Selected Techniques in Water Resources Investigations, 1966-67

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1892

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Compiled by EDITH BECKER CHASE *and* FAITH N. PAYNE

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Papers on new techniques by C. F. Berkstresser, Jr., T. J. Buchanan, E. E. Cerny, E. D. Cobb, M. R. Collings, R. E. Cook, J. R. Crippen, L. C. Davis, Jr., B. Dunn, R. U. Grozier, L. S. Hughes, A. I. Johnson, B. F. Joyner, T. E. Kelly, J. L. Kunkler, O. J. Loeltz, S. E. Rantz, J. Rawson, W. D. Robbins, V. B. Sauer, J. V. Skinner, K. V. Slack, G. F. Smoot, R. E. Sommer, Jr., H. H. Stevens, Jr., R. L. Stewart, J. D. Stoner, C. T. Welborn, J. F. Wilson, Jr., W. L. Yonts, Jr.

'JNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1968

UNITED STATES DEPARTMENT OF THE INTERIOR

STEWART L. UDALL, *Secretary*

GEOLOGICAL SURVEY

William T. Pecora, *Director*

Library of Congress catalog-card No. GS 68-282

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402 - Price $1 (paper cover)

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SELECTED TECHNIQUES IN WATER RESOURCES INVESTIGATIONS, 1966–67

COMPILED by EDITH BECKER CHASE and FAITH N. PAYNE

INTRODUCTION

Increasing world activity in water-resources development has created an interest in techniques for conducting investigations in the field. In the United States, the Geological Survey has the responsibility for extensive and intensive hydrologic studies, and the Survey places considerable emphasis on discovering better ways to carry out its responsibility. For many years, the dominant interest in field techniques has been "in house," but the emerging world interest has led to a need for published accounts of this progress. In 1963 the Geological Survey published "Selected Techniques in Water Resources Investigations" (Water-Supply Paper 1669–Z) as a chapter of the series "Contributions to the Hydrology of the United States." The report was so favorably received that successive volumes were planned. The first volume was "Selected Techniques in Water Resources Investigation, 1965" (Water-Supply Paper 1822).

This, the second volume, contains 28 papers that represent new ideas being tested or applied in the hydrologic field program of the Geological Survey. These ideas, which cover a diversity of subjects, either contribute to the accuracy and ease of field operations or add to the basic knowledge of water resources. The original papers have been revised and edited by the compilers, but the ideas presented are those of the authors.

The general description of dye-tracing techniques on pages 2–4 has been given by the compilers as supplementary information to the several papers that follow.

DYE-TRACING TECHNIQUES—GENERAL DESCRIPTION

For many years scientists have used natural or introduced materials as tracers to study mixing patterns and rates of movements within water bodies. Within the past decade soluble fluorescent dyes have proven to be excellent tracers and generally have replaced previous favorites such as chemical salts and radioisotopes. The dyes are economical, are easy to handle, and may be detected quantitatively in extremely low concentrations in water samples tested in a special instrument called a fluorometer. Most of the dye-tracing work by the U.S. Geological Survey has had to do with time-of-travel measurements and and with discharge measurements by the dye-dilution methods. Other special applications by Survey scientists have served to demonstrate the versatility of dye tracing as a tool in hydrology. Examples include studies of reservoir circulation and flushing, estuary flushing, well-drilling fluid-circulation time, ground-water time of travel, irrigation-water uptake by plants, and the fate of dye-tagged herbicides applied to water courses.

The object of a time-of-travel measurement is twofold: (1) to find out how long it takes a mass of water tagged with dye to travel downstream from one location to another, and (2) to determine how the stream dilutes and disperses the dye in the process. The dye generally is injected almost instantaneously as a slug; at downstream sites water samples are collected periodically or continuously and tested in a fluorometer for the presence of dye. Time-of-travel and dispersion information are then extracted from plots of concentration versus time (fig. 1) for each sampling point. These data are used by water-management agencies to help solve problems involving undesirable contamination of streams, such as thermal loading from powerplants, accidental spills of chemicals, and sewage flushing and dilution. To date, the Geological Survey has measured time of travel on approximately 75 streams, including the Mississippi and Missouri Rivers, in 30 States.

The dye-dilution methods of measuring discharge are useful primarily where it is difficult or impossible to obtain accurate measurements by conventional means. One method involves the downstream "total recovery" of a known quantity of dye injected as a slug; discharge is equal to the amount of dye injected divided by the average area under a set of time-concentration curves, like the one in figure 1, for the measuring cross section. Any loss of dye between the injection and measuring sites decreases the accuracy of the measurement proportionally. A second method utilizes more sophisticated dye-injection apparatus to achieve a constant-rate injection over a continuous timespan; at the measuring site the peak concentration is really a steady plateau of uniform concentration. In the constant-rate-injection method, discharge is simply equal to the rate of injection times the ratio of the injected concentration to the corresponding plateau concentration at the measuring site. Depending upon conditions in the stream, moderate dye loss with the constant-rate-injection method is less critical to measurement accuracy than with the total recovery method. In contrast to discharge measurements, dye loss usually does not seriously affect the results of time-of-travel measurements.

Although time-of-travel measurements usually involve reaches that are many miles long and discharge measurements involve very short reaches, many of the field and laboratory procedures used for the two applications are similar. Seven articles, which cover a wide range of topics on the subject of dye tracing, are given in the present report.

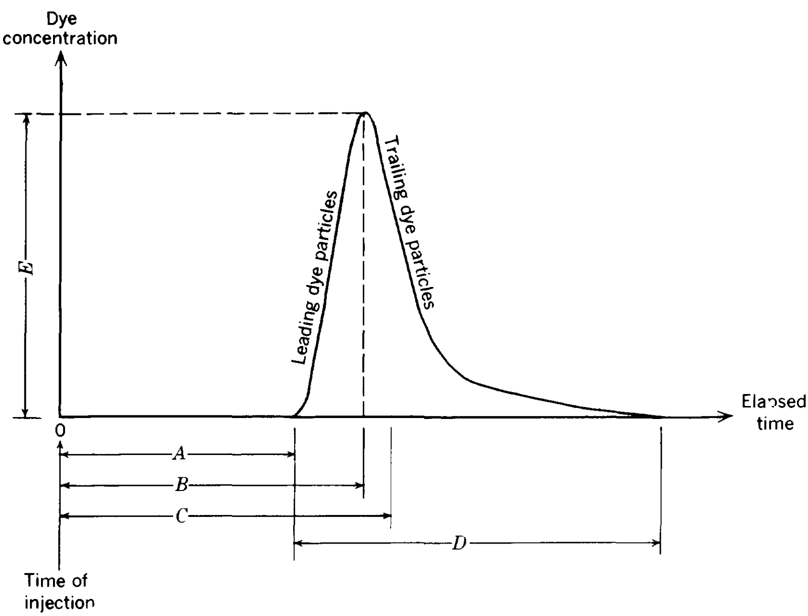

FIGURE 1.—Time-concentration curve for a specific sampling point in a channel cross section, illustrating some of the information which can be extracted: *A*, traveltime of leading edge; *B*, traveltime of peak concentration; *C*, traveltime of centroid (considered to be the average traveltime of the dye to the sampling point); *D*, passage time at the sampling point; *E*, peak dye concentration, parts of dye per billion parts of water (ppb). Similar information from curves for several sampling points is used to determine average values for the cross section.

Some of the topics have general application in dye-tracing work, whereas a few apply to a specific type of study. The topics are presented in their natural sequence: dye selection (Wilson, p. 5), dose computations (Dunn, p. 9), dye-injection apparatus (Cobb, p. 15), field-site selection (Collings, p. 23), sampling systems (Stoner, p. 30), results of a special study (Buchanan, p. 34), and use of photography as an auxiliary tool (Wilson, p. 37).

IMPROVED DYES FOR WATER TRACING

By JAMES F. WILSON, JR.

ABSTRACT

Dye manufacturers are beginning to tailor the properties of certain fluorescent dyes for water-tracing purposes. Various solutions of rhodamine B are now available with specific gravities in the range 1.00 to 1.03. Rhodamine WT, a new dye, exhibits low sorptive tendency and is proving to be an excellent tracer, especially for discharge measurements. Selection of fluorometer filters appropriate to the particular dye used is a critical factor in instrument sensitivity.

INTRODUCTION

Hundreds of commercial dyes are available in a variety of colors. A great number of these are strongly fluorescent, but only a few are known to exhibit the combination of properties essential for water tracing. Generally speaking, tracer dyes must be (1) water soluble, (2) highly detectible by their fluorescence, (3) harmless in low concentrations, (4) inexpensive, and (5) reasonably stable in a normal surface-water environment.

Fluorescein, rhodamine B, and Pontacyl Brilliant Pink B[1] are dyes that were available for other uses when modern dye-tracing techniques were first developed. Recently several dye manufacturers have begun to improve some of these dyes—such as rhodamine B—and to develop new dyes—such as Rhodamine WT—tailored to the tracing needs of oceanographers and hydrologists.

This paper describes the improved and new dyes, outlines the advantages and disadvantages of the four most commonly used dyes, and discusses the importance of using proper fluorometer filters.

RHODAMINE B

A simple, but basic improvement in the common solutions of rhodamine B (usually 30 or 40 percent by weight) has been the adjustment

[1] Pontacyl Brilliant Pink B is a brand name of E. I. du Pont de Nemours & Co.; the same dye is also available from other manufacturers under different names. The use of brand names in this article for identification purposes does not imply official endorsement of any product.

of the specific gravity. Previous solutions were heavy and required premixing with methanol or similar liquid before injection of the dye, to prevent undesirable settling or stratification in the receiving water. For oceanographic tracing, solutions are now available at the specific gravity of sea water, approximately 1.03—du Pont Rhodamine BA, for example. For most fresh-water tracing 1.03 is low enough; rhodamine B solutions with gravities of 1.00 to 1.03 are available from a number of manufacturers. The reduction in specific gravity does not seem to have affected the cost of the dyes, nor to have changed the fluorescence properties of the dyes.

RHODAMINE WT

Rhodamine WT is a new dye, developed by du Pont especially for water tracing. As of this writing (1966) no equivalent dye is known to be available from other manufacturers. The principal advantage of Rhodamine WT is that it is far less susceptible to sorption than rhodamine B. Because the fluorescence properties of the dye are similar (but not identical) to those of rhodamine B, the same fluorometer filters may be used. On the basis of detectibility with the 546 mμ (millimicron) and 590 mμ filters in the fluorometer, Rhodamine WT costs about twice as much as rhodamine B, but only about one-fourth as much as Pontacyl Brilliant Pink B.

A disadvantage of Rhodamine WT is that it is available only in a 20 percent solution that has a specific gravity of 1.19; it is best to dilute it before injection into a stream or other water body. This dye has been used in the field extensively in recent months and has proven to be an excellent tracer.

COMPARISON OF DYES

The most important properties to be considered when selecting a dye are compared in table 1. An excellent general reference on the properties of the rhodamine family of dyes is Feuerstein and Selleck (1963) although it was written before the development of Rhodamine WT.

Rhodamine WT is recommended for discharge measurements or for any other application requiring a high percentage recovery of dye. Pontacyl Brilliant Pink B (or equivalent) is a high-recovery dye but is not economical for large-scale use. Rhodamine B solutions with specific gravities of 1.00 to 1.03 are recommended for most stream time-of-travel measurements and estuarine dispersion studies, primarily because of the cost factor; lower recovery rates generally can be tolerated. Fluorescein is not recommended for surface-water tracing because it is quickly decomposed by sunlight. Fluorescein has the additional disadvantage of being difficult to isolate fluorometrically in high-background waters. All the dyes in table 1, except rhodamine B, are recommended for ground-water tracing.

TABLE 1.—*Comparison of properties of four tracer dyes*

[Rhodamine B and fluorescein are common industrial names; Rhodamine WT and Pontacyl Brilliant Pink B are E. I. du Pont de Nemours & Co. names]

Property	Rhodamine B	Rhodamine WT	Pontacyl Brilliant Pink B	Fluorescein
Color index generic name.	Basic Violet 10		Acid Red 52	Acid Yellow 73.
Formula	$C_{28}H_{31}N_2O_3Cl$		$C_{27}H_{29}N_2O_4S_2Na$	$C_{20}H_{12}O_5$.
Common forms	Powder; 30 and 40 percent solution.	20 percent solution	Powder	Powder.
Unit cost, ratio to rhodamine B.	1	2	3	½.
Cost ratio based on detectibility.	1	2	7	½.
Peak excitation wave length, in millimicrons.	554	558	566	480.
Peak emission wave length, in millimicrons.	578	582	590	510.
Detectibility [1]	High	High	Moderately high	High.
Tendency to be sorbed [2]	do	Low	Low	Low.
Sensitivity to temperature. [3]	do	High	High	Do
Photochemical decay rate. [4]	Moderately low	Moderately low (assumed).	Low	Very high.

[1] Based on the use of the same set of fluorometer filters for all dyes except fluorescein. In addition it is more difficult to isolate the fluorescence of fluorescein from interfering background fluorescence.

[2] Adsorption and (or) absorption by floating, suspended, and boundary materials in the receiving water body.

[3] Fluorescence activity is decreased by higher temperatures and increased by lower temperatures.

[4] The dyes decompose when exposed to sunlight.

NOTE.—The fluorescence of all four dyes is stable over the pH range 5-10 and tends to decrease significantly outside these limits. Also, certain chemicals such as chlorine, if present in the receiving water, may destroy the dyes or cause significant reduction in fluorescence.

FLUOROMETER FILTERS

Rhodamine B, Rhodamine WT, and Pontacyl Pink (or equivalent) have nearly the same spectral properties, making them all highly detectible with the 546 mμ and 590mμ fluorometer filters. Fluorescein, on the other hand, is spectrally different from the other three and requires different filters. Feuerstein and Selleck (1963, p. 3) used a Corning 7–83 filter for the primary and combination of Corning 3–70 and 4–97 filter for the secondary (see Corning Glass Works, 1962); these filters were the basis for the detectibility comparison in table 1. G. K. Turner Associates (written commun., 1963) recommend a combination of Wratten 2A and 47B for the primary and a combination of Wratten 2A and 12 for the secondary (see Eastman Kodak Company, 1965).

Because other dyes available now or in the future may be tried as tracers, attention to selection of proper filters is important. Filter selection should be based upon (1) the excitation and emission spectra of the particular dye tested, (2) the useful output spectrum of the exciting lamp, (3) potential interference from fluorescence of background materials, and (4) potential interference from light scattered in the water sample. A particular new dye may require an entirely different set of filters from that used for rhodamine B. Failure to determine this in advance may result in false conclusions about the detectibility, or even the presence, of the dye.

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Corning Glass Works, 1962, Glass color filters: Corning, N.Y., Corning Glass Works, catalog, 25 p.

Eastman Kodak Company, 1965, Kodak Wratten filters for scientific and technical use: Rochester, N.Y., Kodak Publication No. B–3, 77 p.

Feuerstein, D. L., and Selleck, R. E., 1963, Fluorescent tracers for dispersion measurements: Am. Soc. Civil Engineers Proc. Paper 3586, Sanitary Eng. Div. Jour., v. 89, no. SA4, p. 1–21.

NOMOGRAPHS FOR DETERMINING AMOUNT OF RHODAMINE B DYE FOR TIME-OF-TRAVEL STUDIES

By BERNARD DUNN

ABSTRACT

Concentrations of dye are measured at a known distance below the point of injection to calculate the time of travel of a stream. The amount of dye required for injection into a stream needs to be computed in order to hold the level of concentration within desired limits and to minimize the cost of dye. Nomographs that permit rapid determination of the amount of dye required have been prepared for two of the formulas commonly used in dye studies.

INTRODUCTION

Three methods for determining the amount of dye to be injected into a stream are used by the U.S. Geological Survey in time-of-travel studies. They are a rule-of-thumb method as reported by Buchanan (1964), an empirical formula by E. D. Cobb and J. F. Bailey (U.S. Geol. Survey, written commun., 1965), and a refinement of that formula by J. F. Wilson (U.S. Geol. Survey, written commun., 1966). In computing the amount of dye to be injected into a stream the principal factor to be considered is dispersion. Because stream conditions contributing to dispersion are extremely variable, the formulas used are not exact.

The Geological Survey has adopted the policy that, at any point on a stream where water is removed for human consumption, the maximum concentration of rhodamine B dye shall not exceed 10 ppb (parts per billion) by weight. Fluorometers are used to measure concentrations and, with available attachments and accessories, are sensitive enough to measure concentrations well below 1 ppb. The peak concentrations at the lower end of a reach, or at water intakes, can be computed for 1–2 ppb by weight and, even if the time of travel were underestimated, the prescribed limit of 10 ppb would unlikely be exceeded.

The field determination of the amount of dye needed to be injected into a stream can be time consuming and subject to computational errors. Use of the formulas has been simplified by constructing nomographs for the Cobb-Bailey and Wilson formulas. In both formulas the dye is rhodamine B, 40 percent by weight, specific gravity 1.03.

RULE-OF-THUMB METHOD

The rule-of-thumb method was used in early surface-water dye tracing experiments carried out by the Geological Survey (Buchanan, 1964, p. 6). The amount of dye required was based on an estimate of the volume of water in the reach between the injection point and the sampling point. Experience has shown that an amount of dye required to produce a certain average concentration in this volume will produce a peak concentration at the sampling point of about double the average concentration. The Cobb-Bailey and Wilson formulas described in the next sections are based on much additional experience and are preferred in use.

COBB-BAILEY FORMULA

The amount of dye required for time of travel in a reach by the Cobb-Bailey formula can be estimated from the empirical equation

$$\mathit{V}_d = 3\times 10^7 \frac{C_p}{C_d} Q t_p$$

where V_d = volume of dye solution, in milliliters, to be injected into the stream,

C_p = peak dye concentration, in parts per billion, desired at the terminal site,

C_d = concentration, in parts per billion, of the dye solution injected into the stream,

Q = average discharge of stream, in cubic feet per second,

t_p = estimated time in hours, for the dye peak to travel from the injection point to the terminal site,

and 3×10^7 = combination of conversion factors.

WILSON FORMULA

The Wilson formula is a refinement of the Cobb-Bailey formula and was based on time-of-travel data for a wide variety of stream conditions. The amount of dye required by the Wilson formula is expressed by

$$Ꝟ_d = f \frac{QL}{V} C_p$$

where $Ꝟ_d$=volume of dye solution, in milliliters, to be injected into the stream,

f=coefficient equal to 0.06 divided by the dye solution strength in ratio form (0.4 for 40 percent),

Q=average discharge of stream, in cubic feet per second,

L=length of reach, in miles,

V=estimated average velocity of stream, in feet per second,

and C_p=peak dye concentration, in parts per billion, desired at the terminal site.

Wilson recommends that the amount of dye determined by his formula be doubled in the low-flow range (that flow which is equaled or exceeded more than 90 percent of the time) and quadrupled if there are small dams or long natural pools in the reach.

NOMOGRAPHS

Nomographs for the Cobb-Bailey formula (fig. 1) and for the Wilson formula (fig. 2) were prepared for a rhodamine B dye concentration of 2 ppb at the terminal end of a reach. The nomograph for the Cobb-Bailey formula shows the relation of the dye solution and stream discharge, and the Wilson formula shows the relation of the ratio of the length of the reach to the velocity, stream discharge, and dye solution.

To determine the amount of dye solution from the nomograph for the Cobb-Bailey formula, the user must first determine the discharge and traveltime of the stream. For example, a stream has a discharge of 10 cfs (cubic feet per second) and an estimated traveltime of 5 hours. To determine the amount of dye from the nomograph, enter the abscissa of figure 1 at a discharge of 10 cfs and, where it meets the 5-hour line, read the ordinate as 7.5 ml. When either or both the discharge and time exceed that shown on the nomograph, reduce

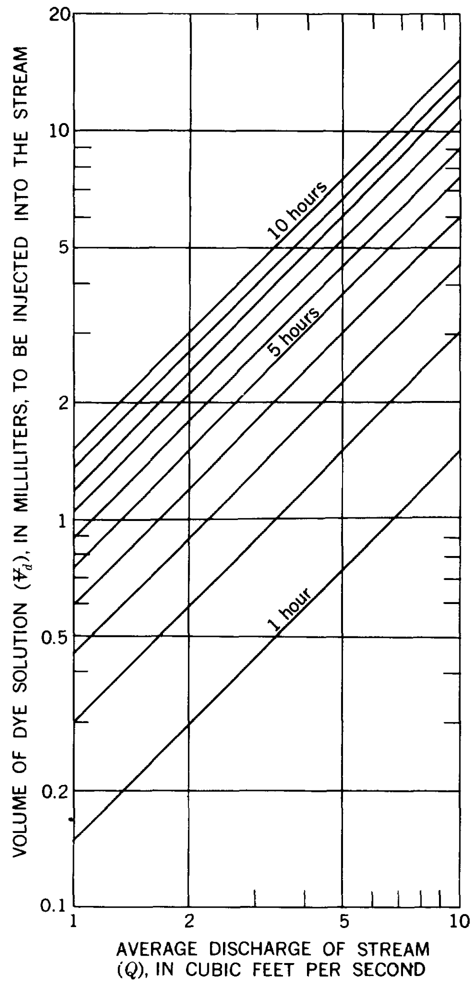

FIGURE 1.—Nomograph for Cobb-Bailey formula for determining amount of 40-percent rhodamine B dye solution for peak terminal dye concentration of 2 parts per billion, based on stream discharge and estimated traveltime of peak concentration.

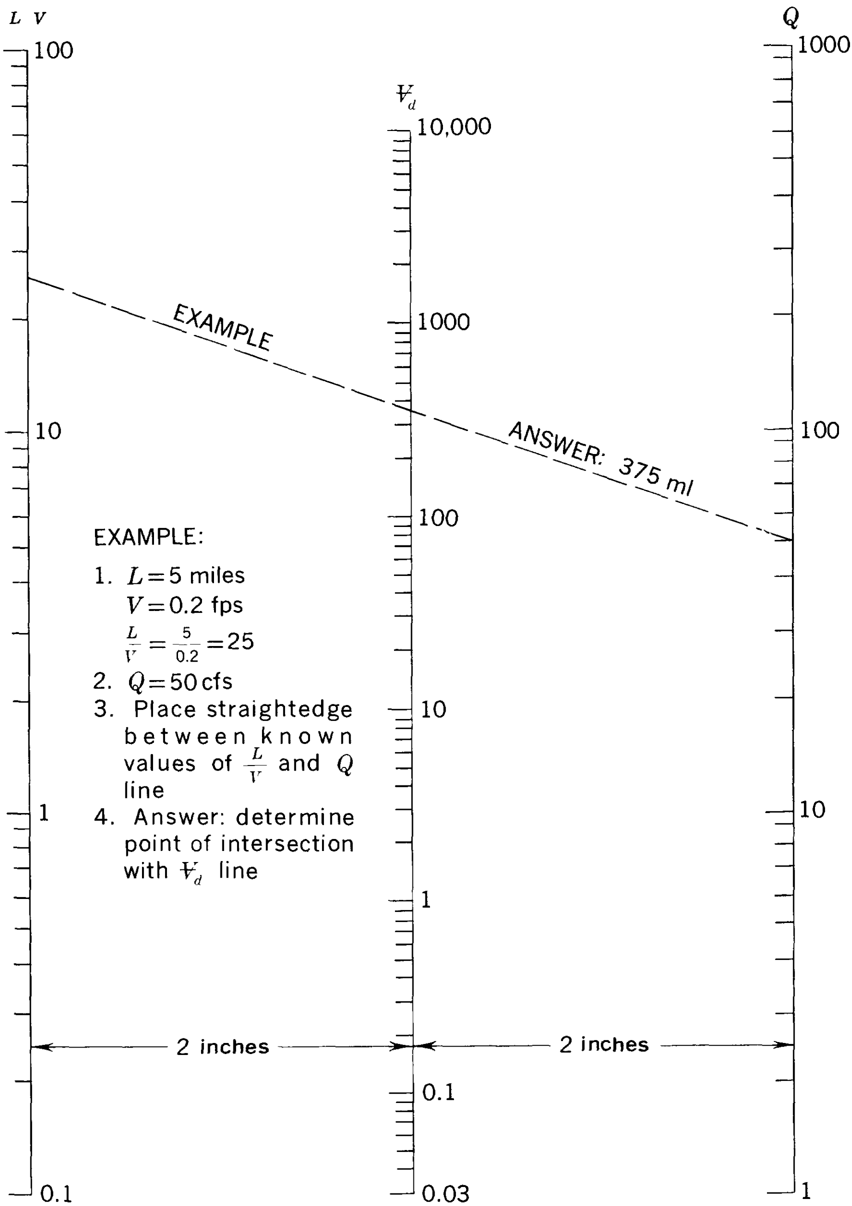

FIGURE 2.—Nomograph for the Wilson formula determining amount of 40-percent rhodamine B dye solution for a peak terminal dye concentration of 2 parts per billion. L, length of reach, in miles; V, estimated average velocity of streams, in feet per second; $\mathcal{V}_d$, volume of dye solution, in milliliters, to be injected into the stream; Q, average discharge of stream, in cubic feet per second.

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the values to fit the logarithmic cycle on the graph, and then obtain the volume of dye solution and multiply it by the same factors used to reduce the discharge and time values. For example, if the discharge is 100 cfs and the time 50 hours (the values of 10 cfs and 5 hours are each changed by a multiple of 10), it is necessary to multiply the 7.5 ml by 100 (10×10) to get the actual volume (750 ml) of dye solution.

To determine the amount of dye solution from the nomograph for the Wilson formula involves three steps. First, the value for the L/V scale is determined by dividing known values of the length of reach and the velocity of the stream; second, the known value of stream discharge is indicated on the Q scale; and third, a straightedge is placed between the values on the L/V and Q scales. The point at which the straightedge intersects the V_d scale is the amount of dye solution needed. (See fig. 2.)

The use of nomographs in determining the amount of dye to be injected into a stream for time-of-travel studies has proven very helpful in the elimination of computational errors. If it is necessary to increase or decrease the peak concentration at the lower end of the reach, the volume of dye obtained from the nomographs can be adjusted readily.

REFERENCE CITED

Buchanan, T. J., 1964, Time of travel of soluble contaminants in streams: Am. Soc. Civil Engineers Proc. Paper 3932, Sanitary Eng. Div. Jour., v. 90, no. SA3, p. 1–12.

CONSTANT-RATE-INJECTION EQUIPMENT FOR DYE-DILUTION DISCHARGE MEASUREMENTS

By Ernest D. Cobb

ABSTRACT

The measurement of stream discharge by the constant-rate-injection dye-dilution method requires accurate injection equipment. Several units that use different principles and have different advantages have been developed. Constant flow rates of dye solution can be maintained by (1) a mariotte unit that maintains a constant head on the discharge orifice, (2) a spring-diaphragm unit that has an automatically adjusted spring-diaphragm-valve mechanism, (3) a floating siphon that maintains a fixed head on the orifice, (4) a constant-level reservoir that stores any solution above a given elevation, and (5) a constant-rate pump that uses a uniform power supply. The mariotte tank is easily and cheaply made and is very reliable; the spring-diaphragm unit is more versatile but also more expensive; and the floating siphon, the constant-level reservoir, and the constant-rate pump all have the advantage that additional solution can be added to the supply reservoir without disrupting the flow rate.

INTRODUCTION

The accuracy of a stream discharge measurement using the constant-rate dye-injection method is directly dependent on the accuracy of the injection equipment used, as seen by examination of the discharge formula

$$Q=\frac{C_1}{C_2}q$$

where Q=stream discharge rate,
C_1=concentration of the injected dye solution,
C_2=concentration of the dye in the sampled stream water, under equilibrium conditions,
and q=discharge rate of the injected dye solution.

Injection rates that fluctuate slightly (about ±2 percent) can be tolerated. However, an injection that changes rate in only one direction can yield serious errors in the measurement of discharge, which depend on the magnitude of the change.

The purpose of this report is to describe several methods of obtaining constant-rate injections. No attempt is made to point out all the difficulties that might be experienced in the use of these various systems.

MARIOTTE UNIT

A mariotte unit is equipment that provides for a constant flow rate of dye solution into a stream by maintaining a constant head on the discharge orifice. (See fig. 1.)

The unit operates as follows: When the discharge orifice is opened, the level of the dye solution in the tank drops and causes a partial vacuum above the liquid. As the level of the liquid continues to drop, the vacuum increases and causes the level of the liquid in the air vent (which is open to the atmosphere) to drop until it reaches the bottom of the vent. As the solution continues to be discharged through the orifice, air enters the tank through the vent and causes an equilibrium between the partial vacuum formed above the liquid surface and the weight of the liquid above the bottom of the air vent. When this equilibrium has been reached, a constant discharge will have been attained and will continue until the liquid in the tank drops to the bottom of the air vent. In practice it has been found that as much as 3 minutes may be required for complete equilibrium to be obtained. During this initial period, higher flow rates will exist as a result of a greater head acting on the orifice.

The flow rate can be controlled by the orifice size, the position of the lower end of the air vent (if the air vent is raised, the head is increased; however, the usable volume of solution is then decreased), the position of the discharge point of the orifice, valves in the orifice, or clamps

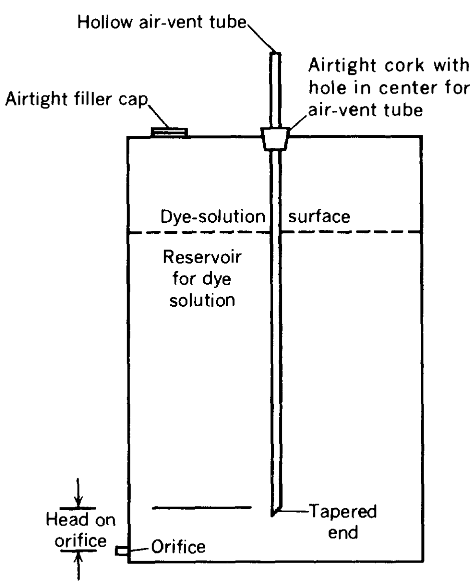

FIGURE 1.—Sketch of the mariotte unit.

on flexible tubes leading from the tank orifice. The latter two are the least desirable as they tend to trap sediment or cause bubbles to form in the discharge line. Once a flow rate is established, all parts of the unit should be left unmoved during the measurement.

Flow rates are usually determined by measuring the time required for the flow to yield a specific volume. Usually a graduated laboratory cylinder and a stopwatch are adequate for this purpose. If the unit has a graduated readout tube, the tank can be volumetrically calibrated and discharges determined by timing the period for the liquid to drop a specific distance in the tube. The unit can also be hung on a scale which in turn is hung from a tripod or a tree, and the discharge can be determined by taking scale readings and the time interval between readings.

Experience has shown that air in some water will cause bubbles to build up in the orifice or discharge line and disrupt the steady flow of solution from the tank. Small amounts of laboratory detergent (1 part of liquid Liquinox detergent, or equivalent, in 100,000 parts of solution) in the dye solution have been found to reduce or eliminate this problem. Sediment or impurities in the dye or water used in the solution have been found at times to clog the orifice. The size of orifice being used and the purity of the water and dye determine the necessity of filtering the dye solution before pouring it into the mariotte tank. The dye solution should be thoroughly mixed before it is poured into the tank.

The dye-solution tanks have been clear plastic containers, 5-gallon water cans, 50-gallon drums, small pieces of clear plastic pipe, and containers of specially prepared material. Clear plastic has the advantages of allowing the operator to see how the unit is functioning and what the level of the solution is in the tank. Materials used should be rigid enough to withstand the air-pressure differential that results in the unit; they also should be rust resistant and easily cleaned.

The lower tip of the air-vent tube should be tapered to prevent the tip from being placed directly on the bottom of the tank and thus obstructing the air flow.

Discharge at more than one point or at different rates may be facilitated by installing more than one orifice in the tank.

Many modifications can be made to the manufacture of the unit as long as there is adherence to the operating principles.

SPRING-DIAPHRAGM UNIT

The spring-diaphragm unit maintains a constant flow rate by means of an automatically adjusted spring-diaphragm-valve mechanism. A unit that meets the requirements for measuring streamflow is manufactured by Aerofeed, Inc., Chalfont, Pa. (See fig. 2.)

The features of the unit are shown in figure 3. Power to operate the unit is derived from compressed air in the storage tank. A foot pump can be used to pressurize the tank. The pressure forces the solution out of the tank, through the flow meter, through the flow-control assembly, and into the stream.

The flow-control or regular assembly on the unit will regulate the flow within ±2 percent of the set discharge as long as a pressure difference of about 5 pounds per square inch or greater is maintained between the inflow to and the discharge from the regulator. Basically, the regulator functions to maintain a constant differential pressure across an externally adjusted orifice regardless of the manner in which the absolute pressures, either upstream or downstream from the orifice, may change. Because the size of the orifice is fixed for any given position of the adjustable needle valve (fig. 4), maintenance of the constant differential pressure across it assures maintenance of a constant flow rate through it.

A sketch of the flow-control assembly is shown in figure 4. The flow enters from the bottom of the unit. A passage from the flow entrance to the lower pressure chamber allows the tank pressure (less pressure losses) to exert a force upward on the underside of the diaphragm. The solution flows through the adjustable needle valve into the upper pressure chamber above the diaphragm where it exerts a force down-

FIGURE 2.—Aerofeed constant-rate-injection unit.

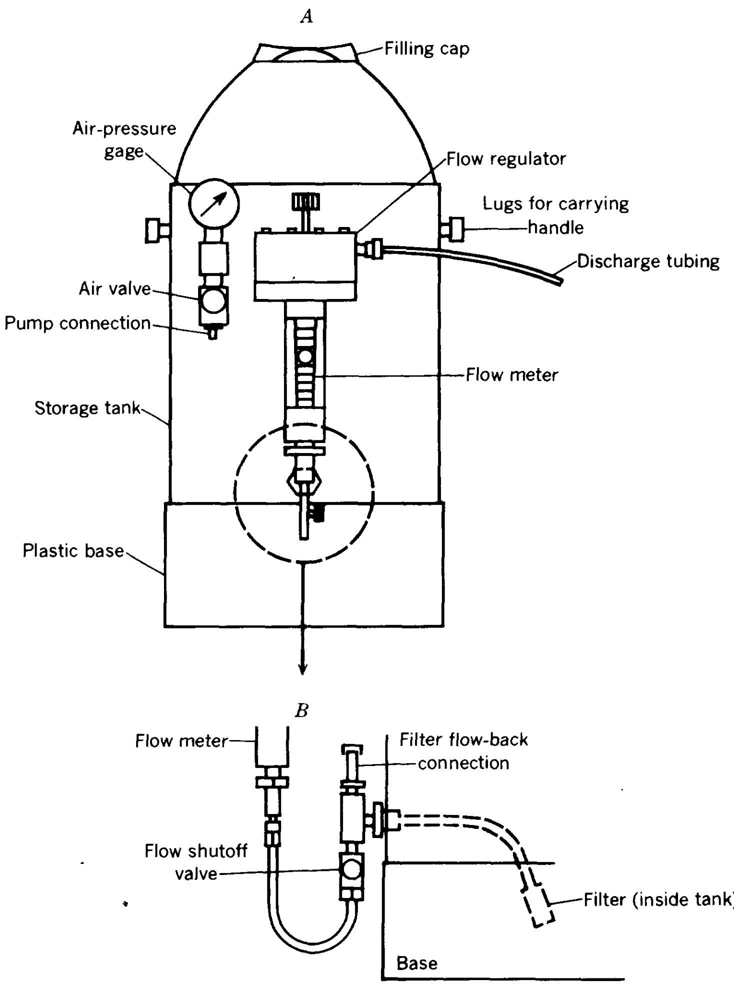

FIGURE 3.—Sketch of the Aerofeed unit. *A*, Tank and its components; *B*, cross section of flow meter.

ward on the diaphragm. This latter force is less than that underneath the diaphragm because of a reduced effective diaphragm area, friction losses, and pressure losses due to bends, contractions, and expansions, but primarily because of the loss of pressure resulting from the solution flowing through the control orifice. A spring also pushes down on the diaphragm exerting an additional constant force. It is this constant force, exerted by the spring, which determines the pressure maintained across the needle valve.

