A STUDY OF METHODS USED IN

# MEASUREMENT AND ANALYSIS OF SEDIMENT LOADS IN STREAMS

FEDERAL INTER-AGENCY SEDIMENTATION PROJECT

## REPORT X

# A FLUID-DENSITY GAGE FOR MEASURING SUSPENDED-SEDIMENT CONCENTRATION

1982

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## REPORT X

## A FLUID-DENSITY GAGE FOR

## *MEASURING SUSPENDED-SEDIMENT CONCENTRATION*

### PART A

### GAGE RESPONSE TO STEADY-STATE

### AND TRANSIENT CONDITIONS

By

J. V. Skinner

1982

A Study of Methods Used in

# MEASUREMENT AND ANALYSIS OF SEDIMENT LOADS IN STREAMS

A Cooperative Project
Sponsored by the
Interagency Advisory Committee on Water Data
Subcommittee on Sedimentation

Participating Agencies

Geological Survey ** Corps of Engineers
Agricultural Research Service
Soil Conservation Service ** Tennessee Valley Authority
Federal Highway Administration ** Bureau of Reclamation
Office of Surface Mining ** Forest Service

## REPORT X

## A FLUID-DENSITY GAGE FOR MEASURING SUSPENDED-SEDIMENT CONCENTRATION

Part A - J. V. Skinner
Part B - J. P. Beverage
Part C - J. P. Beverage and J. V. Skinner

Prepared for Publication by the Project Staff
at St. Anthony Falls Hydraulic Laboratory
Minneapolis, Minnesota

Published by
U.S. Army Engineer District, St. Paul

1982

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## SYMBOLS AND DEFINITIONS

$X$ = The independent variable in a two-variable regression analysis. In suspended-sediment studies, the count produced by the sediment.

$X' = \log_{10} X$

$Y$ = The independent variable in a two-variable regression analysis. In suspended-sediment studies, either the measured or computed concentration of test material.

$Y' = \log_{10} Y$

$S_e$ = The standard error of estimate.

$S_e = \sqrt{\frac{1}{N-2} \Sigma R^2}$ where

$N$ = Number of X-Y data points.

$R$ = Difference between measured Y and predicted Y. The value for each predicted Y is from the regression of measured Y on measured X.

$S_p$ = The standard error of prediction.

$$S_p = S_e \sqrt{1 + \frac{1}{N} + \frac{(X - \overline{X})^2}{\Sigma (X - \overline{X})^2}}$$

Bulk density - For a mixture of sediment and liquid, the ratio of mixture mass divided by mixture volume, expressed in grams per cubic centimeter ($g/cm^3$).

Cell - The commercially-produced unit that consists of the vibrating steel U-tube, the sense coil, the drive coil, and the magnets. All these parts are enclosed in a welded case.

Count - A dimensionless integer equal to the difference between two cumulative counts, each recorded for specific test conditions. Because cumulative count is affected by several factors such as temperature, dissolved-solids concentration and sediment concentration, the test conditions were controlled so that each count is associated with a change in only one factor. For example, when calibrating for sediment concentration, all other factors were maintained constant. One cumulative count was recorded when the U-tube flow contained a measured sediment concentration and the other cumulative count was recorded when the flow was free of sediment.

Cumulative count - Cumulative count is a dimensionless integer that registers the number of pulses produced by a 12.8 kHz oscillator in the time span required for the U-tube to complete 18,430 vibration cycles. When the tube is filled with sediment-free water, the cumulative count is about 2,000,000, although the exact value, which is registered by counter B, depends upon specific test conditions.

Density - For either a liquid or solid, the ratio of mass divided by volume, expressed in grams per cubic centimeter.

Detritus - Bits of organic material such as leaves, grass and twigs.

Dissolved solids - The dissolved constituents remaining after a water sample has been evaporated to dryness.

Dissolved-solids concentration - The ratio of the mass of dissolved solids to the total mass of the dissolved solids and water mixture, expressed in units of parts per million (ppm).

Micrometer - $1 \times 10^{-6}$ meter.

Monodisperse - The size-distribution of a group of sediment particles having equal or nearly equal sizes.

Polydisperse - The size distribution of a group of sediment particles that include a broad range of particle size.

Precision - The dispersion within a group of instrument readings all of which are taken under identical test conditions.

Random errors - Measurement fluctuations that cannot be predicted from existing knowledge of the measuring system or test conditions.

Sediment - Solid particles derived from rocks. In this report sediment does not include organic material.

Sensitivity - A measure of the response of the gage when it is subjected to a change in one specified measurement factor such as sediment concentration or temperature.

Suspended-sediment concentration - The ratio of the mass of dry sediment to the mass of sediment-liquid mixture, expressed in units of parts per million (ppm).

System - The assemblage of components that form the sediment-concentration measuring device. The components consist of the deaeration chamber, vibration isolator, electrical feedback circuit, electrical timing circuit, cell and pumps.

Systematic errors - Measurement errors that consistently reappear when a test is duplicated.

# A FLUID-DENSITY GAGE FOR MEASURING SUSPENDED-SEDIMENT CONCENTRATION

## PART A

## GAGE RESPONSE TO STEADY-STATE AND TRANSIENT CONDITIONS

By J. V. Skinner

## ABSTRACT

A fluid-density gage for measuring suspended-sediment concentration consists of a commercial vibrating U-tube liquid-density cell coupled to a special feedback and digital period-measurement circuit. For steady concentrations of inorganic fluvial-sediment with a nominal density of 2.65 grams per cubic centimeter, the random measurement-error increases with an increase in particle size. For clay concentrations that exceed 500 milligrams per liter (mg/L), the standard error of estimate is less than 3 percent of the indicated concentration; for coarse sand, the error is 12 percent. For concentrations less than 500 mg/L, random errors are nearly independent of concentration. In this low-concentration range the random error is 15 mg/L for clay and 25 mg/L for sand. Because a systematic shift in response occurs with a change in particle size, the gage will require field calibration. The sensitivity to dissolved solids is nearly equal to the sensitivity to inorganic sediments. The gage can be compensated for dissolved solids and temperature. Tests with plastic beads chosen to simulate the density of organic detritus indicate the gage's sensitivity to this material is desirably low.

During unsteady conditions, the instrument requires approximately 9 minutes to adjust to a step-change in liquid temperature, but only 5 seconds to adjust to a step-change in fluid density.

# INTRODUCTION

The suspended-sediment transported by rivers has a vital impact on the design and use of engineering works such as reservoirs, navigation channels, water-supply systems, and soil-conservation projects. Sediment plays an important role in the character and natural balance of aquatic life. When released in the environment, certain toxic materials are adsorbed or absorbed by soil particles. Through erosion, these particles may eventually become part of a river's sediment load.

The demand for information on the movement of sediment has prompted the development of a variety of manual and automatic samplers. However, with manual or automatic samplers, several days to several weeks are required to complete all phases of laboratory sample analysis and to produce quantitative sediment-concentration data. An urgent need exists to reduce both the time and the labor required to collect and analyze these samples. To meet this need a field instrument capable of rapid sediment-concentration analysis is required.

A cantilever U-tube will vibrate at a rate that is sensitive to the density of the substance within the tube. If the substance is a water-sediment mixture, the rate will be sensitive to the concentration of sediment. The relation between vibration rate and sediment concentration indicates that a U-tube density cell may be useful for continuous field-measurements of inorganic suspended-sediment concentration in rivers.

## Purpose and scope

Preliminary tests of a commercially available U-tube density cell indicated that the vibration rate was sensitive not only to sediment concentration but also to several other factors that were sources of measurement interference. The purposes of this report are to (a) describe the relation between vibrational rate and each factor, (b) evaluate the usefulness of the U-tube density cell for continuous field-measurements of inorganic suspended-sediment concentration in rivers, and (c) explain methods for improving the accuracy of the cell.

## THEORY OF OPERATION AND SOURCES OF MEASUREMENT INTERFERENCE

Sediment having a density $\rho_s$, when added to a liquid having a density $\rho_\ell$, will produce a mixture with a density $\rho_m$, as given by the relationship:

$$\rho_m = \frac{\rho_\ell}{1 - (C \times 10^{-6})\left(\frac{\rho_s - \rho_\ell}{\rho_s}\right)} , \qquad (1)$$

where

C is the sediment concentration in ppm.

If $\rho_s$, $\rho_\ell$, and $\rho_m$ can be measured or estimated, the equation can be used to calculate the concentration of sediment in the mixture. With few exceptions the density of fluvial-sediment, $\rho_s$, is equal or nearly equal to 2.65 g/cm$^3$ and the value changes only slightly with temperature. The density of river-water, $\rho_\ell$, depends upon temperature and upon both the quantity and composition of solids dissolved in the water. Temperature can be measured accurately and can be used with standard tables to correct $\rho_\ell$. As explained in Part B of this report, dissolved solids concentration can be estimated from water conductivity readings. Measuring $\rho_m$ is the primary obstacle to calculating C by the "bulk density" relationship described by equation 1.

One method of measuring $\rho_m$ is with a fluid-density gage of the vibrating U-tube type. The vibrational characteristics of a U-tube are similar to those of an elastic beam. An elastic beam attached at one end to an immovable support (figure A-1a) will, when struck a blow, vibrate with a period established by the length, mass, shape, and elastic properties of the beam. As shown in figure A-1b, the peak displacement will gradually diminish because energy will be dissipated within the beam and to the surrounding air. The response will be similar to that of a tuning fork.

Figure A-1c shows a U-shaped tube fastened to a heavy support. Inertia resists acceleration, so, when subjected to small vibrational forces, the heavy support will remain nearly motionless. The closed end

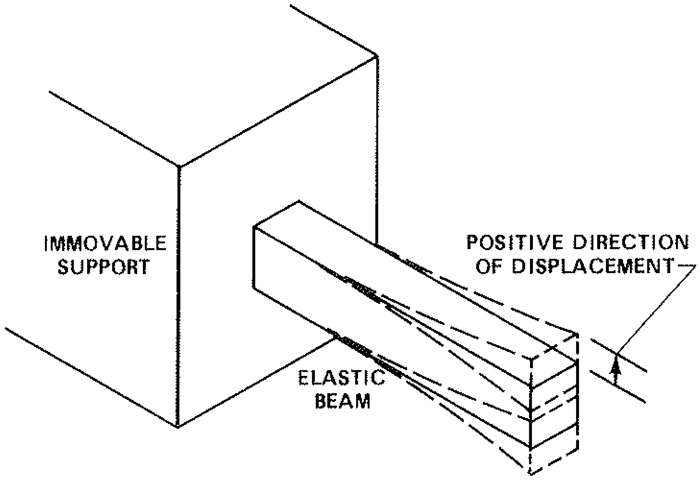

Figure A-1a.--Vibration of a solid cantilever beam.

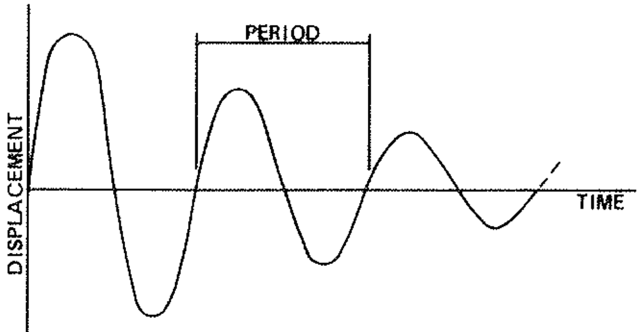

Figure A-1b.--Vibrational damping of a cantilever beam.

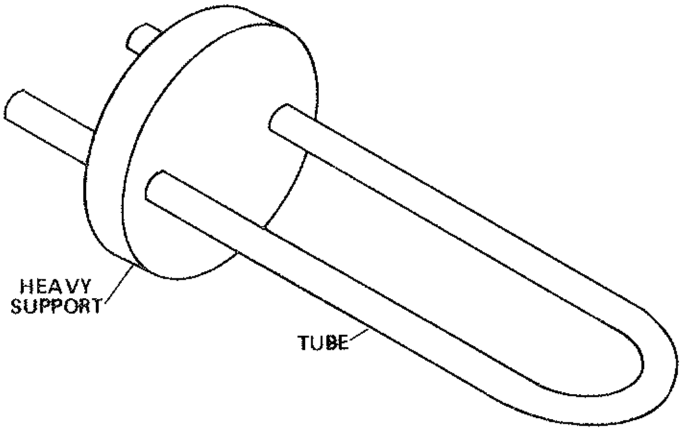

Figure A-1c.--Basic components of a hollow U-shaped cantilever.

Figure A-1.--Vibrational characteristics of an elastic cantilever beam.

of the tube will vibrate with a period established by the length, mass, shape, and elastic properties of the tube. After being struck, the tube will vibrate with a slowly diminishing amplitude, as shown in figure A-1b.

According to Den Hartog (1947, p. 458), a beam with a mass at its free end will vibrate at a natural angular frequency $\omega_\eta$ as given by the relationship:

$$\omega_\eta = \frac{2\pi}{P} = \sqrt{\frac{k}{M + 0.23\ m}} \quad , \tag{2}$$

where $k = \dfrac{3\ EI}{\ell^3}$ ,

$P$ = period of vibration,

$E$ = beam modulus of elasticity,

$I$ = beam cross-section moment of inertia,

$\ell$ = beam length,

$M$ = mass attached to the free end of the beam, and

$m$ = mass of the beam.

When the metal U-tube is completely filled with a sediment-water mixture, the mass of the mixture will add to the mass of the metal tube, $m_t$. The total mass, $m$, is given by the relationship:

$$m = m_t + \rho_m V \quad , \tag{3}$$

where $V$ = volume of the mixture contained within the tube. In equation (1) let

$$\frac{\rho_s - \rho_\ell}{\rho_s} = S \quad ,$$

then substitute $\rho_m$ from the converted form of equation 1 into equation 3 to obtain

$$m = m_t + \frac{V\rho_\ell}{1 - (SC \times 10^{-6})} \quad . \tag{4}$$

Substitute equation 4 into equation 2, solve for P and then simplify to obtain

$$P = \sqrt{\frac{4\pi^2(M + 0.23m_t)}{k} + \frac{0.92\pi^2 V\rho_\ell}{k(1 - SC \times 10^{-6})}} \quad . \qquad (5)$$

Equation 5 may be written as

$$P = \sqrt{A + \frac{B}{1 - SC \times 10^{-6}}} \quad , \qquad (6)$$

where

$$A = \frac{4\pi^2(M + 0.23m_t)}{k} \text{ and}$$

$$B = \frac{0.92\pi^2 V\rho_\ell}{k} \quad .$$

Equation 6 shows the relation between the period of vibration P and the sediment spatial concentration C in ppm. All terms in the expression for A are tube characteristics; consequently, the value of A is independent of mixture characteristics. The value of B is determined by both tube characteristics and liquid density but is independent of sediment concentration. Both A and B are positive and, for a particular liquid density, are constant.

If $\rho_s > \rho_\ell$, which is true for most fluvial sediments, then S will be positive. The fractional term in equation 6 will be positive if $1 - SC \times 10^{-6} > 0$. To satisfy this inequality, C must be within the range $0 < C < 10^6/S$. If C falls in this broad range then, regardless of the magnitude of A, P will be positive and real; furthermore, each value of C will correspond to only one value of P. The one-to-one correspondence between concentration and period forms the basis for this method of concentration measurement.

Detritus, as defined in this report, consists of organic plant material and therefore has a density equal or nearly equal to the density of water. For this mathematical analysis, detritus may be treated as neutrally-buoyant sediment particles. If $\rho_s = \rho_\ell$, then S = 0 and both the fractional term and P in equation 6 are independent of detritus concentration. Freedom from detritus interference is a desirable property for nearly all types of sediment measurements.

If the mixture contains entrained air, the bubbles may, for this discussion, be treated as sediment particles of low density. If $\rho_s < \rho_\ell$, S is negative; therefore, in equation 6, both the fractional term and vibrational period will decrease if the air concentration increases. Because air bubbles will interfere with sediment measurements, they must be removed from the flow before it enters the U-tube.

Mixture density depends on $\rho_s$ and, consequently, on sediment composition. Most fluvial sediments have a density of about 2.65 g/cm$^3$, but at sites where the bulk of the sediment is coal or other material with an unusually high or low density, the period-concentration relation must be carefully established.

Even though temperature is not considered in equations 1 to 6, a change in temperature will change certain characteristics of both the tube and the mixture. A change in temperature will induce a minor change in the modulus-of-elasticity of the metal that forms the tube. However, a more significant change will occur in the tube diameter, length, and wall thickness. A change in diameter and wall thickness will change the term I in equation 2. Another change will occur in the mass, m, which consists of two components: the metallic walls of the tube and the liquid-sediment mixture within the tube. An increase in temperature will expand both the tube diameter and tube length and thereby increase V, the volume of mixture. A change in temperature will also change the liquid density. Equations 1 and 5 indicate that the mixture density and the period will be altered by a change in liquid density. Obviously, temperature will, through a complex mechanism, exert an influence on the vibrational period.

Any substance that adheres to the walls of the tube will increase m and the period. If small quantities of the substance are suddenly dislodged, the period will immediately decrease. River water contains clays and dissolved materials that under some conditions will accumulate on the tube walls. Traces of oil or other lubricants may exert a destabilizing influence on the period.

Extraneous vibration and liquid flow rate are interference sources not considered by equations 1 to 6. Extraneous vibration from the floor or the earth may excite harmonic, subharmonic, or torsional modes of U-tube vibration. Even the transient occurrence of these modes will create errors in the period measurement. Equation 6 contains neither liquid flow velocity nor particle-size terms; however, the equation indicates that the period is established by the instantaneous quantity of sediment within the tube. If the liquid flow rate is too low, relatively large sediment particles that enter the tube will settle to the lowest wall and will remain immobile or will move at a speed slower than that of the liquid. These particles will interfere with a density measurement until they leave the U-tube. At the curved end of the U-tube, particle momentum and the change in flow direction will combine to produce a concentration gradient. Of various points along the tube, the curved end vibrates with the greatest amplitude and, consequently, exerts the greatest influence on vibrational period. Because the gradient is dependent on both particle size and flow velocity, these two factors will exert some influence on vibrational period.

Some error sources will be negligible when sediment concentrations are high. When used to measure moderate to low sediment concentrations, the U-tube must detect extremely small changes in mixture density. For example, 1.0 gram of sediment ($\rho_s = 2.65$ g/cm$^3$) added to a liter of water at 4°C ($\rho_\ell = 1.000$ g/cm$^3$) will, by equation 1, produce a mixture density of 1.000622 g/cm$^3$. Compared to the density of the water, the change is relatively small; however, the sediment concentration of 999 pm is moderately high. In some streams the sediment concentration is frequently less than 50 ppm. Every source of interference will become significant when measuring low concentrations. When the sediment and the interference sources exert a nearly equal influence on the instrument, the resolving power or "limit of detection" has been reached. Certain tests described in the following sections were designed to provide data for an estimate of the limit-of-detection of the density gage.

Equation 6 shows that if measurement errors are minimized by control and compensation, the U-tube can be calibrated to read sediment concentration. Figure A-2a shows the trend of the concentration-period relationship that is the basis of the calibration.

To adapt a U-tube for accurate and continuous measurements, additional parts must be added so that the tube will vibrate steadily. Figure A-2b illustrates the amplifier, coils, and magnets required to sustain the oscillation. A slight movement of the tube is transmitted to the upper permanent magnet, and the relative motion between the magnetic field and the coil induces a voltage, E, in the coil. The amplified voltage, $E_d$, causes a current (I) to flow through the drive coil, which is surrounded by the magnetic field of the lower permanent magnet. This current interacts with the field to exert a force on the lower magnet. The force is transmitted to the end of the tube and causes it to accelerate. The force produces continuous vibration if both the relative magnitude (amplification) and the phase between E and I are properly adjusted.

Various methods may be used to measure and display the period of U-tube vibration. Figure A-3 illustrates the technique used in this study. When the tube is vibrating continuously, the drive-coil voltage $E_d$ (figure A-2b) will be a cyclical time function (figure A-3a) with a period equal to that of the vibrating tube. Figure A-3b shows a series of electrical pulses produced at a stable and precise rate. The pulses are generated continuously by a specially-designed oscillator. The drive-coil period is measured by counting the number of oscillator pulses that occur while the coil voltage completes a predetermined number of cycles.

The counting process is performed with the aid of two counters labeled "Counter A" and "Counter B" in figure A-3c. Counting is manually initiated by pressing a control switch. After a short delay, counter A activates counter B at the beginning of a drive-coil voltage cycle.

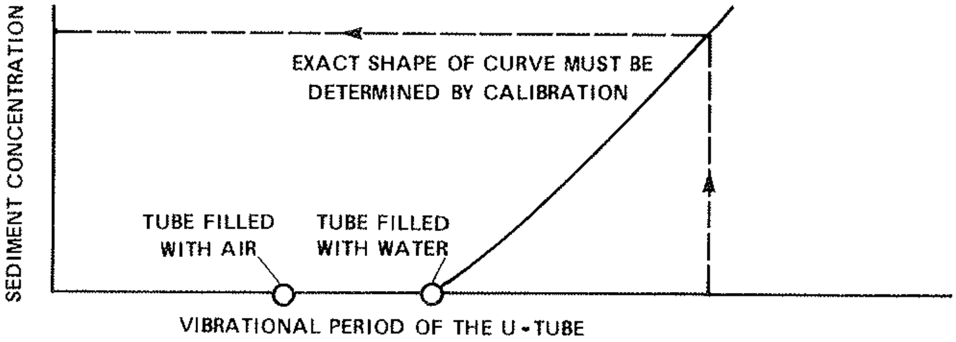

Figure A-2a.--Effect of sediment concentration on vibrational period of a U-tube.

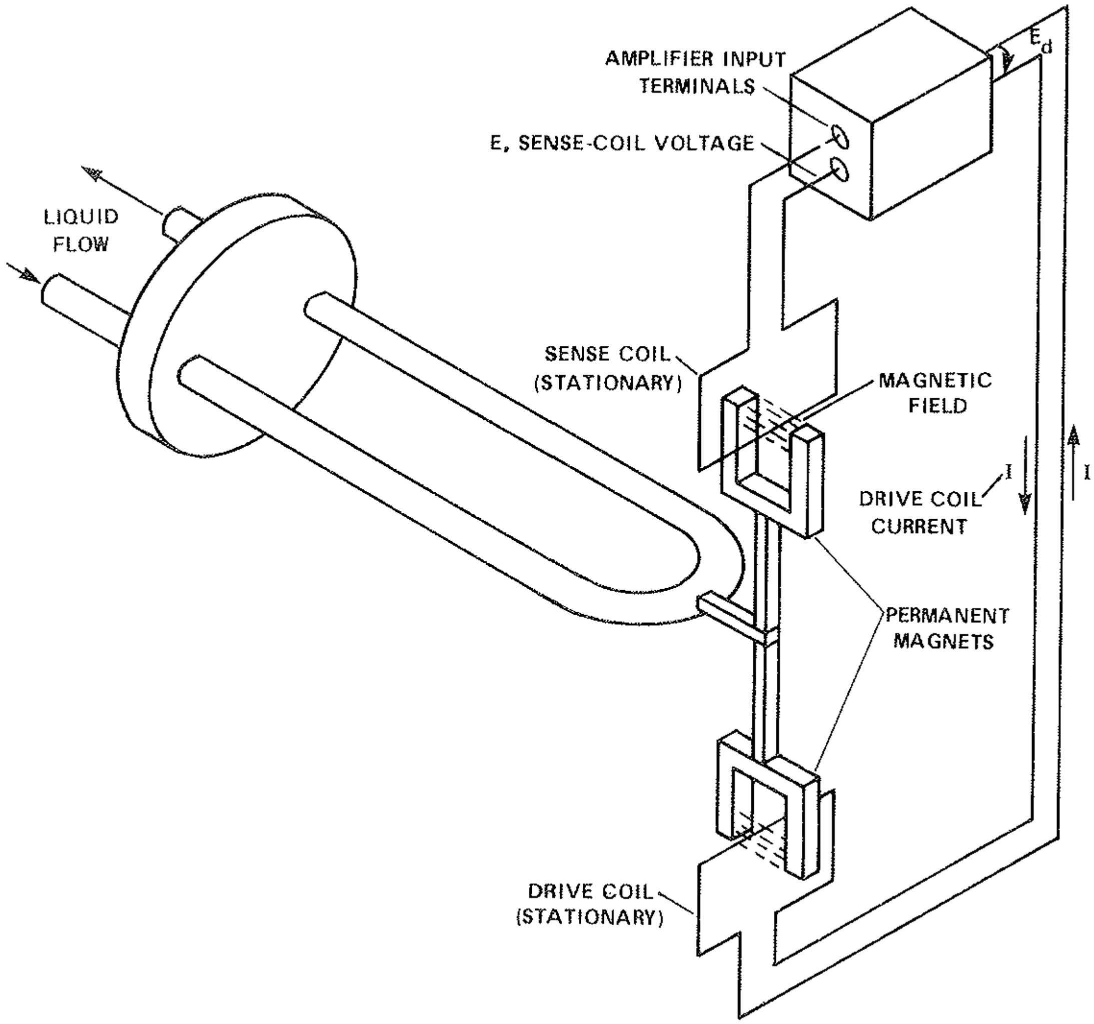

Figure A-2b.--Basic components of the U-tube and feedback circuit.

Figure A-2.--Characteristics and components of a U-tube designed for continuous operation.

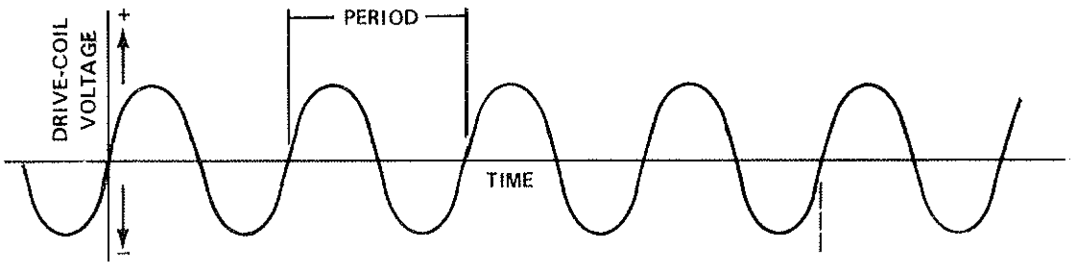

Figure A-3a.--Variation of drive-coil voltage.

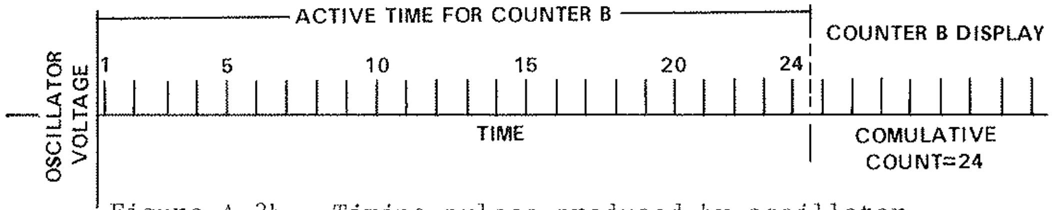

Figure A-3b.--Timing-pulses produced by oscillator.

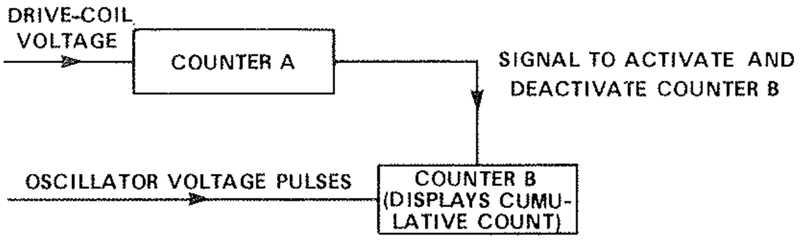

Figure A-3c.--Connection of counters used to measure vibrational period.

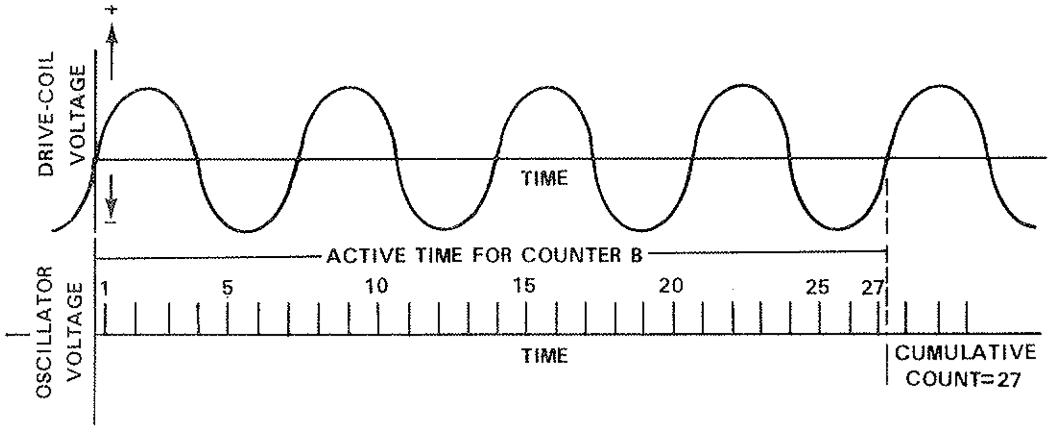

Figure A-3d.--Effect of sediment on U-tube vibrational period as measured by oscillator timing pulses.

