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CONTENTS

VOLUME I

Page

SECTION 1. INSTRUMENTATION

The Sedigraph as an Alternative Method to the Pipet--	
O. G. Lara and Wilbur J. Matthes.....	1-1
Development of a Trace Metal P-61 Point-Integrating Sampler--	
Donald A. Benson.....	1-13
Effects of Nozzle Orientation on Sediment Sampling--	
T. A. Winterstein and H. G. Stefan.....	1-20
Continuous Measurement of Suspended-Sediment Concentration--	
John V. Skinner, Joseph P. Beverage and Gerald L. Goddard.....	1-29
Instruments for Measuring Suspended Sediment--	
James H. Ficken.....	1-40
Small Watershed Automatic Water Quality Sampler--	
K. G. Renard, J. R. Simanton and C. E. Fancher.....	1-51
Innovative Techniques for Collecting Hydrologic Data--	
Andrew J. Bowie and Oscar W. Sansom.....	1-59
Suspended Sediment Monitored by Satellite--	
F. R. Schiebe and J. C. Ritchie.....	1-70
Under Water Mapping River Channels and Reservoirs--	
Timothy J. Randle and James O. Blanton, III.....	1-79

SECTION 1
INSTRUMENTATION

THE SEDIGRAPH AS AN ALTERNATIVE METHOD TO THE PIPET

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ABSTRACT

The SediGraph and the pipet methods of particle-size analysis are compared using the results from replicate runs of reference sediment samples prepared by the U.S. Geological Survey. Tests were designed to provide information on the operational characteristics of the SediGraph method including operator training needed, time required to make a complete analysis, and reproducibility of results under varying conditions.

The results indicate that the SediGraph method takes 50 percent less time to complete an analysis than does the pipet method. The training of qualified operators for the SediGraph method is less demanding and not as critical as for the pipet method. Good reproducibility of results is obtained using the SediGraph method. Results of comparable accuracy also were obtained using varying sediment concentrations and different instrument cells.

Agreement between the SediGraph and pipet results is good for samples having large percentages of fine material (50 to 60 percent finer than one micrometer). The agreement is acceptable for samples having relatively uniform distribution of particle size. For samples having a large percentage of coarse material (65 to 75 percent coarser than 10 micrometers) the SediGraph method results indicate finer particle-size distribution than do the pipet-method results.

Acceptance of an alternative method to the pipet method depends on convenience, availability of qualified operators, efficiency, reproducibility, and comparability of results with the pipet method. This study shows that the SediGraph method fulfills these criteria adequately. The SediGraph method could be adopted by the U.S. Geological Survey as one of the standard methods for particle-size analysis of sediment.

INTRODUCTION

The U.S. Geological Survey is actively searching for an alternative method to the pipet method, which for many years has been one of the accepted methods for determining the size distribution of sediment particles finer than 63 (μ m). There are two reasons for developing an alternative method. One which can be identified as economical, the other equally important reason addresses the present U.S. Geological Survey effort to minimize the uncertainties of our data-collection procedures. The pipet method is becoming progressively more expensive to use because it is a slow, labor-intensive method, and one that requires well-trained and skilled operators. Because the pipet method is slow, the Survey must maintain analytical laboratories at several locations, adding considerably to the total cost of data acquisition. Undoubtedly the data collected in past years contain variations that could be attributed entirely to differences in equipment, in laboratory technique, and in the skill and experience of the operators.

The results of a recent "round-robin" test of blind samples circulated within the Survey, showed surprisingly large variation in results that could be attributed in part to the differences mentioned above.

In searching for other qualified methods, the SediGraph method was considered by some Survey personnel to have potential for being an acceptable alternative method. Current literature on the subject supports this conclusion. Weaver and Grobler (1981) concluded that the SediGraph could be used as a standard tool for the measurement of sediment particle-size distribution based on a study that considered convenience, availability, reproducibility, and comparability of results to those obtained by other methods. Schiebe, Welch, and Cooper (1981), found good agreement between results from the pipet method and the SediGraph method for sediment sizes as small as 1 μm . Shahvar(1978) developed regression equations to convert the SediGraph results to pipet results.

Based on the above background information and other considerations, a decision was made to test the SediGraph as an alternative method to the pipet. The purpose of this paper is to report on the the results obtained from the study. Before discussing the results, a brief description of the methods and materials are presented in the following section.

METHODS

SEDIGRAPH 5000D*

Basic Principle

The SediGraph 5000D Particle Size Analyzer measures the sedimentation rates of particles dispersed in a liquid and automatically presents these data as a cumulative mass percent distribution in terms of the Stokesian or equivalent spherical diameter in micrometers. The instrument determines, the concentration of particles remaining at decreasing sedimentation depths as a function of time. The instrument typically can measure particles with diameters ranging from 0.18 to 50 μm . Diameters larger than 50 or smaller than 0.18 μm can be measured, depending on particle density and the liquid's density and viscosity.

Theoretical Background

Sediment-size analysis depends on the fact that the measured equilibrium velocity of a particle through a viscous medium, resulting from the action of the gravitational force which can be related to the size of the particle by Stokes' Law.

* The use of the brand name in this report is for identification only and does not constitute endorsement by the U.S. Geological Survey or other Federal agencies.

For spherical particles, Stokes' Law is expressed by

$$D = Kv^{1/2} \quad (1)$$

$$\text{where } K = [18\eta/(\rho - \rho_o)g]^{1/2} \quad (2)$$

and D is the diameter of the spherical particle, v its equilibrium sedimentation velocity, and ρ its density. The fluid medium is characterized by viscosity η and density ρ_o ; g is the acceleration of gravity. These equations apply rigorously as long as the particle Reynolds Number $Dv\rho_o/\eta$, is less than 0.3 and they apply up to a Reynolds Number of 0.5 with about 3 percent error. In practice, truly spherical particles are seldom encountered, and Stokes' Law is not exact for any other shape. Because irregular shapes cannot in any case be described by a single linear dimension, it is accepted practice to specify the size of non-spherical particles in terms of the diameter of a sphere of the same material that would have the same sedimentation velocity. Data concerning the sedimentation velocity of suspended particles may be obtained in two ways: (1) By measuring the concentration of particles remaining in suspension as a function of time, or (2) by measuring the quantity of sediment produced as a function of time. The latter approach is less desirable mathematically because of the graphical differentiation required to convert the data to a size-distribution curve.

Tests based on the first approach are traditionally performed in the following way. A dilute, deflocculated dispersion of the fine particle material is stirred to render it homogeneous and then allowed to stand undisturbed while the particles settle. Time is measured from the beginning of the settling period. By Stokes' Law, a particle of diameter D will settle a distance h in time t according to the expression

$$D = K(h/t)^{1/2} \quad (3)$$

where K is given by equation 2. Consequently, after a given time t_i all particles larger than the corresponding diameter D_i will have settled below a given distance h from the surface of the suspension.

The SediGraph uses a finely collimated X-ray beam to measure particle concentration in terms of the transmittance of the suspension relative to the suspending fluid. The transmittance to X-ray wavelengths is a function of the weight concentrations of suspended solids. Because the X-ray beam can be made extremely small, and because it does not disturb the suspension, it constitutes the ideal measuring technique.

If a sample container or cell of a rectangular cross section is irradiated from a direction perpendicular to one of its sides by a collimated X-ray beam, the fraction of the incident radiation transmitted by the cell when filled with the suspension under study is given by

$$I/I_o = [e]^{-N} \quad (4)$$

$$\text{where, } N = (a_l \phi_l + a_s \phi_s) L_1 + a_c L_2 \quad (4a)$$

where I and I_o are the transmitted and incident intensities; a_l , a_s , and a_c the X-ray absorption coefficients of the liquid, the particulate solids, and the cell walls, respectively; ϕ_l and ϕ_s the weight fractions of liquid and solid present in the suspension; L_1 the internal cell thickness in the direction of irradiation; L_2 the total thickness of the cell walls. By using the relation $\phi_l = 1 - \phi_s$ and by defining a transmittance T as the ratio of the transmission of the cell when filled with a sample dispersion to its transmission when filled with pure suspending liquid, there is obtained

$$T = [e]^{-C} \quad (5)$$

$$\text{where, } C = \phi_s (a_s - a_l) L_1 \quad (5a)$$

$$\text{or } \ln T = -A \phi_s \quad (6)$$

where A is a constant for the particular apparatus and suspension components.

By collimating the X-ray beam through horizontal slits with a vertical dimension small compared to the sedimentation depth, h , the measured values of T can be used in calculating the particle size distribution, shown by

$$P = 100 [\ln T_i / \ln T_o] \quad (7)$$

where T_o refers to the transmittance of the initial suspension.

Operating Procedure

The operation of the SediGraph 5000D Particle Size Analyzer is quite simple and straightforward once the operator becomes familiar with operating procedure. A detailed description of the operating procedure is presented in the instruction manual supplied by the manufacturer (Micromeretics, 1982). There are, however, two aspects of this procedure that should be emphasized. These are the techniques of preparing the sample and selecting the rate. The reliability of the results will depend to a great extent on the proper execution of these steps.

A. Preparing the Sample.

The SediGraph 5000D requires that the sediment be well dispersed in a liquid of known density and viscosity and that the difference between the sediment and liquid densities be accurately known. There are no established rules or laws by which complete particle dispersion can be assured. Only guidelines can be offered. Agitation, resulting in the application of strong shear forces, aids dispersion. The more violent the agitation, the better generally is the dispersion. Air bubbles cause misleading results if trapped in the liquid during the agitation. Particular care needs to be taken to avoid bubble entrapment when the liquid is highly viscous. Allowing the suspension to stand undisturbed will eventually result in bubble elimination, but the best agitation procedure is one that will not introduce them initially.

The magnetic stirrer built into the instrument is a convenient means for maintaining a homogeneous particle dispersion but will cause flocculation in certain magnetically susceptible materials. With such particles, stirring can be accomplished by using the ultrasonic dispersion accessory. Chemical wetting or dispersing agents also generally aid dispersion. No particular sample concentration is required in using the SediGraph as long as the dispersed sample decreases the radiation intensity from 60 to 40 percent.

B. Selecting the Rate.

In addition to particle size, the sedimentation rate depends on the liquid viscosity and on the liquid and particle densities. If the liquid is too viscous, sedimentation will be impeded and an unnecessarily long time will be required for analysis. Likewise, if the particles are only a little more dense than the liquid, a long time will be required. Should the particles have a much greater density compared to that of the liquid, sedimentation may be so rapid that Stokes' Law is violated. This means that, for optimum results, care needs to be exercised in selecting the system. Equations 1 and 2 guide the liquid selection and the rate setting to be entered into the instrument. The particle Reynolds Number sets the upper limit of measurable diameter and guides the setting of the starting point of the recorder.

For a given starting diameter, each indicated particle diameter corresponds to a definite sedimentation distance. As shown by equations 1 and 2, the time for a particle of any given diameter to settle a certain distance is proportional to the liquid viscosity divided by the difference in particle and liquid density.

The rate of cell movement built into the instrument to provide the proper settling distance for a given particle diameter is, therefore, related to the density difference divided by the liquid viscosity. The digital program, base rate, and gear ratio of the instrument is such that the rate is defined by

$$\text{Rate} = [211.80 (\rho - \rho_o)] / (50/D_m)^2 \eta \quad (8)$$

where D_m is the maximum particle diameter (the diameter set on the recorder chart prior to beginning a test). When power line frequency is other than 60 cycles per second, the right-hand term in the equation needs to be multiplied by the ratio (60/line frequency).

The density difference ($\rho - \rho_0$) is measured in, grams per cubic centimeter and the viscosity η in centipoise. Generally, D_m will be set at 50 μm , making the denominator ratio of equation 8 equal to unity.

PIPET METHOD

A description of the pipet method is not included in this report. Detailed descriptions of this method can be found in many readily available references such as Guy (1969), Porterfield (1972), and Vanoni (1975).

MATERIALS

The test material available for analyses consisted of seven fluvial-sediment samples collected from various locations around the country by the U.S. Geological Survey. About 40 identical subsamples were prepared for each of the 7 samples, labeled, and distributed to a number of Survey sediment laboratories, for a "round-robin" test in order to determine the variability of pipet analyses between laboratories. A complete set of these samples was made available for this study. A detailed explanation of the techniques used to prepare these samples is found in Delaney and Shroder(1979).

TEST RESULTS

The first set of experiments was designed to supply information on the operational characteristics of the SediGraph. These included the degree of training needed, the time required to make a complete analysis, the effect of varying concentrations on the size-distribution curves, the reproducibility of results, and the effect of changing cells.

The second set of experiments was designed to compare the results from the SediGraph to the results from using the pipet.

SediGraph

1. Time comparison.

The techniques for preparing a sample for SediGraph or pipet analysis are exactly the same. The average preparation time at the U.S. Geological Survey's sediment laboratory in Iowa City, Iowa, is about 24 minutes per sample. Both methods use sediment settling, but the pipet method requires a sample to be withdrawn, evaporated, and weighed, while the SediGraph examines the mass of sediment in a small, well defined point in the sample cell. A detailed step by step comparison of these techniques is beyond the scope of this report. However, knowledge of the time it takes to complete an analysis by each method may be useful at this time.

The average total time needed to complete the size analysis of seven samples to the 2 μm size, using the pipet method is five hours or 43 minutes per sample. The average total time required to complete the same analysis using the SediGraph is 20 minutes per sample or about 15 samples in 5 hours which is double the output of the pipet. It apparently would be possible for a laboratory equipped with a SediGraph to maintain an analytical rate of 18 samples per day which, barring excessive machine down time or malfunction, would equate to about 3,500 to 4,000 samples per year.

The difference in total time for analyses down to 1 μ m, is more significant. It takes about 45 minutes with the SediGraph and 10 to 14 hours with the pipet (If 7 samples are analyzed at the same time the average time per sample would be 85 to 120 minutes).

Regarding the availability of operators, the training of qualified operators for the SediGraph method is less demanding and not as critical as for the pipet method. It is estimated that about 40 hours of training would be sufficient to bring prospective operators to an acceptable level of competence.

2. Reproducibility

One of the most important and desirable characteristics in any method is its ability to reproduce repetitive results of comparable accuracy. Following are the results of experiments designed to test the reproducibility of the SediGraph method.

a) Effect of varying sample concentration.

The manufacturer of the SediGraph recommends a sample concentration of about 3 percent by volume as the optimal concentration. Under normal working conditions in the laboratory, the sample concentrations may deviate significantly from the recommended optimal concentration. Therefore, it is important to determine how wide a range of concentrations can be used without significantly affecting the results.

The results from typical replicate analyses of sediment samples of varying concentration are presented in table 1 and figure 1. Initially each sample exceeded the upper limit of concentration recommended by the manufacturer. Each successive analysis was made by first adding 10 mL of diluted dispersing agent to the sample. Note that the concentration of sample PB1007 (fig. 1) was so low that the sensitivity control of the recorder for the last 2 runs had to be adjusted from its normal operating setting of 100 down to 50 (GRAPH column in table 1), the results, however, were not much different from the preceding runs. These results and the results from the analyses of other samples indicate that the sample concentration may vary through a wide range without affecting the results of the analysis.

b) Effect of interchanging cells.

During the course of routine analysis, it may be necessary to replace the sediment cell for cleaning, repairing, or for other reasons. It is a matter of interest to determine if interchanging cells would have any effect on the outcome of a given analysis. The results of replicate analyses of sample SM1226 using cell A are presented in table 2 and using cell B in table 3 (A and B are used as means of identification only). Comparing the results listed in tables 2 and 3 indicates that the results agree within 3 percent. It also should be noted that the differences are within the limits of accuracy for replicate runs, which according to the manufacturer of the SediGraph is about 3 percent. Based on the results of repetitive analyses for sample SM1226, and on the results of similar analyses of other samples, it is concluded that cells can be interchanged without affecting the results.

RESULTS AND DISCUSSION

The results of particle size analyses from using the SediGraph and the pipet methods have been summarized in tables as well as illustrated in graphs. Typical examples of these data are shown in tables 4 and 5 and in figure 2. The results of analyses of identical samples of the bottom sediment from Rio Puerco River near Bernardo, New Mexico, reported by participating U.S. Geological Survey laboratories, using the pipet method are summarized in table 4. The results of 20 replicate analyses using the SediGraph are summarized in table 5. The mean, standard deviation, coefficient of variation, and the range have been computed and listed at the end of each column. The standard deviation and the coefficient of variation are included to help the reader judge the central tendency of the results. The range was included to show the maximum difference between the results reported by participating districts, using the pipet, and between replicate runs when using the SediGraph. Data from tables 4 and 5 are plotted in figure 2. This figure shows clearly that the differences between laboratory results are wider than those for the SediGraph. The same was true for every sample tested.

In general, the best agreement between the SediGraph and the pipet results was obtained for samples having a large percentage of fine materials, about 50 to 60 percent finer than 1 μ m. For example see the results for Rio Grande floodway at San Acacia, New Mexico, presented in figure 3. The results for two other sediment samples of similar characteristics, one from Rio Grande at Fort Quintan, Texas, and the other from Rio Puerco River near Bernardo, New Mexico, agreed equally well.

The largest difference between SediGraph and pipet results were for samples having large percentage of coarse material, 65 to 75 percent larger than 10 μ m. See the results for Ralston Creek at Iowa City, Iowa (fig. 4).

For samples having a more uniform distribution of particle sizes, such as the one for the Rio Grande at El Paso, Texas (fig. 5), the results show a trend. The SediGraph method indicates a higher percentage of particles at the 32 μ m size than does the pipet method, whereas the opposite is true at the 1 μ m size. Many other samples with similar size distribution characteristics were tested. The results in every case showed the same trend.

In summary, the agreement between the results from the SediGraph and the pipet methods is good for samples having a large percentage of fine materials. The agreement is acceptable for samples having a uniform distribution of particle sizes. The differences are more pronounced for samples having a larger percentage of coarse material. For this type of sample, the SediGraph method consistently defines a finer particle-size distribution than does the pipet method. This agrees with the conclusion reached by Weaver and Grobler (1981), who compared the results of the SediGraph method to the results of various other methods, including the pipet method, and found that the SediGraph method consistently determined a finer particle-size distribution than the other methods. An interesting aspect of their investigation is that Weaver and Grobler (1981) had access to microscopic analyses of the samples. Taking this microscopic data into consideration, they concluded that "The SediGraph method gives a truer reflection of the actual particle size distribution of the sample although it differed from the results obtained by the other methods."

CONCLUSIONS

1. Analyses of particle-size distribution using the SediGraph method take about 50 percent less time than comparable analyses using the pipet method. The average time to complete an analysis using the pipet method down to the 2 μm size is 43 minutes per sample as compared to 20 minutes per sample for the SediGraph method. It appears that a laboratory equipped with a SediGraph could maintain a rate of 18 samples per day, which would equate to an output of 3,500 to 4,000 samples per year. The benefits from operating a laboratory equipped with a SediGraph are obvious. It would considerably reduce the personnel needed to process the present volume of sediment-size analyses. This in turn would result in substantial cost savings to the U.S. Geological Survey. Furthermore, it would practically eliminate a major source of variance in the results, which can be attributed in great part to interlaboratory variations.

2. The training of qualified operators for the SediGraph method is less demanding and not as critical as for the pipet method.

3. The SediGraph method gives good replicate results of comparable accuracy. Good reproducibility of results also was obtained using different cells and varying sediment concentrations.

4. The agreement of the SediGraph method results with those of the pipet method is good as shown in figure 3, particularly for samples having a large percentage of fine material (50 to 60 percent finer than 1 μm).

The agreement also is acceptable for samples having a more or less uniform distribution of particle size (fig. 5). For samples with a larger percentage of coarse material (65 to 75 coarser than 10 μm) the SediGraph method indicates a finer particle size distribution than does the pipet method (fig. 4).

5. It is generally agreed that the choice of an alternative method to the pipet method depends to a great extent on convenience, availability of qualified operators, efficiency, reproducibility, and comparability of results with the pipet method. This study has shown that the SediGraph method fulfills these criteria adequately including, with the exceptions noted, comparability with the pipet method. It also should be noted that the SediGraph method is more readily adaptable to automatic data processing than the pipet method. Therefore the SediGraph method could be adopted by the Geological Survey as one of the standard methods for particle-size analysis of suspended sediment.

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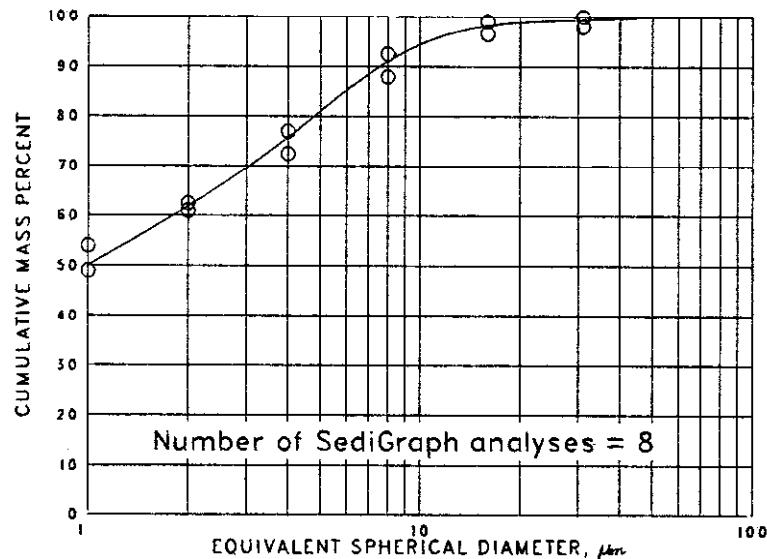


Figure 1. - Replicate analysis to determine the effect of varying concentration for sample PB1007.

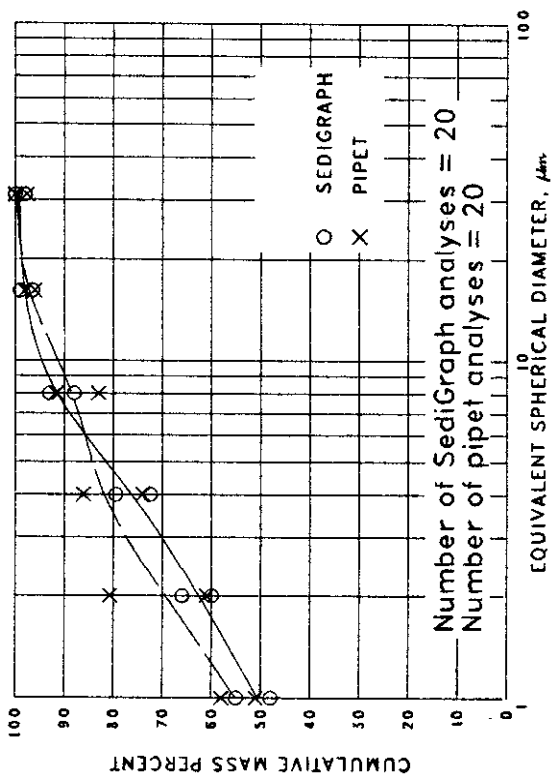


Figure 2. --Comparison of replicate analyses: SediGraph versus pipet methods - Rio Puerco River near Bernardo, New Mexico.

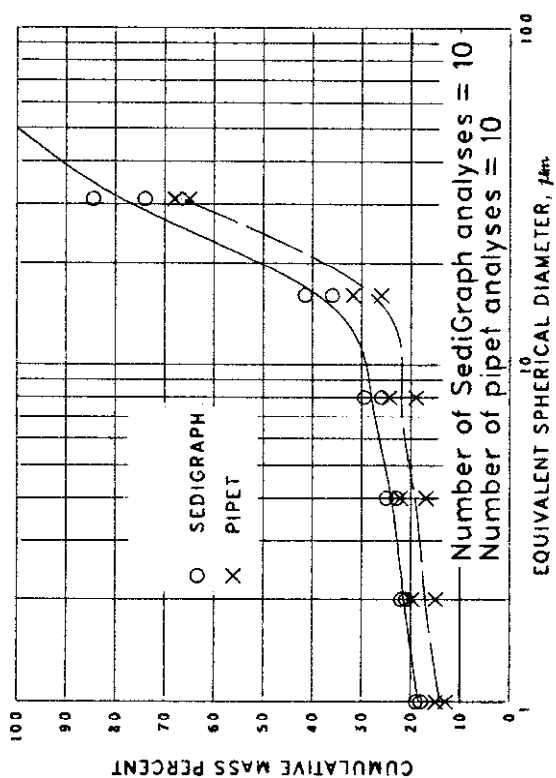


Figure 4. --Comparison of replicate analyses: SediGraph versus pipet methods - Ralston Creek at Iowa City, Iowa.

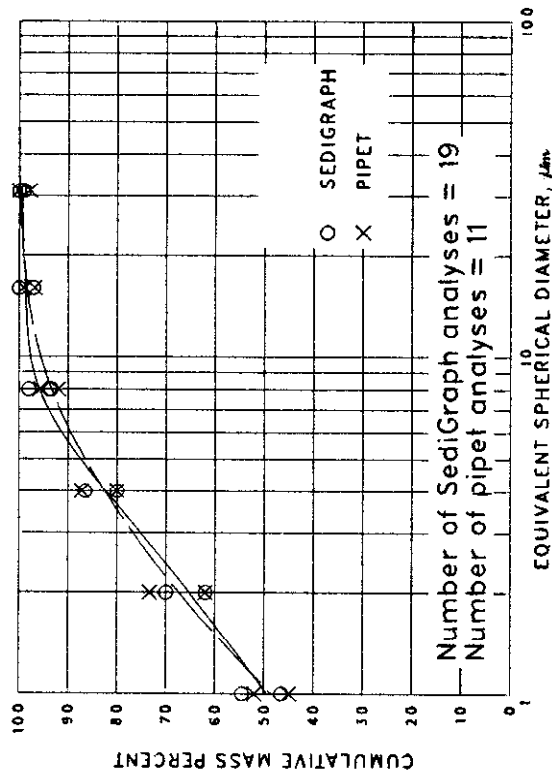


Figure 3. --Comparison of replicate analyses: SediGraph versus pipet methods - Rio Grande floodway at San Acacia, New Mexico.

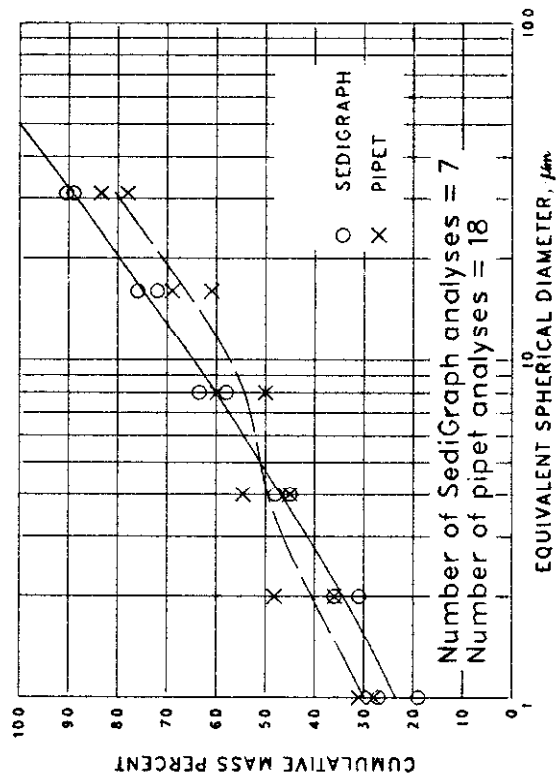


Figure 5. --Comparison of replicate analyses: SediGraph versus pipet methods - Rio Grande River at El Paso, Texas.

Table 1.- Replicate analysis to determine the effect of varying concentrations.

SAMPLE ID.	CELL GRAPH	PERCENT FINER THAN INDICATED SIZE IN MICROMETERS						
		31	16	8	4	2	1	
PB1007	B	100	98.0	96.5	88.0	72.5	62.0	54.0
PB1007	B	100	100.0	98.0	91.5	75.5	62.5	51.0
PB1007	B	100	99.5	98.0	91.5	75.0	62.5	50.0
PB1007	B	100	99.0	98.0	91.0	76.0	61.0	49.0
PB1007	B	100	99.0	97.5	90.5	75.5	61.0	49.5
PB1007	B	100	100.0	99.0	92.5	77.5	62.5	49.5
PB1007	B	50	99.0	98.5	91.5	77.0	62.0	49.0
PB1007	B	50	100.0	99.0	92.0	77.0	61.5	49.0
Mean		99.3	98.1	91.1	75.8	61.9	50.1	
St.Dev.		0.70	0.82	1.37	1.58	0.64	1.71	
Coef. Var.		0.71	0.84	1.50	2.08	1.00	3.42	
Range		100-98	99-96.5	92.5-88	77-72.5	62.5-61	54-49	

Table 2.- Replicate analysis of sediment sample SM1226 to determine the effect of interchanging cells.

CELL		PERCENT FINER THAN INDICATED SIZE IN MICROMETERS						
		31	16	8	4	2	1	
A	85.0	61.0	44.0	34.0	28.0	28.0		
A	85.0	61.0	44.0	34.0	28.0	28.0		
A	85.5	62.0	45.0	35.0	28.5	28.0		
A	85.5	62.0	45.0	35.0	28.0	28.0		
A	86.6	62.0	45.0	35.0	29.0	29.0		
A	86.0	63.0	45.0	34.5	28.5	28.5		
Mean	85.6	61.8	44.7	34.6	28.3			
St. Dev.	0.62	0.75	0.52	0.49	0.41			
Coef. Var.	0.72	1.21	1.16	1.42	1.45			
Range	86.6-85	63-61	45-44	35-34	29-28			

Table 3.- Replicate analysis of sediment sample SM1226 to determine the effect of interchanging cells.

