# FIELD TEST OF AN X-RAY SEDIMENT CONCENTRATION GAUGE[1/]

By

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# INTRODUCTION

A program to develop a gauge capable of continuously measuring the suspended sediment concentration in flowing streams, based upon the attenuation of X-rays as they pass through muddy water, has been conducted for the past four years by Parametrics, Inc., Waltham, Massachusetts. This work was supported financially by the U. S. Atomic Energy Commission, Division of Isotope Development, and was sponsored by the Sedimentation Subcommittee of the Federal Interagency Committee on Water Resources (1). Technical guidance was provided by the Sedimentation Subcommittee's Technical Committee for the Sedimentation project at the St. Anthony Falls Hydraulic Laboratory, Minneapolis, Minnesota.

The development of the design of the sediment gauge and reports of laboratory performance tests have been summarized for earlier models of the instrument by Ziegler and co-workers (2, 3, 4, 5, & 6).

Parametrics sediment gauge, Serial No. 001, was received at the USDA Sedimentation Laboratory in January, 1966. Following the completion of calibration tests in the Laboratory, field installation on Pigeon Roost Creek, Marshall County, Mississippi, was completed February 8. This report details these activities as well as reporting the field results obtained during the test period, February 8 through March 31, 1966. Analyses and interpretations of the results are made and suggestions for improved performance of future models of the sediment concentration gauge are presented.

## EQUIPMENT AND METHODS

Description of the gauge. The Parametrics Sediment Gauge, Serial No. 001, has been described by Ziegler and co-workers (2, 3). The complete unit is shown in Figure 1. It consists of two components, the sensing unit, which is installed in the stream, and a recording unit on shore. The sensing unit contains the radioactive source, about two millicures of cadmium-109 ($t_{\frac{1}{2}}$ = 470 days), the switching mechanism, a reference cell (distilled water), and the scintillation detector. Signals and power are transmitted between the probe and the shore unit by a 50-foot flexible waterproof cable. The shore unit contains the read-out mechanism, programmer, timer, and other necessary electronic circuits. The unit is powered by four 12-volt rechargeable batteries. Several different voltages are supplied to the equipment. In the field tests the streamlined portions on each end of the sensing unit shown in Figure 1 were removed.

Description of gauge operation. According to the manufacturer (3), the gauge operation is as follows:

"The operation of the gauge is based on measuring the ratios of the attenuation of X-rays through the river water and through a reference cell containing distilled water. This ratio is a function of the concentration of suspended sediment in the river water. The X-rays are provided by a cadmium-109 radioisotope whose position is rapidly switched mechanically to allow attenuation measurements to be alternately made on the reference cell and on the river water (Figure 2).

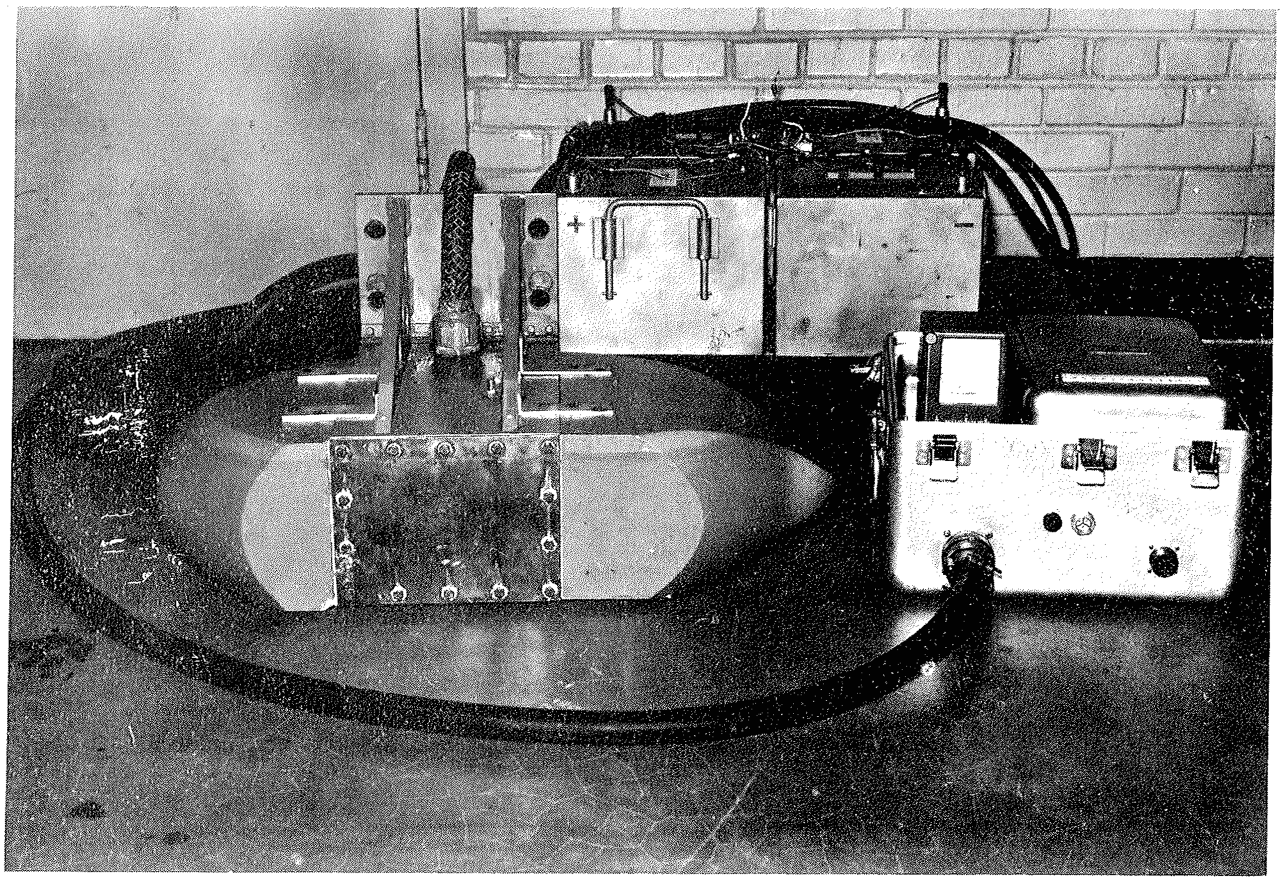

Figure 1. Parametrics sediment concentration gauge. The sensing unit is on the left, the shore unit with recorder is on the right, and the batteries are in the background.

