signal from the change-in-stage switch until the recorder punches. The sampler starts when the recorder punches, and the time of the sampling is recorded on the stage tape by a sample-event marker.

The other PS-67 sampler was used on a stream with a drainage area of 5.83 km^2 (2.25 mi^2). The intake at this site was attached to a steel stake near the right bank. A wooden box housing single-stage samplers deflected debris from the intake (fig. 2d). A combination of a change-in-stage switch and a clock switch was used to trigger samples. When the stage exceeded the level of the float switch mounted in the stilling well, samples were triggered at 150-mm (0.5-ft) intervals by the change-in-stage switch and every 4 hours by the time clock. The memory latch and event marker previously described were also used.

PS-69

The PS-69 sampler is the latest model pumping sampler used in Maryland. It is installed on a stream draining 25.2 km^2 (9.73 mi^2), and is currently being operated to sample storm loads only (fig. 2e). The sampler (72-bottle capacity) is powered by three 12-volt storage batteries and is housed in a 1.8- x 2.4-m (6.0- x 8.0-ft) steel shelter insulated with fiberglass and plywood. The shelter is supported by treated timbers. Commercial electrical power is available for charging batteries and heating the shelter in the winter. The intake is housed in an upright section of reinforced concrete pipe buried in the channel near the left bank. Change-in-stage and clock switches, a memory latch, and a sample-event marker are used to signal and identify samples.

RELIABILITY OF SAMPLERS

The PS-62 sampler was installed at the Northwest Branch Anacostia River near Colesville, Md., in 1966 and has remained in continuous use since that time. It was set up to sample only during storms, as more than 95 percent of the annual sediment load is transported during storms. The sampler has provided good coverage of storms, particularly intense, short-duration thunderstorms, which would have been difficult to sample otherwise (fig. 3).

Between June 1966 and March 1975 there were 220 storms large enough to activate the PS-62 sampler. It provided adequate coverage during 139 storms (63 percent). During the other 81 storms, the sampler either failed completely or failed during the storm, resulting in inadequate definition of sediment concentration. The causes of failures are listed in Table 1. Thirty percent of the failures are attributable to mechanical or functional problems with one of the sampler components, including worn out pump impeller, loose pulleys on the pump, leaks in the flush tank, misalignment of flush-tank plug, and excessive friction

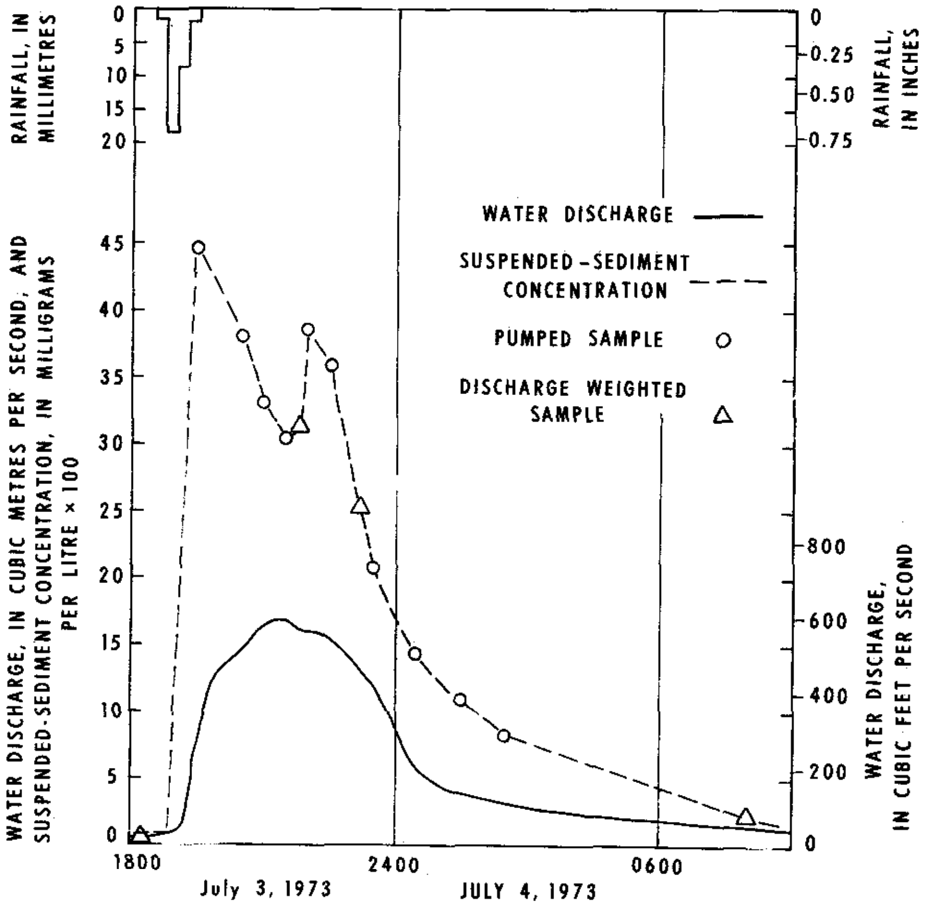

Figure 3. Variation of precipitation, water discharge, and suspended-sediment concentration during a typical summer storm, Northwest Branch Anacostia River near Colesville, Md.

or misalignment of the table-advance mechanism. Other significant problems encountered were weak batteries, frozen intake lines or flush tank, and failure of the sample-signalling device.

Many of the recurring problems were gradually eliminated as experience with the samplers increased. For example, 8.8 percent of the total sample failures for the 10-year period were the result of plugged intakes between 1966 and 1968. The intake was originally attached to steel stakes in the center of the channel. In this location the intake collected debris, which allowed backflushing, but prevented water from entering the intake line to refill the flush tank. Once the tank was emptied, the pump could not be primed for subsequent samples. This problem was eliminated completely when the intake was installed in the retaining wall shown in Figure 2a. The streamlined nature of the wall prevented debris from accumulating on the intake. This type of installation has been recommended by the Sedimentation Project (Federal Inter-Agency Sedimentation Project, 1966).

