Proceedings of Fourth Federal Interagency Sedimentation Conference, Las Vegas, NV 1986

CONTINUOUS MEASUREMENT OF SUSPENDED-SEDIMENT CONCENTRATION

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ABSTRACT

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

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

INTRODUCTION

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

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

ACKNOWLEDGMENTS

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

PRINCIPLE OF OPERATION

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

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

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

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

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

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

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

SOURCES OF MEASUREMENT ERROR

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

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

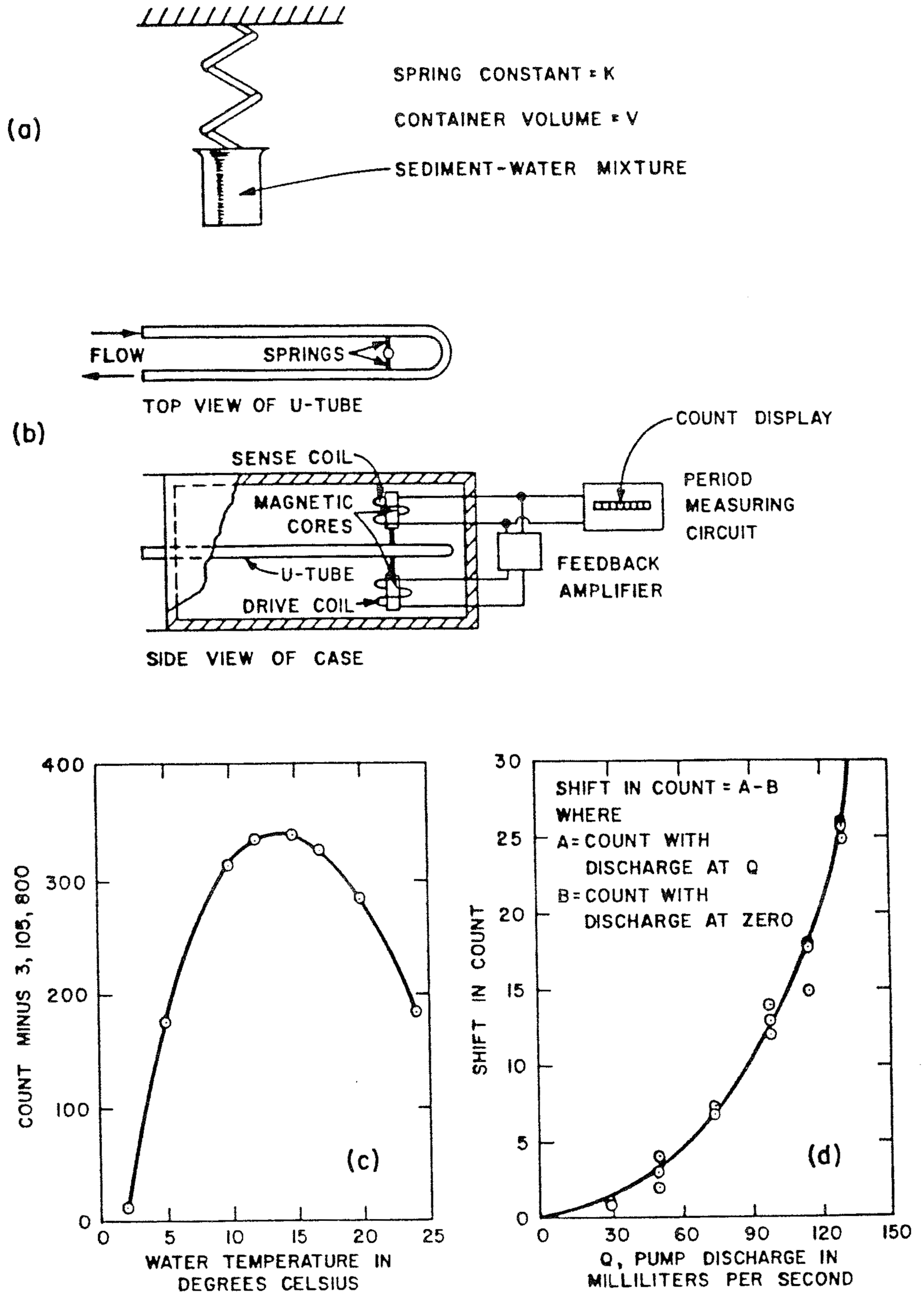

Figure 1.--(a) Spring-container arrangement for measuring sediment concentration. (b) Schematic of a flow-through concentration probe. (c) Relation between count and water temperature. (d) Relation between pumping rate and the shift in count.