When liquid starts to flow through the regulator, an equilibrium condition is rapidly established between the forces acting upward on

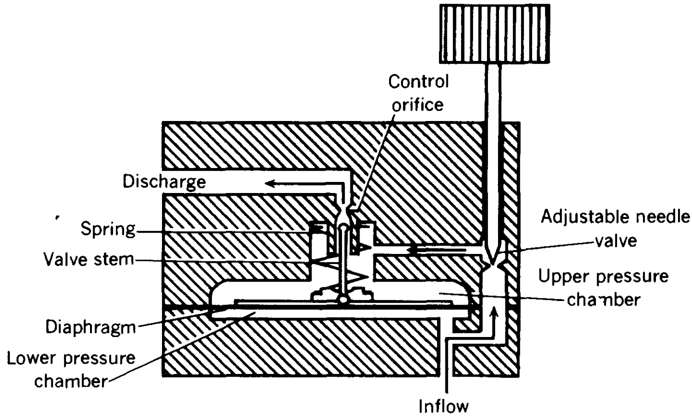

FIGURE 4.—Cross section of the Aerofeed flow regulator

the diaphragm (pressure only) and those acting downward (pressure plus spring). At this equilibrium condition the internal valve will have been driven to some particular position with respect to the control orifice by the action of the spring and the flexible diaphragm. The higher the tank pressure (all other things being equal), the further the valve will enter the control orifice.

When the tank pressure decreases, two events occur simultaneously: (1) the pressure underneath the diaphragm decreases, reducing the upward acting force, and (2) the flow through the needle valve decreases, owing to the decreasing upstream pressure. At this momentarily decreased flow rate through the needle valve, the pressure drop across the valve is reduced, thereby increasing the pressure above the diaphragm and, accordingly, increasing the downward acting force. This combination causes a momentary loss of the original pressure differential between the two chambers and causes the diaphragm to deflect downward a short distance. As the diaphragm moves down, it causes the valve to withdraw slightly from the control orifice, which thereby permits flow through the regulator to increase. As the flow increases, the pressure drop across the needle valve also increases, which thus decreases the force acting downward and slows the downward deflection of the diaphragm until an equilibrium position is once more obtained.

Because tank pressure slowly but steadily drops during normal operation of the injection unit, the positions of the valve and diaphragm are also constantly changing, always drawing the valve further and further out of the control orifice, but always maintaining a nearly constant difference in pressures above and below the diaphragm. If tank pressure were to increase, the direction of the valve and diaphragm movement would be reversed but the unit would still seek equilibrium and maintain the flow rate.

The rate of flow is set by turning the needle-valve control knob to the desired position. The regulator will maintain constant flow rates for discharges of about 25 to 230 milliliters per minute.

The material used in the diaphragm does not allow the regulator to regulate properly for about the first 3 minutes of operation. Volumetric calibrations of the flow rate should not be made during this time.

The flow meter is used to determine approximate flow rates and is used for initially setting the discharge rate. Actual flow rates must be determined by volumetric measurements of the discharge. The meter has a linear scale from 0 to 100 and must be rated by volumetric measurements at various needle-valve settings. This meter rating should be nearly linear. The meter is read by determining the position of a ball in the meter tube. As the flow rate increases, the ball rises in the tube.

The advantages of the unit are (1) flow rates can be regulated over a wide range, (2) low flow rates can be obtained, (3) the unit is portable (it is about 17 inches in height and when empty weighs only about 11 pounds), (4) it has adequate storage (3.14-gallon total-tank volume) for solution to allow measurement of most streams than can be efficiently measured by this method, and (5) no special provisions have to be made for setting it up at the measurement site.

The primary disadvantage of the unit is that it is more expensive than most of the other units.

FLOATING SIPHON

The floating siphon maintains a constant flow rate by maintaining a fixed head on the orifice. Figure 5 is a sketch of the equipment.

The float and orifice drop together as the solution flows out of the storage tank. Because the orifice is then kept at the same elevation relative to the solution surface, the flow is maintained at a constant rate. A counterweight and pulley wheel are used to keep the float in place near the side of the tank.

Sharp bends, sharp or rough entrance conditions, and constrictions in the siphon might cause air to come out of solution and form a bubble at the top of the siphon. These conditions should be avoided if possible because a bubble will reduce the area and the flow rate. The use of water that has been allowed to stand at atmospheric pressure and temperature will help prevent this bubble formation. A clear plastic siphon will enable the user to see if a bubble forms.

The use of a tube which can be attached to the end of the orifice will enable the user to draw the solution through the siphon, at which time

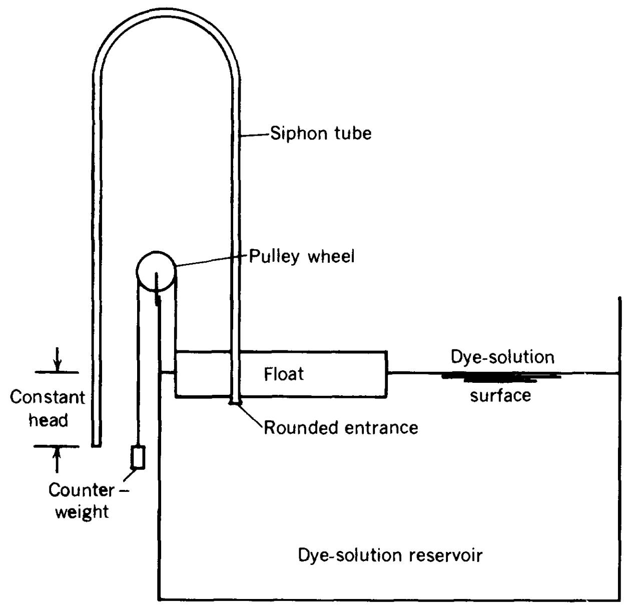

FIGURE 5.—Sketch of the floating siphon.

the tube can be detached and the solution will continue to siphon out of the tank.

A primary advantage of the floating siphon is that dye solution can be added to the storage tank without disrupting the flow rate; hence, the dye solution can be injected into the stream for long periods of time. A disadvantage is the lack of portability of the system.

OTHER CONSTANT-RATE FLOW UNITS

Several other methods may be used to obtain constant flow rates. The constant-level reservoir is one such method. This unit requires three tanks: the first tank drains dye solution into a second tank, which is the constant-level reservoir and is constructed so that any solution above a given elevation discharges over a wide weir into a third tank for storage. The weir should be wide enough and the orifice in the constant-level reservoir at such a depth that a slight variation in inflow to this tank will cause negligible changes in the head and thus in the flow rate.

Another device is a constant-rate pump. A uniform power supply is necessary to assure constant flow rates. Other more sophisticated units are available but are not described herein.

SELECTION OF DYE-INJECTION AND MEASURING SITES FOR TIME-OF-TRAVEL STUDIES

By M. R. Collings

ABSTRACT

Studies using fluorescent dyes for estimating time of travel in streams may be made by either a single-injection method for the entire study reach or a multiple-injection method whereby the study reach is divided into subreaches. The method used is governed by the specific prerequisites of the study, time and personnel limitations, and other factors.

The optimum success of a study depends upon proper selection of dye-injection and measuring sites. Site selection should be made after a comprehensive inventory of the study reach. Factors to be evaluated include channel characteristics of the stream, potential loss of dye, municipal demands, tributary inflow, and stream discharge.

INTRODUCTION

The importance of examining the study reach prior to inauguration of a fluorescent dye time-of-travel study cannot be overemphasized. Every stream has features that must be evaluated properly if the traveltime study is to be completely successful.

This article compares two methods of dye injection and presents factors to be considered in selecting dye-injection and measuring sites for time-of-travel studies. The dye injected by these methods may be affected to some extent by channel characteristics of the stream, potential loss of dye, municipal demands, tributary inflow, and stream discharge. Factors are discussed for selecting injection points that will minimize dye loss and thus maximize dye recovery.

DYE-INJECTION METHODS

Fluorescent dye time-of-travel studies on a stream can be efficiently accomplished by either a single-injection method or a multiple-injection method. The single-injection method is accomplished by injecting the dye at the upper end of the study reach and sampling for fluorescence at selected measuring sites downstream. The multiple-injection method consists of dividing the total reach into subreaches and injecting dye at the head of each subreach either at the same time or in upstream order.

SINGLE-INJECTION METHOD

Some of the features of the single-injection method are:

1. Continuity of data. Simulation of pollutant behavior over the entire study reach makes the method ideal for reconnaissance investigations.
2. Simplicity of planning. The method requires selection of only one injection point at the upper end of the reach and of dye-sampling sites downstream.
3. Number of personnel needed. To define time-concentration curves adequately, several sites may require sampling at the same time. The frequency of sampling sites, the length of subreach dosed, and the stream discharge determine whether the single-injection method will or will not require fewer personnel than the multiple-injection method.
4. Off-scale fluorescence. A large amount of dye is required in a large stream, in a stream at high flow, or in long study reaches. Under these conditions, a dye-sampling point near the injection site may have greater fluorescence than can be recorded by the fluorometer used to detect fluorescence. This problem may be rectified by removing the high-sensitivity kit from the fluorometer, diluting the sample, or placing a neutral density (range-extension) filter over the secondary filters in the fluorometer.

Usually the use of the less sensitive filter combination in the fluorometer is the simplest way to obtain a reading, although a calibration of the instrument with the neutral density filter in place is necessary to evaluate the reading in terms of concentration (parts per billion).

When using either the single- or multiple-injection method, the circumstances govern whether off-scale fluorescence will result. However, usually the first measuring site in the reach can be placed far enough downstream (in relation to discharge) from the injection site so that the dye will be sufficiently diluted.

MULTIPLE-INJECTION METHOD

The multiple-injection method may be accomplished in either of two ways: The simultaneous injection of all subreaches or the injection of each subreach in upstream order. Some features of the simultaneous injection are:

1. Reduction in time required to complete the traveltime study. The time required for completion would be only as long as the time required for the longest (timewise) subreach.
2. Personnel and communication problems become manifold. All subreaches require simultaneous sampling, often at more than one site in each.

3. Dye slugs may overlap. The sampling point at the end of a subreach, by necessity, is also the injection point of the next lower subreach and there is a possibility of dye slugs overlapping. However, this seems to be the exception rather than the rule.

Some features of injection of each subreach in upstream order are:

1. The natural fluorescence of each subreach is insured (also the case with single-injection), and there is no possibility of dye slug overlap.
2. Fewer sites require sampling at the same time; therefore fewer personnel are needed.
3. The time required to complete a particular study is increased.

Several advantages common to both variations of the multiple-injection method are:

1. Dye concentrations can be minimized at water intakes and other sites where there is a definite need to do so. The U.S. Geological Survey's Water Resources Division has a policy which states that the maximum dye concentration at such sites must be less than 10 parts per billion by weight.
2. Effects of changes in river stage during the study are minimized or at least identified.
3. A more thorough understanding of contaminant inflow at points located within the total reach is obtained. The stream may be dosed at the sites of contamination and the dye may be sampled at critical points downstream.
4. The dye cloud is less likely to become so dispersed that detection is difficult and (or) peaks, centroids, or time of dye passage are difficult to determine. This is especially true if storage, such as lakes or reservoirs, exists in the study reach.

FACTORS TO CONSIDER IN SITE SELECTION

Many factors enter into selection of dye-measuring sites for the single-injection method or dye-injection and measuring sites for the multiple-injection method. Every study reach is unique in some way; however, the following description of the effects of some of these factors—channel characteristics of the stream, potential loss of dye, municipal demands, tributary inflow, and stream discharge—will aid in the selection of injection and measuring sites.

CHANNEL CHARACTERISTICS OF THE STREAM

Generally, the steeper the stream gradient, the faster the velocity and the shorter the time of travel through the reach. Therefore, dye-measuring sites may be spaced farther apart on streams with steep gradients.

The channel lithology should be considered when selecting measuring sites. Fluorescent dyes may be partly or almost totally lost through channel sorption. When dye studies are conducted on streams with sorbent channel materials, such as clay, silt, and sand, the measuring sites should be spaced more closely and the progress and concentration of the dye checked as often as feasible. Additional injection points may be selected if the dye is lost. Cobble, boulder, or bedrock channel materials generally do not pose this problem.

During periods of sustained low flows, aquatic vegetation may become well established in stream channels. Parts of an injected slug of dye are delayed by eddies caused by aquatic vegetation. At dye-measuring sites downstream, delays caused by passage of the dye slug through these vegetated and swampy areas may cause multiple peaks or, at least, broad peaks of low concentration.

Reservoirs, lakes, and ponds in a study reach warrant special consideration for time-of-travel studies. A storage area may cause broad low-concentration dye peaks downstream or even multiple peaks similar to those shown in figure 1. The peaks depend on the size and regulation of the reservoir. The time of travel through a water-storage area, whether natural or manmade, is as important as the time of travel in any part of a river reach, and every effort should be made to obtain data through these sections of the river. However, the passage of dye through a very large storage area may be so complex that the area should be bypassed and studied separately at a later date.

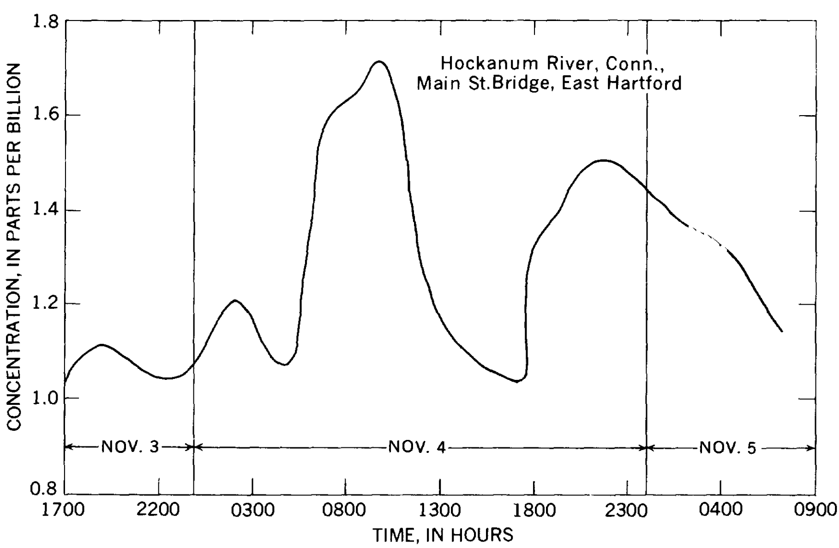

FIGURE 1.—Time-concentration curve at a dye-measuring point below a dam.

POTENTIAL LOSS OF DYE

In addition to natural dilution, which ultimately renders the dye undetectable, the dye is subject to a number of physical and chemical processes which tend to diminish the amount detected at a measuring site. The most important of these processes are sorption, chemical action, and photochemical decay.

The percentage of dye loss in most cases is not great enough to cause serious measuring problems in time-of-travel studies. However, adequate dye should be injected to provide a measurable reading at the most remote sampling site, despite losses. For example, in a measurement of traveltime on the Mississippi River by the Water Resources Division of the Geological Survey (Stewart, 1967), 72 percent of a 4,100-pound dose of rhodamine B dye, 40-percent solution, was recovered 21 miles downstream 14 hours after injection, and 52 percent was recovered at 126 miles after 93 hours. The discharge was 240,000 cubic feet per second. If the river had been dosed to obtain a minimum measurable dye concentration at the 126-mile site without regard to losses, a 52-percent loss at that point may well have rendered the dye undetectable.

High concentrations of sediment or organic material may reduce the peak dye concentration before it reaches the sampling site. Laboratory tests on 40-percent solutions of rhodamine B dye have shown as much as 12-percent dye loss after 4-hour contact with sand and as much as 28-percent dye loss after 2-hour contact with an organic material (Wright and Collings, 1964). In north-central Massachusetts, a sample of river water contaminated by papermill wastes was taken 3 miles below a gaging station (Otter River at Otter River) and tested for dye recovery. Almost instantaneously, 13 percent of the dye was not detectable, after 24 hours 25 percent was lost, but after 48 hours the contaminant in the sample had decomposed and the concentration returned to the initial prepared concentration.

The dyes also are susceptible to destruction or reduced fluorescence due to reaction with other chemicals present in the stream. Chlorine, for example, is very destructive. Where materials of this nature are known to be present, injection and measuring sites should be located accordingly.

The loss of dye by sorption and (or) chemical reaction may be partly or wholly remedied by selecting a fluorescent dye—Rhodamine WT, for example—that is less sorbed than other dyes, by increasing the amount of dye injected, or by selecting the injection sites at shorter intervals along the reach. If large dye losses are expected, stream samples may be collected prior to dosing and known dye concentrations may be prepared and tested with the fluorometer to obtain an estimate of the magnitude of the loss.

Some types of extraneous matter such as algae or detergents may also cause a variable background fluorescence (fluorescence of the water in the stream before dosing) and may mask peaks or even cause multiple peaks. It is always recommended that a good definition of background be obtained at a measuring site before the stream is dosed or at least before the dye slug has reached that site.

Photochemical decay is caused by the reaction of the dye to sunlight and is a function of time exposed. The reaction results in a reduction of dye fluorescence and, if necessary, may be minimized by shortening the length of the subreach. The loss by photochemical decay is probably a minor problem for most traveltime studies when compared with the other causes of dye loss. However, samples should be stored in a dark place and tested as soon as possible.

MUNICIPAL DEMANDS

Domestic or industrial facilities may be concerned with the time it takes a pollutant from an upstream source to reach their intakes and they in turn also may be the source of contaminants to the stream. Therefore, municipalities should be inventoried for possible injection or measuring sites to help determine the time of travel to their water intakes from upstream pollution sources and (or) the dilution characteristics of the river on material from their outfalls.

TRIBUTARY INFLOW

Dye-measuring points directly below tributaries should be selected with care because these tributaries may be contributing pollutant to the main stream and mixing of the main stream and the tributary may not occur immediately. Because of poor selection of a cross-sectional sampling position on the river, dye samples may indicate inconsistent fluorescence, or the peak may not be sampled at all. Several locations in the cross section should be sampled whether immediately below a tributary or not.

STREAM DISCHARGE

For a comprehensive time-of-travel evaluation, dye studies should be made at a high, medium, and low stage of the stream. Enough information should be obtained to formulate the relation between discharge and traveltime. During an individual time-of-travel measurement, the discharge should remain relatively constant at the downstream end of the reach. If the flow changes significantly during a study, the characteristic time of travel for that particular flow will not be obtained; therefore the investigation of a stream reach should be completed as quickly as possible. The longer it takes to make a particular study, the greater the probability that a change in flow will occur.

Even if discharge is steady, conditions may dictate the number and location of injection and sampling sites. Under extreme low-flow conditions, stream velocities may be so slow that the study reach has to be subdivided in order to complete the study in a reasonable time. This has often been the case. On the other hand, under high-flow conditions, high stream velocities may force the use of a single-injection site and widely spaced measuring sites.

SUMMARY

Before a time-of-travel study is started, the stream under investigation should be thoroughly inventoried. The number and location of injection and measuring points should be chosen with care. Consideration of channel characteristics, potential loss of dye, municipal demands, confluence of tributary streams, and stream discharge is essential for any fluorescent-dye study. Estimates should be made of the effects of sorption, chemical reaction, and photochemical decay in order to determine the size of the most efficient dose of dye to inject at a particular site. Ideally, both one-dye injection for the total reach and several injections on selected subreaches would be desirable. However, for economic reasons, usually either one dose or several doses are made; rarely are both methods used on one river study reach. The number of injection and measuring sites selected for a study reach depends on how comprehensive a study is needed; for example, much less data would be needed for a reconnaissance type study than for the solution of a particular pollution problem.

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COMPARISON OF RESULTS USING THREE SAMPLING TECHNIQUES FOR A FLUOROMETRIC DYE STUDY IN A STREAM

By J. D. Stoner

ABSTRACT

Three sampling techniques—grab samples and two different pumping systems—were tested concurrently at a single point in a stream. The means and variances computed for the three sampling methods are shifted from the true means and variances by various time increments. Generally, sampling points along a stream in a time-of-travel or dispersion study are far enough apart to make the error shift insignificant, so that results from different sampling methods are directly comparable. However, some studies require that correction factors be applied to the means and variances.

The use of fluorescent dyes as tracers in dispersion and time-of-travel studies is becoming more prevalent. In any dye study, the water in the stream must be sampled in some manner, and the use of more than one sampling method in a single time-of-travel or dispersion study may be desirable. At a given sampling point the mean of the distribution of dye concentration versus time is used to determine time of travel, and the variance, to evaluate dispersion. The tests discussed below were made to compare the means and variances computed from the data obtained by three different sampling techniques. The work was performed on the Green-Duwamish River, Wash., in cooperation with the municipality of Metropolitan Seattle.

The techniques used in this study were (1) a portable pumping system, (2) a permanent pumping system, and (3) grab sampling. The three techniques were used concurrently at a single test site. The grab-sample site and pump intakes were located as near to each other as practical, thus minimizing differences in dye concentration due to horizontal and vertical velocity variations in the stream. For this study, the length of hose used in the portable pumping system was made equal to that of the pipe installed in the permanent pumping system.

Each continuous pumping system had a Turner Model 111 fluorometer equipped with a flow-through door and a recorder. The recorder produced a continuous trace of fluorometer units versus time.

Just prior to starting the study, the fluorometers were calibrated with appropriate dye standards. These standards were prepared immediately before use by diluting measured quantities of dye with measured quantities of stream water. After calibration, background fluorescence was measured on each of the four sensitivity ranges or each fluorometer. The dye, rhodamine B, was injected into the stream about 2 miles upstream from the study site.

The main components of the portable pumping system were a Jabsco Model 11810 pump and plastic garden hose (½-inch inside diameter). A valving system to control the flow through the fluorometer was used in the pumping systems.

Multiparameter water-quality monitors equipped with permanent pumping systems had been installed at four points along the study reach. One of these permanent installations was used for the second sampling technique, which consisted of a submersible pump suspended from a float in the stream and a 1¼-inch inside diameter polyvinyl chloride pipe that led to the monitor.

The third technique was grab sampling from a highway bridge at the test site. The samples were collected in 16-ounce bottles, each of which contained 1 milliliter of a detergent solution to minimize adsorption of the dye on the glass. The grab samples were analyzed in a fluorometer immediately after the pumping systems were shut down.

Readings obtained from the fluorometers were converted to concentrations of rhodamine B, expressed in parts per billion, in order to compare the three sampling techniques. A common time base was used for the three methods, and smooth concentration-versus-time curves were drawn (fig. 1).

Two problems were experienced during construction of the concentration-versus-time curves. First, the curve based on grab samples peaked at a slightly lower concentration than the curves constructed from the continuous-trace measurements. The actual peak concentration was apparently missed, although the grab samples were taken at frequent intervals. The difference in maximum concentrations (3 percent) and the periods between grab samples (2 minutes) were so small that the mean time is virtually equal to the value that would have been obtained had the actual peak been observed. Second, the fluorometric chart trace of the portable pumping system was driven off scale during a short part of the dye passage. An estimation of the missing segment was made, based on characteristics of this type of curve and previous data obtained at this station.

Curves developed from time-of-travel and dispersion data commonly exhibit very long "tails" after passage of the main body of the tracer. The significance of these tails with respect to time of travel or disper-

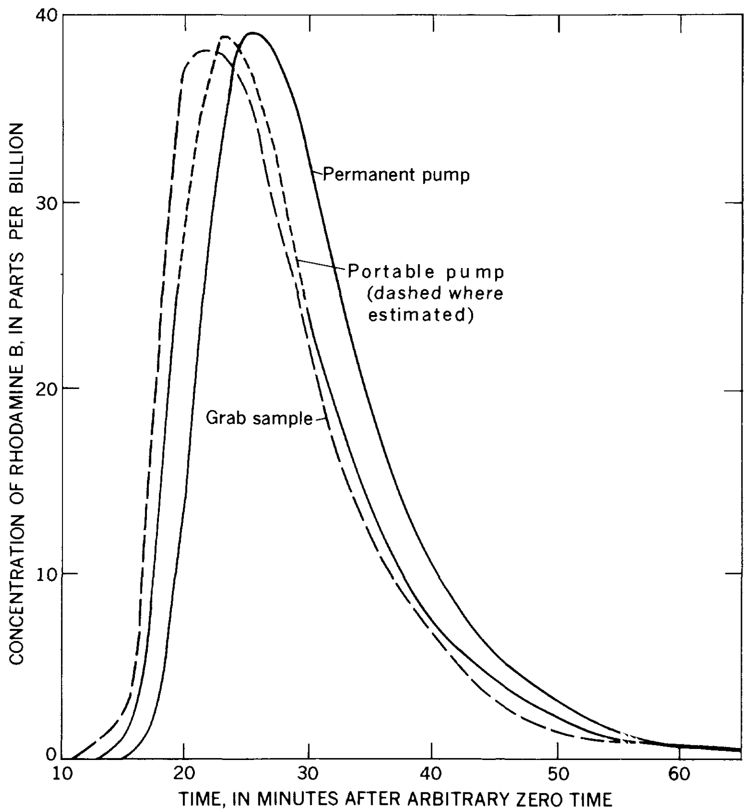

FIGURE 1.—Comparison of concentration-versus-time curves for three sampling techniques.

sion is not completely understood. Long tails have a noticeable effect upon the computation of the means and, especially, the variances of the curves. For this study, only the first 70 minutes of data after time zero (fig. 1) was used in the calculations of the means and variances. Beyond this time the curves are believed to be dependent upon such things as dye sorption by sediments and slow dye release from areas of slack water, rather than dispersion due to stream velocities.

Means for the grab samples, the portable pumping system, and the permanent pumping system were 26.7, 28.1, and 30.4 minutes from time zero, respectively. Thus, the use of various sampling methods yields various means for the same time of travel. A rough laboratory study using the portable pumping system indicated that the required pump-through time was comparable to the time shift from the grab-sample mean.

In most time-of-travel studies, sampling sites are far enough apart to require several hours or even days for travel of the dye cloud from station to station. Under such circumstances, even a 10-minute error would not be significant in determining the time of travel. However, where stations are close together, or traveltime is short, errors of 2 to 5 minutes may be significant. In such a situation, the data from the various sampling methods should be corrected for displacement of the mean.

Unless the sampling system used provides in situ measurements of concentration, it will bias the true mean to some degree. However, if one sampling method is chosen arbitrarily as a standard, as grab sampling was in this report, reduction of the time shift of other systems to that of the standard systems should be relatively simple. Time of travel is normally computed as the difference of means between stations. If all time shifts are corrected to standard values, and time of travel is computed by difference, then the resultant computation should be the true time of travel.

Variances for the grab samples and the portable pumping and permanent pumping systems were 54.93, 63.89, and 63.69, respectively. A statistical analysis showed that the variances for the three sampling techniques were equal at the 10-percent level of significance. In dispersion studies where the variance is needed to compute the dispersion coefficient, the various techniques of sampling that can be utilized must produce equal variances if used concurrently at the same test point. For most longitudinal dispersion studies, equality at the 10-percent level of significance should be adequate. In lateral or vertical dispersion studies, in contrast, equality of variances at the 10-percent level of significance may not be adequate. The use of only one sampling system would perhaps be necessary in these studies.

COMPARISON OF FLOOD-WAVE AND WATER-PARTICLE TRAVELTIMES

By THOMAS J. BUCHANAN

ABSTRACT

By applying the Manning and Chezy formulas, the ratio of the velocity of a flood wave to the mean velocity of water particles is shown to be between 1.3 and 1.7. The results of an actual study with a fluorescent dye in an open channel to determine the ratio show good agreement with the expected ratios in channel reaches without dams, but reaches with dams give ratios greater than 2.0.

Hydrologists have long been interested in the relation between the velocity of a flood wave in an open channel and the mean velocity of water particles in the same reach of the stream. In the past, valid data for these comparisons were almost unobtainable because of the difficulty of defining the mean velocity of the water particles in nonuniform reaches. The time-of-travel techniques discussed previously have made it possible to determine the traveltime of the water particles in such reaches and, thereby, to determine the mean velocity of the stream in the study reach.

The application of the Manning and Chezy formulas (Rouse, 1950) for different types of stream channels allows the determination of the expected ratios between the velocity of a flood wave (v_w) and the mean velocity of the stream (V). Ratios of velocity of flood wave to mean velocity of stream for three types of channels are:

Channel type	Ratio v_w/V	
	Manning formula	*Chezy formula*
Triangular	1. 33	1. 25
Wide rectangular	1. 67	1. 50
Wide parabolic	1. 44	1. 33

By these methods, the velocity of a flood wave is calculated to be between 1.3 and 1.7 times as great as the corresponding mean velocity.

One practical application of this relation is in the field of water supply. Consider the release from a reservoir of good-quality water which will be used at a downstream point for water supply. The time of travel of the flood wave will tell the water purveyor when to expect an increase in flow, and the time of travel of the water particles will tell him when to expect the good-quality water from the reservoir.

An opportunity recently was afforded in the Raritan River basin in central New Jersey to conduct a study of the relation between the traveltimes of a flood wave and water particles. The State of New Jersey had completed the construction of Spruce Run Reservoir in the basin in 1963. The reservoir is used to supply water in the northern part of the State. Some water is sold to a private water company 32 miles downstream from the reservoir, with delivery through the regular river channel. Both State and company officials were interested in determining the length of time for both the flood wave and the water particles released from the reservoir to reach the water company's intake.

The traveltime of the flood wave was determined by increasing the reservoir release by 135 cfs (cubic feet per second) and by observing changes in water stage at selected points downstream. Discharge in the study reach, about 34 miles in length, was about 300 cfs after the increase in flow from the reservoir.

The traveltime of the water particles was determined by injecting a fluorescent dye in the reservoir outfall. This was done after the increased flow for the flood-wave tracking had stabilized in the reach immediately below the reservoir. The dye content was then detected at downstream sampling points with a fluorometer. Sampling points used are listed in table 1.

TABLE 1.—*Sampling points and results of time-of-travel study in New Jersey*

Location	Drainage area (sq mi)	Distance downstream from Spruce Run Reservoir (miles)	Velocity, in miles per hour, of—				Ratio of velocity of—	
			Leading edge of flood wave	Full effect of flood wave	Leading edge of dye	Peak concentration of dye	Leading edge of flood wave to velocity of leading edge of dye	Full effect of flood wave to peak concentration of dye
Hamden	140	3.9	2.6	1.1	1.9	1.0	1.4	1.1
Stanton	142	7.8	2.6	1.4	1.6	1.1	1.6	1.3
Flagtown	260	21.4	2.0	1.3	.9	.8	2.2	1.6
Manville	490	31.3	1.9	1.3	.8	.6	2.4	2.2
Bound Brook	779	33.7	1.9	1.2	.7	.6	2.7	2.0

The results of the study are summarized in table 1. The ratios for reaches to Hamden and Stanton shown in the last two columns are in the range that might be expected in open-channel flow. However, ratios computed for locations downstream from Stanton are larger than might be expected.

In the reach from Stanton to Bound Brook, there are two dams between each sampling point or a total of six dams. The ponded water above these dams slows down the time of travel of the water particles as compared with the traveltime if the dams were not there. Thus, the mean velocity of the water particles traveling through the pools behind these dams will be much slower than those expected in the natural channel.

The reverse effect takes place with regard to the velocity of the flood wave. The velocity of a flood wave is directly proportional to the square root of the mean depth of the cross section. That is, the velocity of the flood wave will increase as the depth increases. Thus, the pools behind the dams tend to increase the velocity of the flood wave.

The unusually high ratios at Flagtown, Manville, and Bound Brook are probably due to the effects of the dams in these reaches.

The study completed in the Raritan River basin is another application of dye-tracing techniques. It offers hydrologists the opportunity to determine the mean velocity of a stream in a natural channel, which can, in turn, be used as an aid in the study of wave characteristics in open-channel flow.

This work was done in cooperation with the New Jersey Department of Conservation and Economic Development, Division of Water Policy and Supply and Division of Fish and Game.

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DYE-CLOUD PHOTOGRAPHY

By JAMES F. WILSON, JR.

ABSTRACT

For some time after a fluorescent dye is injected into a water body, the dye cloud is visible and may be photographed to supplement surface sampling qualitatively and quantitatively. Both vertical and oblique aerial photographs provide synoptic views of the surface distribution of the dye, which facilitates monitoring the spatial distribution of the dye over periods of time. Color photographs are useful for exhibition purposes; black-and-white photographs taken with appropriate filters cost less to publish in reports and are best for quantitative analysis by such techniques as photodensitometry.

INTRODUCTION

The spectacular part of a dye study is the dye injection. The colorful rhodamine dyes stain the receiving water and immediately respond to dispersion and transport mechanisms. Often the dye cloud takes surprising shapes and moves in unsuspected directions. Generally the dye is visible, and hence photographable, for a period of several hours or even days, depending upon the amount of dye used and the size and nature of the water body. This article describes the means of obtaining dye-cloud photographs.

Dye concentrations are determined fluorometrically from a time series of water samples collected at fixed points or from spatially distributed samples collected by traversing the dye cloud rapidly in a boat. Often 35-millimeter color photographs are taken from ground levels (streambanks, bridges, and boats) to record the visible dye, primarily for use later in illustrating talks. However, for some time oceanographers have been using aerial photographs, both in color and in black and white, to supplement surface sampling in the ocean quantitatively, even though the period of dye visibility is relatively short (Reinert, 1965; Ichiye and Plutchak, 1966). Recently hydrologists have recognized the usefulness of aerial photographs of dyes in lakes, streams, and estuaries. (See Fischer, 1966.)

The Phoenix, Ariz., Research Unit, Water Resources Division, U.S. Geological Survey, furnished the aerial photograph shown in figure

3. Robert M. Moxham, Branch of Theoretical Geophysics, Geologic Division, U.S. Geological Survey, furnished the isodensitracer data used in figure 4.