Table 1. Summary of sample failures, PS-62 pumping-sediment sampler, June 1966 to March 1975.

Cause of Failure	Sample Failures
	Total failures, in percent
Mechanical	30.4
Frozen pump, flush tank, or intake lines	16.9
Recorder (signalling device) malfunction	16.9
Weak power source	16.5
Operator error	9.1
Plugged intakes	8.8
Capacity of sampler exceeded	.8
Vandalism	.6

Another change that significantly improved the sampler operation was the installation of commercial electrical power. This provided the capability for heating the shelter and for charging a spare set of batteries at the site. Heating of the shelter eliminated most of the failures associated with freezing. Having a spare set of fully charged batteries significantly reduced the number of failures due to weak batteries. Problems with weak batteries were eliminated after individual, in-line battery chargers were installed in 1972.

Increased operator experience and a standard testing and maintenance procedure also improved the reliability of the sampler. The sampler was serviced after each storm and during monthly inspections of the stage-recording equipment. During each servicing, the batteries were checked, the different phases of the sample cycle were timed, and the sampler was reset and tested. Moving parts of the equipment were oiled and greased or replaced as required. Inspections by experienced personnel other than those responsible for routine servicing were also made at regular intervals. Deficiencies or potential problems overlooked by the regular operator were often noted during these inspections.

The improvement in sampler operation between 1966 and 1975 is illustrated by figure 4. The sampler improved from a 32 percent success rate in 1969 to 84 and 81 percent in 1973 and 1974, respectively. Most of this improvement is attributable to in-line battery chargers that maintained the batteries at full charge throughout the year. The chargers were particularly helpful in the winter, when lower operating temperatures required higher current output.

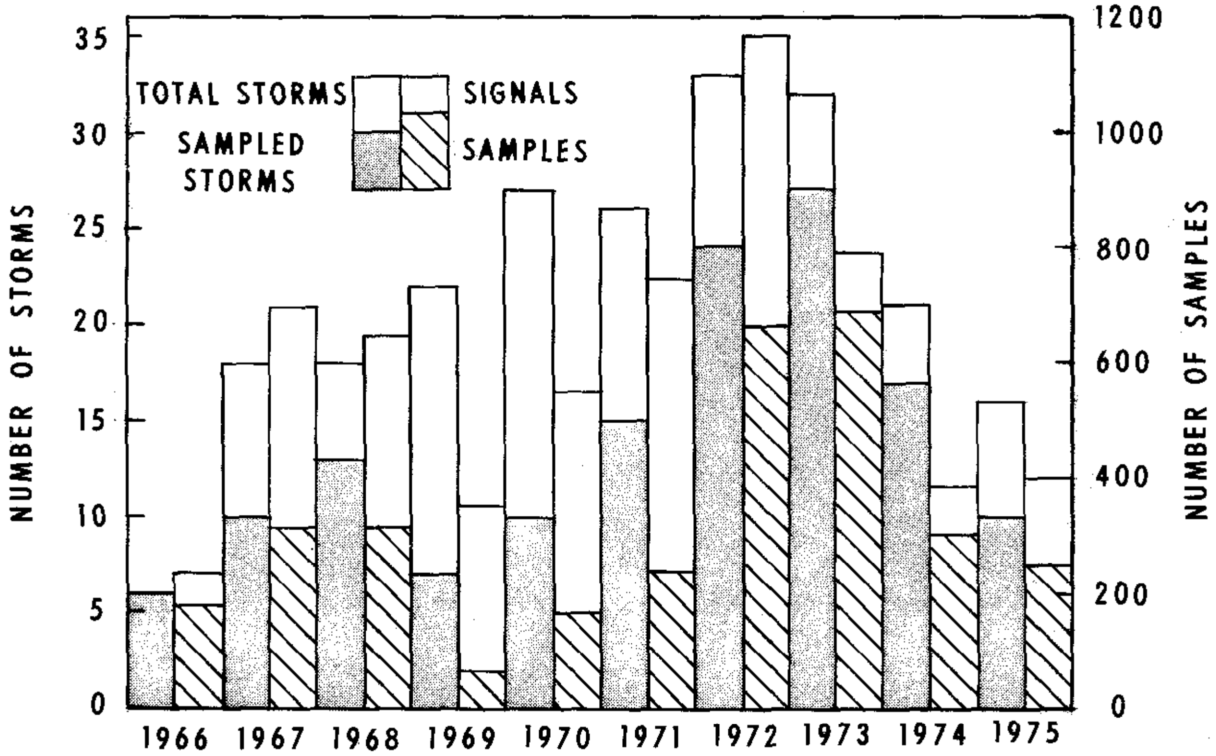

Figure 4. Reliability of the PS-62 pumping sampler, as indicated by the number of sampled storms and the total number of samples collected, 1966-75.

The efficiency of the PS-62 pumping sampler was considered to be very good. Simultaneous pumped samples and discharge-weighted (equal transit rate) samples were consistent throughout the period. Forty-three samples ranging from 20 to 3,300 mg/l (milligrams per litre) were used to calibrate the sampler (fig. 5). The pumped samples adequately defined the mean concentration of the section except for concentrations below 100 mg/l. The higher concentration in low-stage pumped samples is probably attributable to the higher velocities immediately adjacent to the intake wall. Fine sand particles in suspension in this part of the section are not representative of the entire cross section.

Because of the 1:1 relation between concentrations of pumped and discharge-weighted samples, no adjustments to the pumped-sample concentrations were required. The difference between the pumped and discharge-weighted samples below 100 mg/l was not a problem because the concentration in this range generally was defined by hand samples. Note that the channel characteristics and the sediment properties favored uniform mixing in the cross section. Comparable results may not be obtained in other areas.