CELL		PERCENT FINER THAN INDICATED SIZE IN MICROMETERS						
		31	16	8	4	2	1	
B	84.0	60.0	43.5	35.0	29.0			
B	84.0	59.5	43.0	34.0	29.5			
B	84.5	60.0	44.0	34.5	29.0			
B	85.5	60.0	43.5	35.0	29.0			
B	85.0	59.5	43.5	35.0	29.5			
B	85.0	60.0	43.5	35.0	29.5			
Mean	84.7	59.8	43.5	34.8	29.3			
St. Dev.	0.61	0.25	0.32	0.42	0.27			
Coef. Var.	0.72	0.42	0.74	1.23	0.92			
Range	85-84	60-59.5	44-43	35-34	29.5-29			

Table 4.- Replicate analyses of bottom sediment from Rio Puerto River near Bernardo, New Mexico. Pipet method.

SAMPLE ID.		PERCENT FINER THAN INDICATED SIZE IN MICROMETERS						
		31	16	8	4	2	1	
PB9002		99.0	97.0	88.0	82.0	69.0	55.0	
PB9003		100.0	96.0	88.0	82.0	73.0	55.0	
PB9005		100.0	97.0	90.0	83.0	69.0	56.0	
PB9012		101.0	97.0	88.0	80.0	62.0	54.0	
PB9017		100.0	98.0	89.0	82.0	68.0	58.0	
PB9021		99.0	98.0	88.0	83.0	62.0	52.0	
PB9022		100.0	98.0	88.0	84.0	65.0	58.0	
PB9025		100.0	97.0	88.0	81.0	70.0	58.0	
PB9030		99.0	97.0	89.0	81.0	69.0	51.0	
PB9031		97.0	81.0	83.0	81.0	70.0	57.0	
PB9034		100.0	97.0	90.0	85.0	70.0	55.0	
PB9035		100.0	98.0	91.0	84.0	66.0	55.0	
PB1001		99.0	96.0	85.0	74.0	61.0	55.0	
PB1011		100.0	97.0	89.0	79.0	68.0	54.0	
PB1022		100.0	97.0	87.0	79.0	69.0	54.0	
PB1032		100.0	97.0	88.0	80.0	69.0	54.0	
PB9033		98.4	97.3	90.8	86.1	74.1	--	
PB9027		98.3	97.3	89.9	81.7	80.7	--	
PB1025		100.0	97.2	91.7	82.1	80.1	--	
PB1007		97.6	96.7	90.4	83.6	74.0	--	
Mean		99.6	97.1	88.5	81.8	69.4	55.1	
Std. Dev.		0.81	0.56	2.35	2.62	5.21	2.02	
Coef. Var.		0.81	0.58	2.66	3.20	7.50	3.66	
Range		101-97.6	98-96	91.7-83	86.1-74	80.7-61	58-51	

Table 5.- Replicate analyses of bottom sediment from Rio Puerto River near Bernardo, New Mexico. Sedigraph method.

SAMPLE ID.		PERCENT FINER THAN INDICATED SIZE IN MICROMETERS						
		31	16	8	4	2	1	
PB1025		99.0	98.0	91.5	77.0	63.5	51.0	
PB1025		100.0	99.0	91.5	77.0	63.5	53.0	
PB1025		99.0	98.0	92.0	78.0	65.0	53.0	
PB1025		99.0	98.0	93.0	79.0	66.0	53.0	
PB1007		98.0	98.0	92.0	77.0	65.0	54.0	
PB1007		100.0	98.5	88.0	72.5	62.0	51.0	
PB1007		99.5	98.0	91.5	75.0	62.0	50.0	
PB1007		99.0	98.0	91.0	76.0	61.0	49.0	
PB1007		99.0	97.5	90.5	75.5	61.0	49.5	
PB1007		100.0	99.0	92.5	77.5	62.5	49.5	
PB1007		99.0	98.5	91.5	77.0	62.0	49.0	
PB1007		100.0	99.0	92.0	77.0	61.5	49.0	
PB9027		99.0	98.0	92.0	76.0	62.0	50.0	
PB9027		99.0	98.0	90.0	75.0	62.5	50.0	
PB9027		99.0	98.0	92.0	78.0	65.0	50.5	
PB9027		99.0	98.0	92.5	79.5	65.0	51.5	
PB9033		99.0	98.0	91.0	74.0	60.0	47.5	
PB9033		99.0	97.0	90.0	74.5	60.0	48.0	
Mean		99.2	98.0	91.5	76.3	62.6	50.6	
Std. Dev.		0.49	0.64	1.08	1.75	1.83	2.10	
Coef. Var.		0.50	0.65	1.18	2.30	2.93	4.15	
Range		100-96	99-96.5	93-88	79.5-72.5	66-60	55-48	

DEVELOPMENT OF A TRACE-METAL P61 POINT-INTEGRATING SAMPLER

By Donald A. Benson, Mechanical Engineer, Corps of Engineers, St. Paul District.

ABSTRACT

Metal contamination of water samples by the use of a metal sampler is a concern of sampler fabricators and users alike. The P61 trace-metal point-integrating sampler distributed by the Federal Interagency Sedimentation Project addresses the problem by lining the water passageways with Teflon to reduce the contamination. However, the water sample does have to pass through a stainless-steel valve. The project installed a plastic valve and valve block in a P61 point-integrating sediment sampler. A test was performed using two P61 samplers held together side by side, submersed in a tank of water. One sampler had a plastic valve and valve block, and the other had the presently used sleeved-bronze valve block and stainless-steel valve. At regular intervals, the concentration was increased by 200 parts per million (ppm) of a particular size of sediment. The tank water was agitated and a sample drawn from each sampler. This procedure was continued until either sampler failed. Three sizes of graded sediment were chosen, that were capable of passing between the clearance tolerance of the valve and the valve block. In testing the three sizes of sediment, the sampler with the sleeved-bronze valve block failed first. Besides the advantage of being plastic, the trace-metal device appears to work better mechanically when dealing with sediment 100 micrometers (μm) or smaller.

INTRODUCTION

Early in the 1970's the Federal Interagency Sedimentation Project was asked to provide sediment samplers that could be used in the evaluation of trace-metal elements in water samples. In looking into the problem of producing a sampler that provided metal-free contamination, the areas of concern were the nozzle, intake passage, and the container. Most of the containers in the sediment samplers sold by the project are of glass and plastic so the metal container issue was no problem. The nozzle of the P61 sediment sampler in the early 1970's was metal, but the project had been considering a plastic nozzle so the conversion to a plastic nozzle did not appear to be a problem. The other concerns of metal contamination were the intake passage, and possible contamination by the body metal. Since most of the samplers are either bronze or aluminum and contain minute quantities of various types of other metals, it was decided to paint the exterior and the interior of the sampler with a metal-free pore-sealing epoxy paint. During the 70's this type of epoxy paint was commercially available; now, however, the project has located a private manufacturer and can maintain better quality control and supply.

In the case of the depth-integrating sampler, we merely had to extend the plastic nozzle through the passageway and into the container to eliminate any contamination. In the case of the point-integrating sampler, the water sample has to pass through a valve block and porting arrangement as shown in figure 1.

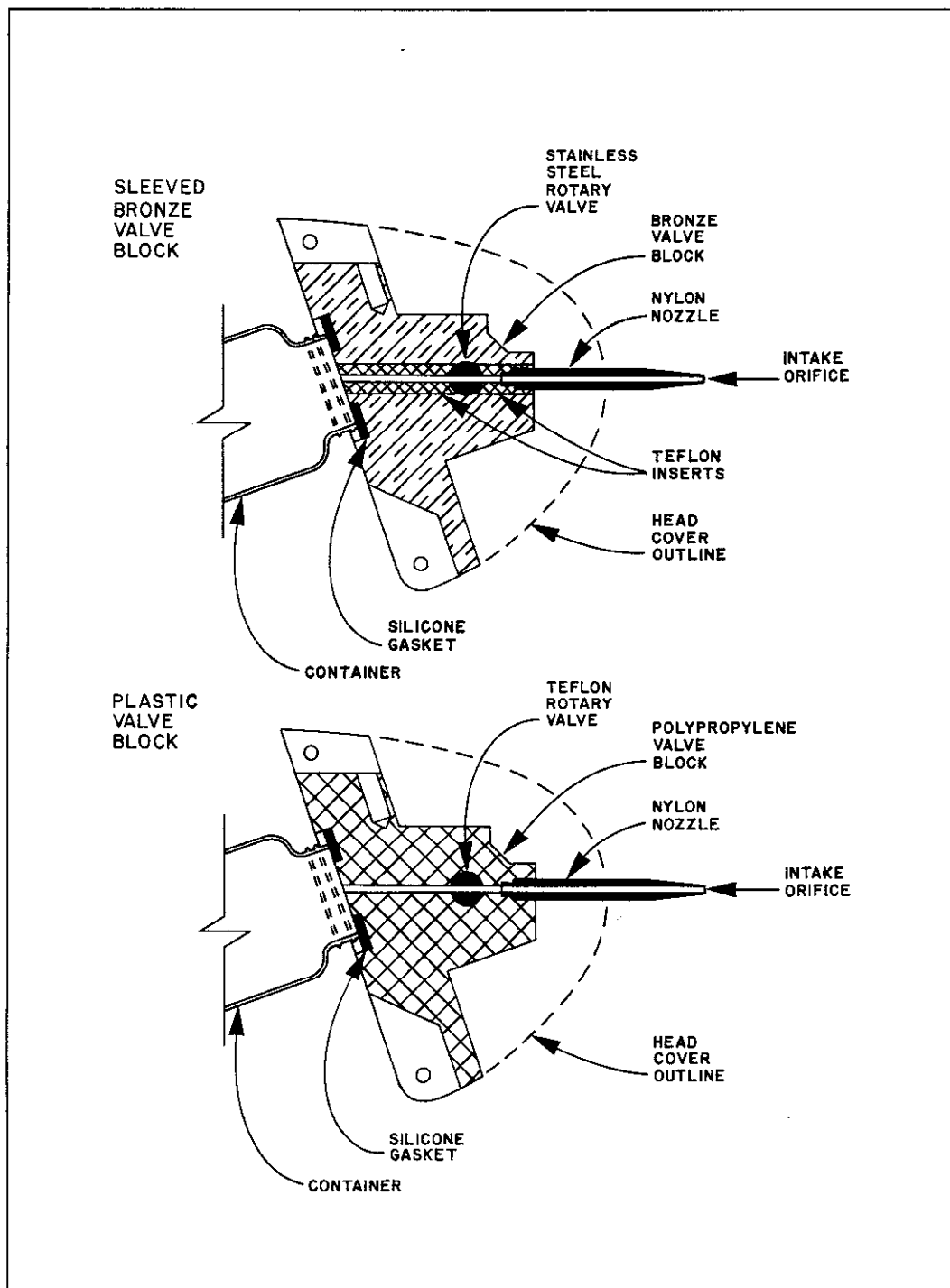


Figure 1.--Valve-block cutaways for P61 Sampler.

EARLY TRACE-METAL POINT SAMPLER DEVELOPMENT

In early trace-metal point-sampler development, the passageway was bored oversize to keep the water sample from being contaminated in the valve-block passageway, and a Teflon sleeve was press-fitted into the valve block, both in front of and behind the porting valve (refer to figure 1). The head gasket and the bottle gasket were replaced with metal-free silicone-rubber gaskets. The stainless-steel rotary valve was unchanged, because the valve and valve block are tapered to keep a snug fit to prevent water leakage. Replacing the stainless-steel valve with plastic would result in excessive wear between the valve and the bronze housing. While this pressed-sleeve adaptation has been used for the last 15 years, there are several disadvantages: 1) the device is not metal-free because we are using a stainless-steel rotary valve, 2) when a plastic nozzle is screwed too tightly into a plastic sleeve the friction bond between the Teflon sleeving and the bronze valve block may be broken. 3) After a period of several years, the Teflon sleeving tends to expand into the rotating area and stop the rotating action. Repairing the Teflon sleeving not only includes replacing the sleeving but requires carefully reaming the valve-plug area or replacing the valve plug. Approximately 85 percent of all repairs to trace-metal samplers are replacing the Teflon sleeving, even though warnings to tighten nozzles only finger-tight are sent out with each sampler. The increased frequency of sleeve replacement prompted the Federal Interagency Sedimentation Project to examine the alternative to the present system.

DEVELOPMENT OF A PLASTIC-VALVE BLOCK

Since the sleeve replacement was the biggest problem, the obvious first choice for an improved trace-metal sampler would be to replace the bronze valve block with a plastic valve block (see figure 2). This would allow use of a plastic rotary valve and eliminate the Teflon sleeving. The first choice of plastic was Teflon for several reasons. We have been using Teflon with good success as a sleeve material, and are satisfied with its lubricity. For the valve block, we needed a seven-inch diameter billet. Local suppliers told us that this Teflon material was not immediately available. Polypropylene was substituted because it was readily available, and has properties relatively close to Teflon. Teflon was used for the small rotary valve. The polypropylene valve block was machined out of a seven-inch diameter billet. Plastic plugs were used to seal any special tooling holes, so all surfaces exposed to water would be plastic. The rest of the valve block has the standard items specified on the drawings. After assembly, the plastic unit was checked for conformity, and checks were made to see if the valve opened and closed properly and had the proper size opening upon actuation.

TEST SET-UP

To provide a test environment for the two P61 sediment samplers, a tank was used capable of holding the two samplers side by side submerged in water. To make sure both P61 samplers received similar samples, they were bolted together so their nozzles were at the same vertical level (see figure 3). An overhead crane was used to raise and lower samplers, when opening the sampler to extract sample bottle and for removing the sampler for disassembly after failure.

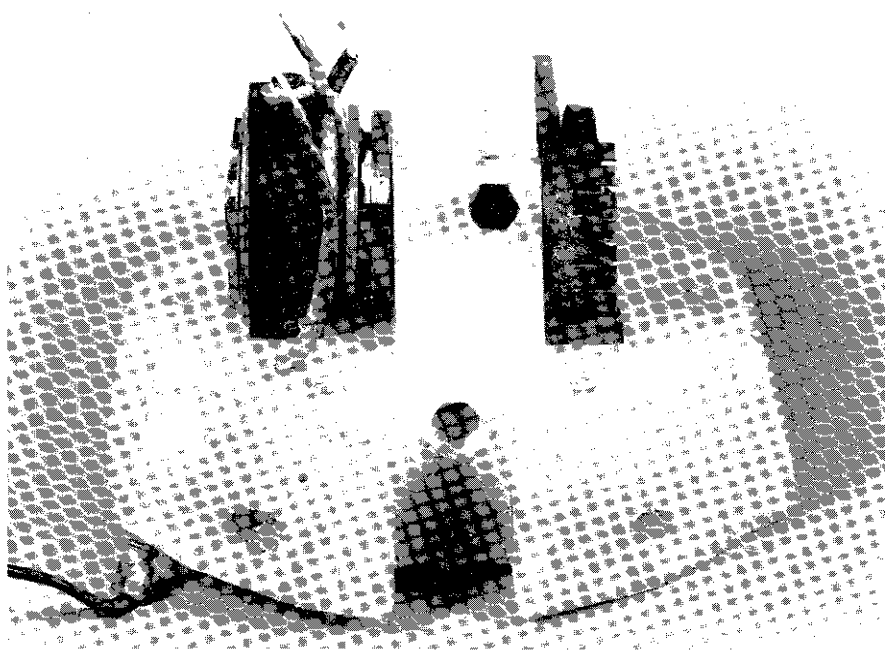


Figure 2.--Plastic-valve block.

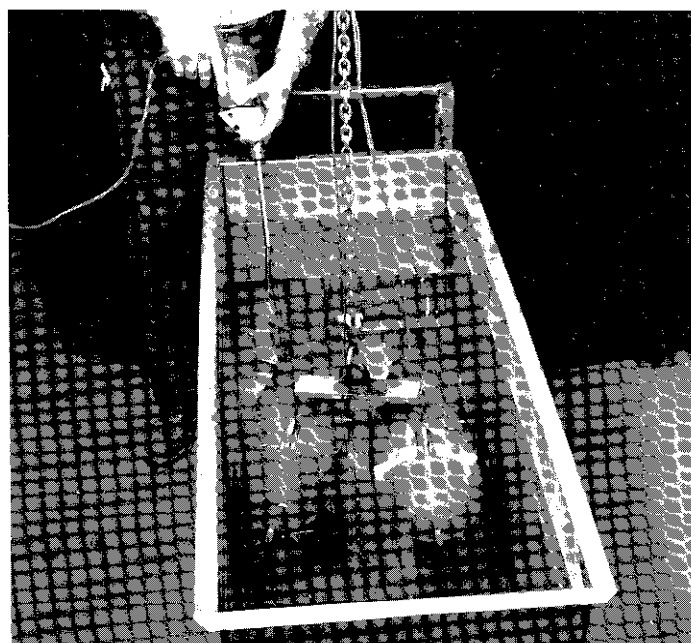


Figure 3.--Samplers in test tank.

SEDIMENT

Only the size and concentration of sediment in the test tank was varied during the tests. Three sizes of sediment that varied from 11.5 to 106 μm were selected. The sizes are numbered and described in figure 4. The two smallest sizes are actually pure quartz, because sand was not available in the sizes wanted. The largest size is the finest sand available from our source, American Graded Sand Company of Des Plaines, Ill. Half of the particles were fine enough to penetrate the clearance between the rotary valve and the valve block. Supplies were adequate so that all tests were made from the same bags of sand.

TEST PROCEDURE

The two P61 samplers were lowered into the tank containing 50 liters (L) of water as shown in figure 3. The water level in the tank was marked and the 50-liter quantity was maintained through the tests. Sediment of the selected size was added to the water to produce a concentration of 200 ppm. The tank was agitated with a large beater to distribute the sediment throughout the tank. Both samplers were actuated and lifted from the tank.

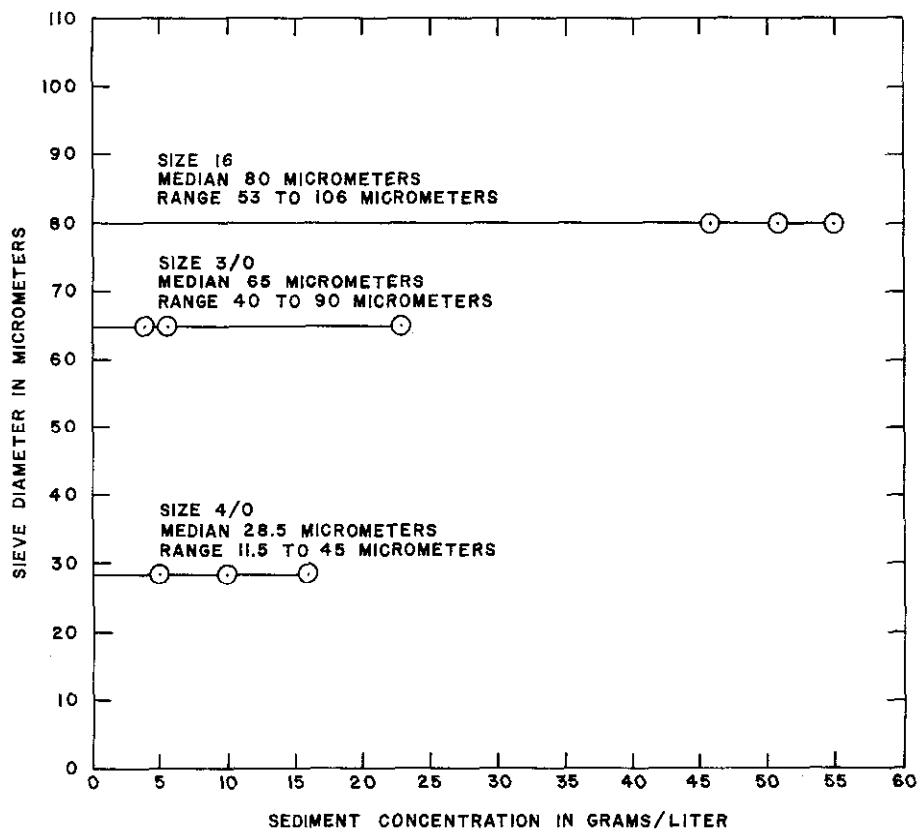


Figure 4.--Occurrence of failure for sleeved P61 Sampler.

The sample container was removed and the contents were poured into a graduated cylinder. The volume of the sample was noted. The containers were returned to the samplers and the samplers were lowered into the tank and soaked for twenty-four hours. Then the sediment concentration was increased another 200 ppm, the water was agitated, and another sample was taken. This procedure was continued until one of the samplers failed to open. The contents of the sampler bottle were analyzed to make sure the sample concentration somewhat represented the water sediment mixture in the tank. After the sleeved-bronze sampler failed, the two samplers were removed from the tank, and observed for physical accumulation of sediment in and around the sampler. The samplers were then carefully disassembled and photographs were taken of critical areas. After all observations, measurements, and photographs were completed, plastic parts were cleaned and metal parts were sandblasted where necessary. After cleaning the parts, they were measured for accuracy and wear; wear if any, was documented. The units were rebuilt, solenoids were checked for proper action, and passage-ways were inspected to see if they would fully open.

TEST RESULTS

Figure 4 shows the occurrence of failure of the sleeved-bronze P61 sampler on the basis of concentration and particle size. In all cases, the cause of failure was due to a buildup of sediment between the two surfaces where rotary movement occurred. The sleeved-bronze sampler always failed first. Because the plastic surface area on the rotary valve on the plastic block sampler was not highly polished, small particles of sediment buried themselves in the microscopic impressions within the plastic valve (see figure 5). It is believed these small particles provided some lubricity,

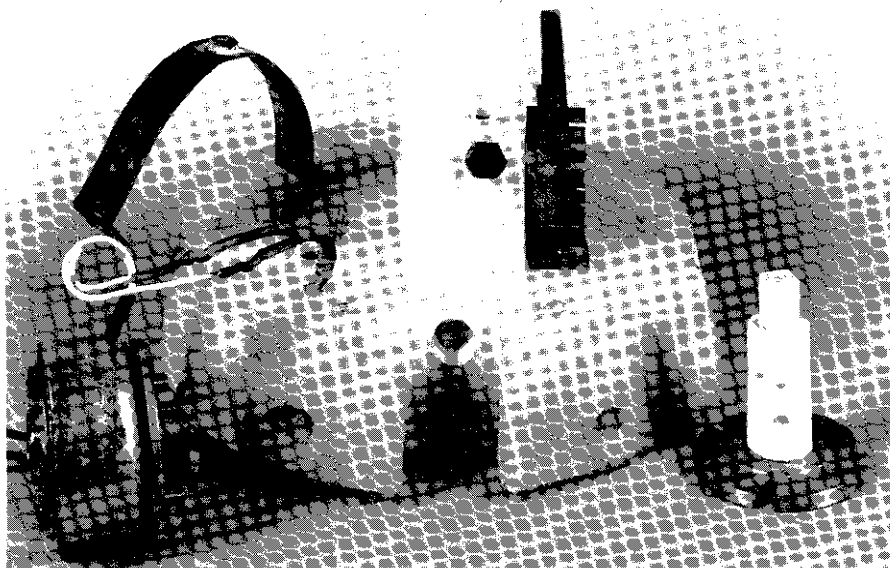


Figure 5.--Plastic-valve block after testing.

because on several occasions, after failure of the sleeved-bronze sampler, when the plastic valve block sampler was pulled out of the water, and it dried out, it would not operate. However, after submersing it in water for a few hours, the unit would operate again. In the case of the sleeved-bronze sampler, once it ceased to function, it never worked again until it was cleaned.

The larger particles of sediment required a longer time to penetrate the clearance between the valve and valve block during the test. Disassembly of the samplers disclosed heavy accumulations of particles around the outside of the valve block and around the solenoid, but none of the sediment was considered the prime reason for failure.

SUMMARY

There will always be a need for point-integrating samplers that are capable of sampling trace metals without contaminating the samples. Three years of tests have shown that a sampler with a plastic valve block and a plastic valve works longer than a sleeved-bronze trace-metal sampler. This study did not involve any investigation of the increased cost of the plastic parts, which could be significant, nor did it involve tests on how large sediment particles might damage the plastic parts.

However, the study has shown that with small sediment particles in suspension, plastic parts work longer and work better than the sleeved-bronze configuration. The purpose of this study was to inform hydrologists that there is an alternative to plastic sleeving, and the alternatives work better in certain instances. As time and money permit, further tests will be made using new materials and additional grain sizes in an effort to provide the best sampler at the lowest cost to do the best job possible.

EFFECTS OF NOZZLE ORIENTATION ON SEDIMENT SAMPLING

By T.A. Winterstein, Hydrologist, U.S. Geological Survey, St. Paul, Minnesota
and H.G. Stefan, Associate Director, St. Anthony Falls Hydraulic Laboratory,
Minneapolis, Minnesota.

ABSTRACT

A study of the effects of nozzle orientation, withdrawal rate, and particle size on suspended-sediment sampling was made at the Saint Anthony Falls Hydraulics Laboratory, Minneapolis, Minnesota. Three sizes of quartz sand-- $d_{50} = 0.06$ mm, $d_{50} = 0.11$ mm, and $d_{50} = 0.20$ mm--were sampled from a 150-mm-wide recirculating flume with a 6.35-mm I.D. nozzle. Two withdrawal rates--isokinetic and twice-isokinetic--were used to remove the sediment samples from 0.67-m/s flow. Seven nozzle orientations to the flow were used; measured clockwise from a horizontal plane with the nozzle mouth pointing directly into the flow they are: 45 degrees, 90 degrees (the nozzle pointing straight up), 135 degrees, 180 degrees (the nozzle pointing directly downstream), 225 degrees, 270 degrees (the nozzle pointing straight down), and 315 degrees.

The sampling efficiency--that is, the ratio of the sediment concentration in the sample to the sediment concentration at the sampling point--varied with the angle between the nozzle and the flow, the sand size, and the withdrawal rate. The sampling efficiency was higher with the twice-isokinetic withdrawal rate than with the isokinetic withdrawal rate for all nozzle orientations. The sampling efficiency was highest when the 0.06-mm sand was sampled and least when the 0.20-mm sand was sampled for all nozzle orientations.

The sampling efficiency decreased as the angle between the nozzle and the flow increased, except when the nozzle mouth was pointing directly downstream. In this position, the sampling efficiency was about 0.90 for all sand sizes and both withdrawal rates, probably because the sand was thrown in front of the nozzle by a turbulent wake from the nozzle, as indicated from dye studies. Because the worst sampling efficiencies (the largest errors) occurred when the nozzle was oriented at 135 degrees and at 225 degrees (45 degrees either side of pointing directly downstream), this phenomenon may disappear if the nozzle is shifted a few degrees in either direction of directly downstream. At the 135-degree and 225-degree orientations, the sampling efficiencies varied from 0.39 for the 0.20-mm sand to 0.84 for the 0.06-mm sand (isokinetic withdrawal rate) and from 0.70 for the 0.20-mm sand to 0.90 for the 0.06-mm sand (twice-isokinetic withdrawal rate).

The experimental results indicate that, for quartz sand, the sampling error is negligible if the material is smaller than a critical size, which varies from 0.035 to 0.06 mm. The critical size is a function of the withdrawal rate and the nozzle orientation.

INTRODUCTION

Suspended-sediment samples are collected from streams to estimate the sediment load of the stream or for water-quality analysis. Because the sampling site may be remote or because the sampling is done on an irregular schedule, automatic pumping samplers are sometimes used to collect the samples. If the sampling nozzle is pointed upstream, the mouth of the nozzle is easily clogged

by debris such as leaves. As a result, the nozzle is commonly set at right angles to the flow or pointing downstream.

Previous research has shown that, if the nozzle is not properly oriented so that it faces into and is aligned parallel to the fluid flow, considerable error is introduced into the sampling process (Federal Interagency Sedimentation Project, 1941). Setting the sampling nozzle at an angle to the flow makes the sampled filament of water curve as it enters the nozzle. Because of inertial forces, a suspended particle will not be able to curve as sharply as the filament of water; the particle may leave the filament and not be sampled. As a result, the sampled suspended-sediment concentration is less than the actual concentration in the stream. Larger particles will not curve as sharply as smaller particles because of larger inertial forces; sampling error will increase as particle size increases (Federal Interagency Sedimentation Project, 1941; Winterstein and Stefan, 1983). Also, the more sharply the filament curves, the more likely particles will leave the filament; the sampling error will increase as the angle between the sampling nozzle and the flow increases (Federal Interagency Sedimentation Project, 1941; Watson, 1954; Raynor, 1970; Winterstein and Stefan, 1983).

Current information on the magnitudes and types of errors because of sampling nozzle orientation is limited; as a result, estimates of sampling errors caused by setting the sampling nozzle at an angle to the flow cannot be made.

Purpose and Scope

The purpose of the experimental study described in this paper was to investigate the magnitude of sampling errors caused by setting the sampling nozzle at an angle to the flow. The study was conducted in a laboratory flume at one discharge and flow depth. Three sizes of quartz sand were used and seven sampling-nozzle orientations to the flow were tested.