AERIAL PHOTOGRAPHS

Aerial photographs are most useful in tracing dye applications where monitoring the spatial distribution of the dye cloud is the principal objective—in estuaries or reservoirs, for example. However, even in time-of-travel measurements, where the temporal distribution of dye concentration is monitored as the dye cloud passes fixed locations, aerial photographs can provide valuable information. Because the first sampling site often is many miles below the injection site, photographs can reveal the initial surface dispersion pattern of the dye cloud and the cloud's configuration as it passes through channel bends, tributaries, and similar features.

The advantages of aerial photographs include the following:

1. Synoptic views of the entire dye cloud or a large part of it are possible.
2. Details of the shape of the cloud may be seeen which are not revealed by surface sampling data.
3. Repetitive coverage at short time intervals is possible.
4. In wide water bodies such as estuaries and lakes, the exact position of the dye cloud may be located in relation to identifiable fixed objects or terrain features.
5. Interference by light glare may be avoided or minimized.

Both fixed-wing aircraft and helicopters have been used for taking aerial photographs. In an early manned Apollo flight a large dye patch in the Gulf of Mexico may be photographed from space. Cameras used range from hand-held 35-mm cameras to large aerial reconnaissance cameras in permanently installed camera mounts.

Low-angle oblique pictures have some value, although vertical photographs are generally best to work with. For example, in a recent study in the Potomac estuary at Washington, D.C., low-angle color movies of the dye immediately after injection proved useful in studying subsequent dispersion patterns.

The altitude at which the aircraft is flown depends upon the size of the water body. Generally the aircraft should fly as low as possible, consistent with safety, but high enough for the photographs to include banks or shorelines and other terrain features needed for location purposes. Strip-film photography would be valuable where the dye is spread out a great distance along a stream. In this method of photography the film rolls past a continuously open slit in the camera at a speed coordinated with the speed of the aircraft. The result would be a continuous picture of the entire dye cloud on a single strip of film.

COLOR PHOTOGRAPHY

Color photographs are useful because the dye can easily be distinguished from similar features such as clouds of sediment. They are good for illustrating talks and for exhibit purposes, but generally are not published because of costs.

Standard color films such as Kodachrome, Aerial Ektachrome, or Aerial Anscochrome may be used. Generally, haze filters and color-enhancement filters should not be used. The rhodamine dyes appear red in reflected light. The dyes also are strongly fluorescent; absorbed light is re-emitted as yellow-orange light. Both reflected and fluorescent light probably contribute to the photographic image. Infrared color film may be useful for color enhancement, but has not yet been used.

BLACK-AND-WHITE PHOTOGRAPHY

Black-and-white photographs are suitable for publication in all kinds of reports. Figures 1 and 2 are good examples. Any panchromatic film may be used but a sharp-cut orange, red, or deep-red filter is recommended. The resulting image will show a white dye cloud against much darker water.

Filters that have been used include Wratten 15, 23A, and 25, and Corning 3–66 (the orange half of commonly used fluorometer filter 590). The relation of the emission (fluorescence) spectrum of the dyes to the transmission spectrum of the Wratten 23A and Corning 3–66 filters is shown in figure 3. Filters may be mounted on the camera or held by hand.

Supplementary color photographs are helpful in distinguishing the dye cloud from clouds of other materials. For example, comparison of figure 2 with a color photograph taken simultaneously confirmed that the muddy cloud in the mouth of the inlet, near the top of the photograph, was not dye. Later color photographs revealed dye in the mouth of the inlet after considerable dispersion.

Besides being suitable for publication in reports, black-and-white photographs are useful for photodensitometric analysis. A densitometer is a device for measuring the magnitude of light transmitted through an exposed and developed film negative. Ichiye and Plutchak (1966) have shown that excellent correlation can be obtained between photodensitometric traces on photographs of dye clouds and the results of surface sampling. An isodensitracer, a more complicated type of densitometer, actually contours the variation in intensity of light passing through a film negative (fig. 4). These tools should prove to be of value in dye studies in lakes and estuaries.

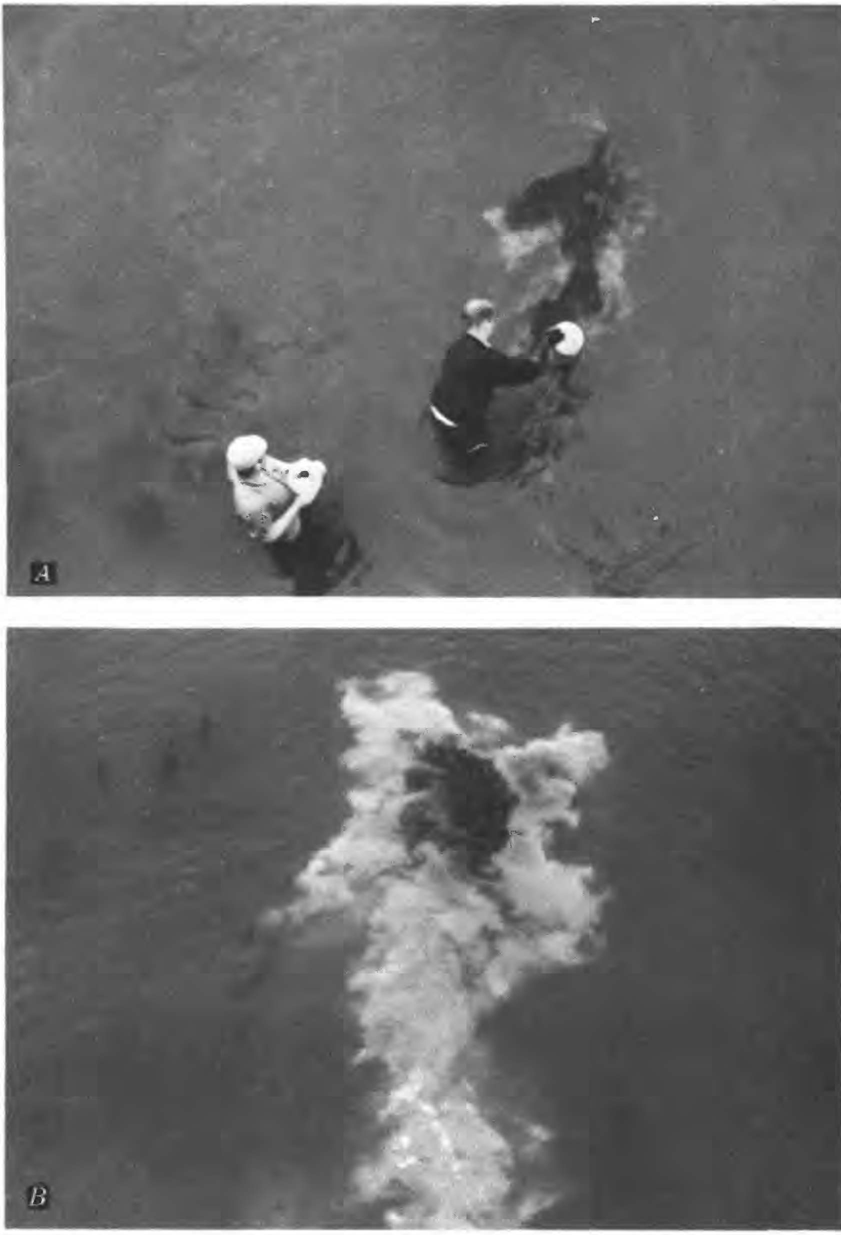

FIGURE 1.—Dye-cloud photographs taken from a low bridge, Grand River at Lansing, Mich., looking downstream. *A*, Injection of dye. *B*, Dye cloud about 5 minutes after injection, same scale as *A*. Dark patches are very high concentrations of dye, deep purple in color, and nearly opaque. (35-mm camera, Kodak Plus X panchromatic film, Wratten 25 filter.)

FIGURE 2.—Vertical aerial photograph of dye cloud in the Potomac estuary at Washington, D.C. (Altitude, 3,000 feet; aerial reconnaissance camera; Kodak Aerecon Safety film; Wratten 23A filter.)

FUTURE POSSIBILITIES

Photographs, of course, are limited to periods of daylight and to dye concentrations that are visible—usually above 25 parts per billion. The possibility of overcoming these two limitations by means of airborne electronic sensors is currently under study by the Geological Survey in cooperation with the National Aeronautics and Space Administration.

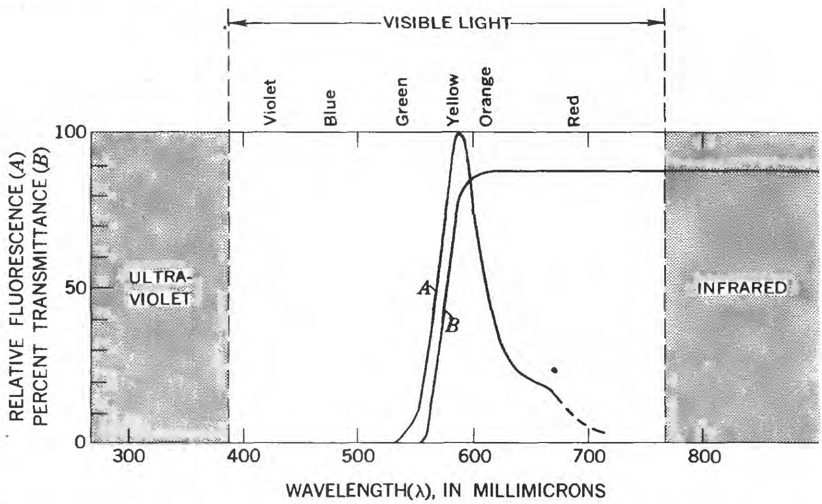

FIGURE 3.—Comparison of dye fluorescence with filter transmission for black-and-white photography. *A*, Generalized emission curve for the rhodamine family of dyes. Ordinates represent amounts of fluoresced light expressed in percent of the peak; absolute values depend on dye concentration and intensity of exciting light. *B*, Generalized transmittance curve for Wratten 23A or Corning 3–66 filters. Ordinates represent percent of incident light transmitted by the filter.

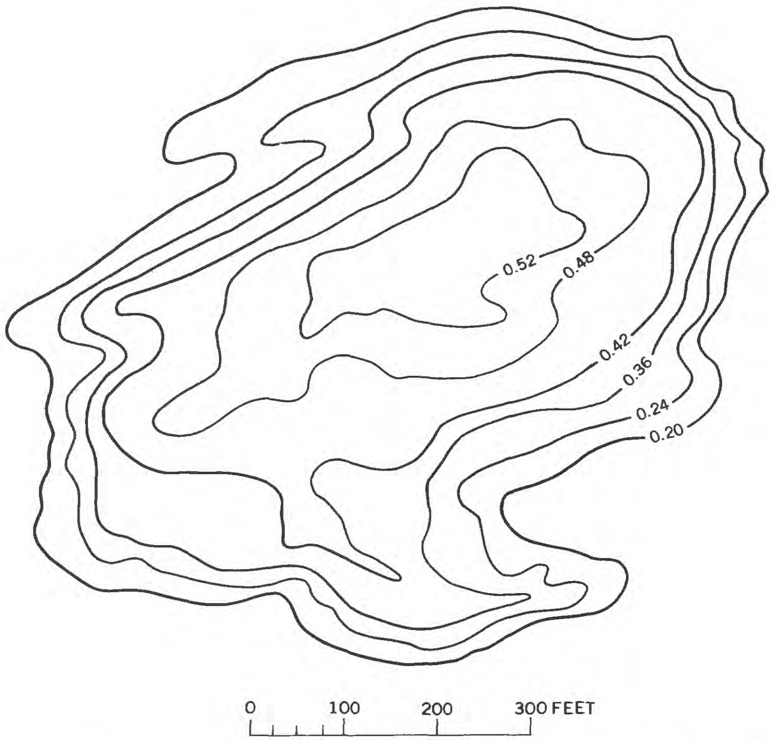

FIGURE 4.—Isolines of relative film density traced directly from an isodensitracer plot for the dye-cloud image in figure 2. Film density is believed to be proportional to dye concentration. (See discussion by Ichiye and Plutchak, 1966, p. 366.) The 0.20 line represents the visible edge of the dye cloud, approximately 0 to 20 parts per billion; the 0.52 line represents approximately 500 parts per billion, based on fluorometric analysis of water samples collected when the photograph was taken.

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A MICROKIT FOR DISSOLVED OXYGEN DETERMINATION

By Keith V. Slack

ABSTRACT

Methods are described for determining dissolved oxygen in a water sample contained in a 10-milliliter hypodermic syringe. Precision is better than 0.5 part per million. The equipment and supplies are standard items that cost less than $15, exclusive of reagents. A 3- by 5-inch card file box will contain all materials needed for up to 50 dissolved oxygen determinations. Reagents for the azide modification of the Winkler method are either drawn into the 10-ml syringe or injected through the tip into the syringe barrel. The sample can be titrated in a small flask or in the 10-ml syringe.

INTRODUCTION

Knowledge of the dissolved oxygen (DO) content of water is important in water-quality investigations to supplement other analyses and to identify situations for which more comprehensive samples are needed. Oxygen "sags" that are below sewage outfalls on waste-receiving streams are familiar examples of the indicator value of DO measurements. Information about the oxygen content of lakes, reservoirs, and ground waters may be even more valuable because of nuisance problems resulting from manganese, iron, hydrogen sulfide, carbon dioxide, color, and low pH which often accompany oxygen deficiency. Although most field chemists recognize these facts, DO data frequently are not collected because the usual method requires excessive amounts of time and equipment.

A simple portable kit for performing the azide modification of the Winkler method rapidly, safely, and with minimum contamination is shown in figures 1 and 2. The cost, exclusive of reagents, is less than $15. All necessary equipment and supplies can be packed into a 3- by 5-inch card file box. The time required for a determination is less than 10 minutes and precision is better than 0.5 ppm (part per million), adequate for most purposes. The methods described in this paper are applicable both in the laboratory and in the field.

SAMPLE COLLECTION

Samples for DO determination may be drawn into a 10-milliliter hypodermic syringe directly from the water body or from a sampling device. In some cases samples may be withdrawn through a large hypodermic needle or a cannula thrust through a rubber fitting on the sampler.

CLARIFICATION

Suspended sediment interferes with DO determination (American Public Health Association and others, 1965, p. 142). Samples may be clarified in a greased 25- or 50-ml syringe to prevent this interference. To a sample in a 50-ml syringe, add 1 ml of 6 percent alum solution and 0.1 to 0.2 ml of concentrated ammonium hydroxide. Gently mix by inversion for about 1 minute and allow the floc to settle with the syringe tip pointing upward. Insert a long hypodermic needle into the 50-ml syringe and withdraw a clear sample into a 10-ml syringe. A 3-inch 19-gauge spinal needle is a convenient size for this purpose.

DISSOLVED OXYGEN DETERMINATION

Either of two methods may be used to introduce reagents into the 10-ml syringe. The first method consists of drawing reagents into the syringe from depressions of a glazed porcelain plate (Burke, 1962). Although the procedure is simple, great care is required to prevent the accidental inclusion of air bubbles which result when slight movement of the syringe plunger during mixing allows a minute bubble to form in the syringe tip. The depression plate method may be inconvenient for use in small boats and during inclement weather. Also, the reagents are exposed to contamination and the accuracy of reagent measurement is not as great as in the second method. Carpenter (1965) noted that errors in the volumes of the alkaline and acid solutions should not exceed 5 percent for proper pH control in Winkler determinations.

A better method of introducing reagents is to inject them from 1-ml syringes through a rubber closure on the tip of a 10-ml syringe. Small serum caps make satisfactory closures, but they leak after repeated puncturing. A more durable closure can be made from a small rubber policeman. The open end of the rubber policeman is cut to the length of the syringe tip and the solid end is cut off leaving about one-eighth inch of rubber for the hypodermic needle to penetrate. The exact quantity of each reagent is introduced from 1-ml syringes equipped with small-gauge needles stuck through the rubber closure

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FIGURE 1.—A microkit for dissolved oxygen determination. Equipment packed in a 3- by 5-inch card file box.

into the barrel of the 10-ml syringe (fig. 3). As the reagents are injected, the plunger of the 10-ml syringe is automatically displaced to accommodate the added volume of liquid.

FIGURE 2.—Contents of a microkit for determining dissolved oxygen in a 10-ml hypodermic syringe by the depression plate method.

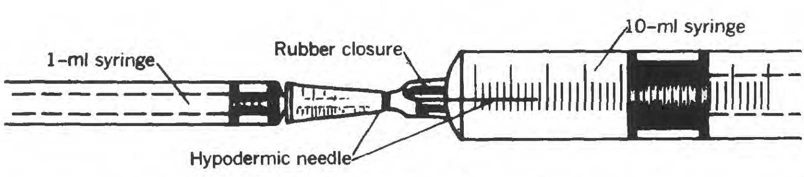

FIGURE 3.—Method of injecting reagents from a 1-ml syringe through a rubber closure into the barrel of a 10-ml syringe.

REAGENTS AND SUPPLIES

Prepare reagents and standard solutions as directed by American Public Health Association and others (1965) or by Rainwater and Thatcher (1960).

	Container
1. Manganous sulfate or chloride (reagent 1)	15-ml bottle.
2. Alkali-iodide-azide (reagent 2)	Do.
3. Sulfuric acid (or phosphoric acid), concentrated (reagent 3)	Do.
4. Sodium thiosulfate 0.0125 or 0.0118 *N*	30-ml bottle.
5. Distilled or demineralized water	15-ml bottle.
6.* Indicator for iodimetry:	
Thyodene powder	8-ml container.
Thyodene solution (0.5 gram per milliliter water) or starch solution.	15-ml bottle.
7. Silicone high-vacuum grease	8-ml container.

GENERAL EQUIPMENT

	Quantity
Box, 3 by 5 by 2¾ inches (or other suitable container)	1
10-ml hypodermic syringe	2
1-ml hypodermic syringe with 25-gauge needle	1
25-ml Erlenmeyer flask	[1] 1
3× pocket magnifier	1
15-ml polyethylene bottle for reagents	[2] 5
30-ml polyethylene bottle	1
8-ml polyethylene container for silicone grease	1
8-ml polyethylene container for Thyodene indicator	[1] 1
Absorbent tissue, sheets, small package	1
Measuring spoon, 0.1 g	[1] 1

[1] Not required if sample titrated in 10-ml syringe.
[2] One additional required if sample titrated in 10-ml syringe.

CALCULATIONS

$$\text{DO ppm} = \text{ml } 0.0118\ N \text{ sodium thiosulfate used} \times 10 \quad (1)$$

$$\text{DO ppm} = \text{ml } 0.0125\ N \text{ sodium thiosulfate used} \times 10.635 \quad (2)$$

See Burke (1962) for method of derivation.

FIXING SAMPLES

DEPRESSION PLATE METHOD

Equipment includes general equipment plus a 92- by 31-millimeter glazed porcelain depression plate.

The procedure is as follows:

1. Place reagents 1, 2, and 3 in separate depressions of the porcelain plate.
2. Draw a water sample into a 10–ml syringe which has been internally coated with silicone grease to inhibit plunger slippage and to prevent air leakage. Hold the syringe tip upward and tap to remove bubbles. Expel the water and refill. With the syringe tip up, expel water to the 9.4-ml mark.

3. Draw 0.2 ml of manganous sulfate solution (reagent 1) into the syringe from the depression plate. Rinse the syringe tip with distilled or demineralized water and wipe dry with tissue. Thoroughly mix the contents by repeatedly upending the syringe. (Note: Slight movement of the plunger during mixing may allow a minute air bubble to form in the syringe tip. Expel it carefully before proceeding.)
4. Draw 0.2 ml of alkali-iodide-azide solution (reagent 2) into the syringe from the depression plate. Rinse and wipe the tip. Mix well as described above. Allow the precipitate to settle. Mix again. Check for air bubble in tip.
5. After precipitate has settled, draw 0.2 ml of sulfuric (or phosphoric) acid (reagent 3) from the depression plate into the syringe. Rinse and wipe the tip. Mix to dissolve the precipitate.

INJECTION METHOD

Equipment includes general equipment plus two rubber closures for 10-ml syringe and three 1-ml syringes with 25-gauge needles. Four 1–ml syringes are required if the sample is titrated in the 10–ml syringe. Label syringes to prevent mixing of reagents.

The procedure is as follows:

1. Fill 1–ml syringes with reagents.
2. Draw a water sample into a 10–ml syringe which has been internally coated with silicone grease. Hold the syringe tip upward and tap to remove air bubbles. Expel the water and refill. With the syringe tip up expel water to the 9.4–ml mark.
3. Place a rubber closure on the tip of the 10–ml syringe (Note: Pinch the open end of the rubber closure between thumb and forefinger to eliminate entrapped air as the closure is forced onto the syringe tip. Both the closure and the tip should be dry and free of grease.)
4. Insert needle of 1–ml syringe (containing reagent 1) through rubber closure into the 10–ml syringe (fig. 3). Slowly inject 0.2 ml manganous sulfate solution into the 10–ml syringe. Withdraw needle from rubber closure and mix the sample by repeatedly upending the syringe.
5. Inject 0.2 ml alkali-iodide-azide solution (reagent 2) as in step 4. Withdraw needle and mix. Allow the precipitate to settle. Mix again.
6. After precipitate has settled, inject 0.2 ml sulfuric (or phosphoric) acid (reagent 3) as in step 4. Withdraw needle and mix to dissolve the precipitate.

TITRATING SAMPLES

Samples fixed by either of the two methods may be titrated over a white surface in a 25-ml Erlenmeyer flask or directly in the 10-ml syringe. The end point is easier to observe in the flask, but with practice the syringe method gives satisfactory results. Titrating in the syringe decreases the amount of equipment and reduces to a minimum the possible loss of iodine by volatilization.

ERLENMEYER FLASK METHOD

Expel the 10.0 ml of solution from the syringe into a 25-ml Erlenmeyer flask. For critical work, draw about 0.5 ml distilled water from a depression plate into the 10-ml syringe, invert, and withdraw plunger to the 10.0 mark to rinse the syringe barrel. Expel rinse solution into the flask. Titrate with standardized sodium thiosulfate solution contained in a greased 1-ml syringe with 0.01-ml graduations. Use a 25-guage needle on the syringe to control drop size. When the iodine color has nearly disappeared, add one measuring spoonful of Thyodene indicator powder (about 0.1 g) and continue titrating to the first complete disappearance of the blue color. (Note: With practice the syringe can be manipulated with one hand while the flask is swirled with the other. Use the thumb and forefinger to actuate the plunger of the 1-ml syringe, fingers around the plunger and barrel.) Estimate readings of the 1-ml syringe to the nearest 0.005 ml with the aid of the 3× pocket magnifier.

SYRINGE METHOD

Begin titration by injecting small increments of standardized sodium thiosulfate through the rubber closure into the 10-ml syringe. Upend the syringes to induce mixing after each addition of sodium thiosulfate. When the iodine color has nearly disappeared, remove the thiosulfate syringe and inject 0.2 ml Thyodene or starch solution into the 10-ml syringe. Remove the syringe containing the indicator solution and leave the hypodermic needle sticking through the rubber closure. Carefully draw about 0.5 ml air into the 10-ml syringe and remove the hypodermic needle. Reattach the 1-ml syringe containing sodium thiosulfate and continue titration to the first complete disappearance of the blue color. (Note: The air bubble improves mixing in the syringe barrel and also allows the operator to see the drop size for the final additions of sodium thiosulfate.)

GENERAL NOTES

Either glass or plastic syringes may be used. Glass syringes are fragile and more expensive than plastic syringes of the disposable type. I prefer plastic syringes for the DO samples and for the reagents, but a good quality glass tuberculin syringe for titrating.

Smudging of the graduations on disposable plastic syringes can be prevented by covering the syringe barrel with transparent, waterproof plastic tape. Transparent heat-shrinkable tubing intended for electrical insulation also may be used as a covering for plastic syringe barrels. Breakage of glass syringes during transit can be reduced by inserting them into lengths of plastic tubing or wrapping with transparent plastic tape.

Air bubbles, which tend to adhere to the rubber ends of plastic-syringe plungers, may be eliminated by placing a generous quantity (0.1 to 0.2 ml) of silicone grease on the end of the plunger and by pressing the plunger tightly into the barrel of the syringe (C. D. Ripple, oral commun., 1966). The air and excess grease are expelled through the tip, and it is possible to draw in a bubble-free water sample. Silicone stopcock grease may be substituted for the high-vacuum grease in this application.

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FIELD KIT FOR DETERMINING ALKALINITY

By J. L. Kunkler

ABSTRACT

Accurate field determinations of alkalinity are possible with the described field kit because the temperatures of the standard buffer solutions and the samples are maintained within 2° C of the temperature of the sampling source. Field determinations of standard solutions indicate that results deviate less than 1 percent from the correct values.

Accurate field determinations of alkalinity are necessary for the study of many types of water problems. For example, the alkalinity of water that is precipitating travertine, a mineral composed of calcium carbonate, may change rapidly after sample collection. Samples from the Sandia Mountains in New Mexico of spring water precipitating travertine have shown changes of more than 0.1 pH unit 30 seconds after collection. Such chemical instability requires that alkalinity be determined in the field at the time of sample collection if the determination is to be useful for geochemical studies.

Alkalinity is usually caused by the presence of bicarbonates, carbonates, and hydroxides in waters.

Consideration must be given to maintaining the standard buffer solutions, the sample, and the electrodes at the temperature of the sampling source if accurate field determinations of alkalinity are to be made. This article describes a simple portable field kit that maintains the temperatures of these items within 2° C of the temperature of the sampling source.

Selected components of the field kit are shown in figure 1. A reservoir and a water bath are constructed from a 5-gallon GI water can and an 8-inch-diameter sieve pan approximately 2 inches deep. A connector for rubber tubing is soldered to the water can about 1 inch above the base. Flow into the water bath from the water can through the rubber tubing is regulated by a valve soldered about one-half inch above the bottom of the water bath. Another connector is soldered to the water bath about one-half inch below the top of the bath and, when tubing is attached, serves as a drain.

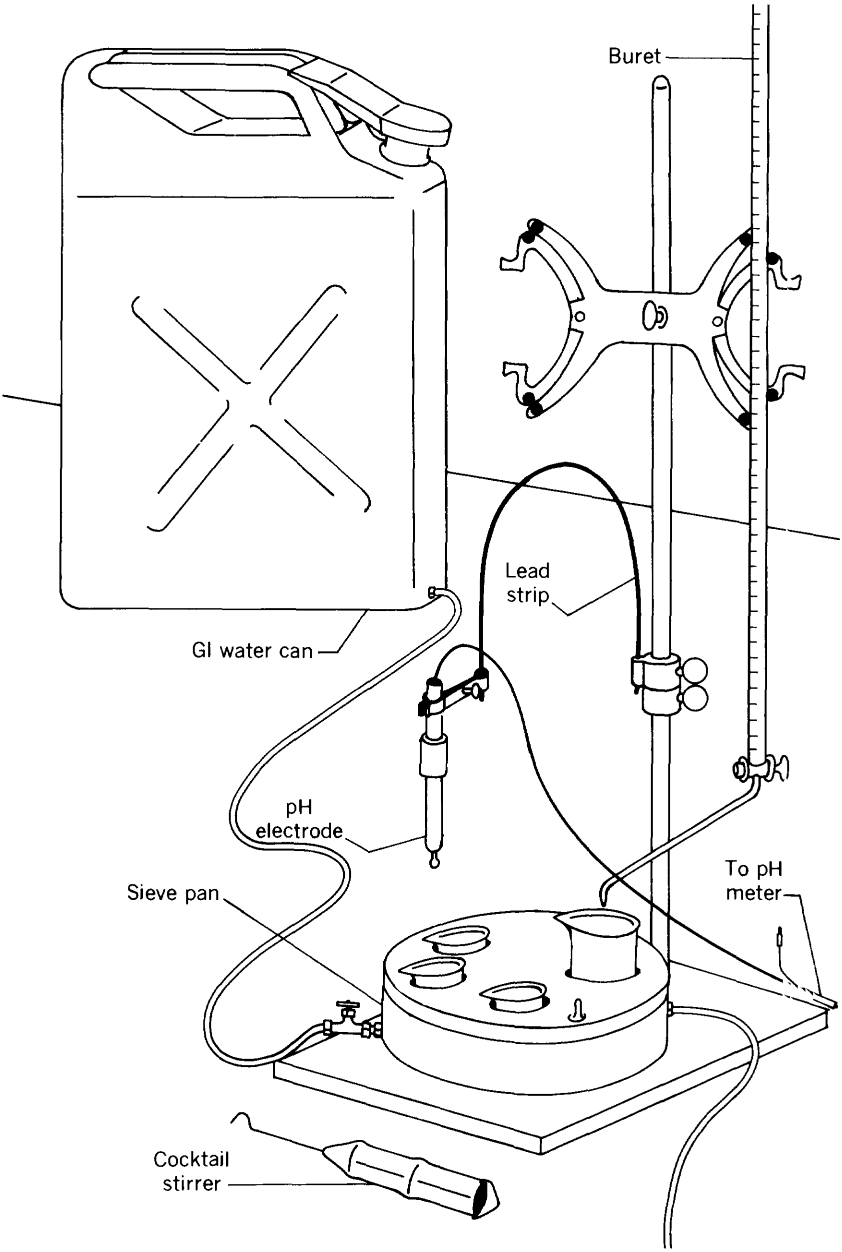

FIGURE 1.—Selected components of field kit for determining alkalinity.

The bath is covered with a lid containing four holes. Three of these holes can accommodate 50-ml (milliliter) beakers and the fourth, a 150-ml beaker. A bolt soldered to the lid serves as a handle to move the lid and position the beakers. Both the reservoir water can and the water bath are painted with several coats of white paint and epoxy resin to minimize heat transfer.

In field operations the water can is filled with water from the sampling source and the valve on the water bath is adjusted for a flow of about one-half pint per minute. The 50–ml beakers are filled with the appropriate standard buffer solutions and placed in the bath water. After water has flowed through the water bath for about 30 minutes and the buffer solutions have been stirred occasionally, thermal equilibrium between the bath water and buffer solutions is usually attained. A portable battery-operated pH meter (not shown in fig. 1) is calibrated with the buffer solutions at the equilibrium temperature. Then a sample of water is collected and titrated in a 150-ml beaker placed in the water bath. The technique of the alkalinity determination is described by Rainwater and Thatcher (1960, p. 94). No attempt is made to bring the titrant to the temperature of the water bath and no attempt is necessary if sufficient time is allowed near the end point for the sample to come to thermal equilibrium with the water bath. A small battery-operated cocktail stirrer is used to stir the sample during the titration.

A combination glass and reference electrode is used to measure pH values. The electrode is attached by an electrode clamp to a thick strip of lead, which is attached to a swivel on a ringstand. The lead strip bends easily and facilitates washing and positioning the electrode.

This apparatus has been field tested on solutions of known alkalinity and results were consistently within 1 percent of the correct values.

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RAPID FIELD FILTRATION OF WATER SAMPLES

By CHARLES F. BERKSTRESSER, Jr.

ABSTRACT

Water samples should be filtered in the field at the time of collection to reduce chemical change when samples are stored. A successful method is to use a pressure-filtration apparatus.

INTRODUCTION

The goal of collecting water samples is to determine the chemical quality of water at the time of collection. Environmental impurities that may alter the chemical nature of water during storage include bacteria and colloids, clay, silt, and sand, as well as algae, insect larvae, tadpoles, leaves, and twigs. Any of these may affect the chemistry of the sample by biologic appropriation or release, adsorption, or other physical and chemical reactions.

Filtration is essential in preserving the chemical quality of samples from biotically active environments or when extraneous matter is present. The following analytical data demonstrate changes presumably caused by an algal bloom in a sample after collection.

	Sample pressure filtered at time of collection	Sample unfiltered, analyzed after algal bloom
Date:		
Collected	January 20, 1966	January 20, 1966
Analyzed	January 29, 1966	February 21, 1966
Bicarbonate ppm	662	420
Carbonate ppm	0	22
Sulfate ppm	2	157
Specific conductance micromhos at 25° C	1, 670	1, 690
pH	8. 2	8. 6

Except for filtration and length of storage time, these samples were collected and stored under identical conditions. The filtered sample exhibited no visible evidence of algal bloom after storage for an additional 7 months. Experience with other samples also indicates that filtration stabilizes alkalinity.

VACUUM FILTRATION

Vacuum filtration is described by Wilder (1966) and Harmon (1966) who attempted to solve the problem of sample preservation. Unfortunately, vacuum filtration alters partial pressures of dissolved gaseous constituents and consequently tends selectively to remove dissolved gases from the sample; for example, carbon dioxide. The following tables shows data for both pressure- and vacuum-filtered samples compared with data for the raw sample. These analyses were made within 48 hours of collection, and presumably before appreciable biotic change had occurred. Analyses of the raw and pressure-filtered samples agree within the experimental limits of the method; the analysis of the vacuum-filtered sample exhibits a significant departure in each constituent and in total alkalinity. Reproducibility better than 2 percent cannot be expected in this determination for the common alkalinity components (bicarbonate and carbonate), but the total alkalinity value is somewhat more stable than the component values (Rainwater and Thatcher, 1960, p. 94). Each of the values above was verified by a second filtration.

	Sample condition		
	Raw	Pressure filtered (100 psi)	Vacuum filtered (2.1 mm Hg)
Bicarbonate ppm	418	420	410
Carbonate ppm	22	24	14
Total alkalinity (as HCO_3) ppm	464	468	438

PRESSURE FILTRATION

Pressure filtration, preferably with nitrogen, is an alternative to vacuum methods. Both carbon dioxide and oxygen are readily available but can react with the water sample. Compressed air contains both carbon dioxide and oxygen and is likewise unsuitable. Helium is chemically suitable but is expensive and may be difficult to obtain. Nitrogen is cheap, readily available, and only slightly soluble in water. No chemical reactions are known to occur in water when nitrogen is introduced under pressure.

In the apparatus and procedure described in the following sections, nitrogen gas was used to produce filtration pressure.

APPARATUS AND MATERIALS

The apparatus (fig. 1, 2) and materials are listed as follows:

Nitrogen gas, compressed (Airco nitrogen OP or equivalent).

Gas-pressure regulator, calibrated to 20 psi (pounds per square inch) or finer.

Stainless-steel pressure vessel, Millipore XX67 000 or equivalent.

Stainless-steel high-pressure filter holder, Millipore XX45 04700 or equivalent.

High-pressure tubing (250+ psi).

Stainless-steel fittings.

Fiberglass prefilter, Millipore AP20 or equivalent.

Plastic-membrane filter, Millipore AP20 or equivalent.

Sample bottle.

FIGURE 1.—Field filtration equipment. From left to right, the nitrogen cylinder and gas-pressure regulator, pressure vessel, high-pressure filter holder, and sample bottle.