Figure A-3.--Technique of period measurement.

Counter B counts oscillator-voltage pulses while counter A advances one count at the end of each drive-coil voltage cycle. When the number stored in A reaches a preset value, A deactivates B which then displays the total number of oscillator pulses. This number is termed the cumulative count. Figure A-3b illustrates the counting process for four drive-coil cycles. After counter B has been deactivated, it displays the cumulative count (24) until manually reset. The cumulative count is proportional to the mean period of U-tube vibration. The same counting technique is used regardless of the substance inside the tube. An increase in sediment concentration will cause the drive-coil period to increase. Compared to figure A-3b, figure A-3d shows a longer period, a longer active time, and a larger cumulative-count (27).

To measure a small change in sediment concentration by a change in U-tube period, the active time must be measured as precisely as possible. Because the active time is registered by the cumulative count, the measurement error could be as large as the time interval between successive oscillator pulses; consequently, the time interval must be as short as electrical design constraints will permit. In the reported studies, the interval was 0.000078139 seconds, which corresponds to a nominal oscillator-frequency of 12.8 kHz. The U-tube has a nominal period of 0.00848 seconds when the tube is filled with water. While the tube completes one cycle of vibration, the oscillator produces about 109 pulses. This pulse rate is much higher than that shown on figure A-3, which was purposely distorted to illustrate the counting process. The active time for counter B corresponds to 18,430 U-tube cycles instead of only 4 cycles as depicted on figure A-3. Cumulative counts were about 2,000,000 instead of 24 and 27 as indicated on the figure. Each circuit is explained in detail in Part C of this report.

## EQUIPMENT AND ARRANGEMENT OF TEST APPARATUS

The tested cell was a Type CL-10HT purchased from Automation Products, Inc., of Houston, Texas.(a) The cell was tested as supplied. Special electronic feedback and period-measuring circuits were constructed for use with the cell. These circuits were operated continuously to insure that all electrical components were in a state of thermal and electrical equilibrium. The period-measuring circuit was designed to measure the vibrational period averaged over about 2½ minutes. The averaging time was long enough to minimize rapid fluctuations in both the rate of instrument vibration and sediment concentration; but the time was short enough to document slow changes in concentration. The cell was equipped with a temperature-sensitive resistor and a special temperature-compensation circuit. However, to achieve a basic understanding of the thermal response of the cell, neither the resistor nor the circuit was used. Instead, the temperature of the mixture pumped through the cell was measured to within ± 0.05°C with a thermistor thermometer. Temperature-response characteristics were derived from these data.

All tests were conducted with the U-tube positioned horizontally, as shown in figure A-4. Compared to a vertical orientation, this position simplified mounting and, according to factory personnel, produced maximum isolation from extraneous vibration. Because Willis and Kennedy (1977, p. 62) noted effects of even small floor vibration on U-tube readings, each end of the cell was cradled in a steel band to provide additional isolation. Each end of the band was attached to an extension spring that was fastened at its upper end to the cell-support frame. The four springs were adjusted to support the entire weight of the cell. The horizontal position has a potential disadvantage in that gravity causes sediment particles to migrate downward toward the tube wall and thereby create vertical concentration gradients. Particles in contact with the wall tend

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(a) The use of the brand name in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey or other federal agencies.

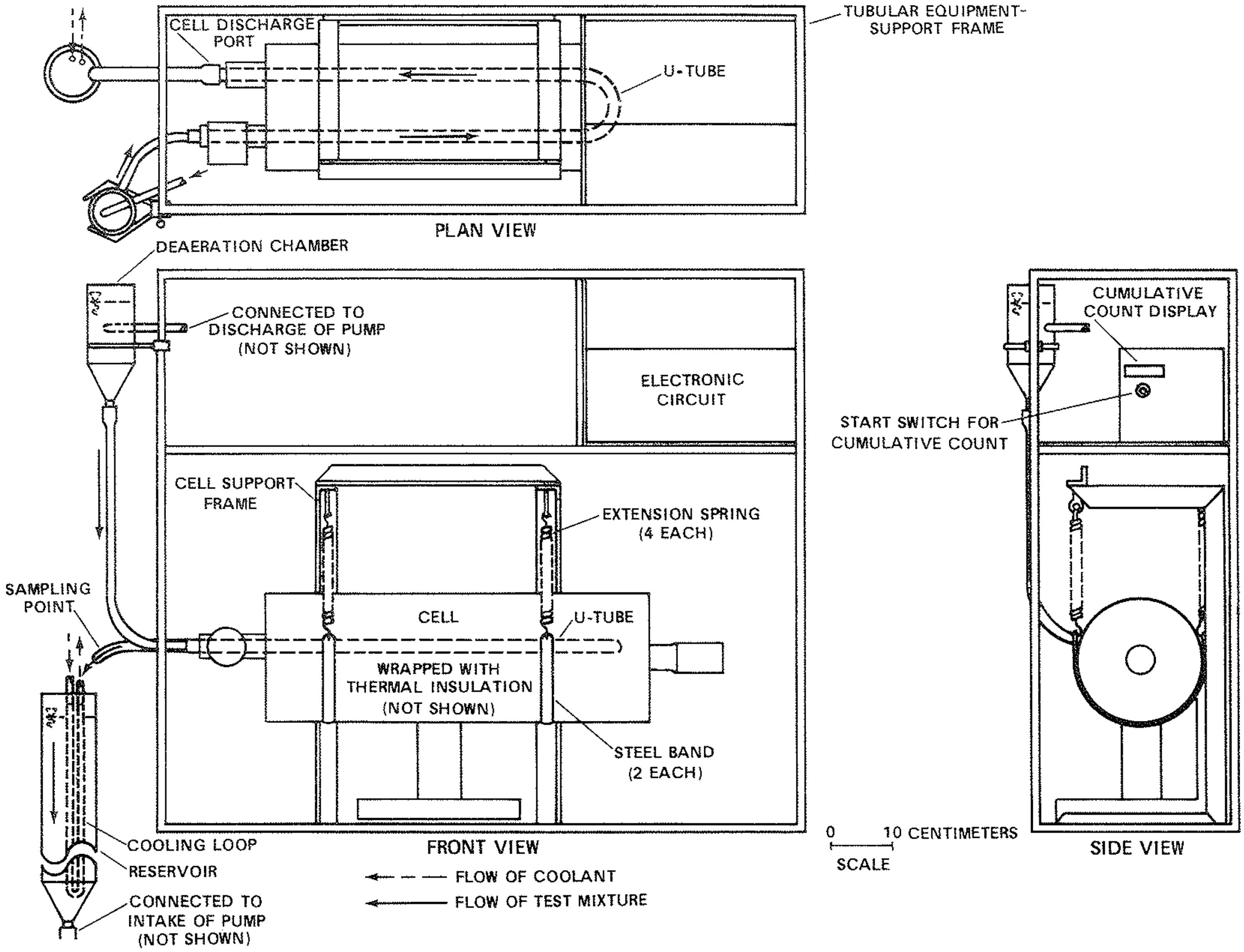


Figure A-4.--Component arrangement for test of U-tube fluid-density gage.

to move at a speed less than the mean fluid speed. Within the tube, high fluid speeds are required to minimize both concentration gradients and differences between the fluid speed and particle speed.

Initial tests indicated that the cell responds to both the temperature of the liquid and, to a lesser extent, the temperature of the air in contact with the case. The cell was wrapped with paper-backed, glass-wool insulation to minimize the effect of air-temperature variations. Because the U-tube and cell case were thermally coupled through the steel plate that served as the cantilever support, the temperature of all cell components gradually reached equilibrium with the temperature of the liquid flowing through the U-tube.

To eliminate air entrained within the test suspension, the system was equipped with a deaeration chamber which consisted of a 12-cm length of 7-cm diameter clear-plastic pipe with one end joined to the large end of a clear-plastic funnel. The middle of the pipe was drilled to fit tightly around a 9.5-mm ID tube that projected horizontally into the pipe and that conveyed the test suspension. The chamber elevation was adjusted to maintain the free water surface above the tube. The length of the projection was adjusted to eliminate vortices. Flow in the pipe was slow to permit essentially all air bubbles to rise and escape through the surface. The free surface also served to attenuate flow-pulsations produced by the pumps.

The discharge from the small end of the funnel was routed into the U-tube which discharged through a flexible tube telescoped over the cell discharge port. The discharge end of the flexible tube was elevated slightly to maintain a positive pressure in the U-tube and to maintain full pipe flow through the U-tube.

From the flexible tube, the test mixture flowed into the reservoir--a 70-cm length of 9-cm diameter clear-plastic pipe. The lower end of the pipe was fitted to the large end of a funnel that routed the mixture to the intakes of peristaltic pumps. Each pump was driven by a small direct-current motor powered by a variable-voltage supply. Flow rate was regulated by adjusting the voltage. The temperature of the circulating test mixture was stabilized and controlled with the aid of a cooling loop that consisted of a copper tube connected through a regulation valve to a laboratory refrigerator. When required, the mixture was warmed with an electric heater.

## STEADY-STATE AND TRANSIENT RESPONSE

The test results are grouped into two broad categories termed "steady state" and "transient." The steady-state category describes several tests, each designed to isolate and chart the instrument's response to only one factor. To perform a test, one factor was selected. Water temperature will be used as an example. To isolate the observed response to water temperature changes, all other factors such as dissolved-solids concentration and suspended-sediment concentration were maintained constant throughout the duration of the test. To chart the response, several data points were recorded. Each data point consisted of a cumulative count reading and the corresponding water temperature. As the term "steady state" implies, the water temperature for each data point was maintained as steady as possible until the cumulative count also stabilized. The group of all data points is termed "the steady state response to water temperature."

In all rivers, factors that affect the U-tube response will change with time. For a particular factor at any chosen instant of time, the rate-of-change will depend upon the water discharge of the river, the weather conditions on the watershed, and several other conditions. Readings obtained from a U-tube that is installed on a river can be interpreted only if both the "steady state" and "transient" response of the instrument are understood. The term "transient" refers to the instrument response as affected by unsteadiness in a test factor. The category of tests termed "transient" describes several tests, each designed to chart the response to one factor.

One factor was selected to perform each test. Again, water temperature will be used as an example. To isolate the response to water temperature changes, all other factors such as suspended-sediment concentration and dissolved-solids concentration were maintained constant throughout the duration of the test. The nature of the unsteadiness was selected to approximate the conditions known to exist on certain rivers. For example, before a runoff event on an ephemeral stream, the U-tube will be empty or will be filled with stagnant water. In either instance the U-tube temperature will gradually equilibrate under the influence of air temperature and solar radiation. At the onset of flow, water pumped from the river to the U-tube will be at a temperature that is different from that of the U-tube. The U-tube will be exposed to a step-change in temperature. Accordingly, a step-change in temperature was used in the laboratory tests. The nature of the unsteadiness was varied among test factors and is described in the section that describes the particular test.

### Steady-state response to the temperature of distilled water

The recirculation system and inside of the U-tube were cleaned and filled with distilled water, then the pumps were adjusted to discharge about 50 mL/s (milliliters per second) through the U-tube. During the first experiment, water temperature was lowered in steps and then raised in steps. At each step the temperature was held constant while one or two cumulative counts were recorded. On figure A-5 the points connected by arrows show the experimental results. The experiment was repeated several times. For temperatures above 9°C, results from each of the other experiments followed a trend similar to that shown on the figure. For temperatures below 9°C the cumulative counts were erratic. The solid data points on figure A-5 are a composite of results from several experiments. To illustrate the scatter clearly, the reading sequence is shown for only the first experiment. Because the data exhibit a smooth trend above 9°C and considerable scatter below 9°C, the response in these two temperature ranges is analyzed separately.

As shown by the solid data points on figure A-5, the cumulative-count distribution was bimodal for temperatures below 9°C. One group was scattered around a cumulative count of about 1,985,800 and the other group was scattered around a cumulative count of about 1,985,770. While collecting

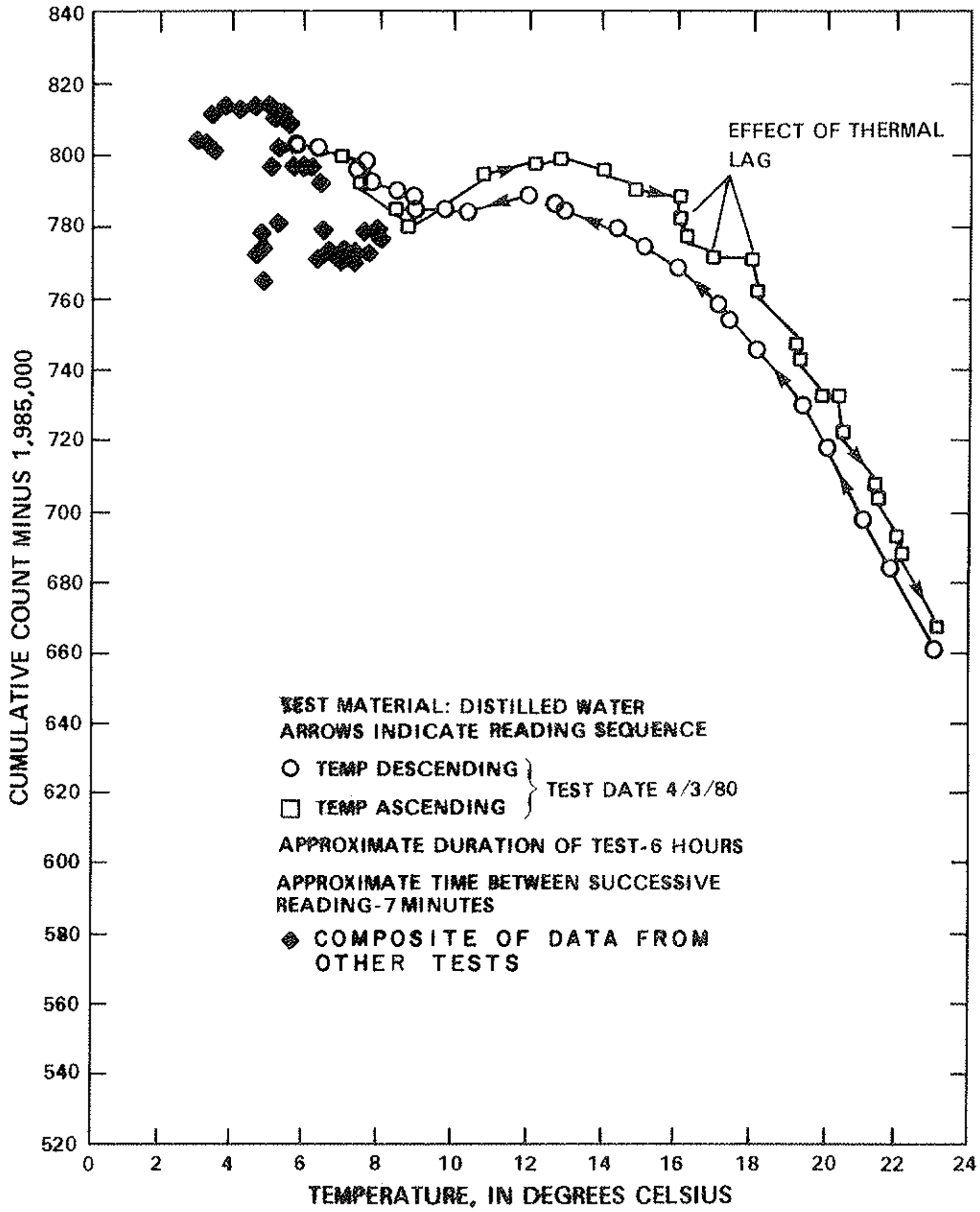


Figure A-5.--Steady-state response to the temperature of distilled water.

one data point, the water temperature was stable, but successive cumulative-count readings varied unpredicably. Occasionally, several successive readings were stable but then, for no apparent reason, the next reading would shift to a higher value. Sometimes a stable series of cumulative counts was followed by an abrupt shift to a lower cumulative count. During one test, the water temperature was stabilized at 5°C. During the following 15-minute period, each cumulative count was larger than the preceding. The rate of cumulative-count increase was nearly steady during the entire period. The last reading was seven units greater than the first. After the last reading had been collected the temperature was slowly raised and then stabilized at 8.3°C. Another series of cumulative counts were collected during a 15-minute interval. The series followed a decreasing trend with the last reading 15 units smaller than the first reading.

An investigation of the cause for the erratic response was hampered by the case (figure A-4) that could not be opened for inspection. All erratic responses occurred below the critical temperature of about 9°C. The author surmised that this temperature corresponds to the dew-point temperature of the air sealed within the case. If a drop of condensate adheres to the outside wall of the U-tube, it will slow the rate of vibration and increase the cumulative count. If the drop falls from the wall, the cumulative count will abruptly increase. If drops of dew form slowly, they will cause a slow increase in cumulative count. Conversely, if the dew evaporates slowly, it will cause a slow decrease in cumulative count. The manufacturer agrees that condensation may be the cause of the erratic response. Replacing the moist air with a dry gas should eliminate the problem; but this replacement was not performed.

For temperatures above 9°C, both curves on figure A-5 show that the relation between cumulative count and temperature is distinctly nonlinear. Both curves are similar in form to the density-temperature curve for water; however, the temperature at which maximum water density occurs (4°C) is different from the temperature at which maximum cumulative count occurs (12°C). The difference is apparently caused by the effect of temperature on A and B in equation 6. Both A and B are sensitive to changes in k that, in turn, is sensitive to changes in the length and diameter of the U-tube.

A change in temperature will induce a total change in cumulative count as shown on figure A-5. This total change consists of two components each produced by different phenomena. One component is caused by liquid density changes and the other component is caused by dimensional changes in the U-tube. The components, if plotted against temperature, will follow different trends; consequently, the total change will follow a third trend different from either component trend.

On figure A-5 the descending-temperature curve is displaced from the ascending-temperature curve. This displacement is caused by the slow rate of heat flow from the water to the U-tube and other parts within the cell. If the water and all parts are at the same initial temperature, a subsequent increase in water temperature will cause heat to flow from the warm water to the cooler parts. As the parts warm, the rate of heat flow will decrease. If the water is stabilized at a warmer temperature, all parts will slowly warm to a new equilibrium. Because cumulative count is sensitive to the temperature of the parts, the cumulative count will drift until the new temperature equilibrium is reached. Successive readings plotted on figure A-5 were collected at about 7-minute intervals. Observations from the transient-temperature response test (described later) indicate that if the intervals had been 9 minutes or longer, the displacement between the two curves would have been less than that shown on figure A-5.

Seven additional replicate tests were run to determine the steady-state response to the temperature of distilled water; however, in contrast to the preceding tests, these tests were conducted under conditions that simulated prolonged use at an unattended field site. Under these conditions, the mass of the metal U-tube will slowly decrease because of wear produced by abrasive particles in the water. Electrical components will be subjected to disturbances caused by power failures. The inside of the U-tube will accumulate a coat of clay-size particles. Also, the cell will be exposed to slow changes in barometric pressure. Acting in concert, the effects of wear, electrical disturbances, clay accumulations, and barometric pressure changes will cause variations in cumulative count. This group of replicate tests was designed to estimate the magnitude of the variations.

Each test was divided into two phases. During the first phase, the power was turned on and the recirculation system was filled with water that contained an arbitrary concentration of clay-size particle, sand-size particle, sodium chloride, and sodium sulfate. At a flow rate of about 50 mL/s, the mixture was pumped through the U-tube for several hours and was then drained. Without cleaning or disturbing the U-tube, the recirculation system was cleaned and then filled with distilled water. During the second phase, the distilled water was pumped through the U-tube while cumulative-count and water-temperature readings were taken. The first cumulative count was taken after the distilled-water temperature had been stabilized at or near room temperature. The water was then restabilized at a lower temperature and another cumulative count was taken. Each stable period lasted about 7 minutes. In steps, water was cooled to about 9°C then, in steps, the water was warmed to room temperature. During each step, the water temperature and cumulative count were tabulated. After the last pair of readings, the distilled water was drained without disturbing the U-tube; then the power was turned off. Each of the seven tests was run on a different day to insure that among tests the cell had been exposed to a range of barometric pressures.

At the conclusion of each test the data were checked for unusually high or unusually low "cumulative counts." Data collected from the first six tests indicated variations from one test to another were random or nearly random. Cumulative counts from the seventh test were several hundred units larger than those from the six preceding tests. In an effort to locate the cause of the unusual response, the entire test apparatus was thoroughly inspected. A slimy deposit had formed on the U-tube walls and this deposit was removed with a test-tube brush coated with a household cleanser. Then the recirculation system was cleaned and filled with fresh distilled water. When the temperature test was repeated, cumulative counts agreed with those collected in the first six tests.

Each temperature reading in the first six tests and in the repeated seventh test was rounded to the nearest degree centigrade; then all cumulative counts recorded at a common rounded temperature were collected into a subgroup. For cumulative counts within each subgroup, the mean and standard deviation were computed. From these parameters three new data sets were formed. The first data set consisted of several pairs, each of which was composed of a rounded temperature and the corresponding mean cumulative count minus one standard deviation. The second data set consisted of several pairs, each of which was composed of a rounded temperature and corresponding mean cumulative count. The third data set also consisted of several pairs, each of which was composed of a rounded temperature and the corresponding mean cumulative count plus one standard deviation. By a least-squares procedure, a fourth order polynominal was calculated for each of the three sets. In all calculations temperature was taken as the independent variable. The three equations are given below:

$$\mu - \sigma = 1{,}985{,}717.2627 + 7.29834\ T + 0.38702\ T^2 - 0.048621\ T^3 + 0.00062106\ T^4 \qquad (6)$$

$$\mu = 1{,}985{,}732.081 + 3.7893\ T + 0.947286\ T^2 - 0.0814229\ T^3 + 0.00126410\ T^4 \qquad (7)$$

$$\mu + \sigma = 1{,}985{,}749.324 + 0.595717\ T + 1.402044\ T^2 - 0.107315\ T^3 + 0.0017719\ T^4 \qquad (8)$$

$\mu$ = mean of the cumulative count,

$\sigma$ = standard deviation of the cumulative count,

$T$ = water temperature in °C.

The trend of the three equations is shown by the curved lines on figure A-6. The vertical distance (measured along the cumulative count axis) between the top curve and middle curve is $\sigma$, a measure of the variation in cumulative count. The standard deviation is about ten units for any temperature. Because readings were taken at about 7-minute intervals, a portion of the variation is caused by thermal lag which also caused the vertical separation between the curves on figure A-5. Comparison of the separation between the curves on figure A-5 with the separation between the upper and lower curves on figure A-6 shows that the combined effects of wear, electrical disturbances, clay accumulations, and barometric pressure changes served to increase the cumulative count variance by only a few units. However, the conclusion regarding the effect of clay accumulation must be tempered by results of the seventh test. This test indicated clay accumulation will, under unpredictable circumstances, cause large changes in cumulative count.

## Steady-state response to the temperature of a clay, silt, and distilled water suspension

Plotted points on figure A-6 show cumulative count and temperature data for a suspension of distilled water mixed with sediment from a streambank. As in the distilled-water tests, the suspension was pumped through the U-tube at a rate of about 50 mL/s. The three curves were obtained by evaluating equations (6), (7), and (8) and then adding 1,115 counts to each computed cumulative count. The addition process translates curves from the equations up the cumulative-count scale without altering the shape of the curves. The translated curves, which are based on distilled-water tests, match the data points for the suspension. Therefore, it is concluded that the variation in cumulative count with temperature is independent of the sediment concentration.

## Steady-state response to the temperature of an aqueous solution

A 10,000 ppm mixture of sodium sulfate in distilled water was used to test the instrument's response to a solution. The solution was pumped through the U-tube at approximately 40 mL/s. At each of several temperatures between 8.4 °C and 25.6 °C, the temperature was stabilized while one or more cumulative counts were collected. Figure A-7 shows plotted data points obtained from the test and also shows three curves obtained by first evaluating equations (6), (7), and (8) at each of several temperatures, and then performing a translation by adding 1,600 to each computed

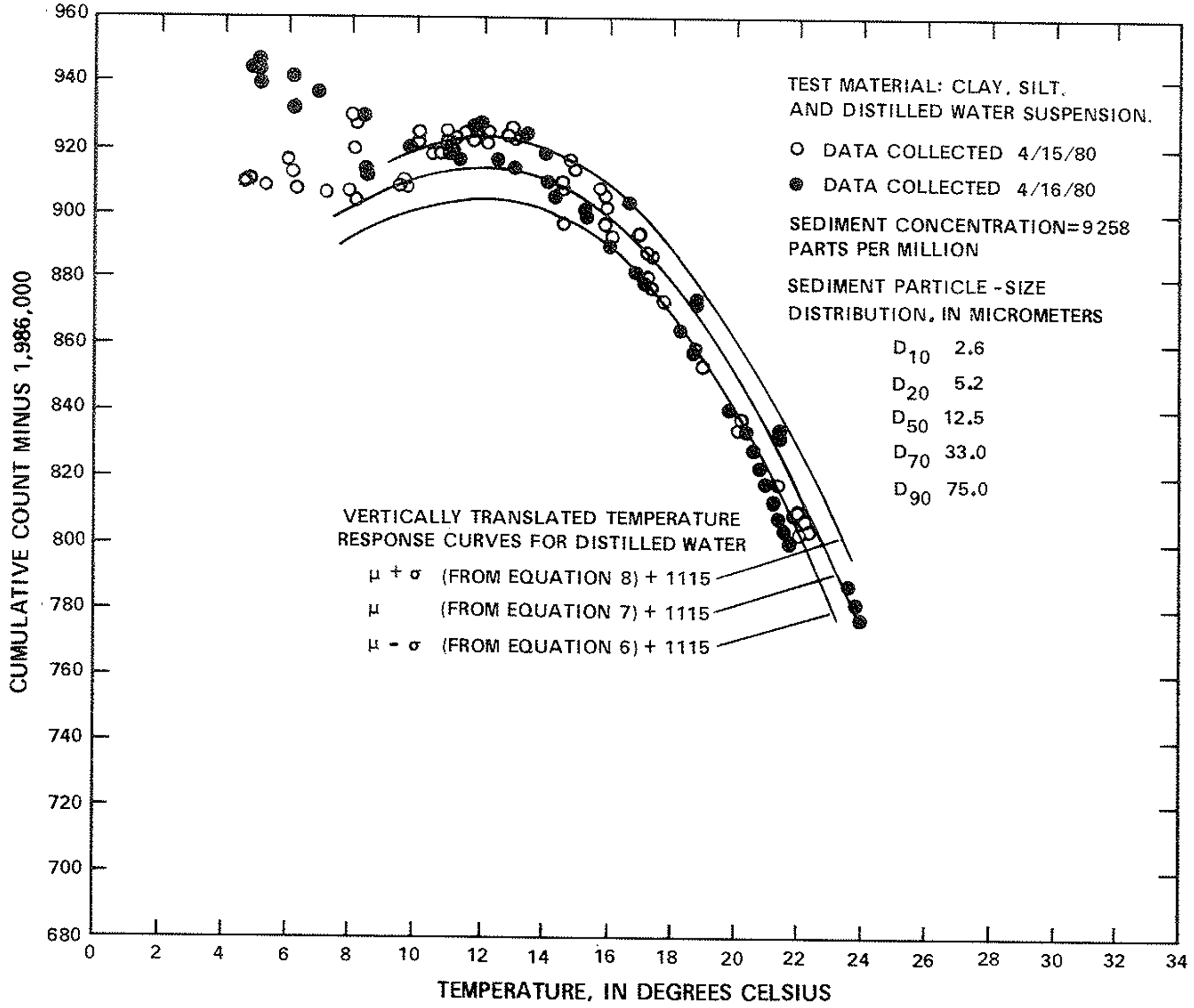


Figure A-6.--Steady-state response to the temperature of a clay, silt, and distilled water suspension.