EXPERIMENTAL SETUP

The experiments were made in a glass-walled flume 150 mm wide, 380 mm deep, and 12.57 m long. The discharge was 0.0167 m³/s; the mean velocity at the sampling location was 0.67 m/s. The 6.35-mm I.D. sampling nozzle was a standard plastic nozzle for the DH-59 and DH-76 suspended-sediment samplers supplied by the Federal Interagency Sedimentation Project. The nozzle was mounted in a holder that held the mouth of the nozzle in the center of the flume and the nozzle parallel to the sides of the flume while the nozzle could be moved through a complete circle around a horizontal axis. The sampling setup is shown in figure 1. The nozzle was located 1.37 m from the upstream end of the recirculating flume. Boundary layers along the flume bottom and flume walls were only partially developed. Concentrations in the center portion of the flume, where the nozzle was located, were uniform in vertical and longitudinal directions, as was verified by preliminary measurements. Three sizes of commercially graded quartz sand were used: $d_{50}=0.06$ mm, $d_{50}=0.11$ mm, $d_{50}=0.20$ mm. The particle Reynolds numbers for the sand ranged from 25.5 to 40.5 for the 0.06-mm sand, from 49.0 to 64.9 for the 0.11-mm sand, and from 80.3 to 113.1 for the 0.20-mm sand.

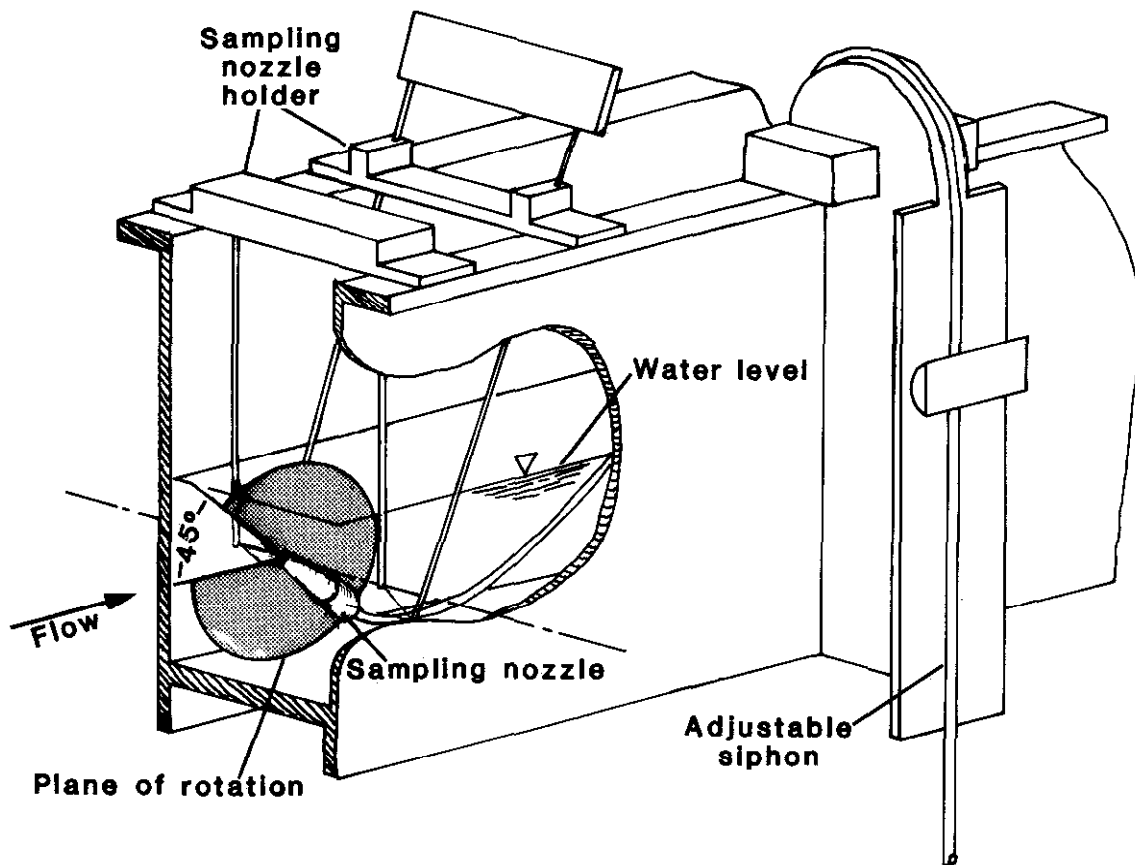


Figure 1.--Experimental setup

The sediment samples were withdrawn through adjustable siphons into containers. Two intake velocities were used: (1) isokinetic, in which the intake velocity was the same as that in the flume at the sampling point, and (2) twice-isokinetic, in which the intake velocity was twice that in the flume. Standard methods were used to determine the sand concentration of the samples (Guy, 1969).

Seven nozzle orientations to the flow were used; measured clockwise from a horizontal plane with the nozzle mouth pointing directly into the flow they are: 45 degrees, 90 degrees (the nozzle pointing straight up), 135 degrees, 180 degrees (the nozzle pointing directly downstream), 225 degrees, 270 degrees (the nozzle pointing straight down), and 315 degrees.

Two types of samples were collected--reference and test. The reference samples were collected isokinetically with the nozzle mouth facing directly into the flow. The test samples were collected with the nozzle set at one of the seven orientations. It was assumed that the average sand concentration of the reference samples collected before and after a test sample was the sand concentration in the flume at the time the test sample was collected. The errors introduced by this assumption are discussed in Winterstein and Stefan (1983). The sampling efficiency was computed as the sand concentration in the test sample divided by the average sand concentration of the reference samples.

RESULTS

Two sets of experimental runs were made: (1) Test samples were withdrawn isokinetically and, (2) test samples were withdrawn at a twice-isokinetic rate. The results of both sets of runs are shown in table 1. All three sand sizes were used in the isokinetic runs. Two sizes of quartz sand--0.06 mm and 0.20 mm--were used for the twice-isokinetic runs. The results are shown in figure 2. The results of the isokinetic and twice-isokinetic runs are compared for the 0.06-mm sand and for the 0.20-mm sand in figure 3.

Table 1. Sampling efficiency for isokinetic sampling and twice-isokinetic sampling

Sand size mm	Nozzle Orientation ¹						
	45°	90°	135°	180°	225°	270°	315°
<u>Isokinetic sampling</u>							
0.06	0.999	0.923	0.833	0.910	0.842	0.942	1.023
	.998		.843	.849	.779	.903	.989
			.823	.950		.904	
				.961			
0.11	.921	.771	.645	.914	.630	.793	.962
	.879			.873			.973
	.925			.903			
0.20	.779	.683	.415	.905	.388	.712	1.072
					.432		
<u>Twice-isokinetic sampling</u>							
0.06	.989	.940	.902	.962	.910	.950	.994
		.946				.934	
						.943	
0.02	.745	.609	.649	.867	.705	.776	1.250
	1.059	.600		.905		.798	1.052
	1.041						1.071

¹ Measured clockwise from a horizontal plane with the nozzle mouth pointing directly into the flow.

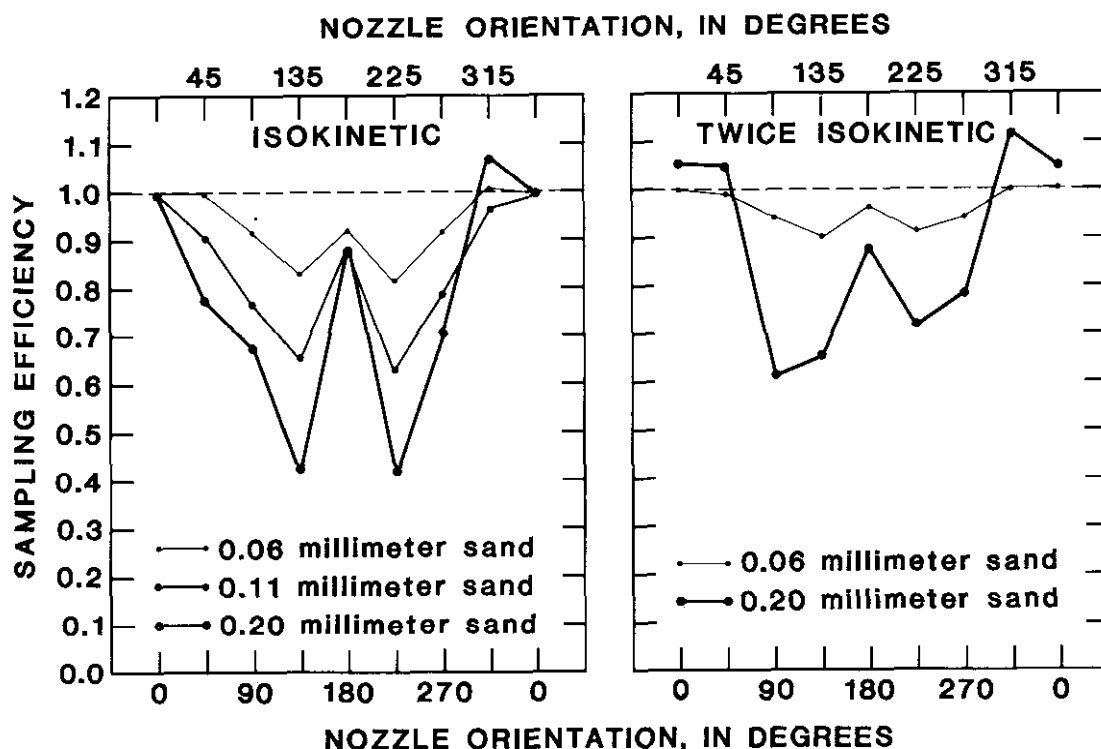


Figure 2.--Sampling efficiencies for all nozzle orientations using quartz sand, both isokinetic and twice-isokinetic experimental runs

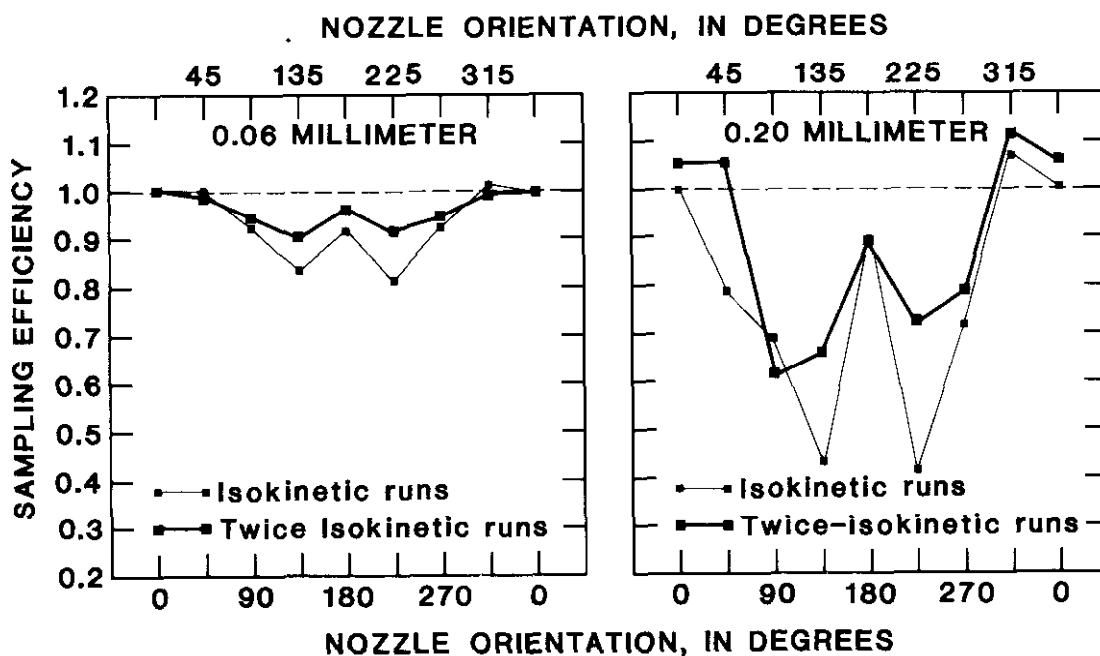


Figure 3.--Sampling efficiencies for all nozzle orientations using 0.06- and 0.20-millimeter quartz sand--isokinetic and twice-isokinetic experimental runs

As expected, the sampling error increased with increasing sand size and increasing angle between the nozzle and the flow, except when the nozzle was pointing directly downstream. Then, the sampling efficiency is about 0.90 for all sand sizes and for both withdrawal rates. An additional experiment was made to see if this unexpected result was a result of turbulence caused by the sampling nozzle, the nozzle holder and support, and/or the siphon tubing. Samples were collected at the 180 degree orientation with a brass nozzle constructed to minimize the flow disturbance at the nozzle mouth from the nozzle, nozzle holder, and siphon tubing. The results of this experiment are compared with the results from the isokinetic and twice-isokinetic experiments in figure 4.

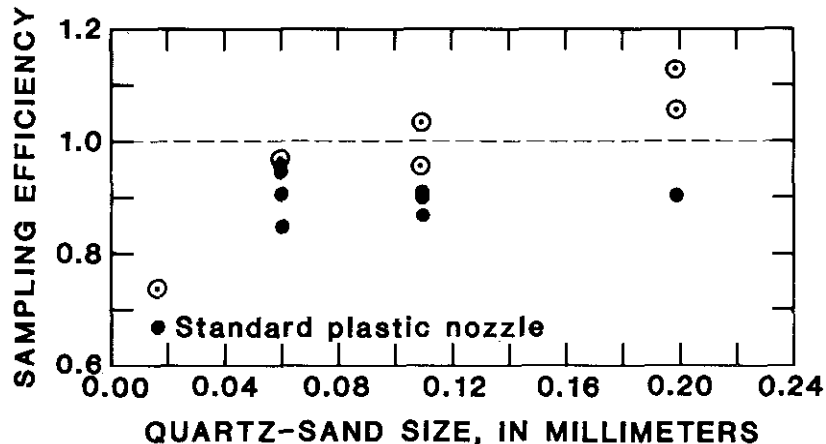
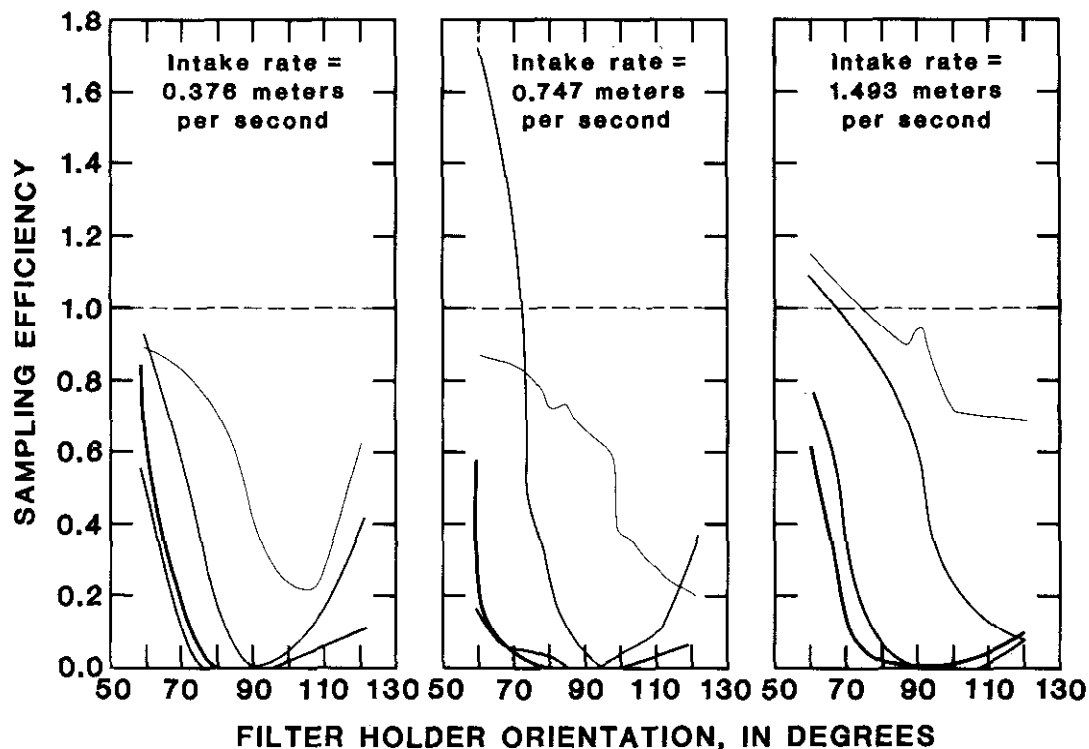


Figure 4.--Comparison of sampling efficiencies at the 180-degree orientation (modified from Winterstein and Stefan, 1983)

Dye studies indicate that the unexpectedly high sampling efficiency at the 180-degree orientation may occur because sand was thrown in front of the nozzle by the turbulent wake shed by the nozzle. Because the worst sampling efficiencies (the largest errors) occurred when the nozzle was oriented at 135 degrees and at 225 degrees, the high sampling efficiency may disappear if the nozzle is shifted a few degrees in either direction of directly downstream.

Raynor (1970) sampled ragweed pollen from air using a filter holder 3.3-cm in diameter and 2.5-cm tall at several wind speeds and intake rates and with filter-holder orientations of from 60 to 120 degrees. He found that, at some windspeeds, the efficiency of the filter holder decreased as the angle changed from 60 to 90 degrees and increased as the angle increased past 90 degrees, as shown in figure 5. He attributed this to the turbulent wake from the filter holder that moved particles into the nozzle against the general wind direction. This effect depended on windspeed. At higher windspeeds, the efficiency continued to drop until the filter-holder orientation reached 120 degrees.



EXPLANATION

WIND SPEED, IN
METERS PER SECOND:

— 0.1	— 0.4
— 0.2	— 0.7

Figure 5.--Efficiency of sampling 0.02-millimeter ragweed pollen from air at different filter holder orientations, windspeeds, and intake rates (modified from Raynor, 1970)

Sampling efficiency increases as the particle size decreases. Extending the experimental trends noted, as shown in figures 6 and 7, indicates that there is a particle size below which the sampling errors are negligible. This minimum size ranges from about 0.035 mm to 0.06 mm and is a function of withdrawal rate and nozzle orientation. The Federal Interagency Sedimentation Project (1941) found that, for nonisokinetic sampling with the nozzle pointing directly into the flow, the errors were negligible for sizes less than 0.06 mm. As a result, the size distribution of suspended-sediment samples collected by an automatic pumping sampler with the nozzle set at an angle to the flow will be biased towards the smaller sediment sizes. Particles in the clay- and silt-size ranges will only be slightly undersampled. Particles in the sand size range will be significantly undersampled. The error because of undersampling will increase as the particle size increases.

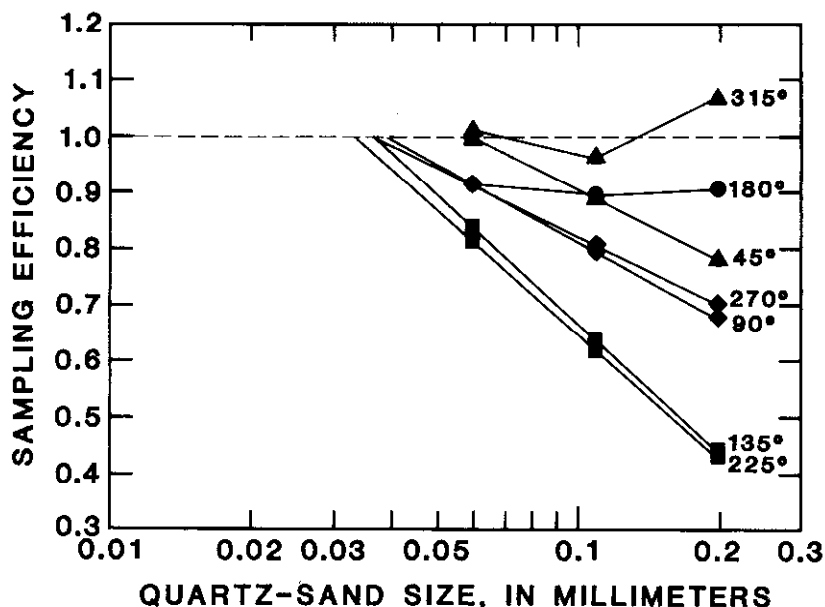


Figure 6.--Sampling trends--isokinetic sampling (modified from Winterstein and Stefan, 1983)

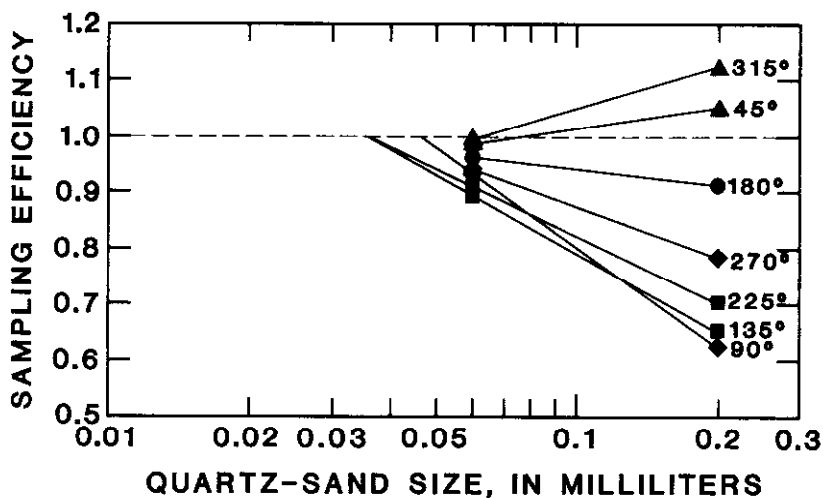


Figure 7.--Sampling trends--twice-isokinetic sampling (modified from Winterstein and Stefan, 1983)

ACKNOWLEDGMENTS

This research was done at the St. Anthony Falls Hydraulic Laboratory, University of Minnesota, Minneapolis, Minnesota. Suggestions and comments which stimulated this research were provided by John Skinner, Chief, Federal Interagency Sedimentation Project, U.S. Geological Survey. Addison Wood and shop personnel at the St. Anthony Falls Hydraulic Laboratory provided suggestions and help in the design and construction of the experimental facility.

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CONTINUOUS MEASUREMENT OF SUSPENDED-SEDIMENT CONCENTRATION

By John V. Skinner and Joseph P. Beverage, Hydrologists, U.S. Geological Survey, Federal Interagency Sedimentation Project, Minneapolis, Minnesota; Gerald L. Goddard, Hydrologic Technician, U.S. Geological Survey, Madison, Wisconsin.

ABSTRACT

A field instrument that collects sediment-concentration data is being tested at a gaging station on Willow Creek in Madison, Wisconsin. River water is pumped through a U-shaped tube that vibrates continuously. The tube's vibrational period is a function of river-water density which, in turn, is related to *suspended-sediment concentration*. At 5-minute intervals, data on vibrational period, water conductivity, and water temperature are recorded. Every 4 hours, the most current data set is automatically transmitted by telephone to a computer that stores the information for processing at a later time. During periods of high flow, the data-collection procedure is occasionally interrupted to take reference readings. The pump is stopped, the U-tube is manually filled with distilled water, and then the vibrational period is recorded. With these reference readings, the data sets can be verified and, if necessary, correction factors can be applied.

The U-tube and the data-collection devices have operated with a high-degree of reliability; however, sampling pump failures have hampered the process of evaluating the U-tube's accuracy. Data collected early in the test program indicated a probable measurement error of about ± 200 milligrams per liter (mg/L) for sediment concentration. Later, the pump was modified to increase and stabilize its discharge. Data from the last storm of record showed the probable measurement error decreased to about ± 25 mg/L.

INTRODUCTION

Development of a sediment-concentration probe is one of the more elusive problems in the field of water-quality monitoring. Probes for measuring water temperature, conductivity, and dissolved oxygen are used routinely at many gaging stations; however, probes for monitoring suspended-sediment concentration are conspicuously absent. This is not to say that solutions to the sediment monitoring problem are entirely lacking. Probes based on electric fields, light rays, sound waves, and gamma waves have met with some success in certain settings; however, all of these approaches have shortcomings. For example, optical probes are inaccurate in high concentration flows and are strongly affected by even slight shifts in grain-size distribution. Gamma probes are inaccurate in low-concentration flows.

This paper summarizes research and development work on a sediment probe based on mechanical vibration and fluid density. As shown later, the vibratory probe has certain deficiencies; however, it presents a sorely-needed alternative in the field of sediment measurements.

ACKNOWLEDGMENTS

Funding for this research program was provided by the following federal agencies: Geological Survey, Army Corps of Engineers, Environmental Protection Agency, Forest Service, Bureau of Reclamation, Agricultural Research Service, Federal Highway Administration, and Bureau of Land Management. Ancillary equipment was provided by the Geological Survey's Hydrologic Instrumentation Facility.

PRINCIPLE OF OPERATION

A way of establishing the relationship between sediment concentration and vibrational frequency is depicted in figure 1a, which shows a container of volume V suspended from a spring with a deflection constant of K . If the container is pulled away from its rest position and then released, the vessel oscillates up and down with harmonic motion. If the container's mass is considered to be negligible, the vibrational period can be expressed as $T = 2\pi \sqrt{V\rho/K}$, where ρ is the density of the water-sediment mixture inside the container. The relationship between C (sediment concentration in parts per million) and ρ is given by:

$$C = 1 \times 10^6 [\rho_s/(\rho_s - \rho_w)][(\rho - \rho_w)/\rho] \quad (1)$$

where ρ_w is water density, and ρ_s is sediment-grain density. If ρ_s , ρ_w , K , and V have fixed values, the vibrational period can be approximated as

$$T = a + b C \quad (2)$$

where a and b are constants. This approximation is nearly exact if C is small and if the particles, container, and water all oscillate together with the same phase and amplitude. As equation 2 shows, T and C are monotonically related so that C can be determined with the aid of a calibration chart and a value for T .

Three additional items are needed to make the system of figure 1a adaptable to river measurements. First, the system must be connected to tubes that carry river water through the container; second, the system must be fitted with a driver that sustains the vibratory motion; finally, the system must be equipped with data-collection equipment that measures and records the vibrational period. Figure 1b shows a system that includes these additions. The case along with its inner parts form a Dynatrol^{*} cell manufactured by Automation Products of Houston, Texas. The case is a massive steel pipe that damps vibration at the open ends of the U-tube. The curved end of the U-tube is free to vibrate as the drive coil, acting by magnetic induction, alternately pulls and pushes on the lower magnetic core. The sense-coil, also working by induction, produces a voltage as the upper magnetic core moves up and down. Springs in the form of cantilevers couple the magnetic cores to the U-tube.

The electrical components on figure 1b were designed by the Sedimentation Project (Beverage and Skinner, 1982). The "feedback amplifier" sustains vibration by accepting motion-induced voltage signals from the sense coil and then delivering an amplified version of these signals to the drive coil. The "period-measuring circuit" compares the period of the drive-coil voltage with the period of a crystal oscillator and then displays a seven-digit number termed the "count." The count reading is proportional to the U-tube's vibrational period.

SOURCES OF MEASUREMENT ERROR

The vibrational period of the U-tube is influenced by several factors that are not related to the concentration of sediment in the water. Understanding the nature and role of these error-producing factors is a critical step in obtaining accurate concentration data.

* Use of trade names in this paper does not constitute endorsement by the U.S. Geological Survey.