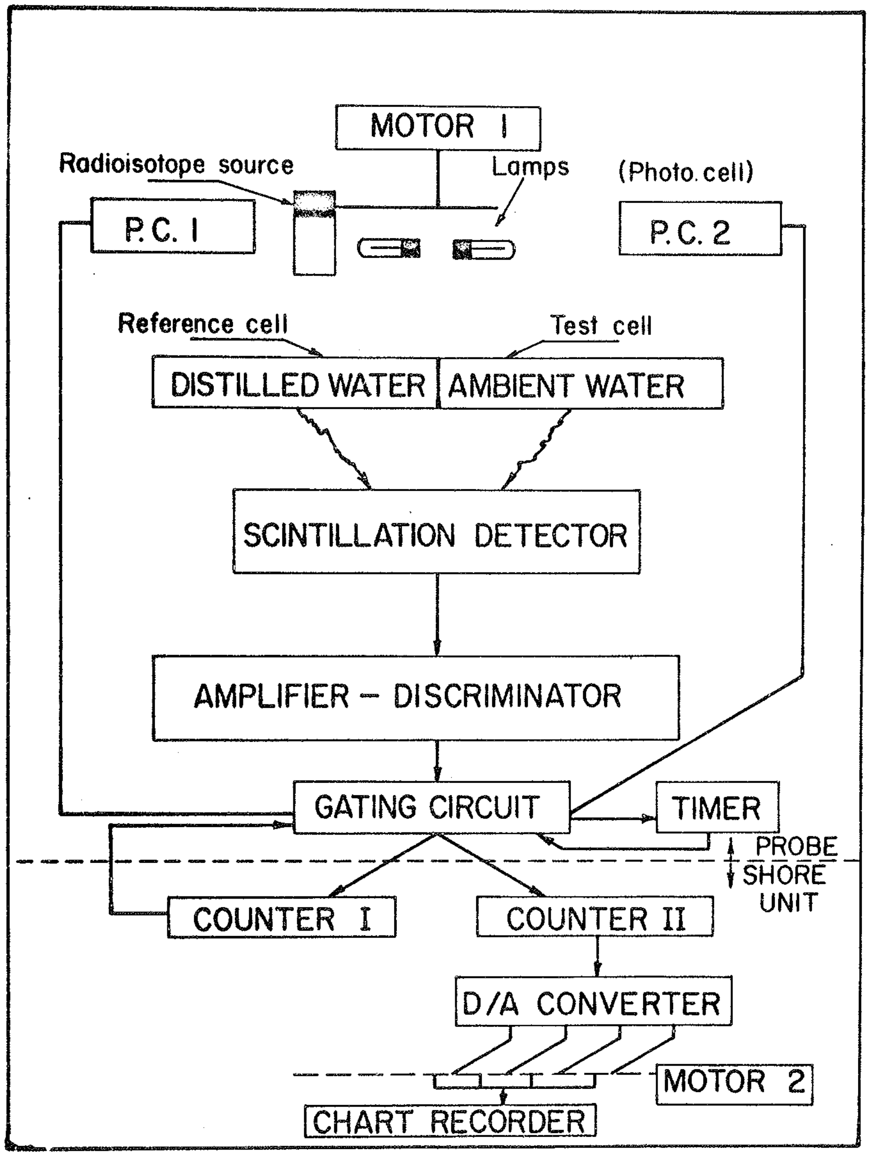


Figure 2. Schematic diagram of Parametrics sediment gauge.

"A scintillation detector converts the X-ray energy into electrical pulses which after amplification are fed into a differential discriminator. It is designed to discriminate pulses over a range equivalent to 9 kev and 40 kev of X-ray energy. The output pulses containing information about the distilled water are then steered by the gating circuit to counter I. Similarly the pulse information from the river water is steered to counter II. The duration during which pulses reach either counter is determined by a highly stable timer. After counter I has received 524,288 pulses it feeds back a signal to the gate circuit, blocking all pulses. At the end of the 15 minute period the chart recorder is activated and the binary information of counter II after processing by the D/A converter is printed out in analog form onto the strip chart. Four analog outputs are recorded, separated by a short time interval of zero amplitude. After all four outputs have been recorded, the counters are automatically reset, starting a new cycle of data acquisition, processing and recording."

Calibration of the gauge. The Parametrics sediment concentration gauge, Serial No. 001, was calibrated in the USDA Sedimentation Laboratory. The detector head was immersed in water in a small tank, and readings were taken over an extended period. After a series of readings were taken to determine the water standard, a bentonite slurry was added to the tank. Slurries of bentonite were prepared which contained increasingly greater amounts of clay. The suspension was thoroughly mixed in the tank and kept in motion by two high-speed stirrers.

Settling out and density currents thus were minimized. After allowing time for mixing and equilibrium, a series of readings was taken with the gauge. When the readings appeared to reach equilibrium, an average of the readings taken over several hours was obtained. Prior readings were discarded as being representative of nonequilibrium (nonuniform concentration) conditions. After taking duplicate samples for gravimetric determination of the clay concentrations, another slurry of greater clay content was added, and so on. The calibration curve is shown in Figure 3.

Each reading obtained from the gauge was a number that was directly proportional to the intensity of the X-rays at the detector. High sediment concentrations gave low readings because of the greater attenuation of the radiation. An average clear water reading of 1652 was obtained for 14 observations on January 14 and 18 additional observations on January 21. These dates bracketed the period of calibration with bentonite slurries.

A comparison of the January 1966 calibration curve with those previously obtained for various models of the Parametrics sediment concentration gauge is shown in Figure 4. The 1963 calibration curve was obtained for an early experimental model. In 1964, when a unit was first assembled for field testing, the greatly reduced sensitivity shown was attributed to a change in the radioactive source used and to a change in the composition of the window in the detector. This decreased sensitivity was largely eliminated in the redesigned unit which was tested briefly by the USDA

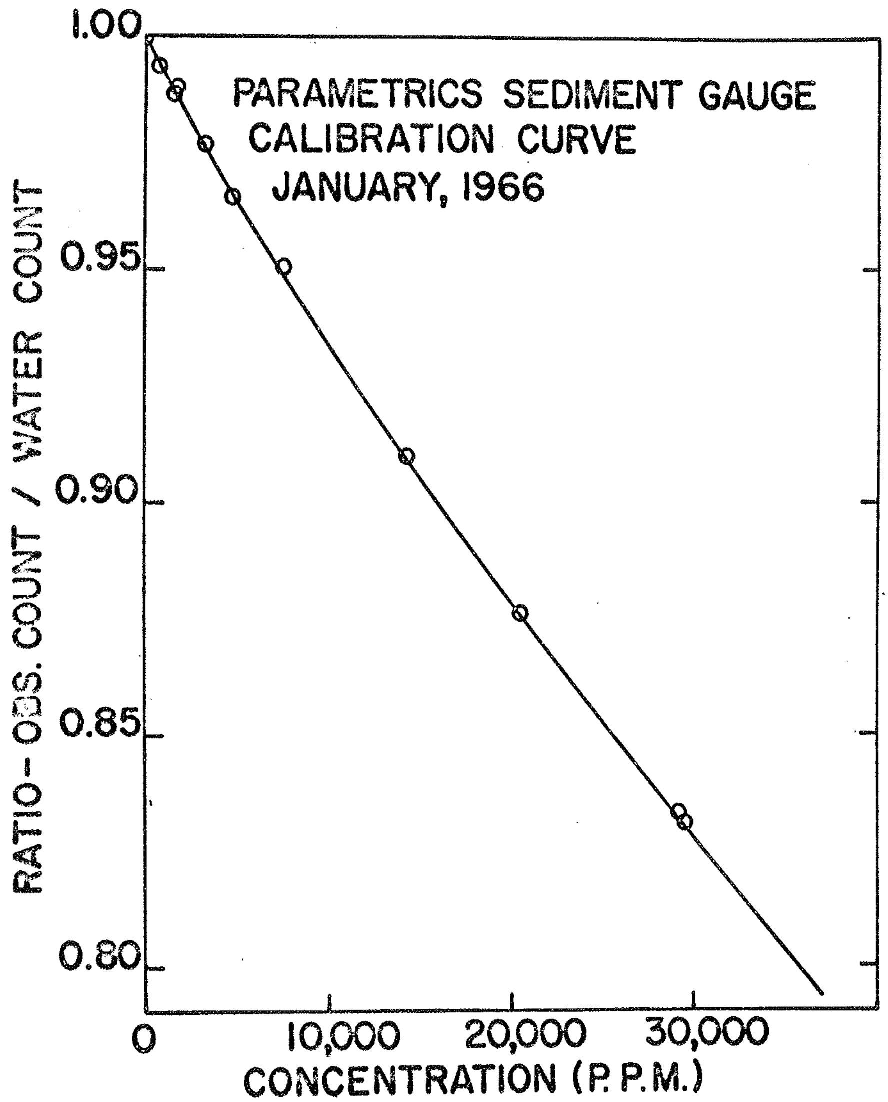


Figure 3. Calibration curve for Parametrics sediment gauge No. 001, January 1966.