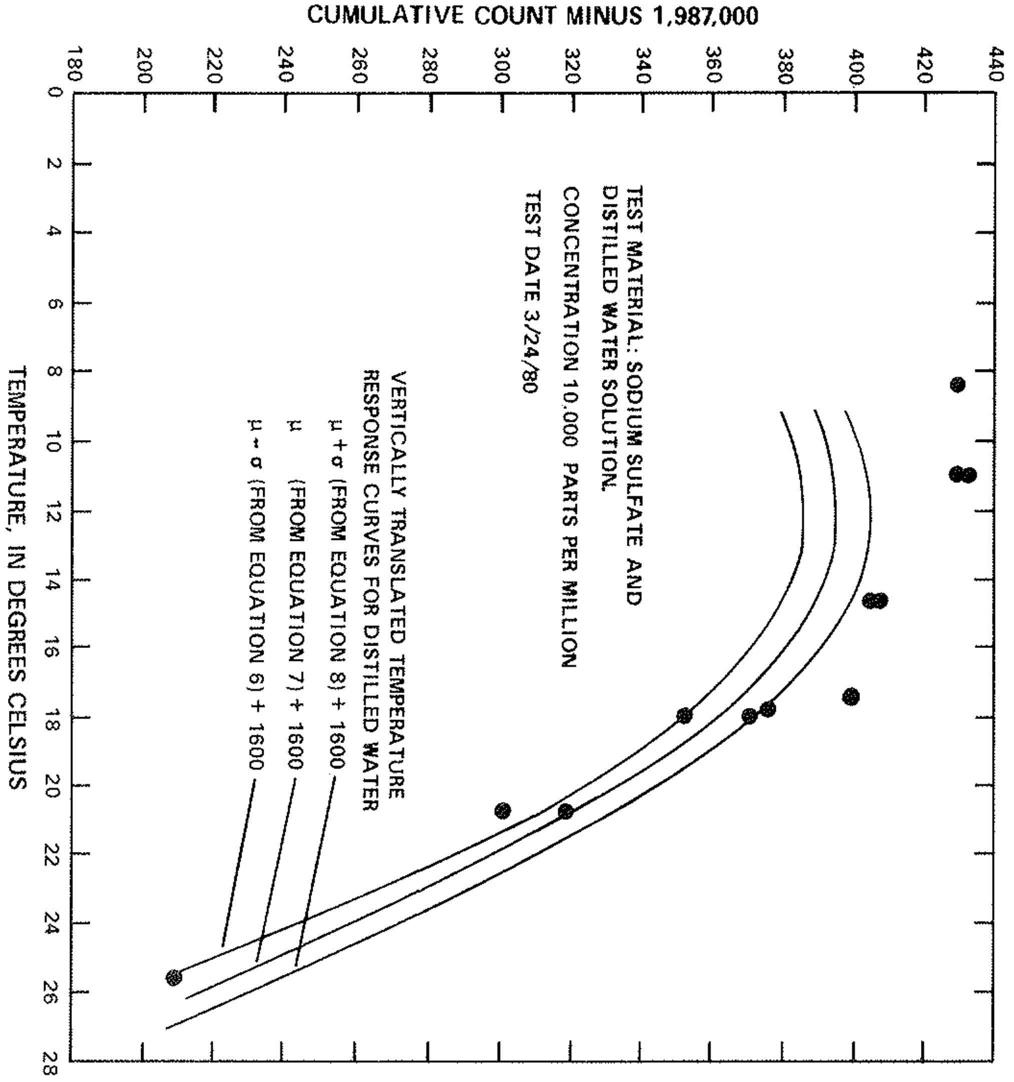


Figure A-7.--Steady-state response to the temperature of an aqueous solution.

cumulative count. The figure shows that for temperatures warmer than 16°C, the trend of the translated curves matches the trend of the data for the sodium sulfate solution. Therefore it is tentatively concluded that for the warmer temperatures, the variation in cumulative count with temperature is independent of dissolved solids concentration. The average of several replicate tests may have indicated the tentative assumption was applicable for temperatures several degrees colder than 16°C. Results of this single test were probably not representative because of the large cumulative-count variation at low temperatures. For example, figure A-6 shows one sediment-suspension test produced cumulative counts considerably larger than those for the translated distilled-water curve, but in the other test, cumulative counts agreed more closely with the translated curves.

## Experimental procedure

Tests were conducted to calibrate the gage for sediment concentration and to determine the effects of sediment particle size and suspension pumping rate. Errors caused by temperature, wall deposits, and dissolved solids were minimized by careful control of test conditions. To minimize temperature errors, all tests were run with the water and cell temperature stabilized at 20.9°C. To minimize wall-deposit errors, the inside of the U-tube was brush-cleaned daily. To minimize dissolved-solids errors, a special procedure was followed. Each morning a storage container was filled with enough clean water to supply the needs for the tests to be run that day. The U-tube and the recirculation system were initially filled from the container and, when necessary, additional water was added from the container. During any single test, all water was added from the same container; so, within the U-tube and recirculation system the concentration of dissolved solids was stable. Distilled water was used for most of the tests and tap water was used for the remainder.

Batches of monodisperse sediments were prepared by dry sieving clean Jordan sand into several different size ranges. Jordan sand is composed primarily of well-rounded quartz grains. The density of the parent Jordan sand and of each monodisperse batch was measured by the pycnometer method. With only minor variations, all densities were 2.64 g/cm$^3$. Sediments transported in rivers span a relatively wide range of sizes, so polydisperse batches of sediments were prepared by blending sediment from several of the monodisperse batches. A batch with a bimodal distribution was prepared by mixing coarse Jordan sand with an equal mass of material referred to as "Spokane sediment," which consisted of sediment from the banks of a stream near Spokane, Washington. The material had a mean particle-diameter of 12.5 micrometers and was a mixture of clay-size and silt-size particles. Two other sediments were tested, one batch from the banks of the Salmon River and the other from the banks of Caspar Creek. The Salmon River sediment was collected from a site on the Klamath National Forest near Sawyers Bar, California. The Caspar Creek site was a few miles from the Pacific coast near Fort Bragg, California.

The Jordan sand had been washed but the other sediments contained bits of grass, leaves and twigs, and some soluble salts. These sediments were processed to remove all organic detritus and soluble salts. Large pieces of leaves, grass and twigs were removed by wet sieving. All remaining organic detritus was removed by soaking each sediment in a hydrogen peroxide solution which was later removed by decantation. Soluble salts were removed by mixing each sediment with distilled water, allowing the sediment to settle, and then decanting the water. For each sediment the process of mixing, settling, and decanting was repeated two or three times.

Before each test, all components in the recirculation system and both straight sections of the U-tube were scrubbed with a test-tube brush. All parts were rinsed, then the recirculation system was filled with about 5 liters of sediment-free water. The recirculation pumps were started and the water temperature was adjusted. After the U-tube reached thermal equilibrium, several cumulative counts were recorded. The cumulative-count mean, which is termed the "background," was proportional to the U-tube period as established by the water and any dissolved solids in the water. After the background had been measured, an arbitrary quantity of sediment from one batch was added to the water. The suspension was pumped through the recirculation system and the U-tube until the concentration was steady. A steady concentration was indicated by steadiness (lack of temporal trends) in successive cumulative counts. Five to 10 minutes of pumping was adequate to produce steady readings. When variations in successive cumulative counts became random, two and sometimes three cumulative counts were recorded and averaged. The difference between this average and the background was entered in the "X" column on the appropriate table in the appendix. This difference, termed the "count," is proportional to the change in period caused by the concentration of sediment within the U-tube. To obtain a sample for concentration analysis, about 700 mL of the suspension was collected at the sampling point (figure A-4). To minimize errors caused by concentration gradients in the flow cross section at the sampling point, the entire flow cross section was sampled. To average short-term temporal variations in concentration, the sample was collected intermittently during a 1-minute interval. The sample was preserved for concentration analysis; then water from the storage container was added to replenish the supply in the recirculation system. After 5 to 10 minutes the concentration and cumulative counts were again recorded and averaged, then the sample-collection procedure was repeated.

Wall deposits were a source of error related to antecedent flow conditions inside the U-tube. If only sediment-free water had been added to replenish that extracted from the recirculation system, the sediment concentration in the U-tube would have decreased each time water was added. This decreasing trend would have created a pattern in the antecedent flow conditions. During some calibration tests that lasted several hours, the pattern was deliberately disrupted by occasionally adding sediment with the water.

While conducting a calibration test, several mixture concentrations were pumped through the U-tube and each concentration was sampled. Each sample along with its container was weighed to the nearest gram then the container tare was subtracted to obtain the mass of the sample. The sediment was separated from the sample water by either settling and decanting or by filtering. After settling and decantation, the sediment was washed into tared aluminum dishes. The contents were evaporated to dryness and then weighed. When filtration was used, water in the sample was drawn through a tared filter with 0.45-micrometer openings; then the filter along with the deposited sediment was dried and weighed. The sediment mass in each sample was measured to the nearest 0.1 milligram. Sediment mass was divided by sample mass to obtain concentration and the result is tabulated in the column "Measured Y" on the appropriate table in the Appendix. The nearly exclusive use of distilled water rendered dissolved-solids corrections negligible for most samples. The exceptions were a few samples that contained extremely small amounts of sediment.

### Pumping rate

Several sediment calibration tests were performed with the flow rate through the U-tube regulated at 50 mL/s. The sediments were retested at flow rates of 85 mL/s and 113 mL/s to test the hypothesis that the instrument was sensitive to the pumping rate. Analysis of count-concentration data indicated a significant difference in gage response between the 50 mL/s tests and the 85 mL/s tests. For a given concentration, the count at 50 mL/s was higher than the count at 85 mL/s. As measured by the standard error-of-estimate, $S_e$, the magnitude of data-scatter was higher at 50 mL/s than at 85 mL/s. For a given concentration, the counts for 85 mL/s and 113 mL/s were nearly equal. For both of these pumping rates, $S_e$ was smaller than that for 50 mL/s. All count-concentration data collected at 50 mL/s are shown in the Appendix, but these data were not processed statistically. The data collected at 85 and 113 mL/s were composited to compute the regression of concentration on count. At a field site, some variation in pumping rate will likely occur. Because the data were composited, the prediction errors (to be discussed later) include the effect of minor pumping-rate variations.

### Regression analysis for high and low counts

For each of the tested sediments, the count (X) and concentration (Y) values were plotted to determine an appropriate transform that would produce (a) a linear regression of concentration on count and (b) a uniform concentration variance about the regression line. Trends in variance were estimated by inspecting the scatter in the plotted data. For high concentrations, a logarithmic transform of both X and Y produced the two desired features; but for low concentrations, the logarithmic transform caused the variance of Y to increase as X approached zero.

For low concentrations, the untransformed values of X and Y formed a linear regression with a nearly uniform variance in Y. The division between low concentrations and high concentrations was difficult to establish. Ultimately, the division was based on X instead of Y. A particular (X) - (Y) data pair was classified as low concentration if X was 50 or less. A count of 50 is equal to a sediment concentration of about 500 ppm. Additional corroboration of the use of 500 ppm as a demarcation limit can be found in Willis and Kennedy (1977, fig. 8). Their calibration points, which are plotted on log-log coordinates, exhibit increased scatter for concentrations less than 500 ppm.

For high concentrations, the uniform variance obtained with the logarithmic transform implies a constant percent-error in concentration estimates. For low concentrations, the percent-error gradually increases and approaches infinity as X approaches zero. The low-concentration error trend is consistent with error trends of many other types of instruments such as voltmeters and scales. With these instruments, certain absolute errors are nearly constant throughout the entire measurement range. Compared to the measured parameter, such as voltage or mass, the absolute errors become increasingly dominant as the measured parameter approaches zero.

### Standard error of estimate for high counts

Table A-1 shows, for each material tested, the regression equation for concentration on count and the standard error of estimate, $S_e$. All

Table A-1.--Summary of statistical analysis of concentration and count data.

Y = sediment concentration in parts per million (ppm)

Y' = $\log_{10}$ of sediment concentration in ppm

X = count

X' = $\log_{10}$ of count

| Material tested (range of particle diameter in micrometers) | Regression equation for Y or Y' | $S_e$, Standard error of estimate for Y or (Y') | Low-count range | | | High-count range | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Standard error of prediction, $S_p$, for Y when X is equal to | | | Standard error of prediction, $S_p$, for Y' when X is equal to | | | | |
| | | | 0 | 25 | 50 | 100 | 316 | 1000 | 3160 | 10,000 |
| Jordan sand (710-833) | Y'= 1.128339+ 0.959866X' | (0.0322) | | | | 0.033569 | 0.032876 | 0.032889 | 0.033615 | 0.035013 |
| | Y = 55.73259+ 10.060116X | 25 | 26 | 27 | 32 | | | | | |
| Jordan sand (350-420) | Y'= 0.9844278+ 1.012223X' | (0.06911) | | | | 0.072356 | 0.070820 | 0.072066 | 0.075946 | 0.082116 |
| Jordan sand (297-350) | Y'= 1.0071815+ 0.988662X' | (0.04689) | | | | 0.049900 | 0.048488 | 0.049155 | 0.052152 | 0.057033 |
| Jordan sand (250-297) | Y'= 1.064291+ 0.975160X' | (0.0183) | | | | 0.019367 | 0.019119 | 0.019540 | 0.020585 | 0.022174 |
| Jordan sand (104-115) | Y'= 0.959322+ 0.982884X' | (0.00586) | | | | 0.00628 | 0.006056 | 0.006099 | 0.006401 | 0.006932 |
| Jordan sand (74-88) | Y'= 0.966424+ 0.982756X' | (0.00607) | | | | 0.009137 | 0.007194 | 0.006368 | 0.007069 | 0.008949 |

Table A-1.--Summary of statistical analysis of concentration and count data--continued.

$Y$ = sediment concentration in parts per million (ppm)

$Y'$ = $\log_{10}$ of sediment concentration in ppm

$X$ = count

$X'$ = $\log_{10}$ of count

| Material tested (range of particle diameter in micrometers) | Regression equation for Y or Y' | $S_e$, Standard error of estimate for Y or (Y') | Low-count range: Standard error of prediction, $S_p$, for Y when X is equal to |  |  | High-count range: Standard error of prediction, $S_p$, for Y' when X is equal to |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|
|  |  |  | 0 | 25 | 50 | 100 | 316 | 1000 | 3160 | 10,000 |
| Jordan sand mixture | $Y' = 1.013554 + 0.971425X'$ | (0.011645) |  |  |  | 0.012518 | 0.012060 | 0.011983 | 0.012324 | 0.013194 |
| Mixture of Jordan sand & Spokane sediment | $Y' = 0.984089 + 0.997562X'$ | (0.01288) |  |  |  | 0.016261 | 0.014337 | 0.013474 | 0.013880 | 0.015456 |
| Spokane sediment ($D_{50}$=12 micrometers) | $Y = 13.40787 + 8.540827X$ | 15 | 17 | 16 | 17 |  |  |  |  |  |
| Little N.F. Salmon R. | $Y' = 1.069671 + 0.963915X'$ | (0.03662) |  |  |  | 0.038079 | 0.037294 | 0.037479 | 0.038620 | 0.040644 |
| Casper Creek | $Y' = 1.054544 + 0.969316X'$ | (0.043574) |  |  |  | 0.0456 | 0.044663 | 0.045241 | 0.047298 | 0.050646 |
| Sodium chloride | $Y' = 0.916974 + 0.995786X'$ | (0.009725) |  |  |  | 0.010564 | 0.01014 | 0.010096 | 0.010438 | 0.01113 |
|  | $Y = 3.921632 + 8.182860X$ | 9 | 11 | 10 | 10 |  |  |  |  |  |

materials listed on the table are sediments except for the last entry which is sodium chloride.

For the high-count range, each $S_e$ was computed from a modified form of the equation for $S_e$ given under "Symbols and Definitions." The modification consists of substituting X' for X and Y' for Y. Each $S_e$ computed from X' and Y' values is shown in parenthesis on table A-1. For the monodisperse sediments (results shown on the first page of table A-1), $S_e$ tends to increase with an increase in particle diameter. A notable exception to the trend is the Jordan sand in the 710- 833-micrometer particle diameter range. The mean $S_e$ for the three largest particle size fractions is 0.049400. This $S_e$, which is in log units, is equivalent to an error of about ± 12 percent. This error applies throughout the sediment concentration range from about 500 ppm to at least the upper test limit, which was about 50,000 ppm.

For the three smallest particle size fractions of Jordan sand, the mean $S_e$ was 0.010077 log units, which corresponds to a concentration error of about ± 3 percent. This error applies from 500 ppm to at least the upper test limit of about 30,000 ppm. For the Salmon River and Caspar Creek samples, the mean $S_e$ was 0.040097 log units which is equivalent to an error of about ± 10 percent.

None of the tested sediment batches were composed entirely of clay-size particles which are smaller than a few micrometers. Sodium chloride was used to calibrate the gage for a mixture containing only small particles. Tests of a special bulk-density measuring device (Beverage and Skinner, 1974) indicated that the relation between mixture density and concentration is essentially the same for an aqueous solution of sodium chloride as it is for an aqueous suspension of sediment with a density of 2.65 $g/cm^3$. Because sodium chloride is soluble, it simulates sediment particles of molecular size. The last row of table A-1 shows results of the sodium chloride test. For the solution, $S_e$ is .009725 log units which is equivalent to a concentration error of about ± 2.3 percent.

The regression equations shown on table A-1 differ among the tested materials. The magnitude of the differences is difficult to assess by inspection of the equations. A single page-sized plot of all equations is also difficult to interpret because many of the regression lines are closely spaced, and because some lines cross. To help the reader visualize the general count-concentration relation and the magnitude of the differences, (figure A-8) was prepared. The graph was formed by first plotting each of the 11 regression equations for the high-count range and then shading the envelope which is the smallest area that includes all regression lines.

Each value of $S_e$ and $S_p$ shown on table A-1 is a statistic of concentration measurement errors which, on detailed plots (not shown), appear to be randomly distributed about their corresponding regression line. If the concentration in the U-tube is steady, the concentration measurement error can be reduced by averaging many concentrations, each computed from a different observation of cumulative count. The percent-errors cited earlier in this section were derived from data on table A-1. These data were computed from observed-count and measured-concentration data points listed in the Appendix. Each count recorded in the Appendix was computed from either a single-cumulative count or the average of two and sometimes three cumulative counts taken successively while the concentration was maintained as steady as possible. A significant reduction in error could be achieved by collecting six or more cumulative counts, and then averaging the computed concentrations. At a field site where the concentration changes very slowly, a moving average composed of six concentration values will smooth the fluctuations caused by the random measurement errors. Six consecutive readings can be obtained in about 15 minutes.

## Standard error of estimate for low-counts

Within the low-count (low concentration) range, Spokane sediment and 710- 833-micrometer Jordan sand were selected to test the response to particles with sand-size dimensions. Again, sodium chloride was used to test the response to particles in the molecular size range. Results obtained with these substances are summarized on table A-1. Additionally,

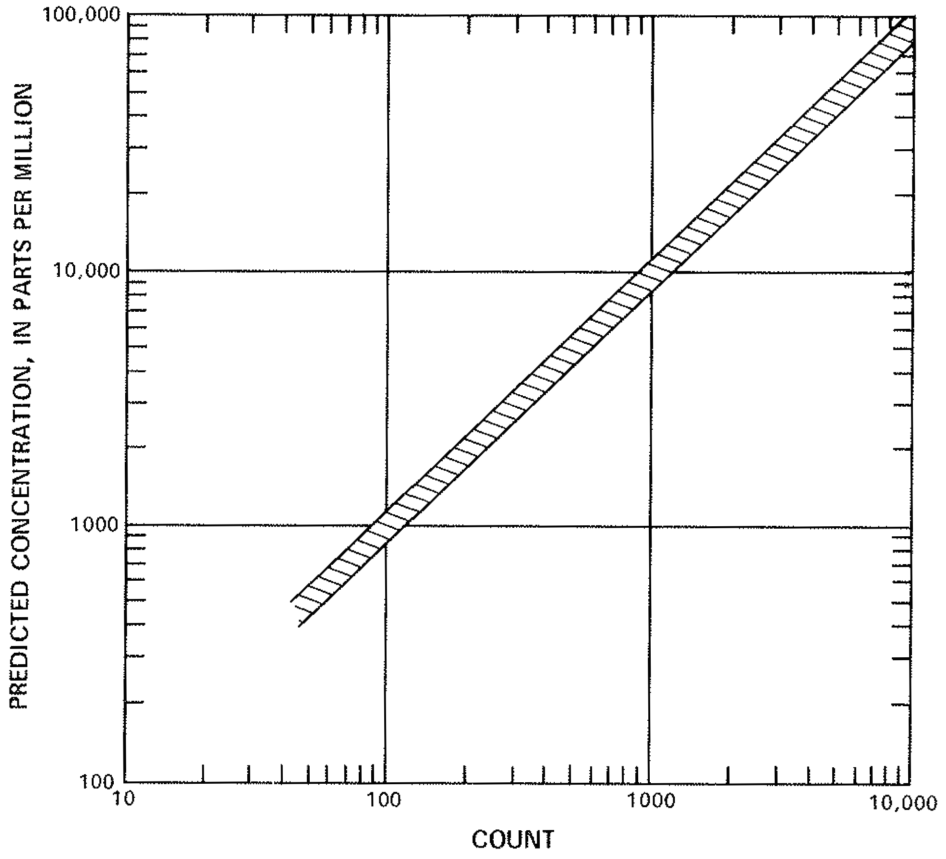


Figure A-8.--Envelope of regression equations for high-count range.

a polydisperse mixture of Jordan sand, sediment from the Salmon River, and sediment from Caspar Creek were used to test the U-tube response to materials typical of those found at some field sites. Figure A-9 shows for each of the six materials a plot of the relationship between count and measured concentration. The trend in table A-1 shows that $S_e$ decreases with a decrease in particle size. $S_e$ is 25 ppm for Jordan sand (710-833), 15 ppm for "Spokane sediment" and 9 ppm for sodium chloride. This trend is consistent with that in the high-count range.

Figure A-9 shows a considerable scatter among the data points for any particular material. Some of the scatter is probably caused by truncation of the cumulative count. Counter B (figure A-3c), which registers cumulative count, truncates all values to the nearest integer. Truncation errors can be decreased by modifying the electronics; but, for field applications, this modification would be of little value unless temperature and dissolved-solids concentration can be determined to within ± 0.005°C and ± 1 ppm, respectively. Other sources of scatter are sampling errors that are discussed in the following section.

To relate the sediment concentration to count, samples collected at the sampling point were analyzed for concentration and then the regression of measured concentration on count was computed. Residual errors, the difference between measured concentration and predicted concentration (computed from the regression equation) appear as scatter on figure A-9. A component of the residual errors are produced by errors in concentration analysis. For low concentrations, weighing errors were equivalent to a measured concentration error of less than ± 0.5 ppm; however, additional errors were introduced by imperfections in other concentration-analysis steps. Separating sediment from the sample water, transferring the sediment from one container to another, and measuring the tare weight of the containers were operations that introduced additional errors. For concentrations that exceeded a few thousand ppm, analysis errors were probably less than about ± 1 percent of the true concentration. For concentrations less than 500 ppm, analysis errors were probably less than about 5 ppm.

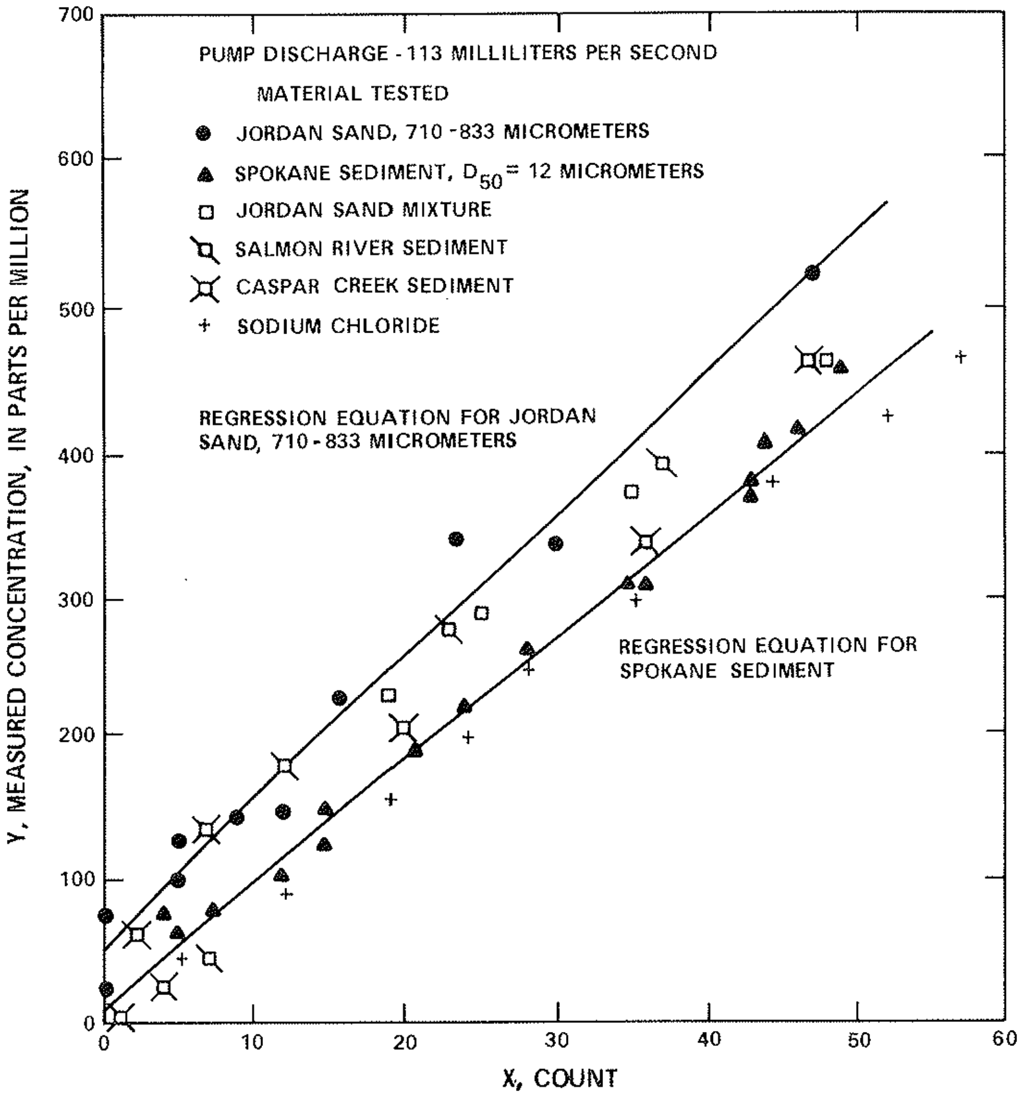


Figure A-9.--Response to low concentrations of sediments and of sodium chloride.

Statistical sampling errors were, for low concentrations, probably more significant than the analysis errors. For low concentrations of large sediment particles, the number of particles within the 5-liter recirculation system limits the probability of accurately sampling the system. The probability of collecting a specified number of particles in a sample can be calculated from the theory of Bernoulli trials. According to this theory, the probability of collecting k particles in a sample is:

$$B = \binom{\eta}{k} f^{k} q^{\eta - k}$$

where $\eta$ = number of particles in the recirculation system

$k$ = number of particles collected in the sample

$$f = \frac{\text{volume of sample}}{\text{volume of liquid in the recirculation system}}$$

$q = 1 - f$

$$\binom{\eta}{k} = \frac{\eta!}{k!\ (\eta - k)!}$$

The left column of table A-2 lists six assumed values for the sediment concentration in the recirculation system. For each assumed concentration, the number of particles ($\eta$) in the system was computed. All particles were assumed to be spheres, each with a diameter of 800 micrometers and a density of 2.65 g/cm$^3$. The top row of table A-2 shows four sample concentration error limits. If a sample concentration is to differ from the system concentration by an amount equal to or less than a given error limit, k must be between two numbers $k_1$ and $k_2$. These two numbers were computed for each combination of sediment concentration and error limit. The probability (P) that k will be between $k_1$ and $k_2$ was computed as:

$$P = \sum_{k_1}^{k_2} B\ (k, \eta, f)$$

Table A-2 shows the probability for each combination.

Table A-2.--Theoretical occurrence probabilities of sampling errors falling within assigned limits. Probabilities are for a 700-mL sample extracted from a 5-liter recirculation system. The sediment particles are assumed to be 800-micrometer spheres with a density of 2.65 g/cm$^3$.

| Recirculation-system sediment concentration in parts per million | Probability that sample concentration error will be equal to or less than error limit<br>Sample-concentration error limits in percent<br>± 1 | ± 2.5 | ± 5.0 | ± 7.5 |
|---|---|---|---|---|
| 10 | 0.00 | 0.03 | 0.03 | 0.03 |
| 50 | .06 | .12 | .30 | .42 |
| 100 | .12 | .24 | .44 | .60 |
| 500 | .20 | .46 | .77 | .93 |
| 1000 | .27 | .60 | .91 | .99 |
| 5000 | .55 | .94 | .99 | .99+ |

For a sediment concentration of 10 ppm and an error limit of ± 1 percent, a probability of zero was assigned because the conditions require subdivision of a particle. For a large number of particles, a Bernoulli distribution approaches a normal distribution so the value of P was approximated by using the DeMoivre-Laplace Limit Theorem (Feller, 1957, p. 68).

Data in table A-2 show that for any chosen error limit, probabilities decrease with a decrease in system concentration. In the experimental tests, the sediment concentration in the sample was assumed equal to the concentration in the U-tube. Both concentrations were assumed to be equal or nearly equal to the concentration in the recirculation system. Data in table A-2 show that a sample concentration can differ from the recirculation-system concentration; by analogy, a sample concentration may also differ from the U-tube concentration. If the recirculation system concentration is 100 ppm, a sample concentration will be accurate to within ± 5 percent with a 0.44 probability. If the system concentration is 10 ppm, all computed probabilities are very small; consequently, the sampling error will almost certainly exceed ± 7.5 percent.