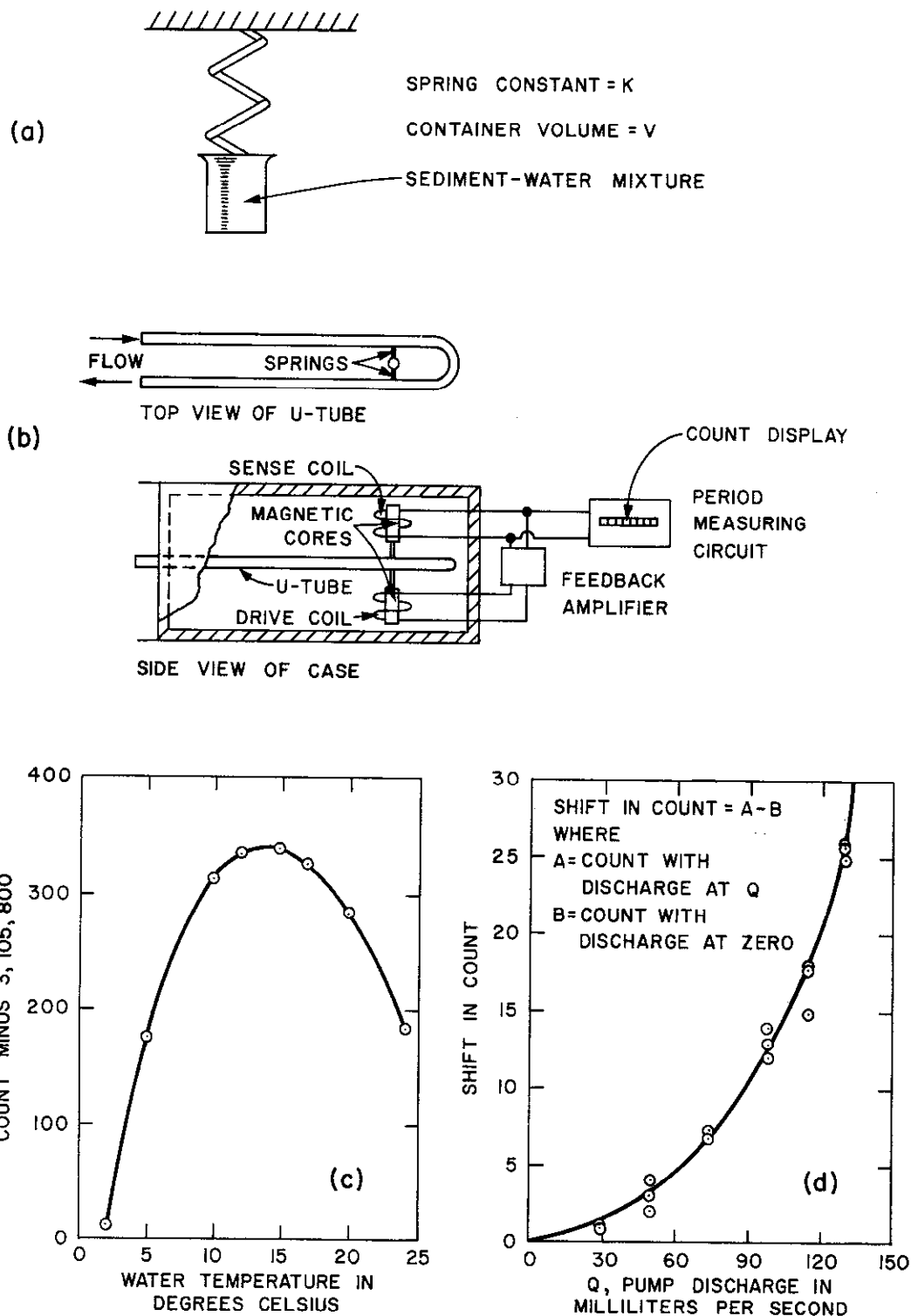


Figure 1.--(a) Spring-container arrangement for measuring sediment concentration. (b) Schematic of a flow-through concentration probe. (c) Relation between count and water temperature. (d) Relation between pumping rate and the shift in count.

Temperature is a significant factor because it alters the density of the water in the U-tube. As temperature drops, the ρ_w term in equation 1 increases until its value reaches a maximum at 4°C. The term then decreases slightly as the temperature declines toward 0°C. A temperature shift also changes the characteristics of all parts inside the instrument case. For example, a downward shift in temperature causes the springs to contract and become stiffer. All of these changes combine to produce the relationship shown on figure 1c. The graph shows that, for temperatures near 14°C, the count is only slightly affected by warming or cooling trends. At other temperatures, the count shifts dramatically with even slight changes in temperature. A warming trend starting at 0°C causes the count to increase whereas a warming trend starting at 20°C causes the count to decrease. Rapid changes in temperature create additional problems related to thermal lag. If water temperature drops abruptly, the count begins to shift but at a slow rate. Eventually the count restabilizes, but the adjustment time may be as long as 1 hour. Apparently, this thermal lag is caused by the weak thermal coupling between the U-tube and the springs, as shown on figure 1b. When the temperature of the water shifts downward, heat immediately begins to flow from the warm springs to the cool U-tube; however, this heat transfer occurs slowly because the junction is a slender rod with a small cross-sectional area. As the springs cool, they become stiffer--in other words, their K value (see fig. 1a) increases.

Compounds dissolved in the water are another source of measurement error. The relation between solution density and dissolved-solids concentration depends upon the solute's chemical composition. For compounds normally present in river water, however, this chemical factor is almost insignificant. Equal concentrations of sodium chloride, potassium chloride, and sodium sulfate all shift the count by nearly equal amounts, for example. Laboratory tests reveal another interesting fact: The gage responds to dissolved solids and to suspended sediment (specific gravity = 2.65) with nearly equal degrees of sensitivity (Beverage, 1982).

Variation of flow rate through the U-tube is another potential source of error. As flow-rate shifts to higher values, the vibrational period lengthens (and the count increases), as shown by the trend in figure 1d. The reason for this lengthening has not been definitely established. A possible cause is related to system damping. Kinetic energy delivered to the water by the vibratory motion is continuously carried away by the flow. An increase in energy loss gives rise to an increase in system damping: Timoshenko (1948, p. 38) shows that an increase in damping causes an increase in vibrational period.

Additional perturbations in vibrational period are caused by air bubbles in the water, by particles that stick to the walls of the U-tube, and by vibration of the instrument case. Air bubbles speed the vibration by decreasing the mass within the U-tube. Particles clinging to the tube walls have the opposite effect--they increase the mass. Earth and floor vibrations usually contain a component of frequency that matches the natural frequency of the U-tube. When transmitted to the instrument case, this component adds energy to the U-tube and thereby alters the system damping.

Shifts in sediment-grain size create errors, because the instrument responds more strongly to small particles than to large ones. A slurry containing only clay-size particles shifts the period about 25 percent more than a slurry containing only sand-size particles. This shift in instrument sensitivity is probably caused by slippage between the vibrating water and the suspended particles. Instead of moving in step with the vibrating water, large particles remain nearly stationary as the water sweeps back

and forth around them. Clay-size particles move with the water, and the particles and water vibrate as a unit. Grain-size errors are related to the hydraulic and sediment characteristics of the gaging site.

FIELD INSTALLATION

An experimental U-tube system was installed at the Willow Creek station near Madison, Wisconsin. Willow Creek drains about 3 mi² in a fully developed residential area. The station, which is about 300 ft downstream of a storm-sewer outlet, has a control consisting of a 6-ft wide Parshall flume installed in a concrete weir. The station was chosen because it is readily accessible to personnel at the U.S. Geological Survey District Office, and because it has a shelter with electric power and telephone service.

The experimental apparatus is shown on figure 2. The solid-arrowed lines indicate flow paths when the system is operating in the "monitoring" mode. River water flows through the pump, the heat exchanger, and the U-tube. Discharge from the U-tube flows down through the right leg of the Y fitting at the pinch valve and then empties into the river-water container. Overflow from this container empties into a waste line leading outside the shelter. Every 5 minutes, the data logger prints the count reading along with river-water temperature and conductivity. Every 4 hours, these readings are merged with file numbers, dates, times, and stage readings and are transmitted by telephone to a computer at the office. In the monitoring mode, all equipment operates automatically.

The dashed arrows on figure 2 show flow paths when the system is operating in the reference mode. About 2 quarts of distilled water are pumped into the U-tube to displace the river water. Then the flow is stopped and a count reading is recorded. Switching the system into the reference mode requires several manual operations. The operator stops the pump, rotates the pinch valve to the right, and then restarts the pump in the opposite direction. After the distilled water in the reference container has been transferred to the U-tube, the operator stops the pump and waits until the electronic circuits record the new count reading. The operator then refills the reference container from a separate distilled-water reservoir and proceeds to restore the system to the monitoring mode. During periods of low flow when little sediment is moving, a reference count reading is taken every few days; during periods of high flow, a reference reading is taken every few hours.

All of the components shown on figure 2 serve a purpose in eliminating or compensating for measurement errors discussed in the previous section. The springs at the top of the U-tube isolate the case from floor vibrations; the thermal insulation isolates the case from fluctuating air temperatures and thereby allows the entire instrument to operate at river-water temperatures. The heat exchanger and the stirring paddle in the reference container maintain the distilled water at the same temperature as the river water. The U.S.G.S. Minimonitor senses river-water temperature and conductivity so that correction factors can be applied. Discharge through the U-tube is regulated by a speed-controlled motor on the peristaltic pump. A vacuum inside the case prevents moisture from condensing on the outer walls of the U-tube within the case.

FIELD-TEST PROCEDURE

The field-tests were designed to evaluate the dependability and accuracy of the apparatus in figure 2. Performance during base-flow is monitored but most of the testing focuses on storm-related events. When a storm is forecast, an operator starts the servicing procedure by installing a new tube in the peristaltic pump. This step is probably the most critical and troublesome phase of the entire testing program. After a

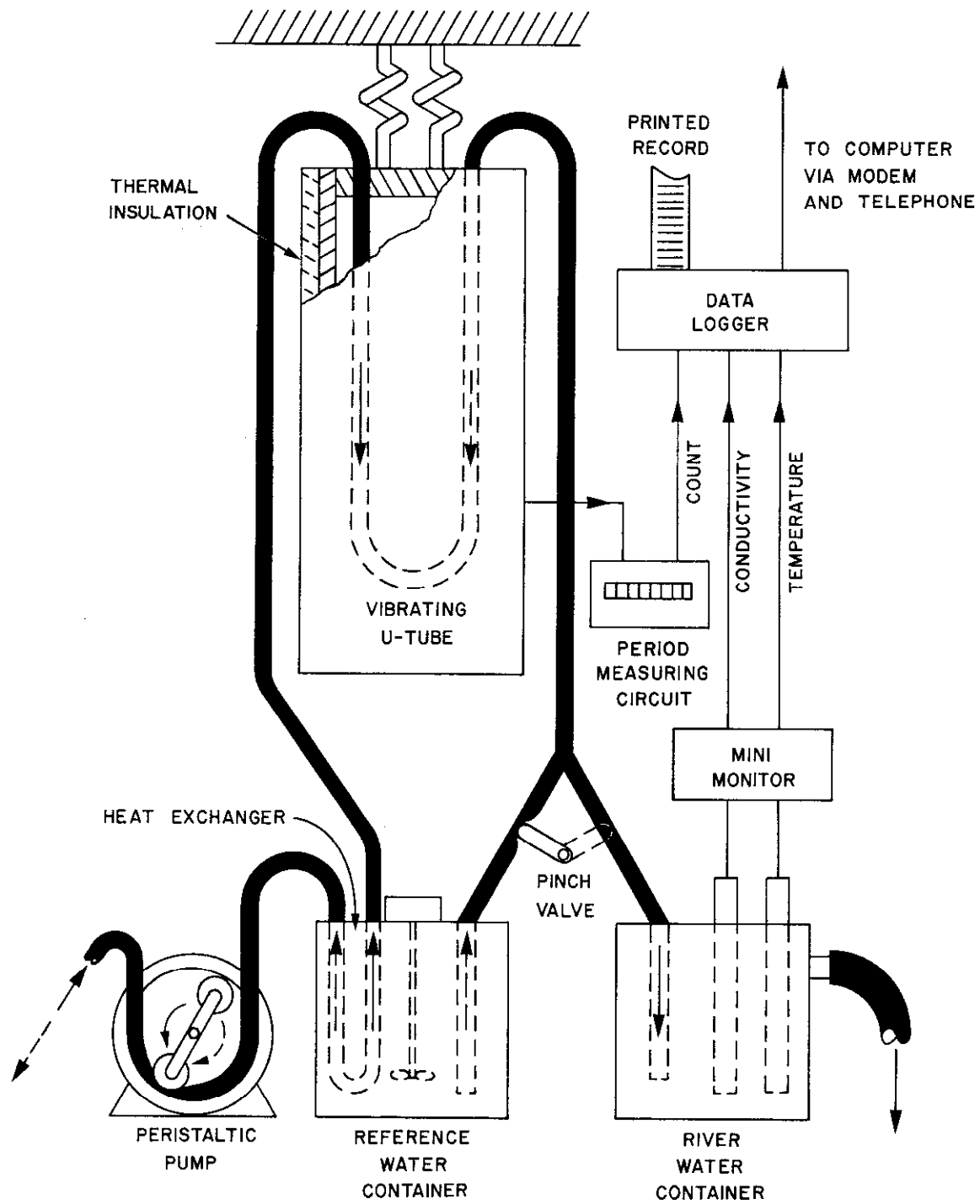


Figure 2.--Field apparatus for monitoring suspended-sediment concentration.

few hours of continuous operation, the pump tubing begins to develop hairline cracks. At first, small air bubbles leak through the cracks and become entrained in the U-tube flow. Later, the cracks lengthen, the air leaks increase, the pump rate begins to diminish, and the count readings are disturbed to a greater and greater degree. After about 12 hours of operation, the cracks reach the high-pressure side of the pump and water begins to leak onto the floor. Sometimes the leak or a diminished flow-rate is the first indication that a problem has been developing and that many of the previous count readings are invalid.

Cleaning the U-tube is another important part of preparing the equipment for a runoff event. Hoses leading to the U-tube are disconnected and a bottle brush that is soldered to a flexible speedometer cable is repeatedly pulled around the U-tube loop to clean the inside surfaces.

During the storm, the operator stays at the site and periodically takes reference readings and also collects samples from the discharge end of the U-tube.

DATA REDUCTION

The data-reduction process involves several steps that will be explained by an example extracted from the last data obtained in the test program. The complete data set began at 1800 hours on October 18 and ended at 0755 hours on October 19. A sample of this record is shown in table 1. The following discussion explains the entries starting with the left column.

Mode--"R" denotes readings collected in the reference mode: "M" denotes readings collected in the monitoring mode.

Time--Central-standard time.

Stage--River-stage in feet.

Raw count--All of these data are from the record produced by the data logger shown on figure 2. Occasionally a minor discrepancy of one unit appeared between the raw count registered on the data logger and the raw count displayed on the period-measuring circuit.

Temperature--River-water temperatures measured by the Minimonitor (see figure 2).

Pump Q--Pump-discharge data. Numbers in parentheses are discharges measured by the operator, the remaining numbers are estimates. Notice that a value of zero has been entered for all "R" readings because the distilled water in the U-tube was stagnant while the raw-count reading was being collected.

Specific conductance--River-water conductance measured by the Minimonitor (see figure 2).

Base temperature--These numbers are assigned during the data reduction process and are used as pivotal points for correcting "raw count" reading for shifts in river-water temperature. A group of consecutive readings in the temperature column is selected so that the beginning and end of the group is centered above and below a reference reading. The approximate mean temperature for the group is entered in the base temperature column.

Base Q--These numbers are assigned during the data-reduction process and are used as pivotal points for correcting the "raw count" readings for shifts in pump discharge. Assigning entries in this "base Q" column is analogous to assigning values in the "base-temperature column." A group of consecutive readings in the pump Q column is selected so that the beginning and end of the group is centered above and below a reference reading. Groups in the "pump Q" column coincide with groups in the temperature column. The approximate mean of the pump Q readings is entered in the base Q column.

Temperature correction--Values are changes in count produced by shifting temperatures from values in the temperature column to corresponding values in the base-temperature column. All changes in count are read from an enlarged plot of figure 1c.

TABLE 1.--Sample of field test data for the vibrating U-tube program.

WILLOW CREEK AT MADISON, WISCONSIN

OCTOBER 18, 1984

R		Reference mode		M		Monitoring mode		e				Estimated value		()		Measured independently	
Mode	Time	Stage (feet)	Raw count	Temp (°C)	Pump Q (mL/s)	Specific conduct. (μ S/cm)	Base temp. (°C)	Base Q (mL/s)	Temp. corr.	Q corr.	Corr. count	Net Count	Diss.- solids conc. (mg/L)	Suspended- sediment- conc. (mg/L)			
M	2030	4.73	3106178	12.2	124	36.0	12.2	120	0	-2	3106176	19	21	101			
M	2035	4.71	3106176	12.2	124	40.5	12.2	120	0	-2	3106174	17	23 (26)	86 (132)			
M	2040	4.78	e3106176	12.4	124	42.0	12.2	120	-1	-2	3106173	16	25	77			
M	2045	4.98	3106176	12.2	(123)	47.0	12.2	120	0	-1	3106175	18	27	88			
M	2050	5.04	3106182	12.3	123	50.0	12.2	120	0	-1	3106181	24	28	126 (148)			
M	2055	5.08	3106271	12.0	123	30.5	12.2	120	2	-1	3106272	115	18	718 (726)			
R	2100	5.12	3106136	12.1	0	-	12.2	120	1	20	3106157	0	0	0			
M	2105	5.13	3106225	12.3	118	27.5	12.2	120	0	0	3106225	68	17 (17)	418 (499)			
M	2110	5.12	3106200	12.2	(118)	27.5	12.2	120	0	2	3106202	45	17	271 (224)			
M	2115	5.00	3106188	12.2	118	27.0	12.2	120	0	2	3106190	33	16	195 (176)			
M	2120	4.91	3106178	12.3	(118)	28.5	12.3	117	0	0	3106178	28	17	162 (132)			
M	2125	4.76	3106172	12.3	118	28.0	12.3	117	0	0	3106172	22	17	124			
R	2130	4.70	3106132	12.4	0	-	12.3	117	-1	19	3106150	0	0	0			
M	2135	4.61	3106168	12.2	(116)	31.0	12.3	117	0	0	3106168	18	18 (17)	97 (106)			
M	2140	4.56	3106164	12.1	116	30.5	12.3	117	1	0	3106165	15	18	77 (82)			
M	2145	4.56	3106166	12.0	(116)	31.5	12.3	117	2	0	3106168	18	19	96			
M	2150	4.66	3106168	12.2	115	32.0	12.3	117	0	0	3106168	18	19	96 (102)			
M	2155	4.72	3106172	12.1	115	31.0	12.1	115	0	0	3106172	21	18	116 (128)			
M	2200	4.76	3106178	12.2	114	31.5	12.1	115	-1	0	3106177	26	19	147 (152)			
M	2205	4.79	3106176	12.4	114	31.5	12.1	115	-2	0	3106174	23	19	128			
M	2210	4.79	3106180	12.1	(113)	30.5	12.1	115	0	0	3106180	29	18	168 (156)			
M	2215	4.76	3106233	11.7	113	31.0	12.1	115	3	0	3106236	85	18	526 (456)			
M	2220	4.71	e3106220	12.2	113	31.5	12.1	115	-1	0	3106219	68	19	416			
R	2225	4.68	3106134	12.2	0	-	12.1	115	-1	18	3106151	0	0	0			
M	2230	4.61	3106170	12.1	(112)	33.5	12.1	115	0	0	3106170	19	20	102 (113)			
M	2235	4.56	3106168	12.4	(108)	34.0	12.1	115	-2	2	3106168	17	20 (16)	89 (114)			
M	2240	4.54	3106168	12.4	(122)	34.5	12.1	115	-2	-1	3106165	14	20	70			

Q correction.--Values are changes in count produced by shifting the pump discharges from values in the pump Q column to corresponding values in the base Q column. All changes in count are read from an enlarged plot of figure 1d.

Corrected count.--Each value is the sum of three numbers: Raw count, temperature correction, and Q correction. For example, at 2055 hours the corrected count of 3106272 is obtained by the following computation: $3106271 + 2 - 1$.

Net count.--Each value is the difference of two numbers in the corrected count column; one is opposite the chosen time, the other is opposite the concomitant "R" entry. For example, at 2050 hours the net count of 24 is obtained by the following computation: $3106181 - 3106157$. The net-count data is proportional to the sum of two concentrations: dissolved-solids and suspended-sediment. Laboratory tests show that the proportional constant is about 6.4. This constant is used later in computing values in the "suspended-sediment concentration" column.

Dissolved-solids concentration.--Numbers in parentheses are laboratory values. As suggested by Beverage (1982), these analyses were plotted against conductivity readings and this relationship (see fig. 3a) was then used to convert all conductivity readings in table 1 to dissolved-solids concentrations.

Suspended-sediment concentration.--Values shown are computed by multiplying net counts by 6.4 and then subtracting dissolved-solids concentrations. The numbers in parentheses are sediment concentrations obtained by analyzing samples collected from the discharge end of the U-tube.

FIELD-TEST RESULTS

The "suspended-sediment concentration" column in table 1 shows discrepancies between computed and sampled concentrations. For example, the computed value is 86 mg/L at time 2035, whereas the measured value is 132 mg/L. Figure 3b compares computed and sampled values for the sixteen pairs listed on the table. The scatter on figure 3b indicates that the "probable error statistic" is about ± 25 mg/L. In other words, half of the plotted points deviate from the line of equality by less than 25 mg/L. By comparison, data for storms that occurred early in the test program had a much larger probable error--about ± 200 mg/L.

Two factors reduced the probable error in the October 18 data. One factor is related to river-water temperature. During October 18, temperatures were not only stable but plotted near the level part of the temperature-correction curve. This led to the small temperature-corrections in table 1. The other factor is related to the pump. Experience has taught the importance of replacing the pump tubing frequently and of stabilizing the pumping rate at about 115 mL/s. During many of the early tests, the pumping rate fell to about 50 mL/s--a rate that probably allowed sediment to deposit at the bottom of the U-tube.

A time-series plot of the October 18 event is shown in figure 3c. Several features should be noted. The instrument recorded sharp sediment peaks when there was little change in stage. Sediment peaks of this nature probably would be missed in a manual-sampling program. Also, it is unlikely that a sediment-rating curve would reflect the rapid fluctuations. The 5-minute interval between successive measurements is required to detect both shape and amplitude of each spike. Shorter time intervals are possible.

Finally, one point must be emphasized: Figure 3c represents the sediment concentration at the pumping intake and not the mean concentration in the river cross section.

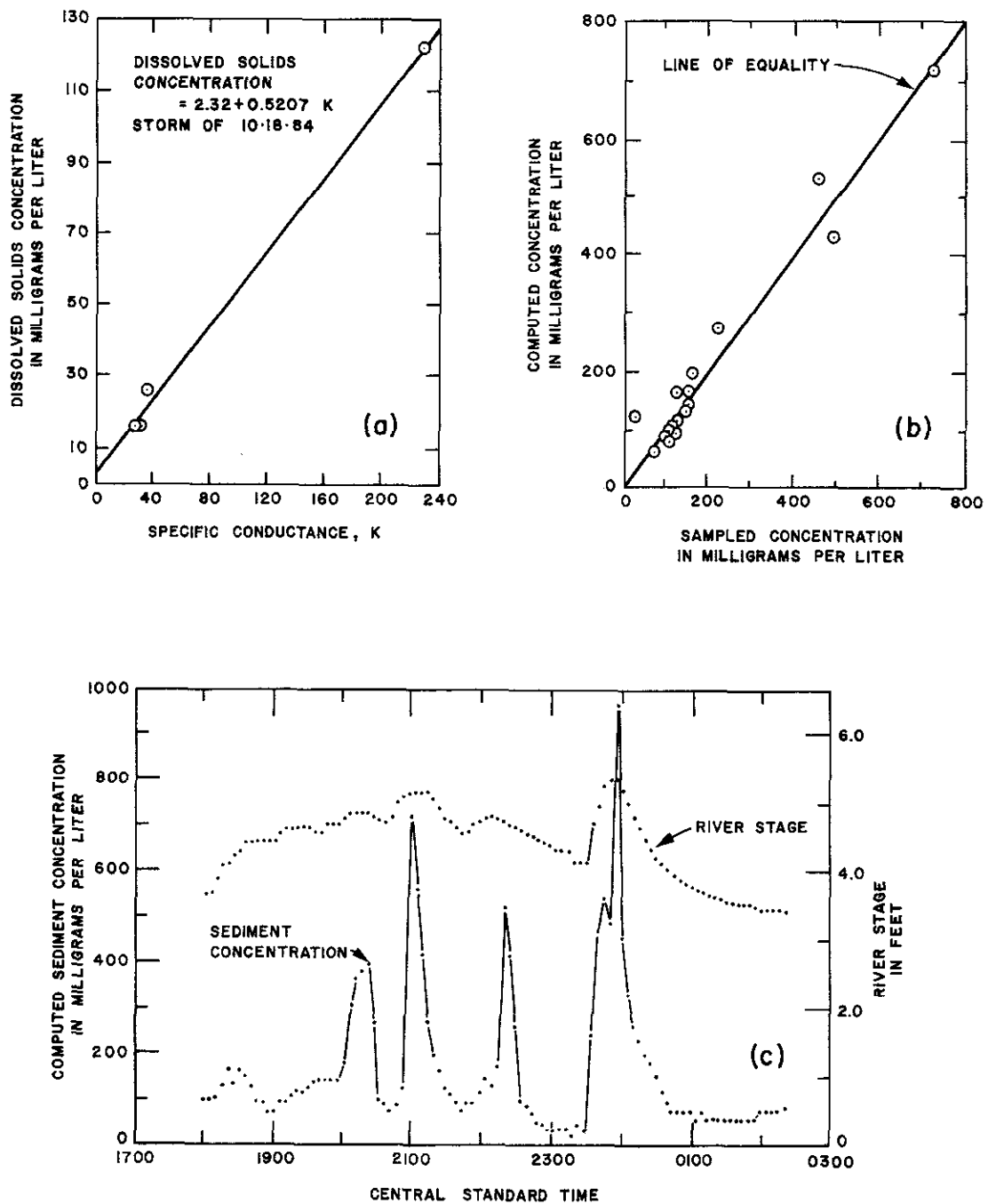


Figure 3.--(a) Relation between dissolved-solids concentration and specific conductance at the Willow Creek site on Oct. 18, 1984. (b) Comparison of computed and sampled concentrations for storm of Oct. 18-19. (c) Stage and computed sediment-concentration hydrograph for same storm.

FUTURE DEVELOPMENT

Future work with vibrational-type sensors will follow two directions. In one direction, work on the U-tube will be continued. Studies will focus on improving the hardware (principally the pump) and correcting the U-tube's temperature-response problems. In the other direction, research on a new style of vibrating gage will be started. This gage will consist of a straight tube inside a streamlined, submersible case.

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INSTRUMENTS FOR MEASURING SUSPENDED SEDIMENT

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ABSTRACT

In recent years, a high priority has been placed on advancing the technology for determining the concentration and size distribution of suspended sediment, both in the field and laboratory. The U.S. Geological Survey's Instrument Development Laboratory is investigating the application of off-the-shelf commercial instrumentation to satisfy the needs and requirements of the sediment community. These activities include the support of testing and evaluation in the field and laboratory. Instruments utilizing basic phenomena such as x-rays, ultrasonics, infrared and other light, and inertial characteristics are being evaluated. Existing equipment is being updated and/or redesigned to incorporate technical improvements. Major emphasis is on the quality of collected data and the reduction of cost in acquiring the data.

INTRODUCTION

In support of the U.S. Geological Survey's requirements for automated hydrologic data collection, instrumentation services have been consolidated into a single organization known as the Hydrologic Instrumentation Facility (HIF) (fig. 1). Instrumentation developed and supported by the HIF is installed at thousands of data-collection stations throughout the country providing data for numerous hydrologic assessments, studies, and other programs. The IDL (Instrument Development Laboratory) is that part of the HIF directly concerned with research, design, and development activities that update and modify existing instrumentation and customize commercial equipment to meet specialized requirements for the Survey.

One area of high priority to the IDL is the utilization of commercial instrumentation and equipment to satisfy the needs of the sediment community. There is a long-standing need to rapidly measure the concentration and size distribution of suspended sediment transported in rivers and streams. Normally, streams are sampled daily during periods of high flows; samples are collected manually by observers and at some stations automatically by programmed sampling equipment. These samples are sent to a laboratory and analyzed for concentration and particle-size distribution by techniques that are cumbersome, time consuming, and labor intensive. Daily sediment loads are computed based on results of the sample analyses, knowledge of the stream discharge, and other pertinent characteristics.

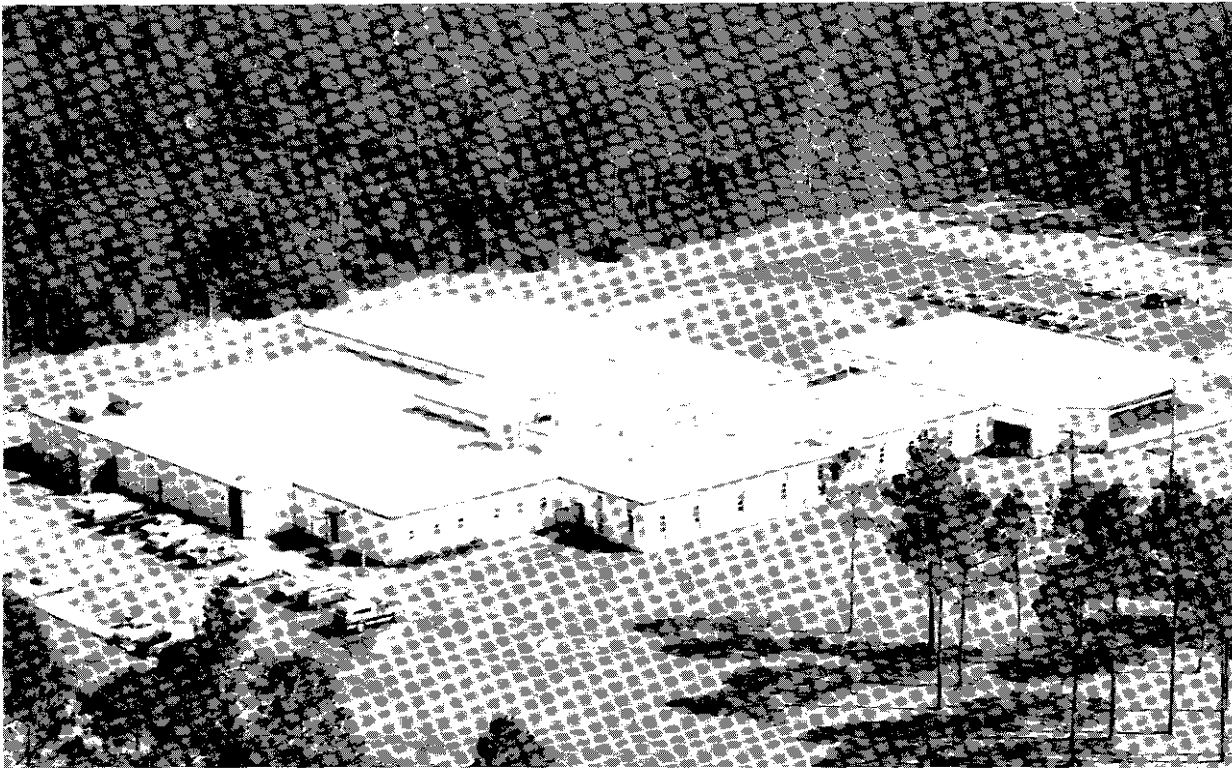


Figure 1. U. S. Geological Survey's Hydrologic Instrumentation Facility.