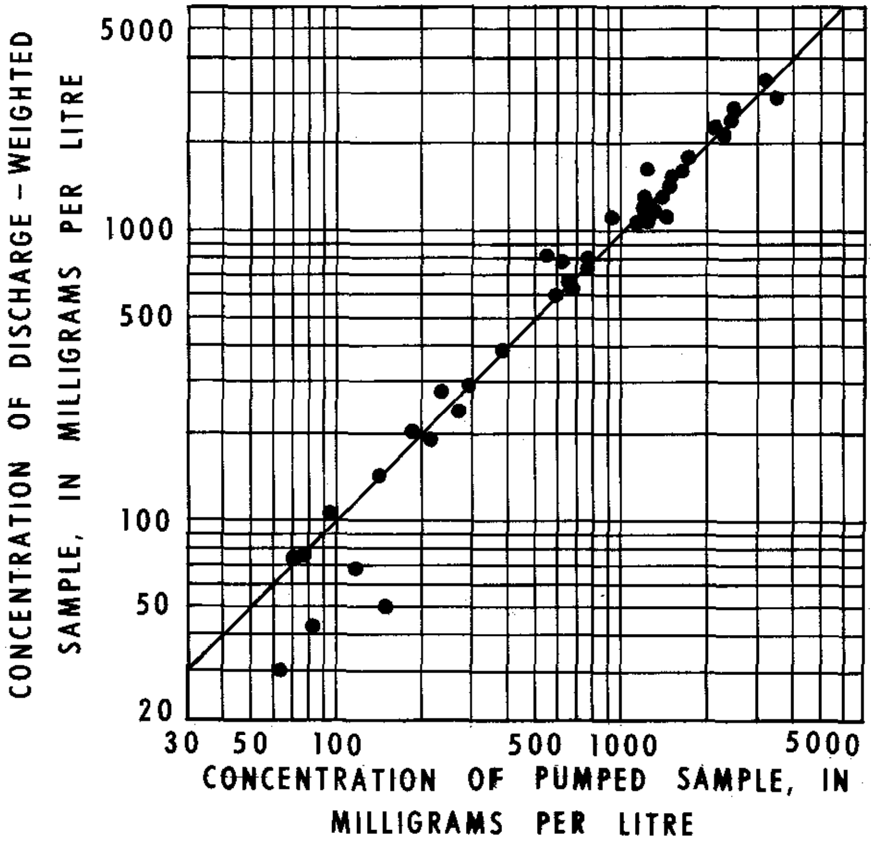

Figure 5. Relation between the concentration of discharge-weighted and pumped samples, Northwest Branch Anacostia River near Colesville, Md., 1966-75.

The reliability of the other pumping samplers varied, depending on site conditions. The PS-66 sampler gave very good service, particularly after individual battery chargers were installed to maintain the batteries at full charge. Most of the failures with this sampler were associated with misaligned switches that controlled the position of the sampler nozzle in a rectangular grid. The PS-69 sampler has provided very reliable service during its short period of use. There have been some problems with the memory latch unit, resulting in a greater number of samples than required for defining the sediment concentration. This sampler probably would provide adequate sample coverage for 90 percent of the storms if commercial electrical power were available and the intake structure were properly designed.

The PS-67 samplers operated well in the spring and summer. There were some instances of intake plugging, but otherwise the samplers operated satisfactorily as long as the batteries were recharged at regular intervals. Winter operation of these samplers without electricity for heating shelters and charging batteries was not practical. Antifreeze was used in the flush tank and intake lines for two winters, but on many occasions a small rise would signal a sample, the antifreeze would flush out, and the water remaining in the pump would freeze before the sampler could be serviced. After replacing cracked pump caps many times, winter operations were discontinued. The need to recharge batteries at weekly intervals in cold weather also contributed to the discontinuance of winter operations at sampler installations without electricity.

SUMMARY

Ten years of experience with automatic pumping-sediment samplers in Maryland shows that they can be a valuable tool for sediment investigations. They are particularly useful on small flashy streams where there is insufficient warning time to obtain manual samples. A PS-62 sampler was used for storm coverage on a stream draining 54.6 km^2 (21.1 mi^2) between 1966 and 1975. The sampler operated satisfactorily for 139 of 220 significant storms. The addition of commercial electrical power and an improved intake structure increased the sampler reliability from 32 percent in 1969 to 84 percent in 1973. Calibration samples collected between 1966 and 1975 indicate that pumped samples accurately represented the mean sediment concentration of the stream.

Other samplers developed by the Federal Inter-Agency Sedimentation Project provided service equal to or better than the PS-62 sampler. Limited experience with the PS-69 sampler indicates that it probably would be reliable 90 percent of the time if the installation were properly designed and adequately maintained. To assure reliable service from any pumping-sediment sampler a sampler installation needs to include the following: (1) A streamlined intake structure to prevent debris accumulation and intake plugging; (2) Commercial electrical power and battery chargers to maintain the batteries at full charge; (3) A heated, well-insulated shelter to prevent freeze-ups and excessive battery drain in the winter (as dictated by climate). A standard maintenance and testing procedure during servicing also needs to be established for each installation.

REFERENCES

Federal Inter-Agency Sedimentation Project, 1966, Progress Report - Laboratory Investigation of Pumping-Sampler Intakes, Report T: Washington, D. C., 59 p.

_______________________________________ 1974, Catalog - Instruments and Reports for Fluvial Sediment Investigations: Washington, D. C., 61 p.

DETERMINING SUSPENDED SEDIMENT LOADS FROM TURBIDITY RECORDS

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ABSTRACT

The Pennsylvania Department of Transportation and the U.S. Geological Survey are cooperating in several field studies to evaluate sediment-control measures used during highway construction. Among the parameters being monitored are suspended-sediment concentration and turbidity. Sediment loads are calculated from suspended-sediment and water-discharge data, but some sediment loads must be determined indirectly because it is virtually impossible to obtain sufficient suspended-sediment samples to define all runoff conditions adequately. Sediment discharge-water discharge correlation curves have proved unreliable for streams affected by highway construction, so an alternate method using the turbidity record was developed during these studies.

The field data reveal a good correlation between daily mean discharge-weighted turbidity and daily mean discharge-weighted suspended-sediment concentration. Turbidity is monitored and recorded continuously, and the daily mean discharge-weighted turbidity is calculated from the turbidity and water-discharge data. During periods when there are insufficient suspended-sediment data, the daily mean discharge-weighted suspended-sediment concentration is determined from the turbidity-sediment correlation and used with the daily mean water discharge to calculate a daily sediment load.