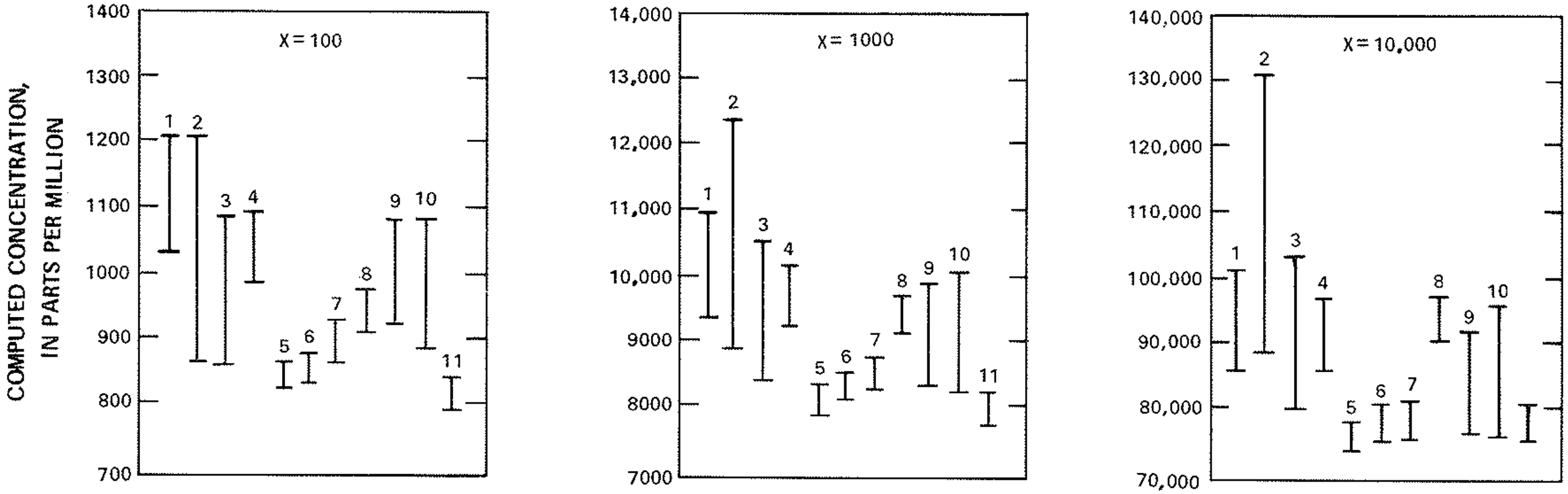
If any probability in table A-2 is recomputed for a smaller particle diameter, the recomputed value will be greater than that shown in the table. For 62-micrometer particles, all probabilities are only slightly less than one. The smallest probability is 0.88 for a system concentration of 10 ppm and an error limit of ± 1 percent. For a particular recirculation-system concentration, a suspension of small particles can be sampled more accurately than a suspension of large particles. The sampling error decreases with a decrease in particle diameter and the trend is consistent with the trend shown on figure A-9. Particles of Spokane sediment are smaller than those of the 710- 833-micrometer Jordan sand. The figure shows that within the Spokane sediment data, the scatter is less than the scatter within the Jordan sand data. Sodium chloride ions have the smallest particle diameter. The scatter within this data group is less than that within any other data group.

## Response to particle size

Equation 5 indicates the period (or count) will be sensitive to sediment concentration but will not be sensitive to sediment particle size; however, the equation is approximate and does not include the effect of slip between the fluid and the particles. The instrument responds to the spatial concentration of sediment within the tube; but the spatial concentration may differ from the discharge-weighted concentration which was determined from the samples. The difference is caused by slip, which is the difference between liquid velocity and particle velocity. Both velocities directed parallel to the U-tube axis. Generally, the velocity difference increases with an increase in particle diameter.

Another particle-size effect that may be significant is the unsteady motion caused by the vibration of the tube. This vibration, which is transverse to the axis of the tube, causes the body of liquid to oscillate at an amplitude different from that of the particles. The difference in amplitude will increase with an increase in particle size. Willis and Kennedy (1977, p. 60) mentioned this phenomenon which is caused by particle-fluid slip measured transverse to tube axis. They state, "In theory, the output of the density cell should be dependent on sediment particle size. Heavier particles should lag the fluid mass in response to the vibrations since they are coupled to the tube by only drag forces or impacts on the sides of the tube. Suspensions of finer particles should behave more nearly like a homogeneous fluid." An additional effect probably occurs at the curved end of the tube where particles separate from the streamlines of the fluid.

To determine the particle-size effects for the high count range, the predicted concentration (based on discharge-weighted samples) and the associated prediction error were calculated for each tested sediment at counts of 100, 1000, and 10,000. Figure A-10 shows a plot of the results. Each computed concentration, Y, is plotted as a bar with the midpoint situated opposite the concentration as calculated from the appropriate regression equation (table A-1). The length of each bar is $2S_p$ and indicates



EXPLANATION

| CODE | MATERIAL | PARTICLE SIEVE-SIZE RANGE, MICROMETERS | CODE | MATERIAL |
|---|---|---|---|---|
| 1 | Jordan sand | 710 - 833 | 7 | Jordan-sand mixture |
| 2 | Jordan sand | 350 - 420 | 8 | Mixture of Jordan sand & Spokane sediment |
| 3 | Jordan sand | 297 - 350 | | |
| 4 | Jordan sand | 250 - 297 | 9 | Salmon River sediment |
| 5 | Jordan sand | 104 - 115 | 10 | Caspar Creek sediment |
| 6 | Jordan sand | 74 - 88 | 11 | Sodium chloride solution |

Figure A-10.--Concentration prediction-errors for counts of 100, 1000, and 10,000.

the magnitude of the prediction error. At X = 1,000, where most prediction errors are smallest, certain trends are evident. The monodisperse sediments show a decrease in Y with a decrease in particle size. For the polydisperse sediments, the predicted Y falls between the values for the coarsest sand and the finest sand. The Y values for the two finest sands (code 5 and 6) and the sodium chloride (code 11) are nearly identical. Although less well defined, similar trends are evident in the bar graphs plotted for counts of 100 and 10,000. Figure A-11 is plotted for X = 1,000, and shows data for the sodium chloride and only the monodisperse sediments. Although the data are scattered, the points and the least-squares equation indicate that predicted concentration increases with an increase in particle diameter.

### Comparison of the standard error of estimate with the standard error of prediction

Table A-1 tabulates the standard error of prediction, $S_p$, for each material tested and for each of several X values. For any material, $S_p$ is larger than $S_e$ because of the finite number of paired values and the finite tested-range of concentrations. For a specific field application, $S_p$ can be reduced by calibrating the instrument as often as possible and by performing each calibration through a concentration range that is as wide as possible. With extensive field calibration, $S_p$ will approach but will never be less than $S_e$. $S_e$ is established by the random variations within the instrument itself.

### Transient response to the temperature of water

The instrument's response to a sudden, or "step-change," decrease in water temperature was measured. The temperature of the cell and water were stabilized at 29.2°C. After the cumulative count stabilized, the heat exchanger in the recirculation system and an additional heat exchanger in the U-tube supply line were activated to rapidly cool and then stabilize the liquid temperature at 20.8°C. The cooling process required about 1 minute.

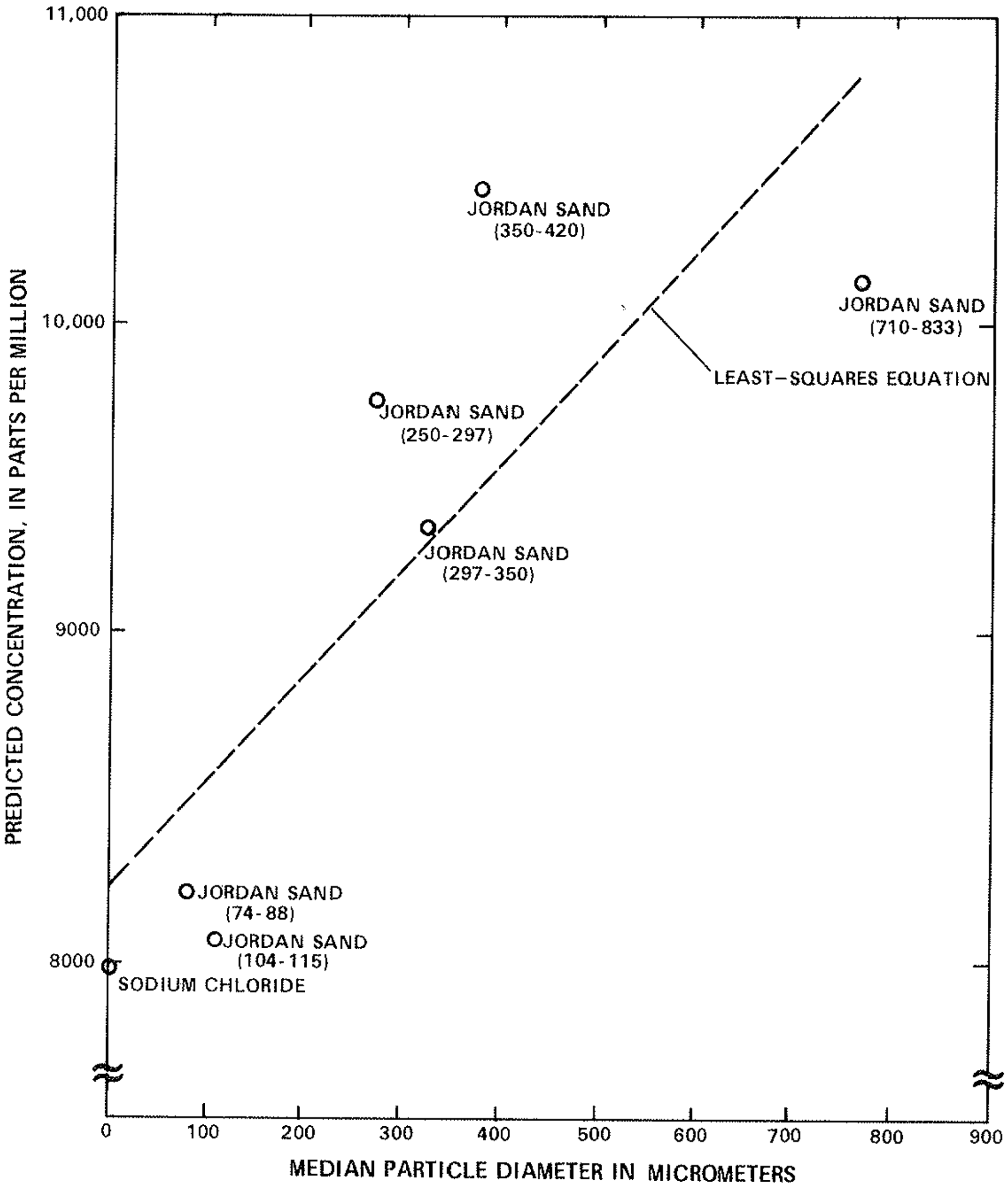


Figure A-11.--Relation between particle diameter and predicted concentration for a count of 1000. Numbers in parenthesis indicate range of particle diameters in micrometers.

Cumulative counts were collected successively during the cooling process and during a long period after the temperature stabilized. A plot showed that cumulative counts increased after the cooling process started. The rate of increase slowed and after about 9 minutes the cumulative count stabilized at a new and higher value.

The response to a step-change increase was measured by a procedure similar to that used in the step-change decrease test. The water and cell temperature were stabilized at 16°C, then an electric heater was activated to warm the water rapidly to 22°C. The warming process required about 1½ minutes. A plot showed that after warming started, the cumulative count decreased for about 7 minutes. After 7 minutes the cumulative counts were stable.

To measure the response time of the gage under ideal test conditions, the step change must occur during an interval that is short compared to the interval required for the vibrational period to stabilize. Also, the vibrational period must be recorded continuously so that the exact moment of stabilization can be determined. In the experiment, both requirements were compromised. The large volume of water in the recirculation system and the limited capacity of the heat exchangers lengthened the step-change interval. Also, because of the long active time for the electronic counters, cumulative count was displayed at 2½-minute intervals. Because of these compromises, the true response time is estimated to be about 9 minutes ± 1 minute.

## Transient response to the concentration of suspended sediment

In a river, turbulent eddies that burst against the bed will launch sediment into suspension. Some of the sediment will disperse in the flow and some, under the influence of gravity, will return to the bed. At any point in the flow, the sediment concentration will be unsteady, so water pumped to the U-tube will contain fluctuating amounts of suspended sediment.

Two tests were performed to measure the gage response to unsteadiness in sediment concentration. To determine particle-size effects, one test (table A-3) was run with Jordan sand (297- 350-micrometer size range), a moderately coarse material, and the other test (table A-4) was run with Spokane sediment, a fine material. Each test consisted of exposing the U-tube to three different temporal patterns of fluctuating sediment concentration. Each pattern, termed a subtest, was completed during one count interval of 155 seconds. Within a test, the pattern varied among the three subtests. Among all six subtests, the same quantity of sediment was discharged through the U-tube. Among all six subtests, the pumping rate was stable, so the same quantity of water was discharged through the U-tube.

Certain procedures were the same among all subtests. Water from a container, termed the source, was pumped through the U-tube. The discharge was collected in another container, termed the sink. Prior to a subtest the source was filled with clean tap water, then the water was pumped through the U-tube for about 20 minutes to allow the water temperature and cell temperature to stabilize at 23°C. Several cumulative counts were taken for the clean water. During all subtests the pumping rate was maintained at 50 mL/s.

For subtest 1, (table A-3) the electronic counter was started then 75 seconds later 20 grams of prewetted Jordan sand were injected into the deaeration chamber. To simulate an abrupt concentration change, all the sand was injected during a period of only 10 seconds. On table A-3 the injection time of 1/2 indicates the sediment was injected when the cumulative count interval was half complete. At the end of the interval, the cumulative count was recorded on table A-3 in the column labeled "cumulative count for suspension."

For subtest 2, the recirculation system was cleaned and filled with fresh tap water. Water temperature and cell temperature were again stabilized, then cumulative-counts were collected for the clear water. The electronic counter was started; then 50 seconds later, when the count interval was approximately 1/3 complete, 10 grams of prewetted Jordan sand

Table A-3.--Response to unsteady concentrations of Jordan sand.

Liquid temperature 23°C
Pump rate 50 mL/s
Nominal count interval 155 s
Computed discharge-weighted concentration
for 155-s count interval =2,574 ppm (1).
Test material - Jordan sand, 297-350 micrometers

| Cumulative count for clear water | Dry mass of material injected, gram | Injection time, fraction of count interval | Cumula-count for suspension | Count |
|---|---|---|---|---|
| | | Subtest 1 | | |
| 1985241 | 20 | 1/2 | 1985765 | 524 |
| | | Subtest 2 | | |
| | 10 | 1/3 | | |
| 1985238 | 10 | 2/3 | 1985705 | 467 |
| | | Subtest 3 | | |
| 1985233 | 5 | 1/5 | | |
| | 5 | 2/5 | | |
| | 5 | 3/5 | | |
| | 5 | 4/5 | 1985564 | 331 |

(1) Discharge-weighted concentration in ppm =2,574 = $\frac{a \times 10^6}{a + bc}$ .

a = 20 g = mass of sediment discharged through U-tube, in grams.

b = 155 = nominal count interval in seconds.

c = 50 = pump rate in g/s.

Table A-4.--Response to unsteady concentrations of a clay-silt mixture.

Liquid temperature 23°C
Pump rate 50 mL/s
Nominal count interval 2.5 m
Computed discharge-weighted concentration
for 155-s count interval = 2,574 ppm (1).
Test material - Spokane, Washington sediment

| Cumulative count for clear water | Dry mass of material injected, gram | Injection time, fraction of count interval | Cumula-count for suspension | Count |
|---|---|---|---|---|
| | | <u>Subtest 1</u> | | |
| 1985256 | 20 | 1/2 | 19855505 | 249 |
| | | <u>Subtest 2</u> | | |
| 1985261 | 10 | 1/3 | | |
| | 10 | 2/3 | 1985508 | 247 |
| | | <u>Subtest 3</u> | | |
| 1985254 | 5 | 1/5 | | |
| | 5 | 2/5 | | |
| | 5 | 3/5 | | |
| | 5 | 4/5 | 1985499 | 245 |

(1) Discharge-weighted concentration in ppm = $2,574 = \frac{a \times 10^6}{a + bc}$ .

a = 20 g = mass of sediment discharged through U-tube, in grams.

b = 155 = nominal count interval in seconds.

c = 50 = pump rate in g/s.

were injected into the deaeration chamber. About 50 seconds later, when the count interval was 2/3 complete, an additional 10 grams of prewetted sand were injected. At the completion of the cumulative count interval, the cumulative count was recorded. Subtest 3 was conducted in the same manner as subtest 1 and subtest 2, except that four injections (5 grams each) were made at equally spaced time intervals.

Among subtests 1, 2, and 3, equal quantities of water and equal quantities of sediment passed through the U-tube; consequently, the discharge-weighted sediment concentration among all subtests was equal. The only difference between subtests 1, 2, and 3 was the degree of unsteadiness in sediment concentration. Subtest 1 represented the greatest unsteadiness, and subtest 2 and subtest 3 represented progressively lesser degrees of unsteadiness. The trend represents an asymptotic approach to steady concentrations. Table A-3 shows that for Jordan sand, the count progressively decreased as the degree of unsteadiness decreased.

Except for a different sediment, the second test (table A-4) was conducted in the same manner as the first test. Table A-4 shows that for Spokane sediment, the count decreased as unsteadiness decreased; but, compared to the Jordan sand tests, the decrease was small. Obviously particle size affects the response. The effect is probably related to the residence time of the sediment within the U-tube. The fine sediment from Spokane, Washington was readily transported in suspension, but the coarse Jordan sand probably migrated to the bottom of the tube and moved at a velocity considerably slower than the water velocity. For coarse sediment, pumping rates higher than 50 mL/s will minimize the residence time.

## Transient response to the concentration of dissolved solids

In a river, a change in water discharge is usually accompanied by a change in dissolved-solids concentration. The rate of the concentration change may be comparatively large during the onset of flow in an ephemeral stream.

To test the response of the U-tube to an abrupt change in dissolved-solids concentration, the U-tube inlet was connected through a short section of tube to one leg of a "Tee" tubing connector. Another leg was connected to the discharge port of the recirculation pump, and the remaining leg was connected to an elevated container filled with a potassium chloride (KCl) solution premixed to a concentration of 21,334 ppm. The high concentration produced a solution with a density considerably higher than that of tap water. Pinch clamps were arranged so that either clear tap water or the KCl solution could be routed through the U-tube. To monitor the U-tube vibration, a special instrument was used to measure and print the time required for the U-tube to complete 100 cycles. The instrument operated continuously and required only about 1 second to measure 100 vibrational cycles and print the time.

To start the test, clear tap water was pumped through the instrument until the temperatures of the water, cell, and KCl solution were equal. After the cumulative count stabilized, the printer was started, then a few seconds later the clamps were switched to stop the flow of tap water and start the flow of KCl solution. Figure A-12 shows nine period measurements collected prior to the valve switch-time, which was plotted as zero on the elapsed-time scale. After the valve was switched, the three subsequent readings remained steady but the fourth reading (plotted at 8 seconds) shifted to a new value. Except for minor variations, all remaining period readings were steady.

To measure accurately the system response to a step change in dissolved-solids concentration and the associated step change in density, the liquid change time must be short compared to the instrument response time. The total storage volume between the valves and the discharge end of the U-tube was 150 mL. The measured flow rate of the KCl solution was 45.6 mL/s, so about 3.3 seconds were required to complete the liquid change. The time is approximate because of the manner in which the KCl solution purged the tap water from the U-tube. Most of the water was forced ahead of the solution as it advanced into the U-tube. The remainder of the water was ejected more slowly by turbulent mixing at the horizontal interface between the two fluids and at the tube wall. As figure A-12 shows, the period restabilized about 8 seconds after the valves had been switched. After deducting 3.3 seconds for the replacement time, about 4.7 seconds were required for the instrument to restabilize. This response time is a function of both the mechanical and electrical characteristics of the U-tube and also of the electrical characteristics of the custom-made feedback loop.

In a similar test, Mahmood and others (1979, p. 44) observed that for a step increase in NaCl concentration, the instrument output completed 96.13 percent of its ultimate change in 37.5 seconds. This longer response time may have been caused by damping within the electrical converter which Mahmood used with the cell.

## DATA REDUCTION PROCEDURE TO CORRECT FOR TEMPERATURE AND DISSOLVED SOLIDS

Figure A-13 illustrates the data-reduction procedure to obtain suspended-sediment concentration by correcting the count for both water temperature and dissolved-solids concentration.

If water temperature is steady or nearly steady, temperature hysteresis effects will be minimal. The two curves on figure A-5 can be approximated as a single curve similar to the one labeled "temperature response curve for water" on figure A-13a. If the material in the U-tube is water mixed with dissolved solids, the temperature response curve for the mixture will be the "temperature-response curve for water" shifted up the count axis. The shift depends upon the total concentration of all substances in the water. If sediment is added to the mixture, the total concentration will increase. The new response curve is shown on the top of figure A-13a. To minimize the effects of drift caused by deposits on the U-tube walls, count instead of cumulative-count is plotted on the vertical axis of figure A-13a. For a particular mixture, the count is the difference between the cumulative-count for the mixture and the cumulative-count for the water. Both cumulative counts must be measured at equal temperatures.

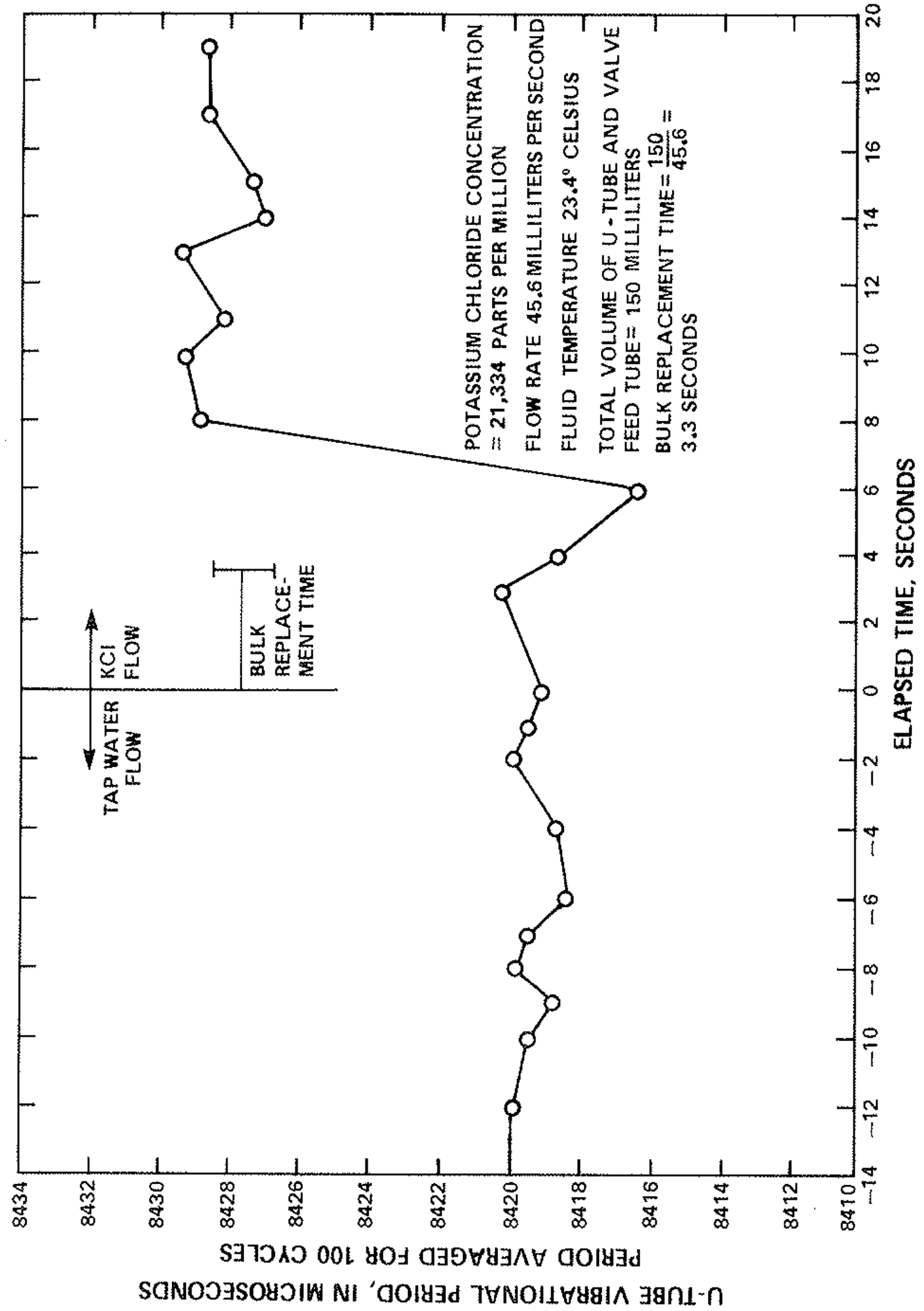


Figure A-12.--Transient response to a change in dissolved-solids concentration.

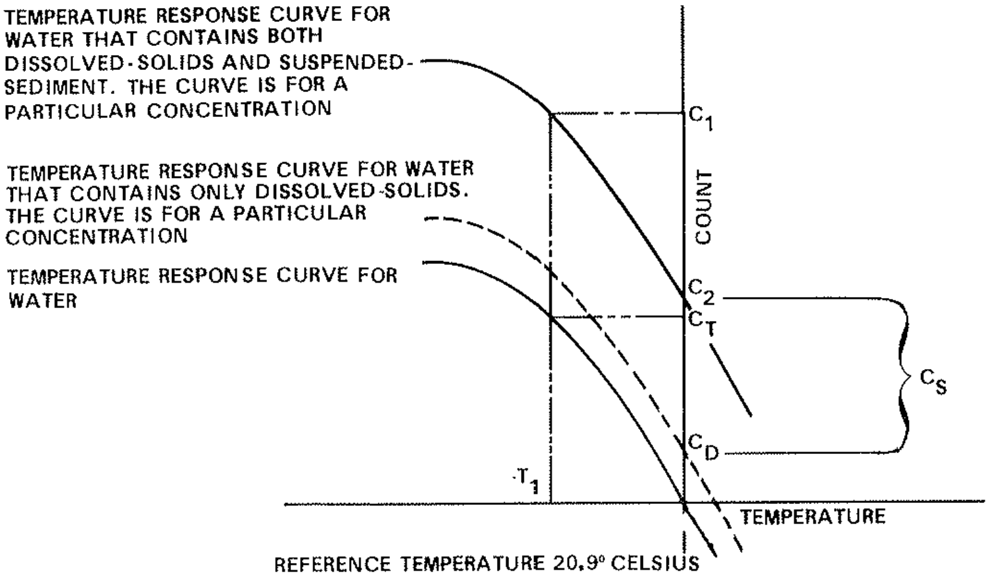


Figure A-13a.--Temperature response to water and to mixtures.

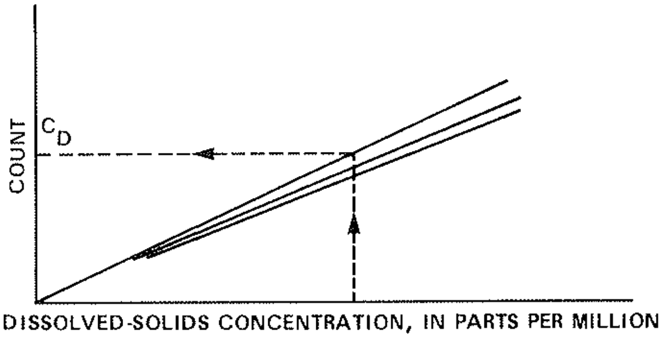


Figure A-13b.--Isothermal response to dissolved solids.

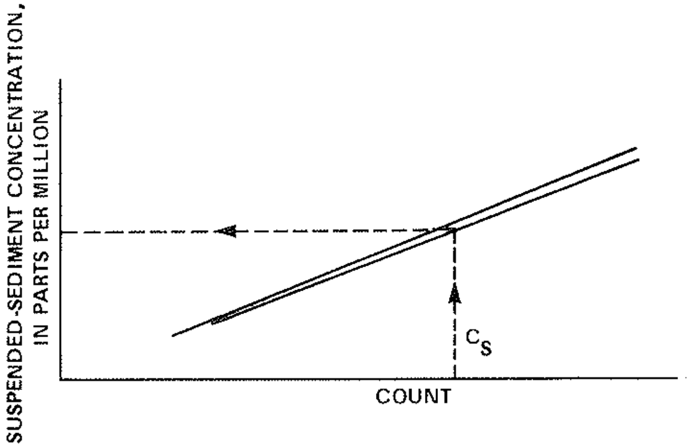


Figure A-13c.--Isothermal response to sediment.

Figure A-13.--Graphical representation of data-reduction procedure to correct for temperature and dissolved solids.

Suppose that a count of $C_1$ (figure A-13a) is observed at a temperature of $-T_1$, measured relative to a reference temperature of 20.9°C. If the mixture is slowly warmed to the reference temperature, the count $C_2$ is obtained. The change, $C_1 - C_2$, is equal to $C_T$ which is read from the temperature-response curve for water. $C_2$ is the sum of $C_D$, which is produced by the dissolved-solids, and $C_s$, which is produced by the sediment. If for the dissolved solids, both the concentration and the chemical composition are known, then as shown on figure A-13b, $C_D$ can be obtained from a regression of count on dissolved-solids concentration. On figure A-13b three regression lines are shown to emphasize the fact that the regression depends upon the chemical composition of the dissolved solids. As shown on figure A-13c, $C_s$ can be converted to suspended-sediment concentration by using a regression of sediment concentration on count. Two regression lines are shown to emphasize that the regression will depend upon both sediment particle size and sediment density.