Other means of detecting and measuring concentrations of suspended sediment both at the stream and in the laboratory should be investigated in order to improve accuracy and to reduce the cost of analyses and records computations.

At the IDL, a project has been ongoing since 1982 to investigate the needs of the Survey for sediment instrumentation. The objectives of this project are to:

- o Evaluate recently developed commercial instrumentation for measuring the concentration and particle-size distribution of suspended sediment.
- o Determine what benefits might accrue such as labor-savings, increased accuracy, and quality of measurements from the use of such instrumentation.
- o Indicate what future development would be needed to improve such instrumentation.

The approach that the IDL uses for the investigation areas follows: Commercial technical literature is scanned for offerings of new instrumentation and improved old instrumentation that might have possible application.

In many cases, ads are placed in the Commerce Business Daily indicating the specific needs for instrumentation. Discussions are held with manufacturers' representatives to provide additional information. In some cases after procurement, an instrument may need to be altered or interfaced to other equipment in order to achieve the desired application. Since few in-house facilities exist at the IDL to evaluate instrumentation for long-term measurement of suspended sediment, the instrumentation is sent to Survey Districts having the stream sites and flow conditions, as well as the capability and the willingness to operate and evaluate the instrumentation. The IDL provides instrumentation, equipment, test plans and technical assistance. The Districts are required to furnish implementation plans, progress reports and final reports. In addition, support is provided when necessary to research activities that can provide technical assistance in specialized areas.

Purpose

The purpose of this paper is to summarize the progress made during the last few years in the evaluation of instrumentation and equipment for the automatic monitoring of sediment concentration and size and is based on activities by the District personnel involved in the various instrument evaluations. Some of the activities covered in only general terms here will be specifically reported at this conference by the individuals directly involved in the evaluations.

X-RAY PARTICLE SIZE ANALYZER

Description and Theory of Operation

The SediGraph¹ 5000D particle size analyzer is manufactured by Micromeritics Instrument Corporation, and uses x-ray technology to automatically determine the particle-size distribution of sediment in a water-sediment mixture. The results of a determination are presented as a plot of the (Stokes) equivalent spherical diameter versus cumulative mass percent finer. The instrument has a size measurement range of 0.1 to 100 microns equivalent spherical diameter. Cost of the SediGraph was about \$22,000.

Field Testing and Evaluation

The Iowa District of the Geological Survey has a sediment laboratory capable of handling all types of sediment analyses, and personnel who having experience and expertise with various analytical methods. O.G. Lara and W.J. Matthes of the district proposed to operate the SediGraph in parallel with the pipet system and to analyze identical samples with each method. The pipet method has been used by the Survey for many years and requires skilled technicians. Results of the analyses were to be compared and evaluated to determine if the SediGraph would be an acceptable alternative to the pipet method. A SediGraph was procured by the IDL and sent to Iowa for test and evaluation where the study was conducted in 1983.

Results

Lara and Matthes (1985, 'The SediGraph as an Alternative Method to the Pipet': Iowa City, Iowa, U.S. Geological Survey, unpublished paper, 11p.) report that the best agreement between the pipet method and the SediGraph was obtained with samples having a large proportion of fine sediment, in the range of 50- to 60-percent finer than one micron equivalent spherical diameter. Samples having the largest proportion of coarse sediment, 65- to 75-percent larger than 10 microns in diameter, had the largest differences in values when determined by both methods.

Time for the analysis of a sample by the SediGraph was about 50-percent less than the pipet method. Training of an operator for the SediGraph is less demanding than for the pipet method. The study also showed the SediGraph method to be convenient, efficient, reproducible, and the results to be comparable with the pipet method. In addition, it is more readily adaptable to automatic data processing than the pipet method.

Lara and Matthes recommended that the SediGraph be considered for adoption as the standard method for particle-size analysis of suspended sediment.

VIBRATING U-TUBE FLUID-DENSITY GAGE

Description and Theory of Operation

J.V. Skinner and J.P. Beverage of the Federal Interagency Sedimentation Project conducted laboratory tests to evaluate the usefulness of a vibrating U-tube fluid-density gage for continuous field measurement of the concentration of inorganic suspended sediment in rivers. Their reports (Beverage and Skinner, 1974; Skinner, 1982) indicate that the density gage has many desirable features and is sensitive to the changes in density that occur when sediment is suspended in water. However, corrections need to be applied to compensate for the effects of temperature and dissolved solids on the density of the water-sediment mixture.

A vibrating U-tube is essentially an elastic beam with one end attached to a fixed support. The response is similar to that of a tuning fork. When the ends of a U-tube are fastened to a heavy support, the free end will vibrate; the period of vibration is dependent on the length, mass, shape, and elastic properties of the tube. A water-sediment mixture in the tube will also vibrate. The mass of the water-sediment mixture will vary with the suspended-sediment concentration, thus affecting the period of vibration. A sensing coil, amplifier, driving coil, and permanent magnets are added to keep the U-tube vibrating continuously. An accurate counter is used to determine the average period of vibration over a time length of about two and one-half minutes. As the water-sediment mixture is pumped through the vibrating U-tube, the period of vibration varies directly and linearly with the density of the water-sediment mixture or the sediment concentration if compensation is made for other variables such as temperature and dissolved solids.

Field Testing and Evaluation

The Wisconsin District submitted a proposal to evaluate the vibrating U-tube density meter on Willow Creek at Madison, Wisconsin. In 1982 the IDL provided a vibrating U-tube and supporting instrumentation to J.V. Skinner of the Federal Interagency Sedimentation Project and a test apparatus was constructed (fig. 2). The apparatus included a U-tube, a USGS minimonitor for measuring temperature and specific conductance, a calibrating solution tank, several pumps, and a solid-state recorder-printer. All this was mounted in a rack suitable for installation at the Wisconsin field site. In addition, an automatic sampler was provided to obtain samples to cross-check the values reported by the U-tube density meter. Total instrument costs exceeded \$10,000.

W.J. Rose and G.L. Goddard of the Wisconsin District installed the apparatus in the late summer of 1983. The station was then operated throughout 1984.

Results

Goddard (written commun., 1984) reported that a total of 11 flow events were monitored in 1983 and 1984 during which instrument readings were recorded and sediment samples taken.

During the events, Goddard experienced problems with the pump and operation of the apparatus. Some of the problems he corrected; others required modification to the apparatus design. The solid-state data-recording system proved to be quite successful. The district's Prime computer was programmed to call the station automatically, retrieve data from the recorder, and store the data in a master file for later analysis.

Goddard found that because Willow Creek was so quick to respond to storm events, he needed to get to the station in a short time in order to

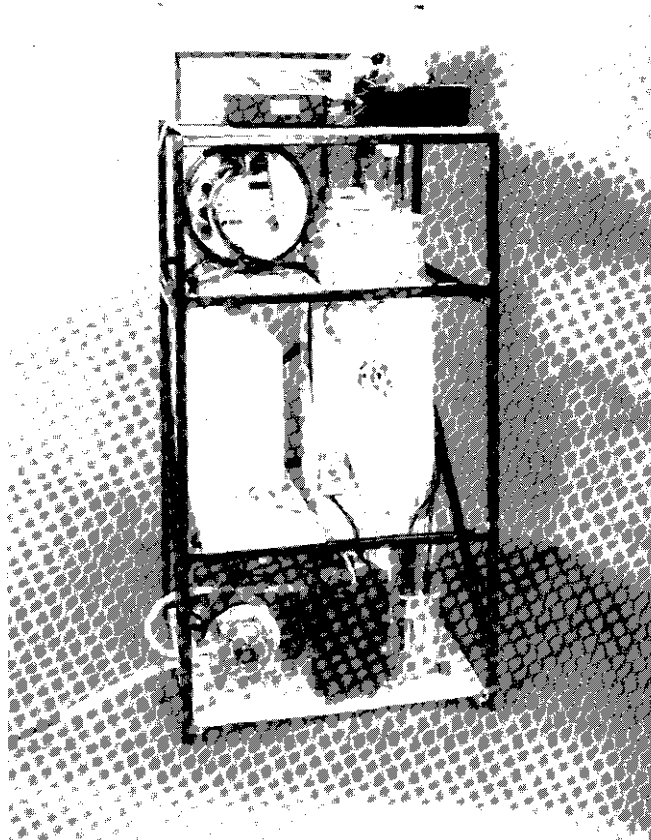


Figure 2. Vibrating U-tube densiometer apparatus.

oversee an event. He also found that the concentrations of suspended sediment during most of the event were not great enough to completely test a broad variance in readings obtained from the density meter.

John Skinner (written commun., 1984) looked at the Willow Creek field data and reported that all but one of the field samples had "total concentrations" of sediment less than 1100 mg/l and the data exhibited more scatter than concentrations obtained from a density meter operated in his laboratory. Most of the low-concentration data are within an error band that is about ± 250 mg/l wide.

Skinner indicates that unsteadiness seems to be a problem, perhaps caused in part by the method of collecting field samples. He also found that density-meter readings jumped to levels unexplainable by changes in dissolved solids, water temperature, or suspended sediment. The readings may have been caused by air leaking into the system.

Skinner shows that the output reading of the density meter shifts with the rate of flow through the U-tube. With the present system, a water-discharge shift may easily go undetected, resulting in a reading change erroneously attributed to a shift in sediment concentration.

Skinner notes that one of the advantages of the density meter is that it collects a nearly continuous record and, therefore, is able to document short-term events that may be important in the sediment-transport process. He shows an example of this capability by using the data from an event at Willow Creek, to calculate that of the sediment discharged during the event, 95 percent passed the station in only ten minutes.

Goddard recommends that a different type of pump be used, one providing a more reliable and continuous flow than the peristaltic pump now in use. He suggests changes in the design to improve the operation and servicing of the density-meter apparatus. Some of the suggested design changes to improve operation are an intake strainer and an automatic backflush and/or shutoff system chambers to prevent accumulation of sediment. Goddard indicates that values of temperature and specific conductance should be recorded more often and the flow rate should be monitored. Goddard also recommends that the density apparatus be installed at a site having hydrologic characteristics more suitable for evaluation of the meter. He suggests a site on Pheasant Branch at Century Avenue in Middleton, Wisconsin. Pheasant Branch is less flashy than Willow Creek and has longer periods of storm runoff. A large shelter with electric power is also available at the suggested site.

ULTRASONIC SUSPENDED-SOLIDS METER

Description and Theory of Operation

The ultrasonic suspended-solids meter is a device having an underwater probe suspended on a plastic pipe. The probe cage contains an ultrasonic transducer (transmitter) and receiver with a stainless steel reflector. Electronic circuitry is mounted in a shelter streamside and a shielded cable is connected to the probe.

An ultrasonic signal is generated at the transducer and passes through the water-sediment mixture in the gap between the transducer and the stainless steel reflector. Suspended-solids particles in the probe gap absorb and scatter ultrasonic waves and attenuate the signal as it passes to the reflector and back. The received signal is analyzed electronically and displayed as a voltage generated representing percent solids.

The instrument is manufactured by Markland Specialties Engineering, Ltd, Ontario, Canada, and is marketed primarily for automatically detecting and measuring sludge in waste-treatment tanks. Since the meter has a range of 0.05 percent (500 mg/l) to 7 percent (70,000 mg/l), suspended-solids field test sites need to be selected that have rivers carrying relatively high concentrations of suspended sediment.

Field Testing and Operation

The IDL procured two ultrasonic solids meters for evaluation at selected field sites. The Vancouver, Washington, subdistrict office agreed to evaluate one meter which was installed on the North Fork of the Toutle River at Kid Valley, Washington. This is a daily sediment station equipped with a PS-69 pumping sediment sampler. A chart recorder was installed to record the voltage output from the ultrasonic solids meter; the output was to be compared with results from the P-69 pumping sampler.

The New Mexico District agreed to evaluate an ultrasonic solids meter and installed it at a site on the Rio Grande Floodway at San Acacia, New Mexico. A shelter was constructed, and the meter and recorder were installed (figs. 3 and 4). D.E. Funderburg and D.R. Rankin were involved in evaluating the meter, with Kim Ong providing technical assistance.

Results

At the time the ultrasonic suspended-solids meter was procured, four water-sediment mixtures were submitted to the Markland Company for testing with their meter. Some mixtures contained silt, clay, and sand; others contained no sand. Results (J. Tansony, written commun., 1982) of the tests on these samples (fig. 5) indicate that all four samples showed about the same meter outputs at concentration levels from about one percent to four and one-half percent solids. Above this concentration, however, the samples containing the sand showed greater sonic attenuation (greater meter output) than the samples containing only silt and clay. The meter output was linear from one percent to ten percent with the silt-clay samples. Particle-size distribution does affect the rating curve, especially at higher concentrations.

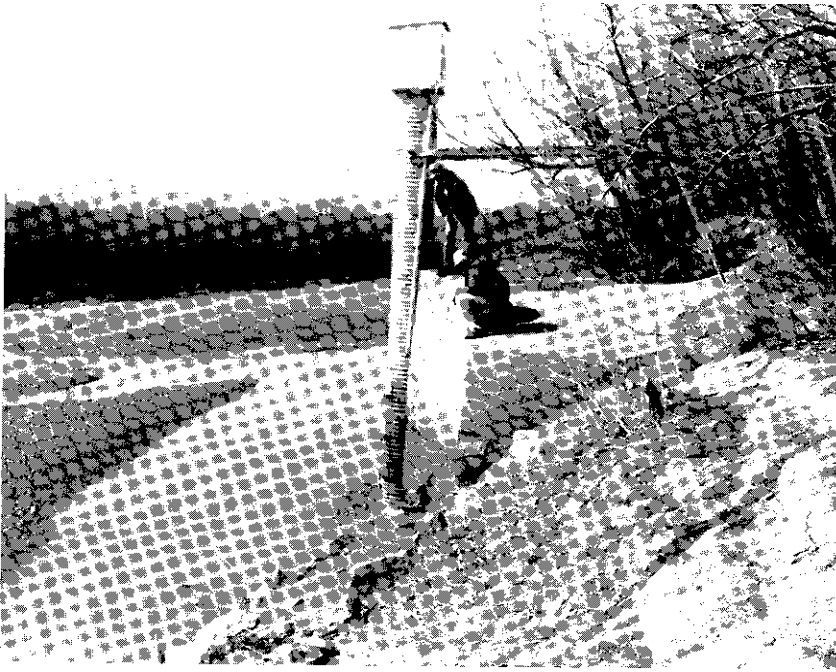


Figure 3. The field evaluation site on the Rio Grande Floodway at San Acacia, New Mexico.



Figure 4. D. R. Rankin holding an ultrasonic probe.

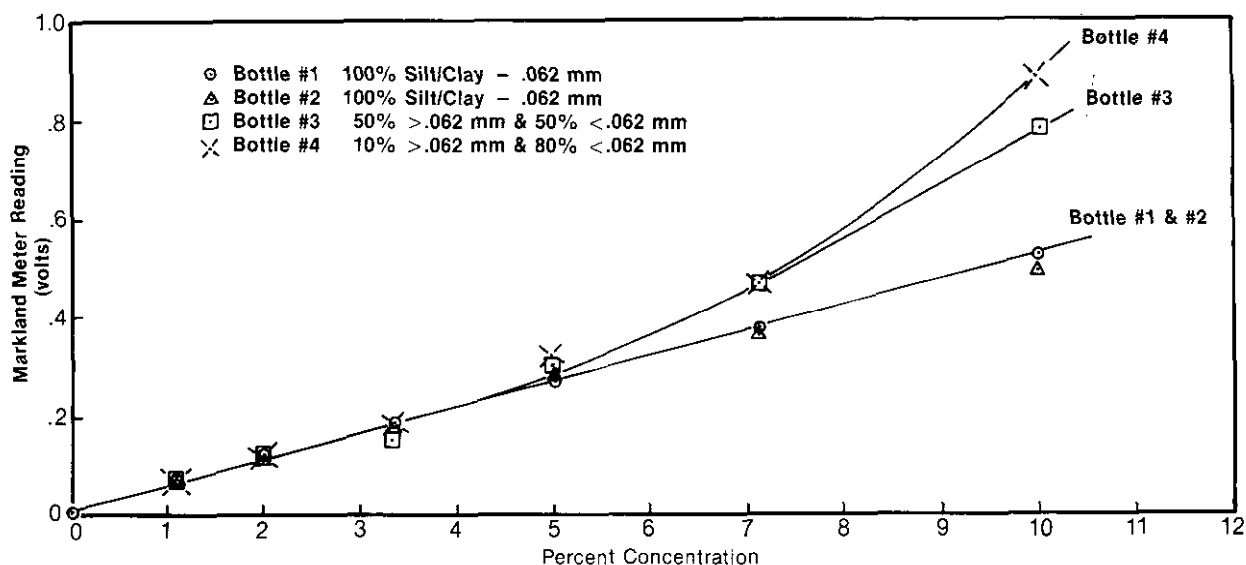


Figure 5. Graph showing ultrasonic suspended-solids meter readings versus concentration in four samples of Mt. St. Helens silt/clay/ash slurry.

Rick Kittelson, (written commun., 1984), Vancouver, Washington, reports that there is a correlation between the output of the ultrasonic suspended-solids meter and actual concentrations as obtained from a point sampler in close proximity to the probe. (The data show that all comparisons were made at sediment concentrations ranging between 1470 to 5070 mg/l, which was less than the five percent of the full-scale output of the meter.)

On May 14, 1984, a minor eruption of Mount St. Helens produced a high sediment-concentration flow in the North Fork Toutle River. Comparison of sediment concentrations in the PS-69 samples with the meter readings show that the ultrasonic meter did follow the peak.

Kittelson indicated that the small strip-chart recorder used with the ultrasonic meter was a hindrance because of the difficulty in reading the narrow chart paper. Kittelson recommended using some other data logger or recorder having better resolution than the small recorder. He also found that grass and other debris were easily trapped in the probe cage and tended to block the ultrasonic signal. However, the meter did indicate when increases in concentration occurred and he found the instrument to be a helpful tool in computing the sediment-discharge record.

D.E. Funderburg and D.R. Rankin (written commun., 1984) indicated that after 22 months of operation in New Mexico the ultrasonic suspended-solids meter was not well suited for reliable documentation of sediment concentrations observed at that site. For many periods, often of long duration, the water level dropped below the probe. Funderburg also found that the probe took

about five days to resaturate after drying. He recommended further evaluation at a more suitable site. He selected a location on the Rio Grande Conveyance Channel at San Acacia, New Mexico and the ultrasonic solids meter was installed at that site.

Another common occurrence was that sediment concentrations were too low (well under 5000 mg/l) for the meter to accurately measure them. In addition, scum on the transducer and reflector surfaces tended to block the ultrasonic signal. Grass and debris trapped in the probe cage also interfered with or blocked the signal.

Funderburg indicated that he found the meter to be generally well designed and well built, requiring little maintenance or repair, and after initial calibration needed little readjustment in the field. The unsuccessful performance of the instrument was mainly due to site conditions.

FURTHER ACTIVITIES

X-Ray Particle-Size Analyzer

The IDL contemplates no further activity associated with the X-Ray Particle-Size Analyzer unless technical advances associated with this method takes place.

Vibrating U-Tube Fluid-Density Gage

The IDL will support the activities of the Federal Interagency Sedimentation Project and the Wisconsin District. The density gage will be installed at a new site having higher concentrations of suspended sediment than the previous site.

Ultrasonic Suspended-Solids Meter

The IDL will support further evaluation of the suspended-solids meters in Washington and New Mexico. In New Mexico, the meter has been installed at another site more suited to the measuring capabilities of the meter.

Other Instrumentation

Two Optical Suspended-Solids Meters are now being procured for evaluation. These are battery-powered instruments using a four-part beam system to reduce the effects of fouling and partial obscuring of windows. They are suitable for ranges in concentration of suspended sediment lower than that measured by the ultrasonic solids meter. One meter will be installed in New Mexico at the same site as the ultrasonic meter. The other will be installed in Kentucky. The PS-82, a newly designed automatic sampler for suspended sediment, is being procured from the Federal Interagency Sedimentation Project. The sampler will be installed and operated at the New Mexico evaluation site.

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SMALL WATERSHED AUTOMATIC WATER QUALITY SAMPLER

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ABSTRACT

A total-load, automatic sediment sampler has been developed for use with pre-calibrated runoff-measuring devices in association with small watershed water quality research. The system collects individual samples periodically during a runoff event at the exit of the precalibrated measuring flume. The system consists of two parts, the sampler and the sample storage mechanism. The sampler is a vertical slot which traverses across the flume exit on a horizontal rail. The traverse speed of the slot is controlled by the design criteria of the sample storage mechanism. On early models of the unit, sample storage was a revolving table with a capacity of 18 two-liter bottles. For these early units, the traverse speed was made variable and regulated by the flow depth and, in turn, by the discharge rate. Subsequent designs have replaced the revolving table with a continuous chain to which the sample bottles are attached. In this design, the slot makes multiple traverses until a preset sample size is obtained. Following filling, the bottle is lifted from the position where the discharge from the slot fills the bottle. Each traverse (bottle filling) is recorded on the water stage recorder. System power is obtained from a 12-volt battery charged by a photovoltaic cell. This allows sampler operation in remote areas where conventional electrical power is not economically available.

INTRODUCTION

The need for water quality sampling has been greatly increased by non-point pollution legislation associated with Section 208 of PL 92-500. To accomplish the mandates of the legislation, information was required on the pollution resulting from management alternatives for the infinite combination of climatic, soil, topographic conditions, and land uses in the United States. Such data then, when used with physically based models, allow making the decisions necessary to eliminate and/or control nonpoint pollution sources.

Water quality sampling in small watershed studies is difficult because unpredictable storms cause rapid watershed response to precipitation events, and precludes personnel being present; conventional AC power is often not available to power equipment that might be used to collect samples; and most battery operated pumping-type samplers (widely used in many nonpoint pollution research efforts) have intakes at fixed positions in a flow cross-section. Since sediment and other pollutants vary widely with depth and across the stream, fixed intakes become a variable position relative to the cross section and discharge of an individual flow. As such, it is difficult to resolve these point concentration estimates into total discharge rates or yields.

In ephemeral streams of the southwestern U.S., stream channels are characteristically steep (slopes $> 1\%$), contain large quantities of coarse alluvium (geometric mean grain size of 1 to 3 mm), and the flow depths and discharges

vary rapidly in time in response to air-mass thunderstorms which are of high intensity and short duration. Collecting water quality samples under such conditions requires that the sampler can:

- (1) obtain discrete samples throughout the hydrograph,
- (2) sample the entire flow depth and width,
- (3) sample at remote sites using battery power,
- (4) sample unattended,
- (5) sample coarse and fine sediments and chemicals,
- (6) sample multiple runoff events,
- (7) sample at different frequencies because of expected concentration variations.

The sampling equipment developed in response to these design requirements evolved from a series of experiments and experience with a number of prototype designs at the Southwest Rangeland Watershed Research Center. The earliest example of this concept of automated sampling equipment was developed by Libby (1968) for use on Walnut Gulch large supercritical flumes. Libby's sampler only traversed half the width of flow, required AC power, was not automatic, and sampled only the bottom 30 cm of flow. Dendy (1973) developed a sampler similar to the one described here, except that his only collected bulk samples, not discrete ones through time, and did not use photovoltaic battery chargers. The first generation of this automatic sampler was reported at the Third Interagency Sedimentation Conference (Renard et al., 1976). The current version includes the use of a supercritical flow measuring flume (Smith et al., 1981), a multistage timer for sampling interval control, and a sample-bottle storage-mechanism on a continuous chain that lifts filled sample bottles from the filling position to the storage facility. Throughout the development, simplicity and low maintenance were essential design considerations. The flume and sampler were built for under \$20,000.

Figures 1a and 1b show a typical flume-sampler installation on the Walnut Gulch Experimental Watershed near Tombstone, Arizona. The $1.4 \text{ m}^3/\text{s}$ supercritical flume measures the surface outflow from a 3.68 ha watershed. A schematic diagram of the essential features of the sampler and flume is given in Figure 2.

GENERAL SAMPLER OPERATION

Essential features of the sampler consist of: (1) energizing switch (activated from water level recorder), (2) traversing slot at flume exit, (3) power system for traversing slot, (4) fixed slots beneath flume exit, (5) continuous chain for sample storage, (6) bottle filling sensor, (7) photovoltaic cell for charging 12-volt DC battery, (8) marking system to show sample collection time on stage graph, and (9) a system of electronics to control the sampling sequences and other mechanical operations.

Energizing switch: The sampler is activated by an on-off switch that has been attached to a gear on the flume water-level recorder. In applications used in Arizona, the switch was set so sampling cycles would start when the flow was deeper than 5 cm (smaller flows require too many traverses of the slot to obtain an aliquot sufficiently large for laboratory analysis).

Traversing slot: The traversing slot (made of stainless steel to minimize

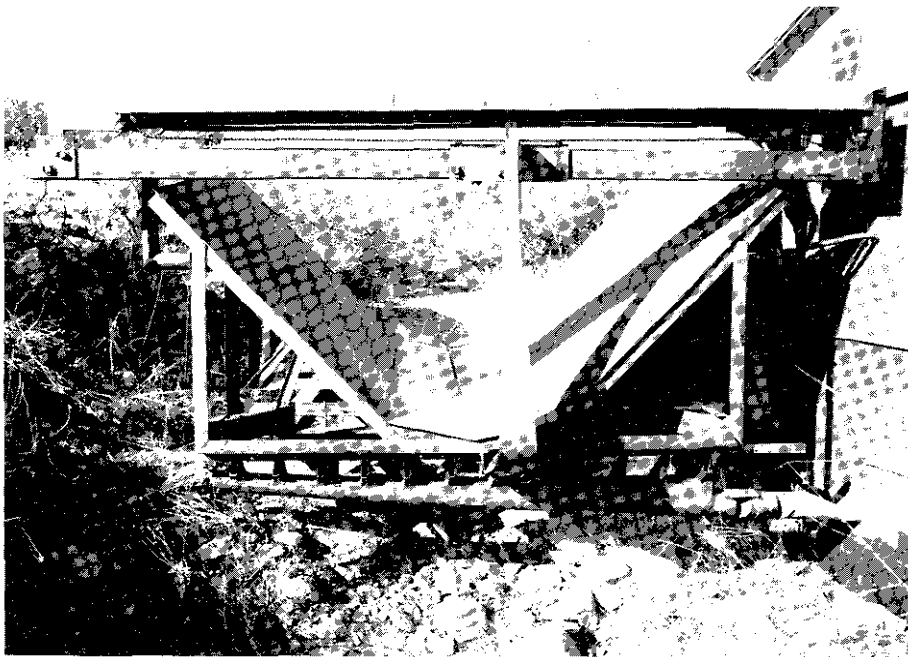


Fig. 1a. Typical slot sampler as installed on a $1.4 \text{ m}^3 \text{ s}^{-1}$ super critical flume. The downstream view shows the moveable and fixed slots, the flume, and the bottle storage mechanism house.

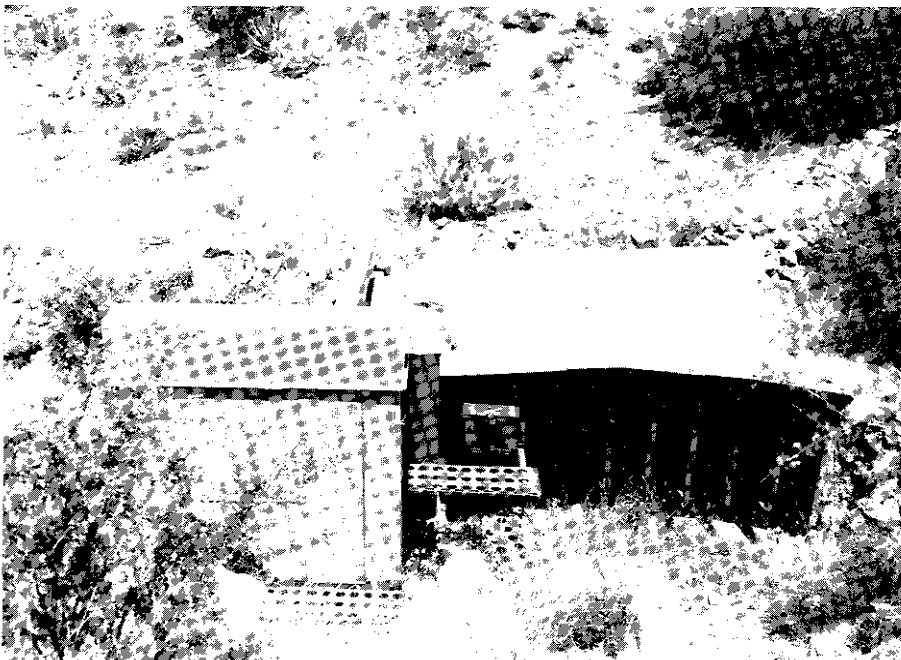


Fig. 1b. A side view of the flume and sampler installation.