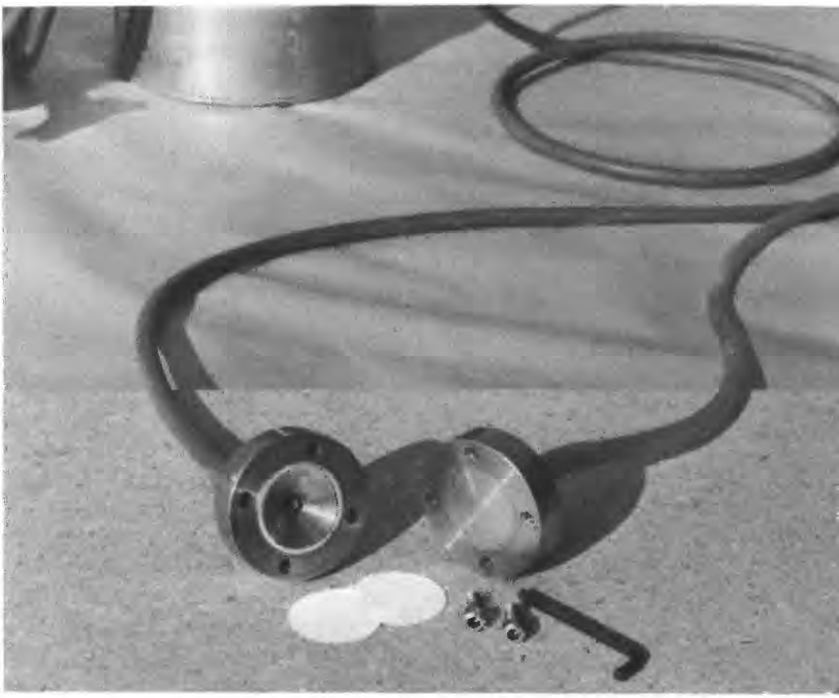

FIGURE 2.—Details of pressure filter holder. Right half shows filter support and discharge line. White discs are the fiberglass prefilter and plastic-membrane filter. Screws fasten two parts as seen in figure 1.

OPERATION

Water samples generally are collected in the pressure tank. Rinse the container at least twice with sample water before collecting the sample. If the water is particularly turbid or contains gross solid material, such as leaves, spores, or larvae, a sample may be collected temporarily in a clean container, sealed tightly, and stored in darkness until the material has a chance to settle. A siphon with an upturned intake that rises above the sediment layer at the bottom of the sample bottle can be used to separate the sample from the solids. Darkness during storage is necessary to minimize phototropic activity.

The nitrogen cylinder is connected to the pressure tank with tubing via a gas-pressure regulator. This regulator should be calibrated to at least 20 psi. A minimum pressure (breakthrough pressure) of 50 psi is required to initiate flow through the filter system. Normal operating pressure, which depends upon the relief valve on the pressure tank, is about 100 psi.

The filter system consists of a prefilter and a filter in the holder (fig. 2). The prefilter is a fiberglass pad that removes coarse material and reduces buildup of unsorted-size material. The filter used by the author is a plastic membrane that removes material coarser than 0.45 micron. A 0.45-micron pore size seems to provide a satisfactory compromise between removal of particulate matter for most analytical purposes and a satisfactory flow rate. For special purposes, such as the removal of all colloids, smaller pore sizes have been suggested (V. C. Kennedy, oral commun., 1966); however the flow rate is substantially reduced. A typical filtration rate for water samples through 0.45-micron filters is about 0.2 gallon per minute. Use of the fiberglass prefilter generally extends filter life at least fourfold.

SAFETY CONSIDERATIONS

Commercial nitrogen tanks are heavy and unwieldy. Therefore, they should be anchored securely in the vehicle and in such a position that injury to the driver does not occur.

SUMMARY

Solids may cause changes in water quality of samples during storage; it is therefore desirable to remove particles in the field. Filtration is the best method of doing this; both vacuum filtration and pressure filtration are feasible. However, vacuum filtration and pressure filtration with chemically active gases may cause chemical changes in the sample. The author chose nitrogen gas for pressure filtration because of low cost, availability, and low chemical activity. This sample apparatus has furnished excellent results.

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FIELD MONITORING OF THE QUALITY OF WATER DURING THE DRILLING OF WELLS

By JACK RAWSON

ABSTRACT

During the drilling of wells, aquifers at different depths that yield water of different chemical composition may be penetrated. Although fluid-conductivity logging of the wells provides an indication of the total dissolved-solids content of the water in the several aquifers, conductivity alone does not indicate the types and concentrations of individual ions in the water. In conjunction with conductivity measurements, simple, rapid, and accurate visual methods of analysis for chloride, sulfate, and hardness can be conducted in the field to provide more detailed and reliable information on the chemical composition of the water as it is reached.

INTRODUCTION

Multiple-aquifer wells may penetrate formations that yield water of different chemical composition. Dissolved constituents in the water from some of these aquifers may limit or preclude the use of the water as a domestic supply. Field monitoring of the quality of water during the drilling of wells permits immediate decisions by management and thus eliminates the necessity and cost of maintaining a drilling crew on standby while waiting for a chemical analysis from a laboratory possibly several hundred miles away.

If sufficient data on the chemical composition of the water are obtained as the water is reached during drilling, those formations that yield water of poor quality can be identified and sealed off to prevent contamination of water from the other formations. Regardless of whether a well penetrates one or several aquifers, field analyses will aid in determining if the well should be developed as a domestic supply or abandoned.

The suitability of a water for domestic use depends partly upon the types and concentrations of various ions in the water. Constituents or properties in excessive amounts that often preclude the use of a water as a domestic supply include dissolved solids, chloride, sulfate, and hardness. According to the U.S. Public Health Service (1962), the suggested limits for dissolved solids, sulfate, and chloride in drinking water are 500 ppm (parts per million), 250 ppm, and 250 ppm, respectively. Fluid-conductivity logging of a well provides some indication of the total dissolved-solids content of water in an aquifer. However, conductivity alone does not identify the types and concentrations of individual ions in the water. More detailed and reliable information on the chemical composition of the water can be obtained by simple, rapid, and accurate methods of analysis.

METHODS OF FIELD ANALYSIS

Selected visual laboratory methods for the determination of chloride, sulfate, and hardness are suitable for field use. Chloride can be determined by the Mohr method of using silver nitrate as the titrant and potassium chromate as the indicator (Rainwater and Thatcher, 1960, p. 141–143). Detection of the end point in this method is facilitated by illuminating the titration with yellow light. Sulfate can be determined visually by using barium chloride as the titrant and a dioxane-thorin solution as an indicator (Rainwater and Thatcher, 1960, p. 279–281). Because many metal ions interfere with this method, all metals are removed before titration by passing the sample through an ion-exchange column charged with Amberlite IR–120 and operating on the hydrogen cycle. Hardness can be titrated visually with disodium dihydrogen ethylenediamine tetraacetate (Na_2 EDTA) by using Eriochrome Black T as the indicator (Rainwater and Thatcher, 1960, p. 174–176).

The total dissolved-solids content of water can be estimated by electrical conductivity measurements. Although no exact relation exists between dissolved solids and specific conductance, the following general relation is applicable unless the water has an unusual composition:

$$\text{Dissolved solids (ppm)} = \text{specific conductance (micromhos)} \times 0.65 \pm 0.1.$$

Equipment for the determinations includes filter holders, filter flasks, filter paper, pipets, burets, beakers of assorted sizes, chloride dishes, stirring rods, a battery-powered lamp with a yellow bulb (or yellow goggles), an ion-exchange column, and a portable conductivity meter.

Because the equipment takes little space and requires no electrical power, it can be assembled and water samples can be analyzed at the drilling site. Where no more convenient space is available, the rear compartment of a station wagon is adequate.

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COLLECTION OF REPRESENTATIVE SAMPLES WITH REFERENCES TO VARIOUS METHODS OF DRILLING

Regardless of whether the water sample is analyzed in the field or laboratory, the chemical analysis is only as useful as the sample is representative. Although a representative sample may be collected during either the cable-tool or rotary methods of drilling, the cable-tool method is especially advantageous for detecting water-bearing formations and for the frequent collection of water samples. Generally the small amount of drilling fluid used in cable-tool drilling does not seal off a water-bearing formation. The aquifer can be detected readily; contaminants can be flushed from the formation with a minimum of bailing or pumping; and a representative water sample from the formation can be obtained by pumping or with a point sampler.

In the rotary method of drilling, the bore hole is kept full of heavy mud that is circulated to cool the bit, return the cuttings to the surface, and prevent caving. Due to its specific gravity, this fluid may exert a greater pressure against the walls of the hole than water flowing in from a formation. The mud tends to penetrate and seal the pore spaces of a formation and prevent water in a formation under low hydrostatic pressure from entering the hole. As a result, some water-bearing formations may be misinterpreted as dry. Drilling fluid continuously lost by seepage through the walls of the hole may contaminate water in formations. Therefore, identification of all water-bearing formations penetrated by a rotary-drilled well and collection of representative water samples may require the use of packers to isolate the individual formations and may require long periods of pumping or surging to flush drilling contaminants from the formations.

PRACTICAL APPLICATION OF FIELD MONITORING OF THE QUALITY OF WATER DURING TEST DRILLING

In July 1963 the National Park Service began test drilling to locate a source of water for a proposed campground and ranger station in the Castolon area, Big Bend National Park, Tex. (fig. 1). The results of previous work in the area indicated that any fresh-water-bearing beds found in the area might be immediately underlain by beds containing water unsuitable for domestic use. The author went to Castolon to monitor the quality of water during the drilling.

Three test wells were drilled in the Castolon area. Wells T–1 and T–2 were drilled in the dry channel of Blue Creek. Blue Creek heads in the Chisos Mountains and a large part of its course is deeply incised in rocks of Tertiary or Cretaceous age. The rocks of Tertiary age consist of bedded tuff, welded tuff, tuffaceous sandstone, conglomerate, and lava; the rocks of Cretaceous age consist of gypsiferous marl, clay, silt, sandstone, and coal (Leggat, 1963, p. 7). At the drilling sites, Blue Creek occupies an alluvial-filled channel cut in very fine, easily eroded silt.

Test well T-3 was drilled in the dry channel of Alamo Creek (fig. 1). Sedimentary rocks of Late Cretaceous age and volcanic rocks of

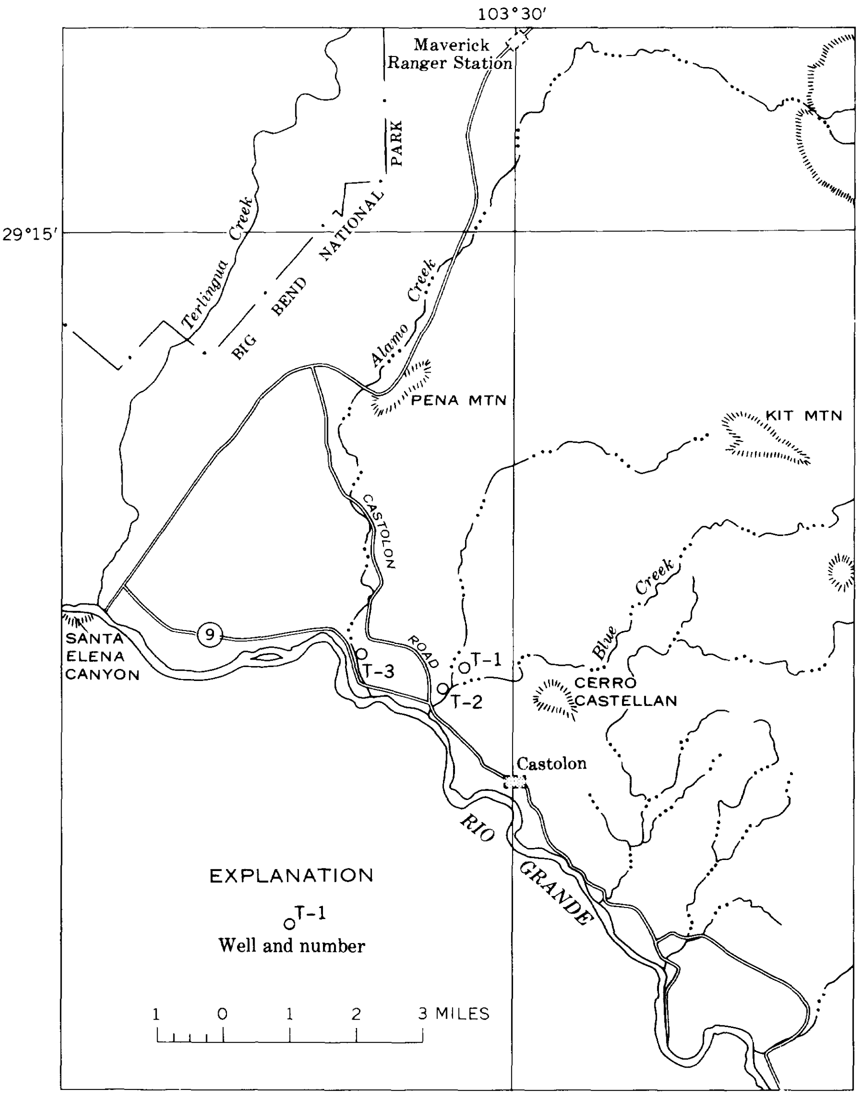

FIGURE 1.—Map of Castolon area, Big Bend National Park, Brewster County, Tex., showing locations of test sites.

Tertiary age are exposed in a large part of the drainage area of Alamo Creek (Leggat, 1963, p. 13). At the drilling site, the wide channel of Alamo Creek is filled with alluvium.

The three test holes were drilled by the cable-tool method. As each well was drilled, formation samples were collected at 5-foot intervals; and when water was reached, the yield was estimated by bailing. A water sample for chemical analysis was collected with a Foerst sampler. Drillers' logs for the test holes are given in table 1 and the results of chemical analyses are given in table 2.

TABLE 1.—*Logs of test wells in the Castolon area, Big Bend National Park, Brewster County, Tex.*

[Driller: C. Langlitz]

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Castolon test well 1					
Silt	3	3	Clay, gray, slight brown tint	5	140
Sand	25	28	Clay, gray, with trace of gray shale	5	145
Sand, fine-grained	9	37	Shale, gray	15	160
Sand, with clay	3	40	Clay, gray, shaly	10	170
Clay, yellow, with some gray	5	45	Clay, gray	5	175
Clay, grayish-yellow	5	50	Clay, gray, sandy	5	180
Clay, blue, silty	10	60	Clay, greenish-gray, sandy	10	190
Clay, blue	10	70	Sand, greenish-gray, argillaceous	5	195
Clay, brownish-gray	5	75	Sand, greenish-gray, with some clay	5	200
Clay, brownish-gray, containing very fine gravel	5	80	Sandstone, greenish-gray	10	210
Clay, gray, slight brown tint	5	85	Sand, greenish-gray argillaceous	5	215
Clay, reddish-brown	35	120			
Clay, grayish-brown	15	135			
Castolon test well 2					
Sand and gravel	20	20	Clay, brownish-gray	5	45
Sand and gravel, silty	5	25	Clay, brown	5	50
Sand and gravel	15	40	Clay, grayish-brown	10	60
Castolon test well 3					
Silt, light-brown	10	10	Clay, reddish-brown	5	55
Sand and gravel	36	46	Clay, yellowish-gray	10	65
Clay, grayish-brown	4	50	Clay, reddish-brown	4	69

TABLE 2.—*Field analyses of water from test wells in the Castolon area, Big Bend National Park, Brewster County, Tex., in 1963*

[Results in parts per million except as indicated]

Well	Depth (feet)	Date of collection	Sulfate (SO_4)	Chloride (Cl)	Hardness as $CaCO_3$	Specific conductance (micromhos at 25° C)[1]
U.S. Public Health Service drinking water standards			250	250	----------	---------
T-1	200	July 11	<5	778	26	2,300
2[2]	25	July 13	228	33	60	900
2	47	July 14	68	10	16	450
2	60	July 16	54	7.0	36	410
3	46	July 17	338	14	124	1,020
3	68	July 19[3]	364	13	96	1,100
3	68	July 19[4]	316	13	128	1,090

[1] Field conductivity instrument was later found to have been operating improperly. Results shown are believed to be about 200 micromhos too low.
[2] Sample possibly contaminated by river water used in drilling.
[3] Time of collection, 7:00 a.m.
[4] Time of collection, 6:30 p.m.

A water-bearing sand was penetrated in well T-1 (table 1) at a depth of about 200 feet. However, field analyses showed that the dissolved-solids (as indicated by specific conductance) and sulfate content of the water exceeded the limits recommended by the U.S. Public Health Service. The well was then deepened to 215 feet, where a trace of oil was discovered. Therefore, the hole was plugged, capped, and abandoned.

A water-bearing sand was penetrated by well T-2 at a depth of about 18 feet (table 1). At a depth of 25 feet, the hole was cleaned out and the yield was estimated by bailing; but before a representative sample could be obtained, the hole caved. The hole was again drilled to 25 feet and was bailed for only a brief period before the collection of a water sample. As a result, the sample undoubtedly was contaminated with drilling fluid, but because the estimated yield was only about 1 gpm (gallons per minute) and because the hole could not be kept open, casing was installed and drilling was continued to a depth of 47 feet, where a more representative sample was obtained. A chemical analysis of water from this depth (table 2) indicated that the water was suitable for domestic use, but the yield was estimated to be only about 3 gpm. Therefore the hole was deepened to 60 feet and a chemical analysis of the water from this depth (table 2) indicated that the water was suitable for domestic use. Consequently, the well was completed with 6-inch casing, torch slotted from 15 to 45 feet, and was developed as a possible domestic supply.

Well T-3, in the channel of Alamo Creek, penetrated a water-bearing sand and gravel at a depth of about 32 feet (table 1). The hole was deepened to 46 feet where a sample of water was collected for chemical analysis. The analysis (table 2) indicated that the dissolved-solids and sulfate content of the water exceeded the limits recommended by the U.S. Public Health Service. Subsequently the hole was deepened to 69 feet. Between depths of 50 and 69 feet a nonwater-bearing clay was penetrated and drilling was discontinued. The hole was bailed, the yield was estimated, and another sample for chemical analysis was collected. The analysis (table 2) confirmed that the dissolved-solids and sulfate content of the water exceeded the limits recommended by the U.S. Public Health Service. Nevertheless, the analysis indicated that the water could be used as a supplementary supply in the event that well T–2 could not yield a sufficient quantity of water. The well was completed and developed as a possible supplementary domestic supply.

Field monitoring of the quality of water found during the drilling of test wells in the Castolon area, in conjunction with the collection and evaluation of formation samples, indicated that a single, but different, aquifer was penetrated by each well. More importantly, the field analyses provided almost immediate information on the suitability of the water for domestic use. These data permitted immediate decisions by management and eliminated the necessity of maintaining a drilling crew on standby while waiting for results of chemical analyses from a distant laboratory.

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SAMPLING APPARATUS TO MINIMIZE AERATION OF WATER COLLECTED AT SHALLOW DEPTHS FOR THE DETERMINATION OF DISSOLVED GASES

By B. F. Joyner

ABSTRACT

A sampling apparatus for collecting nonaerated water from shallow depths for the determination of dissolved gases can be assembled from materials available in any chemical laboratory. The device can be used in water only 1 inch deep; conventional samplers for the same purpose cannot be used in water less than 18 inches deep.

Frequently it is desirable to collect water samples for the determination of dissolved gases such as hydrogen sulfide or oxygen. Samples should be collected with a minimum of aeration to prevent loss of the gases. Conventional sampling apparatus consists of a cylindrical brass container 4 inches in diameter and 16 inches high that has an internal built-in platform, a screw cover with an inlet orifice to which a tube is connected, and a special 300-milliliter sample bottle that rests on the platform. When the sampler is assembled, the tube from the inlet extends to the bottom of the sample bottle. A sample is collected by lowering the apparatus, upright, into a water body and by allowing enough time for the water flowing into the sample bottle to be displaced three times. Excess water overflows into the brass container. This apparatus is efficient, but it is expensive ($75 for the brass container and $1.95 for each sample bottle). Also, because it must remain upright during sampling, it cannot be used in water less than about 18 inches deep.

Figure 1 shows a simple piece of apparatus that is effective in the collection of samples for the determination of dissolved gases. The sampler can be assembled in a few minutes from materials that should be available in any laboratory—a polyethylene bottle, glass and rubber tubing, a two-hole stopper, and an aspirator.

The illustrated sampler has been used since 1960 to collect samples for hydrogen sulfide determinations from shallow water in Everglades National Park in southern Florida. Most of Everglades National Park is covered with shallow water, except during droughts. Often the water is so shallow that the use of conventional apparatus for sampling is not practical.

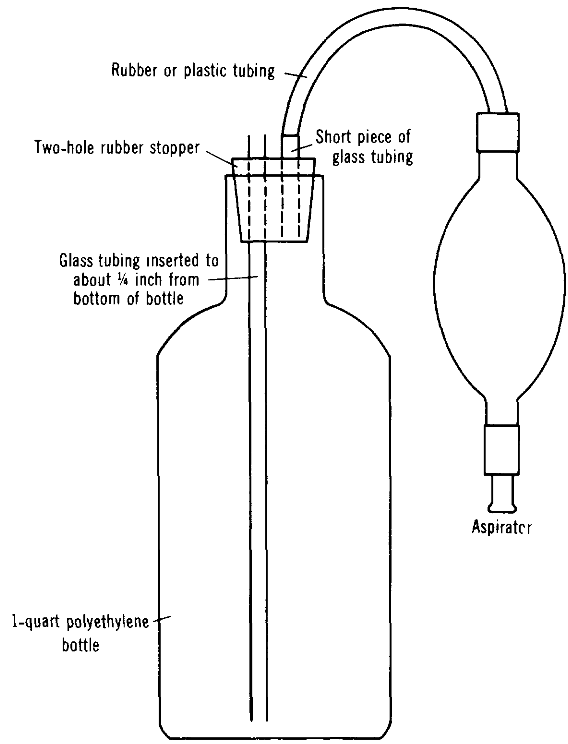

FIGURE 1.—Assembled sampler for collecting non-aerated water at shallow depths.

With this new apparatus, the bottle is lowered to collect a sample at the desired depth, and the aspirator, which is held above the water surface, is operated. As air is evacuated from the bottle by the aspirator, water flows in. After the bottle is filled, the water should be displaced at least three times by continuing to operate the aspirator. To sample very shallow water, the bottle can be placed on its side. Another method, by which samples can be collected from water only 1 inch deep, is to attach a piece of rubber or plastic tubing to the inlet glass tube and to place the free end of the attached tubing in the shallow water.

The new sampler has been used also to collect lake samples from depths as great as 25 feet. Theoretically, samples could be collected at any depth by attaching a sufficiently long piece of flexible tubing to the inlet of the bottle. However, the difficulty of displacing water in the bottle increases with sampling depth. This problem could be solved by using a more effective vacuum system.

USE OF CARBON DIOXIDE IN BUBBLE GAGES TO PREVENT PRECIPITATION OF CALCIUM CARBONATE

By WALLACE D. ROBBINS and LEON S. HUGHES

ABSTRACT

The tube mouth of the gas-purge system of a bubble gage may become blocked over a period of time by precipitation of calcium carbonate when nitrogen gas is bubbled through the tube into water containing high concentrations of calcium and bicarbonate in solution. Carbon dioxide substituted for nitrogen has proved successful in preventing the precipitation of calcium carbonate at the bubble-gage orifice. The conversion from nitrogen to carbon dioxide is inexpensive, and thereafter, operation and maintenance costs of the bubble gage are reduced substantially.

The tube mouth of the gas-purge system of a bubble gage may become blocked over a period of time by precipitation of calcium carbonate when nitrogen gas is bubbled through the tube into water containing high concentrations of calcium and bicarbonate in solution.

A bubble gage measures the elevation of a water surface by sensing pressure above an orifice submerged in the body of water of which the elevation is being determined. The pressure head of water at the orifice is transmitted by a gas-purge system, through flexible polyethylene tubing, to a servomanometer that operates a continuous water-stage recorder. Nitrogen gas from a storage cylinder in the recorder shelter feeds into the pressure system and bubbles slowly from the sensing orifice. The pressure at the orifice, and hence in any part of the system, is related to the head or depth of water over the orifice. The bubble gage is described in more detail by Barron (1963, p. Z4).

When the polyethylene tube becomes partly blocked by a precipitate of calcium carbonate, more pressure is required to force gas bubbles from the orifice. This increase in line pressure is reflected back to the servomanometer and causes the recorder to indicate a higher water stage than actually exists.

The base flow of streams that drain limestone terranes is likely to be saturated with calcium and bicarbonate. Analyses of typical waters from such areas have shown 75 ppm (parts per million) of calcium and 250 ppm of bicarbonate.

The presence of high concentrations of calcium and bicarbonate in solution is possible only when a large amount of carbon dioxide is available. Hem (1959, p. 71–78) discusses the relation of carbon dioxide in solution to the solubility of calcium carbonate. Water containing carbon dioxide dissolves calcium carbonate until an equilibrium is established with calcium and bicarbonate ions in solution:

$$CaCO_3 + CO_2 + H_2O \rightleftharpoons Ca^{+2} + 2HCO_3^{-1}.$$

If carbon dioxide is being added to the system represented by the above equation, solution continues; if it is removed from the system, deposition occurs.

Surface water, being in contact with the air, is usually stable with respect to carbon dioxide and calcium carbonate. However, when nitrogen gas is bubbled through the water, some of the nitrogen is dissolved and part of the carbon dioxide is displaced from solution, which changes the equilibrium condition and causes the precipitation of calcium carbonate. At the orifice of the bubble-gage tube, where the water of the stream is continuously in contact with the nitrogen gas, maximum displacement of carbon dioxide and maximum precipitation of calcium carbonate occur. Figure 1 compares a clean orifice with one partly closed by precipitation of calcium carbonate.

FIGURE 1.—Orifice of bubble-gage tubing before and after deposition of calcium carbonate. Outside diameter of tubing is three-eighths inch; inside diameter, one-eighth inch. Photograph enlarged (about × 4).

The substitution of carbon dioxide for nitrogen in the gas-purge system prevents the precipitation of calcium carbonate at the bubble-gage orifice. As the carbon dioxide contacts the water at the tube mouth, part of the gas is dissolved; thus the capacity of the water to dissolve calcium carbonate and to hold calcium and bicarbonate ions in solution is increased. Therefore, a precipitate never forms.

Only minor inconveniences have been experienced in converting to the use of carbon dioxide. The regulators furnished with bubble gages do not fit the valves on carbon dioxide cylinders, but a valve with proper threads is available from gas suppliers for about $5, or a threaded adapter, costing about $2.50, can be used to connect the nitrogen regulator to the carbon dioxide valve. The pressure gage does not show how much carbon dioxide remains in the cylinder, because the pressure remains the same (except for variations due to temperature) until the cylinder is almost empty. It is necessary, therefore, to weigh the cylinder to check its contents. This is easily done with inexpensive bathroom scales.

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POLYETHYLENE OIL TUBES FOR STILLING WELLS

By Robert L. Stewart

ABSTRACT

A polyethylene oil tube used in the stilling well of a lake- or stream-gaging station is an efficient and economical device to prevent ice from affecting the continuous water-stage (gage-height) record. The tube can be installed and removed without disturbing the gaging station structure and its instruments.

Many lake- and stream-gaging stations use a stilling well to obtain a continuous record of water stage (gage height). If the stilling well is exposed to and unprotected from subfreezing air temperatures, ice often forms in the well and affects the recording of water stage. Various devices are used to prevent the formation of ice in a well; the most common one is a tube or cylinder of oil. A head of kerosene, or No. 1 fuel oil, in a tube within the well lowers the elevation of the water surface and protects it from freezing air temperatures.

A polyethylene oil tube has an advantage over a metal or rigid oil tube because it is flexible and can therefore be installed in the well, and removed, with a minimum of effort and without disturbing the gaging-station structure or its instruments. The low cost and simple construction features of a polyethylene oil tube justify seasonal or yearly replacement, if necessary, although experience indicates the tubing will last a number of years in continuous operation.

The tube is made by fitting a formed 3/8-inch-thick steel hoop, the same diameter as the tubing, at each end of a desired length of tubing; 3 inches of tubing should be allowed at each end to be turned back, and outside, over the hoop (fig. 1). Metal clamps (hog rings) fitted around the hoop and through the tubing will hold the hoop in place. The completed oil tube should be re-rolled until it is ready to be lowered into the well. Care should be taken not to fold it, particularly at the lower end, as a sharp crease might fracture the material and the oil will leak out.

The oil tube can be suspended from the floor of the gage house, or from the recorder shelf, by several methods. The simplest method is to suspend the tube from the recorder shelf using three long-threaded eyebolts and three S-hooks (fig. 2*A*). Another method is to use a shelf bracket, attached to the side of the well, below the floor (fig. 2*B*).

FIGURE 1.—Formed steel ring fitted into one end of roll of polyethylene tubing.

The oil tube should be positioned so that the bottom end of the tube is well below the lowest stage, or water level, expected. This will prevent loss of oil from the tube at extreme low stages. Ten gallons of oil (kerosene) in a 14-inch-diameter tube will be about 1.25 feet thick. About 5 pounds of extra weight attached to the bottom end of the tube will overcome the buoyant effect of the 10 gallons of oil and help keep the tube plumb. A polyethylene oil tube longer than 30 feet may require a weighted guywire hung from each eyebolt through the inside of the tube to keep it open and plumb.

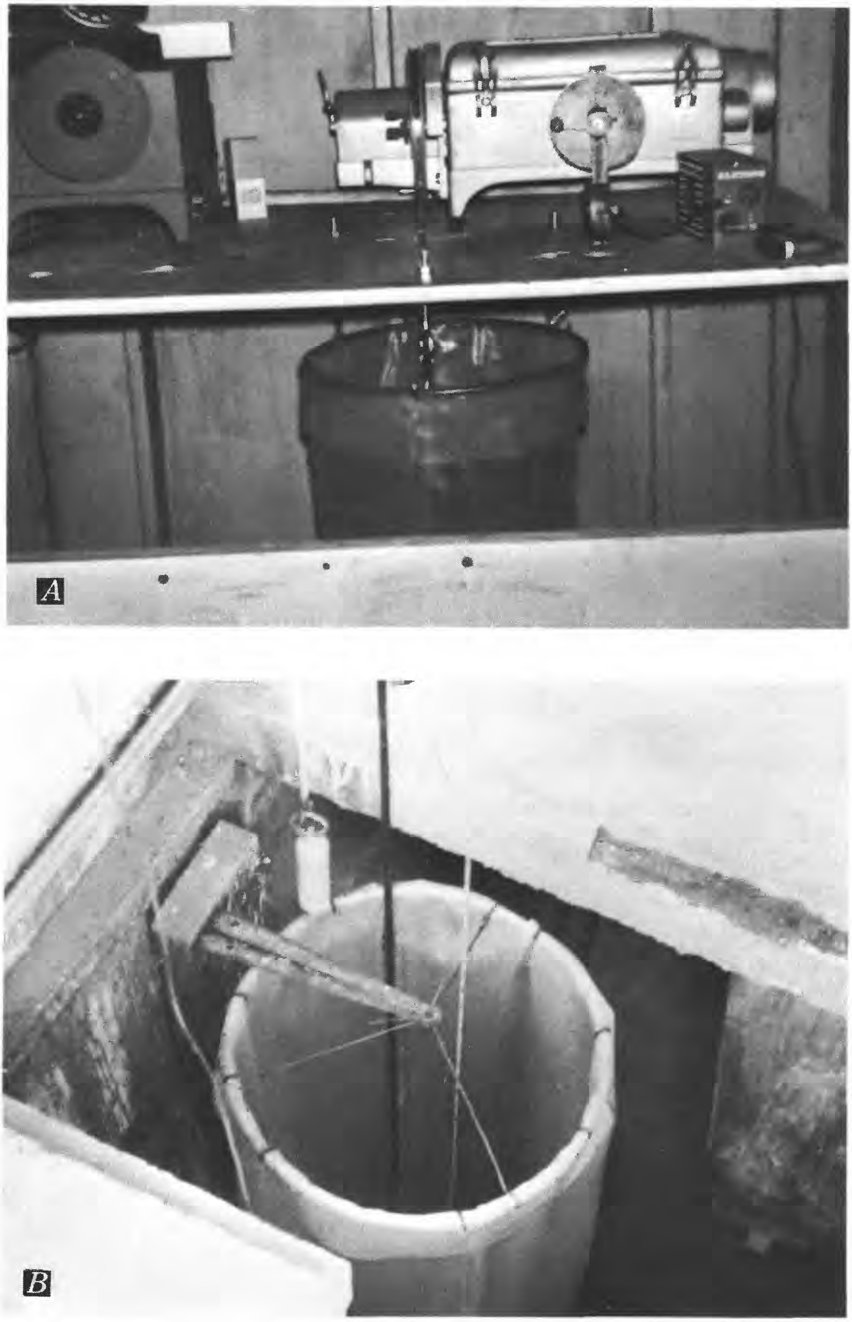

FIGURE 2.—Polyethylene oil tube. *A*, Suspended from recorder shelf. *B*, Suspended under floor of shelter.

WATER-MANOMETER–AIR-LINE ASSEMBLY FOR DETERMINING DEPTH TO WATER IN WELLS

By O. J. Loeltz

ABSTRACT

A combination water-manometer–air-line assembly provides an accurate and reliable means for obtaining water-level measurements in wells. The assembly is especially adapted to the rapid measurement of changing water levels during and immediately after pumping tests. It successfully overcomes many of the deficiencies of conventional methods.

INTRODUCTION

At some time during most pumping tests, it is necessary to obtain successive depth-to-water-level measurements within short time intervals. Conventional means for making water-level measurements generally meet this requirement, but sometimes conditions are such that the conventional means are inadequate in one or more respects. The water-manometer–air-line assembly overcomes the inadequacies of the other methods.

The steel-tape method is perhaps the most commonly used method of measuring depth to water in wells. A measurement involves chalking the first few feet of the tape, inserting sufficient tape to reach below the water level, reading the tape at the measuring point, removing the tape, and reading the top of the submerged part of the tape. In many wells the last is difficult and sometimes impossible because cascading water or a wet casing or pump column may have wet the tape above the water level in the well.

The time required to obtain successive measurements depends on the depth to water. When the depth to water exceeds several tens of feet, the desired frequency of readings becomes impractical. Also, the probability of getting the tape stuck in the well increases with the number of insertions and the depth to the water surface.

The electric sounder, one model of which is described by LeBlanc (1966), has considerable advantage over the use of a steel tape in that the time required for making successive measurements of water level is not dependent on the depth to water. The sounder line need be moved only the distance that the water level changed since the previous measurement to obtain a new measurement. Although electric sounders are designed to function satisfactorily even when water is cascading into a well or after the electrode passes through a column of oil floating on the water, malfunctioning occurs too often at a time when the collection of data is essential to the success of a pumping test. The lack of reliability under all conditions is the principal shortcoming of the electric sounder method.

Many large-capacity pumped wells are equipped with an air line (copper tubing or small-diameter pipe), an air gage, and suitable connections for supplying air to the line, generally by means of a hand-operated pump. Enough air is pumped into the system to drive all water from the air line and maintain it free of water. The pressure required for this condition is shown by the maximum reading that can be maintained on the air gage. This, in turn, will depend on the distance the air line is submerged below the water level in the well. The water depth at which the hydrostatic pressure equals the pressure indicated by the air gage is then subtracted from the length of the air line to obtain the depth to water.