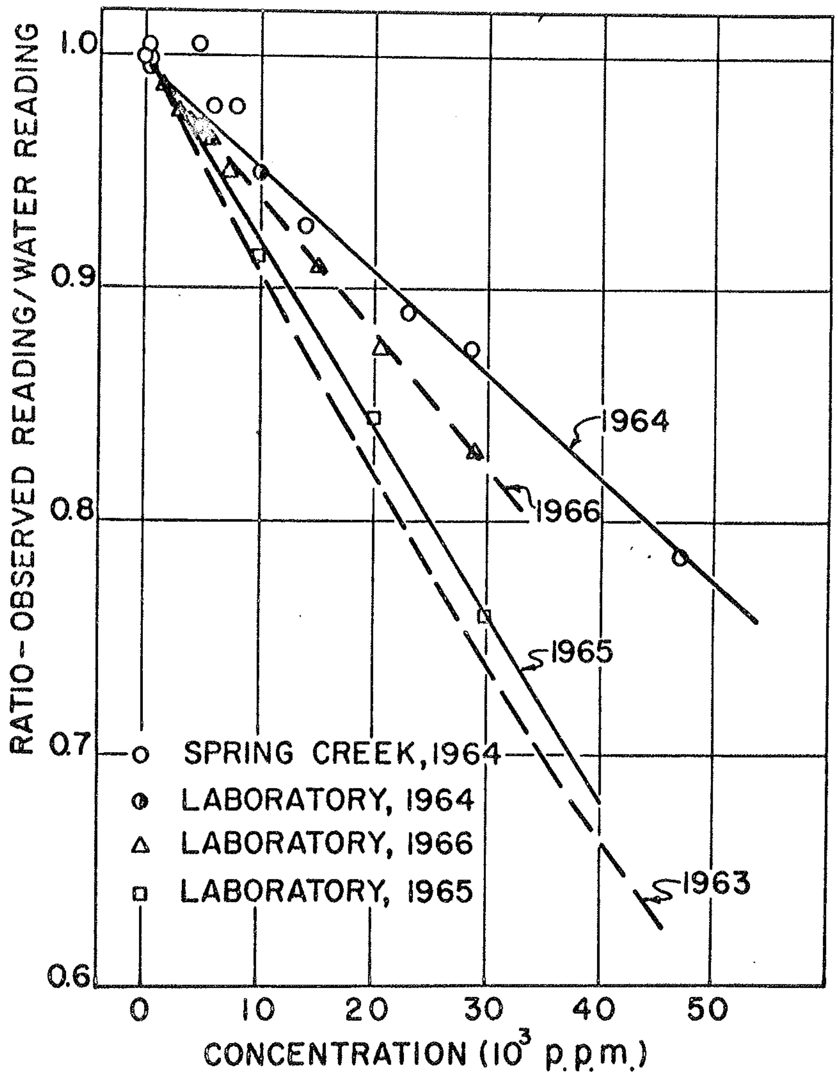


Figure 4. Calibration curves for Parametrics Sediment Concentration Gauges.

Sedimentation Laboratory in October of 1965. Mechanical failures in the timing mechanism necessitated the return of the electronic read-out unit to the manufacturer. Upon return of this equipment, the calibration curve marked as 1966 was obtained. The noted decrease in sensitivity of the 1966 curve is not presently under stood.

Field installation. The Parametrics sediment gauge was installed at Station 17 (50.2 square miles of drainage area) in the Pigeon Roost Creek Watershed, Marshall County, Mississippi. The channel bed at Station 17 is approximately 70 feet wide and water flows continuously at a rate of 8 to 10 second-feet with a mean solids concentration of from 5 to 20 p.p.m. During direct storm runoff, peak flow rates of 6720 second-feet have been recorded with a peak suspended sediment concentration of about 15,000 p.p.m.

The sediment gauge installation consisted of:

1. A shield (Figure 5) of welded steel attached to the steel bridge piling with horizontal wales spaced 0.5 foot apart. The shield was built 14.5 feet high to provide the necessary protection to the sensing unit from large floating debris.

2. A vertical steel channel with a traveling dolly (Figures 6 and 7) on which the sensing unit was attached. The steel channel was so arranged as to orient the probe in the direction of flow.

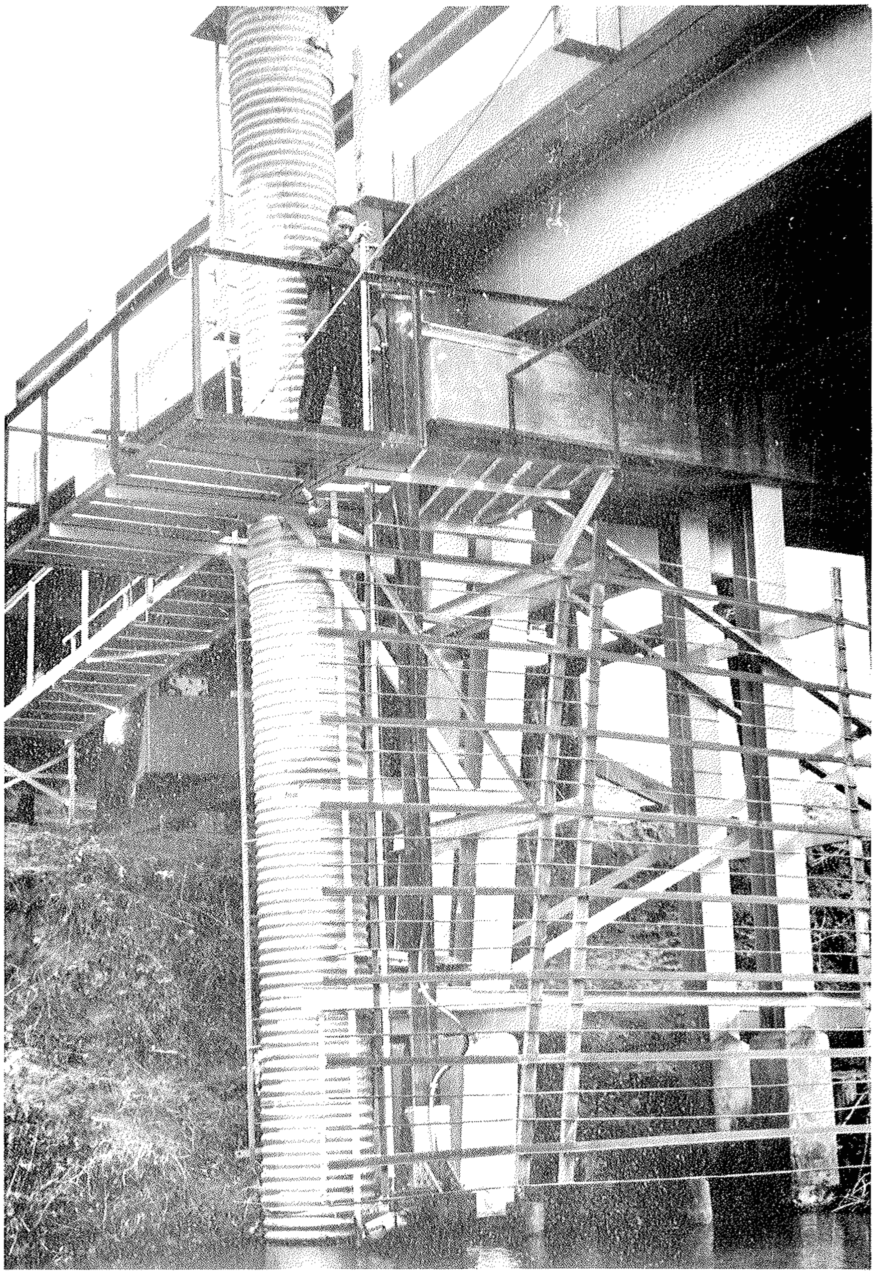

Figure 5. Stilling well (with Stevens A-35 continuous chart recorder) and Parametrics sediment gauge installation at Station 17, Pigeon Roost Creek, Marshall County, Mississippi.

Figure 6. Installation of Parametrics sediment gauge at Station 17 showing traveling dolly with detector head attached. Note signal cable is loosely fastened to the steel cable holding the dolly.