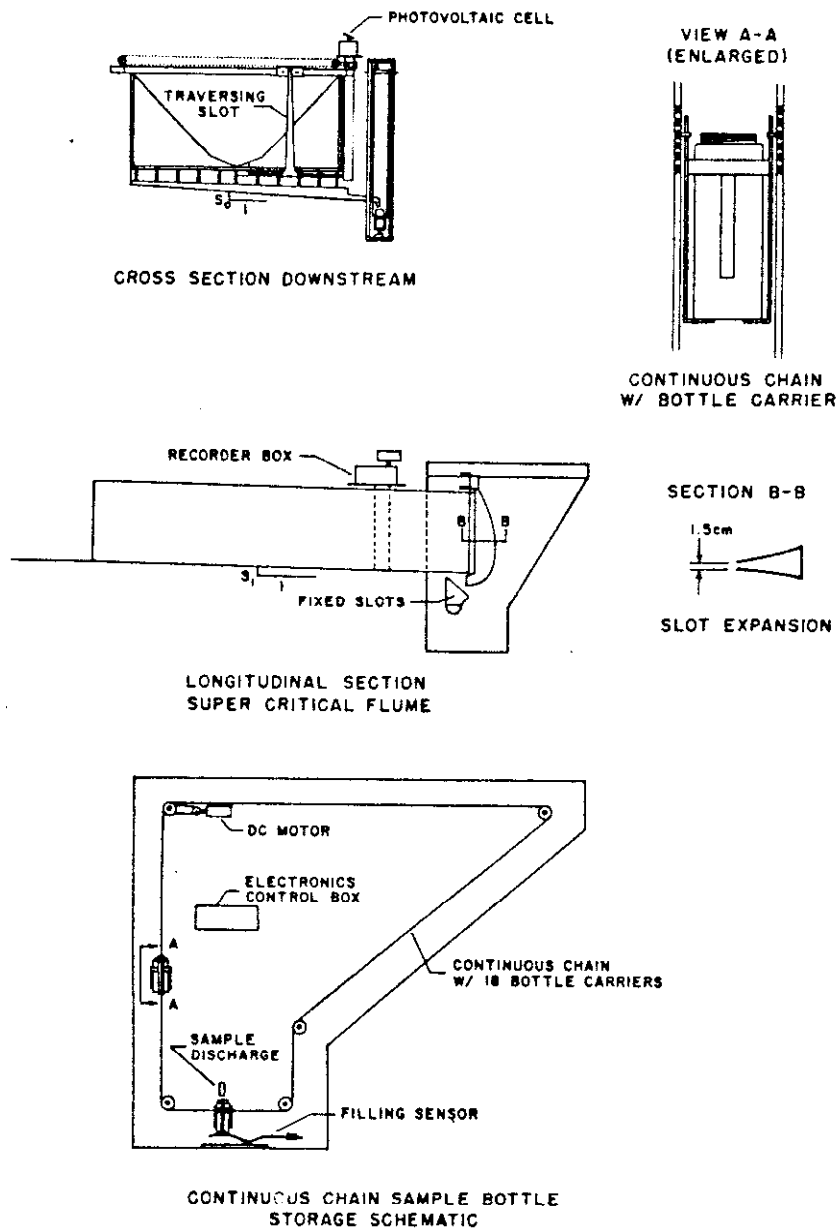


Fig. 2. Schematic diagram of slot sampler mechanism.

sample chemical contamination) has a constant 1.5 cm opening at the flume exit. The slot diverts an aliquot of the water-sediment-chemical mixture from the flume exit water jet as the slot traverses the flow. The slot's flared design diverts the mixture from a horizontal to a downward direction, and the mixture is then directed onto the fixed slots beneath the flume. This design eliminates pressure buildup in the slot, and prevents flow expulsion above the water surface at the flume exit. Because the slot moves through the flow at a constant rate, an integrated (velocity) sample of the mixture is taken.

Power for traversing slot: A 12-volt DC motor is used to drive the traversing slot across the flume exit. A continuous chain imparts the power at

the top of the slot with wheels running on a horizontal rail affixed to the flume. Bearing-equipped wheels at the bottom of the slot absorb the horizontal force of the water impinging against the slot and hold the mechanism in a vertical position.

Fixed slots: Ten fixed slots are positioned immediately beneath and evenly spaced across the flume exit such that the water from the traversing slot discharges onto the fixed slots and further splits the sample. The spacing of the fixed slots is the same as the exit port width of the traversing slot, and the opening of the fixed slot is the same as that of the traversing slot so both can sample the same sized material. The water-sediment-chemical mixture then flows by gravity through the slot collector tube to the sample storage facility, where it is deposited in individual sample bottles. The fixed slots and slot collector tube are made of stainless steel and PVC to minimize chemical contamination.

A note of caution is needed at this point. Care must be taken to ensure that tailwater does not become high enough to cause water to flow into the fixed slots or the bottom of the storage compartment where the filling sensor is positioned. Thus, the flume and sampler can be used only in locations where there is sufficient gradient to install the equipment.

Continuous chain for sample bottle storage: Eighteen sample bottles are stored on a continuous chain driven by a 12-volt DC motor similar to the one used to drive the traversing slot. The drive motor is activated by the timer and a sample bottle is moved into sampling position just before the traversing slot begins its traverse. After the traversing slot has completed its sampling sequence, the continuous chain drive motor is again activated and the filled bottle is moved from its sampling position. Thus, no bottle is under the slot collector tube during a non-sampling period. This eliminates the possibility of sample contamination if water should enter the fixed slots because of dripping at the flume overfall or rain entering these slots during non-sampling periods.

Bottle-filling sensor: During a slot traverse, a bottle is positioned in the sampling position which is located under the collector tube from the fixed slots and over a weighing mechanism that determines when a sufficient sample has been taken to meet laboratory processing criteria (approximately 1 liter). The weighing mechanism consists of two counterweighted arms that direct the sample bottle into position for weighing. The weighing mechanism is connected to a filling sensor switch that is switched off when the sample reaches a predetermined weight. If, after each slot traverse, the sample bottle and water are not heavy enough to activate the filling sensor, the slot will traverse the flow again. This sequence continues until either the filling sensor is activated, indicating an adequate sample weight has been taken, or the preprogrammed sample time interval is exceeded. Limit switches at either end of the traversing slot chain mechanism cut power to the slot drive motor at the end of a traverse if (a) the bottle filling sensor has indicated an adequate sample, (b) the sample time interval has been exceeded, (c) all the sample bottles are filled, or (d) the flow is less than 5 cm deep.

Photovoltaic cell for battery charging: The single 12-volt automobile-type battery used to power this sampling equipment is trickle charged with a 0.125 amp photovoltaic cell. Experience with this mechanism has been excellent,

and the battery has maintained a charge for as long as 5 years.

Sample time marking: A solenoid activated pen marks sample times on the lower edge of the chart of the flume's analog water level recorder simultaneously with each sample bottle filling.

SAMPLER LOGIC

Figure 3 details the logic flow path of the sampler sequencing. The sampler is in a standby condition when there is no flow or a flow less than 5 cm depth is occurring in the flume and the sample storage unit has empty sample bottles. In this condition, the traversing slot is on the limit switch at one side of the flume exit; the sequential timer is off and ready to begin cycle one of the timing sequence; and a sample bottle is not directly under the collector tube from the fixed slots.

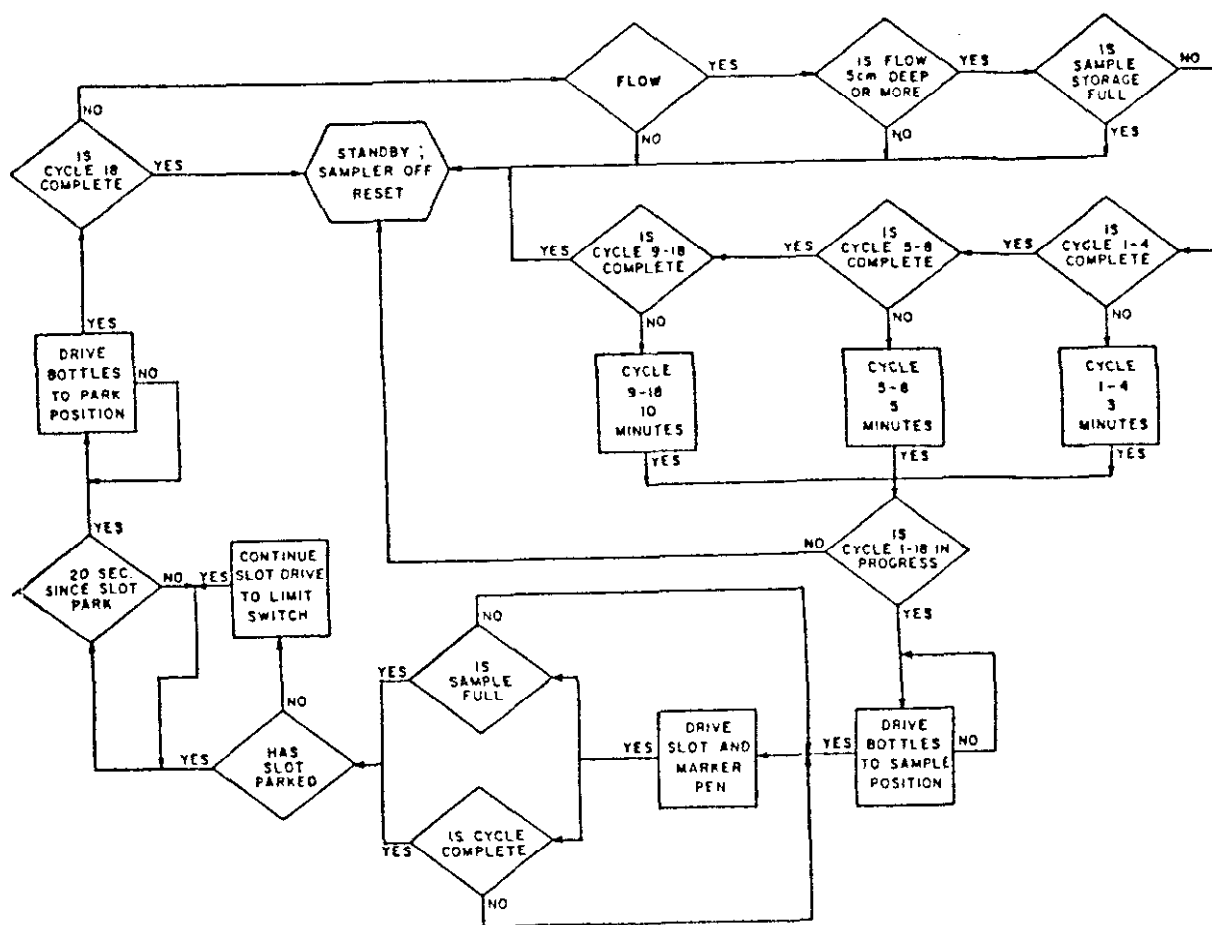


Fig. 3. Logic flow path for traversing slot sampler.

If a flow occurs when the sampler is in this standby condition and the depth exceeds 5 cm, the energizing switch on the water level recorder activates the sequential timer which is set to take 4 samples at 3 min intervals, 4 samples at 5 min intervals, and 10 samples at 10 min intervals (the number of samples, at any interval, and the interval time are variables that can be adjusted on the sequential timer). This sampling sequence insures that the most rapidly

changing portion of the hydrograph will be adequately sampled and that, as often occurs in our environment, more than one storm a day can be sampled without forfeiting complete quantification of the sedigraph. Sampling safeguards provided for include: not refilling a sample bottle (the continuous chain is limited to just one revolution), assurance that the traversing slot is not in the flow during a non-sampling sequence, and efficient use of electrical power (all circuits are off during the standby condition).

SAMPLER PERFORMANCE

The traversing slot sampler has performed well on experimental subwatersheds at Walnut Gulch and the Santa Rita Experimental Range near Tucson, Arizona. An example of a hydrograph and corresponding sedigraph from a small watershed at Walnut Gulch is shown in Figure 4 (Simanton et al., 1980). The sharp rise at the beginning of the hydrographs of this storm with two periods of rainfall excess shows the importance of short-interval sampling. Without the short interval between samples, much of the sediment concentration variability (circles), and the associated sediment transport variations, would have to be estimated. Furthermore, this two-event storm, with less than 20-min between periods of rainfall excess, also illustrates the need for the sampler to reset to the short sampling interval, and having a relatively large capacity for sample bottles (note that 14 of the 18-bottle total capacity were used for this event). The storm occurred late in the evening, when there would have been no one available to sample the remote watershed.

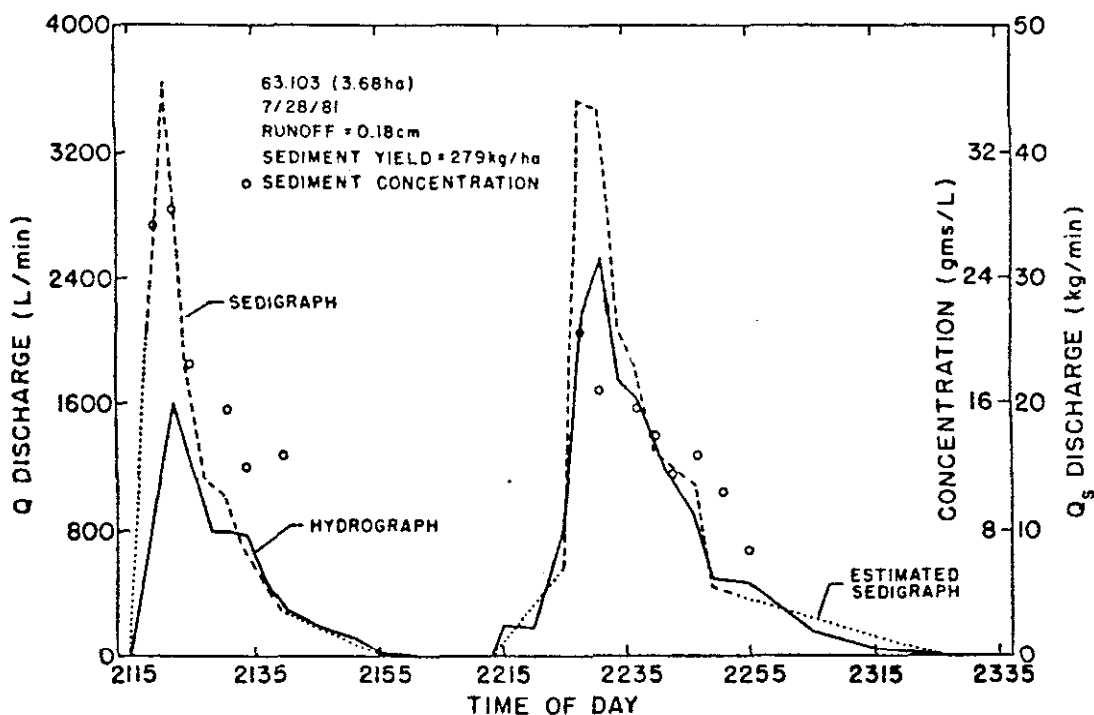


Fig. 4. Hydrograph and sedigraph for the double peak storm event on the 3.68-hectare Lucky Hills Watershed on Walnut Gulch.

A full-scale prototype of the traversing and fixed slot mechanism was tested in the perennial flow of the San Pedro River adjacent to Walnut Gulch. This testing, with carefully controlled conditions, although restricted to flows of only 0.3 m³ S⁻¹, showed that the concentration determined with the slot sampler agreed almost perfectly with depth integrated samples collected with a US D-48 sampler through the flume overfall.

Using known inputs of sediment concentration, we found that the traversing slot indicated concentrations were about 10 percent higher than those obtained with a US D-48 depth-integrating sampler and with dip-sampling methods. As the concentrations of coarse sediment increase, we would expect that the traversing slot would give a more reasonable estimate of the mean concentration when compared to other sampling methods.

SUMMARY

A traversing slot sampler has been developed which provides discrete aliquots of the water-sediment-chemical mixture leaving small watersheds. The sampler was designed to operate at remote sites using stored DC battery power charged by a photovoltaic cell. The sampler diverts aliquots of the outflow from a precalibrated measuring device, and deposits the material in individual sample bottles. The sampler has an electro-mechanical timer which allows samples to be taken throughout rapidly changing discharges, and thereby define concentration variations. In comparison tests between the traversing slot, US D-48 hand sampler, and dip samples, concentrations were about 10% higher in samples obtained with the traversing slot sampler.

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INNOVATIVE TECHNIQUES FOR COLLECTING HYDROLOGIC DATA

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ABSTRACT

The USDA Sedimentation Laboratory in cooperation with the U. S. Army Corps of Engineers established a comprehensive data collection facility on the Goodwin Creek research watershed in northern Mississippi for the study of agricultural hydrology and stream channel stability. This 21.4 Km² watershed has been intensively instrumented to study the movement of water and sediment from agricultural lands and the problems of instability in stream channels. Most of the field data acquisition takes place at fourteen supercritical-flow flumes strategically located on Goodwin Creek and its major tributaries. Advance technology is being used for acquisition of much of the hydrologic data. A major part of the system involves the use of VHF-radio for data transmission. Description of the instrumentation and experiences with the data acquisition system are presented.

INTRODUCTION

A cooperative study on streambank stability was undertaken in 1977 between the U. S. Department of Agriculture's Sedimentation Laboratory (Oxford, Mississippi) and the U. S. Army Corps of Engineers Vicksburg District (Vicksburg, Mississippi). One phase of the cooperative study required the establishment of a research watershed based on a set of criteria developed for site selection. The purpose of the watershed is to provide data needed to estimate the impact of upstream land use and watershed processes on sediment supply and transport in stream channels and how this affects channel stability. The data will be used to develop and calibrate mathematical models of the watershed streamflow and sediment transport processes.

The watershed selected for instrumentation is Goodwin Creek, a 21.4 Km² catchment located in the Yazoo River basin of northern Mississippi. Goodwin Creek has a variety of sediment source areas and channel problems which are representative of other bluff line tributaries draining into the Yazoo River. Land use in the watershed is almost evenly divided among cultivated, pasture and wooded land.

One important phase of the field research program is the development and testing of instrumentation and data acquisition systems. The watershed has a variety of instruments and a VHF-radio remote telemetry network with a computerized data-base. This is a relatively new approach to data acquisition for a research watershed. This system as installed was built to specifications developed by the USDA Sedimentation Laboratory. This paper describes the instrumentation and data acquisition system and includes discussions on modifications and criteria for successful operation. Comments based on experience with the system are given.

FIELD STRUCTURES AND INSTRUMENTATION

The Goodwin Creek Watershed was divided into fourteen subcatchments with supercritical flow flume constructed at each of the drainage outlets (Fig. 1).

The flumes were designed to operate in the supercritical range because of the high sediment loads in Goodwin Creek Channels. The drainage area above the subwatersheds (flume sites) range from 0.06 Km² to 21.4 Km² (Table 1).

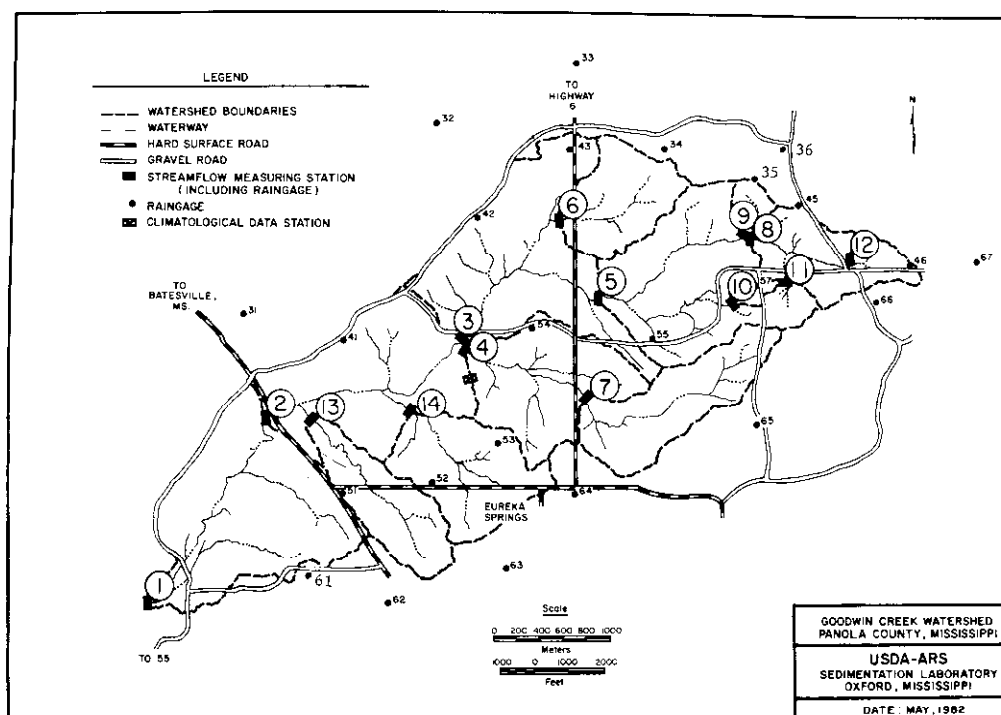


Figure 1. Goodwin Creek Watershed Map

Each of the flume sites was selected to meet specific research needs and accessibility criteria. On the main stem of Goodwin Creek, at least 60 percent of the total inflow to each structure is measured by other structures upstream.

The flumes were designed and constructed to serve dual purposes; they control degradation of the channel bed in the highly erosive streams and they serve as flow measuring devices. All flumes were constructed of reinforced concrete supported on sheet piling except site 10 where sheet metal was used. The design discharge for each flume was selected as the 100-year probable event.

The calculated 100-year recurrence interval peak discharge for each of the 14 gaging sites is given in Table 1. The flumes at the smaller gaging sites (4-9 and 11-14) are "V" shaped with side slopes of 1 on 2 (Fig. 2). The larger flumes located at gaging sites 1, 2, and 3 have a floor with side slopes of 1 on 5 and walls with side slopes of 1 on 2 (Fig. 3). The floor section included in the larger flumes permits the structure to fit into the channel while still providing the desired hydraulic characteristics. In order to assure passage of all sediment entering the measuring section, the flumes were designed with a longitudinal slope of 4 percent.

Table 1. Design Parameters for Supercritical Flumes

Gaging Site No.	Drainage Area Km ²	100-yr Discharge cms	Depth at Measuring Section Meters	Total Depth of Flume Meters	Bottom Width Meters (Sideslope)	Distance to Meas. Section Meters	Flume Length Meters
1	21.39	176	3.08	4.27	9.14(1/5)	4.27	8.53
2	17.92	156	2.90	3.96	9.14(1/5)	4.27	8.53
3	8.78	91	2.21	3.20	9.14(1/5)	4.27	8.53
4	3.57	45	2.30	3.20	V*	3.66	7.32
5	4.30	57	2.53	3.66	V	3.66	7.32
6	1.19	17	1.55	3.20	V	2.44	4.88
7	1.60	31	2.01	2.90	V	2.44	4.88
8	1.55	28	1.93	3.05	V	2.44	4.88
9	0.18	13	1.38	2.59	V	2.44	4.88
10	0.06	3	0.79	0.91	0.61(1/5)	1.83	2.44
11	0.28	10	1.24	2.44	V	2.44	4.88
12	0.30	11	1.31	2.29	V	2.44	4.88
13	1.24	23	1.76	1.98	V	2.44	4.88
14	1.63	24	1.52	1.98	V	2.44	4.88

* V indicates entire flume is V-shaped.

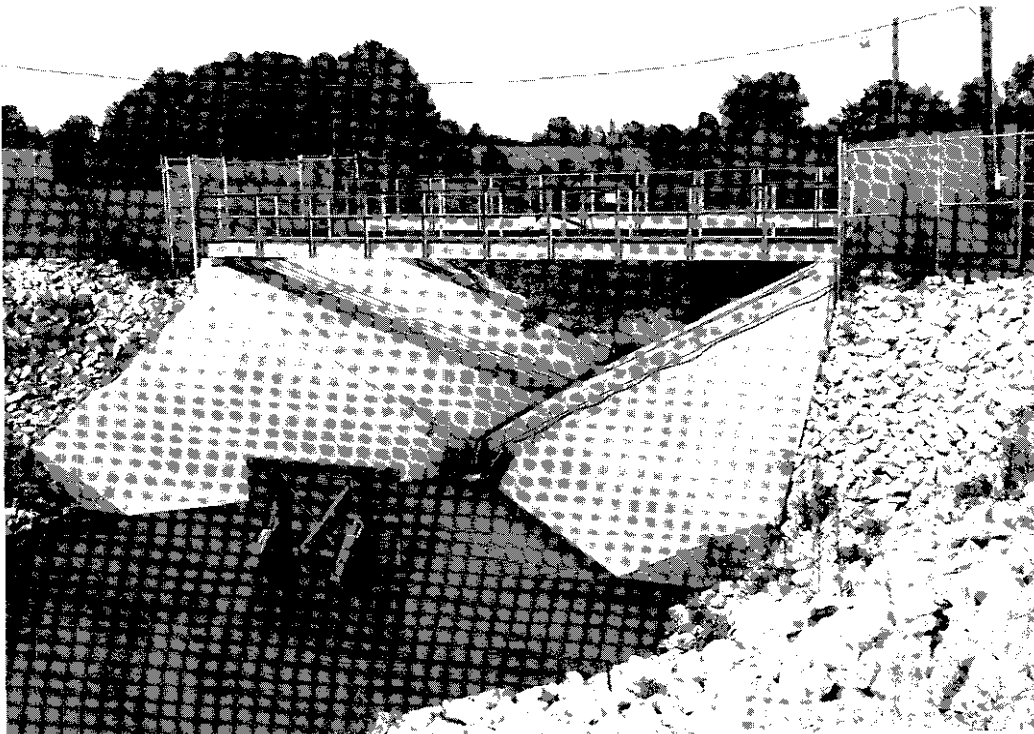


Figure 2. Supercritical Flow Flume: Vee-Shaped Cross Section

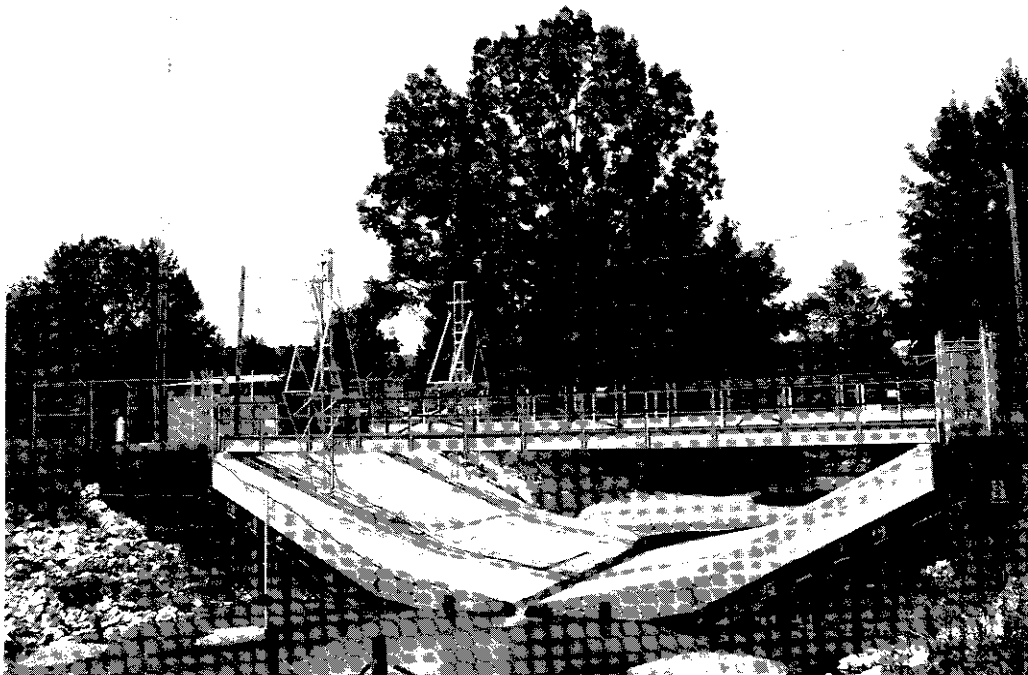


Figure 3. Supercritical Flow Flume: Compound-slope Cross Section

Instrumentation at each streamflow gaging site includes an electronic data acquisition system which consist of a VHF radio telemetry system with microcomputer. The microcomputer collects, temporarily stores and upon demand transmits the data to a central computer at the Sedimentation Laboratory. The microcomputers have a capacity to accommodate up to 31 sensors, however, only 16 sensors are provided for at the present time at each gaging site. Each sensor at a gaging site is interrogated by the microcomputer at predetermined intervals depending upon the response time needed.

Measurements collected at each gaging site and transmitted through the telemetry system include water stage in the flume measuring section and in the channel below the flume, accounting of automatically pumped sediment samples, water temperature, soil temperature, and precipitation. Air temperature is collected and transmitted from four sites. In addition to data from the streamflow gaging sites, data from a climatological station near the center of the watershed is also transmitted through the telemetry system. These measurements include: precipitation, barometric pressure, relative humidity, wind speed, wind direction, air temperature, soil temperature and solar radiation. A summary of data collected and transmitted through the telemetry system is given in Table 2.