This method of determining sediment loads from the turbidity record suggests a possibility for computer computation of sediment loads. Instrumentation now in use for recording water-quality parameters on digital-punch tape could be used to record the output from a turbidimeter. Then, for streams having a good correlation between suspended-sediment concentration and turbidity, simultaneous water-discharge and turbidity data could be used to determine sediment loads by computer.

INTRODUCTION

The U.S. Geological Survey, in cooperation with the Pennsylvania Department of Transportation, has been collecting suspended-sediment and turbidity data in streams affected by highway construction to evaluate the effectiveness of various erosion-control and sediment-control measures. Determining the suspended-sediment discharges in each of these streams is an essential part of these studies. One problem encountered in computing suspended-sediment discharges is the difficulty in estimating loads for periods when suspended-sediment data are not available.

Erosion and fluvial sediment movement from construction areas are highly variable and much greater than normal. Sediment discharge-water discharge correlation curves are not reliable for estimating suspended-sediment discharge under these conditions. This paper presents a method for determining suspended-sediment loads based on the correlation between daily mean discharge-weighted suspended-sediment concentration and daily mean discharge-weighted turbidity.

EQUIPMENT

Gaging stations for the sediment-control studies are equipped with digital and graphic stage recorders, automatic sediment samplers, and continuously operating surface-scatter turbidimeters with strip-chart recorders. The turbidimeters have been modified to change ranges automatically, so that the turbidity record is well defined at both low and high turbidity. A part of the turbidity record for September 13-14, 1974, obtained at one of the gaging stations, is shown in figure 1. Discontinuities occur where the turbidimeter switched ranges, first from the 0-1000 range to the 0-100 range on the upper strip chart, then back to the 0-1000 range on the lower strip chart, and finally back again to the 0-100 range.

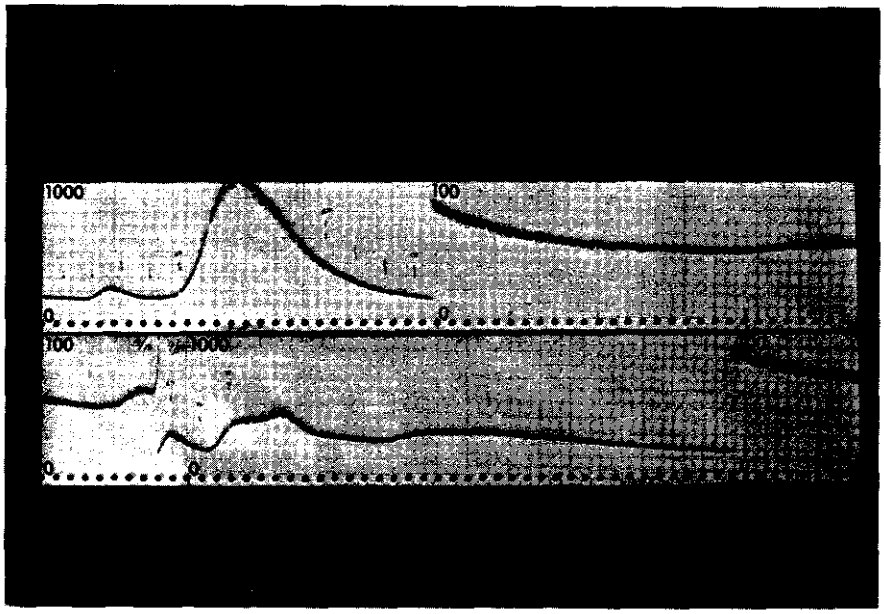


Figure 1.--Part of continuous-turbidity record showing three automatic range changes. Tick marks indicate when suspended-sediment samples were collected by automatic sampler.

The turbidimeter provides a signal that activates the automatic sediment sampler when the turbidity rises above a pre-set level. A small lamp added to the turbidimeter is wired so that it lights each time the sediment sampler collects a sample. This causes an apparent increase in turbidity, which marks the turbidity record, as can be seen in figure 1. Also, the time of sampling is marked on the graphic-stage record by draining a portion of the water circulated through the sediment sampler into the stilling well.

COMPUTATION OF RECORDS

During periods when suspended sediment data are available, sediment discharge is computed on a daily basis according to the methods described by Porterfield (1972). Daily mean discharge-weighted suspended-sediment concentration and daily mean discharge-weighted turbidity are computed as shown below:

$$C_w = \frac{\Sigma (tqc)}{Q_w T} \qquad (1)$$

or

$$C_w = \frac{Q_s}{Q_w k} \qquad (2)$$

$$J_w = \frac{\Sigma \ (tqj)}{Q_w T} \qquad (3)$$

where

C_w = daily mean discharge-weighted suspended-sediment concentration

t = time interval of a sub-divided day

q = mean water discharge during time interval t

c = mean suspended-sediment concentration during time interval t

Q_w = daily mean water discharge

$T = \Sigma t$ (24 hrs)

Q_s = daily suspended-sediment load

k = constant (0.0864 for Q_s in tonnes and Q_w in cubic metres per second, and 0.0027 for Q_s in tons and Q_w in cubic feet per second)

J_w = daily mean discharge-weighted turbidity

j = mean turbidity during time interval t.

The methods for determining t, q, and c are explained by Porterfield (1972). The value j is obtained from a turbidity-time graph in the same way that c is determined from a concentration-time graph.

When insufficient data are available to develop a concentration graph, the turbidity graph can be used with the corresponding hydrograph to determine a daily mean discharge-weighted turbidity. The daily mean discharge-weighted suspended-sediment concentration can then be determined from the correlation between turbidity and suspended-sediment, and suspended-sediment discharge can be computed by the formula:

$$Q_s = Q_w C_w k \qquad (4)$$

CONCENTRATION-TURBIDITY CORRELATION

The correlations between daily mean discharge-weighted suspended-sediment concentration and daily mean discharge-weighted turbidity for several streams below areas of active highway construction are shown in figure 2. The sediment discharge-water discharge correlation for each stream is also shown for comparison. The superiority of the concentration-turbidity correlation is easily apparent in the slope as well as in the smaller amount of scatter. Thus, turbidity-concentration relations are more accurate than sediment discharge-water discharge curves in determining daily loads.