The principal shortcoming of the above method is that the gage for measuring the air pressure rarely is sufficiently accurate or sensitive to obtain the data that are needed. This shortcoming is eliminated by use of a water manometer in conjunction with a modified air-line system that limits the length of the submerged part of the air line to the height of the water-manometer measuring tube.

PRINCIPLES OF OPERATION OF A WATER MANOMETER

Figure 1 represents an open vessel filled with water to a level, *A*; an air tube with shutoff valve, *C*; an airtight container filled with water to a level, *D*; and a relatively small-diameter tube, open to the atmosphere, that extends a short distance above water level, *E*. The pressure in the air tube is just sufficient to maintain the air line free of water. Under this condition, the vertical height of the water column, *ED*, equals the length, *AB*, that the air tube is submerged.

This is true because (1) the pressures at levels *B* and *D* are equal, (2) the pressures at *A* and *E* are equal (both atmospheric), (3) the differences in pressure between levels *B* and *A* and levels *D* and *E* therefore are equal, and (4) the differences in pressure arise from the hydrostatic pressure of columns of water of lengths *AB* and *DE*.

It follows, therefore, that the height of the water column in the tube above the level of the water in the airtight container equals the

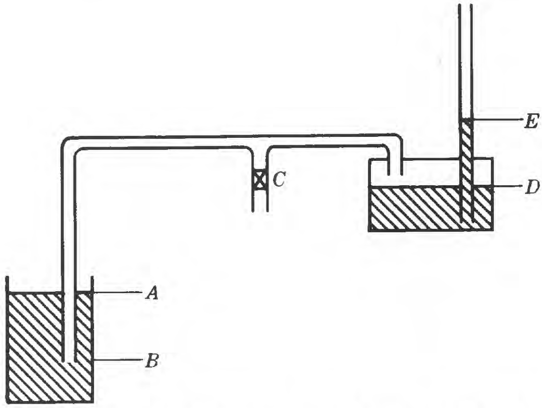

FIGURE 1.—Sketch showing water levels in a water-manometer–air-line assembly when the air line is maintained free of water

depth to which the tube in the open container is submerged. If the open container is thought of as a well, the use of a water manometer for determining the depth to which an air line is submerged is readily apparent.

DESCRIPTION AND OPERATION OF THE ASSEMBLY

Figure 2 shows typical dimensions and materials for assembling a simple water-manometer–air-line apparatus. Sketch *A* shows dimensions for the manometer stand. Sketch *B* shows one combination of tubing, valve, and other accessories. This arrangement is secured to the base of the stand in any convenient manner. Sketch *C* shows the air line and its fittings.

A few drops of food coloring can be added to the water in the inkwell reservoir to facilitate reading the manometer. The reservoir is filled to about the halfway point, which then becomes the zero mark for any height of water level in the manometer tubing that is maintained as a result of submergence of the end of the air line below the water level in a well. The height of the water level in the tube above the zero level of the reservoir can be measured in a variety of ways. A length of steel tape graduated in feet and hundredths of a foot should be satisfactory; or marks showing feet, tenths of a foot, and midway points between tenths of a foot can be made on the support piece for the manometer tubing. Because the inside diameter of the glass tubing is small, the water level in the inkwell reservoir lowers insignificantly when water is displaced into the glass tubing of the manometer. Therefore, if the water level in the inkwell reservoir is at the zero mark of

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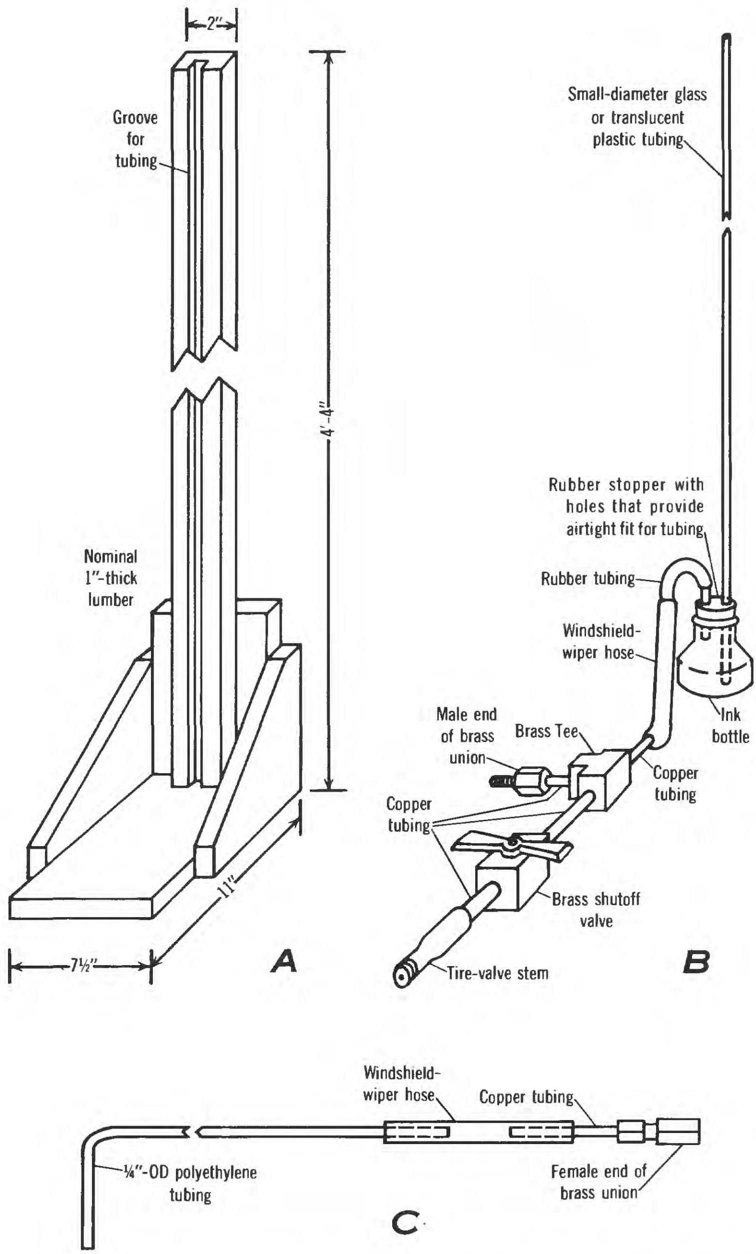

FIGURE 2.—Sketches showing dimensions and materials for a water-manometer–air-line assembly.

the scale when the air line is not submerged, the submerged distance can be read directly on the scale when the air line is submerged.

Any decrease in ease of reading the manometer when plastic tubing is used is offset by the fact that the plastic tubing is virtually unbreakable and flexible. Thus, the height of the manometer can be reduced when in transit or can be extended to increase the range of submergence over that range which is practical when using a single piece of glass tubing.

Figure 3 is a photograph of a manometer and its accessories. Mounted on the same stand is a mercury manometer that can be used instead of the water manometer should this be desirable. Also shown are a coil containing several hundred feet of small-diameter polyethylene tubing, a graduated steel tape with weight (to which has been taped several feet of air tube), and a type of air pump that is convenient for use with the manometer.

Figure 4 shows the assembly in use during a pumping test. The vise-grip pliers often are convenient for maintaining the desired marking on the steel tape at the measuring point.

The procedure for measuring depths to water is to attach one end of the air-line tubing to the steel tape so that the end of the tubing is at the zero marking on the steel tape. Plastic tape can be used to make the attachment. The tubing and the steel tape are then attached at other convenient points, between 10 to 20 feet apart, until a length near the maximum depth to be measured is reached. Making the length of the tubing between intervals slightly longer than the steel tape will keep the tubing from interfering with the free hanging of the tape in the well. The reading of the tape at the measuring point should indicate the depth of the end of the air line below the point.

Determining the depth of the end of the air line on the basis of the steel tape marking at the measuring point is much more precise than using a calibrated air line because the length of the polyethylene tubing changes significantly with time, tension, and temperature. These changes can easily exceed 1 percent of the suspended length of the air line and are difficult to evaluate.

The other end of the air line is fitted to the manometer by means of the brass union shown in figure 2. The pump is attached to the tire stem valve and the shutoff valve is closed.

The weighted steel tape with air line properly attached is then lowered into the well until submergence of the air line is indicated by a slight rise of water level in the manometer. The amount of submergence is determined by (1) pumping sufficient air into the system to more than purge the air line of water, (2) closing the valve between the air pump and the system before the excess pressure is dissipated,

FIGURE 3.—Water manometer, mercury manometer, and accessories.

and (3) noting the height at which the water column in the manometer tubing stabilizes above the water level in the reservoir.

The depth to water below the measuring point is the difference between the steel-tape marking at the measuring point and the height of the water column in the manometer.

FIGURE 4.—Water-manometer–air-line assembly in field use.

Computations are simplified by setting the full foot markings of the steel tape at the measuring point. Changes in water level are shown by changes in the height of the column of water in the manometer tubing between successive determinations of the amount of submergence. Although declining water levels can be ascertained in an airtight system merely by noting the decline of the water column in the manometer tubing, experience has shown that it is good practice to increase the pressure above that required for purging the air line for each determination of amount of submergence.

When the top of the column of water approaches either limit of the manometer tubing, the steel tape (and hence the end of the air line) is raised or lowered to again attain a satisfactory height of the water column.

A column of oil floating on the water in the well casing introduces problems regardless of the method of measurement, but these problems probably are less troublesome with the air-line method than with other methods. If the air line terminates in water below the oil, the manometer may be read directly without correction; but if the air line terminates in oil, corrections must be applied. The corrections can readily be computed if the depth to the bottom of the oil column and the oil's specific gravity are determined.

These determinations can be made under stable water-level conditions by increasing the submergence, carefully measured by the steel tape, and comparing these differences in submergence with corresponding differences in manometer readings.

The ratio of a difference in manometer readings to a change in submergence will be 1 for all changes in submergence below the oil-water interface and will be less than 1, the specific gravity of the oil, for all changes above the interface.

At the end of the test, the plastic tape used to join the steel tape and the air line is removed. Lengths of air line up to 200 feet may be conveniently coiled, lasso style, into loops 2 feet or so in diameter. Greater lengths probably can best be handled by rolling the tubing onto a suitable spool from which any needed length can be unwound.

Small-diameter polyethylene tubing is available in continuous lengths up to 500 feet, in multiples of 100 feet, at a cost of a few cents per foot. The glass, copper, and rubber tubing in needed diameters and other materials are available locally. The air pump that is shown in figures 3 and 4 has the advantage of one-hand operation, which leaves the other hand free to operate the shutoff valve of the manometer.

Many variations can be incorporated in the system. In some areas where large changes in water level occur, a mercury rather than a water manometer may be more satisfactory. However, considerably more care must be used in preventing air leaks if the submergence is to be several tens of feet, and, of course, changes of water level of less than 0.05 foot will be hard to measure.

Another variation is the use of a pressurized air tank in lieu of the hand pump for purging the air line. However, care must be taken that all the air supply to the manometer is valved off completely when making a reading, or the height of the water column in the manometer will be too high by an unknown amount.

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MINIMUM AND MAXIMUM WATER-LEVEL RECORDING DEVICES

By T. E. Kelly

ABSTRACT

To supplement periodic water-level measurements in observation wells, two inexpensive devices were constructed to determine the minimum and maximum water levels between visits to a well site. The minimum water level is determined by use of a float, and the maximum water-level device is a modification of a crest-stage station. The devices measure to an accuracy of 0.1 foot.

During the early 1940's a statewide network of observation wells was established in North Dakota, but for various reasons many of these wells were measured only biannually. The measurements were made during the spring and fall when the water levels were rising and declining, respectively. Consequently, numerous water-level measurements were obtained without knowledge of the annual range of water-level fluctuations. The measurements would have been more useful if they had indicated the annual minimum and maximum water levels for each well, and, consequently, the annual storage changes in the aquifer. The dates of the annual maximum and minimum water levels were not critical as they could have been approximated from precipitation data, records from observers, or automatic recorders measuring similar wells in the same general area.

Two inexpensive devices were designed to measure the minimum and maximum water levels in a well between inspections. The devices can be made and installed for less than $10, and each will last indefinitely.

Minimum water level is measured by use of a spool of fishing leader and a float of nearly any description. A standard 2½-inch water-level float has been used in North Dakota; but weighted cork, a dowel, or Styrofoam could also be used and at less expense. Nylon leader wound on a disc-shaped spool is obtainable in most sporting goods stores. It is available in a variety of strengths; the most satisfactory strength is 15- or 18-pound test. As shown in figure 1, the leader is threaded through one or more eye hooks and attached to the float, which is lowered into a well.

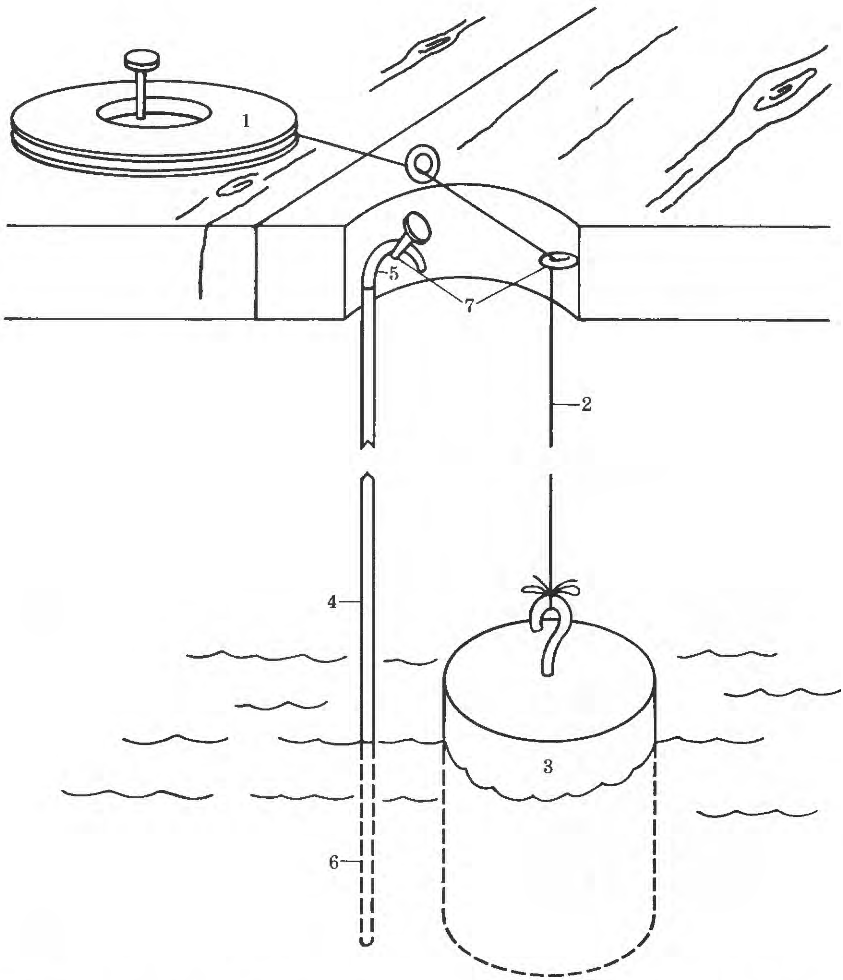


FIGURE 1.—Devices for measuring minimum and maximum water levels in wells. 1, Plastic spool of nylon fishing leader; 2, nylon leader (15-pound test); 3, standard 2½-inch water-level float; 4, transparent ⅜-inch polyethylene tubing containing powdered cork; 5, ¼-inch inside diameter (ID) brass tubing; 6, ¼-inch (ID) brass tubing, slotted and filled with shot; 7, measuring points.

As the water level declines, the float pulls the leader material from the spool. When the water-level trend reverses, the leader becomes slack, but friction of the spool prevents it from rewinding. The lowest water level in the well since the previous inspection is determined by measuring the amount of leader between the measuring point and the float plus the distance from the float-leader connection to the waterline on the float. It is advisable to mark the waterline on the float before the float is installed.

The maximum water-level device is a modification of a crest-stage station. This device consists of a length of transparent ⅜-inch polyethylene tubing, two short lengths of ¼-inch (ID) brass tubing, lead shot, and several pinches of powdered cork. An elbow of brass tubing is inserted into the upper end of the polyethylene tubing and is used to suspend the device in the well. Eight to 12 inches of brass tubing is crimped at one end, slotted with a hacksaw, and filled with lead shot or fishing sinkers. Several pinches of powdered cork are put into the plastic tubing, and the weighted brass tubing is attached to the lower end. The plastic tubing is suspended in the well with the slotted brass tubing below the depth of anticipated maximum water level (fig. 1).

As the water level rises, the powdered cork rises on the water in the tube. After the peak is reached, the water level in the tubing declines; but the cork adheres to the walls of the tube and marks the maximum water level. The maximum level is determined by gently pulling the tubing from the well and measuring the distance between the measuring point and the top of the cork. Any kinks in the polyethylene tubing will prevent the movement of the cork and will cause an anomalous indication of maximum water level. The cork should be replaced annually.

The two devices can be used in nearly any well larger than 2 inches in diameter. In smaller diameter wells a weighted dowel instead of the standard float can be used satisfactorily. Deep water levels may be a limiting factor. At depths exceeding 50 feet there is appreciable stretch in the nylon leader; however, this can be reduced by using a larger diameter leader. Fine copper wire can also be wrapped on the spool and used instead of leader material. Transparent polyethylene tubing costs about $0.20 per foot and is the most costly item of the installation.

The greatest advantage in using these devices is that three water-level measurements can be obtained for each visit to the site regardless of the interval between visits. Figure 2 shows the relation of the monthly minimum and maximum water levels at a particular well to the measurement made during each visit for the period May 1965 to November 1966. During the declining phases the taped measurements correspond to the minimum monthly water levels; during the rising phases the taped measurements correspond to the maximum monthly water levels.

A pilot test was made using these two devices in a well having a continuous recorder. The maximum and minimum water levels recorded by the two devices were within 0.1 foot of those shown by the recorder.

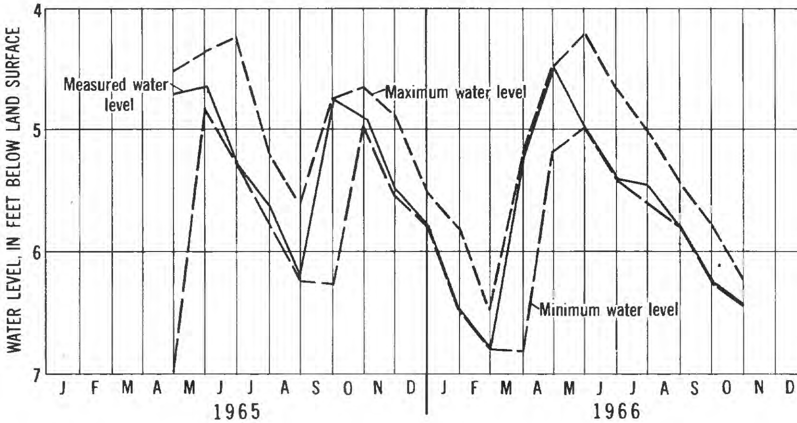


Figure 2.—Hydrograph showing relation of monthly measurements to the minimum and maximum water levels in one observation well.

SERVOPSYCHROMETER

By Woodrow L. Yonts, Jr.

ABSTRACT

A servopsychrometer has been designed that obtains accurate and instantaneous relative humidity observations, which are used to check the operation of recording hygrothermographs used in water resources investigations.

Greater water use and water shortages in recent years have emphasized the need for more reliable means of measuring factors affecting evaporation. As more reservoirs for water supply and other purposes, particularly heat dissipation, are constructed, water losses due to evaporation can be appreciable. A direct method of measuring evaporation from a free-water surface has not been developed; consequently, various indirect techniques have been used. These techniques include mass transfer, energy budget, water budget, and pan evaporation.

Relative humidity readings are part of all these techniques except the water-budget method. Generally, relative humidity and dry-bulb temperature are continuously recorded on a hygrothermograph. A sling psychrometer normally is used to check the hygrothermograph. The sling psychrometer consists of wet- and dry-bulb thermometers mounted on a common back to which a short length of chain with a wooden handle is attached. Ventilation is provided by whirling the psychrometer.

The servopsychrometer was developed when differences greater than 2 percent in hygrothermograph and sling psychrometer readings were common in normal operation. These differences were attributed to two factors: (1) the hygrothermograph was inside a louvered shelter, but the sling psychrometer readings were taken outside, and (2) the inability of the observer to read instantaneous maximum depression of the mercury in the wet-bulb thermometer on the sling psychrometer.

The servopsychrometer was designed so that the maximum depressions of mercury of the wet-bulb thermometer are readily visible. Its size allows it to be used near the hygrothermograph inside the instrument shelter. The shelter is the standard U.S. Weather Bureau meteorological instrument shelter known as the cotton-region type.

The servopsychrometer consists of a small direct-current motor, a 6-blade fan, two 6-volt batteries, and wet- and dry-bulb thermometers on a common holder. The thermometers and the motor, to which the fan is attached, are mounted on a frame made of Plexiglas (fig. 1*A*). The 6-blade fan was formed by joining together two 3½-inch-diameter propellers from plastic model airplanes. The motor operates best on

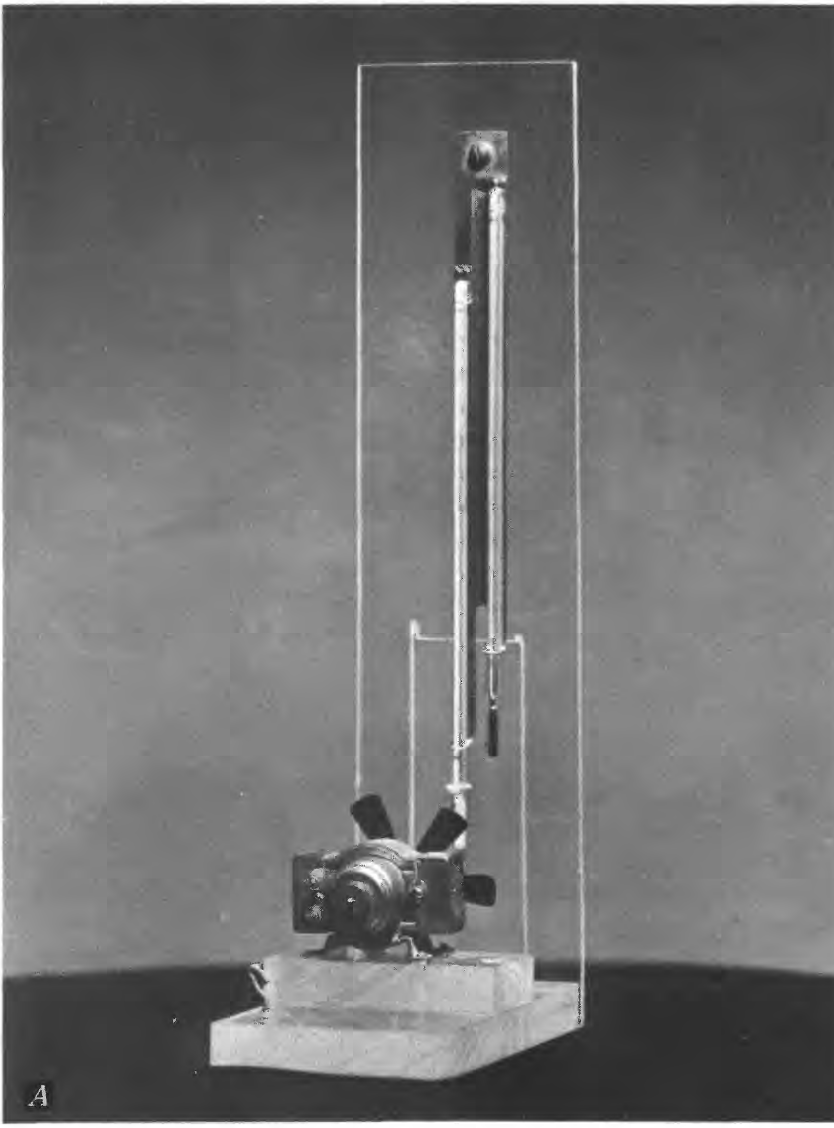
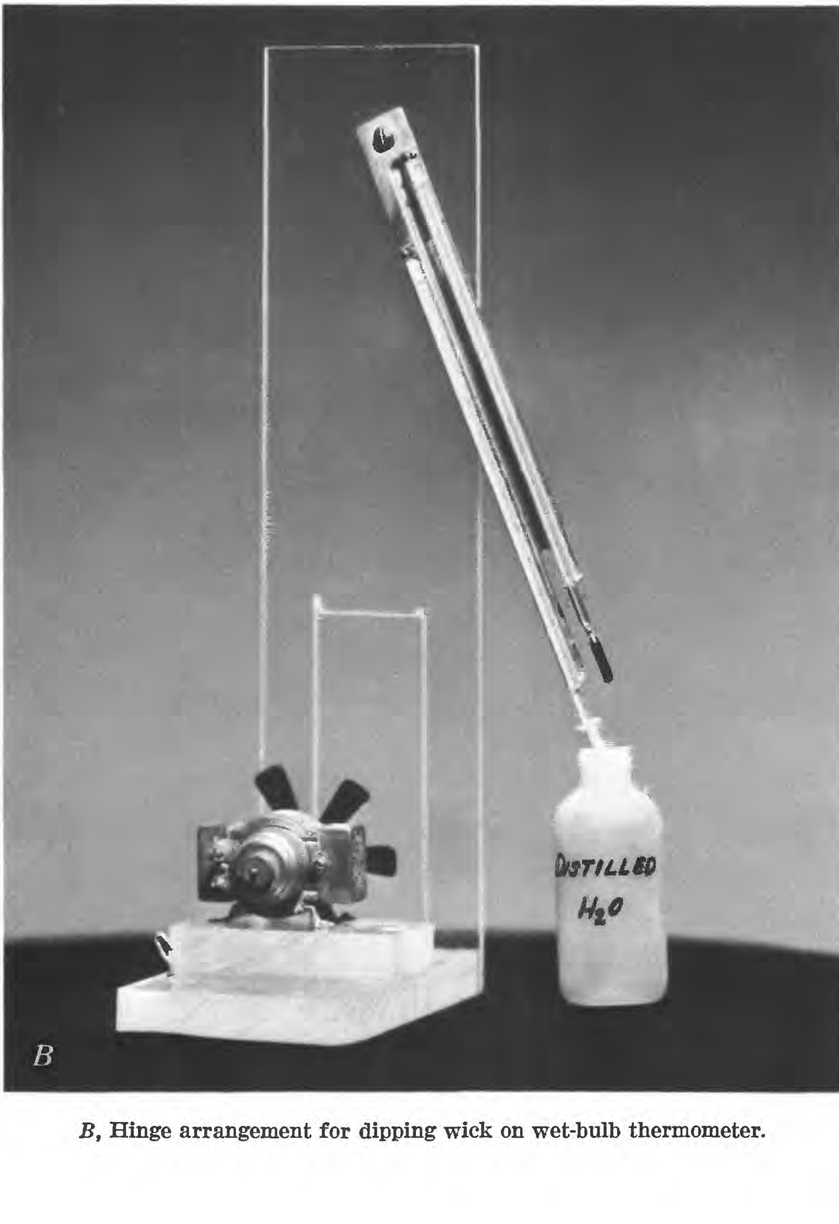


FIGURE. 1 (above and facing page).—Servopsychrometer. *A*, Parts, except power source, mounted on stand.

about 12 volts and can be used on up to 24 volts. A convenient power source is two lantern-type 6-volt batteries wired in series. Motors are available at most hobby shops. Plexiglas was used for the frame, but wood could be substituted. The thermometers, wet- and dry-bulb, were detached from the sling of a sling psychrometer and mounted on the Plexiglas stand. A hinge arrangement (fig. 1*B*) permits the thermometer holder to swing out from the stand and the wet-bulb (wick-



***B*, Hinge arrangement for dipping wick on wet-bulb thermometer.**

covered) thermometer to be dipped into a small bottle of distilled water.

The servopsychrometer motor is small, and heat transfer to the thermometers is negligible. If a larger motor is used, heat generation may be significant enough to cause erroneous readings. However, a larger motor can be used by placing the fan in a reverse position at one end of a funnel-shaped box and by mounting the thermometers at the opposite end of the box. This would permit air to be pulled through the funnel from the thermometers toward the motor and prevent the heat from passing across the thermometer bulbs.

Maintenance of the servopsychrometer is relatively simple. The wick of the wet-bulb thermometer should be changed at least once a month—or more frequently if necessary—to keep a clean wick on the bulb. Deposition of mineral salts on the wick, or a dirty wick, will cause erroneous wet-bulb readings. The motor should be oiled periodically. Battery life averages about 6 months.

The total cost of the parts and construction of the servopsychrometer, including 1 hour of labor, is about $15.

The servopsychrometer has been in operation since June 1962, and results have been excellent. Simultaneous humidity readings have differed 2 percent or less when both instruments were in the shelter. Readings and interpretations of the hygrothermograph chart have been more accurate.

RAFT FOR EVAPORATION-MEASUREMENT EQUIPMENT

By RICHARD U. GROZIER

ABSTRACT

Deterioration of steel barrels in rafts used to support equipment for determining evaporation on reservoirs was eliminated by using plastic foam instead of steel barrels for raft buoyancy. Special frames were devised to hold the plastic foam and the frames were fastened together in a design that made the new raft both safe and sturdy.

Evaporation from reservoirs has been studied for several years by the U.S. Geological Survey. Some of the principal types of data for such studies must be collected by instruments situated on rafts moored near the center of reservoirs. For example, windspeed must be recorded by an anemometer and surface temperature of reservoir water by a thermometer near the center of a reservoir to accurately determine evaporation by the mass-transfer theory. A study by Harbeck (1962, p. 102) briefly mentions the type of raft commonly used—one in which empty steel barrels provide buoyancy.

A steel-barrel raft is made of four 55-gallon steel barrels attached together inside a welded frame of steel angles. About every 2 years the steel barrels have to be replaced because of rusting. Each replacement job amounts to practically rebuilding the raft because the welded framework must be taken apart and then reassembled. The barrel rafts also have very little freeboard and are so unstable that it is dangerous for more than one man to be on a raft at one time.

Another type of raft can be built, however, that eliminates many of the problems of the barrel raft. Instead of steel barrels, slabs of plastic foam are used to give buoyancy. Plastic foam can be obtained in almost any desired size or shape and it will support about 60 pounds per cubic foot.

A construction diagram of a raft built with plastic foam instead of barrels for buoyancy is shown in figure 1. Two slabs of plastic foam, each 8 feet long, 25 inches wide, and 12½ inches deep, are used. Each slab weighs about 20 pounds but will keep afloat nearly 1,000 pounds of load. A single slab easily floats the weight of a man and the instruments used to collect data on windspeed and surface-water temperature; how-

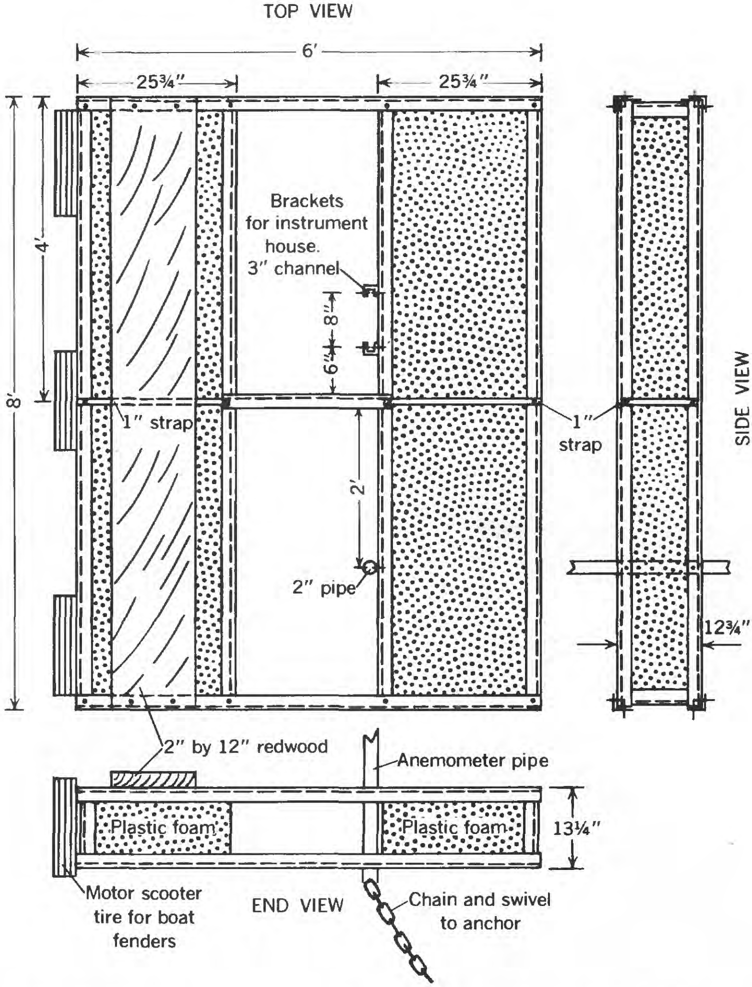


FIGURE 1.—Details of construction of raft in which plastic foam slabs are used for buoyancy.

ever, for greater stability and ease of design, two slabs of plastic foam are used. Because plastic foam is soft and its edges are easily damaged, a frame made of 2- by 2- by ⅛-inch steel is placed around each foam slab. Each frame is made in two pieces, top and bottom, and then joined together at the corners around a foam slab and at the center on the outside. Each half frame is the same except that a redwood plank is attached to one to form a walkway for tending the instruments. When the two frames around the foam slabs are fastened together, a sturdy compact unit is formed that weighs about 250 pounds (including a shelter for the instruments). This unit will take considerable rough treatment without damage to the plastic foam slabs. All metal parts are given one coat of rust-preventive paint and one coat of aluminum paint. The completed raft is shown in figure 2.

FIGURE 2.—Finished raft with anemometer and instrument house in place.

Some advantages of plastic-foam rafts over barrel rafts are:

1. Greater stability, and, therefore, safety.
2. Will not sink, even if perforated many times by rifle fire.
3. Rides more evenly.
4. Nonsusceptibility to chemicals in water.
5. Low maintenance costs.

Although it costs slightly more to make a plastic-foam raft (total cost about $130) than a barrel raft, the maintenance of a foam raft is much less than that of a barrel raft. The Texas District of the Water Resources Division, U.S. Geological Survey, has been using foam rafts for more than 3 years, and no maintenance has been required. Some of the rafts have been moved from one reservoir to another by truck and have not been damaged.

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Harbeck, G. E., Jr., 1962, A practical field technique for measuring reservoir evaporation utilizing mass-transfer theory: U.S. Geol. Survey Prof. Paper 272-E, p. 101-105.