In addition to 13 precipitation gages at the streamflow gaging sites and climatological station, there are 23 other standard recording weighing precipitation gages located at sites both inside and outside the watershed that provide a comprehensive rainfall monitoring network for Goodwin Creek

Table 2. Summary: Goodwin Creek Data Collected and Transmitted Via Telemetry System

Data Type	Site Number														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	50 ¹
Flow Depth	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
Pumped Sample	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
Precipitation	x	x	x		x	x	x	x		x	x	x	x	x	x
Water Temperature	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
Air Temperature		x	x	x								x			x
Soil Temperature	x	x	x	x	x	x	x	x		x	x	x	x	x	x
Wind Speed															x
Wind Direction															x
Humidity															x
Barometric Pressure															x
Solar Radiation															x
Water Surface Slope		x													
Battery Voltage	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x

¹ Climatological Data Station

(Fig. 1). These gages could not be connected to the electronic data acquisition system because of the cost factor.

A microcomputer capacity of 31 sensors provides an opportunity for expanding hydrologic studies at each gaging site. One such study involves the measurement of water surface slopes upstream from gaging site 2. The instrumentation for this study is connected to the telemetry system at site 2 and consists of differential pressure transducers and a manometer purge system for measuring the water surface slope along 152 m of straight channel reach. This is a new approach to collecting field data for computing flow resistance coefficients related to sediment transport and bed material movement.

The remaining instrumentation at the gaging sites consist of one footbridge across the channel at the downstream end of the flume and another upstream a distance equal to approximately half the flume length. These bridges are used to support stream flow sampling devices and personnel collecting flow data in the conventional manner.

DATA ACQUISITION SYSTEM

Remote Telemetry System

The remote data acquisition system used by the Sedimentation Laboratory is a flexible computer based system designed to collect and transmit hydrological and meteorological data from remote unmanned sites. The system consists of a mini-computer controlled radio network with real time multi-tasking operations, VHF repeater, and 14 microcomputer controlled real time data collection systems. A schematic of the VHF-radio telemetry system is shown in

Figure 4. The current system configuration will support up to thirty stations.

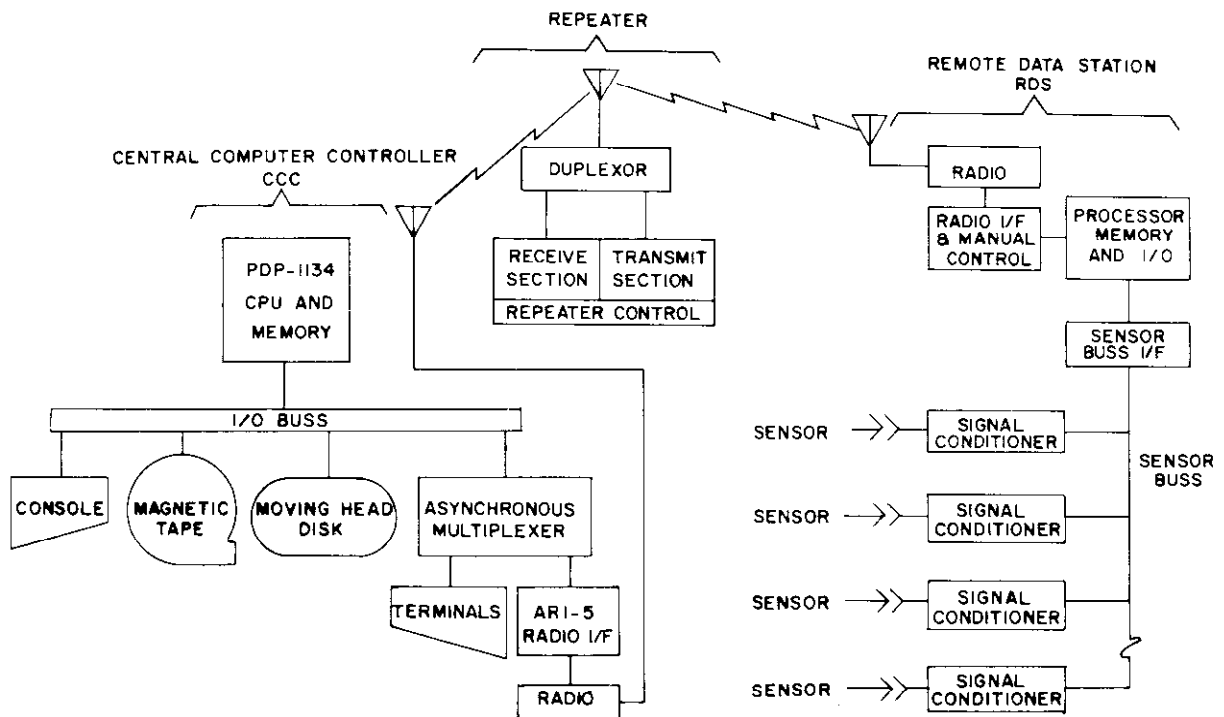


Figure 4. VHF-Remote Telemetry System

Data is collected on a timed basis from the various sensors at individually selected sample rates and stored in the microcomputer memory for later transfer to the central facility controlling system located at the Sedimentation Laboratory. Each station is polled a minimum of once every thirty minutes. An individual station may be interrogated by radio using the automatic scheduling of the central computer or interrogated manually using an auxiliary terminal. The stations may also be interrogated at the site, or a response may be initiated by a test switch. The selected station will respond with a user programmed station identification and check sum followed by the installed sensors data lists, each with its own check sum. The station sends the time in minutes and hundredths of minutes. Each sensor has a field programmed sample rate of one minute to 165 minutes. The data message from the station is examined for proper format, proper station identification, and each sensor check sum. If an error is detected, the station is polled again to recover the lost data. After a complete message is received, it is logged onto the disc file for later transfer to magnetic tape for data reduction. If errors are not recoverable, the data files are flagged as containing errors and the erroneous message is logged for later manual interpretation. The central facility data controller, repeater, and station also provide voice communication capabilities for use in system tests and maintenance.

Water Stage Recorder

A conventional water stage recorder was selected for obtaining records of water levels. The recorders were modified by using a direct drive coupling to a potentiometer using excitation voltage provided by the analog interface card

and calibrated for 1 volt change to equal 0.3 m (1.0 ft) stage rise. This output is the signal sampled by the telemetry system. Data points are taken at one minute intervals with the system being very responsive to all stage changes in channel flow. This method has been highly satisfactory and maintains calibration with no electronic or mechanical drift. The system has provided data with approximately 1/400 of 1 cm (1/1000 of 1 inch) accuracy. The recorders are used with standard time-stage charts which provide a hard copy backup in the event of failure of some component of the telemetry system during storm runoff.

Precipitation Gage

A standard weighing recording precipitation gage is used for obtaining records of rainfall at each of the streamflow gaging sites. A method very similar to the one used for the stage recorder is used to transmit data.

Raingages are equipped with transmitters consisting of a special purpose 25K potentiometer coupled to each gage. Excitation voltage from the analog interface card is applied to the potentiometer and calibrated to give readings from 0-36 cm in one minute intervals. Data stations are capable of 1/400 of 1 cm accuracy, but some difficulty in mechanical calibration of the raingages has been experienced. Each raingage is also equipped with a standard depth recording chart for a backup in case of lightning or other failure during storms.

Air, Water and Soil Temperature Interface

Temperature probes are installed at the 14 gaging sites for accumulation of water and soil temperature data. Outside air temperature is recorded at 4 gaging sites.

The thermistor air temperature card provides the capability to interface with a thermistor temperature sensor. The resistance of the probe is related, nearly linearly, to the probe temperature. The temperature interface card measures the resistance of the thermistor composite, conditions this reading to obtain a voltage proportional to the probe temperature, and switches this voltage to the ADC upon command. The specified ambient operating temperature range for both the sensor and the card is -23 C to +50 C. Probe accuracy, air temperature card accuracy and ADC card accuracy combined is better than or equal to ± 0.3 C.

Validyne Transducer Indicator System

The model DP7 variable reluctance differential pressure transducers are used in Goodwin Creek with a regulated bubbler system for fast, responsive, and accurate measurements of channel water surface slopes. The system consists of four transducers installed in pairs on opposite sides of the channel and spaced 152 m apart. The transducers are contained in small metal instrument houses with one house containing, in addition to the transducer, a conventional bubble gage and water level recorder for monitoring purposes.

The method used to interface the pressure transducers with the telemetry system is basically the same as with other signals dealing with analog input. As the flow depth increases, pressure on the transducers increases and

amplifies the signal change to the carrier demodulators and gives a corresponding readout on the digital panel meter. This signal is wired to the telemetry data collection system and gives readouts at one minute intervals. Several calibration checks indicate that the calibration and accuracy of the system can be maintained over long periods of time.

Sediment Sampling

In designing the instrumentation for hydrological studies on the Goodwin Creek Watershed, as much automation as possible was originally planned in order to reduce personnel requirements. In sediment sampling, however, automation possibilities were limited and most of the sampling program was designed to utilize conventional methods.

Two different types of sampling techniques were planned. The first type of sampling is a point sample obtained from a fixed position in the flow cross section with a pumping type sampler. The sampler intakes are fastened 15 to 30 cm above the bottom of the flume and 90 to 300 cm upstream from the downstream end of the flume. Samples are pumped automatically at fixed time intervals as long as the water stage remains above a pre-selected level.

The second type of sampling requires the collection of storm flow samples in the conventional manner using a depth integrating suspended sediment sampler. Samples are obtained at equally spaced verticals in the flow cross section with the sampler lowered and raised at a constant speed in each vertical. Samples collected in this manner provide a good representation of the mean suspended sediment concentration in the flow cross section except for an unsampled zone 9 to 15 cm in depth immediately above the bottom of the flume (Bowie et al., 1972).

Automatic Pumping Sediment Sampler

Two types of pumping samplers are being used in the Goodwin Creek Watershed. These are the PS 69 sampler and the Chickasha sampler. The PS 69 sampler has a good back-flush system and a capacity of 72 samples, but its operation is limited to 7.6 m of head. It shows high pump failure when sampling heavy sand concentrations. These samplers are used only at sites where these limitations are not a factor.

At sites where the sample intakes are long distances from the pump and where heavy sand concentrations are involved, Chickasha samplers are used. These samplers are modified to use a different pump that can handle the heavy sand concentrations and pump continuously under adverse conditions. This is an air-operated double-diaphragm pump that will self-prime up to 30.5 m head, is easily controlled by air pressure, is simple to maintain, and can pump particles up to 3 mm in diameter.

System operation requires the stream flow to reach some predetermined depth suitable to each specific site. When this depth is reached, a float switch is tripped to apply power to an air solenoid valve that starts the pump. The pump then runs continuously except for preset 15 second air purged back-flush periods that allow 7.0 kg/cm² of air from the compressor to be applied to the sampler intake to remove any leaves or other debris that may have accumulated. After the back-flush interval, the samples are taken. A solenoid installed on

the water stage recorder marks the chart at the time and stage when each sample is taken. Simultaneously, a sample collection signal is sent to the telemetry data acquisition system. This method provides telemetry data with hard copy for back-up in case of electronic failure due to lightning or other power failure.

Suspended-Sediment Sampler

Numerous devices have been developed over the years for sampling sediment concentrations in stream flow (Miller and Bowie, 1965). Some of the more commonly used sediment samplers are available on the open market. However, investigators involved in sedimentation research have, to a certain extent, developed or modified equipment for sediment sampling according to the demands of the particular problem at hand. The Sedimentation Laboratory has developed an electrical power operated device to aid in collecting suspended sediment samples. This device (rig) is mounted on a footbridge and permits sampling of storm flow at selected verticals in the flume cross section. A standard US DH-48 sediment sampler attached to a rigid strut suspended from the rig is used to collect depth-integrated samplers at the normal measuring section in the flume.

Due to an inherent limitation in the design of the depth-integrating suspended sediment samplers, a depth of 9 to 15 cm near the flume bed is unsampled. To eliminate this unmeasured zone and determine the difference in concentration between a normal section and total load section, another sampling device of the same type described above is mounted on the downstream bridge to collect samples of the total sediment through sand size passing over the downstream edge of the flume. The intake nozzle of the DH-48 sampler is traversed completely through the full depth of flow at the back edge of the flume. The structural design of the sampling rig permits orientation of the intake nozzle into the direction of flow for all samples collected.

Bedload Sampler

One of the primary concerns in studies of total sediment transport is the determination of the sediment discharge of coarse materials or those particle size generally referred to as bedload. As a general rule, sediments <2.0 mm in diameter can be measured fairly easy. The main problem is the determination of bedload sediment >2.0 mm that move along in almost continuous contact with the streambed.

Previous studies have shown that in order to accurately measure bedload discharge, it is necessary that the sampler be designed to sample the largest and smallest bedload particles, to be stable on the bed, and to orient vertically and horizontally so that all particles have an equal opportunity for entrance. In addition to design requirements, there are a number of other hydrologic factors that may affect the performance of a bedload sampler. One of the most important factors is the uneven bed configuration found on the natural channel bottoms (Hubbell, 1964). The problem of uneven bed configuration should be minimized where sampling is done in a flume cross section.

Sediment from the Goodwin Creek Watershed is composed of material ranging in size from fine clay to gravel. In many reaches of Goodwin Creek, a

substantial part of the bed material is composed of gravel size particles. Because of the need to include the transported bed load with the total suspended sediment load, the Sedimentation Laboratory has recently initiated a bedload sampling program in conjunction with the ongoing sampling program at gaging sites 1, 2, and 3 (Figure 1).

A modified Helley-Smith type sampler is used for collecting the bedload samples. The sampler is modified to the extent that the entrance nozzle was redesigned from a square 7.62 cm orifice to one geometrically shaped to rest firmly on the sloping floor surface of the flume without any void area beneath the orifice. The required square area of the orifice was retained. The unit is constructed to be interchangeable with the D-48 sampler on the previously described sampling rig used at the normal measuring section in the flume. Attachment to the rigid strut suspension used on the sampling rig helps to fulfill the requirements for a satisfactory bedload sampler.

Transient Protection Devices

Transient protection devices are used in the Goodwin Creek Watershed to protect the field instrumentation and data accumulation system during the typically severe thunderstorms that commonly occur in the area. Transient voltages, whether produced by line fault conditions, power switching, or lightning, can destroy a common digital and analog system. The primary objective of transient protection is to prevent component failure and to provide revival capability of affected equipment.

Transzorb fast reacting power zener diodes were installed on all signal lines entering the field stations. This would be sufficient transient protection on most installations. However, the Goodwin Creek Watershed is located in an area of severe thunderstorm activity and further protection is required. This is especially true where sensors are located well above the ground line. The installation of gas-discharge tubes directly at the sensor cable interface on above ground sensors was found to be a very effective device for eliminating large transients. Additional grounding procedures were also required for the radio transmitter system. A ground plane 4.6 m in diameter was constructed approximately 1.0 m below the ground surface and attached to a 1.8 m long ground rod driven in the ground at the base of the antenna tower. A ground wire was attached to the top of the antenna tower and extended down one leg of the tower to the ground rod. This technique has almost completely eliminated lightning interfering with data transmission.

SUMMARY

The use of a system such as the one described in this paper is very important in the collection of research watershed data, particularly as modern technology is improved. The cost effectiveness depends on several factors, (1) the quality of data, (2) the need for time synchronization of data from different locations, (3) the importance of minimizing delay in having data available for processing, and, (4) the importance of making real time responses to the measurements made by the system.

An important element of the system has been the inclusion of backup recorders for streamflow stage and precipitation data. The presence of charts has not only helped build confidence in an unfamiliar system, but has helped prevent

data loss during possible catastrophic events such as station failure due to lightning.

Electronic systems have been made very dependable. Down time has not been a problem. All installations, ground procedures, maintenance and calibrations have been done by the Electronics Department at the USDA Sedimentation Laboratory.

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SUSPENDED SEDIMENT MONITORED BY SATELLITE

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ABSTRACT

Research concerning the remote sensing of suspended sediment in surface waters has been carried out in three stages; 1) laboratory measurements were made under carefully controlled conditions using a large optical tank facility where sediments collected from two different impoundments were suspended, 2) hand held spectroradiometer measurements were made at 25 nanometer intervals in the visible and near infrared spectrum over impounded water containing various concentrations of suspended sediments, and 3) data obtained from over thirty environmental satellite (LANDSAT) scenes over a period of four years were analyzed, and correlated with ground truth data. The laboratory and hand held radiometer results show that reflectance in the near infrared region, 700-950 nanometers, is nearly proportional to suspended inorganic sediment concentrations. The LANDSAT data show definite but lower correlation with suspended sediments at the same near infrared wavelengths with the added benefit of providing a synoptic image.

INTRODUCTION

Remote sensing by aircraft or satellite offers an attractive and economic means of monitoring and assessing the quantity and quality of water bodies. This method of measurement is attractive if the focus of interest is one individual lake and even more attractive if the focus is a number of lakes, reservoirs, and rivers in an entire region.

By definition, remote sensing is the measurement of some physical variable by means of a distant sensor. In general the sensor may detect any type of energy emanating from an object. In this study we discuss only those detectors which detect electromagnetic radiation in the visible or near infrared range. Spectral measurements of light being reflected from or being emitted by the object provide information about it. By using scanning sensors with narrow fields of view it is possible to obtain information about the size of the object and distinguish it from its background.

In this paper the remote sensing of water bodies is considered. Water free of contaminants or suspended particles has well defined optical properties and a characteristic reflectance spectra, a specific fraction of the incoming energy being reflected at each wavelength in the visible-near infrared range. When particles are suspended in the water light is both reflected and adsorbed by the particles. Sediment particles behave differently than algal cells. White clay particles behave differently than red clay particles. The spectra and amount of the energy that is scattered back and reemergent from the water depends upon both the optical nature and concentration of the suspended particles.

The simple measurement of surface area of agricultural impoundments in a region may be used as an indicator of water stress, either flooding or drought, in a region. The persistent presence of high concentrations of suspended sediment in an individual lake or lakes in a region may be used as an indicator of problems of erosion, particularly the depletion of the clay component of the soil, on the associated watersheds. The systematic decrease of reservoir surface area in the vicinities of inflowing streams may be used as an indicator of erosion and deposition of the larger sized soil components on the watershed. The persistent presence of algae is an indicator that excessive nutrients are flowing into the water body suggesting their presence or abundance on and loss from the watersheds.

It is the purpose of this paper to outline the research conducted by the Agricultural Research Service to develop the technology required to use the remotely sensed data routinely available from satellites and aircraft to measure and assess the aquatic environment.

TECHNICAL BACKGROUND

The incoming solar spectrum as measured at the top of the atmosphere and at sea level on clear days has been studied and established. The solar spectrum is a measure of the incoming solar energy density, as a function of wavelength (Robinove, 1982). The ratio of the reflected to incident radiation from a terrestrial object at a given wavelength is the spectral reflectance. The characteristics of both the reflected energy spectra itself and the reflectance spectra are highly dependent on the characteristics of the reflecting object.

There are two different properties of water that affect the reflected energy. The first is the chemical content of the water, an example being a water dyed red with Rhodamine dye would give different spectra than an uncontaminated water due to absorption. Second, suspended particulates affect the scattering of underwater light and in particular the amount of energy scattered back out of the water. This second effect is addressed in this paper.

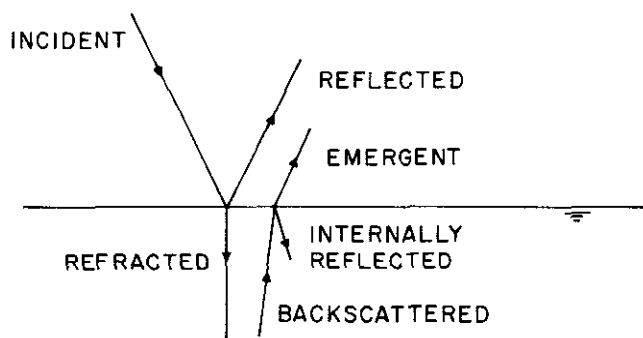


Figure 1. Schematic of solar radiation balance at the Air-Water interface.

The solar radiation balance at the air and water interface is shown schematically in Figure 1. The remotely sensed appearance of water is the result of both the directly reflected component and the back scattered emergent component. When open water appears blue to the eye, the back scattered emergent component is nearly absent and the observed energy is primarily due to surface reflection. The reflectance under these circumstances is nearly independent of wavelength and the spectrum appears flat.

In the presence of suspended sediment, the reflectance increases and reaches a maximum in the visible red portion of the spectrum. The maximum sensitivity to the suspended sediment concentration exists in the red and near infrared portions of the spectra.

Suspended sediment can be distinguished from algae because where phytoplankton (algae) dominates, the reflected spectra has different appearance. The highest reflection occurs in the green and the highest absorption occurs in the red and blue. The absorption is probably due to the photosynthetic pigments in algae, namely the chlorophylls and carotenoids. Research is needed to adequately define the spectral characteristics of various algal compositions and concentrations. Some results of our measurements are shown in Figure 2 to illustrate the differences between blue water, a chlorophyll dominated situation and a suspended sediment dominated situation (Schiebe and Troeger, 1982).

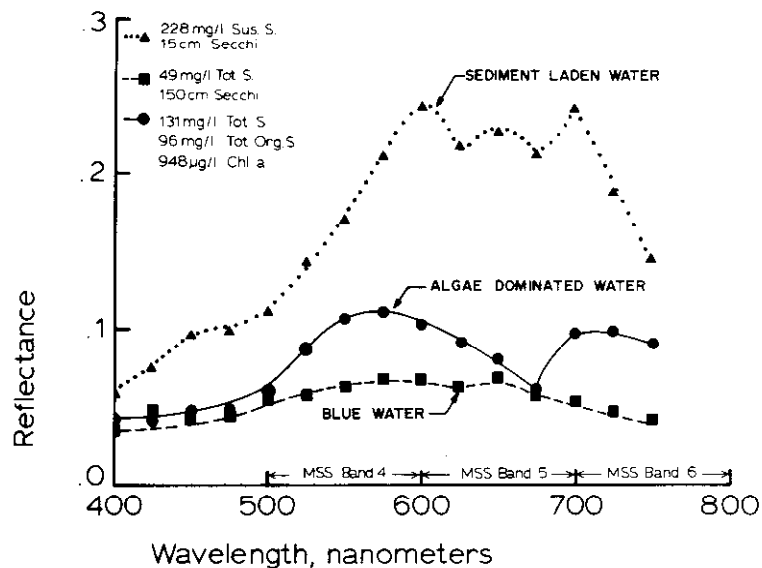


Figure 2. Illustration of spectra from blue water, algae dominated water, and sediment laden water.

RESEARCH SITES

Several impoundments in north Mississippi were used in the early research. As the study progressed, Lake Chicot in southeastern Arkansas became the principal study area for the project (Nix and Schiebe, 1984). Other lakes have been used to supplement the main data set from Lake Chicot. The lake was formed in a cutoff channel of the Mississippi River approximately 600 years ago. The lake receives runoff from a 930 square kilometer watershed which is, for the most part, cropped with cotton and soybeans. The lake is typical of lakes affected by agricultural runoff in this part of the country.

One major reason for selecting this lake is that an 8 year biweekly limnological data set is available for ground truth. These data include total and dissolved solids, temperature, chlorophyll, and many others. In addition the lake is separated by a causeway into north and south basins, with the north basin remaining essentially clear and containing higher quality water. The south basin receives most of the sediment laden water from the watershed. The difference in water quality is visibly evident.

RESULTS AND DISCUSSION

Research was undertaken to determine if a quantitative relationship could be established between reflected solar radiation and the amount of sediment suspended in the water. Research was conducted at three stages. Samples were collected for laboratory studies, insitu measurements of radiance were made from a boat, and Landsat images were analyzed.

Laboratory studies were conducted in cooperation with the Marine Spectral Signature Laboratory at the NASA Langley Research Center in Hampton, VA (Witte et al., 1981). Sediments were resuspended in a 11,600 liter tank illuminated at 32280 lumina per meter square with an

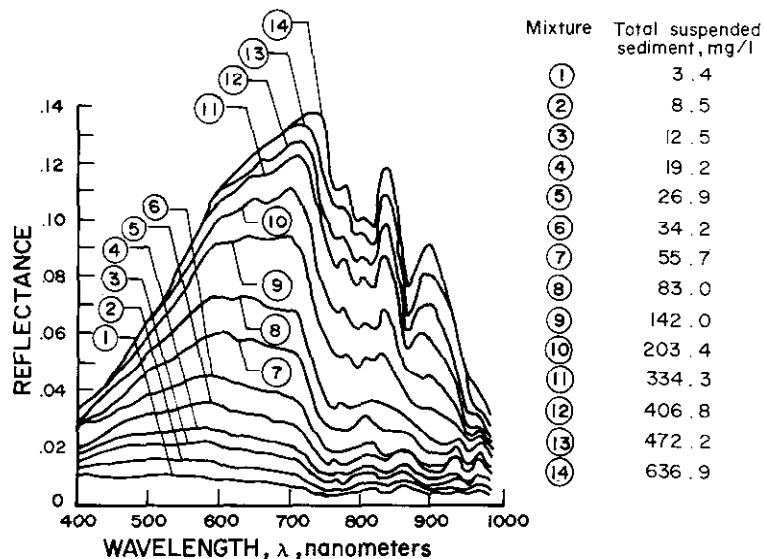


Figure 3. Spectral reflectance signatures from resuspended Lake Chicot sediments (after Witte et al., 1981).

"artificial Sun". Upwelled radiance measurements were made between 400 and 1000 nanometers. These studies showed that as the suspended sediments concentration is increased there is increased reflectance. The reflectance spectra from resuspended Lake Chicot sediments (Figure 3) for suspended sediments concentrations from 6 to 691 mg/l illustrate reflectance plotted against wavelength. As suspended sediment increased, the magnitude of the reflectance increased except at the lower wavelengths where little signal separation was measured. At higher wavelengths there is a good signal separation for all concentrations. There is a shift toward longer wavelengths as suspended sediment increased. A similar set of data collected from the John H. Kerr Reservoir (Witte et al., 1982), a Corps reservoir along the North Carolina-Virginia border, showed nearly identical results. When the data are examined by plotting reflectance against suspended sediments at a constant wavelength it is seen with the Kerr Reservoir data that at wavelengths less than 650 nm as sediment concentration goes above 100 mg/l the reflectance tended to become saturated and flatten

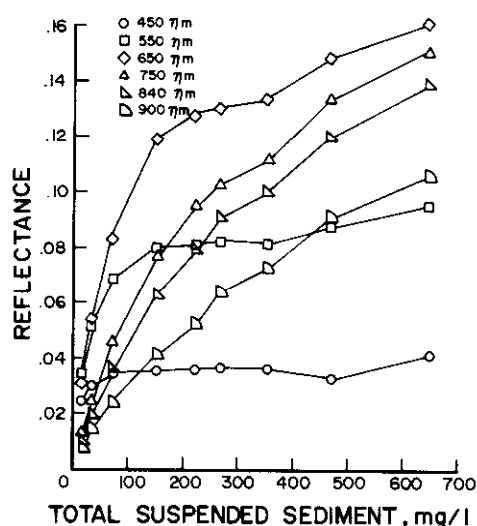


Figure 4. Laboratory studies of reflectance as a function of Kerr Reservoir suspended sediments (after Witte et al., 1982).

out (Figure 4). At wavelengths greater than 650 nm there was good signal separation up to 990 mg/l. A similar plot for Chicot gave even better results (Figure 5). The results were consistent even between the two quite different watersheds (Piedmont Mountain vs Delta). The basic conclusions from the laboratory studies were that there is good signal separation of reflectance from suspended sediments and that the best wavelengths for quantitatively estimating suspended sediments greater than 100 mg/l would be in the near infrared range 650 to 900 nanometers.

In situ studies of the reflected solar radiation were conducted on a number of north Mississippi reservoirs as well as on Lake Chicot. These

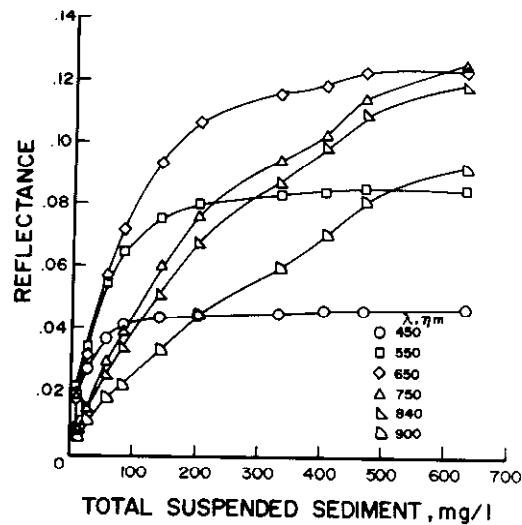


Figure 5. Laboratory studies of reflectance as a function of Lake Chicot suspended sediments (after Witte et al., 1981).

studies used a portable spectroradiometer equipped with a fiber optics conduit and a teflon diffusing screen (Ritchie et al., 1976). Reflected solar irradiance was measured normal to the water surface and incident solar irradiance was measured at 180 degrees from the water surface.