Not all of the scatter in these sediment discharge-water discharge correlations is the result of highway construction. Concentration-turbidity correlations and sediment discharge-water discharge correlations for two streams not affected by construction are shown in figure 3. These graphs show about the same scatter as those for the streams affected by construction.

DISCUSSION

There is no universal relationship between turbidity and suspended-sediment concentration, but there is often a good correlation for individual streams, probably because the material in suspension in a stream is a characteristic of the basin. It seems reasonable to expect a better correlation between turbidity and suspended-sediment concentration than between water discharge and suspended-sediment discharge because turbidity and suspended-sediment concentration respond similarly to many factors that are not directly related to water discharge. For example, in a highway construction area the quantity of sediment entering a stream is not necessarily related to runoff but may be related to earthmoving near the stream.

Water discharge and suspended-sediment concentration may not correlate well for many reasons (Gregory and Walling, 1973). Poor correlation for the two streams not affected by construction results partly from influences such as occasional grading of dirt and gravel roads and dairy farming. Variations in the magnitude and rate of water-discharge increase also have a great effect on sediment concentration and load. No seasonal effects are apparent for these streams, but the hysteresis effect is very obvious, both for individual storms and for storm periods lasting several days.

A continuous turbidity record makes it possible to develop good sediment-discharge records with fewer sediment samples than might otherwise be needed because there is a good correlation between turbidity and suspended-sediment concentration for many streams. It greatly increases the reliability of pro-rated concentrations determined from intermittent samples and also helps in shaping concentration graphs during storm periods.

Turbidity records might also be used for determining suspended-sediment discharges by computer methods for streams where there is a good correlation between turbidity and suspended sediment. Instrumentation presently available could be used to record turbidity on digital tape. This record and the turbidity--suspended-sediment relationship could be used in conjunction with water-discharge records for computer computation of sediment loads. Naturally, it would still be necessary to obtain enough suspended-sediment and turbidity data to develop a correlation and to verify it occasionally. Loss of accuracy in determining sediment loads by using the correlation between sediment and turbidity rather than by conventional methods would have to be evaluated. This could be complicated by the fact that the absolute accuracy of computed loads is unkown because there are many uncertainties in sampling for and computing sediment loads by conventional methods (Guy, 1970).

Disadvantages of obtaining turbidity records are that turbidimeters require 120 VAC and that the pumps and intakes require frequent maintenance. A disadvantage of using the turbidity-concentration correlation to determine sediment discharges is that the correlation may become poorer as the percentage of sand in the sediment mixture increases.

REFERENCES

Gregory, K. J., and Walling, D. E., 1973, Drainage basin form and process: New York, John Wiley and Sons, 456 p.

Guy, H. P., 1970, Fluvial sediment concepts: U.S. Geol. Survey Techniques Water-Resources Inv., book 3, chap. C1, 55 p.

Porterfield, George, 1972, Computation of fluvial-sediment discharge: U.S. Geol. Survey Techniques Water-Resources Inv., book 3, chap. C3, 66 p.