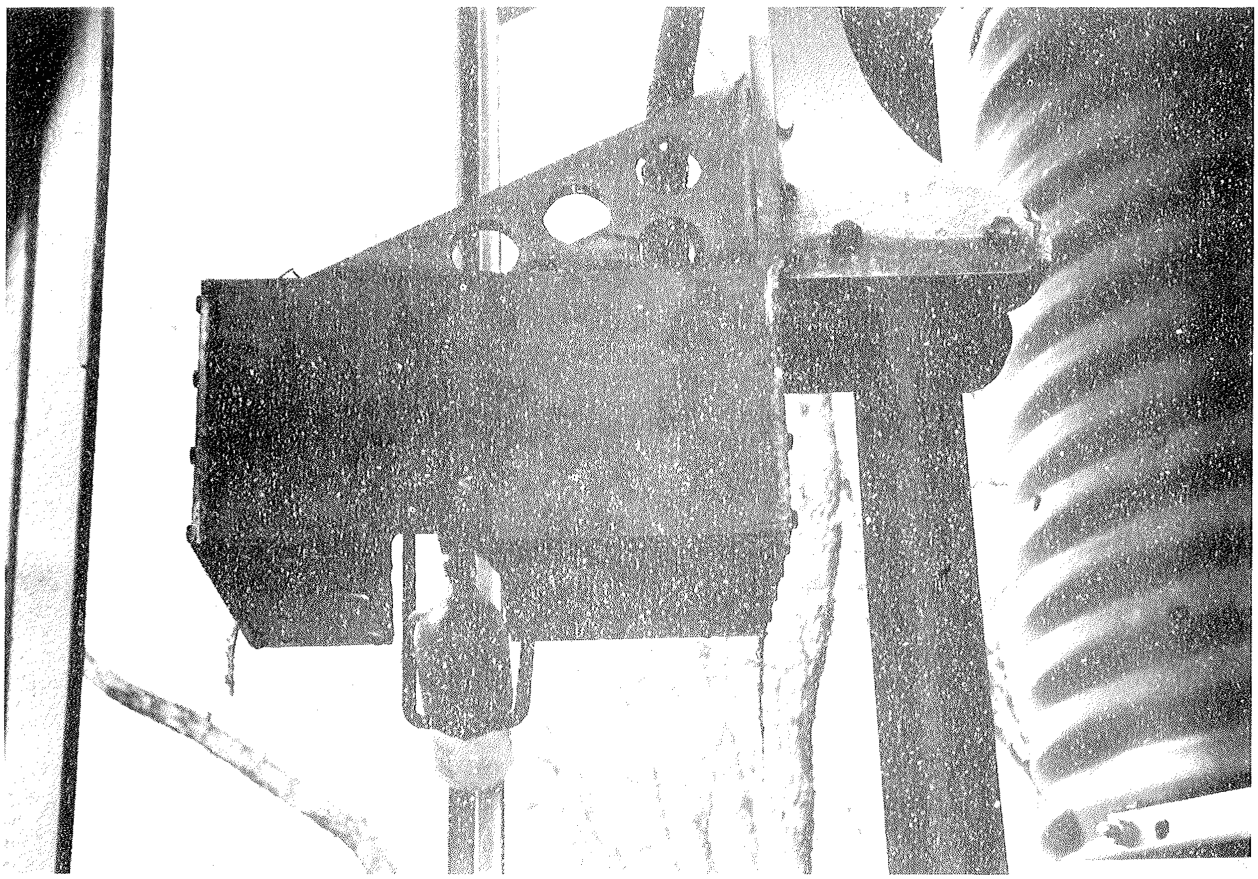

Figure 7. Closeup view of Parametrics sediment gauge and DH-48 sampler. View of the detector head is from upstream. The "window" in the channel of the detector can be seen. Support of dolly by steel channel is detailed.

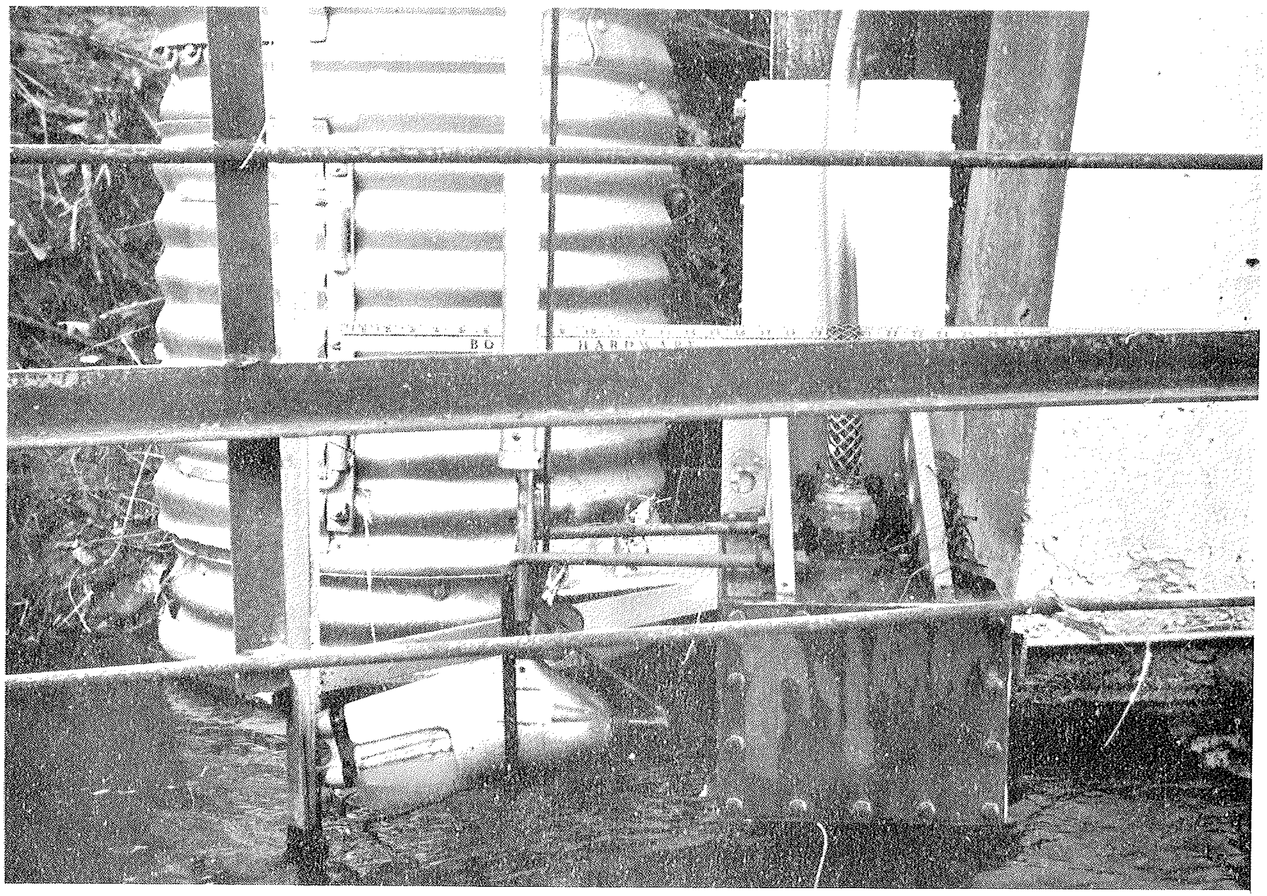

Figure 8. Closeup of U. S. DH-48 modified hand sampler and detector head of Parametrics sediment gauge. Note position of nozzle of the DH-48 sampler and mechanism for opening and closing.

3. A stilling well (Figure 5) with a Stevens A-35 continuous chart recorder[1/] which provided a complete water stage record throughout the period of storm runoff.

4. A U.S. DH-48 hand sampler (1), (Figures 7 and 8), modified to collect point samples for comparison with those from the Parametrics sediment gauge. A vertical guide was mounted on the support beams and a bracket was attached to the sensing unit (Figures 6 and 7) so that point samples of the sediment-water mixture could be obtained as the suspension flowed out of the channel of the sensing unit.

5. A working platform above the probe with a catwalk to the stream bank (Figure 5).

6. An instrument shelter on the bank which housed the shore unit and the battery pack.

Field operation of the gauge. From the operating experience gained in the laboratory during calibration it was not deemed desirable, or even possible, to operate the Parametrics sediment gauge for 7 days without servicing. The differential drain on the batteries was such that some cells would be very weak while others would be relatively fresh. It was the policy, therefore, to charge the batteries 2 or 3 times a week.

Practically no sediment is transported during base flow at Station 17. Base flow, therefore, provided

1/ Trade names are provided for information and do not imply endorsement by the U. S. Department of Agriculture.

an opportunity for evaluating the continuous performance of the Parametrics unit. Observations during these flow conditions could be used to check on the consistency of clear water readings. Therefore, the instrument was operated several times a week for one to three days under base flow conditions to obtain a knowledge of the operating characteristics of the unit with time.