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WATER-STAGE AND RAINFALL DUAL RECORDER

By GEORGE F. SMOOT AND THOMAS J. BUCHANAN

ABSTRACT

An instrument that records both cumulative rainfall and flood stages is used on streams with small drainage basins to help define flood frequencies. The stilling well and stage-recording mechanism are installed so that 5-, 10-, or 20-foot ranges of a stage above a predetermined gage height can be recorded during 24 hours; more than 24 hours of flood record on one chart may be difficult to read. Record automatically begins after water stage reaches the predetermined height. The rainfall recorder can register any number of inches of rain because of a siphon system attached to the rainfall-measuring reservoir. After 5 inches of rain have fallen, the siphon empties the reservoir and a new recording cycle is begun. Rainfall record is continuous between service visits to an instrument, which may be 6 to 8 weeks apart if no flood occurs. Both cumulative rainfall and water stage are recorded on one polar coordinate chart with the time of day (but not the date) of an event defined. Rainfall is recorded with an accuracy of ±0.025 inch; different stage ranges are recorded with different accuracies of from ±0.025 foot for a 5-foot range to ±0.10 foot for a 20-foot range.

INTRODUCTION

Many State and Federal agencies are presently engaged in programs to define flood frequencies in small drainage basins. Additional studies are being proposed, particularly in basins of 1 to 10 square miles in area. Most of the present programs provide for recording peak stages by use of the crest-stage gage.

Although data on peak stages on small streams (for the collection of which the crest-stage gage is an efficient device) are the primary facts needed to determine flood frequencies in small drainage basins, flood hydrographs and rainfall records are also extremely helpful—if they can be obtained at a reasonable cost. But to economically record both a chart of changes in water stage (a hydrograph) and rainfall data, an instrument is needed that records two types of information simultaneously. In addition, the instrument should be simple, inexpensive, sturdy, and automatic and should require a minimum of servicing.

When studies of flood frequencies in small drainage basins were initiated, no commercial recorders were available that fulfilled these requirements. Therefore, it was decided to design and build the type of recorder needed. In 1962 the Instrument and Development Unit, Water Resources Division, U.S. Geological Survey, developed a small water-stage recorder and distributed 100 units to Survey field offices. The experience gained during the use of these water-stage recorders led to the development of an improved and more versatile instrument that fulfills the requirements of a device for use in a small drainage basin.

The new instrument is called an SR recorder (fig. 1) because it registers both stage and rainfall. It consists of four basic sections—the chart table and chart drive, the stage-recording mechanism and stilling well, the rainfall-recording mechanism and rainwater reservoir with siphon, and the housing.

CHART TABLE AND DRIVE

The chart table and chart drive consist of a 5½-inch-diameter horizontal disc (the chart table) that is made to rotate about a central vertical axis by a battery-wound timing mechanism. The timing mechanism insures that the chart-table speed is one complete rotation each 24 hours and that the rotation is evenly distributed. A small flashlight battery is used to wind the timer. The battery usually lasts about 6 months. A polar coordinate chart (made of Mylar) fits on top of the chart table. It has radial lines to mark time divisions and concentric circles to indicate levels of stage or amounts of rainfall. The usable width of the chart in recording either rainfall or stage changes is 2 inches. The entire chart table and drive can be removed from the SR recorded by unfastening three screws. (See fig. 2.)

STAGE RECORDER

Part of the stage recorder is shown on the right side of figure 2. A 2-inch-diameter pipe is fastened inside the pipe flange to act as a stilling well. The lower end of the pipe is covered with a perforated pipe cap so that water can enter when the stream reaches a certain stage. When water enters the pipe, a 1½-inch-diameter plastic float rises with the water level inside the pipe. The float is suspended from the float wheel by several feet of light stainless steel cable that will not stretch or contract when the temperature or humidity changes. Also suspended inside the stilling-well pipe is a counterweight, which is attached to the counterweight drum by a few feet of silk or nylon fishline. Because the counterweight line is not attached directly to the float line, it is not important if the counterweight line stretches or contracts slightly.

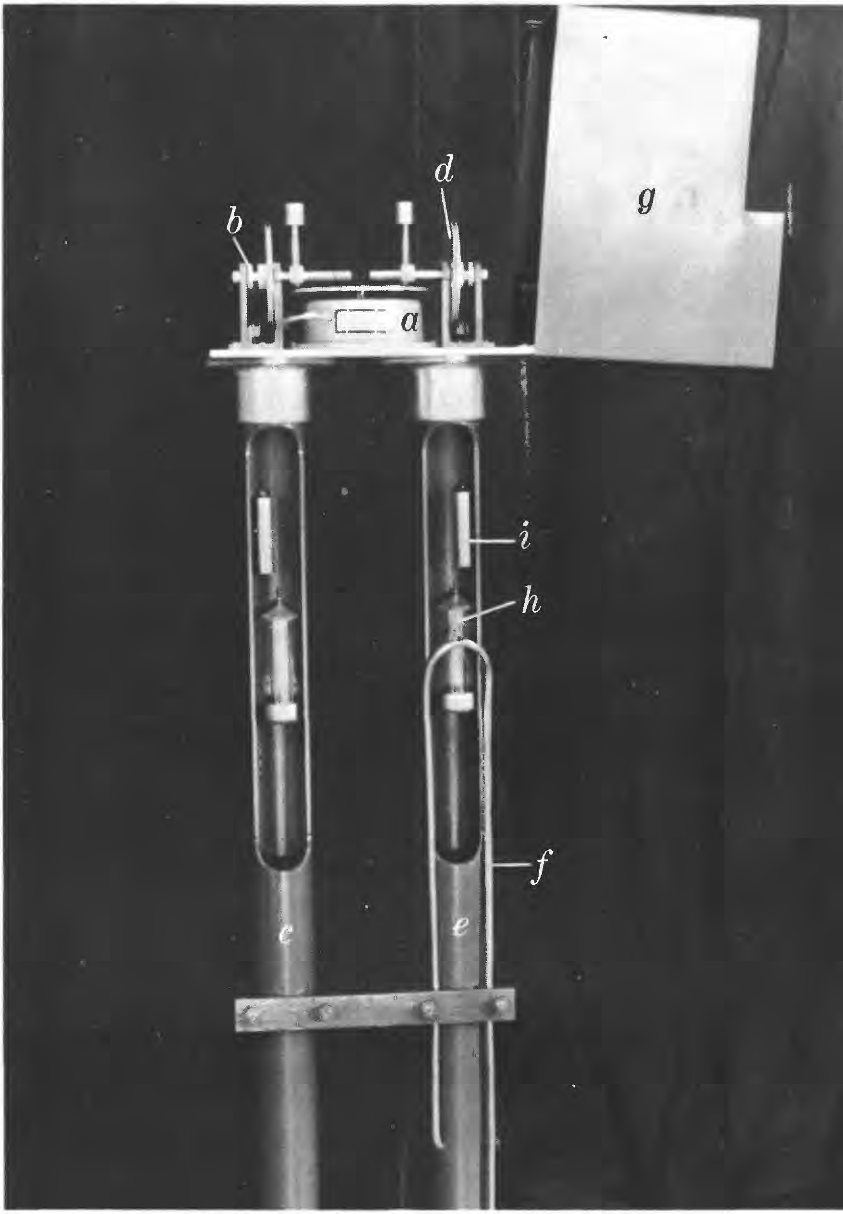

Figure 1.—Assembled water-stage and rainfall dual recorder viewed from the rear: *a*, Chart drive; *b*, stage-recording mechanism; *c*, stage stilling well; *d*, rainfall-recording mechanism; *e*, rainwater reservoir; *f*, siphon; *g*, housing; *h*, float; and *i*, counterweight.

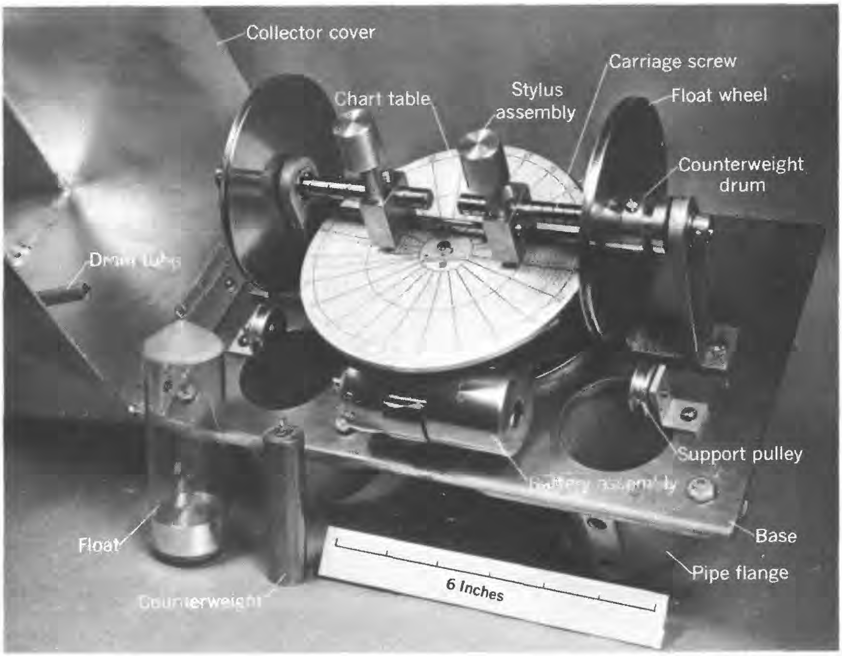

FIGURE 2.—Front view of SR recorder before assembly and attachment to stilling well and rainwater reservoir.

The weights of the float and counterweight and the diameters of the float wheel and the counterweight drum are arranged in such a way that the line to the float is always kept just taut but without strain whether the float and the water are rising or falling. As the float and the counterweight go up or down, the counterweight drum or the float wheel is given a rotary motion, which in turn is transmitted to the stage-recording carriage screw.

As the carriage screw turns, a linear horizontal motion is given to the stylus assembly because a pawl attached to the assembly fits into the carriage screw groove and must follow backward or forward along the groove as the screw moves. A piece of pencil lead inserted in the stylus assembly traces the horizontal movements of the assembly as the chart table slowly rotates.

Carriage screws are available to scale 5, 10, or 20 feet of change of stage onto the 2-inch space on the chart, according to what range of stage is to be recorded. All the screws are the same length, but the screws for large ranges in stage have a greater number of groove turns. All the stage-recording carriage screws have right-hand threads.

The stilling-well pipe must be as long as the range of stage to be recorded plus adequate length for the counterweight to move up and down without touching the float. A stilling well for recording a 20-foot range of stage would need to be about 23 feet long. A pipe for recording a 5-foot range of stage would need to be a little over 6 feet long.

RAINFALL RECORDER

Part of the rainfall recorder is shown on the left side of figure 2. The arrangement and function of pipe, counterweight, float, float wheel, carriage screw, and stylus assembly is virtually the same as in the stage-recording mechanism. A few differences should be noted, however. The carriage screw for the rainfall-recording mechanism has a left-hand thread, and only screws that scale 5 feet of change of stage in the rainwater-reservoir pipe onto the 2-inch space on the chart are available. While the trace of the stage-recording mechanism on the chart shows the true time at which a stage change occurs, the trace of the rainfall-recording mechanism is 12 hours ahead of the time of the actual event. This displacement is because the chart time divisions are alined with the stage-recording mechanism and the rainfall-recording mechanism is 180°, or twelve 1-hour divisions on the polar coordinate chart, away from the stage-recording mechanism.

The rainwater-reservoir pipe is 2 inches in diameter and must be a little over 6 feet long. The lower end is closed with a pipe cap and the upper end is attached to the pipe flange on the left side of the SR recorder. Water drains from the rain collector built into the recorder cover through a tube into the rainwater-reservoir pipe. The collector and pipe are built so that water rises 1 foot in the pipe for 1 inch of rain. When the reservoir pipe is installed, the bottom 2 inches is filled with water so that the float will sit properly in the pipe; the carriage screw and stylus assembly are adjusted so that 2 inches of water in the pipe reads as 0 inches of rainfall on the recording chart. A small amount of light oil is placed on the surface of the water to curtail evaporation, which would make the water fall below the "no rainfall" level.

One of the most important parts of the rainwater-reservoir pipe is the external siphon (see fig. 1), which consists of a long U-shaped piece of copper tubing. One leg of the siphon tubing extends below the "no rainfall" water level on the outside of the reservoir pipe. The other leg of the siphon is exactly 5 feet long, and the end is soldered to a small hole in the reservoir pipe at the "no rainfall" level. This hole leads to the inside of the rainwater-reservoir pipe. When enough rain has fallen (5 inches) so that the water level has risen 5 feet above the "no rainfall" level, or to the top of the inverted U of the siphon, the siphon is tripped and the accumulated 5 feet of water in the reservoir pipe drains out through the siphon in about 2 minutes. The rainfall-recording stylus moves back to read 0 inches of rainfall on the chart, and a new cycle of rainfall record is begun. Because of the siphon arrangement, an unlimited number of inches of rain can be recorded.

During servicing visits to the SR recorder, the accumulated water in the rainwater-reservoir pipe can be drained either by pouring more water into the pipe to trip the siphon or by taking out a small pipe plug at the "no rainfall" level. Either method drains out any water above the "no rainfall" level and returns the stylus to its original setting. One point should be remembered, however. If the rainwater-reservoir pipe is set so low that both the siphon outlet and the pipe plug are below high stream stages, the siphon will not work and the pipe plug cannot be removed during high water. In other words, during high water only 5 inches of accumulated rainfall could be recorded and considerable rainfall record might be lost. One solution to this problem is to connect the siphon outlet to a watertight drum or reservoir equipped with a snorkel tube that extends above any likely high water. Connected to this extra reservoir, the siphon will operate normally even though its outlet from the recorder reservoir is below the river level. The snorkel tube is necessary to keep the air pressure in the extra reservoir the same as air pressure outside—if it were not the same, the siphon would not operate properly.

DUAL RECORDER HOUSING

The housing of the SR recorder consists of a cover and a base plate with flanges on the bottom to accommodate two 2-inch-diameter pipes (fig. 3). The pipes are attached to the flanges by means of setscrews. One of the pipes, generally the stage pipe, supports the housing and is firmly fastened to some structure in the stream. The cover of the housing is attached to a side edge of the base plate by a hinge (fig. 2). One side of the cover is built in a special shape to be a rainfall collector. Rainwater runs through a hole in the center of the collector into a drain tube (fig. 2) and from there into the rainwater-reservoir pipe. The cover can be locked to the base plate to prevent vandalism.

DISCUSSION

SR recorders are purposely installed in such a way that they will record only the flood stages of a stream. The bottom of the stilling pipe of the stage recorder is set at the height at which it is desired that stage recording begin. Unless water in a stream rises past the bottom of the stilling-well pipe and moves the float upward, the stylus of the stage-recording mechanism stays on the "0 stage" mark, or the innermost circle on the polar coordinate chart, and inscribes an identical circle each day as the chart rotates continually. If water rises past

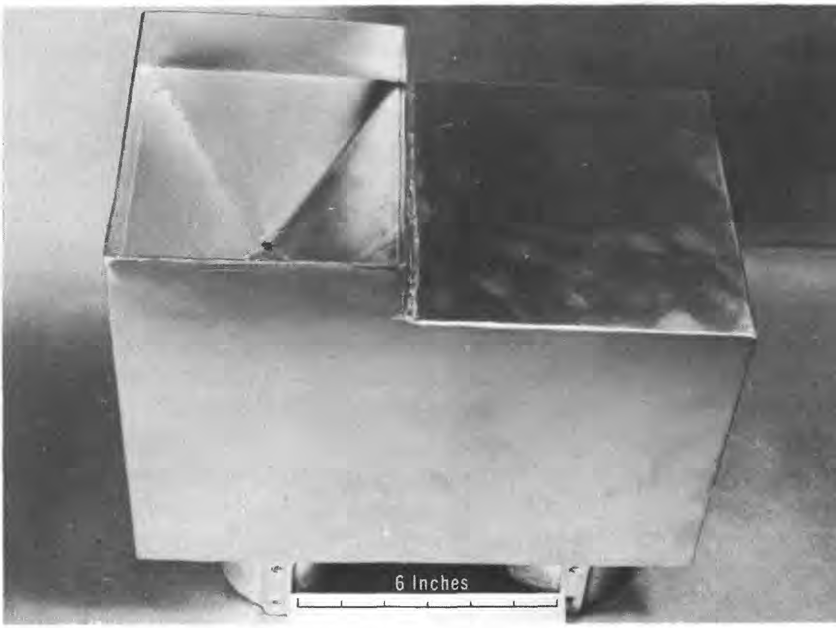

FIGURE 3.—Housing of water-stage and rainfall dual recorder with cover closed. Note opening for rainwater.

the bottom of the stilling well and moves the float upward in the stage pipe, the stylus assembly moves from the inner circle on the chart toward the edge as the water rises. Service personnel should put a new chart on the recorder after about 24 hours of stage recording; unless they do, the stage record from one 24-hour period may be confused with record from the next 24 hours.

The accuracy with which stage can be registered, if the recorder is functioning properly, depends upon the range of stage to be recorded. The larger ranges of stage can be recorded with less precision than the smaller ranges. Assuming that a recorder chart can be read to the nearest 0.01 inch, a 5-foot range of stage can be recorded to the nearest 0.025 foot, a 10-foot range of stage, to the nearest 0.05 foot, and a 20-foot range of stage, to the nearest 0.10 foot.

Unlike the stage recorder, which only registers after water reaches a certain height, the rainfall recorder indicates any measurable quantity of rain that occurs. The rainfall stylus inscribes identical circles on the innermost chart circle, or the "0 rainfall" mark, until a rain. Then, as the float in the rainwater reservoir moves upward, the rainfall stylus moves toward the edge of the chart. When the rain stops, the float in the reservoir stops rising, and the stylus starts a new series of circles at some distance from the chart center. This pattern continues until 5 inches of rain have fallen. Then the rainwater reservoir empties itself, the stylus moves back to its original position, and a new recording cycle begins. While this method of recording is very useful in determining the total amount of rain that falls at a recorder site during a period, it does not indicate the date of any particular rainfall event. If the date of a rain is needed, it must be determined from other sources than the recorder.

The accuracy with which rainfall can be recorded is quite high. Again, assuming that a recorder chart can be read to the nearest 0.01 inch, rainfall records can be read to the nearest 0.025 inch.

Besides being used as components in a dual stage and rainfall recorder, the rainfall recorder and the stage recorder can be used separately if it is desired to register only rainfall or stage at a location.

POLAR COORDINATE CHART READER FOR STAGE-RAINFALL RECORDER

By V. B. Sauer

ABSTRACT

The river-stage and rainfall dual recorder makes graphs on a polar coordinate chart that may be difficult and time consuming to read if done by inspection or with scales. The polar coordinate chart reader determines the coordinates of any point on the chart simply, accurately, and consistently. The chart reader consists of a time mechanism and a stage mechanism arranged so that simultaneous readings of time and stage (or cumulative rainfall) can be obtained with one setting of a stylus. Time intervals read can be as small as 10 minutes, and they can be estimated to 5 minutes. Stage can be read to 0.01 foot and rainfall to 0.01 inch. However, the accuracy of such readings depends on the accuracy of the original chart.

INTRODUCTION

The river-stage and rainfall dual recorder (or SR recorder) graphs stage and rainfall simultaneously on a single polar coordinate chart. Visually reading numerous point coordinates from such a chart is difficult and time consuming. Inaccurate readings may result.

One problem in reading a polar coordinate chart with radial divisions representing time intervals, such as hours, is that the time subintervals are hard to estimate because the distance along arcs for a subinterval is different at the outer edge of the chart than at the inner edge. On the chart from an SR recorder, for example, the distance that represents 1 hour along the innermost arc is 0.12 inch; the distance that stands for 1 hour along the outermost arc is 0.65 inch.

Concentric circles, which represent cumulative rainfall or stage measurements, are always equidistant on an SR-recorder chart. But the same distances between circles (always 0.10 inch) may represent different stage changes on different charts because of the different carriage screws that can be used to scale stage changes. And on many charts the stage scale is not the same as the rainfall scale. (See the preceding article by Smoot and Buchanan.) All these differences of scale complicate the task of a person who reads and interprets an SR-recorder chart.

Another fact that interpreters of SR charts must remember is that rainfall records are displaced 12 hours ahead of the actual rainfall. Therefore, time corrections are required in reading the chart.

The polar coordinate chart reader (see fig. 1) was originally designed to simplify the reading and interpretation of SR-recorder charts. The reader consists of two basic units—the time mechanism and the stage mechanism—arranged so that simultaneous readings of time and stage coordinates are obtained with one stylus setting. With modifications, such as a larger chart table and different scale markings, the reader could be used on any polar coordinate chart.

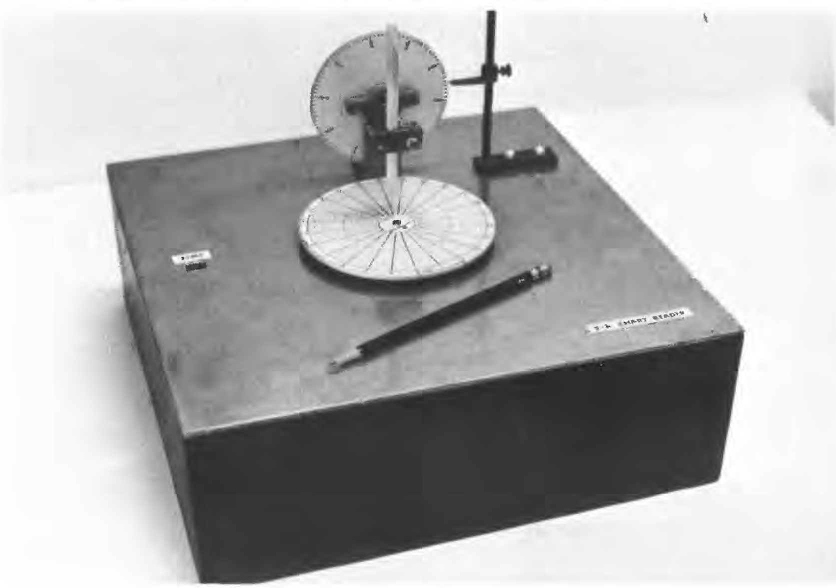

FIGURE 1.—Polar coordinate chart reader designed specifically for SR-recorder charts.

TIME-READING MECHANISM

The time mechanism consists of a vertical shaft, set in bearings, directly connected to a 12-inch-diameter time wheel and to a $5\frac{1}{2}$-inch-diameter chart table. (See figs. 2 and 3.) The shaft is a standard SR-recorder carriage screw machined to fit the bearings and chart table, which are also obtained from an SR recorder. The time wheel is a $\frac{3}{8}$-inch-thick plywood disk attached to the shaft by means of a float wheel from an SR recorder. The time scale is printed on a 12-inch-diameter piece of scale-stable drafting film, which is glued to the top of the plywood disk. The chart table and time wheel are shown

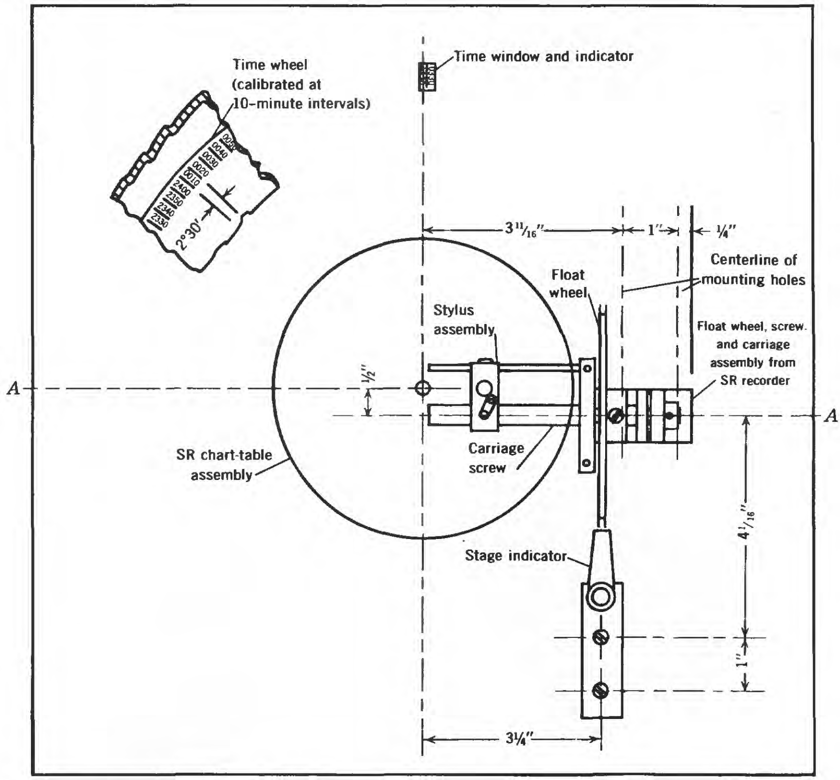

FIGURE 2.—Top view of polar coordinate chart reader showing stylus assembly, carriage screw, and float wheel of stage-reading mechanism and cutaway view of time wheel. *A–A'* is line of section shown in figure 3.

in figure 4. A more durable time wheel could be constructed from a material that is not likely to warp, such as aluminum plate or stainless steel plate. Markings could be scribed or etched on such a material.

All the time-reading mechanism, except the chart table, is enclosed in a box, as shown in figures 2 and 3. A small window in the cover plate shows the time to which a chart has been turned. Time markings show hours or 10-minute subdivisions of hours (fig. 2).

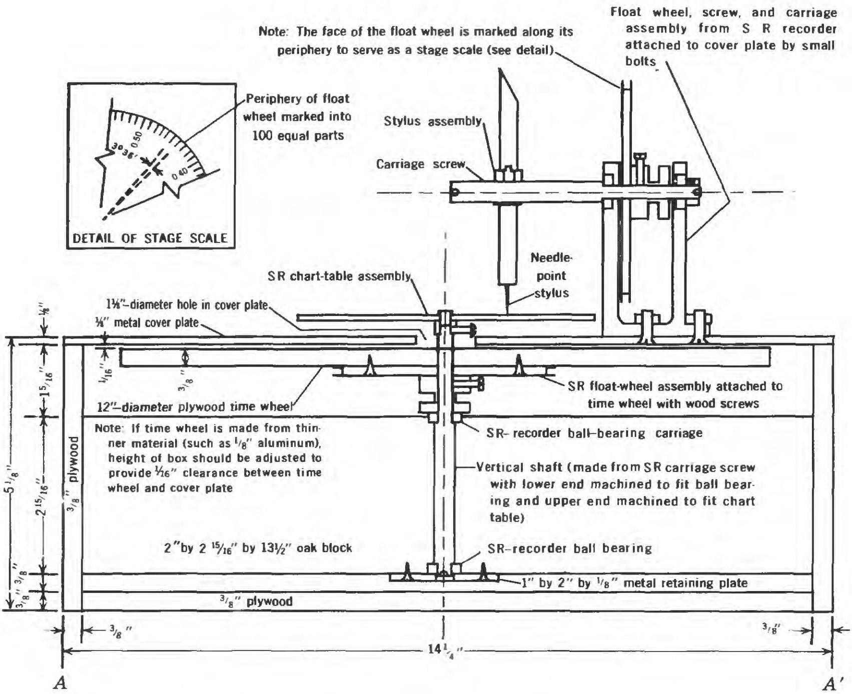

FIGURE 3.—Section *A–A′* through chart reader shown in figure 2. Sections of stage-reading mechanism and of time wheel (attached to chart-table assembly). Detail of stage scale marked on inside of float wheel of stage-reading mechanism.

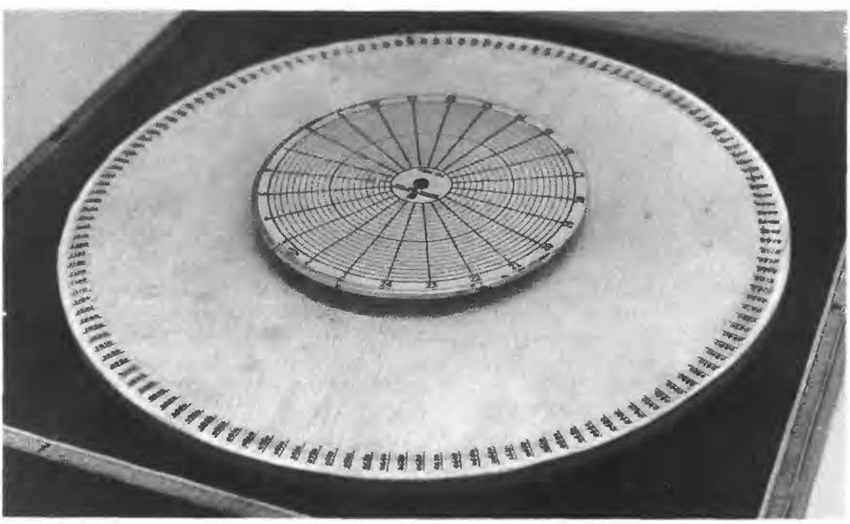

FIGURE 4.—Chart table and time wheel with cover of box removed.

STAGE-READING MECHANISM

The stage-reading mechanism consists of a float wheel, carriage screw, stylus assembly from an SR recorder, and a stage indicator. The stage scale is printed on a 4-inch-diameter piece of drafting film, which is glued to the inside face of the float wheel. A needlepoint stylus is inserted into the stylus assembly to use as a pointer at locations on the SR chart attached to the chart table. The stage scale, stage indicator, and stylus are shown in figure 5.

The stage-reading mechanism is attached to the cover plate of the chart-reader box and is alined so that the needlepoint stylus, as it moves horizontally, will trace a line exactly above one of the radial lines marking an hour on an SR-recorder chart. This alinement must be as nearly perfect as possible so that accurate time readings will be obtained near the center of a chart as well as at the edge. A stage indicator is set near the right edge of the stage scale (fig. 2).

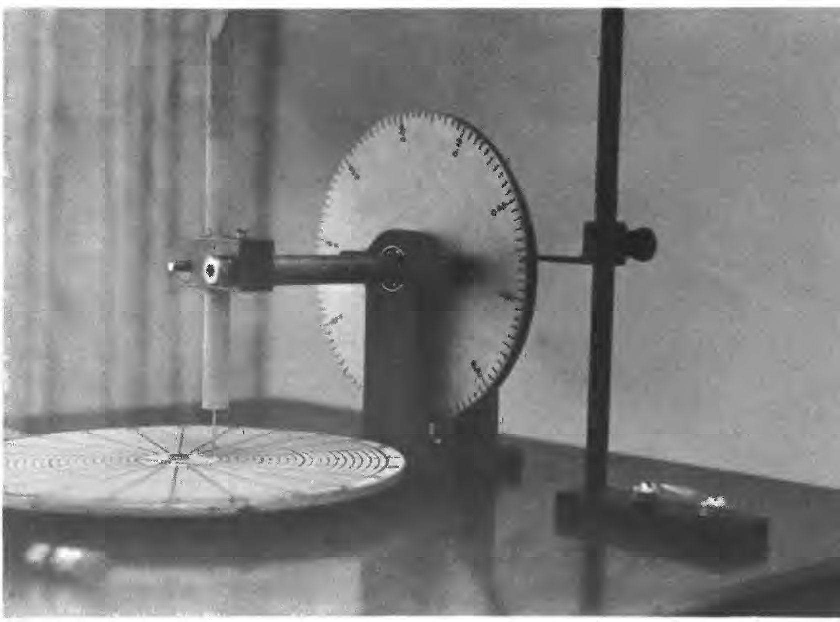

FIGURE 5.—View of stage-reading mechanism with stylus and stylus assembly alined with chart.

READING AN SR CHART

Reading an SR chart correctly requires that the correct carriage screw be used in the stage-reading mechanism. That is, a chart on which a 5-foot range of stage was recorded requires a carriage screw in the reader that scales 5 feet into 2 inches (the effectiveness width of the chart); a chart on which a 10-foot range of stage was recorded requires a carriage screw that scales 10 feet into 2 inches. Reading a group of charts can be done with a minimum of carriage-screw changes by reading all charts with a 5-foot stage range in one group, all charts with a 10-foot stage range in another group, and all charts with a 20-foot stage range in a third group. All rain records should be read when the 5-foot stage range carriage screw is in the reader. A screwdriver, a small Allen wrench, and a few seconds are all that are required to change a carriage screw.

To read a chart, place it on the chart table and turn the table until an hour marking shows in the time window. Then slip the chart until the same hour is alined with the needlepoint stylus. Fasten the chart to the table with a clip or tape; the time should now read correctly in the time window when any other time on the chart is alined with the stylus. The stage is set by alining the stage indicator with the stage wheel when the stylus is pointing at a known stage on the chart (generally the base line or peak stage). Usually the stage-scale wheel is loosened and turned to read the correct hundredth of a foot next to the indicator; when it reads correctly, the stage-scale wheel is tightened. Stage corrections, if uniform, are therefore eliminated. One revolution of the stage-scale wheel represents 1 foot of stage; therefore, foot readings must be remembered.

The stage record of the chart is read starting from the first time at which the stage trace is above the base line (innermost concentric circle). The stylus is moved until it is directly over the stage trace. The stage height and time are noted. The time wheel is advanced the desired time interval, the stylus is relocated just over the stage trace, and the stage scale is read at the indicator. This procedure is continued throughout the period of stage rise and fall, and the readings are tabulated in a convenient form for determining discharge or for future reference. The same procedure is used for the rainfall record.

Compensation for the 12-hour displacement of the rain record can be immediately made by slipping the chart to read the correct time rather than the 12-hour-in-advance time.

The accuracy of reading a flood-stage hydrograph or rainfall record in this manner depends upon the accuracy of the original record. With reasonable care, time can be read at 5- or 10-minute intervals. Although stage can be read to 0.01 foot on any chart with the chart reader, the accuracy of the figure depends on the stage range of the original recording. Rainfall can be read to 0.01 inch. If consistent methods are used throughout the reading of a chart, good readings can be obtained. One innovation that might improve accuracy somewhat would be use of a light source to project a pinpoint of light on the chart instead of using the needlepoint stylus. This technique would insure better alinement with the stage or rainfall trace.

CORRECTING RIVER VELOCITIES MEASURED FROM AN UNANCHORED SHIP

By Luther C. Davis, Jr.

ABSTRACT

The problem of correcting observed Amazon River velocities that were measured from a nonstationary ship was solved by measuring the distance the unanchored vessel drifted during the 40- to 50-second velocity measurement period. By applying the rate of drift, in feet per second, to the observed velocity reading obtained by current meter, a corrected river-velocity reading was computed.