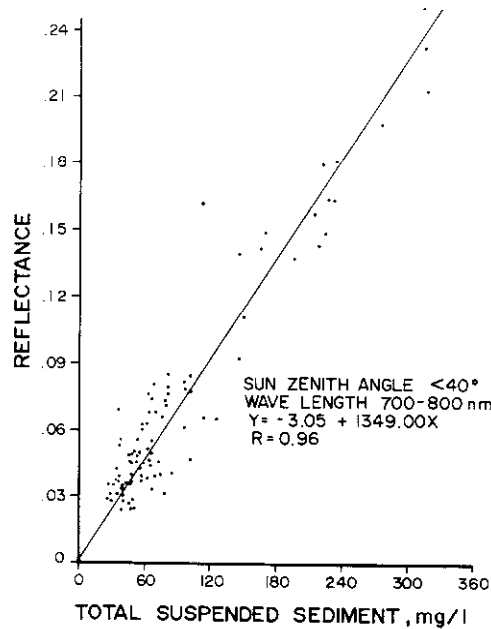


Figure 6. Insitu reflectance as a function of suspended sediments in several north Mississippi reservoirs (after Ritchie et al., 1976).

Figure 6 illustrates field measurements of reflectance showing that results were similar to those measured in the laboratory. Correlation coefficients of .90 to .94 were found for uncorrected reflectance data and increased to .93 to .96 when we subtracted the Fresnel surface reflection and used only the emergent radiance due to the scattering from the suspended particles.

The third phase of the studies deal with LANDSAT MSS sensor data. To date, 33 images have been analyzed. From these images 63 observations, 32 in the south basin of Lake Chicot and 31 in the north basin, have been analyzed with the associated ground truth measurements. The scenes represent a fairly uniform seasonal distribution of dates over the three year period 1976 to 1979 including the entire range of suspended sediments in the lake. Suspended sediment values in the data set ranged from 1 to over 800 mg/l.

The measured satellite data was converted first to radiance and further to top of atmosphere reflectance so that the data set would be on the same basis for all 33 scenes. The results of correlating the LANDSAT data to measure suspended sediment using a linear model is presented in Table 1.

Table 1a. Correlation coefficients for Radiance.

MSS Band	Total Solids	Suspended Solids
4	.48	.51
5	.65	.68
6	.64	.69
7	.51	.57

Table 1b. Correlation coefficients for Reflectance.

MSS Band	Total Solids	Suspended Solids
4	.51	.52
5	.65	.68
6	.73	.78
7	.57	.63

Linear correlation analyses between MSS data and the measured water data indicated that radiance in band 5 and 6 were almost equally related to total and suspended sediments. Reflectance, in band 6 was better correlated to total and suspended sediment than any other reflectance band or to the radiance correlations. The patterns shown are similar to relationships found in laboratory and in situ studies. These correlation coefficients are lower than the values calculated in the more controlled laboratory and insitu studies. Laboratory and insitu studies have shown that the near infrared wavelengths in bands 6 and 7 would be best for determining suspended sediments over 100 mg/l. From our analyses of laboratory, insitu, and Landsat data it appears that the near infrared range, 700 to 800 nanometers, is the best spectral interval to use since the data does not tend to become saturated until suspended sediment loads are greater than 500 mg/l and even then it does appear to become

saturated at the nearly 1000 mg/l levels that we measured in this study. Both laboratory and insitu studies indicated that MSS band 7 should be almost as good as band 6. However upon analyses of Landsat MSS band 7 in this study it is evident that this band has definite limitations. We believe this is because of the low digital response in band 7 due to low incident solar energy and relatively high solar radiation absorption by the water itself resulting in a much lower signal to noise ratio.

CONCLUSIONS AND CURRENT RESEARCH

This study demonstrates the technical possibility of a remote sensing system to monitor the suspended sediments concentrations in surface waters. Repeatable laboratory and insitu results show linear relationships between reflectance in the near infrared land and suspended sediments. The correlation coefficients related to the LANDSAT derived edge of atmosphere reflectance values and suspended sediment are somewhat lower than those related to the ground level reflectance values. This result is expected because of the noise added to the signal by particle light scattering in the atmosphere and by the different atmospheric path lengths of the incident and reflected light.

Current research is being pursued in 4 areas. First, the significance of the greater spectral and spatial resolution of the LANDSAT Thematic Mapper sensor is being examined. Second, the three year satellite and ground truth data base is being extended to cover an additional 5 years. The increased size of the data base will allow greater confidence in the statistical results. Third, basic research is being conducted to improve understanding of the interaction between suspended particles of various types and the underwater and emergent light fields. Fourth, research is underway to develop convenient atmosphere corrections allowing the top of the atmosphere reflectance value to be transformed to ground level reflectance.

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UNDER WATER MAPPING RIVER CHANNELS AND RESERVOIRS

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ABSTRACT

Bathymetric maps were produced at minimal cost for two U.S. Bureau of Reclamation sites: The tailrace of Glen Canyon Dam, in Arizona, and El Vado Reservoir, in New Mexico. The maps were made with the use of an integrated sounding and microwave positioning system and a computer graphics package. The boat's on-board computer determined coordinates and stored the data while in the field. The data were then electronically transferred to the office computer for analysis and map production.

INTRODUCTION

Collection and analysis of underwater topographic data can be both time consuming and costly. Whether attempting to determine deposition in a reservoir or changes in a river bottom the difficulties in data collection and analysis are the same: Collecting enough data to define a topographic map but not so much as to make field costs prohibitive or overburden the office analysis.

Using a computer to compute and digitally record three dimensional coordinates, while in the field, can greatly reduce the costs of data collection and office analysis. This paper will describe how this was done by the Bureau of Reclamation at two of its sites: The Glen Canyon Dam tailrace, in Arizona, and El Vado Reservoir, in New Mexico.

DATA MEASUREMENT TECHNIQUE

A boat with an integrated sonar and microwave positioning system was used at both locations. The microwave positioning system uses two transmitter/receivers, placed on shore, to compute a triangulation with the microwave tower on the boat. Shore station sites are carefully selected at points where the horizontal and vertical coordinates are known and, more importantly, where they define a reasonable triangle with the boat and have a line of sight with the entire work area (see figure 1). The boat cannot cross the line connecting the two shore stations. Meeting these requirements usually means moving the shore stations a few times to map long reaches.

The operator selects several lines in the immediate work area (all in view of the shore stations) each defined by two sets of coordinates and enters them into the boat's on-board computer. The boat's computer converts the microwave signals to distance, performs triangulation, and computes the coordinate position of the boat. Simultaneously, the depth is sounded and

the horizontal coordinates and depth are digitally recorded on magnetic tape. All of this occurs at the operator's specified frequency (specified by time or distance). The computer is then able to inform the pilot where the boat is relative to line via a track indicator and also plot the boat's path.

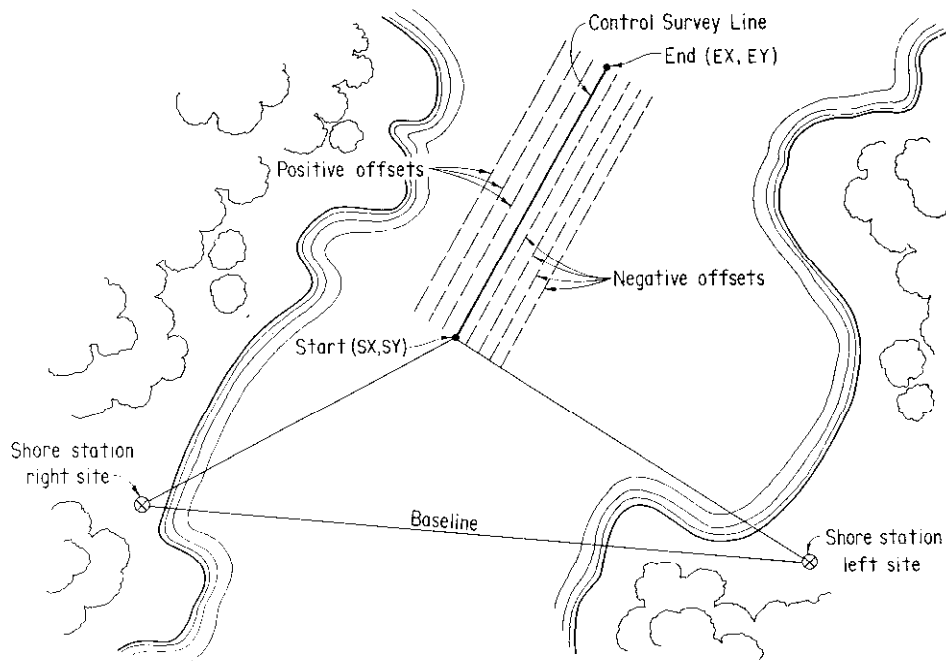


Figure 1 - Typical Layout for Bathymetric Survey

ANALYSIS OF BATHYMETRIC DATA

Since the field data is digitally recorded on site, a large part of the work is already done. The magnetic tape, produced on the boat, is played back on a microcomputer in the office and the data is transferred to the mainframe computer to be analyzed by the Surface II Graphics System, developed by the Kansas Geological Survey. The digitally recorded depths are checked against the sonar chart for any mistakes caused by sonar signal interference and are converted to elevation from the known water surface elevation. Incorrect depths and corresponding horizontal coordinates are deleted.

The Surface II Graphics System is used in four phases: The first phase plots the horizontal position of the data; the second phase converts the data into a uniform grid, using a search technique specified by the user; the third phase plots a contour map from the uniform grid; and the fourth phase, if desired, computes the areas of all closed contours.

Plotting the horizontal position of the data enables the user to choose a uniform grid spacing, search techniques and corresponding parameters, and also determine if additional data are required, either above or below water. Data for areas above water, that are unchanging, may often be digitized from existing contour maps. Coordinates from a high contour may also be used to define a map boundary or outline.

The Surface II Graphics System has the ability to use any one of several techniques to convert data to a uniform grid by estimating elevations at the grid nodes. The scheme that works well, for hydrographic data collected along several lines, is a distance weighted average of up to four points from any one quadrant. For a given grid node, this scheme divides the data into quadrants, at a user defined orientation, and searches for the four closest points within a maximum search radius for each quadrant. If the search cannot find at least one point from a certain number of quadrants, the test fails and the elevation for the grid node is null or blank. The search scheme is most likely to fail at the edge of the data set and it is useful to provide additional data near its boundary. The quadrant search works well for data measured along range lines because it assures that data from more than one range line will be used.

After the data are converted into a uniform grid, producing topographic maps is relatively simple. The contours are determined by linearly interpolating elevations between grid nodes and may be smoothed by a piecewise Bessel function. The horizontal scale of the contour map, contour interval, and plot medium are chosen by the user. The user also has the option of drawing closed depression contours with hatches. Outlines of objects such as bridges, roads, or buildings (specified by coordinates) that help reference the map may be drawn by the Surface II Graphics System. If the contour map has blanked areas or looks unreasonable, then one must go back to the original data and create a new uniform grid matrix.

Computing areas of contours is a valuable tool in monitoring reservoir sedimentation or scour and/or fill in river channels. Areas can be computed from the coordinates used by Surface II Graphics to draw closed contours. This information can be used to provide an accurate estimate of the volume of the reservoir. When contour areas are computed, a table is produced listing all contour levels; their areas, if closed; coordinates of the area's centroid or coordinates of the beginning of an unclosed contour; and whether or not the contour is a depression. To determine areas from unclosed contours, the user must either artificially close the contour and planimeter the area or close the contour using Surface II Graphics by either expanding the search radius or adding more data.

GLEN CANYON DAM TAILRACE

A bathymetric map was made of the tailrace area, on the Colorado River downstream of Glen Canyon Dam, describing erosion patterns caused by large dam releases in 1983 (see figure 2). Data were measured, on October 16, 1983, approximately every 25 feet along lines parallel to flow and approximately 50 feet apart. In addition, data were collected along the alinement of both spillways, the outlet works and perpendicular to the flow at established range lines. Figure 3 shows the distribution of data that were used in producing the contour map. Collecting data parallel to the flow on rivers with strong currents is by far the easiest way to maneuver the boat. Data were collected in the tailrace while the discharge from Glen Canyon Dam was 25,000 ft³/s. Because of the current the boat tracked along flow lines rather than straight lines. The important thing is that the data are evenly distributed and the straightness of the boat's path is of no consequence.

Additional data were digitized from the 3150 contour of a design drawing. Surface II Graphics converted 1740 data points (three-dimensional coordinates) into a uniform grid matrix and then produced a topographic map with a contour interval of 2 feet. Features such as the dam and powerplant, spillway outlets, and bridge were digitized from the design drawing and drawn on the map by the Surface II Graphics system (see figure 4).

EL VADO RESERVOIR

A bathymetric map was made of El Vado Reservoir to produce a new reservoir capacity table and measure the deposition of sediment since its completion. Data were collected every 50 feet along range lines spaced approximately 300 feet apart. Data above reservoir level were obtained by a ground survey crew at the upstream end of the reservoir's right arm and also by digitizing five high contours from an existing topographic map. Figure 5 shows the distribution of data used in producing the topographic map. If any overlap occurred between the field data and the data digitized from the contour map the field data was used exclusively.

The data are closely spaced along the range lines relative to the spacing of the range lines themselves. This is because of the constant 50-foot spacing instruction given to the on-board computer. While this close spacing of data is unnecessary near the center of the reservoir, it is necessary near the shore line. An improved method for collecting the data would be to use a constant time interval where the boat could move slowly near the shore and faster where the depth is more constant. This would provide the necessary detail without collecting excessive data.

The Surface II Graphics system was used to 90-percent capacity when it converted 23,825 points to a uniform grid matrix. A 5-foot interval topographic map was then produced (see figure 6) from the uniform grid matrix.



Figure 2 - Glen Canyon Dam and Tailrace, AZ, 1983

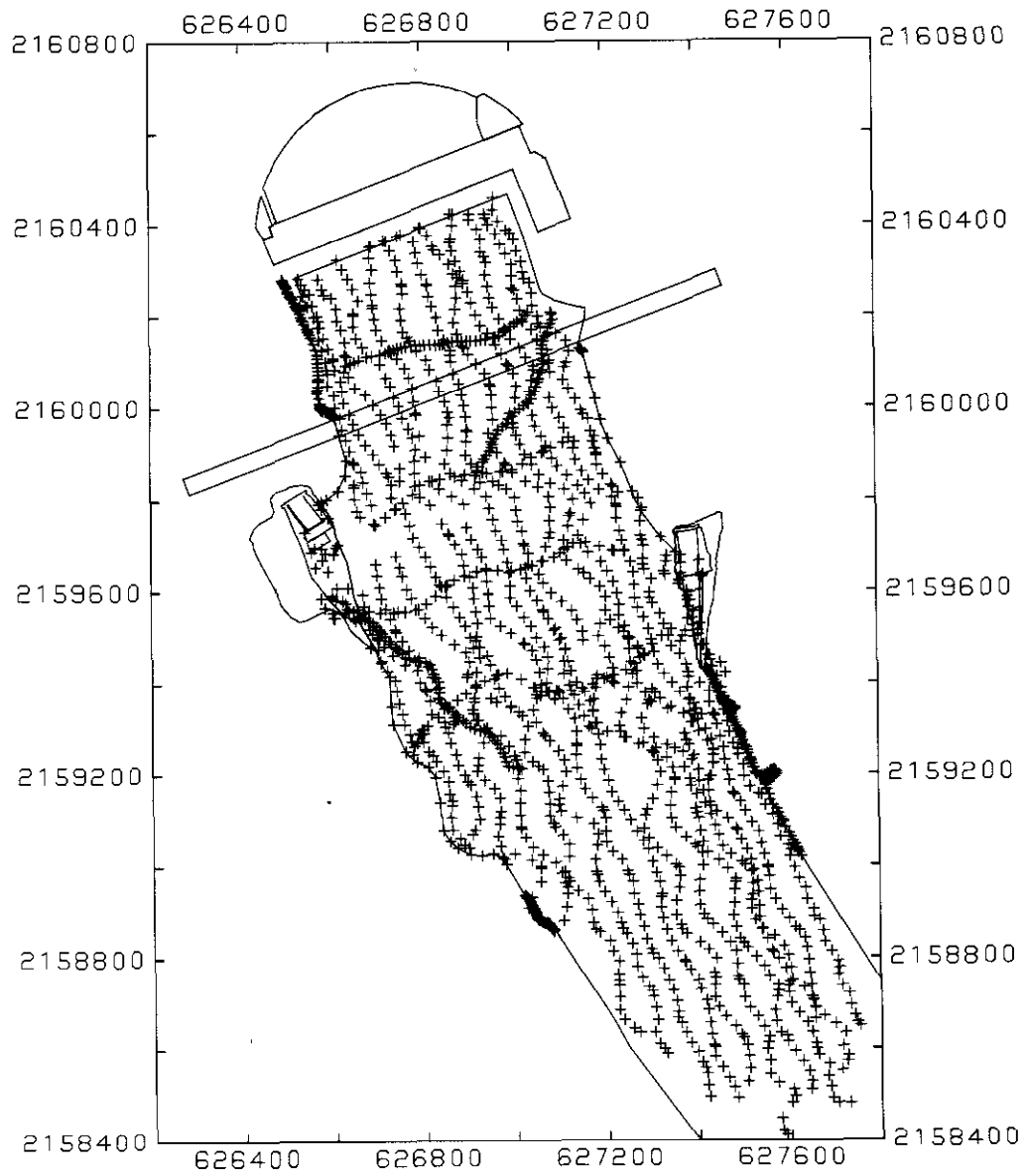


Figure 3 - Data points collected at the Glen Canyon
Dam Tailrace, AZ

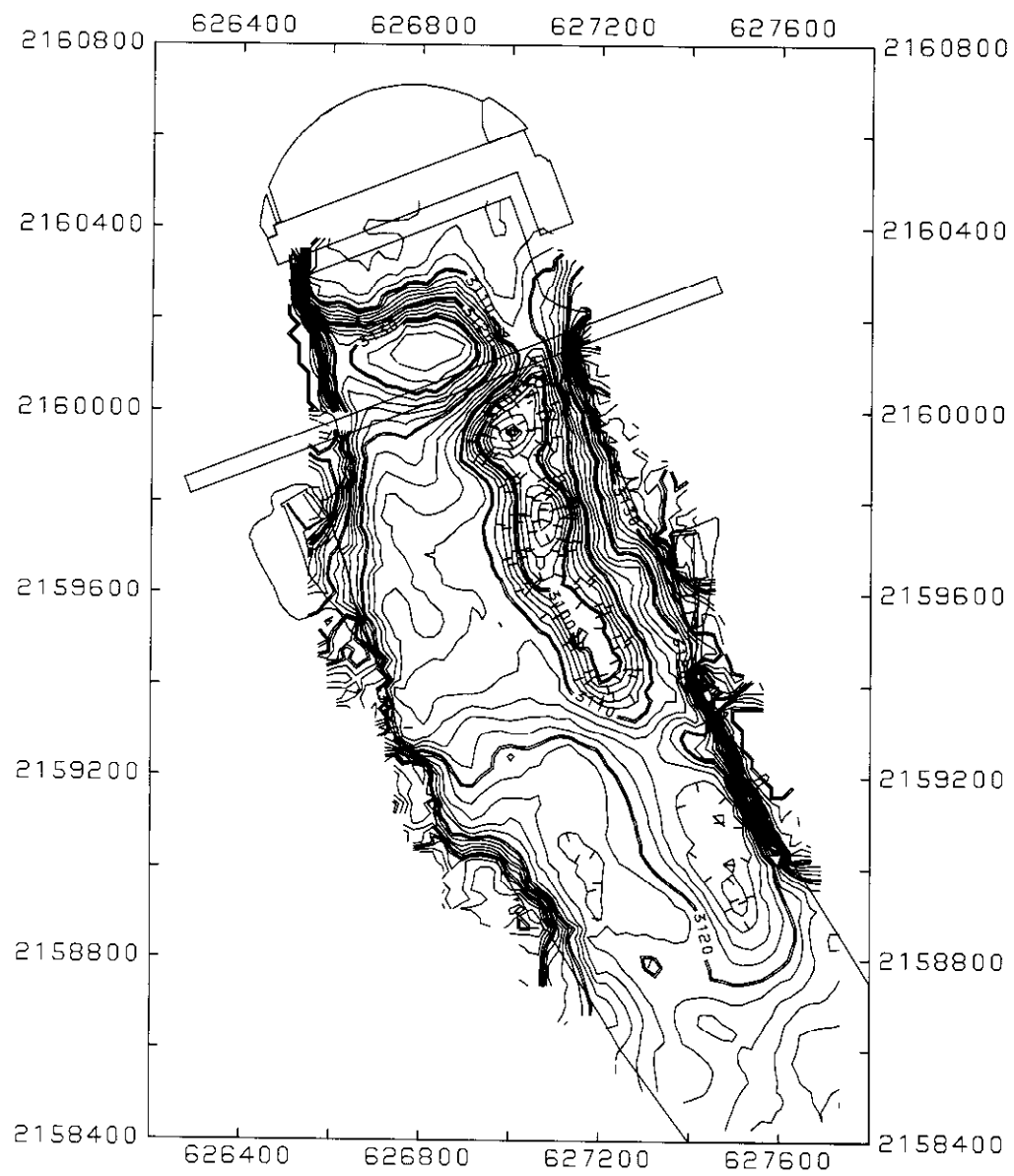


Figure 4 - Bathymetric Map of the Glen Canyon Dam Tailrace

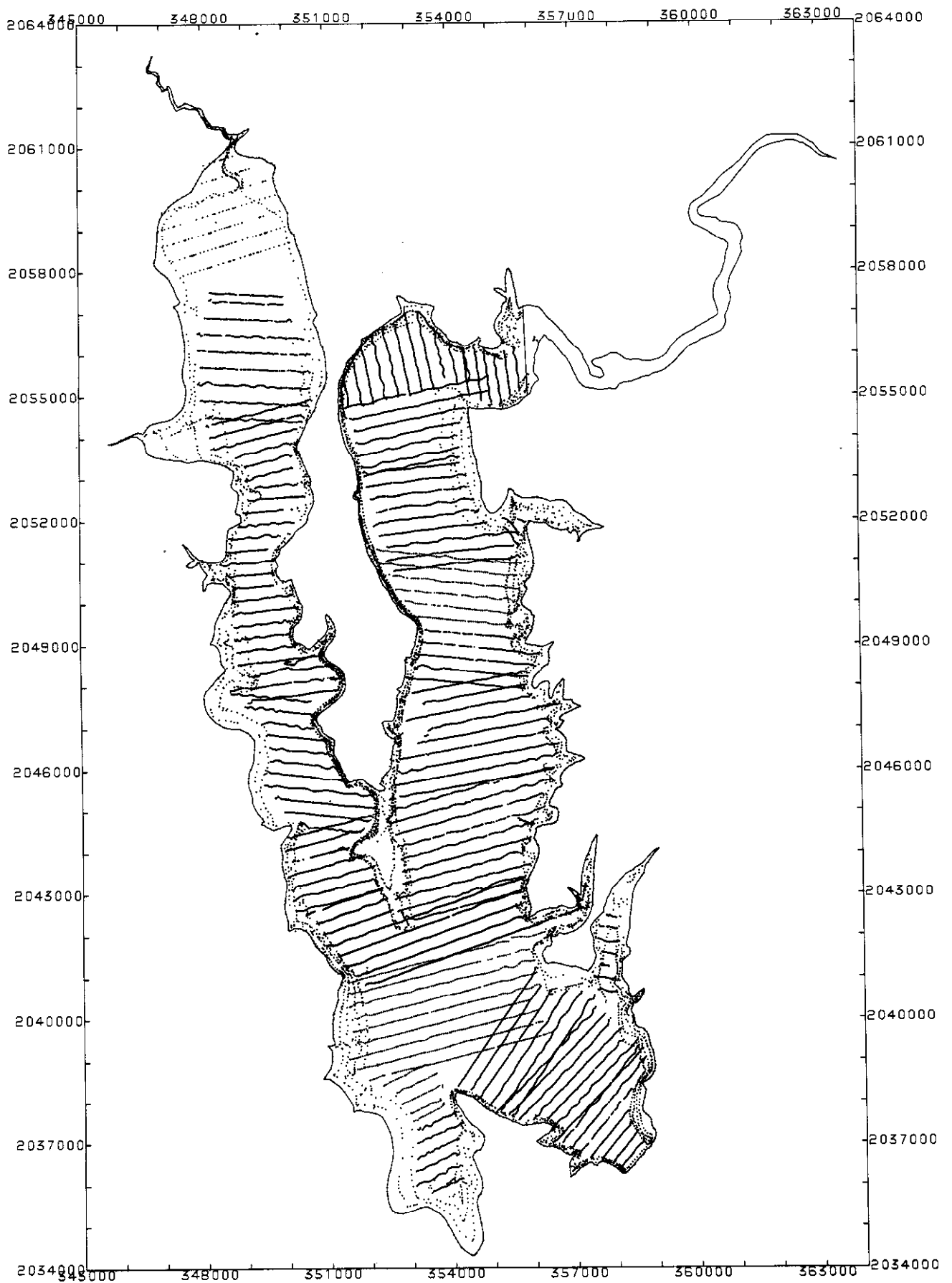


Figure 5 - Data points collected at El Vado Reservoir, NM

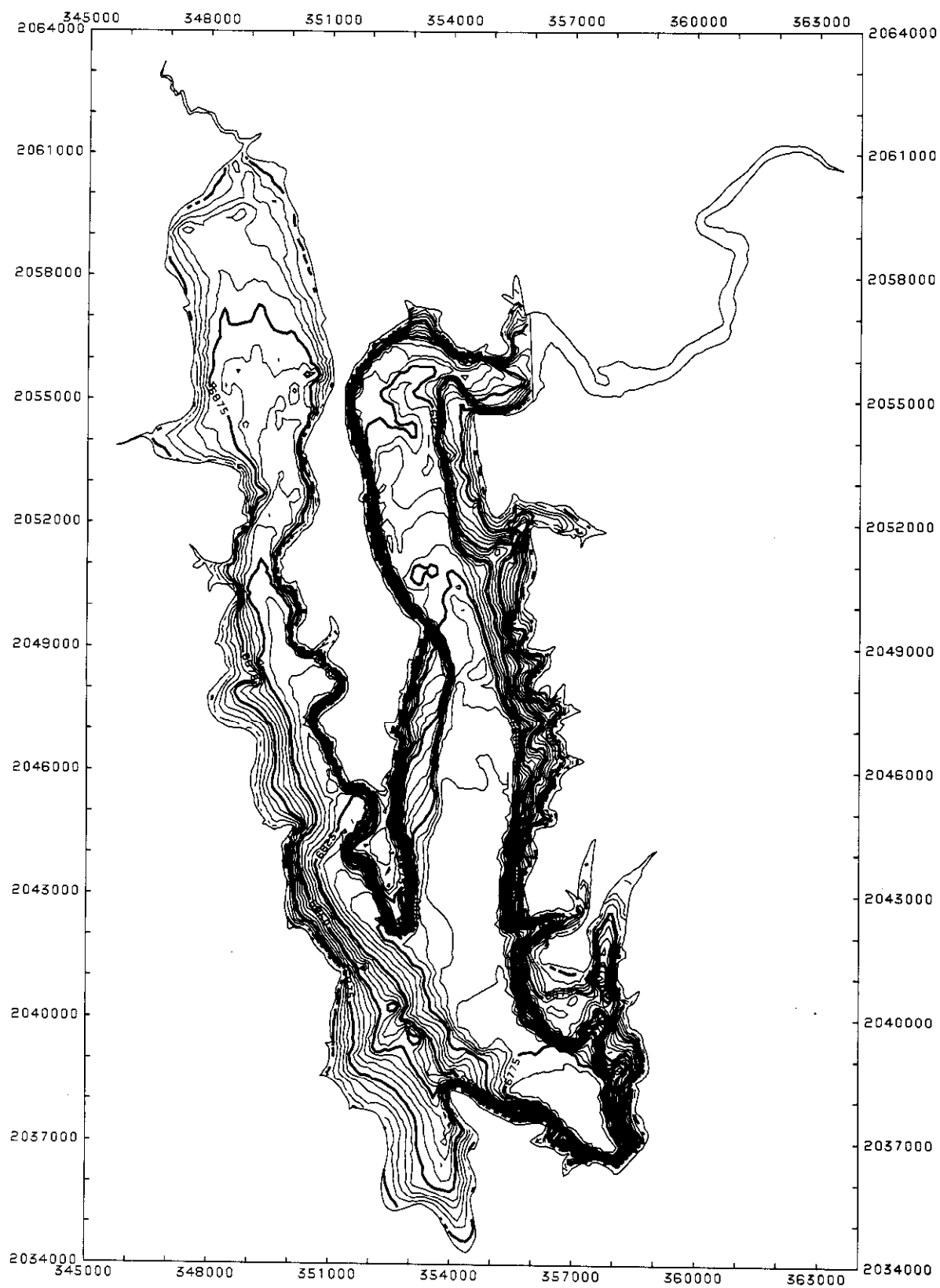


Figure 6 - Bathymetric Map of El Vado Reservoir, NM

CONCLUSIONS

Collecting bathymetric data from a boat with an on-board computer, that can digitally record three-dimensional coordinates, may save considerable time and money both in the field and office. Accuracy of reservoir capacity computations will also be improved over and above that of methods based only on a survey of range lines.

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