An alternate method of correcting for both temperature and dissolved solids is to measure periodically the cumulative count taken on a reference sample. Ideally, the reference sample must consist of water that is free of sediment and that contains dissolved solids at a concentration equal to that in the river water. At sites where dissolved-solids concentration is steady or nearly steady, reference samples can be prepared from the river water. A theoretical study indicates that in a shallow 16-cm diameter container, a reference sample can be automatically prepared in 3 hours. The sediment will be removed by settling. The reference sample would be free of all particles and flocs with fall velocities great than 0.00046 cm/s. This fall velocity corresponds to a particle fall diameter of about 2 micrometers. A fresh reference sample can be prepared every 3 hours, then cumulative counts taken on each reference sample can be merged with cumulative counts taken on untreated river water. The complete process would consist of two superimposed cyclical operations. The first operation would consist of reading and storing cumulative counts taken on untreated river water that would be pumped through the density gage. A "river-water" cumulative count would be collected every 3 minutes. The second operation would consist of diverting a sample of untreated river water to the settling container. Three hours later, the reference sample would be pumped from the container, then circulated through the U-tube while a cumulative count was read and stored. After the cumulative count has been stored, the reference sample would be purged from the U-tube. Then a fresh river-water sample would be pumped to the settling chamber to start the next cycle.

At convenient times all stored cumulative counts would be retrieved and tabulated in order of collection. Each cumulative count would be classified as either a reference reading or a river-water reading then, the tabulation would be subdivided into groups. Each group would consist of one reference reading and all river water readings that were collected during an interval starting 1½ hours before the reference was pumped and ending 1½ hours after the reference was pumped. Within each group, the count would be obtained by subtracting the reference reading from each river water reading. If within a group both river temperature and dissolved-solid concentration were steady, each count in the group could be converted directly to sediment concentration. Conversion would be through the regression relation depicted on figure A-8 or through an appropriate regression equation from table A-1.

The reference-sample method has several advantages. All required data will be generated by the density cell. Temperature and conductivity will not be required. The effect of wall deposits will be included in all cumulative counts; consequently, each count will be insensitive to these deposits.

The method has certain disadvantages. Both a storage container and several electrically-operated valves will be required. A process-control circuit of moderate complexity will be required. The sediment suspended in the river water must contain only a small quantity of particles smaller than 2 micrometers.

Another method of compensating for dissolved solids is to estimate the dissolved-solids concentration from water-conductivity readings. This method is discussed in Part B of this report.

# INSTRUMENT PRECISION

Four tests were conducted to measure the density-cell precision (variation among cumulative counts) as affected by clay deposited on the U-tube walls. Tests 1, 2, and 3 (table A-5) were run on different days. For a few days preceding each of the first three tests, the U-tube was exposed to water that contained cohesive clays and dissolved solids. This mixture formed a thin deposit on the walls of the tube. Prior to each test the tube was flushed with clear water, but no effort was made to remove the deposit. The recirculation system was drained and then filled with distilled water. Flow through the U-tube was regulated at 50 mL/s. As the cell approached thermal equilibrium, cumulative counts slowly drifted. The water temperature was stabilized at 20.9 ± .05°C. After the cell temperature stabilized, the variation among cumulative counts became essentially random. Each test consisted of collecting and analyzing a series of cumulative counts to determine the magnitude of the random variation. Table A-5 shows for each test the standard deviation of cumulative count. The smaller the standard deviation the greater the precision. Among tests 1, 2, and 3 the standard deviation differed but slightly. The largest value was 1.72 for test 3. At the conclusion of test 3 the distilled-water temperature was lowered to 14°C, the cell temperature was restabilized, then another series of cumulative counts were collected and analyzed. Table A-5 (test 4) shows the standard deviation was not signicantly different from those measured at 20.9°C.

Within a test, random variations in cumulative count were caused by slight temperature changes, the least-count resolution of the counter, changes in the wall deposit, and unknown changes in the cell components. Figure A-5 shows that at room temperature, a 1°C change in water temperature will cause an 18-unit change in cumulative count. Based on this relation, the ± 0.05°C variation within these tests caused a ± 0.9-unit variation in cumulative count. The least-count resolution of one unit caused a random variation of ± 0.5-units. The slight temperature variations combined with the least-count resolution will account for nearly all of the observed random variation in cumulative count. During any test, both wall deposits and cell components were quite stable.

Table A-5.--Response to deposits on U-tube wall.

Tube was not cleaned between or during tests.
All tests conducted with an air temperature of about 20°C.
Flow rate through the U-tube - 50 mL/s.

| | | | | Cumulative-count statistics | | |
|---|---|---|---|---|---|---|
| Test date and number | Distilled water temp, °C | Cumulative count minus 1,985,000 | Frequency of occurrence | Total number of cumulative counts observed | Mean cumulative count minus 1,985,000 | Standard deviation of cumulative count |
| 4/3/80 | 20.9 ± 0.05 | 707 | 1 | 8 | 705.75 | 0.71 |
| | | 706 | 4 | | | |
| (1) | | 705 | 3 | | | |
| 4/7/80 | 20.9 ± 0.05 | 703 | 1 | 30 | 699.33 | 1.65 |
| | | 702 | 1 | | | |
| (2) | | 701 | 4 | | | |
| | | 700 | 6 | | | |
| | | 699 | 13 | | | |
| | | 698 | 2 | | | |
| | | 697 | 2 | | | |
| | | 694 | 1 | | | |
| 4/18/80 | 20.9 ± 0.05 | 733 | 2 | 29 | 729.03 | 1.72 |
| | | 732 | 2 | | | |
| (3) | | 731 | 0 | | | |
| | | 730 | 3 | | | |
| | | 729 | 11 | | | |
| | | 728 | 8 | | | |
| | | 727 | 1 | | | |
| | | 726 | 2 | | | |
| 4/18/80 | 14.0 ± 0.05 | 814 | 6 | 30 | 812.43 | 1.22 |
| | | 813 | 10 | | | |
| (4) | | 812 | 7 | | | |
| | | 811 | 6 | | | |
| | | 809 | 1 | | | |

The mean cumulative count of test 4 differed from those of tests 1, 2, and 3 because of the difference in water temperature. The differences among mean cumulative counts for tests 1, 2, and 3 are statistically significant. The difference between test 2 and test 3 is highly significant and was probably caused by a change in the mass of the clay deposit. This change occurred between the two tests.

After the fourth test the instrument was subjected to a special test that was conducted with the water and cell temperature at 20.9°C. For about six hours, a water-sediment mixture was pumped through the U-tube. Then the recirculation system was flushed and, more importantly, the straight section of each leg of the U-tube was scrubbed with a bottle brush coated with an abrasive cleanser. The recirculation system was filled with water, and a series of cumulative counts were collected after the temperature stabilized. The mean cumulative count decreased to 1,985,220. Compared to the means for tests 1, 2, and 3, the change was highly significant and was caused by removal of the clay deposit. During the following ten weeks, the special test was replicated many times. Results of these tests showed a dramatic improvement in cumulative-count stability. Sudden unexpected changes in cumulative count never occurred among the tests.

To attain high precision and long-term stability, the U-tube must be cleaned daily. More frequent cleaning will be necessary if a wall deposit accumulates rapidly.

## RESPONSE TO SEDIMENT DENSITY

Equation 5 indicates the period is sensitive to the SC product. For neutrally buoyant particles, S is zero (or very small); consequently, these particles should affect the period only slightly. To obtain empirical confirmation, a suspension of styrene beads with a density of 1.04 g/cm$^3$ was tested. Styrene was selected because its density is much lower than the density of Jordan sand and of the other natural sediments tested. Also, because it is almost neutrally buoyant, styrene is similar to many forms of organic detritus present in river water.

To measure the gage response, the recirculation system was filled with distilled water, the pump rate and temperature were stabilized, and then a few cumulative counts were averaged. When styrene was added to the recirculation system, the cumulative count increased 335 units. Analysis of a sample indicated the styrene concentration was 40,800 ppm; therefore, the gage sensitivity (change in cumulative count/change in concentration) was 0.008211 counts/ppm. For comparison, figure A-8 shows the average sensitivity to the Jordan sand and to the other natural sediments is much larger, about 0.1 counts/ppm.

## RESPONSE TO A MAGNETIC SEDIMENT

The U-tube is made of a stainless-steel alloy with a low magnetic permeability; but the case, which encloses the U-tube, is made of structural steel with a high magnetic permeability. The sense coil and drive coil contain unknown types of magnetic materials.

The instrument was tested to determine if magnetic sediment particles are attracted and retained by the tube. Taconite, a magnetic sediment, was wet-sieved through a screen with 44-micrometer openings; then the particles retained by the screen were emptied into the recirculation system. Pump rate and water temperature were held steady at 50 mL/s and 20.9°C respectively. The particles increased the cumulative count by about 140 units. After the cumulative count data had been collected, the screen was positioned to filter the U-tube discharge. After two minutes the screen had removed all particles. With the water free of taconite the cumulative count returned to the value originally obtained with sediment-free water. The test, which was repeated several times, indicated that magnetic forces were too weak to adversely affect instrument operation. Forces generated by the 50-mL/s flow rate were sufficient to overcome all magnetic forces between the particles and the magnetic components in the cell.

## SUMMARY OF RESPONSE CHARACTERISTICS

The primary goal of this study was to determine the response of the gage to various concentrations of sediment. However, the response to several other factors was measured and each response is summarized in this section.

Sediment - A log-log plot of sediment concentration versus instrument response (count) is linear for concentrations that exceed 500 ppm. The linear relation applies for a wide range of concentrations. The highest concentration tested was 97,000 ppm. For sediment concentrations less than 500 ppm, a plot of concentration versus count is linear. The ratio of count to concentration depends to a minor degree upon concentration, but is about 1/10 through the entire range from 0 ppm to 97,000 ppm. In approximate terms, a count change of one unit corresponds to a sediment concentration change of about 10 ppm.

When the U-tube is exposed to a steady concentration of sediment, individual counts will scatter about a mean value. The scatter, as gaged by the standard error-of-estimate, corresponds to a random error of about ± 12 percent of the concentration that is indicated by the mean count. This random error applies when the sediment is coarse sand. For fine sand, the error is about ± 3 percent. Both errors apply to sediment concentrations in the range from 500 to 50,000 ppm. For concentrations less than 500 ppm, the scatter is nearly independent of sediment concentration. The random error is about ± 25 ppm for sand suspensions and ± 10 ppm to ± 15 ppm for clay suspensions.

The instrument is sensitive to sediment particle size. In general, the instrument is less sensitive to coarse sand than to fine sand, silt, and clay. Intermediate particle sizes follow the trend. To create the same count with coarse sand as with a clay-silt mixture, the sand concentration must be about 25 percent higher.

For equal discharge-weighted concentrations, an unsteady sediment concentration will register as a count that is larger than the count registered by a steady concentration. The difference between the two counts will decrease with a decrease in particle size.

Water temperature - All tests were conducted without the automatic temperature compensator that is supplied with the cell. For temperatures near 20°C the change in cumulative count is proportional to the change in temperature. A temperature change of 1°C causes the cumulative count to change 16 units. This cumulative-count change is equivalent to a sediment concentration change of 160 ppm. For temperatures colder than 9°C the instrument responds in an erratic fashion. The problem is believed to be caused by moisture condensing on the outside of the U-tube.

Magnetic sediments - The instrument contains magnetic components, but they do not react with magnetic sediment particles to retard or interfere with their motion through the U-tube.

Entrained air - The instrument will respond to air entrained in the water that flows through the U-tube. The air can be nearly eliminated by properly designing the hydraulic components connected to the inlet port of the U-tube.

External vibration - Floor vibration transmitted to the cell will probably affect the response. A vibration isolator composed of four springs and a simple support frame will eliminate the potential problem.

Dissolved solids - Solids dissolved in the water will be registered by the instrument. The exact magnitude of the response depends upon the chemical composition. In approximate terms, equal concentrations of dissolved solids and suspended solids (density 2.65 $g/cm^3$) will produce the same response.

Flow rate - Flow rate affects the gage in an indirect fashion. The gage responds primarily to the spatial concentration of the mixture within the

U-tube. The spatial concentration and the discharge weighted-concentration differ when, within the U-tube, the sediment particles and the water move at different speeds. When the water flow rate is low, some particles will settle to the bottom of the tube and move slowly or intermittently. Particles that move in this fashion cause the gage readings to be erratic. The minimum recommended water discharge is 85 mL/s. The maximum tested discharge was 113 mL/s. Higher discharges may be beneficial.

Density of particulate matter - Both theoretical and experimental results indicate the instrument is sensitive to the density of particulate matter suspended in the water. Most fluvial sediments have a density of about 2.65 $g/cm^3$. At most sites, variations from this value will be too small to cause significant errors. Material such as organic detritus, which has a density nearly equal to that of water, will register but only if the concentration is extremely high. Dense sediments, such as taconite, will cause the gage to over-register.

Tube cleanliness - Deposits that adhere to the walls of the U-tube will not move with the water; consequently, they will cause a difference between the static concentration and the discharge-weighted concentration. Observations indicate the count will increase as the deposit accumulates. Periodic cleaning with a tube brush and mild abrasive is essential in order to minimize gradual shifts in the readings.

## CONCLUSIONS

The vibrating U-tube fluid-density gage, combined with the precision feedback and timing circuit, responds to a wide range of sediment concentrations. Clay concentrations as high as 97,000 ppm were included in the tests.

The principal sources of measurement interference are water temperature, solids dissolved in the water, and deposits that adhere to the inside walls of the U-tube.

The gage is sensitive to the density of the sediment suspended in the water. The gage is insensitive to organic detritus and substances with a density nearly equal to that of water.

The gage is sensitive to sediment particle size. The gage is more sensitive to clay and silt than to coarse sand.

The discharge through the U-tube should exceed 85 mL/s to minimize both the effect of particle size on sensitivity and the random measurement errors. To minimize drift in the gage reading, the inside walls of the U-tube must be cleaned regularly.

When the sediment concentration exceeds 500 ppm, individual gage readings fluctuate randomly about a mean. The magnitude of the fluctuation is related to both the sediment particle size and sediment concentration. For monodisperse suspensions of coarse sand, the standard error-of-estimate is ± 12 percent of the indicated concentration. The indicated concentration is the value that corresponds to the mean reading. For monodisperse suspensions of fine sand and clay, the standard error-of-estimate is about + 3 percent of the indicated concentration. For polydisperse suspensions which are typical of natural streams, the standard error-of-estimate is less than + 12 percent, but greater than ± 3 percent.

For sediment concentrations less than 500 ppm, random fluctuations in gage readings increase in particle-size but the fluctuations are nearly independent of concentration. For clay and silt, the standard error-of-estimate is 15 ppm. For sand the error of estimate is 25 ppm.

Sodium chloride is a convenient substance to use for instrument calibration.

The gage is rugged, the operating principle is simple and operating voltages are low. Compared to gamma-type sediment gages, the fluid density gage contains no hazardous radiation sources or fragile radiation detectors.

## FUTURE RESEARCH AND DEVELOPMENT

Test results described in this report show that the gage has many desirable features, but they also show that certain deficiencies must be corrected. The following topics should be investigated:

The cause of anomalous readings at low temperatures must be determined. The value of filling the inside of the case with a dry gas should be studied.

Cell orientation and its influence on both random measurement errors and systematic particle-size effects should be studied. The vertical orientation may be advantageous. If the U-tube is mounted with the curved section below the tube ends, gravity will tend to concentrate sediment in the tube. If the pump is suddenly stopped while the tube is full, sediment will slowly settle into the curved section. As the particles settle, the change in period may yield useful information regarding particle-size distribution. Also, the settling process may serve to improve the sensitivity to low sediment concentrations.

A mathematical model of the system should be constructed and verified. A model that includes not only the mechanical elements of the tube but also the flow of water and sediment through the tube will serve as a valuable tool to explain the observed particle-size effects.

Equipment for reference-sample preparation should be developed and evaluated.

A flow event in a selected river should be simulated and then combined with both instrument characteristics and pumping-intake characteristics to analytically perform an error analysis for the system. The analysis would provide criteria for selection of field installation sites and selection of the optimum procedure for gage operation.

The method outlined under "Data reduction procedure to correct for temperature and dissolved solids" should be laboratory-tested and verified.

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# APPENDIX

# COUNT AND CONCENTRATION DATA FOR SUSPENSIONS AND SOLUTIONS

Table A-6.--Count and measured-concentration data for high concentrations of Jordan sand with a size range of 710-833 micrometers and with a mixture flow-rate of 85 mL/s.

Test material: Jordan sand. Temp. in degrees Celsius: 20.9.
Flow rate in mL/s: 85 . Particle diameter in micrometers: 710-833.
Method of size segregation: dry·sieving.
Method of concentration measurement: gravity settling, decantation, and weighing.
Comments: U-tube cleaned prior to test.

| X, count | Measured Y, concentration in ppm | Predicted Y, concentration in ppm(a) |
|---|---|---|
| 1 * | 11 * | |
| 573 | 5846 | 5967 |
| 260 | 2842 | 2795 |
| 120 | 1216 | 1330 |
| 58 | 708 | 662 |
| 29 * | 369 * | |
| 10 * | 156 * | |
| 1616 | 15776 | 16144 |
| 5014 | 44755 | 47865 |
| 2004 | 19839 | 19848 |
| 889 | 9782 | 9067 |
| 395 | 4044 | 4176 |
| 183 | 1818 | 1995 |
| 97 | 882 | 1085 |
| 56 | 700 | 640 |
| 6215 | 55952 | 58821 |
| 2343 | 20982 | 23060 |
| 1040 | 10918 | 10575 |
| 435 | 4943 | 4581 |
| 185 | 1942 | 2016 |
| 91 | 1045 | 1020 |
| 38 * | 435 * | |
| 17 * | 311 * | |

(a) Predicted Y calculated from the regression equation
$\log Y = 1.128339 + 0.959866 \log X$.
This equation applies only to high concentrations defined as those required to produce a count greater than 50.
Data pooled from 85 mL/s and 113 mL/s (table A-7) flow rates to compute the equation.

* Valid reading but because X was less than 50, this datum was not used in the regression analysis.

Table A-7.--Count and measured-concentration data for high concentrations of Jordan sand with a size range of 710-833 micrometers and with a mixture flow-rate of 113 mL/s.

Test material: Jordan sand. Temp. in degrees Celsius: 20.9.
Flow rate in mL/s: 113 . Particle diameter in micrometers: 710-833.
Method of size segregation: dry sieving.
Method of concentration measurement: gravity settling, decantation, and weighing.
Comments: U-tube cleaned prior to test.

| X, count | Measured Y, concentration in ppm | Predicted Y, concentration in ppm(a) |
|---|---|---|
| 1 * | 8 * | |
| 7177 | 70513 | 67534 |
| 4092 | 39942 | 39383 |
| 2317 | 23315 | 22814 |
| 1427 | 14414 | 14327 |
| 902 | 9945 | 9224 |
| 532 | 6428 | 5557 |
| 231 | 2443 | 2495 |
| 144 | 1672 | 1585 |
| 89 | 999 | 998 |

(a) Predicted Y calculated from the regression equation $\log Y = 1.128339 + 0.959866 \log X$.
This equation applies only to high concentrations defined as those required to produce a count greater than 50.
Data pooled from 85 mL/s and 113 mL/s (table A-6) flow rates to compute the equation.

* Valid reading but because X was less than 50, this datum was not used in the regression analysis.

Table A-8.--Count and measured-concentration data for low concentrations of Jordan sand with a size range of 710-833 micrometers and with a mixture flow-rate of 113 mL/s.

Test material: Jordan sand. Temp. in degrees Celsius: 20.9.
Flow rate in mL/s: 113 . Particle diameter in micrometers: 710-833.
Method of size segregation: dry sieving.
Method of concentration measurement: gravity settling, decantation, and weighing.
Comments: linear regression on untransformed variables.
U-tube cleaned prior to test.

| X, count | Measured Y, concentration in ppm | Predicted Y, concentration in ppm[(a)] |
|---|---|---|
| 47 | 523 | 529 |
| 30 | 333 | 357 |
| 16 | 225 | 217 |
| 0 | 26 | 56 |
| 23 | 338 | 287 |
| 12 | 148 | 176 |
| 5 | 127 | 106 |
| 0 | 76 | 56 |
| -4 | 13 | 15 |
| -1 | 25 | 46 |
| 9 | 141 | 146 |
| 5 | 100 | 106 |
| -1 | 68 | 46 |

(a) Predicted Y calculated from the regression equation
$Y = 55.73259 + 10.060116\ X$.
This equation applies only to low concentrations, defined as those that produce a count of 50 or less.

Table A-9.--Count and measured-concentration data for high concentrations of Jordan sand with a size range of 710-833 micrometers and with a mixture flow-rate of 50 mL/s.

Test material: Jordan sand. Temp. in degrees Celsius: 20.9.
Flow rate in mL/s: 50. Particle diameter in micrometers: 420-833.
Method of size segregation: dry sieving.
Method of concentration measurement: gravity settling, decantation, and weighing.
Comments: U-tube cleaned prior to test.

| X, count | Measured Y, concentration in ppm | Predicted Y, concentration in ppm[(a)] |
|---|---|---|
| 152 | 1325 | |
| 126 | 1540 | |
| 196 | 2880 | |
| 434 | 3067 | |
| 1599 | 8780 | |
| 1282 | 8884 | |
| 1521 | 9921 | |

(a) Predicted Y and regression equation were not computed because of low flow-rate.

High concentrations are defined as those that produce a count greater than 50.

Table A-10.--Count and measured-concentration data for high concentrations of Jordan sand with a size range of 350-420 micrometers and with a mixture flow-rate of 50 mL/s.

Test material: Jordan sand. Temp. in degrees Celsius: 20.9.
Flow rate in mL/s: 50 . Particle diameter in micrometers: 350-420.
Method of size segregation: dry sieving.
Method of concentration measurement: gravity settling, decantation, and weighing.
Comments: U-tube cleaned prior to test.

| X, count | Measured Y, concentration in ppm | Predicted Y, concentration in ppm(a) |
|---|---|---|
| 271 | 1394 | |
| 163 | 1500 | |
| 295 | 2030 | |
| 201 | 2363 | |
| 347 | 2530 | |
| 362 | 2591 | |
| 524 | 3300 | |
| 434 | 3570 | |
| 532 | 4370 | |
| 818 | 5030 | |
| 777 | 5835 | |
| 860 | 5950 | |
| 879 | 5961 | |

(a) Predicted Y and regression equation were not computed because of low flow-rate.

High concentrations are defined as those that produce a count greater than 50.

Table A-11.--Count and measured-concentration data for high concentrations of Jordan sand with a size range of 350-420 micrometers and with a mixture flow-rate of 85 mL/s.

Test material: Jordan sand. Temp. in degrees Celsius: 20.9.
Flow rate in mL/s: 85 . Particle diameter in micrometers: 350-420.
Method of size segregation: dry sieving.
Method of concentration measurement: gravity settling, decantation, and weighing.
Comments: U-tube cleaned prior to test.

| X, count | Measured Y, concentration in ppm | Predicted Y, concentration in ppm(a) |
|---|---|---|
| 7 * | 47 * | |
| 725 | 10046 | 7581 |
| 1295 | 13900 | 13637 |
| 841 | 11151 | 8810 |
| 504 | 7003 | 5247 |
| 287 | 2308 | 2967 |
| 145 | 1599 | 1487 |
| 99 | 969 | 1010 |
| 69 | 678 | 701 |
| 54 | 414 | 547 |
| 44 * | 273 * | |

(a) Predicted Y calculated from the regression equation
$\log Y = 0.984428 + 1.012223 \log X$.
This equation applies only to high concentrations defined as those required to produce a count greater than 50.
Data pooled from 85 mL/s and 113 mL/s (table A-12) flow rates to compute the equation.

* Valid reading but because X was less than 50, this datum was not used in the regression analysis.

Table A-12.--Count and measured-concentration data for high concentrations of Jordan sand with a size range of 350-420 micrometers and with a mixture flow-rate of 113 mL/s.

Test material: Jordan sand. Temp. in degrees Celsius: 20.9.
Flow rate in mL/s: 113. Particle diameter in micrometers: 350-420.
Method of size segregation: dry sieving.
Method of concentration measurement: gravity settling, decantation, and weighing.
Comments: U-tube cleaned prior to test.

| X, count | Measured Y, concentration in ppm | Predicted Y, concentration in ppm(a) |
|---|---|---|
| 2 * | 18 * | |
| 3630 | 33147 | 38712 |
| 2265 | 20339 | 24016 |
| 1474 | 13963 | 15547 |
| 925 | 9342 | 9701 |
| 618 | 6133 | 6450 |
| 398 | 3946 | 4131 |
| 265 | 2873 | 2737 |
| 170 | 1939 | 1746 |
| 112 | 1222 | 1144 |
| 76 | 785 | 773 |
| 52 | 546 | 526 |

(a) Predicted Y calculated from the regression equation
$\log Y = 0.984428 + 1.012223 \log X$.
This equation applies only to high concentrations defined as those required to produce a count greater than 50.
Data pooled from 85 mL/s and 113 mL/s (table A-11) flow rates to compute the equation.

* Valid reading but because X was less than 50, this datum was not used in the regression analysis.

Table A-13.--Count and measured-concentration data for high concentrations of Jordan sand with a size range of 297-350 micrometers and with a mixture flow-rate of 50 mL/s.

Test material: Jordan sand. Temp. in degrees Celsius: 20.9.
Flow rate in mL/s: 50. Particle diameter in micrometers: 297-350.
Method of size segregation: dry sieving.
Method of concentration measurement: gravity settling, decantation, and weighing.
Comments: None.

| X, count | Measured Y, concentration in ppm | Predicted Y, concentration in ppm(a) |
|---|---|---|
| 155 | 1079 | |
| 335 | 1971 | |
| 448 | 4103 | |
| 695 | 4401 | |
| 679 | 4529 | |
| 1127 | 5565 | |
| 959 | 5903 | |

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(a) Predicted Y and regression equation were not computed because of low flow-rate.

High concentrations are defined as those that produce a count greater than 50.

Table A-14.--Count and measured-concentration data for high concentrations of Jordan sand with a size range of 297-350 micrometers and with a mixture flow-rate of 85 mL/s.

Test material: Jordan sand. Temp. in degrees Celsius: 20.9.
Flow rate in mL/s: 85 . Particle diameter in micrometers: 297-350.
Method of size segregation: dry sieving.
Method of concentration measurement: gravity settling, decantation, and weighing.
Comments: U-tube cleaned prior to test.

| X, count | Measured Y, concentration in ppm | Predicted Y, concentration in ppm[(a)] |
|---|---|---|
| 5182 | 39951 | 47815 |
| 1056 | 10487 | 9921 |
| 486 | 5041 | 4606 |
| 282 | 2538 | 2689 |
| 143 | 1226 | 1374 |
| 88 | 659 | 850 |
| 31 * | 363 * | |
| 30 * | 61 * | |

(a) Predicted Y calculated from the regression equation $\log Y = 1.007182 + 0.988662 \log X$.
This equation applies only to high concentrations defined as those required to produce a count greater than 50.
Data pooled from 85 mL/s and 113 mL/s (table A-15) flow rates to compute the equation.

* Valid reading but because X was less than 50, this datum was not used in the regression analysis.

Table A-15.--Count and measured concentration data for high concentrations of Jordan sand with a size range of 297-350 micrometers and with a mixture flow-rate of 113 mL/s.

Test material: Jordan sand. Temp. in degrees Celsius: 20.9.
Flow rate in mL/s: 113 . Particle diameter in micrometers: 297-350.
Method of size segregation: dry sieving.
Method of concentration measurement: gravity settling, decantation, and weighing.
Comments: U-tube cleaned prior to test.

| X, count | Measured Y, concentration in ppm | Predicted Y, concentration in ppm(a) |
|---|---|---|
| 1 * | 7 * | |
| 2411 | 23081 | 22440 |
| 1545 | 14980 | 14453 |
| 963 | 9877 | 9057 |
| 605 | 5961 | 5720 |
| 385 | 3771 | 3659 |
| 257 | 2520 | 2454 |
| 174 | 1634 | 1669 |
| 121 | 1348 | 1165 |
| 80 | 802 | 774 |
| 58 | 593 | 563 |
| 43 * | 424 * | |

(a) Predicted Y calculated from the regression equation
$\log Y = 1.007182 + 0.988622 \log X$.
This equation applies only to high concentrations defined as those required to produce a count greater than 50.
Data pooled from 85 mL/s and 113 mL/s (table A-14) flow rates to compute the equation.

* Valid reading but because X was less than 50, this datum was not used in the regression analysis.

Table A-16.--Count and measured concentration data for high concentrations of Jordan sand with a size range of 250-297 micrometers and with a mixture flow-rate of 50 mL/s.

Test material: Jordan sand. Temp. in degrees Celsius: 20.9.
Flow rate in mL/s: 50 . Particle diameter in micrometers: 250-297.
Method of size segregation: dry sieving.
Method of concentration measurement: gravity settling, decantation, and weighing.
Comments: None.

| X, count | Measured Y, concentration in ppm | Predicted Y, concentration in ppm(a) |
|---|---|---|
| 138 | 1245 | |
| 450 | 2655 | |
| 513 | 4005 | |
| 756 | 4500 | |

(a) Predicted Y and regression equation were not computed because of low flow-rate.

High concentrations are defined as those that produce a count greater than 50.

Table A-17.--Count and measured concentration data for high concentrations of Jordan sand with a size range of 250-297 micrometers and with a mixture flow-rate of 113 mL/s.