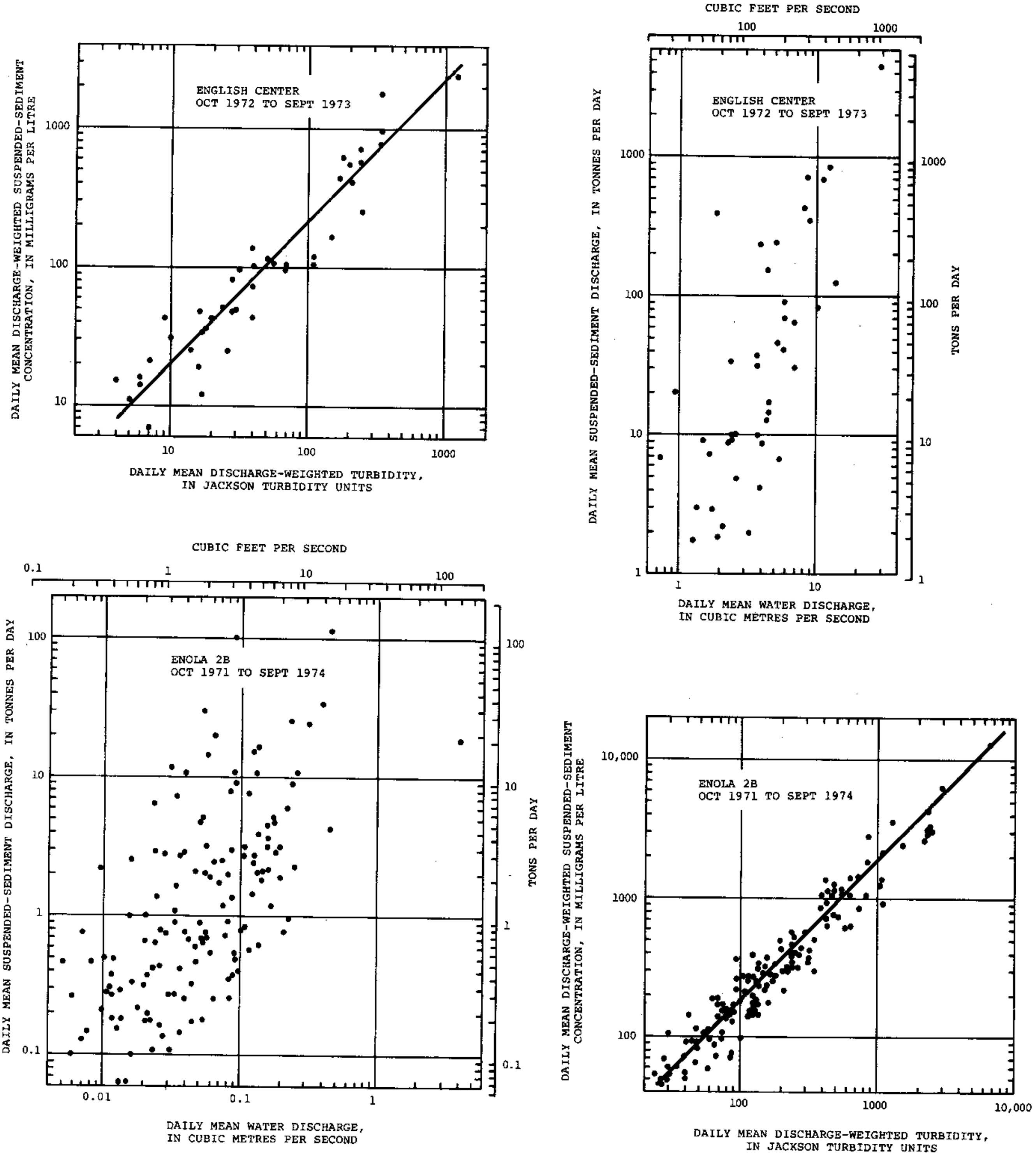
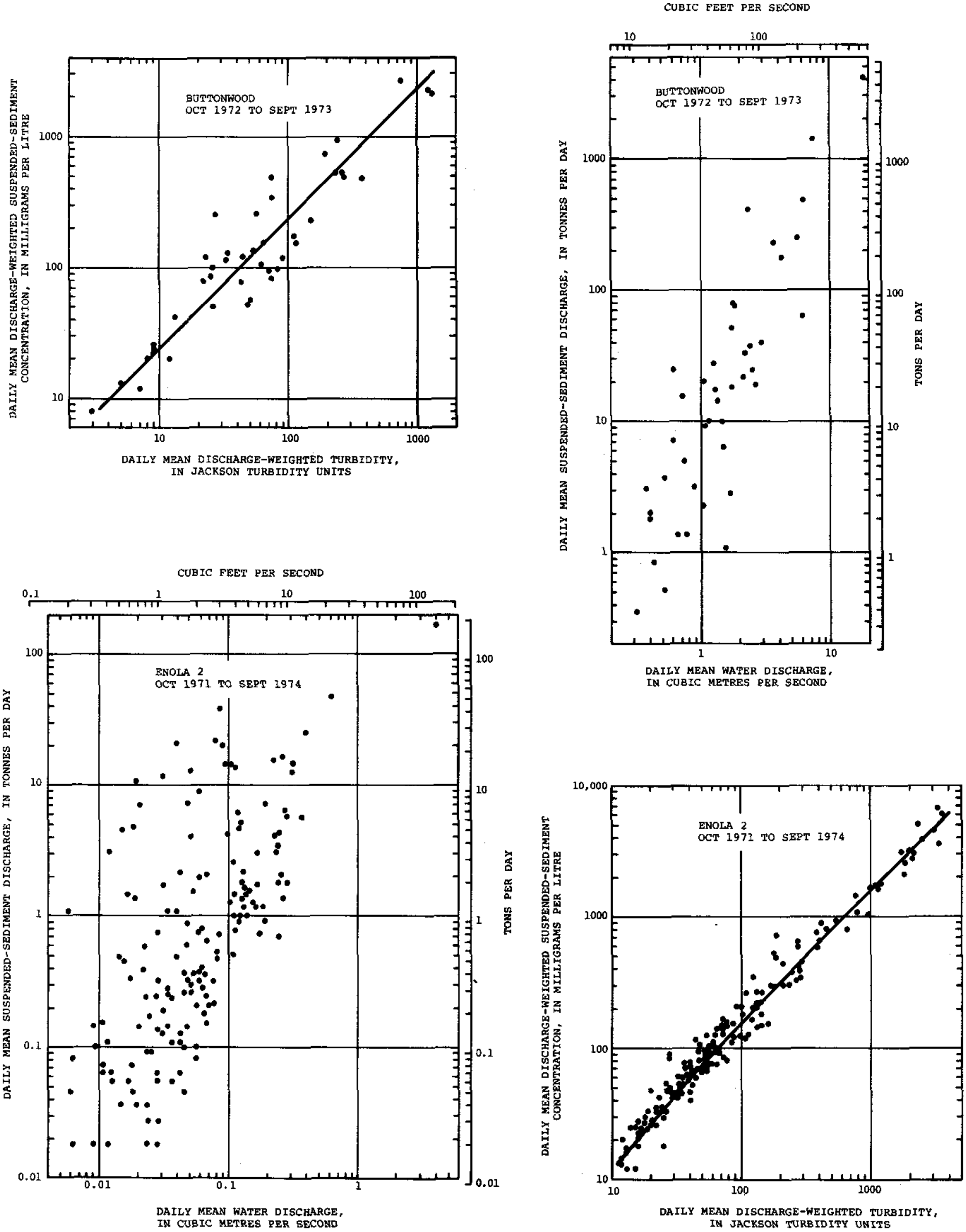


Figure 2.--Correlation of daily mean discharge-weighted suspended-sediment concentration with daily mean discharge-weighted turbidity compared with sediment discharge-water discharge correlations for several streams affected by highway construction.