Ideally, the unit would be operated for 6 to 24 hours before a storm, through a complete runoff event, and for 12 to 24 hours after the flood runoff ceased. The standard, water reading would be taken as the mean of the base flow measurements.

During flood runoff, hand samples were collected and the time at which each sample was taken was noted. The hand samples were taken with the modified DH-48 sampler at a point immediately behind the channel in the Parametrics director head (Figure 6). As only a short time, usually less than a minute, was involved in filling the bottle, the hand samples represent, more nearly, instantaneous samples, whereas the Parametrics read-out is an integrated value.

The clock time and sample numbers were noted on the strip chart of the Parametrics gauge. Frequently, the time of read-out of the Parametrics gauge was also noted. This was necessary in order to correlate number of read-outs with clock time.

# EXPERIMENTAL FIELD RESULTS

Field observations of runoff events. Furing the reported test period, February 8 to March 31, 1966, three storms of interest occurred. The data from these three storms are discussed in order of their occurrence.

## 1. Storm on February 9-10, 1966

On February 9 and 10, from 4½ to 5 inches of rain fell in the watershed above Station 17. A storm of this magnitude and intensity will occur about twice a year at this location. In Figure 9, flow, sediment concentration as determined by a U. S. DH-48 hand sampler, and sediment concentration as recorded by the Parametrics gauge are shown as a function of clock time. The discharge and sediment concentrations were typical of a major storm.

Hand sampling did not begin until the peak discharge had passed. During the time in which hand samples were taken the agreement between hand samples and the Parametrics gauge was good, although the comparison is for a low concentration. The general appearance of the sediment concentration curve, based on the Parametrics gauge readings, when compared with the hydrograph, seems plausible.

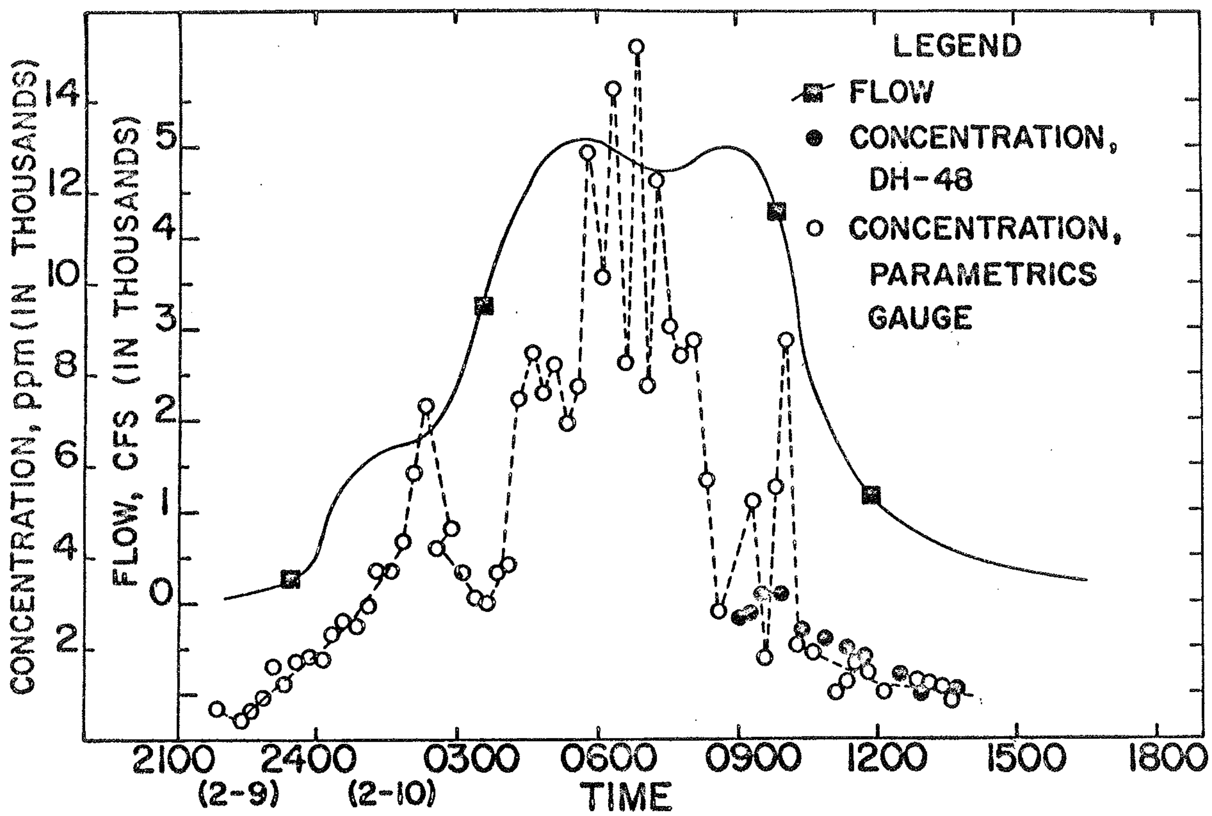


Figure 9. Runoff and sediment concentration for storm of February 9-10, 1966.

At the highest discharge there was considerable variation in successive sediment gauge readings, i.e., 0500 to 0800 hr. During this storm the detector head was about 9 inches from the bed at base flow. It was thought the observed variation might reflect passage of sand dunes (and consequently a variation in measured concentration). This being the first big storm of the year, large amounts of debris were present.

2. Storm on February 12, 1966

This storm was much the smallest of the three, based on the discharge rate (Figure 10). From 1-1/2 to 1-3/4 inches of rain fell over the watershed. Runoff was observed at about 0500 hr. on the 12th and continued for some 16 hours. The Parametrics gauge was activated at 0940 hr. Only a few hand samples were taken during this storm. Gauge values for sediment concentration were a little less than the hand-sampled values. There was considerable variation in the concentration reported by the Parametrics gauge. This saw-tooth effect may largely be explained by the inherent variation in the decay rate of the radioisotope. However, the abrupt change in reported concentration by the Parametrics gauge at 1330 hr. can not be explained. It appears that two levels of operation were involved. More will be said on this matter. A discussion of the negative concentration values will also be given below.