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

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

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

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

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

FIELD INSTALLATION

An experimental U-tube system was installed at the Willow Creek station near Madison, Wisconsin. Willow Creek drains about 3 mi^2 in a fully developed residential area. The station, which is about 300 ft downstream of a storm-sewer outlet, has a control consisting of a 6-ft wide Parshall flume installed in a concrete weir. The station was chosen because it is readily accessible to personnel at the U.S. Geological Survey District Office, and because it has a shelter with electric power and telephone service.

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

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

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

FIELD-TEST PROCEDURE

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

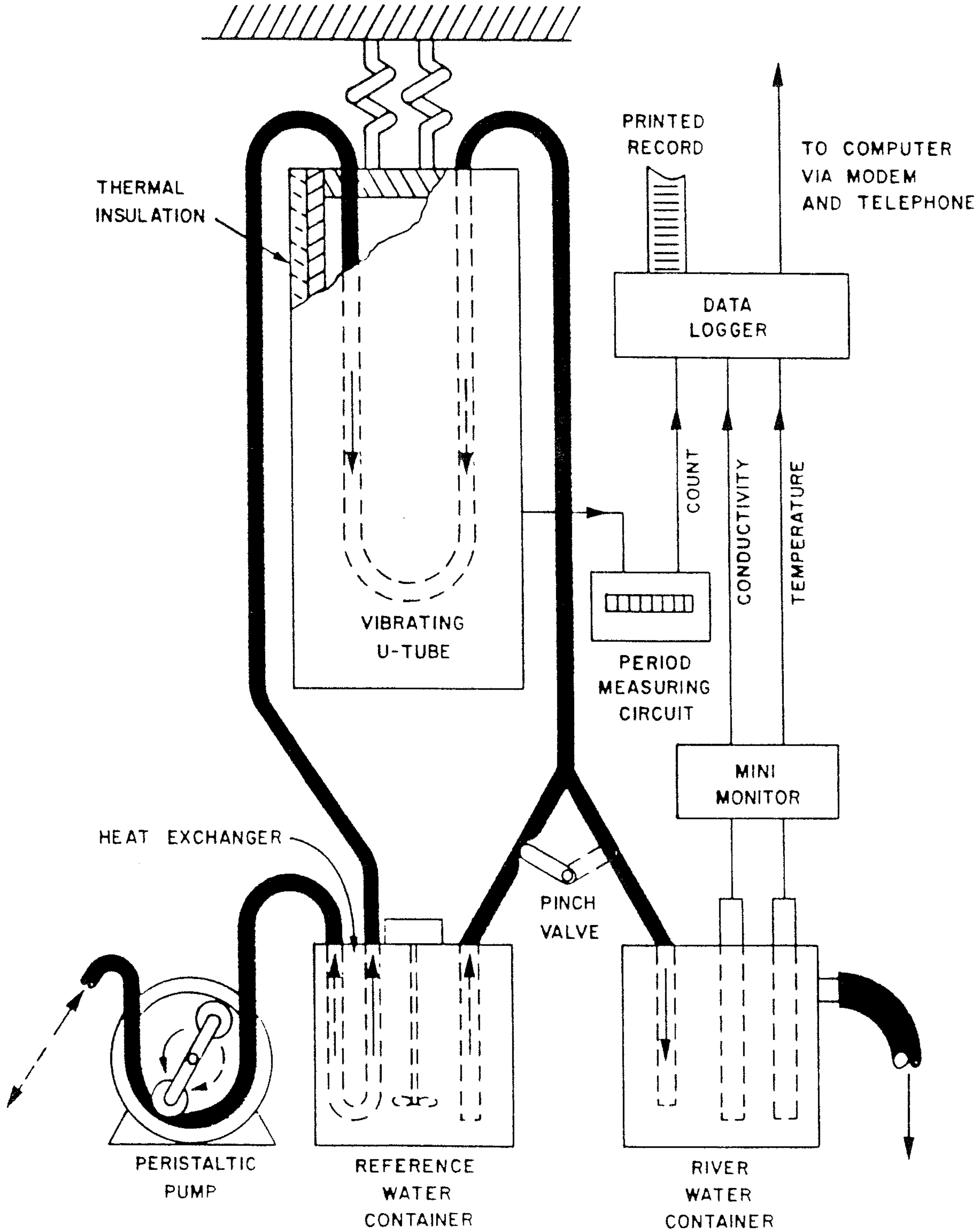

Figure 2.--Field apparatus for monitoring suspended-sediment concentration.

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

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

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

DATA REDUCTION

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

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

Time.--Central-standard time.