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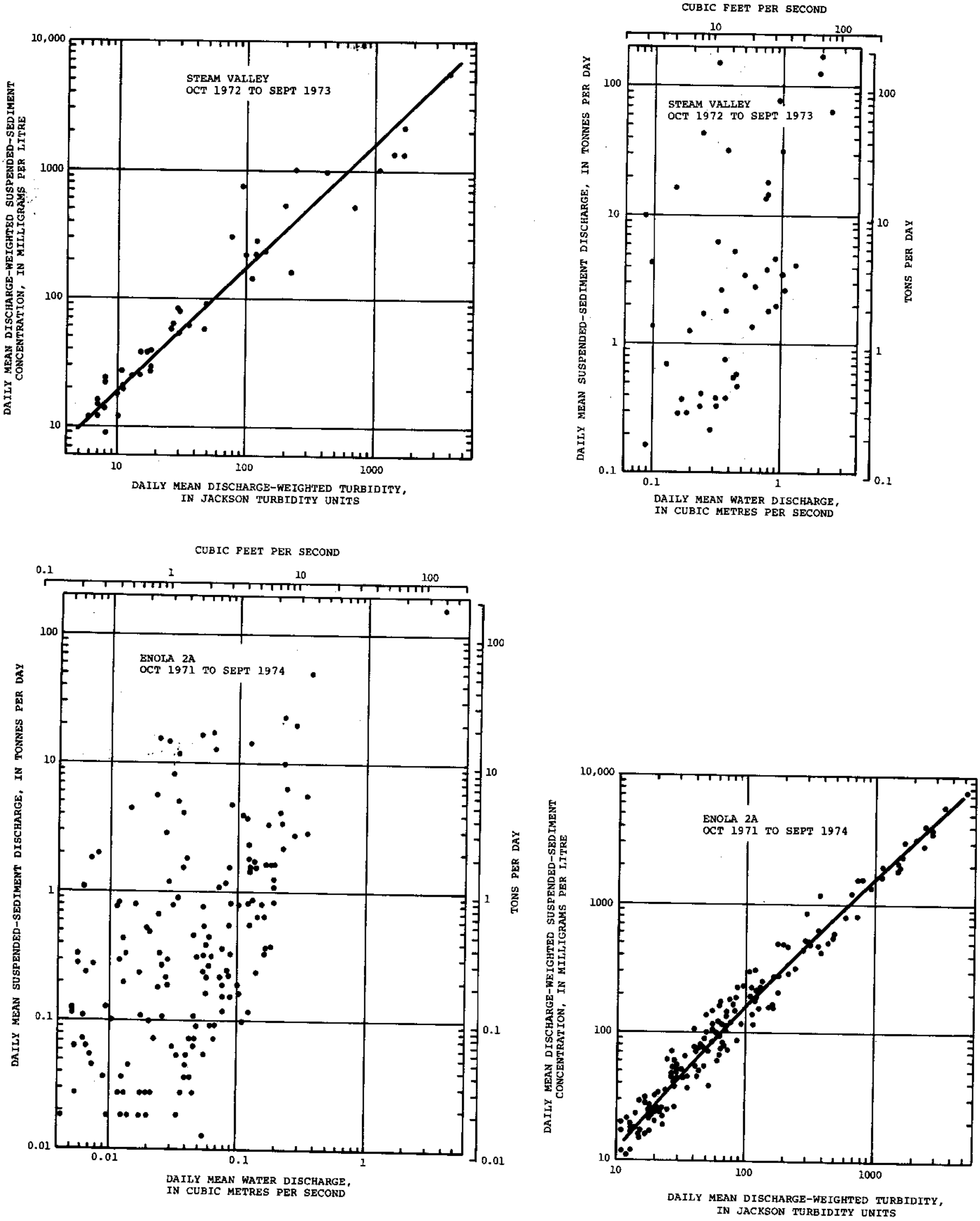