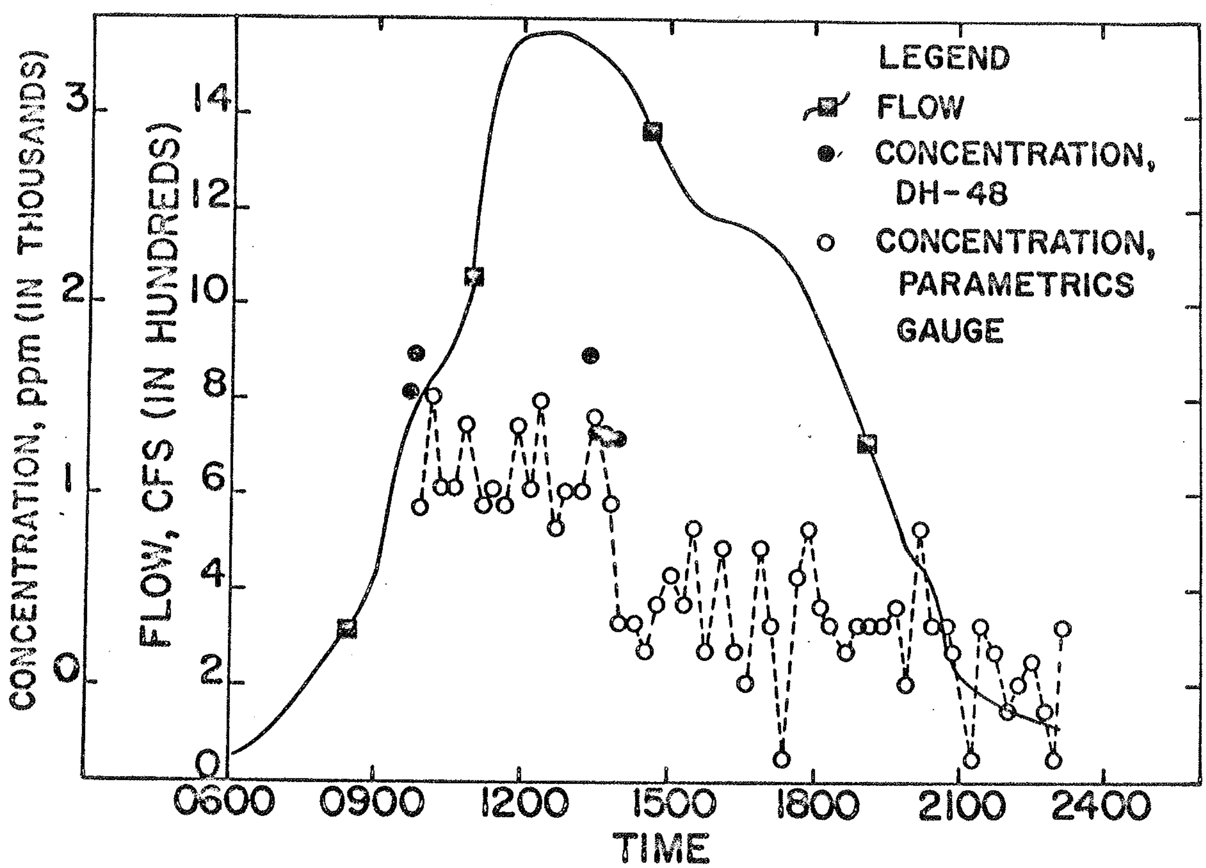


Figure 10. Runoff and sediment concentration for storm of February 12, 1966.

3. Storm on March 3-4, 1966

Good coverage of the storm on March 3-4 was obtained. About 1½ inches of rain were recorded in the watershed. Base flow readings were obtained before and right up to the time of the rise, (Figure 11). Numerous hand samples were obtained during the rise and recession of the hydrograph. This storm produced a typically shaped hydrograph.

The gauge-measured concentrations during the first hour were a little higher than those obtained by hand sampling. Thereafter, the sample concentrations were about 20 percent higher than those indicated by the gauge. The reasons for these differences and for the reversal in direction of the differences are not known. The concentrations, as indicated by the Parametrics gauge, displayed a fluctuation about a mean trend line after 2100 hours that was of a magnitude to be expected because of the random decay pattern of the radioisotope (Figure 11). The standard deviation is approximately 200 p.p.m. for this gauge.

The mean of the preceding base flow readings of 1628 was used as the clear water standard for computing the sediment concentrations.

Field observations in low water. To supplement the laboratory calibration and to assure that no significant changes in operating characteristics of the Parametrics sediment gauge occurred, measurements of sediment concentration of base flow were made before and after the selected storm events. Very little sediment is

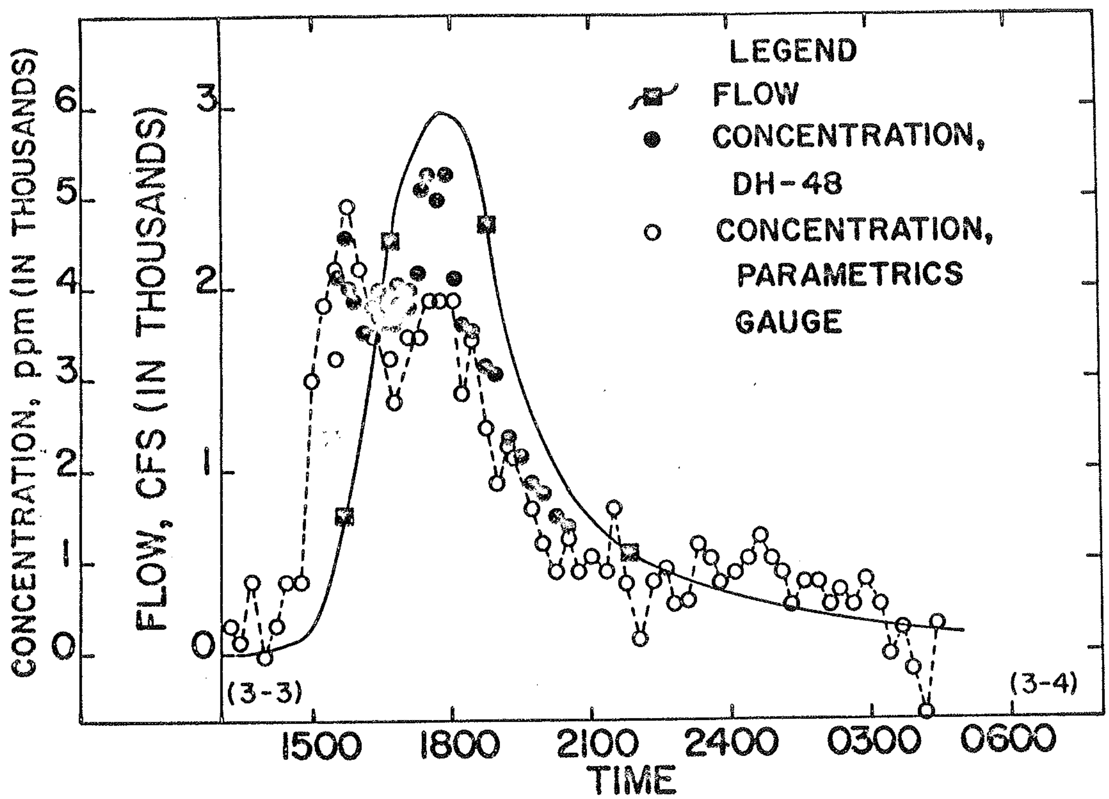


Figure 11. Runoff and sediment concentration for storm of March 3-4, 1966.

carried at discharges of less than 10 to 12 second-feet at Station 17. This is insignificant insofar as the sensitivity of the Parametrics gauge is concerned. A summary of the base flow measurements is given in Table 1. For each period, the number of observations (gauge read-outs), the mean value and the probable error of the mean are given.

The calibration curve for the sediment gauge is based on the standard value taken for water. This laboratory calibration was made with tap water whose dissolved solid content is comparable to the concentration of Pigeon Roost Creek at base flow. If this clear water value varies unpredictably, the computed ratios would not be compatible with those for the calibration curve. Examples of this possible error are readily found on examination of the data. At times the use of the laboratory standard for computing sediment concentration would yield a negative concentration; i.e., the observed readings on the sediment gauge chart are more than the standard. A different water standard must be used. In most cases when the above-cited instance occurs, it will be found that the base flow mean reading prior to, or after, the storm event is indeed lower than the laboratory standard. In the case of the storm on March 3, it seemed necessary to use the base flow mean (March 2-3) to compute meaningful concentrations.

Table 1.--Base flow readings obtained with the Parametrics sediment gauge, Station 17, Pigeon Rooost Creek, Mississippi, February-March, 1966.

| Date | Conditions* | Number of Gauge Readings | Mean Gauge Reading | Probable Error |
|---|---|---|---|---|
| Jan. 14 | Laboratory | 10 | 1652 | ± 1.0 |
| Jan. 21 | " | 18 | 1652 | ± 0.7 |
| Feb. 8-9 | Base flow, 8-10 c.f.s. | 115 | 1647 | ± 0.3 |
| Feb. 14-15 | " | 70 | 1661 | ± 0.3 |
| March 2-3 | " | 85 | 1628 | ± 0.4 |
| March 7-8 | " | 117 | 1649 | ± 0.3 |
| March 8-9 | " | 91 | 1646 | ± 0.6 |
| March 10-11 | " | 89 | 1645 | ± 0.6 |

* Essentially clear water.

The temperature of the base-flow water does not vary greatly. In the laboratory, a 10 to 20° F. change in water temperature did not affect the calibration results. However, when hourly mean base flow water readings were plotted against hourly mean air temperatures as a function of time, a striking response of read-out to temperature was observed (Figures 12 and 13). Air temperatures were measured at the North Mississippi Branch Agricultural Experiment Station, some 8 miles away. These data are illustrative of the observed data. Similar results were obtained for each series of measurements.

A preliminary analysis of the base flow data obtained in February and the first 9 days of March indicated that the readings not only decreased with increasing air temperature but also decreased with increasing time by approximately 0.8 times the number of days between readings. This adjustment was made and the hourly means replotted against air temperature as shown in Figure 14. Data obtained subsequent to March 9 are erratic and do not conform to the trend of the earlier data, except for data obtained on March 28 (not shown), which may be a happenstance. This erratic behavior was possibly due to a malfunction in the gears of the timing mechanism as the timer failed completely on March 31.