INTRODUCTION

During the summer and fall of 1963, a field party composed of engineers and technicians of the U.S. Geological Survey, the University of Brazil, and the Brazilian Navy made discharge measurements of the Amazon River at Óbidos, Brazil, a point about 500 miles upstream from the river's mouth. Owing to the absence on the Amazon of any river-spanning structures such as bridges or cableways, the conventional platforms from which most large rivers are measured in the United States, a ship of the Brazilian Navy was used as the measurement platform. Use of a ship in making discharge measurements normally would present no particular problem if the vessel could be anchored at each of the observation points of the selected measuring section. However, because of depths as much as 200 feet, anchoring the ship at each of approximately 25 observation points across the measuring section was found to be overly time consuming and mechanically impractical. It was therefore necessary to make measurements from an unanchored ship held as closely as possible on station by varying the engine speed and rudder settings. By making velocity measurements from an unanchored ship, however, an error was introduced to the observed river-velocity reading because of the drift of the ship that occurred regardless of expert ship handling during the 40- to 50-second measurement period. To determine the magnitude and direction of this error, a method was employed that utilized a tellurometer system, a theodolite, and a walkie-talkie radio circuit.

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EQUIPMENT

The tellurometer, for measuring distance, is in common use by the Topographic Division of the Geological Survey for surveying, but it has not been previously used in stream gaging. The system consists of a master unit and a remote unit; it operates much on the radar principle. In practice a series of microwaves are transmitted by the master unit. These impulses are received by the remote unit, run through the circuitry of the receiver, and transmitted to the master unit. The time it takes these impulses to travel the round trip is indicated on the instrument panel of the master unit. These readings are then converted to distance in feet. During the Amazon measuring operations, the master unit was mounted near the bow of the ship (fig. 1), and the remote unit was mounted on shore at one end of the measuring section (fig. 2). A theodolite, a compact surveying instrument used in this application for measuring azimuth angles, also was mounted on shore alongside the remote tellurometer unit (fig. 2). Operators were required for the theodolite and for each of the two tellurometer units.

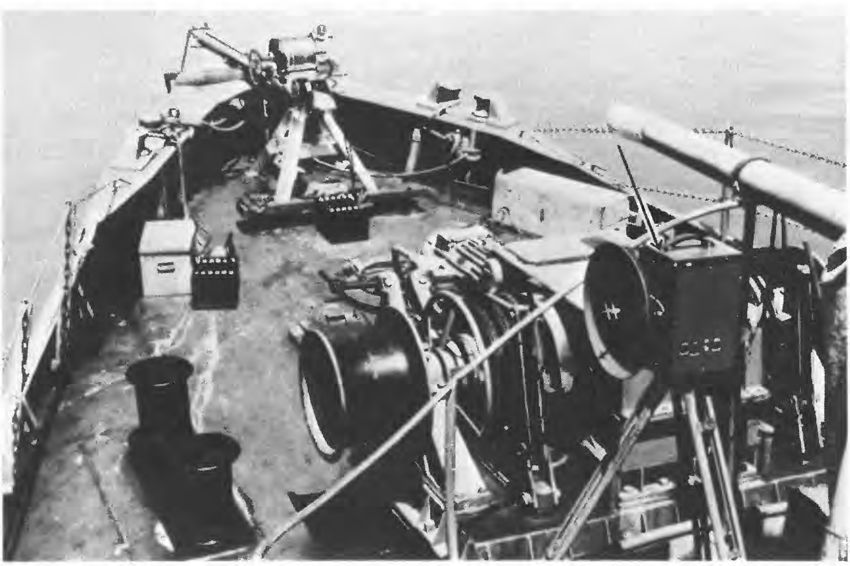


FIGURE 1.—Stream-gaging equipment arrangement on bow of Brazilian naval vessel. Master tellurometer indicated by arrow.

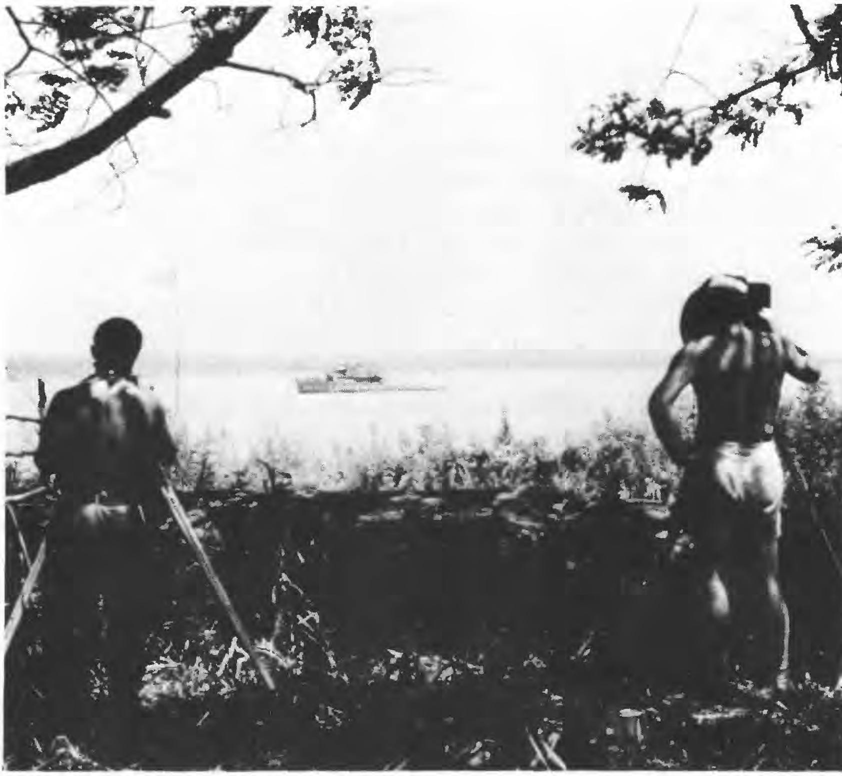


FIGURE 2.—Theodolite (left) and remote tellurometer (right) on right bank of Amazon River measuring section at Óbidos, Brazil.

PROCEDURE

After the ship had been stabilized as accurately as possible at the observation station of the measuring section, the following procedure was used to determine the corrections to be applied to the observed velocity readings:

1. When the current-meter count was started, the shipboard (master) tellurometer operator instantly recorded the exact distance the ship was located from the reference point on shore where the remote tellurometer and the theodolite were located.
2. Concurrently, the shore-based theodolite operator, having received the starting signal by walkie-talkie, recorded the azimuth angle of the ship's location.
3. As soon as the current-meter count was completed, from 40 to 50 seconds later, second tellurometer (distance) and theodolite (azimuth angle) readings were made.

Referring to figure 3, and bearing in mind that angle α was in almost every case smaller than 1°, we can see that for practical purposes the difference between the first (*A–B*) and second (*A–C*) tellurometer readings is the lateral distance (*B–B′*) the ship moved during the 40- to 50-second interval the current-meter count was being made. The difference between the theodolite readings is the angular distance (α) the ship moved during the same interval of time in an upstream or downstream direction. Knowing the linear ship-to-shore distance, we can trigonometrically convert this angular distance to a linear distance (*B′–C*) by using either the tangent or sine function of angle α. These two linear distances (*B–B′*) and (*B′–C*) then constitute the components of the ship's horizontal movement during the velocity measurement interval.

In computing the correction to be applied to the observed velocity, the two components were converted to rates of movement, in feet per second. These values along with the observed river velocity were then plotted as shown in figure 4. The upstream-downstream component was either a positive or negative value depending on which direction the ship drifted during the current-meter count interval; whereas, the lateral component was always a negative value.

The application of corrections to the observed (measured) velocity reading is shown graphically in figure 4. (The graphical solution was found to be both simpler and less time consuming than the mathematical solution.) A vertical line of arbitrary length is drawn to represent the direction of the corrected river velocity. From an arbitrary point (*B*) on this line, the lateral component of the ship's rate

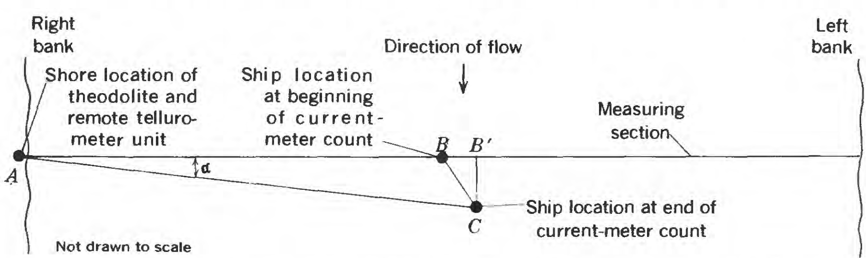


FIGURE 3.—Sketch showing typical drift pattern of ship during 40- to 50-second velocity-measurement period.

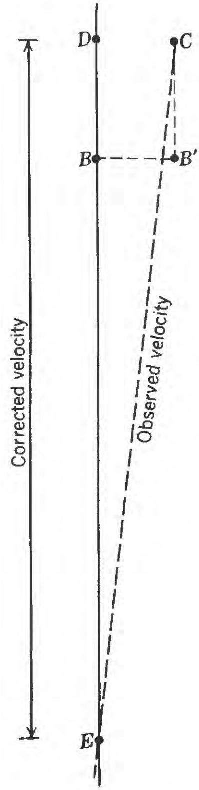


Figure 4.—Graphical application of corrections to observed velocity to obtain corrected velocity reading.

of movement during the velocity count period is shown as B–B'. The downstream component of the ship's rate of movement during the same period is shown by line B'–C. This component (B'–C) also is plotted as distance B–D on the vertical line drawn initially. From point C, the observed velocity measured by the current meter during the 40- to 50-second velocity measurement period is plotted as C–E; this provides an intersection point (E) from which the corrected velocity (D–E) can be scaled off.

PATTERNS OF BACKWATER AND DISCHARGE ON SMALL ICE-AFFECTED STREAMS

By R. ELTON COOK and EDWIN E. CERNY

ABSTRACT

A temporary stream-gaging station was built on an ice-free reach to determine the winter discharge patterns on an ice-affected stream in northern New Mexico. Records from a nearby ice-affected gaging station were compared to records of the temporary station to determine the local daily backwater pattern. The methods used in the study can be applied to improve winter discharge records and the interpretation of winter records of gage height on ice-affected streams.

INTRODUCTION

The annual task of estimating winter mean daily discharges of small ice-affected streams from gage-height records, a few discharge measurements, and daily temperature and precipitation records can be both tedious and time consuming. Backwater caused by ice affects the gage height record so that discharges must be estimated.

Unfortunately, the effects of ice on small streams, such as height of backwater, change with geographic location, with altitude, with weather trends, from drainage basin to drainage basin, from stream to stream, and even from site to site on the same stream. This article outlines a new method of determining the effects of ice, and backwater caused by ice, on the gage heights recorded at particular sites on ice-affected streams. The geographic area in which the outlined method was devised and tested is the Southern Rocky Mountains in northern New Mexico.

STREAMS IN THE SOUTHERN ROCKY MOUNTAINS

Some basic information on conditions and streams is given below. This information is helpful in estimating winter mean daily discharges but falls short of what is needed to complete reasonably accurate winter discharge estimates without great expenditure of time.

Most winter days have several hours of sunshine. Ice and (or) snow melts on sunny afternoons, even on days when maximum air temperatures remain below freezing. The minimum daily temperature most often occurs around 0700 hours and the maximum between 1300 and 1500 hours. The difference between minimum and maximum temperatures for most 24-hour periods is 30° to 40° F. Temperatures are relatively mild during storms but drop sharply afterward.

Small streams in the Southern Rocky Mountain area are generally shallow with steep gradients and high velocities. Anchor ice, the type that attaches on stream beds or on submerged objects, rarely forms. Shore ice forms first and builds toward the center of the stream. The thread of the stream freezes last. Typical ice cover is shown in figure 1.

Water overflowing the ice cover often causes layering. A stream may at times have as many as three layers of ice with some water flowing between layers. Recession of flow can withdraw vertical support and allow ice to slab off or slough into a stream (fig. 2).

A complete freezeout, where all flow has gone into temporary storage as ice, is unusual.

Ice may form on streams in the area for short periods at any time from November through March. Ice on a stream causes backwater that increases and is generally greatest during morning hours; backwater decreases markedly near noon and on some days may be completely eliminated by ice breakup. Stream discharge is generally lowest in the early morning and highest in the early afternoon.

FIGURE 1.—Typical ice storage on a small stream. The ice bridges the stream, but water has almost unobstructed flow underneath the ice. About 4 inches of snow cover is on top of the ice.

FIGURE 2.—Backwater and ice storage at permanent gaging station on the Rio Grande del Rancho. Part of bridged ice has sloughed into channel. Note open water in sunny reach upstream.

PLANNING AND PREPARATION

First, an attempt was made to analyze winter stage and discharge patterns from gage-height records available for each gaging station in the Southern Rocky Mountains in northern New Mexico. The records for ice-affected periods disclosed some interesting patterns of backwater and discharge, and this information could be used—but more specific data and some field verification were needed.

Therefore, it was decided to investigate ice-affected streamflow at seven stream-gaging stations in an exploratory program.

In the past, many attempts have been made to calculate backwater and discharge effects on ice-affected streams from a study of the causes. After considering the large number of causes, and the difficulty of evaluating the effects of each, it was decided that an empirical study of the effect of ice on streamflow might be a promising approach.

Next, a specific method of investigation had to be chosen that would enable several questions to be answered clearly. It seemed to the authors that three important questions about ice-affected streamflow were:

1. Did backwater have a pattern of recurrence that could be related to other phenomena, such as weather?
2. Was the daily discharge pattern consistent enough to justify extrapolation of discharge from the gage-height recorder graph?
3. Was the daily discharge pattern consistent enough so that a discharge measurement taken at any particular time of the day had a definable relation to the mean discharge for that day?

A direct method of answering the last two questions for any particular site would be to make 10 to 15 discharge measurements per day for 2 or 3 days and from these to construct a discharge hydrograph, which could, in turn, be related to the pattern of backwater from ice. We, and others before us, have used this very difficult method as the only feasible one at some sites.

Another, and less fatiguing method, which the authors used, is to construct a supplementary gaging station at a site selected for its relatively free-flow conditions near the original ice-affected station. A gage-height or discharge record collected at the supplementary site can be used to study the relation of actual discharge to backwater from ice at the regular gaging station.

GAGING STATION NEAR TALPA, NEW MEXICO, ON THE RIO GRANDE DEL RANCHO

Of the seven stream-gaging stations studied in the exploratory program, the station near Talpa, N. Mex., on the Rio Grande del Rancho (fig. 3) has been selected for individual discussion.

The Rio Grande del Rancho is a small, meandering, pool-riffle-pool stream with a drainage area of 83 square miles and a main reach above the gaging station 13 miles long. The average altitude of the drainage area is about 8,000 feet. The flood plain is narrow, though some meadows are flooded during normal high flows, and the terrain bordering the flood plain ranges from foothills and small valleys to relatively steep mountains. Ground cover is medium to heavy and consists of grass or forests of conifers and aspens. Areas of bare rock or barren soil are negligible. The main valley of the stream receives several hours of sunshine most days, but some sites are continually shaded because of local topography or vegetation. Annual precipitation averages 16 inches. Winter precipitation, as snow, equals about 1 inch of water per month. Winter discharges of the Rio Grande del Rancho range from 3 to 10 cfs (cubic feet per second) of clear water.

FIGURE 3.—Free-flow conditions at permanent gaging station on the Rio Grande del Rancho; discharge about 5 cubic feet per second.

A reconnaissance was made to find a suitable site for an ice-free supplementary gaging station during a period of severe backwater conditions due to ice. An ice-free reach was found in an open meadow about 1,000 feet upstream from the permanent gage. The unobstructed channel at the new location consisted of a long, deep pool fully exposed to sunshine; there may have been some ground-water inflow at the head of the pool. This location seemed ideal for the supplementary gaging station, though it would have been unsuitable for a regular station because of overbank flows at medium and high stages.

In one working day two men installed a temporary supplemental gaging station consisting of a sharp-crested rectangular weir control, a continuous water-stage recorder, a recording thermograph, and a vented shelter to hold the recording equipment.

Current-meter measurements rated the weir at near the theoretical stage-discharge relation. Comparative measurements showed that discharges at the new gaging station and at the regular gaging station were equivalent and that discharge at the supplementary station could be substituted for discharge at the regular station. Frequent visits or inspections verified that the gage pool of the temporary station was usually free of ice and that the control weir was clear even when some ice did form on the pool. Figures 4 and 5 show the contrast between ice cover at the permanent and supplementary gages.

FIGURE 4.—Complete ice cover and submerged control at permanent gage on the Rio Grande del Rancho. Overflow and partial thaw make ice appear as water in the photograph.

FIGURE 5.—Free flow at supplementary gaging station while permanent gaging station was affected by ice.

ANALYSIS OF RECORDS COLLECTED

Fifty-three days of records were collected in the winter of 1959-60 at the supplementary gaging station. Because of short incomplete or doubtful periods, only 39 days of record were used for analytical purposes. Statistically, 39 days of gage-height data supported by a known stage-discharge relation are far superior to the data that might have been collected during a 3-day series of current-meter measurements.

Gage heights for 3 days on which backwater from ice occurred at the regular gaging station are shown in figure 6. The fluctuations in gage height are not identical for the 3 days, but they are strikingly similar. The gage heights at the regular station that would have corresponded to the actual discharges were calculated from data collected at the supplementary gaging station.

Gage heights for another period of 3 days at the permanent gaging station are shown in figure 7. The gage-height fluctuations indicate that in the morning hours there was considerable backwater but that in the afternoon there was free flow under bridged ice (a condition verified by field inspection). Again, gage heights at the regular station that would have corresponded to actual discharges were calculated from data collected at the supplementary station. Note that the maximum discharge during a day may be as much as 400 percent of the minimum.

In the past it was believed, and often verified by measurements, that discharge measurements made in the morning gave results less than the daily mean discharge and that afternoon measurements gave results greater than the daily mean. Opinions differed as to what quantitative relation any given discharge measurement had to the daily mean discharge.

For the Rio Grande del Rancho near Talpa, the percentage of the daily mean discharge of discharge measurements made at any particular hour is shown in figure 8. This graph was derived from records obtained at the temporary gaging station; the relation of discharge at a particular hour to daily mean discharge would be different at another station on the same stream and different on another stream. For example, discharge on another small ice-affected stream less than 6 miles from the temporary gaging station had almost no daily pattern of fluctuation. Other stations studied had pronounced fluctuation patterns in daily discharge in which maximum flows occurred from 1300 to 1500 hours. Such diverse discharge patterns emphasize the need of an individual curve for each station.

The hydrograph in figure 9 shows daily mean discharges, precipitation, and maximum, mean, and minimum daily temperatures for 27

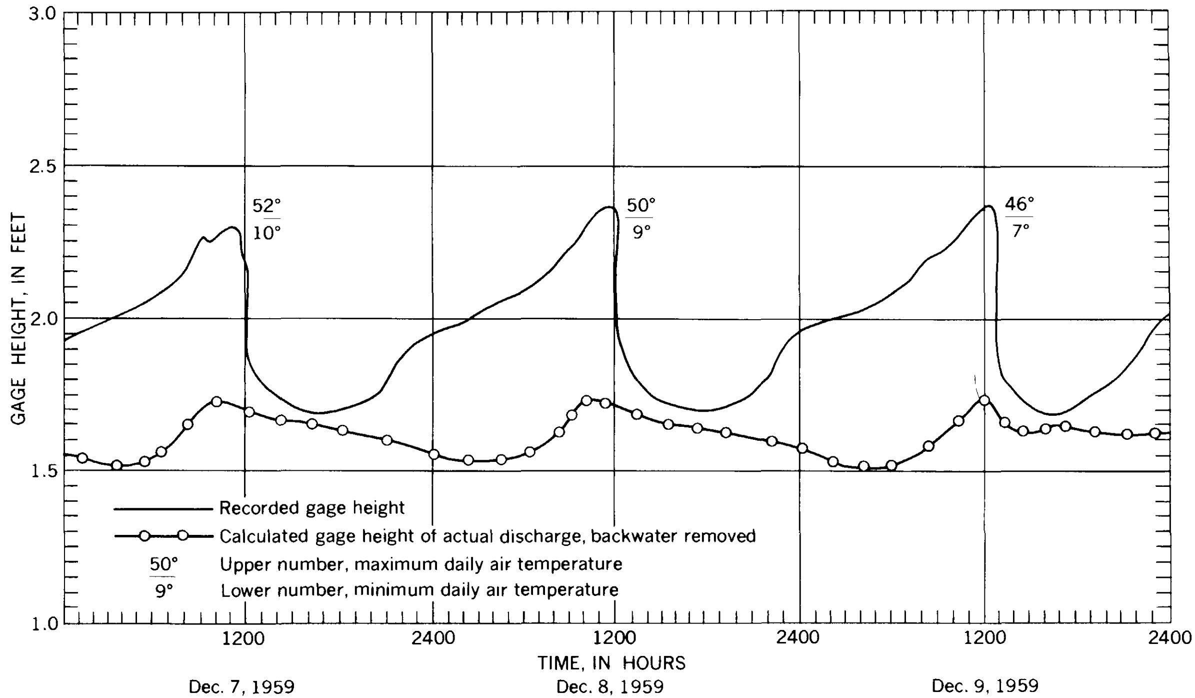


FIGURE 6.—Pattern of backwater from ice at permanent station. Calculated gage height of open water was obtained from data collected at supplementary gaging station. Maximum and minimum temperatures, in degrees Fahrenheit, are from the recording thermograph operated at the supplementary station.

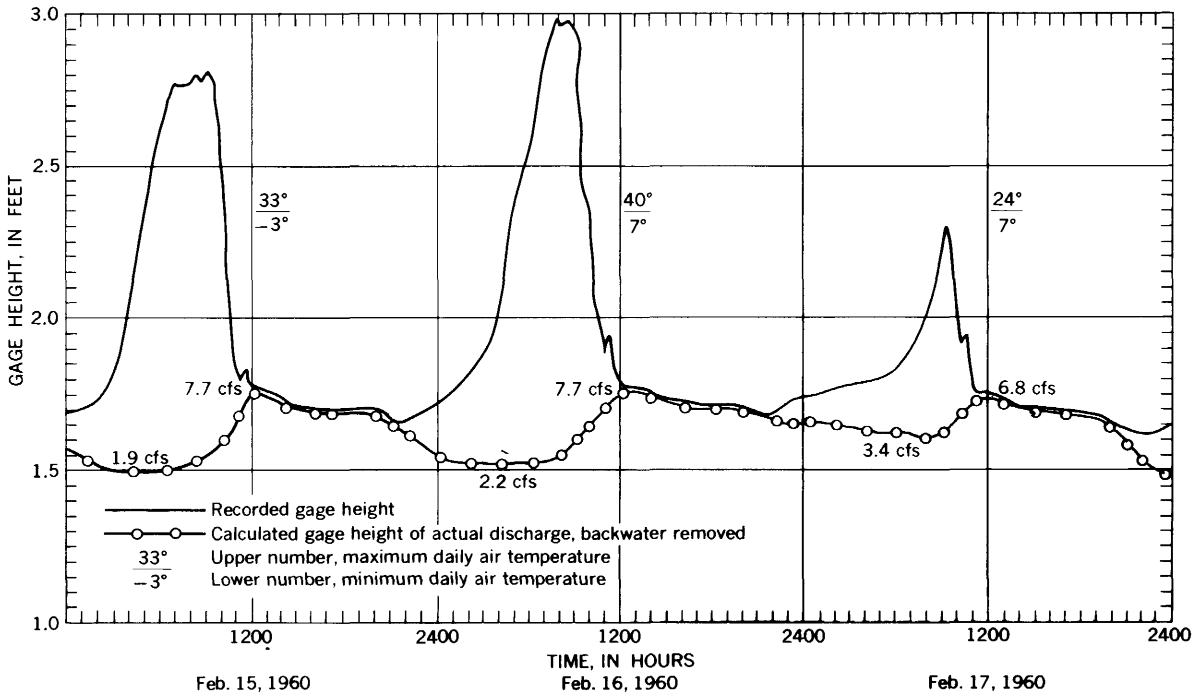


FIGURE 7.—Extreme backwater during morning hours but free flow under bridged and (or) cantilevered shore ice during afternoons at permanent gaging station. Maximum and minimum discharges in cubic feet per second are shown for each day. Temperatures are in degrees Fahrenheit.

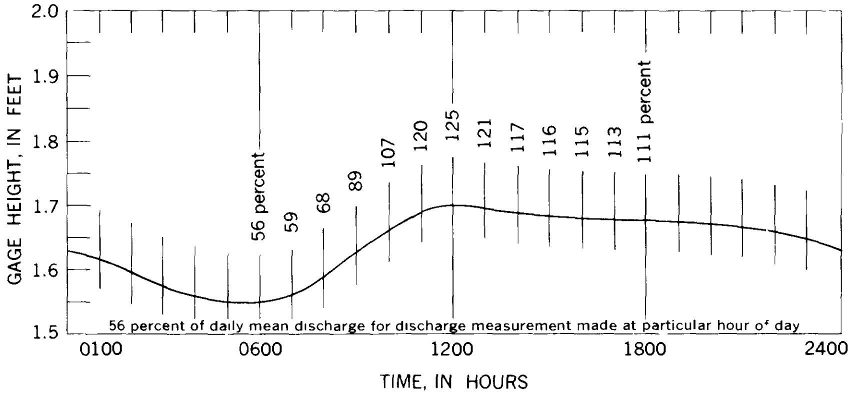


FIGURE 8.—Mean gage-height curve based on 39 days of winter gage-height records at temporary station. The percentage figures indicate the relation that a winter discharge measurement made at a particular hour would have to daily mean discharge.

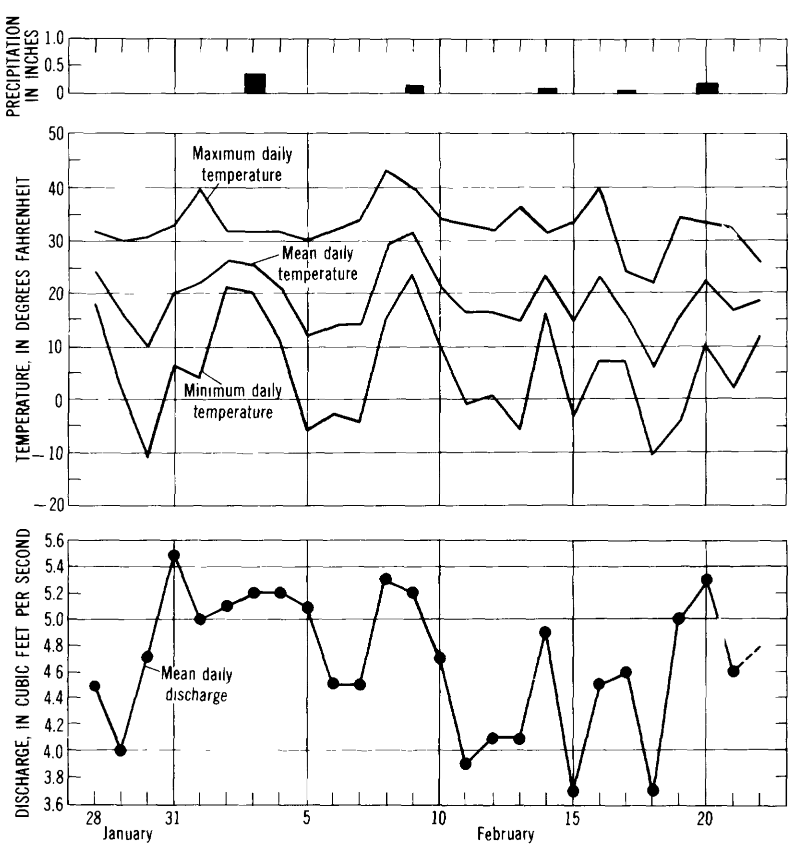


FIGURE 9.—Hydrograph of mean daily discharge. Precipitation and maximum, mean, and minimum daily temperatures are also shown.

days in January and February 1960 at the temporary station on the Rio Grande del Rancho.

If the temporary gaging station had not been built, a synthetic hydrograph for the same 27 days could have been estimated for the original gaging station from two or three actual discharge measurements and a few daily discharges based on parts of the gage-height record corrected for backwater effect. A synthetic hydrograph for an entire winter could have been estimated in a similar manner. Fortunately, periods of backwater are generally separated by periods of free flow caused by a succession of warm days; the periods of free flow are used to correct and interpret the estimated periods of a hydrograph.

OBSERVATIONS

Many of the following observations about constructing gaging stations on ice-affected streams may be common knowledge, but emphasis on items previously recognized but given a minimum of attention may be useful.

In building either temporary or permanent gaging stations on ice-affected streams, an attempt should be made to place a station where it has maximum exposure to sunlight. Winter reconnaissance may reveal suitable sites that are relatively ice free.

Nonmetallic flumes are less apt to ice up than metallic ones. Nonmetallic stilling wells and float cylinders, where practical, are less conducive to deep freezing inside the gage well. Both gage well and float cylinder can be eliminated by using a bubble gage.

An unobstructed, nonrestricted channel downstream from the gage control is highly desirable. On ice-affected streams controls are frequently submerged by ice forming on the control or by an ice jam creating a temporary dam downstream. Also, ice will form sooner and build up faster on wide, shallow, riffle controls than on those with more constriction through which water moves with higher velocities.

Sharp-crested, or blade, controls are probably the least conducive to ice formation if adequate free fall is available. Free-flow Parshall flumes make good controls on ice-affected streams except that water inside the intake pipes may freeze because the pipe intakes are close to the water surface. Funnel, or self-cleaning, flumes may work well because they induce higher water velocities both in the approach to the control and over the control crest.

CONCLUSIONS

Lasting benefits may be derived from locating a temporary gaging station in a reach of stream that has been observed to be relatively free of ice during sustained cold weather. This study indicates that such a station can be used, in conjunction with a nearby ice-affected station, to determine the local pattern of backwater from ice on the stream. A known backwater pattern for a permanent gaging station can be utilized in the annual analysis of winter streamflow records. Information gathered by the method of investigation used in this study makes it possible to reconstruct much of an ice-affected gage-height record with fair confidence.

In addition, the daily discharge pattern ascertained from gage-height records at a temporary ice-free gaging station can be used to relate discharge measurements made at a nearby permanent gaging station at any particular hour of the day to the daily mean discharge.

Finally, using the information obtained from an ice-free temporary station can save substantial time annually in interpreting the winter records of an ice-affected permanent station. Also, the results of interpreting records of an ice-affected station should be of improved quality.

312-670 O—68——9

VARIABLE-SPEED POWER EQUIPMENT FOR DEPTH-INTEGRATION SEDIMENT SAMPLING

By CLARENCE T. WELBORN and JOHN V. SKINNER

ABSTRACT

The power units used in collecting depth-integrated suspended-sediment samples must be capable of lowering and raising a sediment sampler at a constant speed and must operate over a range of speeds. Two different power units were built and tested in an attempt to develop an efficient method of controlling transit rates. Power equipment with a series-wound motor was developed by the U.S. Geological Survey and equipment with a shunt-wound motor was developed by the Federal Inter-Agency Sedimentation Project. Both units proved successful; they differ primarily in the type of motor used and in the general method of motor-speed control.

INTRODUCTION

Depth-integrated sediment samples are usually collected either by wading the stream and using a light-weight sediment sampler or by using 50- or 100-pound sediment samplers on a hand-operated crane and winch. The latter method, which is commonly used when sampling from bridges, boats, or cableways, becomes laborious.

To collect depth-integrated suspended-fluvial-sediment samples, a depth-integrating sampler must be lowered to the bottom of the stream and raised again at a uniform rate, the sample being continuously collected throughout the stream depth. If the rate (speed) of transit is not too rapid, the pressure inside and outside the container will be balanced and the filling rate will be regulated by the stream velocity. It is important that the sampler be lowered and raised at a speed that does not exceed 0.4 of the stream velocity and that the rate of travel of the sampler be uniform; however, the rate of travel for lowering the sampler does not have to be the same as that for raising the sampler.

Certain basic requirements must be met by a power unit if the device is to be used at several different sites for collecting samples of suspended sediment. At any given site the unit must be capable of lowering and raising a sediment sampler at a constant speed. The unit must be capable of operating over a range of speeds because the allowable transit rate is determined by water depth and velocity, both of which may vary with time and location. For convenience the unit should be battery powered and electromechanically efficient.

Several different power units for use with suspended-sediment samplers have been developed and are being used. Most of the existing units utilize a series-wound motor, and the common method of speed control has been either series-connected rheostats or on-off switches. Each of these methods has certain disadantages. The series-rheostat method has a low efficiency because the entire motor current must flow through the rheostat. The resulting heat generated by the rheostat represents wasted battery power, which must be replenished by frequent recharging. The on-off switch method has inherent poor speed regulation because the motor is either off or operating at full power. Intermediate speeds can be achieved by manually switching the motor on and off at a rapid rate, but this causes the sampler to move in a jerky fashion.

In an attempt to develop an efficient method for controlling transit rates, two different power units were built and tested. The two units differed primarily in the type of motor and in the general method of motor-speed control.

SEDIMENT SAMPLERS USED WITH POWER EQUIPMENT

Depth-integrated sediment samplers used with power equipment range in weight from 50 to 300 pounds. The light-weight samplers (depth-integrating), 50 and 62 pounds, are used only to collect sediment samples continuously throughout the stream depth; the heavier samplers (point-integrating), 100 to 300 pounds, can be used to collect sediment samples at any point beneath the surface of a stream. The heavier samplers also can be used to collect depth-integrated samples.

These samplers have a cast bronze streamlined body in which a sample container (pint or quart milk bottle) is enclosed. The sample is collected through an intake nozzle that projects from the nose of the sampler into the stream; the rate of the sample intake can be controlled by the size of the nozzle. Nozzles used have an inside diameter of $\frac{1}{4}$, $\frac{3}{16}$, or $\frac{1}{8}$ inch, and the nose of the sampler is drilled and tapped to accommodate any of these standard nozzles. An exhaust port on the side of the head of the sampler points downstream and permits air to escape from the bottle as it is displaced by the water-sediment sample. Tail vanes are an integral part of the sampler to orient the sampler nose upstream.

A depth-integrated sampler continuously accumulates a sample of the water-sediment mixture by moving vertically at a constant speed and by admitting the water-sediment mixture through the nozzle at a velocity equal to that of the stream. The 100-, 200-, and 300-pound samplers have electrically operated valves that also permit point-integrated samples to be collected.

The samplers are raised and lowered by a sounding reel that is mounted on a crane or bridge rail. The power equipment used with the reel is discussed below.

POWER EQUIPMENT UNITS

SERIES-WOUND MOTOR

The standard power unit used by the U.S. Geological Survey is a 24-volt series-wound direct-current aircraft starting motor that is normally operated by either a 6- or 12-volt storage battery. Whether powered by 6 or 12 volts the standard equipment has no provision for varying the speed (other than by braking) of the sounding reel, which is a component of the standard equipment. Some means of varying the speed of the sounding reel is essential for proper depth integration of a sediment sampler. For example, the transit rates in water of 100-pound and 50-pound sediment samplers lifted by a sounding reel driven by the standard motor powered by a 12-volt battery are about 4 fps (feet per second) and 6 fps, respectively. Both transit rates generally exceed the maximum rate permitted by the design of the sediment samplers used by the Geological Survey.