Test material: Jordan sand. Temp. in degrees Celsius: 20.9.
Flow rate in mL/s: 113 . Particle diameter in micrometers: 250-297.
Method of size segregation: dry sieving.
Method of concentration measurement: gravity settling, decantation, and weighing.
Comments: U-tube cleaned prior to test.

| X, count | Measured Y, concentration in ppm | Predicted Y, concentration in ppm(a) |
|---|---|---|
| 3 * | 20 * | |
| 3569 | 33802 | 33775 |
| 2223 | 21025 | 21286 |
| 1406 | 13574 | 13617 |
| 921 | 9303 | 9014 |
| 615 | 6056 | 6080 |
| 401 | 4250 | 4006 |
| 247 | 2393 | 2498 |
| 166 | 1580 | 1695 |
| 121 | 1251 | 1245 |
| 81 | 821 | 842 |
| 59 | 658 | 618 |

(a) Predicted Y calculated from the regression equation $\log Y = 1.064291 + 0.975160 \log X$. This equation applies only to high concentrations, defined as those that produce a count greater than 50.

* Valid reading but because X was less than 50, this datum was not used in the regression analysis.

Table A-18.--Count and measured concentration data for high concentrations of polydisperse Jordan sand ($D_{50} \cong 50$ microns) and with a mixture flow-rate of 50 mL/s.

Test material: Jordan sand. Temp. in degrees Celsius: 20.9.
Flow rate in mL/s: 50 .
Particle diameter in micrometers: $D_{50}$ = 135 by visual accumulation tube.
Method of segregation: None.
Method of concentration measurement: gravity settling, decantation, and weighing.
Comments: U-tube cleaned prior to test.

| X, count | Measured Y, concentration in ppm | Predicted Y, concentration in ppm(a) |
|---|---|---|
| 174 | 1430 | |
| 292 | 2520 | |
| 413 | 2950 | |
| 475 | 3500 | |
| 565 | 3890 | |
| 781 | 5970 | |
| 1107 | 8000 | |
| 1422 | 10100 | |

(a) Predicted Y and regression equation were not computed because of low flow-rate.
High concentrations are defined as those that produce a count greater than 50.

Table A-19.--Count and measured concentration data for high concentrations of Jordan sand with a size range of 104-115 micrometers and with a mixture flow-rate of 85 mL/s.

Test material: Jordan sand. Temp. in degrees Celsius: 20.9.
Flow rate in mL/s: 85 . Particle diameter in micrometers: 104-115.
Method of size segregation: dry sieving.
Method of concentration measurement: gravity settling, decantation, and weighing.
Comments: U-tube cleaned prior to test.

| X, count | Measured Y, concentration in ppm | Predicted Y, concentration in ppm[(a)] |
|---|---|---|
| 1 * | 7 * | |
| 147 | 1232 | 1229 |
| 116 | 991 | 974 |
| 87 | 722 | 734 |
| 69 | 587 | 584 |
| 57 | 473 | 484 |
| 47 * | 291 * | |
| 35 * | 308 * | |
| 29 * | 261 * | |
| 3661 | 28542 | 28969 |
| 2879 | 22828 | 22875 |
| 2222 | 17842 | 17733 |
| 1639 | 13070 | 13148 |
| 1218 | 9808 | 9821 |
| 971 | 7972 | 7860 |
| 761 | 6130 | 6186 |
| 584 | 4740 | 4769 |
| 462 | 3784 | 3788 |
| 360 | 3028 | 2964 |
| 284 | 2381 | 2348 |

(a) Predicted Y calculated from the regression equation $\log Y = 0.959322 + 0.982884 \log X$. This equation applies only to high concentrations, defined as those that produce a count greater than 50.

* Valid reading but because X was less than 50, this datum was not used in the regression analysis.

Table A-20.--Count and measured concentration data for high concentrations of Jordan sand with a size range of 74-88 micrometers and with a mixture flow-rate of 50 mL/s.

Test material: Jordan sand. Temp. in degrees Celsius: 20.9.
Flow rate in mL/s: 50 . Particle diameter in micrometers: 74-88.
Method of size segregation: dry sieving.
Method of concentration measurement: gravity settling, decantation, and weighing.
Comments: U-tube cleaned prior to test.

| X, count | Measured Y, concentration in ppm | Predicted Y, concentration in ppm.(a) |
|---|---|---|
| 374 | 2360 | |
| 625 | 4334 | |
| 1021 | 6617 | |
| 1539 | 10329 | |
| 2056 | 15058 | |
| 2808 | 19370 | |
| 4205 | 30524 | |
| 5022 | 35959 | |
| 5406 | 37403 | |
| 6891 | 44643 | |

(a) Predicted Y and regression equation were not computed because of low flow-rate.
High concentrations are defined as those that produce a count greater than 50.

Table A-21.--Count and measured concentration data for high concentrations of Jordan sand with a size range of 74-88 micrometers and with a mixture flow-rate of 113 mL/s.

Test material: Jordan sand. Temp. in degrees Celsius: 20.9.
Flow rate in mL/s: 113 . Particle diameter in micrometers: 74-88.
Method of size segregation: dry sieving.
Method of concentration measurement: gravity settling, decantation, and weighing.
Comments: U-tube cleaned prior to test.

| X, count | Measured Y, concentration in ppm | Predicted Y, concentration in ppm(a) |
|---|---|---|
| 1 * | 11 * | |
| 2771 | 22327 | 22372 |
| 2250 | 18109 | 18231 |
| 2027 | 16327 | 16453 |
| 1580 | 12952 | 12880 |
| 1257 | 10411 | 10288 |
| 980 | 8033 | 8055 |
| 775 | 6350 | 6396 |
| 616 | 5209 | 5104 |
| 412 | 3485 | 3437 |
| 332 | 2711 | 2780 |

(a) Predicted Y calculated from the regression equation $\log Y = 0.966424 + 0.982756 \log X$. This equation applies only to high concentrations, defined as those that produce a count greater than 50.

* Valid reading but because X was less than 50, this datum was not used in the regression analysis.

Table A-22.--Count and measured concentration data for high concentrations of polydisperse Jordan sand ($D_{50} \cong 120$ microns) and with a mixture flow-rate of 85 mL/s.

Test material: Jordan sand mixture. Temp. in degrees Celsius: 20.9.
Flow rate in mL/s: 85 .

| | | | | | | |
|---|---|---|---|---|---|---|
| Particle diameter in micrometers: | 350 | 250 | 175 | 125 | 88 | 62 |
| percent finer: | 98 | 78 | 67 | 56 | 28 | 5 |

Method of segregation: None.
Method of concentration measurement: gravity settling, decantation, and weighing.
Comments: U-tube cleaned prior to test.

| X, count | Measured Y, concentration in ppm | Predicted Y, concentration in ppm(a) |
|---|---|---|
| 1 * | 7 * | |
| 308 | 2768 | 2698 |
| 216 | 1918 | 1911 |
| 161 | 1420 | 1437 |
| 119 | 1066 | 1071 |
| 84 | 816 | 764 |
| 66 | 606 | 604 |
| 48 * | 461 * | |
| 35 * | 370 * | |
| 25 * | 286 * | |
| 19 * | 227 * | |
| 2342 | 19910 | 19358 |
| 1553 | 13449 | 12988 |
| 6464 | 51913 | 51900 |
| 4286 | 35094 | 34819 |
| 2942 | 24425 | 24159 |
| 2068 | 17116 | 17154 |
| 1473 | 12309 | 12337 |
| 1075 | 8925 | 9085 |
| 815 | 6763 | 6943 |
| 620 | 5230 | 5323 |
| 466 | 3932 | 4034 |
| 363 | 3082 | 3164 |
| 285 | 2388 | 2502 |

(a) Predicted Y calculated from the regression equation
$\log Y = 1.013554 + 0.971425 \log X$.
This equation applies only to high concentrations, defined as those that produce a count greater than 50.

* Valid reading but because X was less than 50, this datum was not used in the regression analysis.

Table A-23.--Count and measured concentration data for high concentrations of a bimodal population with a mixture flow-rate of 113 mL/s.

Test material: equal parts Jordan sand 710-833 and Spokane, Wash. clay. Temp. in degrees Celsius: 20.9.
Flow rate in mL/s: 113.
Particle diameter in micrometers: bimodal.
Method of size segregation: None.
Method of concentration measurement: gravity settling, decantation, and weighing.
Comments: U-tube cleaned prior to test.

| X, count | Measured Y, concentration in ppm | Predicted Y, concentration in ppm(a) |
|---|---|---|
| 1 * | 9 * | |
| 8368 | 79238 | 78912 |
| 5143 | 45798 | 48557 |
| 3284 | 31206 | 31039 |
| 2142 | 20620 | 20267 |
| 1497 | 14482 | 14176 |
| 1087 | 10713 | 10301 |
| 781 | 7563 | 7408 |
| 579 | 5571 | 5496 |
| 448 | 4176 | 4255 |
| 355 | 3334 | 3374 |
| 283 | 2605 | 2691 |

(a) Predicted Y calculated from the regression equation
$\log Y = 0.984089 + 0.997562 \log X$.
This equation applies only to high concentrations, defined as those that produce a count greater than 50.

* Valid reading but because X was less than 50, this datum was not used in the regression analysis.

Table A-24.--Count and measured concentration data for high concentrations of Spokane, Washington clay with a mixture flow-rate of 50 mL/s.

Test material: Spokane, Wash. clay. Temp. in degrees Celsius: 20.9.
Flow rate in mL/s: 50.
Particle diameter in micrometers: $D_{50}$ = 12 (pipette analysis).
Method of size segregation: tested as received.
Method of concentration measurement: gravity settling decantation, and weighing.
Comments: sediment treated with hydrogen peroxide and washed; U-tube cleaned prior to test.

| X, count | Measured Y, concentration in ppm | Predicted Y, concentration in ppm(a) |
|---|---|---|
| 1135 | 9790 | |
| 1574 | 13700 | |
| 2328 | 20300 | |
| 3111 | 26900 | |
| 3878 | 33600 | |
| 4575 | 39700 | |
| 5782 | 50000 | |
| 6524 | 56300 | |
| 7217 | 61800 | |
| 8216 | 68800 | |
| 9540 | 82500 | |
| 11763 | 97100 | |

(a) Predicted Y and regression equation were not computed because of low flow-rate.
High concentrations are defined as those that produce a count greater than 50.

Table A-25.--Count and measured concentration data for low concentrations of Spokane, Washington clay with a mixture flow-rate of 113 mL/s.

Test material: Spokane, Wash. clay. Temp. in degrees Celsius: 20.9.
Flow rate in mL/s: 113 .
Particle diameter in micrometers: $D_{50}$ = 12 (pipette analysis).
Method of size segregation: tested as received.
Method of concentration measurement: vacuum filtration at 0.54 micron and weighing.
Comments: sediment treated with hydrogen peroxide and washed; U-tube cleaned prior to test.

| U, count | Measured Y, concentration in ppm | Predicted Y, concentration in ppm(a) |
|---|---|---|
| 8 | 78 | 82 |
| 35 | 305 | 312 |
| 43 | 375 | 380 |
| 36 | 303 | 321 |
| 28 | 258 | 253 |
| 24 | 217 | 218 |
| 21 | 187 | 193 |
| 15 | 146 | 142 |
| 15 | 123 | 142 |
| 12 | 100 | 116 |
| 4 | 77 | 48 |
| 5 | 64 | 56 |
| 53 * | 479 * | |
| 46 | 414 | 406 |
| 93 * | 794 * | |
| 49 | 455 | 432 |
| 43 | 365 | 381 |
| 73 * | 596 * | |
| 78 * | 690 * | |
| 136 * | 1169 * | |
| 113 * | 989 * | |
| 82 * | 719 * | |
| 63 * | 562 * | |
| 53 * | 456 * | |
| 44 | 403 | 389 |
| 76 * | 669 * | |
| 62 * | 512 * | |

(a) Predicted Y calculated from the regression equation $Y = 13.40787 + 8.540827 X$. This equation applies only to low concentrations, defined as those that produce a count of 50 or less.

* Valid reading but because X was greater than 50, this datum was not used in the regression analysis.

Table A-26.--Count and measured concentration data for high concentrations of Salmon River sediment with a mixture flow-rate of 50 mL/s.

Test material: Little N.F. Salmon R. Temp. in degrees Celsius: 20.9.
Flow rate in mL/s: 50.

| | | | | | | |
|---|---|---|---|---|---|---|
| Particle diameter in micrometers: | 700 | 500 | 350 | 250 | 175 | 125 |
| percent finer: | 97 | 75 | 35 | 35 | 10 | 4 |

Method of size segregation: tested as received.
Method of concentration measurement: gravity settling, decantation, and weighing.
Comments: U-tube cleaned prior to test.

| X, count | Measured Y, concentration in ppm | Predicted Y, concentration in ppm(a) |
|---|---|---|
| 143 | 1161 | |
| 374 | 2348 | |
| 676 | 6170 | |
| 2267 | 16247 | |

(a) Predicted Y and regression equation were not computed because of low flow-rate.
High concentrations are defined as those that produce a count greater than 50.

Table A-27.--Count and measured concentration data for high concentrations of Salmon River sediment with a mixture flow-rate of 85 mL/s.

Test material: Little N.F. Salmon R. Temp. in degrees Celsius: 20.9.
Flow rate in mL/s: 85.

| Particle diameter in micrometers: | 700 | 500 | 350 | 250 | 175 | 125 |
|---|---|---|---|---|---|---|
| percent finer: | 97 | 75 | 35 | 35 | 10 | 4 |

Method of size segregation: tested as received.
Method of concentration measurement: gravity settling, decantation, and weighing.
Comments: U-tube cleaned prior to test.

| X, count | Measured Y, concentration in ppm | Predicted Y, concentration in ppm(a) |
|---|---|---|
| 1 * | 8 * | |
| 429 | 3506 | 4047 |
| 153 | 1482 | 1498 |
| 95 | 985 | 946 |
| 57 | 581 | 578 |
| 37 * | 390 * | |
| 23 * | 279 * | |
| 12 * | 178 * | |
| 6962 | 48044 | 59393 |
| 3871 | 33176 | 33731 |
| 2154 | 18730 | 19171 |
| 1283 | 11693 | 11634 |
| 818 | 7286 | 7539 |
| 543 | 4890 | 5079 |
| 363 | 3219 | 3445 |
| 261 | 2328 | 2507 |
| 188 | 1661 | 1827 |

(a) Predicted Y calculated from the regression equation $\log Y = 1.069671 + 0.963915 \log X$.
This equation applies only to high concentrations defined as those required to produce a count greater than 50.
Data pooled from 85 mL/s and 113 mL/s (table A-28) flow rates to compute the equation.

* Valid reading but because X was less than 50, this datum was not used in the regression analysis.

Table A-28.--Count and measured concentration data for high concentrations of Salmon River sediment with a mixture flow-rate of 113 mL/s.

Test material: Little N.F. Salmon R. Temp. in degrees Celsius: 20.9.
Flow rate in mL/s: 113 .

| Particle diameter in micrometers: | 700 | 500 | 350 | 250 | 175 | 125 |
|---|---|---|---|---|---|---|
| percent finer: | 97 | 75 | 35 | 35 | 10 | 4 |

Method of size segregation: tested as received.
Method of concentration measurement: gravity settling, decantation, and weighing.
Comments: U-tube cleaned prior to test.

| X, count | Measured Y, concentration in ppm | Predicted Y, concentration in ppm(a) |
|---|---|---|
| 7 * | 46 * | |
| 303 | 3182 | 2894 |
| 182 | 1944 | 1771 |
| 123 | 1331 | 1214 |
| 86 | 829 | 860 |
| 61 | 623 | 617 |
| 1384 | 13774 | 12516 |
| 873 | 9208 | 8027 |
| 4964 | 46986 | 42868 |
| 3236 | 30337 | 28380 |
| 898 | 9045 | 8249 |
| 634 | 6303 | 5897 |
| 469 | 4495 | 4410 |
| 329 | 3069 | 3134 |
| 253 | 2559 | 2433 |
| 194 | 1713 | 1883 |
| 159 | 1419 | 1555 |

(a) Predicted Y calculated from the regression equation $\log Y = 1.069671 + 0.963915 \log X$.
This equation applies only to high concentrations defined as those required to produce a count greater than 50.
Data pooled from 85 mL/s and 113 mL/s (table A-27) flow rates to compute the equation.

* *Valid reading but because X was less than 50, this datum was not* used in the regression analysis.

Table A-29.--Count and measured concentration data for high concentrations of Caspar Creek sediment with a mixture flow-rate of 50 mL/s.

Test material: Caspar Creek. Temp. in degrees Celsius: 20.9.
Flow rate in mL/s: 50.

| Particle diameter in micrometers: | 500 | 350 | 250 | 175 | 125 | 88 | 62 |
|---|---|---|---|---|---|---|---|
| percent finer: | 98 | 86 | 72 | 55 | 36 | 22 | 14 |

Method of size segregation: tested as received.
Method of concentration measurement: gravity settling, decantation, and weighing.
Comments: U-tube cleaned prior to test.

| X, count | Measured Y, concentration in ppm | Predicted Y, concentration in ppm(a) |
|---|---|---|
| 320 | 2457 | |
| 401 | 3217 | |
| 651 | 5198 | |
| 857 | 7352 | |
| 1375 | 10080 | |
| 2338 | 17534 | |
| 3296 | 23105 | |

(a) Predicted Y and regression equation were not computed because of low flow-rate.

High concentrations are defined as those that produce a count greater than 50.

Table A-30.--Count and measured concentration data for high concentrations of Caspar Creek sediment with a mixture flow-rate of 85 mL/s.

Test material: Caspar Creek. Temp. in degrees Celsius: 20.9.
Flow rate in mL/s: 85.

| Particle diameter in micrometers: | 500 | 350 | 250 | 175 | 125 | 88 | 62 |
|---|---|---|---|---|---|---|---|
| percent finer: | 98 | 86 | 72 | 55 | 36 | 22 | 14 |

Method of size segregation: tested as received.
Method of concentration measurement: gravity settling.
Comments: None.

| X, count | Measured Y, concentration in ppm | Predicted Y, concentration in ppm(a) |
|---|---|---|
| 4 * | 29 * | |
| 79 | 817 | 783 |
| 113 | 907 | 1108 |
| 68 | 638 | 677 |
| 47 * | 464 * | |
| 36 * | 337 * | |
| 20 * | 235 * | 207 |
| 7 * | 138 * | |
| 116 | 1568 | 1137 |
| 74 | 623 | 735 |
| 2 * | 63 * | |

(a) Predicted Y calculated from the regression equation
$\log Y = 1.054544 + 0.969316 \log X$.
This equation applies only to high concentrations defined as those required to produce a count greater than 50.
Data pooled from 85 mL/s and 113 mL/s (table A-31) flow rates to compute the equation.

* Valid reading but because X was less than 50, this datum was not used in the regression analysis.

Table A-31.--Count and measured concentration data for high concentrations of Caspar Creek sediment with a mixture flow-rate of 113 mL/s.

Test material: Caspar Creek. Temp. in degrees Celsius: 20.9.
Flow rate in mL/s: 113 .

| Particle diameter in micrometers: | 500 | 350 | 250 | 175 | 125 | 88 | 62 |
|---|---|---|---|---|---|---|---|
| percent finer: | 98 | 86 | 72 | 55 | 36 | 22 | 14 |

Method of size segregation: tested as received.
Method of concentration measurement: gravity settling, decantation, and weighing.
Comments: particle size degradation occurred during test.

| X, count | Measured Y, concentration in ppm | Predicted Y, concentration in ppm[(a)] |
|---|---|---|
| 1 * | 5 * | |
| 3997 | 36212 | 35137 |
| 3102 | 27757 | 27482 |
| 2471 | 22604 | 22045 |
| 1925 | 17171 | 17306 |
| 1539 | 13869 | 13931 |
| 1255 | 11647 | 11432 |
| 1022 | 9317 | 9368 |
| 811 | 7396 | 7487 |
| 670 | 6149 | 6222 |
| 426 | 3938 | 4011 |
| 299 | 2830 | 2846 |
| 165 | 1551 | 1600 |
| 136 | 1283 | 1326 |
| 96 | 928 | 946 |

(a) Predicted Y calculated from the regression equation $\log Y = 1.054544 + 0.969316 \log X$.
This equation applies only to high concentrations defined as those required to produce a count greater than 50.
Data pooled from 85 mL/s and 113 mL/s (table A-30) flow rates to compute the equation.

* Valid reading but because X was less than 50, this datum was not used in the regression analysis.

Table A-32.--Count and measured concentration data for high concentrations of sodium-chloride solution with a mixture flow-rate of 50 mL/s.

Test material: sodium chloride. Temp. in degrees Celsius: 20.9.
Flow rate in mL/s: 50.
Particle diameter in micrometers: (solution).
Method of size segregation: not applicable.
Method of concentration measurement: computed from quantity added to recirculation loop.
Comments: U-tube cleaned prior to test.

| X, count | Measured Y, concentration in ppm | Predicted Y, concentration in ppm[a] |
|---|---|---|
| 64 | 499 | 519 |
| 124 | 999 | 1004 |
| 604 | 4975 | 4856 |
| 1195 | 9900 | 9580 |

(a) Predicted Y calculated from the regression equation

$$\log Y = 0.916974 + 0.995786 \log X.$$

This equation applies only to high concentrations defined as those required to produce a count greater than 50.

Data pooled from 50 mL/s and 113 mL/s (table A-33) flow rates to compute the equation.

Table A-33.--Count and measured concentration data for high concentrations of sodium-chloride solution with a mixture flow-rate of 113 mL/s.

Test material: sodium chloride. Temp. in degrees Celsius: 20.9.
Flow rate in mL/s: 113.
Particle diameter in micrometers: (solution).
Method of size segregation: not applicable.
Method of concentration measurement: computed from quantity added to recirculation loop.
Comments: U-tube cleaned prior to test.

| X, count | Measured Y, concentration in ppm | Predicted Y, concentration in ppm(a) |
|---|---|---|
| 70 | 596 | 568 |
| 125 | 1000 | 1012 |
| 259 | 2074 | 2090 |
| 509 | 4067 | 4095 |
| 770 | 6129 | 6184 |
| 1275 | 10143 | 10219 |
| 2537 | 20177 | 20274 |
| 3751 | 29792 | 29927 |
| 4969 | 39428 | 39597 |
| 6127 | 48574 | 48782 |

(a) Predicted Y calculated from the regression equation $\log Y = 0.916974 + 0.995786 \log X$.
This equation applies only to high concentrations defined as those required to produce a count greater than 50.
Data pooled from 85 mL/s and 113 mL/s (table A-32) flow rates to compute the equation.

Table A-34.--Count and measured concentration data for low concentrations of sodium-chloride solution and for a mixture flow-rate of 113 mL/s.

Test material: sodium chloride.
Flow rate in mL/s: 113.
Particle diameter in micrometers: (solution).
Method of size segregation: not applicable.
Method of concentration measurement: computed from quantity added to recirculation loop.
Comments: U-tube cleaned prior to test.

| X, count | Measured Y, concentration in ppm | Predicted Y, concentration in ppm(a) |
|---|---|---|
| 5 | 47 | 45 |
| 12 | 92 | 102 |
| 19 | 153 | 159 |
| 24 | 199 | 200 |
| 28 | 247 | 233 |
| 35 | 294 | 290 |
| 40 | 332 | 331 |
| 44 | 378 | 364 |
| 52 | 419 | 429 |
| 57 | 464 | 470 |

(a) Predicted Y calculated from the regression equation
$Y = 3.921632 + 8.182860 X$.
This equation applies only to low concentrations, defined as those that produce a count of 50 or less.

## PART B

# DISSOLVED-SOLIDS COMPENSATION

by

J. P. Beverage

## INTRODUCTION

The action of the vibrating U-tube, liquid-density gage described in Part A is similar to that of a pendulum: the period of vibration is directly proportional to the mass of the tube and the mass density of the liquid within the tube. The tube's mass is constant, but the mass of the liquid varies with the quantities of the entrained sediments, dissolved materials, and the temperature of the liquid. The raw instrument reading (count) can be used to give a first estimate of the sediment concentration. This estimate can be refined if the water temperature and the concentration of dissolved solids (CDS) are known. The need to correct for changes in CDS is related to the desired accuracy of the suspended-sediment measurement. If changes in CDS are much more than a small fraction of the sediment concentration, the mass-density measurement must be corrected or compensated. This part of the report will describe some of the approaches for estimating or compensating for dissolved solids; the errors inherent in each approach will be discussed.

## CONDUCTANCE AND DISSOLVED SOLIDS

Conductance, a measure of water's ability to transmit an electrical current, varies with temperature and dissolved salts. Because dissolved salts become ionized in water and because ions support electrical current, conductivity should be an index of the concentration of dissolved solids. As the temperature increases, the activity of the ionized salts increases, which increases the conductivity. Because of the temperature dependence, conductivity is usually expressed in terms of specific conductance in micromhos per centimeter (μmho/cm) at 25° Celsius. (See Hem, 1970, p. 96, for a description of units.) The terms conductance and conductivity will be used interchangeably with specific conductance through the remainder of this report and will be symbolized by K.

Hem (1970, pp. 96-103) discusses specific conductance and its relation to dissolved solids. He states (p. 99): "Natural waters are not simple solutions. They contain a variety of both ionic and undissociated species, and the amounts and proportions of each may range widely. When applied to natural water, therefore, the conductance determination cannot be expected to be simply related to ion concentrations or to total dissolved solids, and a rigorous theoretical development of the meaning of conductivity values is rarely justifiable. The determination is easily made, however, and gives results which are very useful in a practical way as general indications of dissolved-solids concentration or as a base for extrapolating other analytical data when the general characteristics of the solution already are known from previous work."

Having stated his caveat, Hem shows the K-CDS relation for composite samples of the Gila River at Bylas, Arizona for the 1944 water year. He states (p. 99) that, "A reasonably well-defined relationship is indicated for the range (in concentration)," which varied from about 300 to 3300 milligrams per liter (mg/L).

In this example, he concludes the CDS value can be obtained from a K value, "with an uncertainty of only about ± 100 mg/L." Because Hem's value was approximate, this writer computed a $S_e$ (standard error of estimate) of 28 mg/L from the published data. All of the published CDS values were within ± 70 mg/L of the regression line. These results certainly encourage further study.

To assess the accuracy of a laboratory conductivity meter, the conductance of 1,000-μmho/cm conductivity water was measured every 5° from 0° to 30° C. The value of the standard error of prediction, $S_p$, was 5.24 μmhos/cm, which was equivalent to about 2.7 mg/L of dissolved solids. Automatic field measurements generally cannot match this level of accuracy.

## DISSOLVED-SOLIDS COMPENSATION SCHEMES

When selecting a dissolved-solids compensation scheme, four obvious options come to mind:

a) Ignore the correction. This approach is acceptable when the dissolved-solids concentration is much less than the sediment concentration.

b) Use a conductivity measurement to estimate CDS with a constant CDS/K ratio or an empirically determined linear (CDS = a + bK) or multivariate (CDS = a + bK + cQ....) equation, or even a seasonally adjusted relation.

c) Use periodic samples to adjust the K-CDS relation and estimate intervening CDS from the K measurements. Collection period for the samples might vary between once daily and once each maintenance visit.

d) Determine a CDS correction each time the sediment concentration is determined. This is the ideal approach, especially if the instrument can be configured to determine CDS and to compensate automatically for it.

The best scheme at a given site might well be a combination of some of these options. For example, an early configuration of the instrument determined dissolved solids once every three hours. Intermediate density measurements could be corrected by means of specific conductivity measurements and an updated K-CDS relation.

Of the four dissolved-solids compensation schemes considered, the first (ignoring the correction) is the simplest and has the most potential for error. However, the error is biased because some dissolved salts are always present. By not correcting, the apparent sediment concentration will be too high. As stated earlier, this approach will succeed only if the dissolved-solids concentration is much less than the suspended-sediment concentration (CSED) and is relatively constant.

The second scheme involves several choices. The first of these uses a constant CDS/K ratio. The mean ratio of all 1355 analyses examined in Table B-1 was 0.6455, the same value (0.65 ± 0.1) given by Rainwater and Thatcher (1960, p. 84). However, if this value is used at a site with a very high ratio (such as the 0.96 given by Hem, 1970, p. 99), computed values of CDS could be almost 50 percent too low. A sample computation will help to illustrate the possible errors. Let's assume a K value of 700 μmho/cm in a stream carrying 50 mg/L suspended sediment. If CDS/K = 0.65, the estimate of dissolved-solids concentration is 455 mg/L. If the stream in truth had a CDS/K = 0.96, the best estimate would be 672 mg/L for CDS. The difference in the two estimates of CDS is 217 mg/L, or four times the assumed sediment concentration value attributable to the CDS compensation scheme. The sediment concentration should be more than 10 times the potential error in CDS in order to minimize that error. That is, CSED should be greater than 2,200 mg/L in this instance. Obviously, if a stream's CDS/K ratio was known to be equal to 0.96, that value should be used. We seek here only to estimate the possible error when assuming a wrong CDS/K ratio.