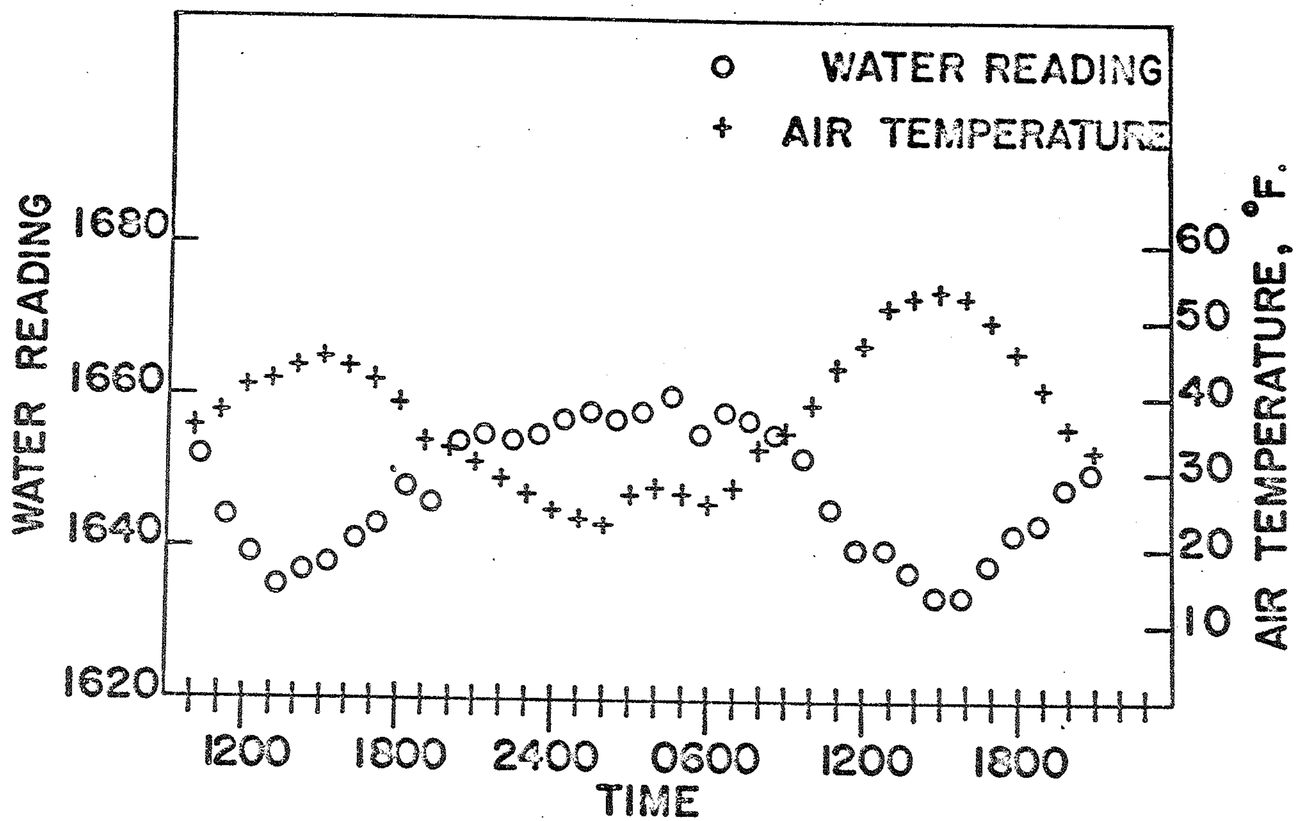


Figure 12. Hourly mean air temperatures and hourly mean water readings (base flow) of the Parametrics sediment gauge, March 7-8, 1966.

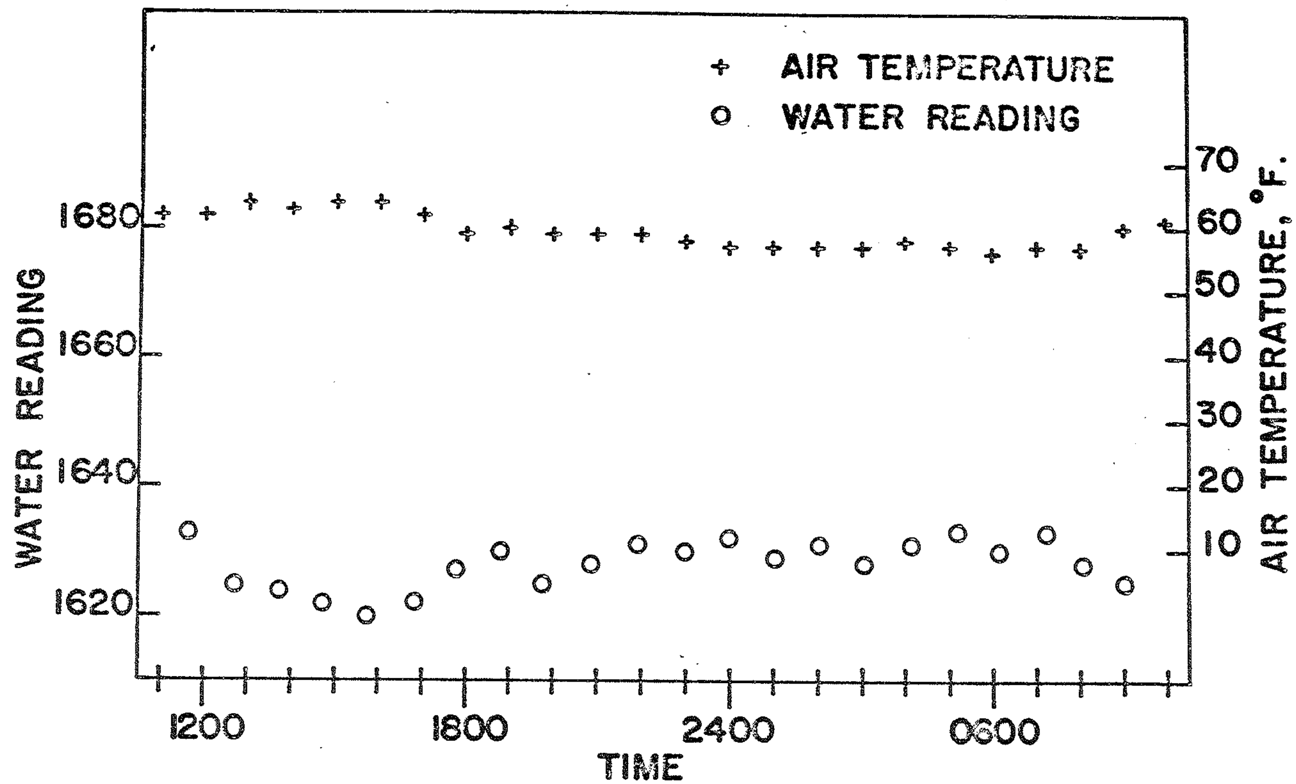


Figure 13. Hourly mean air temperatures and hourly mean water readings (base flow) of the Parametrics sediment gauge, March 2-3, 1966