Figure 2.--Continued

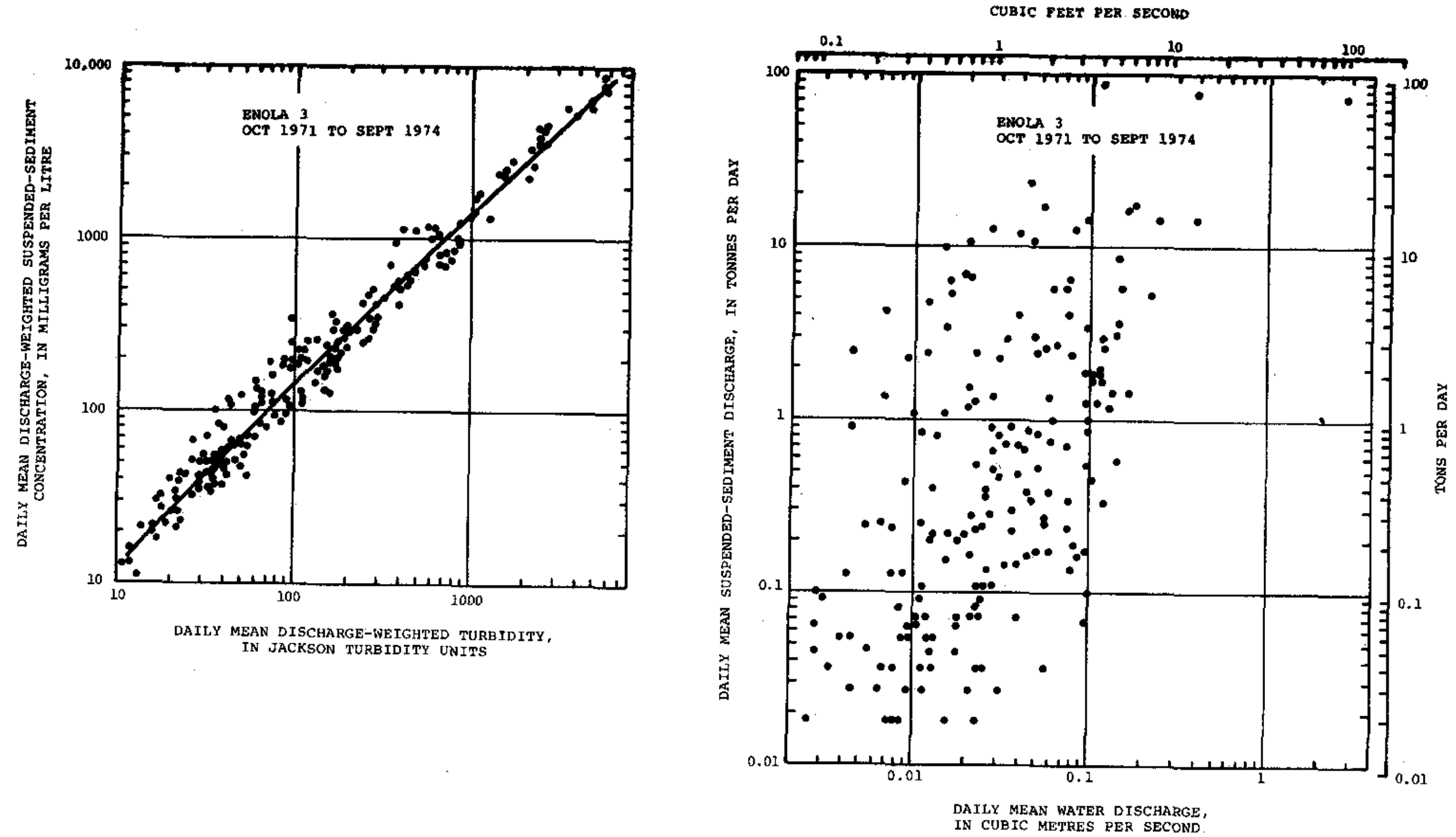

Figure 2.--Continued

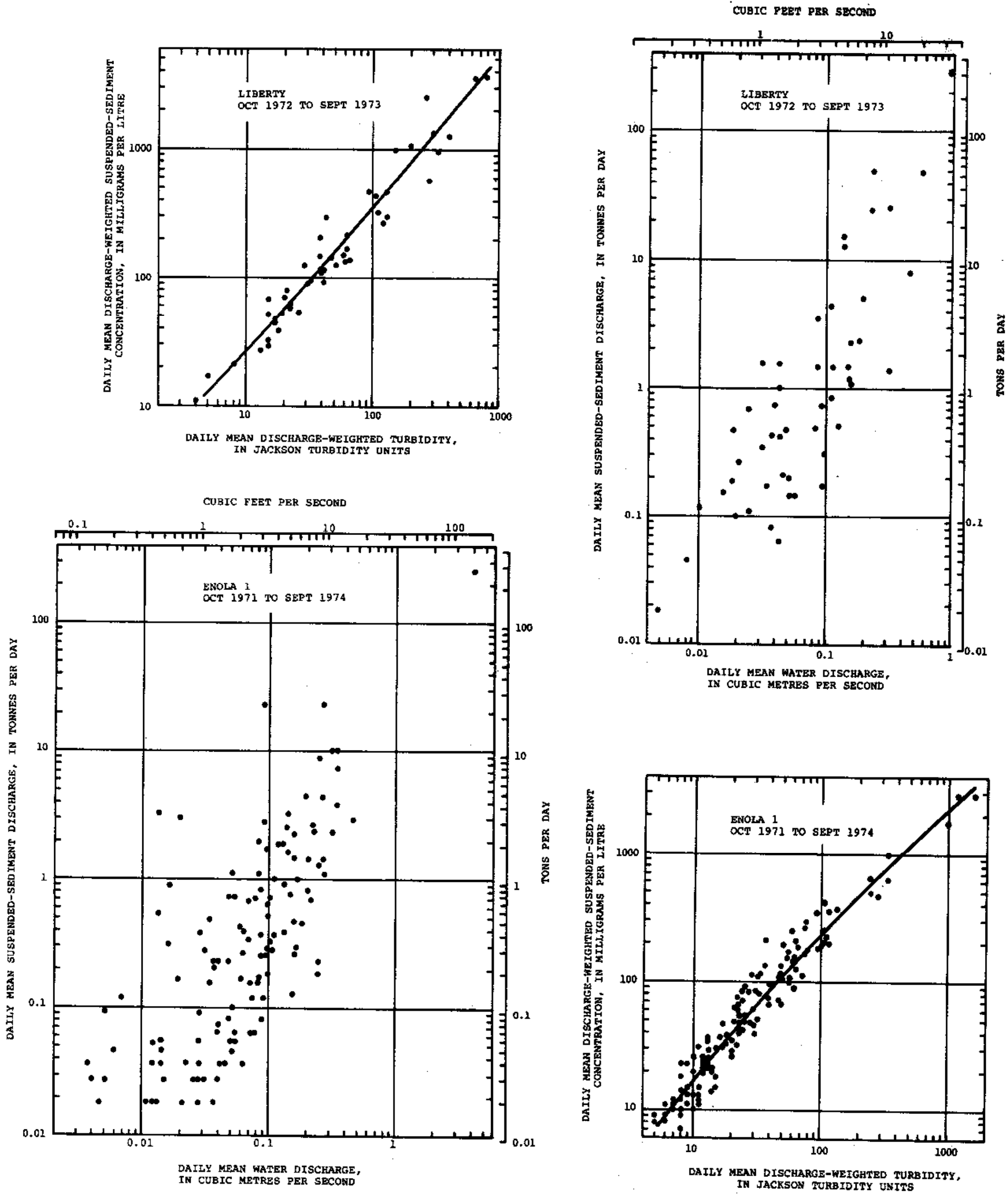

Figure 3.--Correlation of daily mean discharge-weighted suspended-sediment concentration with daily mean discharge-weighted turbidity compared with sediment discharge-water discharge correlations for two streams not affected by highway construction.

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16. Abstracts

In the 13 years since the last conference, there has been a large amount of research and development work. The work group recommended that a third conference be held in March 1976. Of the 130 workers in sedimentation who indicated a willingness to prepare and present papers at this Third Federal Inter-Agency Conference on Sedimentation, the committee has accepted about 80 papers for publication in the proceedings. The broad topics covered are the following: Sediment yield and sources; Erosion and sediment control; Physical and chemical properties of sediment; Sediment transport and deposition; Channel adjustments; Coastal zone sedimentation; and Instrumentation.

17. Key Words and Document Analysis. 17a. Descriptors

*Sedimentation
*Sediment transport
*Soil erosion
*Surface water runoff
Coastal zone management
Erosion control
Watersheds
Urban areas
Forest land
River basin development

*Meetings

Physical properties
Chemical properties
Suspended sediments
Estuaries
Channel improvements
Aquatic biology
Test equipment

17b. Identifiers/Open-Ended Terms

Suspended sediments
Urban hydrology

17c. COSATI Field/Group 8H 8G 13B

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