Another possibility within the second scheme, that of using a simple linear regression, holds much promise for many streams. Table B-1 summarizes pertinent data for 43 station years of published records for 26 stations throughout the central and western United States from 1944 through 1970. Most of the analyses are for composites of 10 or 11 daily samples. Some of the composites are for shorter periods, especially during periods of varying discharge. A glance at the table shows the magnitude of the station-to-station variations. Mean annual dissolved-solids concentrations range from 203 to 13,320 mg/L, for instance. Of more immediate importance, however, are the year-to-year variations at stations with several years of data.

The concept of temporal consistency at a site was tested at eight of the multi-year sites. The first year's linear K-CDS regression equation was used to compute the dissolved-solids concentration, $CDS_c$, of each analysis in subsequent years. For each site, an error histogram was prepared for $\Delta CDS = CDS_c - CDS$. These histograms are given in figures B-1 through B-8. The zero of the abscissa in each figure is at the composite $\overline{CDS}$ value for the estimated years. In figure B-1, for example, the zero on the abscissa represents the mean of all the published CDS values in 1965 and 1967. In figure B-6, the computed values are all

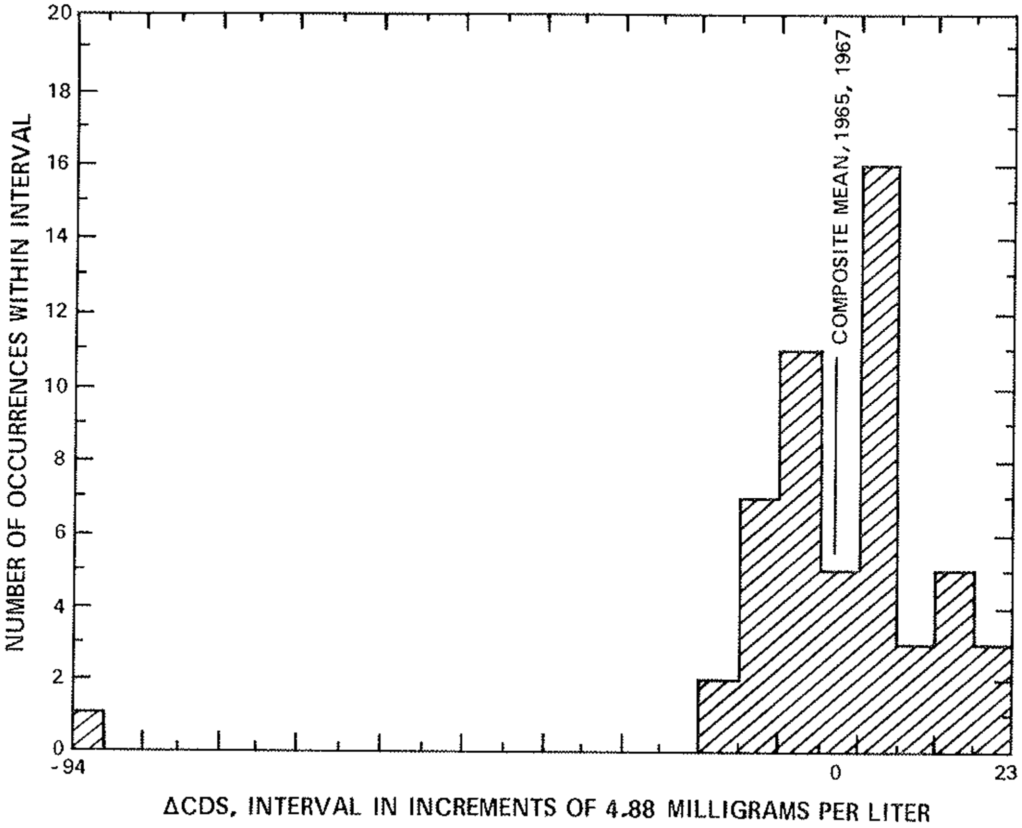

Figure B-1.--Error histogram for Yellowstone River at Billings, Mont., for water years 1965 and 1967 computed from 1955 K-CDS relation.

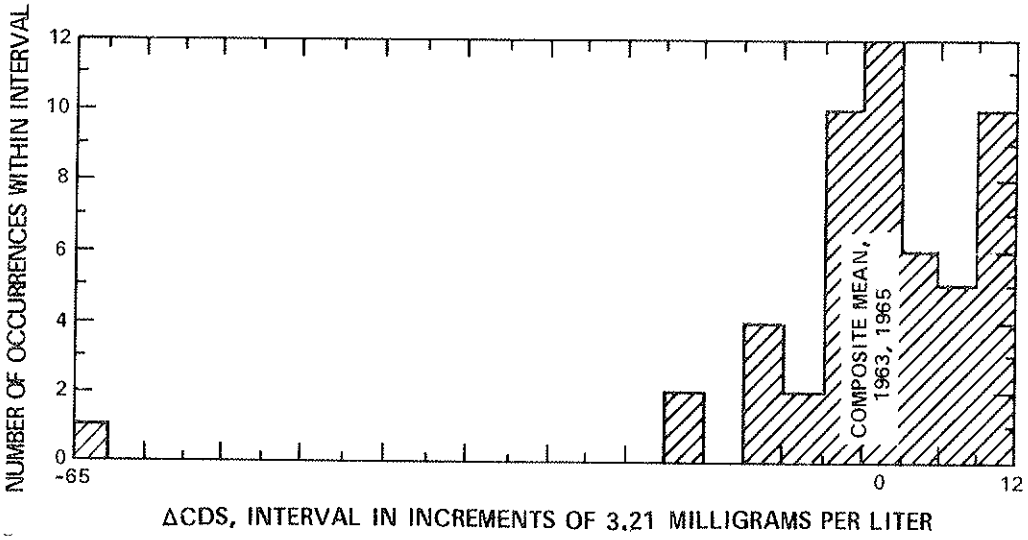

Figure B-2.--Error histogram for Missouri River at Nebraska City, Nebr., for water years 1963 and 1965 computed from 1955 K-CDS relation.

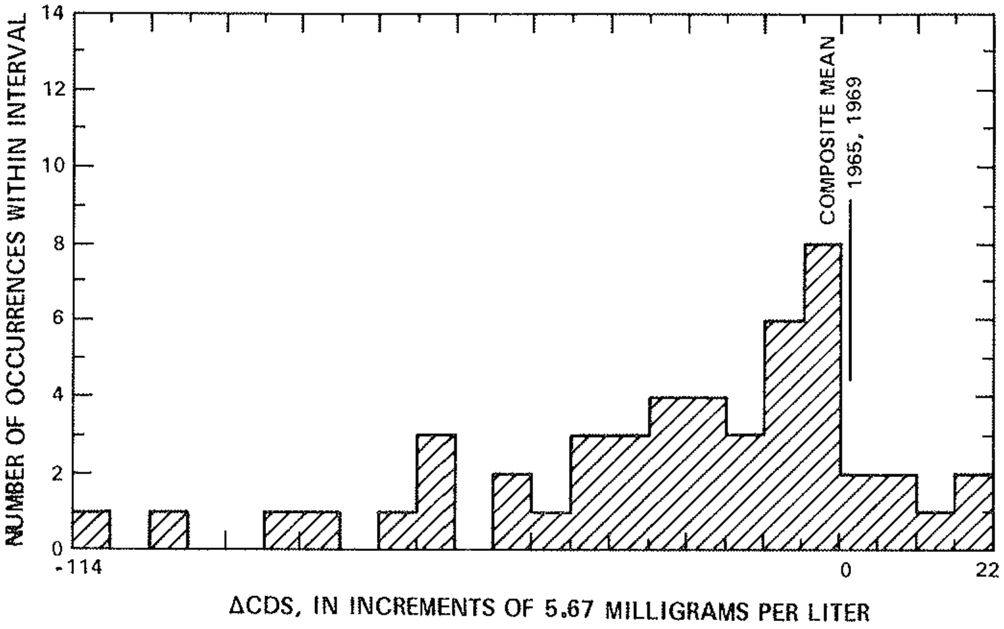

Figure B-3.--Error histogram for the Saline River at Tescott, Kans., for water years 1965 and 1969 computed from 1963 K-CDS relation.

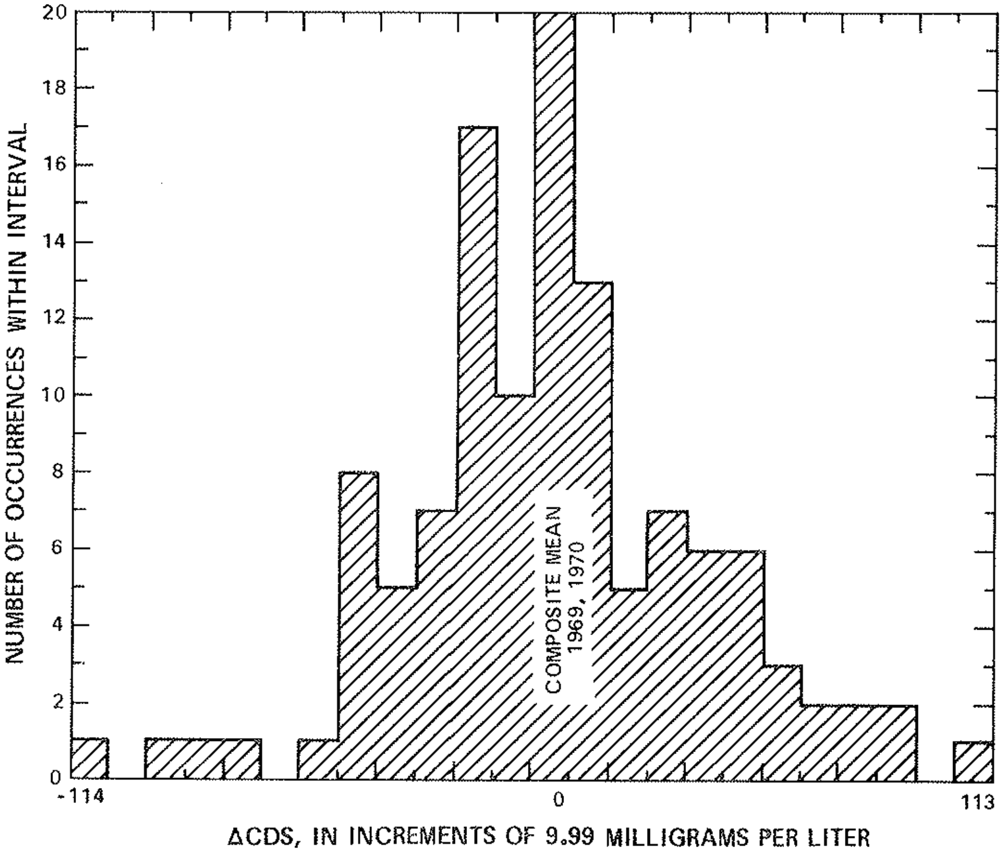

Figure B-4.--Error histogram for the Arkansas River at Arkansas City, Kans., for water years 1969 and 1970 computed from 1967 K-CDS relation.

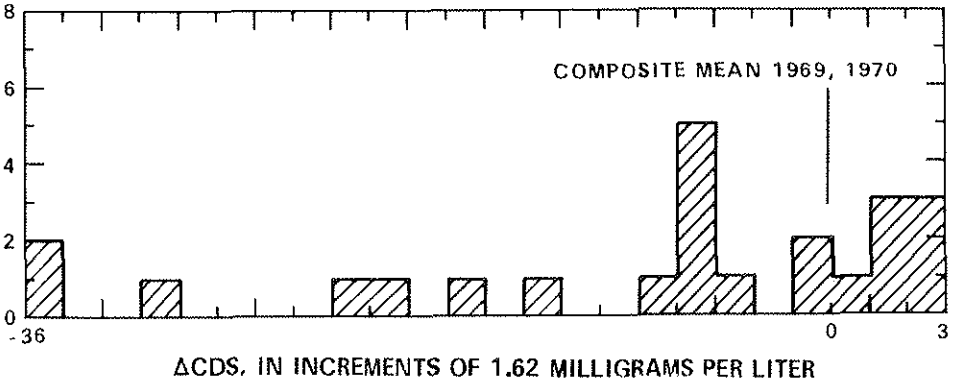

Figure B-5.--Error histogram for the Mississippi River at Luling Ferry, La., for water years 1969 and 1970 computed from 1967 K-CDS relation.

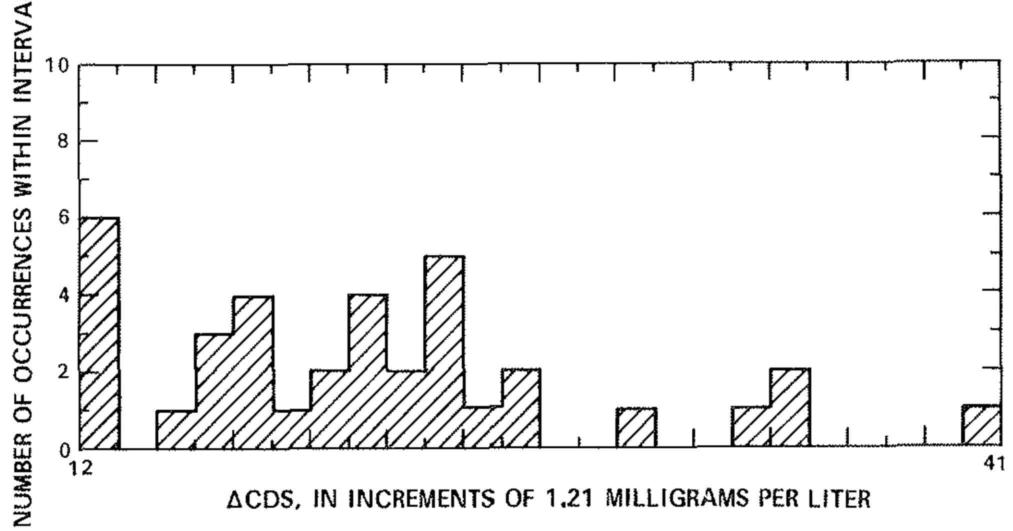

Figure B-6.--Error histogram for the Colorado River near Wharton, Tex., for water years 1965 and 1967 computed from the 1944 K-CDS relation. Note that the composite mean CDS for 1965 and 1967 was less than the left margin and is not shown.

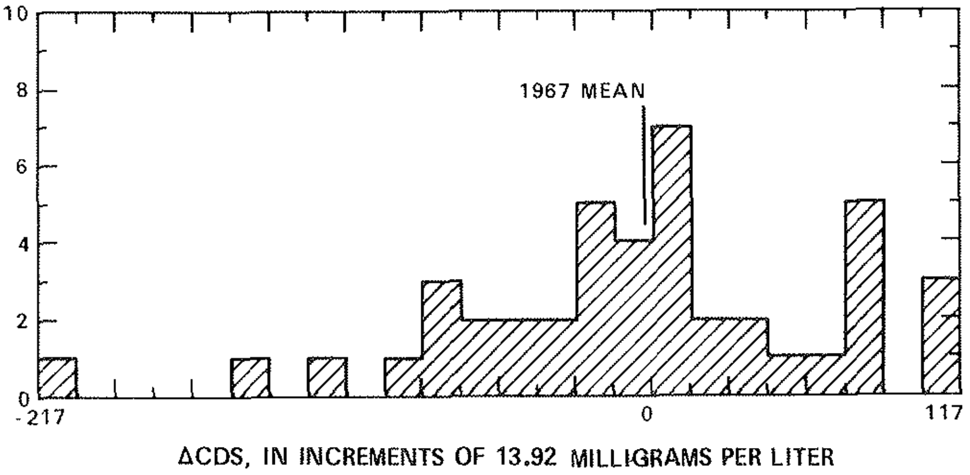

Figure B-7.--Error histogram for the Rio Grande Conveyance Channel at San Marcial, N. Mex., for the 1967 water year computed from the 1965 K-CDS relation.

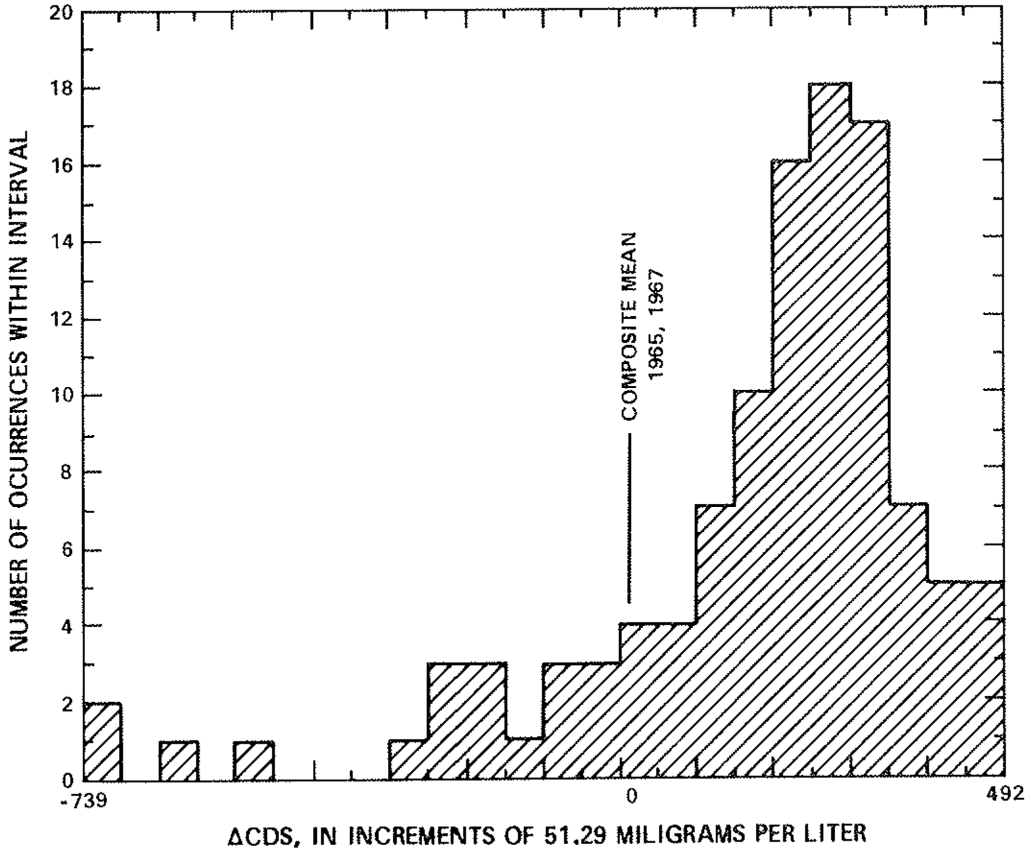

Figure B-8.--Error histogram for Pecos River at Artesia, N. Mex., for water years 1965 and 1967 computed from the 1944 K-CDS relation.

greater than the composite $\overline{\text{CDS}}$, and thus all values plot to the right of the zero which isn't shown.

The error histograms document a remarkable temporal consistency, although more than twenty years separates the base year's K-CDS relation from the estimated data in two cases (figs. B-6 and B-8). The spread from minimum to maximum $\Delta\text{CDS}$ values ranges from about 5 to about 25 percent of the mean annual dissolved-solids concentration, $\overline{\text{CDS}}$. The modal $\Delta\text{CDS}$ values at all eight stations are within 5 percent of the composite $\overline{\text{CDS}}$ for the estimated years, and three of the modes are within 0.25 percent of the composite $\overline{\text{CDS}}$. The Pecos River station (fig. B-8) is the worst of the group; its modal $\Delta\text{CDS}$ value of 250 mg/L is just under 5 percent of the composite $\overline{\text{CDS}}$. The Missouri River station (fig. B-2) is the most stable of the group; 51 of the 52 $\text{CDS}_c$ values are within 5 percent of the measured value, and the $\Delta\text{CDS}$ mode is only 0.17 percent of the composite $\overline{\text{CDS}}$. In other words, using the K-CDS relation for 1955 gave an error larger than 15 mg/L only once in the two years (1963, 1965) of estimated record. During this period, CDS values ranged from 258 to 579 mg/L. The invariability with time at this site is probably the result of the large, fairly uniform drainage with several large reservoirs. The Colorado River at Wharton, Texas (fig. B-6) is an example of a stream showing a slight shift in the K-CDS relation. All of the estimates were too high, by amounts from 12 to 41 mg/L; but 31 of 36 estimates were within the range from 12 to 27 mg/L greater than the measured CDS. In this instance, adding 20 mg/L to the estimated CDS would bring 86 percent of the estimates to within 8 mg/L of the measured CDS. More than twenty years elapsed between the base year and the test years.

The following table quantifies the difference between estimated and actual composite $\overline{\text{CDS}}$ values for the eight stations in figures B-1 through B-8:

| Fig. | River | Site | State | Estimate composite $\overline{\text{CDS}}$ (mg/L) | Actual composite $\overline{\text{CDS}}$ (mg/L) | Percentage difference |
|---|---|---|---|---|---|---|
| B-1 | Yellowstone | Billings | Mont. | 220.4 | 220.6 | 0.091 |
| B-2 | Missouri | Nebraska City | Neb. | 444.4 | 444.3 | - .023 |
| B-3 | Saline | Tescott | Kan. | 1450. | 1475. | 1.69 |
| B-4 | Arkansas | Arkansas City | Kan. | 886.8 | 886.6 | - .023 |
| B-5 | Mississippi | Luling Ferry | La. | 250.1 | 260.0 | 3.81 |
| B-6 | Colorado | Wharton | Tex. | 290.7 | 269.4 | -7.91 |
| B-7 | Rio Grande | San Marcial | N. Mex. | 799.5 | 800.3 | .100 |
| B-8 | Pecos | Artesia | N. Mex. | 5404. | 5247. | -2.99 |

Excepting the Colorado River station (fig. B-6), these differences are less than 4 percent. As noted in the preceding paragraph, the Colorado River station would be improved by adding 20 mg/L to the estimated CDS values. In this manner the difference between composite means would be less than one-half percent. The cause of this shift of the K-CDS relation is not known; nor is it known whether the shift is permanent.

A natural stream contains a mixture of salts. The relative mixture depends on the geology and geography of the upstream watershed, on the distribution and intensity of precipitation, on the contribution from ground water, and on man's activities. Uniform geology and geography upstream from a site will normally give a stability to the K-CDS relation for the runoff at the site. At such sites, a single relation should suffice for several years. Other streams might require a seasonal K-CDS relation, or possibly a complex melding of relations depending on the relative contribution of upstream tributaries.

The third and fourth dissolved-solids compensation schemes (using a periodic sample with a K-CDS relation and determining a CDS correction for each analysis) are most simply tested in the field. As these schemes are more expensive, they will find use at sites where the $\overline{CDS/K}$ ratio or the K-CDS relation is in doubt, or not sufficiently accurate.

Errors due to dissolved solids can be separated into random and systematic types. Random errors can be minimized by averaging many measurements at similar dissolved-solids and sediment concentrations. Systematic errors bias measurements in one direction only, although at times one may partially cancel another. Systematic errors are generally reduced by suppression at the source. A systematic bias in dissolved-solids concentrations can arise in the K-CDS relation, the determination of CDS, or the conductivity meter. We have discussed the first; and the latter two are a matter of laboratory technique. The accuracy of the conductivity measurement is dependent on the quality of the instrument, the care taken in its use, and in the frequency of recalibration. Typical accuracies for conductivity meters are on the order of one to three percent. These accuracies can be maintained only with a regular schedule of probe cleaning and recalibration.

Table B-2 lists minimum daily sediment concentrations and the approximate concomitant dissolved-solids concentration for some of the stations listed in Table B-1. The typical pattern is for dissolved-solids concentrations to be high when sediment concentrations are low. Unfortunately, the least accurate estimates of dissolved-solids correction may occur at low sediment concentration where the error in the correction can easily exceed the sediment concentration itself. For the data shown, the standard error of prediction of CDS varies from about 1.2 to 38 times the minimum sediment concentration, $CSED_{min}$. Two-thirds of the $S_p$ values were less than 2.1 times $CSED_{min}$. For these lower ratios, an increase in the number of maintenance and inspection visits, and therefore in the number of check samples can provide the increased accuracy needed to compute an acceptably accurate dissolved-solids correction for instances where CSED is low and CDS is high. For high $S_p$/CSED ratios, a scheme to compensate for the dissolved solids in each measurement should be adopted.

Table B-1.--Dissolved solids concentrations (CDS) for selected river stations and water years. Maximum and minimum values are from published data. Coefficients a and b are for the regression equation CDS = a + bK. The sample size is n. The values $\overline{K}$ and $\overline{CDS}$ are simple annual means and are not discharge-weighted as usually published. $S_{pmax}$ is the maximum standard error of prediction during the period. All concentrations are in mg/L.

| Water year | River | Location | State | Dissolved solids concentration | | n | a | b | $\overline{K}$ | $\overline{CDS}$ | $S_{pmax}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | max | min | | | | | | |
| 1963 | Red (North) | Fargo | N. Dak. | 492 | 305 | 28 | - 7.291 | 0.6667 | 602.1 | 394.2 | 23.6 |
| 1965 | do. | do. | do. | 415 | 196 | 21 | - 8.390 | .6296 | 488.5 | 299.1 | 22.3 |
| 1955 | Sheyenne | Warwick | N. Dak. | 1,230 | 223 | 37 | - 22.14 | .6851 | 1,043 | 692.2 | 13.7 |
| 1963 | Mississippi | Anoka | Minn. | 248 | 163 | 20 | 59.02 | .4550 | 326.2 | 207.4 | 9.51 |
| 1965 | Chippewa | Milan | do. | 657 | 385 | 11 | - 11.60 | .6948 | 771.4 | 524.4 | 24.3 |
| 1965 | Minnesota | Carver | do. | 673 | 390 | 11 | 35.23 | .6167 | 795.4 | 525.9 | 17.3 |
| 1944 | Iowa | Iowa City | Iowa | 402 | 167 | 27 | - 7.004 | .6389 | 473.9 | 295.8 | 7.84 |
| 1955 | Des Moines | Des Moines | do. | 584 | 256 | 18 | - 15.64 | .6710 | 619.3 | 399.9 | 12.4 |
| 1955 | Yellowstone | Billings | Mont. | 472 | 110 | 28 | - 3.259 | .6539 | 385.9 | 249.1 | 10.6 |
| 1965 | do. | do. | do. | 460 | 94 | 27 | 2.319 | .6483 | 365.8 | 239.5 | 22.7 |
| 1969 | do. | do. | do. | 311 | 78 | 26 | - 9.622 | .6663 | 318.8 | 202.8 | 8.27 |
| 1963 | Missouri | Williston | N. Dak. | 586 | 296 | 26 | 14.92 | .6477 | 694.9 | 465.0 | 18.3 |
| 1965 | do. | do. | do. | 582 | 262 | 23 | - 19.94 | .6912 | 671.2 | 444.0 | 6.05 |
| 1955 | Missouri | Nebraska City | Nebr. | 532 | 341 | 25 | - 43.64 | .7257 | 699.6 | 464.1 | 5.04 |
| 1963 | do. | do. | do. | 556 | 360 | 17 | 42.54 | .6125 | 740.3 | 495.9 | 15.7 |
| 1965 | do. | do. | do. | 579 | 258 | 35 | - 24.89 | .6945 | 639.5 | 419.3 | 6.95 |
| 1955 | Republican | Cambridge | do. | 414 | 204 | 28 | - 26.23 | .7114 | 506.6 | 334.2 | 10.6 |
| 1963 | Saline | Tescott | Kans. | 2,620 | 434 | 17 | 23.80 | .5735 | 2,426 | 1,415 | 85.9 |
| 1965 | do. | do. | do. | 3,560 | 200 | 36 | 29.13 | .5817 | 2,588 | 1,535 | 21.7 |
| 1969 | do. | do. | do. | 2,340 | 202 | 13 | 11.25 | .5883 | 2,206 | 1,309 | 45.9 |
| 1967 | Arkansas | Arkansas City | do. | 4,090 | 273 | 54 | - 7.361 | .6107 | 1,783 | 1,081 | 43.8 |
| 1969 | do. | do. | do. | 1,560 | 197 | 76 | - 3.588 | .6055 | 1,315 | 792.4 | 32.2 |
| 1970 | do. | do. | do. | 1,580 | 173 | 53 | - 16.97 | .6177 | 1,681 | 1,022 | 44.4 |
| 1974 | Canadian | Sanchez | N. Mex. | 1,570 | 272 | 39 | -105.8 | .8108 | 1,404 | 1,033 | 14.8 |
| 1944 | Red | Gainesville | Tex. | 4,790 | 757 | 20 | -217.0 | .6710 | 3,884 | 2,389 | 90.5 |

Table B-1. (Cont'd)

| Water year | River | Location | State | Dissolved solids concentration max | Dissolved solids concentration min | n | a | b | $\overline{K}$ | $\overline{CDS}$ | $S_{pmax}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1967 | Mississippi | Luling Ferry | La. | 328 | 175 | 34 | 8.712 | 0.5691 | 412.6 | 243.5 | 4.97 |
| 1969 | do. | do. | do. | 302 | 172 | 11 | 24.45 | .5666 | 412.0 | 257.9 | 19.6 |
| 1970 | do. | do. | do. | 309 | 192 | 9 | - 35.80 | .7000 | 424.0 | 261.0 | 23.5 |
| 1944 | Brazos | South Bend | Tex. | 6,350 | 431 | 56 | - 17.79 | .5838 | 4,886 | 2,834 | 132. |
| 1944 | Colorado | Wharton | do. | 323 | 229 | 17 | 23.23 | .5561 | 472.7 | 286.1 | 9.79 |
| 1955 | Colorado | Wharton | do. | 345 | 163 | 21 | 17.88 | .5194 | 470.7 | 262.4 | 8.47 |
| 1967 | do. | do. | do. | 356 | 183 | 15 | 8.114 | .5471 | 495.6 | 279.3 | 5.20 |
| 1944 | Rio Grande | San Acacia | N. Mex. | 1,030 | 216 | 38 | - 27.11 | .7028 | 709.1 | 471.3 | 15.0 |
| 1965 | Rio Grande | San Marcial | do. | 1,360 | 275 | 35 | - 32.49 | .7049 | 924.0 | 618.8 | 41.8 |
| 1967 | do. | do. | do. | 1,700 | 386 | 43 | -149.4 | .8046 | 1,180 | 800.3 | 64.1 |
| 1944 | Pecos | Artesia | do. | 7,970 | 2,290 | 40 | 340.5 | .6824 | 5,887 | 4,358 | 113. |
| 1965 | do. | do. | do. | 14,700 | 478 | 66 | 154.8 | .6809 | 6,502 | 4,582 | 221. |
| 1967 | do. | do. | do. | 17,500 | 1,260 | 45 | 25.25 | .7044 | 8,766 | 6,200 | 268. |
| 1944 | Toyah | Pecos | Tex. | 18,500 | 882 | 40 | -649.0 | .7734 | 17,950 | 13,230 | 542. |
| 1944 | Colorado | Glenwood Springs | Colo. | 623 | 117 | 37 | 6.820 | .5709 | 667.2 | 393.6 | 6.00 |
| 1944 | San Juan | Ship Rock | N. Mex. | 691 | 115 | 36 | - 20.91 | .7045 | 646.6 | 434.6 | 9.76 |
| 1944 | Colorado | Lees Ferry | Ariz. | 1,250 | 223 | 36 | - 38.17 | .7060 | 1,210 | 816.2 | 12.6 |
| 1944 | Gila | Solomonville | do. | 731 | 217 | 38 | 49.77 | .5447 | 901.0 | 540.6 | 9.96 |

Table B-2.--Annual minimum sediment concentration and concomitant dissolved solids concentration for selected stations in Table B-1. All concentrations are in mg/L.