Stage.--River-stage in feet.

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

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

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

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

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

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

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

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

WILLOW CREEK AT MADISON, WISCONSIN

OCTOBER 18, 1984

R Reference mode M Monitoring mode e Estimated value ( ) Measured independently

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

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

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

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

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

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

FIELD-TEST RESULTS

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

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

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

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

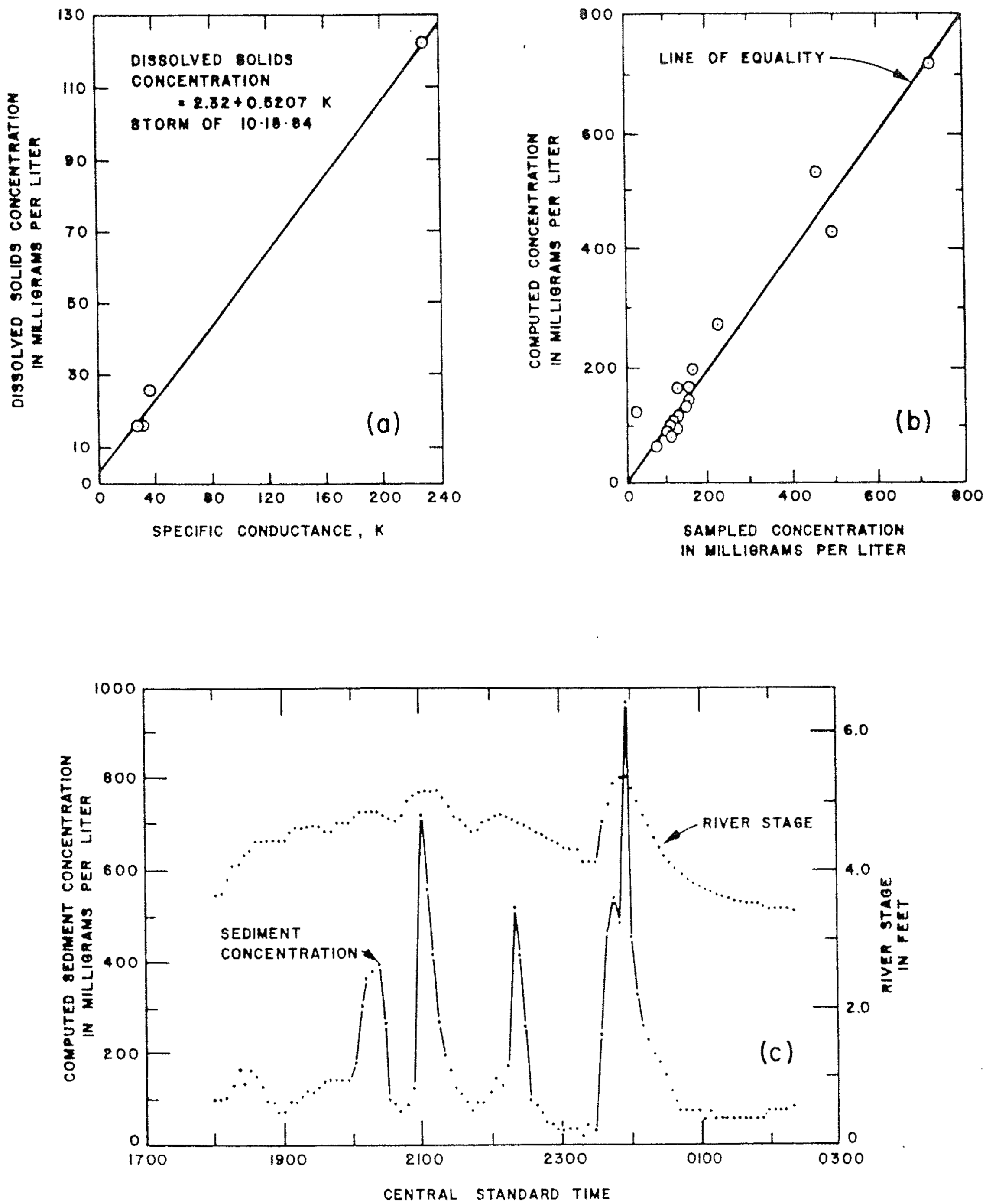

Figure 3.--(a) Relation between dissolved-solids concentration and specific conductance at the Willow Creek site on Oct. 18, 1984. (b) Comparison of computed and sampled concentrations for storm of Oct. 18-19. (c) Stage and computed sediment-concentration hydrograph for same storm.

FUTURE DEVELOPMENT

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

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