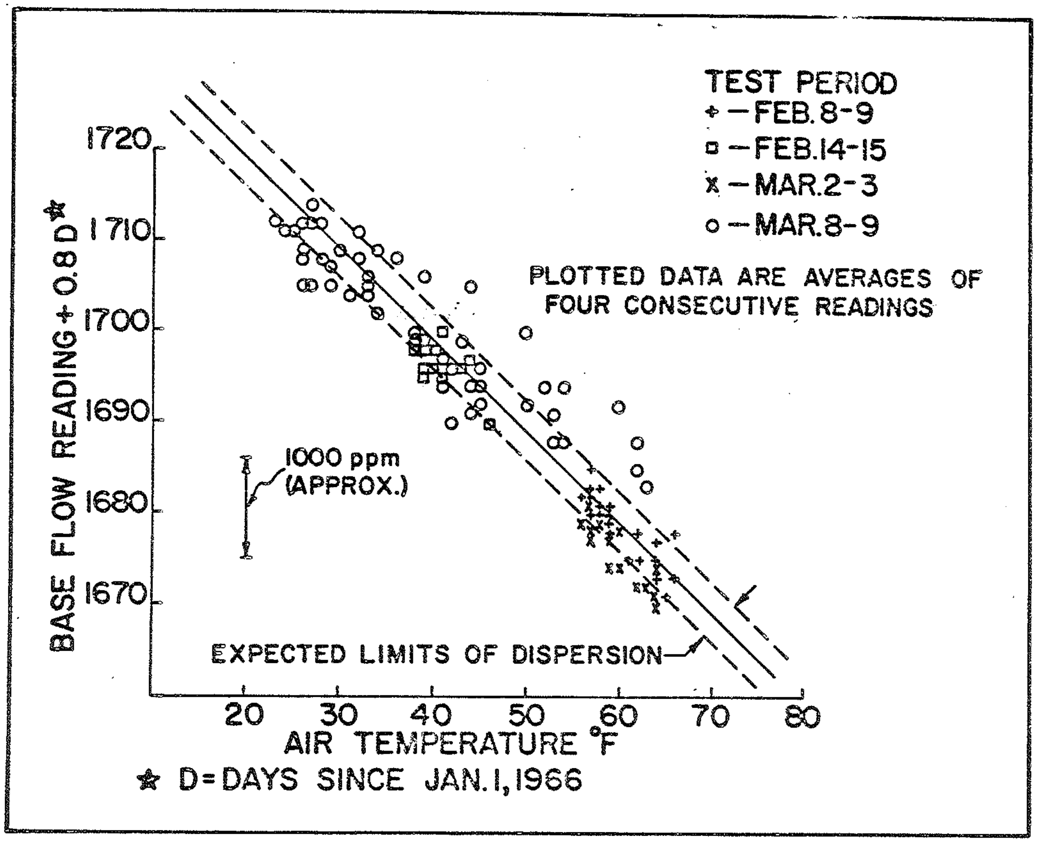


Figure 14. Variation of adjusted base flow readings with temperature.

The trend line of Figure 14 may be symbolically expressed as:

$$R = 1737 - (F + 0.8D)$$

where R = gauge readings

F = temperature degrees Fahrenheit

D = days since January 1, 1966

The dashed lines that bracket the trend line for the data obtained prior to March 9 represent the limiting values to be expected from the random decay pattern of the radioactivity of the isotope. This is computed on the basis of plottings of averages of 4 consecutive 15-minute readouts, using the ratio of 524,288 impulses per 15-minute readout (as stated in the manual accompanying the gauge) to the mean readout value, and the assumption that the standard deviation of the impulse count is equal to the square root of the count. The dispersion (approximately $\pm 3\sigma$) of the early data is seen to be somewhat greater than expected even after adjustments for age and temperature.

## DISCUSSION AND CONCLUSIONS

Specifications. The specifications for the Parametrics gauge, Serial No. 001, as given by the manufacturer in the accompanying instruction manual are essentially those agreed upon at the Inter-agency Sedimentation Subcommittee meeting in Minneapolis in 1964.

They are:

1) Concentration range: 500 to 50,000 p.p.m. of sediment of density averaging 2.65 g/cm$^3$.

2) Accuracy: $\pm$ 20% at 1000 p.p.m. by weight, better at higher concentration.

3) Read-out: The total number of counts of river water are recorded every 15 minutes on a strip chart.

4) Service period: 7-1/2 days.

5) Operating Temperature: a) Measuring head 32 to 85$^\circ$ F. b) Shore station 20 to 120$^\circ$ F.

6) Power: 4 lead-acid batteries of 100-AH capacity each, at 12 V nominal.

These specifications will be discussed in turn.

1) Concentration range

The field trials did not test the response of the equipment at the high end of the scale because the maximum concentration was only 15,000 p.p.m. The practical lower limit of detection was about 500 p.p.m. The errors associated with concentration measurements less than 1000 p.p.m. increase rapidly with decreasing concentration.

2) Accuracy

At 1000 p.p.m. the accuracy is to be $\pm$ 20% (by weight). This means one should be able to distinguish between a suspension at 1000 p.p.m. and one at 1400 p.p.m. From the calibration curve this difference is calculated as equivalent to about 5 units on the chart readout. This difference is statistically significant, provided the unit is functioning properly and the variance, or data spread, is not great. The erratic, up-and-down, or saw-tooth response of the gauge to sediment concentrations less than 1000 p.p.m. has been noted. These short-period variations are in the range of magnitude to be expected from the random decay process of the radioisotope. The standard deviation for this gauge for this source of variation is about 200 p.p.m.

In addition to the observed temperature effect on water readings, the early data showed a progressive decrease in water readings with increasing age of the device. Also, from the gauge records that were obtained during two flood events and from the gauge records for the base flow conditions of mid-March, there appears to be a large amount of unexplained erratic behavior.

3) Read-out

The read-out mechanism is set for somewhat more than a 15-minute period. On a 15-minute basis, some 40 minutes are lost during a 24-hour period. For routine use, a 3-minute correction was necessary every 2 hours to maintain read-out time on clock time.

4) Service period

The unit has functioned up to five days with no battery servicing. Because of the differential battery drain it was thought desirable to recharge the batteries more frequently than once a week. The timer motor in the shore unit failed after 237 hours of actual field operating time.

5) Operating temperature

The measuring head performed within its specifications. The shore station was, as noted above, temperature sensitive. It is not meeting specifications.

6) Power

The use of 4 lead-acid batteries tapped at differing voltages leads to differential discharge of the battery cells. This makes it difficult to recharge the battery evenly or quickly. This is a serious operating problem and one that should be eliminated by the use of a voltage divider within the shore unit to permit the use of 12 volts only from the storage batteries.

<u>General recommendations</u>. The use of the octal read-out system on a strip chart recorder can be improved without added expense. The read out should be digital and with an option of being on punched tape that can be handled by existing tape-to-computer converters.

The detector head is overly large. If this unit could be made smaller and the corners rounded, it would create less of a problem in a debris-laden stream.

Operation of the unit from AC power would be advantageous. Batteries operating through an inverter would act as emergency power source. Such an AC unit might be produced at a lower cost than the DC unit.

Interest has been shown in a shorter read-out time for this instrument. At its present level of sensitivity such a reduction in counting time would adversely affect the detection limits of the gauge. Unless greater sensitivity can be obtained, or unless the device is to be used in streams with high concentrations, the use of the shorter time constant would be of doubtful utility.

In conclusion, the Parametrics sediment concentration gauge has shown promise in its first full-fledged field tests, all things concerned. Several components of the gauge are not up to design specifications. The next model of the gauge should be capable of greater accuracy and reliability if the below-standard elements are improved and the stability of the unit is improved by installation of improved components.

# REFERENCES


1. Subcommittee on Sedimentation, Inter-Agency Committee on Water Resources. 1963. A study of methods used in measurement and analysis of sediment loads in streams. Determination of fluvial sediment discharge, Rpt. No. 14, St. Anthony Falls Hydraulic Laboratory, Minneapolis, Minnesota.

2. Bird, Leonard L., John Papadopoulos, Roy A. Rex, and C. A. Ziegler. 1963. Radiological mechanisms for geophysical research. Annual Report. Parametrics, Inc., Waltham, Mass., AEC Res. and Development Rpt. NYO 10,220.

3. Bramson, M., and C. A. Ziegler. 1964. Radiological mechanisms for geophysical research. Annual Report. Parametrics, Inc., Waltham, Mass., AEC Res. and Development Rpt. NYO 10,221.

4. Papadopoulos, John, F. B. Sellers, C. A. Ziegler, and J. R. McHenry. 1964. Sediment gauge for rivers and streams. Second Annual Oak Ridge Radioisotope Conference. USAEC-TID-7689, p. 142.

5. Papadopoulos, J., Sellers, F. B., Ziegler, C. A., and McHenry, J. R. 1964. Sediment gage for rivers and streams. Trans. Am. Geophysical Union, Vol. 45, No. 1, p. 55.

6. Ziegler, C. A., Papadopoulos, J., and Sellers, F. B. 1964. Development of a sediment gauge for natural waters. Thirteenth Hydraulics Division Conference, Vicksburg, Mississippi. (August 1964).