Column A is the mean daily sediment concentration, column B is the dissolved-solids at time of minimum daily sediment concentration.
The CDS ratio is column B divided by column A.
The $S_{pmax}$ ratio is the maximum standard error of prediction of dissolved-solids concentration divided by column A.

| River | Location | State | Year | $CSED_{min}$ (A) | CDS (B) | CDS Ratio | $S_{pmax}$ Ratio |
|---|---|---|---|---|---|---|---|
| Iowa | Iowa City | Iowa | 1944 | 5 | 402 | 80 | 1.6 |
| Des Moines | Des Moines | do. | 1955 | 5 | 860 | 172 | 2.1 |
| Saline | Tescott | Kans. | 1963 | 10 | 1,550 | 155 | 8.6 |
| do. | do. | do. | 1965 | 18 | 1,930 | 107 | 1.2 |
| do. | do. | do. | 1969 | 5 | 1,440 | 288 | 9.2 |
| Arkansas | Arkansas City | do. | 1965 | 23 | 1,250 | 54 | 1.9 |
| do. | do. | do. | 1969 | 25 | 1,450 | 58 | 1.3 |
| do. | do. | do. | 1970 | 31 | 1,580 | 51 | 1.4 |
| Rio Grande | San Marcial | N. Mex. | 1965 | 25 | 564 | 23 | 1.7 |
| do. | do. | do. | 1967 | 35 | 730 | 21 | 1.8 |
| Pecos | Artesia | do. | 1965 | 9 | 4,000 | 444 | 25 |
| do. | do. | do. | 1967 | 7 | 6,430 | 919 | 38 |

# CONCLUSIONS

1) At some sites, the K-CDS relation demonstrates a remarkable temporal consistency, often remaining constant for decades.

2) The accuracy of conductivity-derived dissolved-solids corrections depends upon the relative magnitude of CSED and CDS. When CSED is high and CDS is low, the condition occurs during the most significant storm events, using a reasonably accurate K-CDS relation can give an accurate compensated sediment concentration.

3) Even though a K-CDS relation is generally accurate, when low sediment concentrations coincide with high dissolved-solids concentrations, the error in the dissolved-solids correction easily can exceed several multiples of the sediment concentration. When this is the case, the usual persistence of the low sediment concentration period allows collection of several manual samples which will improve the estimate of average sediment concentration.

4) The precise determination of individual sediment concentrations for the high CDS - low CSED case can be achieved only when both are measured simultaneously.

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# PART C

# DESCRIPTION OF MEASURING ELECTRONICS

by

J. P. Beverage and J. V. Skinner

## INTRODUCTION

The density-gage purchased from the manufacturer included an electronics unit that contained an analog-meter output display. The meter had a 0 to 100 scale, with full scale corresponding to a sediment concentration of about 50,000 mg/L. The special measuring electronics designed by the authors has a much greater concentration range and maintains good resolution throughout the range. It is possible to convert the analog output to a digital output, but the direct digital measurement eliminates conversion errors. The other major reason for designing special circuits was the concern for exciting the drive coil only at the resonant freqquency. A description of the instrument should help the reader understand the concept.

The closed end of the U-tube is mechanically coupled to the center of a rod (fig. C-1). Each end of the rod supports an armature for a fixed electromagnetic coil. An electric current supplied to one coil, the drive coil, induces motion in the armature and this motion is transmitted to the U-tube and the sense-coil armature. Movement of the sense-coil armature induces a voltage in its coil. This voltage is a function of the velocity of the tube. A sinusoidal current in the drive coil will exert a sinusoidal force on the tube and thereby induce a sinusoidal voltage in the sense coil. Once set into vibration the tube stabilizes at its natural frequency. The factory electronic unit supplies a 20-volt, square-wave voltage signal at the resonant frequency. A square wave contains a fundamental frequency and all odd multiples of that fundamental. The drive-coil force is proportional to drive-coil current. Current harmonics are suppressed (but not eliminated) by the self-inductance of the drive-coil. To minimize possible mechanical harmonic vibrations, the

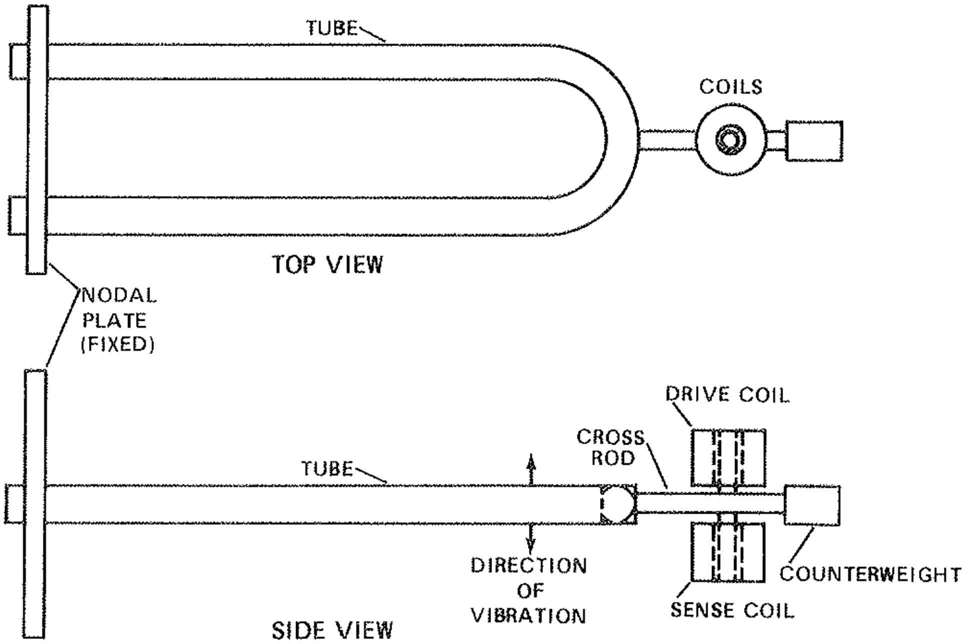

Figure C-1.--Schematic drawing of vibrating U-tube.

authors designed the special electrical feedback loop which suppressed harmonics by generating a sinusoidal drive-coil voltage. To minimize the effect of all electrical and mechanical nonlinearities in the relations between current, voltage, force, and displacement, the drive-coil voltage was regulated at a low amplitude of only a few volts.

The range of densities, which can be measured with one set of electrical components in the feedback loop is illustrated in figure C-2. Water and other denser fluids were used. The upper point represents an equivalent sediment concentration of 683,000 mg/L, which is beyond the concentration of most streams (Beverage and Culbertson, 1964). The average period of vibration was measured by a separate electronic instrument.

To summarize, the special electronics circuits were designed to improve the instrument in three areas: (1) extend the concentration range (without switching electrical components), (2) change the display from analog to digital, and (3) reduce the possibility of higher order mechanical harmonics. These electronics circuits allow the instrument to measure equivalent sediment concentration from 0 to more than 600,000 mg/L.

This report describes the special circuits developed to make the desired improvements in the instrument.

## FEEDBACK CIRCUIT

The feedback circuit (fig. C-3) amplifies and filters the sense-coil voltage. The conditioned signal is impressed across the drive coil and causes the U-tube to vibrate at its resonant frequency.

The primary feedback loop consists of amplifiers 1, 2, and 3. Amplifier 1 increases the sense-coil voltage 100 times, and also attenuates (filters) spurious, high-frequency variations in the sense-coil voltage. Amplifier 2 is connected to the output of an analog multiplier which combines the signal from amplifier 1 and the output from the automatic-gain control (AGC) loop (discussed below). The output of amplifier 2 passes through a high-pass (DC-blocking) filter to amplifier 3, which is a unity-gain buffer.

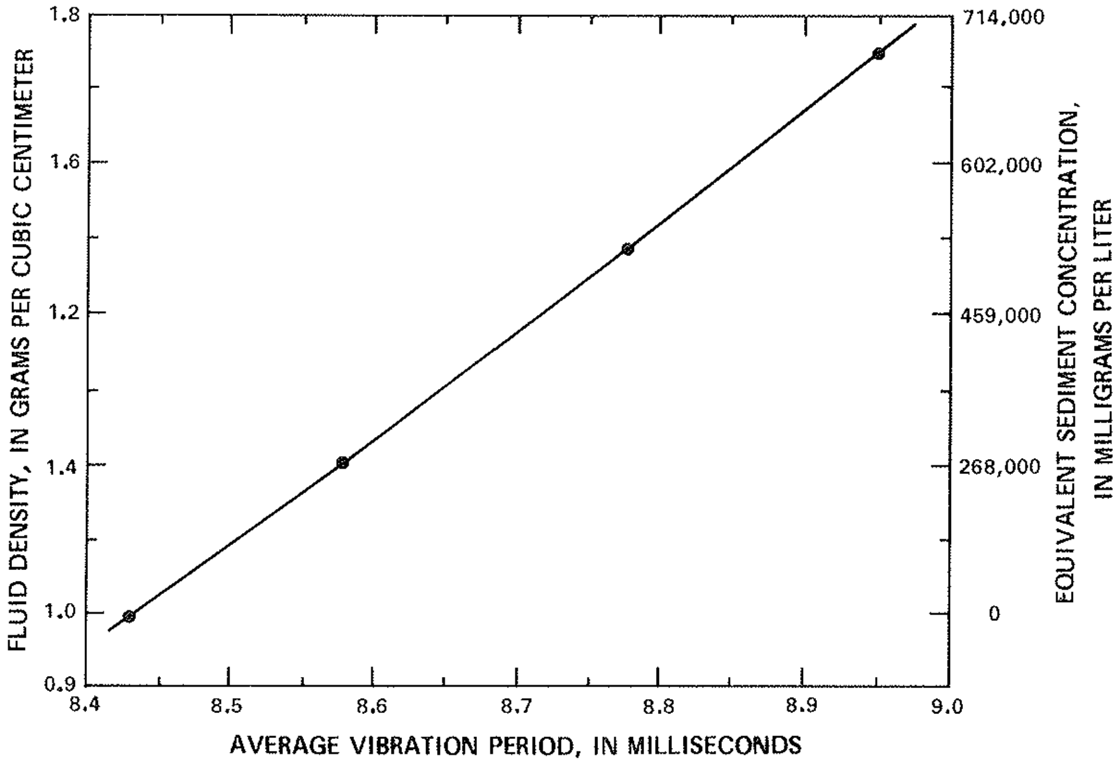

Figure C-2.--Graph relating fluid density and average vibration period.

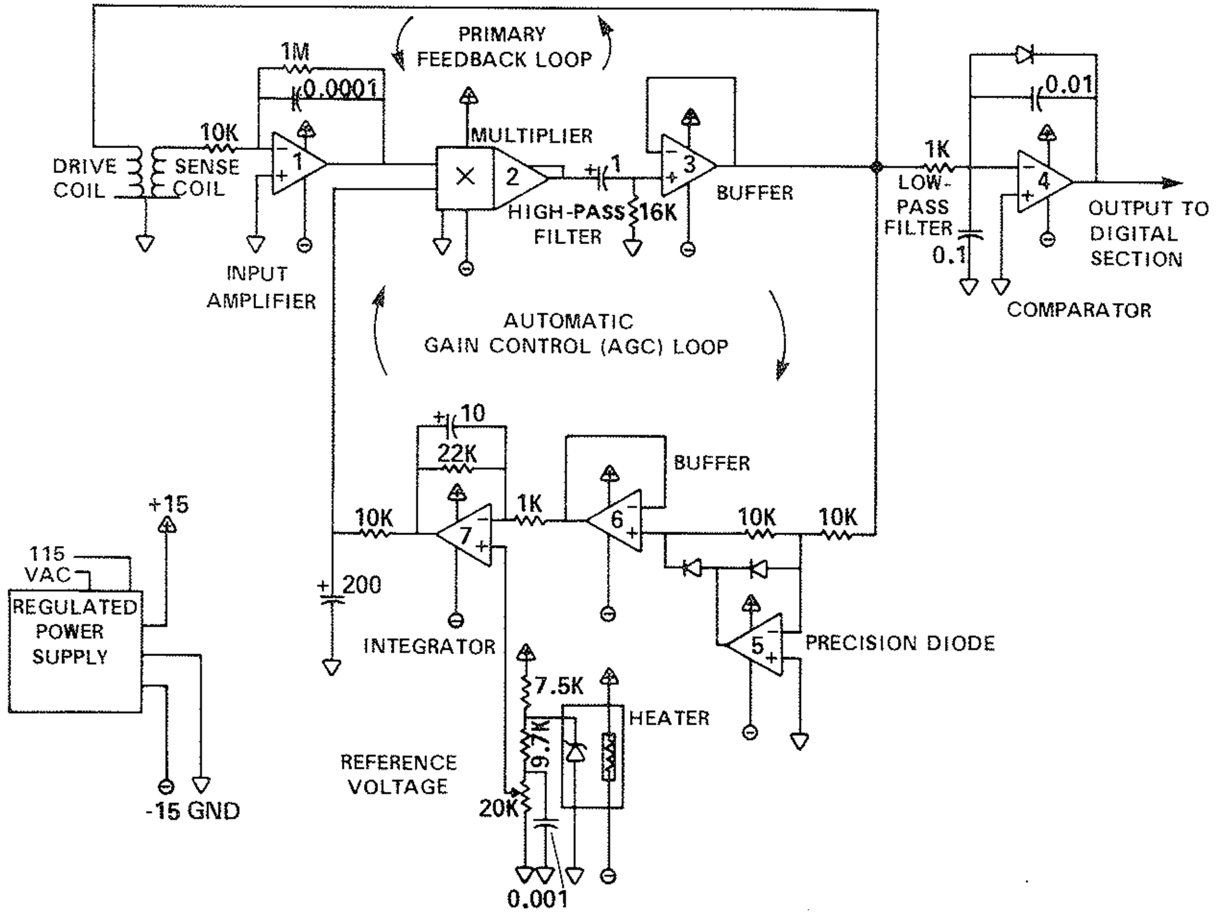

Figure C-3.--Schematic diagram of feedback circuit. All resistances are in ohms and all capacitances in microfarads.

The amplitude of the U-tube vibration and the sense-coil voltage are both sensitive to the root-mean-square (RMS) amplitude of the drive-coil voltage. Without some means of drive-coil voltage amplitude control, the amplitude of the U-tube vibration will either decay to zero or will steadily increase until limited by some undesirable non-linear response within the mechanical or electrical system. The AGC loop provides the necessary control. Amplifiers 5, 6, and 7 constitute this loop. Amplifier 5, two 10K resistors, and two diodes form a "precision diode circuit" (see Graeme and others, 1971, p. 245-247) which accurately rectifies the drive-coil voltage. The rectified voltage is transmitted to amplifier 6 (wired as a buffer) and then to amplifier 7. The output of amplifier 7 is proportional to the difference between the rectified signal and the regulated reference voltage. Amplifier 7 transmits this signal to one input of the multiplier. If the drive-coil RMS voltage decreases below a stable, quiescent operating level, the output of amplifier 7 will increase the output of amplifier 2, which, in turn, will cause the multiplier output to increase. The RMS drive-coil voltage will be increased by amplifier 3. When the RMS drive-coil voltage increases, the sense-coil voltage will increase the voltage supplied to the primary feedback loop. This increase acts to lower the output voltage of the AGC loop and thereby stabilize the RMS drive-coil voltage.

The drive-coil voltage is also fed through a low-pass filter to amplifier 4. It is connected so that the gain varies in a discontinuous fashion with the polarity and with the instantaneous magnitude of the drive-coil voltage. Amplifier 4 converts the sine-wave, drive-coil voltage into positive square-waves which are transmitted to the digital timing circuit.

All amplifiers and the multiplier were chosen for their minimal temperature sensitivity, low internal noise, and long-term stability.

## DIGITAL TIMING CIRCUIT

The average U-tube vibration period is measured by a circuit that counts the number of cycles generated by a stable reference oscillator during a period determined by a fixed number of drive-coil signal oscillations. This technique allows direct digital measurement of the average U-tube vibrational period. The objective is accomplished in the following manner.

The positive square-wave signal from amplfier 4 (fig. C-3) is further sharpened by two inverting NAND gates, 6DC and 6DD (fig. C-4). The square-wave pulses pass into the 12-stage binary counter, 1D. The two counters, 1D and 2D, and the two flip-flops, 3DA and 3DB, constitute the gate-control circuit. The timing cycle begins when the reset line goes to zero volts. Counter 1D begins counting. When its second output goes high after two counts, flip-flop 3DB turns on NAND gate 4DC which then activates gates 4DB and 4DA. After being switched, gate 4DA transmits pulses from the reference oscillator to the output-display counter. After 18,430 counts, the "5" output of counter 2D goes high and toggles flip-flop 3DA, which turns off gates 4DC, 4DB, and 4DA. When gate 4DA closes, the output-display counter holds the final count until reset.

The timing cycle is initiated by a positive-voltage pulse to the photo-coupler 7D. When this occurs, a pulse is passed through gates 6DA and 6DB to the timer, 5D. The timer's output, the reset line, goes high for a pre-set period; then it goes back to zero volts. While the reset line is high, both counters are set to zero counts, and each flip-flop "Q" output is set low while the "$\overline{Q}$" output is set high. Also, the output-display counter is reset to zero counts. The timer is set for a long interval, more than 20 seconds, to enable the pumped flow to approach an equilibrium.

## REFERENCE OSCILLATOR

The period-measuring scheme requires an oscillator with a stable frequency; however, the frequency need not be the same for all gages. Each instrument must be calibrated for the particular reference frequency chosen; furthermore, the frequency must be chosen so that the average period of U-tube vibration is subdivided into enough parts to obtain sufficient accuracy in the period measurement. The reference frequency chosen for this gage was 12.8 kHz. With the U-tube filled with

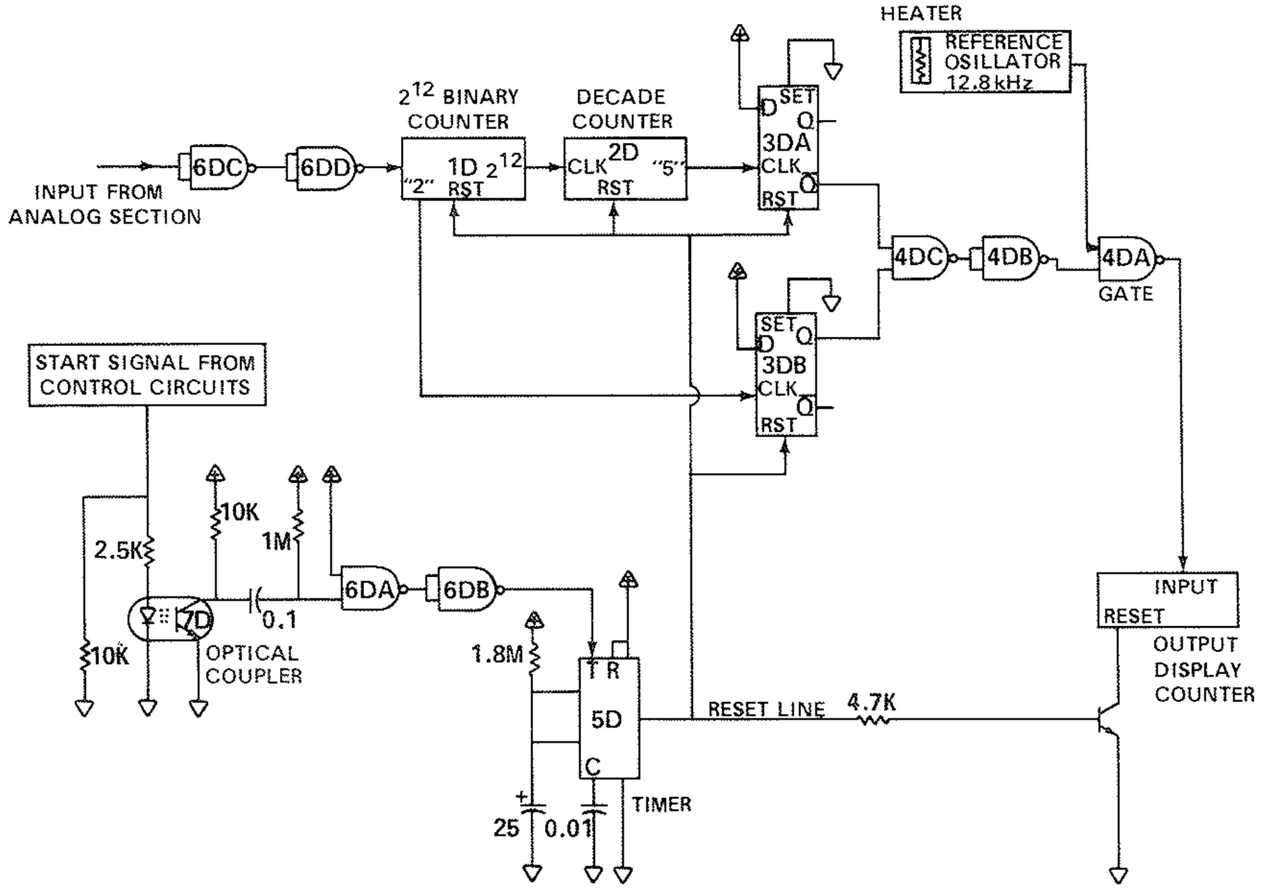

Figure C-4.--Schematic diagram of digital timing circuit. All resistances are in ohms and capacitances in microfarads. RST denotes reset and CLK denotes clock input.

distilled water the oscillator completes about 108 cycles while the U-tube completes one cycle. The accuracy of the period measurement was enhanced by timing a large number (18,430) of U-tube cycles instead of only one cycle. At completion of a timing cycle, the time required for the U-tube to complete 18,430 cycles was measured with an error equal to or less than one part in 1,990,440 parts (108 x 18,430); however, the error will be larger if the oscillator frequency is unstable.

Changes in the reference-oscillator frequency will, if uncorrected, result in errors in the predicted sediment concentration. The frequency will shift with changes in temperature. A high-quality, crystal-type reference oscillator was used. Temperature variations were minimized by placing the oscillator in a small, thermostatically-controlled chamber (oven) set for 65° ± 1°C. Tests run at an ambient air temperature of 22°C indicated the oscillator required about 15 minutes to reach a quasi-stable state after power had been applied to the oscillator and oven. The oscillator frequency drift ratio, $R_f$, in parts per million (ppm) is

$$R_f = (\Delta f/f)10^6 \qquad , \qquad (1)$$

where $\Delta f$ = magnitude of oscillator-frequency shift in Hertz (Hz), and $f$ = nominal oscillator frequency in Hz.

As explained in part A of this report, the gage was calibrated by experimentally determining a relation between sediment concentration and count which is defined as the difference between two cumulative counts, one taken with sediment-laden water in the U-tube and one taken with sediment-free water in the tube. To assess the concentration error caused by a frequency shift, assume that two cumulative counts are taken on sediment-free water. Furthermore, between the two tests assume that the oscillator frequency shifts by an amount $\Delta f$, but that all other test factors such as water temperature and dissolved-solids concentration are stable. Assume the U-tube vibrates at an equal rate during the two tests. The two cumulative counts would be collected during equal time intervals, each of T seconds duration. C, the difference between the two cumulative counts, would be

$$C = T(\Delta f)$$

Substitution of $\Delta f$ from equation (1) yields

$$C = TR_f f \times 10^{-6} \quad . \qquad (2)$$

Nominal values for T and f are 155 seconds and 12,800 Hz, respectively. For these values and an oscillator frequency drift ratio of 1 ppm, equation 2 yields C = 1.98 units. The average of all sediment-calibration tests reported in part A indicates a sediment concentration of about 10 mg/L corresponds to a C of one unit. Equation 2 shows the concentration error will be proportional to $R_f$ and the error will be about 20 mg/L for each ppm of oscillator-frequency shift.

Both long-term and short-term frequency shifts were observed. The short-term shift was determined from several period measurements taken during an interval of several minutes. The oscillator had a mean period of 78.139 259 μsec (12,797.664 Hz) with a standard deviation of 0.000 032 μsec (0.0052 Hz). Based on frequency, the standard deviation is 0.41 parts per million which corresponds to a sediment-concentration error of about 8 ppm.

In long-term drift tests, a slow, sinusoidal change in the oscillator period was observed over several hours. The period varied from a minimum of 78.139 21 to a maximum of 78.139 31 μsec over an average interval of 41.6 seconds. Based on frequency, the variation amounted to about ±0.64 ppm which is equivalent to a sediment concentration error of ±12 ppm. When the oven was chilled suddenly with a Freon gas the 42-sec variation continued undisturbed although the crystal frequency changed.

# FUTURE DEVELOPMENTS

## Constant subtractor circuit

In the present configuration, the output-display counter shows all cumulative counts gated during the timing period. Cumulative counts of 1,985,520 or more are common. The large cumulative count makes it difficult to read differences quickly. Another gate and counter circuit can be added to the output count line to minimize data storage complexity. This final gate will wait 1,982,464 counts before transmitting the remaining counts to the output-display counter. In effect, this subcircuit will subtract the constant from the final value.

## Data manipulation

The raw output display, even with the subtractor circuit, is not the sediment concentration. The concentration is more nearly related to the difference between the count obtained with the sediment-laden water and the count obtained with sediment-free water at the same temperature. The sediment-free water must have the same dissolved-solids concentration as the sediment-laden water. If a cumulative count is made of the sediment-free water, that cumulative count can be stored and used with successive counts of sediment-laden water if the temperatures remain within a narrow range and if the dissolved-solids concentration also remains within a narrow range. Automatic periodic measurements of stream water temperature and specific conductance allow verification of the constancy of these parameters and also at least slight adjustment to the sediment-free count when the parameters move outside the defined limits. There are pre-programmable integrated circuits presently available which can perform the necessary data manipulation and computation. The final output could be sediment concentration in mg/L. The adaptation of such a device to the present instrument would greatly increase its usefulness.

## Data transmission and storage

The transmission and storage of the computed sediment-concentration data are not serious problems. Commercial equipment to accomplish these objectives is readily available in a variety of forms. Data are routinely transmitted by means of telephone and radio, both directly and by rebroadcast through satellites. Local storage of data is possible in a variety of ways:

1. Direct printing of the data;
2. Graphical recordings on film and paper;
3. Magnetic recordings on tape, disc, or the newer "magnetic bubble" devices;
4. Semiconductor memories, both temporary and permanent; and
5. Punched paper tape or cards.

The particular means chosen must ultimately be decided on the basis of reliability, cost, convenience, system capacity, ease of maintenance, and possibly other factors. The basic sediment-concentration instrument should be provided with an option, at least, of storing data within the instrument and a means of coupling to a data-transmission system.

## CONCLUSIONS

The measuring circuits described in this report satisfy the requirements set forth:

(1) the capability of measuring the average vibrational period over a very wide range of sediment concentration.

(2) provides the drive coil with a low, but constant-amplitude, sinusoidally varying voltage, which is at the resonant frequency and "clean" (free of harmonic noise), and

(3) measures the mean resonant period digitally.

Direct digital measurement facilitates digital display and data manipulation, transmission, and storage.

## LIST OF REFERENCES

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Graeme, J. D., Tobey, G. E., and Huelsman, L. P., eds, 1971, Operational amplifiers, design and applications: New York, McGraw-Hill, 473 p.