In trying to develop an efficient method of controlling transit rates, it was first suggested that a rheostat be used to control the voltage supply to the motor. However, a rheostat of the size necessary would be too bulky for the portable equipment used by the Geological Survey. The variable-speed power equipment that was finally designed and is now used by the Water Resources Division in Texas is shown in figure 1*A*. The power equipment, which is mounted on a crane and dolly, can be adapted to field trucks as shown in figure 1*B*. The non-standard items in figure 1 include a heavy-duty multiple switch, two 6-volt heavy-duty storage batteries, and the motor clutch.

The multiple switch (*a* in fig. 1) consists of two pieces of ¼-inch insulating board; six silver-alloy contacts and a control arm on the front of the multiple switch; and electrical connections to each contact and to the control arm at the back of the switch.

The power supply (*b* in fig. 1) is two 6-volt heavy-duty storage batteries. The batteries must be altered so that each cell of the batteries has a positive and negative connection. Then, when the batteries are connected in series, any voltage from 2 to 12 volts, in multiples of 2, can be delivered to the motor.

When 50- or 62-pound sediment samplers are used, a clutch must be on the motor to overcome the friction in the motor (*c* in fig. 1). Without the clutch these lighter weight sediment samplers could not be

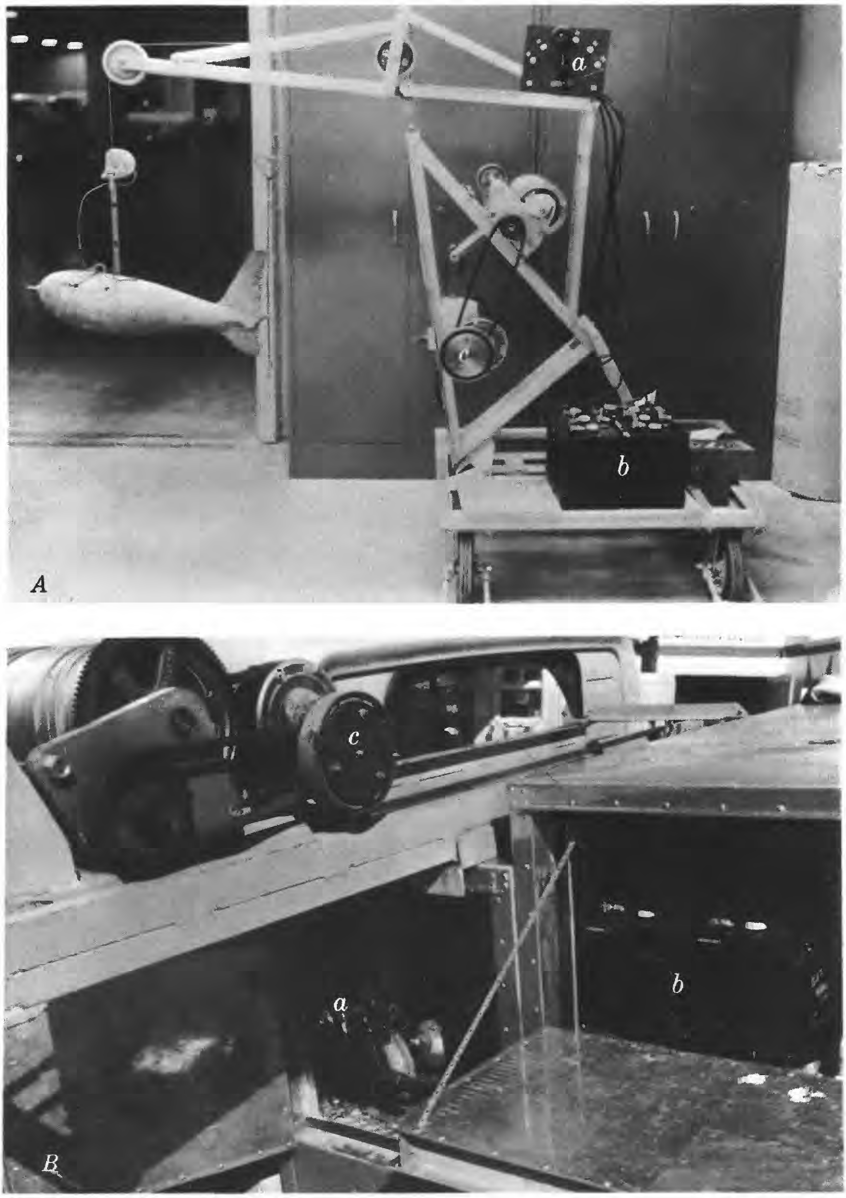


FIGURE 1.—Views of variable-speed power equipment with a series-wound motor: *a*, Multiple switch; *b*, storage batteries; and *c*, Grozier clutch. *A*, Arrangement of equipment. *B*, Adaption of equipment to field trucks.

used with the variable-speed equipment discussed here. The motor clutch, which was designed by Richard U. Grozier, Geological Survey, was made from parts of a standard centrifugal clutch as used on motorscooters. Additional information on the design of the motor clutch is available in the office of the U.S. Geological Survey, Water Resources Division, Austin, Tex.

The motor is activated by a 12-volt solenoid, and 12 volts must be supplied to the solenoid at all times. By proper wiring and insulation of the solenoid from the vehicle, 12 volts can be delivered to the solenoid, and voltage from 2 to 12 volts can be supplied to the motor (fig. 2). Four volts to the motor is about the minimum voltage that can be used with the sediment samplers. Changing the voltages to the motor by switching to the 4-, 6-, 8-, 10-, or 12-volt circuit will make the upward speed of a 100-pound sediment sampler in water range from 0.5 fps to 4 fps. The speed of a 50- or 62-pound sampler will be a little faster. The downward speed of the sampler is controlled by the brake on the winch after the motor is disengaged from the power pulley by the action of the clutch.

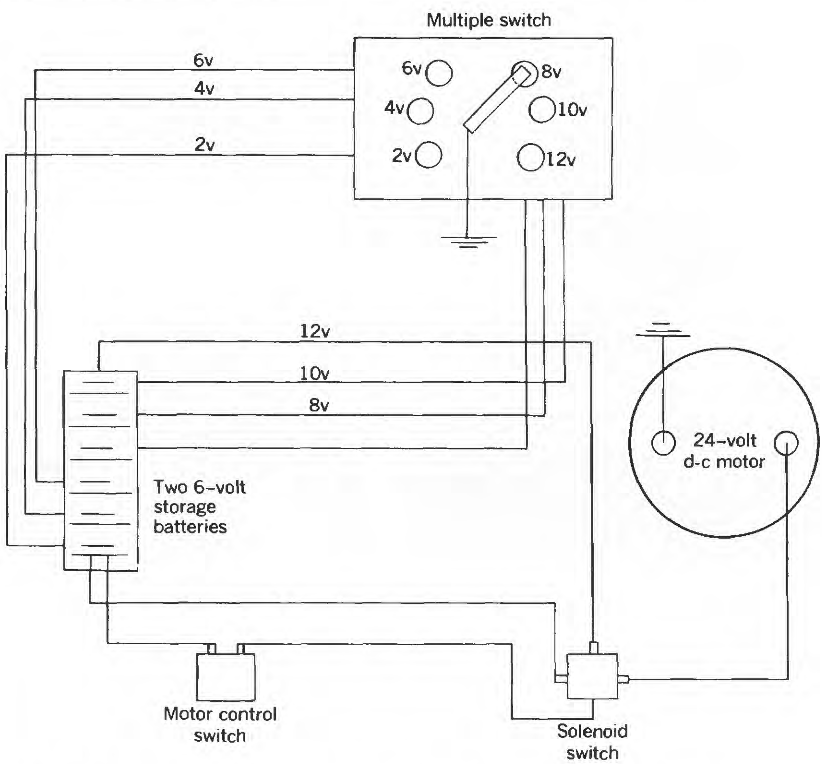


FIGURE 2.—Schematic wiring diagram for the variable-speed power equipment with a series-wound motor.

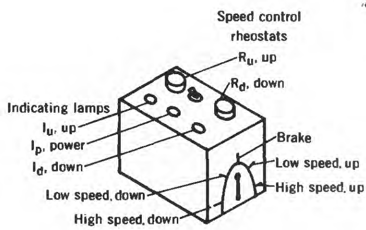
SHUNT-WOUND MOTOR

A shunt-wound motor differs from a series-wound motor with respect to the resistance and connection of the field winding and to the possible methods of speed control. The field resistance of the shunt-wound motor is several hundred times greater than the resistance of the field winding of an equivalent horsepower series motor, and, as the name implies, a shunt-wound motor has the field connected in shunt (in parallel) with the armature.

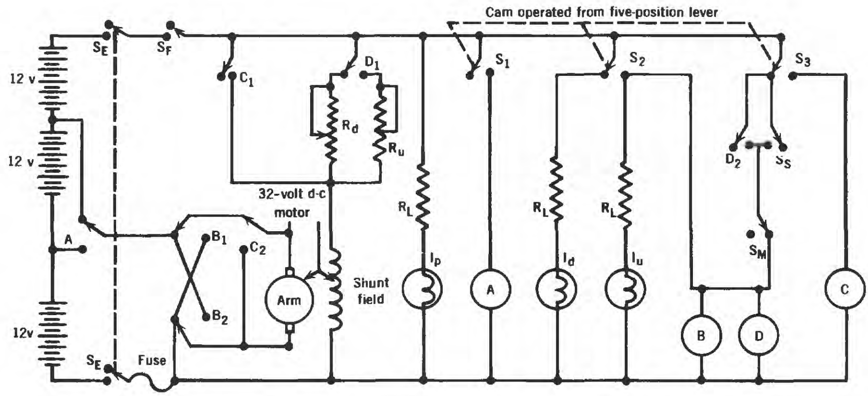
The speed of a shunt-wound motor can be varied in two ways: one method is to connect the field to a constant voltage supply and vary the armature voltage; the other method is to connect the armature to a constant voltage supply and vary the field current. The field current is normally less than about 5 percent of the current supplied to the motor through its armature and field. Because the field current is small, a rheostat can be used to change the field current without lowering the overall motor efficiency by more than about 4 percent. This loss in efficiency is almost negligible in comparison with mechanical losses in speed-reduction equipment, such as belts and pulleys, which are present in any power-operated hoist.

In the experimental power unit that was constructed, both armature voltage and shunt field current variation were utilized as methods of speed control. As figure 3 indicates, the armature was connected through relay A contacts to either 12 volts or 24 volts. With the field current held constant, doubling the armature voltage caused the motor speed to double. The shunt field was connected through either rheostat R_d or R_u to 36 volts. Relay D was wired so that while the sampler was being lowered the shunt field current was supplied through R_d and while the sampler was being raised the field current was supplied through R_u. Both rheostat settings could be adjusted by the operator. With the two separate rheostats, the operator could adjust the raising and lowering speeds independently. The rheostats provided a continuously variable speed control over a speed ratio of 2:1. The combination of the two speed-control methods allowed the operator to adjust the transit rate of a 100-pound sampler to any value between 0.5 and 2.0 fps.

Reversal of sampler traverse directions could be done either automatically or manually. Reversal of motor rotation was performed by the contacts of relay B, which changed the polarity of the applied armature voltage. For automatic reversal, relay B was activated through switches S_3, S_S, and S_M. The automatic reversal signal originated with switch S_S, which was mounted near the tip of the crane. The switch was restrained by a spring-loaded pulley that was supported by the suspension cable. When the sediment sampler struck the



DETAIL OF REMOTE CONTROL
APPROXIMATELY 5" by 5" by 4"

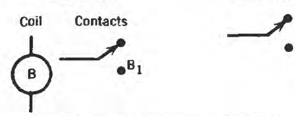


Positions of switches S_1, S_2, and S_3 during various phases of operation

Switch	Phase				
	High speed down	Low speed down	Brake	Low speed up	High speed up
S_1	Relaxed	Depressed	Depressed	Depressed	Relaxed
S_2	Relaxed	Relaxed	Relaxed	Depressed	Depressed
S_3	Relaxed	Relaxed	Depressed	Relaxed	Relaxed

Relay (A–D)

Switch (S)



Note: Arrows point to relay and switch contacts that are normally closed. Relay contacts are normally in deenergized position and switches are normally in relaxed position

FIGURE 3.—Schematic diagram showing wiring and operation of the variable-speed power equipment with a shunt-wound motor.

bottom of the stream, the suspension cable went slack, switch S_s closed, and current immediately flowed to the coil of relays B and D. While relay B contacts were reversing the armature voltage, relay D contacts were simultaneously performing the two functions of switching the field rheostats and bypassing switch S_S. The bypass contacts insured a continuous supply of power to relay B even after cable tension had been restored. For manual reversal the operator could open toggle switch S_M. Power could then be supplied to relay B only through switch S_2 that was coupled to a manually operated five-position lever. The positions of switches S_1, S_2, and S_3 in relation to the five positions of the manually operated control lever are shown on the cam chart in figure 3.

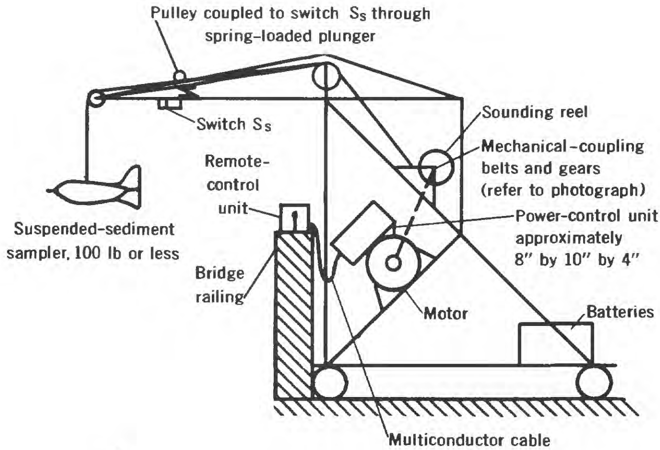
The power unit also was equipped with a circuit that enabled the shunt-wound motor to function as an electromagnetic brake. The operator could switch the control lever to the brake position and thus energize relay C through switch S_3. Relay C contacts performed the two functions of applying 36 volts to the shunt field and short-circuiting the motor armature. With the armature shorted and disconnected from a power supply, the motor functioned as a viscous damping device. The damping, when combined with the friction of the belting, was sufficient to hold a 100-pound sampler suspended. The brake function, when combined with the four lowering and raising functions, gave the operator complete sampler control with only one operating lever.

In its final form, the power equipment consisted of six major parts: remote-control unit, power-control unit, batteries, shunt-wound motor, automatic reversing switch, and speed-reduction equipment. (See table 1 for an itemized list of parts.) The parts were mounted on a crane and the motor was mechanically coupled to a sounding reel as shown in figure 4. The mechanical coupling consisted of two stages of belting between the motor shaft and the power shaft of the reel. Overall speed reduction from motor shaft to reel drum was 40 : 1.

Some difficulty was encountered with arcing on relay B contact when automatic reversing was used. The almost instantaneous reversal of the motor rotation caused large surge currents of 90 to 100 amperes to pass through the relay contacts. It was found that manual reversal reduced the contact burning considerably but increased slightly the reversal time.

The complete crane and power equipment was transported to the U.S. Corps of Engineers office at Omaha, Nebr., for testing. At the testing site the automatic reversal was not used because samples were collected only while the sampler was moving from the streambed upward. Between battery charges, the Corps field personnel were able to collect 40 to 50 samples with a 100-sampler operating through a lift of about 100 feet. The testing team reported that operation was very favorable.

In general, the power unit met the requirements for use with suspended-sediment samplers. With a 100-pound sampler, speed regulation could be maintained within about 5 percent over the 0.5 to 2.0



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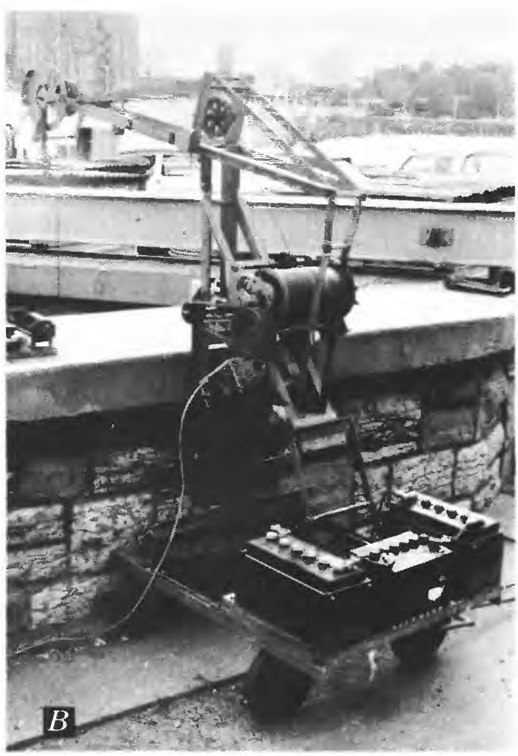
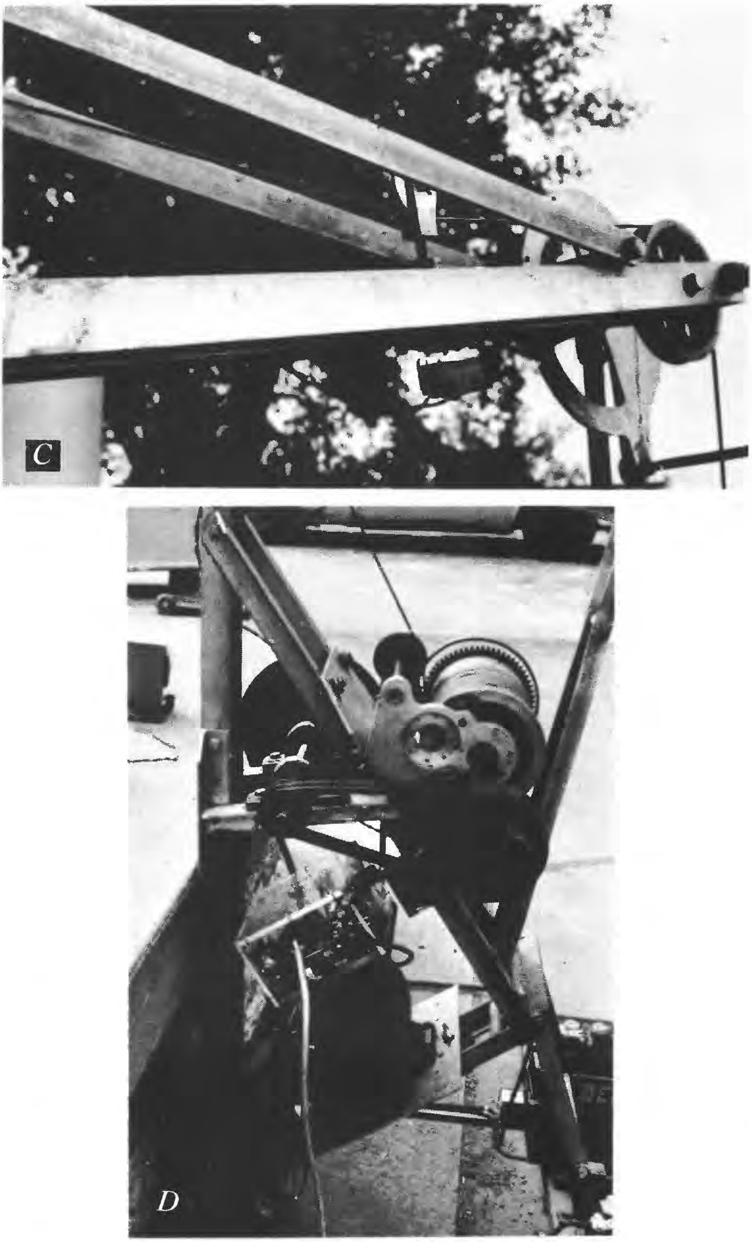


FIGURE 4 (above and facing page).—Views of variable-speed power equipment with a shunt-wound motor. *A*, Sketch of equipment; *B*, power equipment;



C, reversing mechanism; and *D*, hoist details.

TABLE 1.—*Components of variable-speed power equipment with shunt-wound motor*

Component	Location	Description	Function
Batteries (three required).	Rear of crane	12 volts, 55 amperes	Power supply and counterweight.
Fuse	Power-control unit	40 amperes	Motor protection.
Indicating lamp:			
I_d	Remote-control unit	24–36 volts, minature	Indicates downward traverse.
I_u	do	do	Indicates upward traverse.
I_p	do	do	Indicates control power on.
Motor	Frame of crane	¾-horsepower 32-volt d-c, shunt wound.	Prime mover.
Relay:			
A	Power-control unit	Single-pole double-throw, heavy duty, 36-volt d-c coil, 25-ampere contacts.	Coarse speed control. Applies either 12 or 24 volts to motor armature.
B	do	Double-pole double-throw, heavy duty, 36-volt d-c coil, 25-ampere contacts.	Controls direction of motor rotation.
C	do	do	Short motor armature for electromagnetic brake action.
D	do	Double-pole double-throw, light duty, 36-volt d-c coil, 5-ampere contacts.	Permits operator to adjust up and down traverse speeds independently. Overrides automatic reversing switch S_s after sampler reverses traverse at stream bottom.
Resistors, R_L (three required).	Remote-control unit	Fixed carbon	Drops 36-volt supply to voltage level required by indicating lamps.
Switch:			
S_1	do	Single-pole double-throw, light duty, snap action with roller leaf actuator, 28-volt d-c, 10 amperes.	Switches power to coil of relay A.
S_2	do	do	Switches power to coil of relays B and D.
S_3	do	do	Reverses direction of motor rotation and simultaneously inserts appropriate R_d or R_u rheostat in field circuit; switches power to relay C to set motor run or brake mode.
S_E	Power-control unit	Double-pole double-throw, heavy duty, toggle, 250-volt a-c, 20 amperes.	Main power disconnect.
S_F	Remote-control unit	Single-pole single-throw, heavy duty, toggle, 250-volt a-c, 20 amperes.	Remote power disconnect.
S_M	do	Single-pole double-throw, heavy duty, toggle, 120-volt a-c, 5 amperes.	Switches control of motor reversal to switch S_S or to manually operated five-position lever.
S_S	Arm of crane	Single-pole double-throw, light duty, pushbutton, 120-volt a-c, 5 amperes.	Automatically reverses motor rotation when suspension cable is slack.
Rheostat:			
R_d	Remote-control unit	25 watts, wire wound	Vernier speed control for lowering samples.
R_u	do	do	Vernier speed control for raising samples.

fps range. This range of speed probably would be adequate to meet the requirements at most sampling sites. The overall efficiency, measured as the rate of change of sample potential energy divided by the power drain from the batteries, was about 40 percent. Roller chains and sprockets were later substituted for the V-belts and pulleys shown in figure 4, and the efficiency was increased to about 50 percent. The motor functioned as a generator while the sampler was being lowered at high speed, and battery charging currents in excess of 5 amperes were observed.

The shunt-wound motor power equipment was developed from work financed by the Federal Inter-Agency Sedimentation Project. Acknowledgment also is due B. C. Colby and T. F. Beckers, formerly assigned to the Federal Inter-Agency Sedimentation Project, both of whom assisted with the design and testing of the prototype.

COST

A cost comparison of the two power units is shown in the following tabulation:

Series-wound unit

Materials:	
Motor	$170
Batteries	60
Switch	65
Clutch	45
Total	340
Labor	60
Total	400

Shunt-wound unit

Materials:	
Motor	$175
Batteries	45
Remote-control unit	40
Power-control unit	50
Mechanical coupling (V-belt)	65
Total	375
Labor	300
Total	675

SUMMARY

The advantage of either the series-wound or the shunt-wound power equipment for sediment sampling is that the power equipment relieves the fieldman of much laborious work. Also the equipment enables the fieldman to control the transit rate better than by manual control.

A comparison of the series-wound and the shunt-wound power units reveals that the two units differ with respect to complexity, efficiency, maintenance, degree of control, and initial cost. The shunt-wound unit affords a greater degree of control and efficiency but at the expense of greater complexity, cost, and maintenance. The series-wound unit, because of the smaller number of parts, has a lower initial cost, is more rugged, and requires less maintenance.

ELECTRIC CONTROL SYSTEM FOR DUAL OPERATION OF CURRENT METER AND SUSPENDED-SEDIMENT SAMPLER

By HERBERT H. STEVENS, Jr., and ROBERT E. SOMMER, Jr.

ABSTRACT

An electric control system permits monitoring a current meter and operating a U.S. P–61 suspended-sediment sampler without surfacing the equipment. Use of this control system reduces the time required for observing velocity and sediment concentration in major streams.

Water discharge and sediment concentration of streams are usually determined by obtaining water velocity and stream depth with a current meter and sounding weight and by collecting suspended-sediment samples with a sampler. Dempster and Stevens (1965) described the use of a U.S. P–61 suspended-sediment sampler as a sounding weight for the current meter in place of the usual Columbus-type weight and described the meter-rating corrections that are required for this sampler suspension. This combination of current meter and sediment sampler expedites the collection of velocity and sediment data.

Since voltage requirements of the current meter and sediment sampler are very different, the electric circuits must be separated. Alternatives are sequential connection of the current meter and headphones or sediment sampler and sampler control switch to the available two-wire circuit, which requires raising the assembly from the water to the bridge level between observing velocities and sampling sediment; substitution of a three-wire circuit, which is an expensive operation; or the use of a system such as the diode-connected control described in this article. The electric control system as explained below permits sequential monitoring of the current meter and operation of the sediment sampler without surfacing the equipment.

The two parts of the electric control system are a selective control switch in a battery box that is mounted on the crane (fig. 1*A*) and a diode voltage-divider that is placed on the hanger bar between the current meter and sediment sampler (fig. 1*B*). A schematic wiring diagram for the control system is shown in figure 2. The DPDT (double-pole double-throw) selective control switch changes voltage and reverses polarity in the inner wire of the suspension cable. When

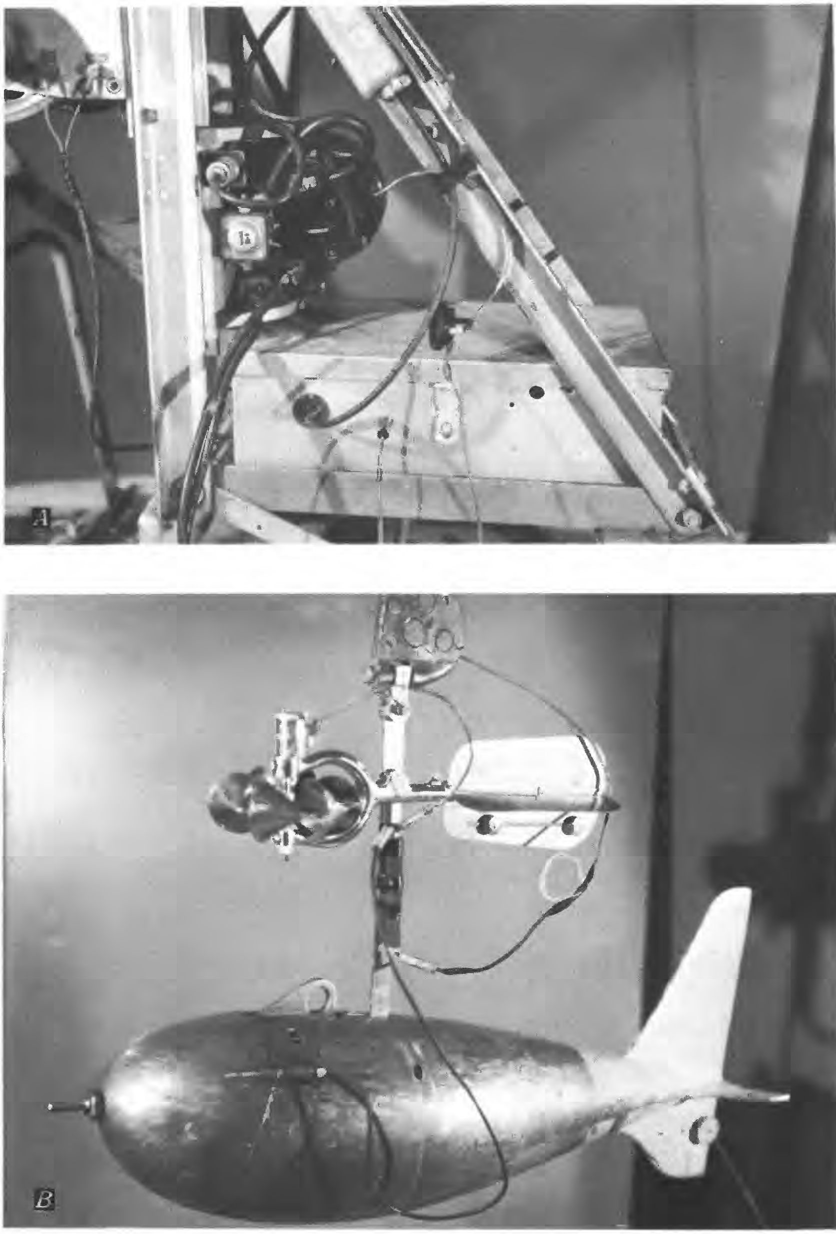


FIGURE 1.—Current-meter and sediment-sampler control system. *A*, Selective control switch and battery box; *B*, diode voltage-divider taped to hanger bar between Price current meter and U.S. P–61 suspended-sediment sampler.

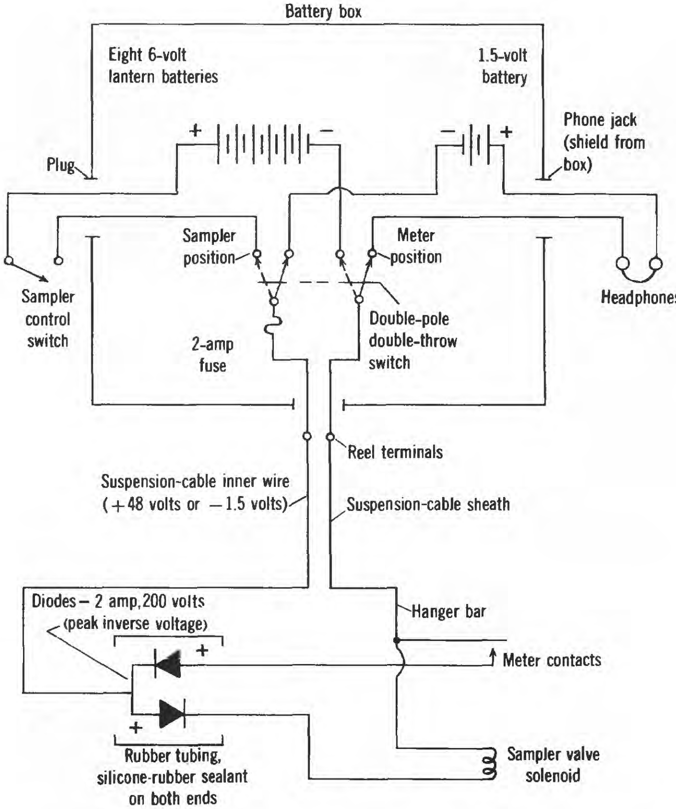


Figure 2.—Schematic wiring diagram of electric system used as a control of Price current meter and U.S. P–61 suspended-sediment sampler.

the DPDT switch is in the meter position, a negative 1.5 volts is supplied to the inner wire through the headphone circuit; when the switch is in the sampler position, a positive 48 volts is supplied to the inner wire through the sampler control switch. The diode voltage-divider consists of two diodes, encased in a waterproof housing, that are connected in opposite polarity to the inner wire of the suspension cable. One of these diodes is connected to the meter and the other diode is connected to the sampler. The meter diode allows 1.5 volts to flow through the meter contacts while the sampler diode blocks the 1.5 volts from the sampler solenoid. Conversely, the sampler diode allows 48 volts to flow through the sampler solenoid while the meter diode blocks the 48 volts from the meter contacts.

The electric control system has provided reliable and trouble-free service during 2 years of field use. Use of the control shortens data-collection time and prolongs reel-motor battery life by reducing the number of times the equipment must be raised or lowered between the bridge and the stream.

REFERENCE CITED

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CHARACTERISTICS OF LOGARITHMIC RATING CURVES

By S. E. Rantz

ABSTRACT

An understanding of the shapes of logarithmic rating curves is requisite for analyzing the stage-discharge relation of a stream. The principles that govern the shapes of rating curves are demonstrated. As a general rule, linear logarithmic rating curves for section control have slopes greater than 2; linear logarithmic curves for channel control have slopes less than 2.

INTRODUCTION

The rating curve, or stage-discharge relation, for a stream is usually plotted on logarithmic graph paper to simplify analysis of the characteristics of the stage-discharge relation. Analysis of the rating is perhaps of only academic interest where the entire range of stage of the rating curve is defined by discharge measurements. However, rating curves are often incompletely defined by measurements and must be extrapolated beyond the stage of the highest discharge measurement or must be interpolated between discharge measurements made at greatly differing stages. When rating curves are incompletely defined by measurements, a knowledge of the characteristics of logarithmic rating curves is needed so that extrapolation or interpolation can be performed on a rational basis.

STAGE-DISCHARGE CONTROLS

A prerequisite for any discussion of logarithmic rating curves is an understanding of the functioning of stage-discharge controls on streams. Two types of controls are section and channel. Section control exists when the geometry of a single cross section of a stream controls the relation between stage and discharge. Often the cross section that is the control for lower stages is not the control for higher stages. A cross section downstream may become effective at higher stages by causing backwater that submerges the original low-water control, or channel control may become effective at higher stages. Channel control exists when the geometry and roughness of a long reach of channel, downstream from a gage, control the relation between stage and discharge. Channel control is generally effective at high stages; the most common exception is when the section control is a high dam or weir that does not become submerged at high flows.

A logarithmic rating curve is seldom a straight line or gentle curve for the entire range in stage at a site on a stream. Even if a single cross section of channel is the control for all stages, a sharp break in the contour of the cross section causes a break in the slope of the rating curve. Commonly, however, a break in slope of the rating curve is due to the low-water section control being submerged because a downstream section control or channel control becomes effective.

THEORY OF LOGARITHMIC RATING CURVES

The general equation of any straight line drawn on logarithmic graph paper is

$$Y = aX^m, \tag{1}$$

where Y = the dependent variable,
X = the independent variable,
a = the value of Y when X equals 1,
and m = the slope of the line.

If this same straight line is a rating curve, or a segment of a rating curve, its equation is

$$Q = pH^b, \tag{2}$$

where Q = the discharge, in cubic feet per second,
H = the head, or depth, of water on the control, in feet,
p = the discharge when H equals 1 foot,
and b = the slope of the line.

Because the dependent variable, Q, is conventionally plotted as the abscissa of the rating curve, slope, b, is computed as the ratio of the horizontal projection of a segment of the curve to the vertical projection.

Commonly, the gage height of the water surface does not represent depth of water. For example, if the gage is set to sea-level datum, gage height obviously will not represent depth except in the special case where the elevation of the control is exactly at sea level. Therefore, to transform gage height of the water surface to head or depth of water (H in eq. 2), we must subtract the effective gage height of the control, or the gage height of effective zero flow, e, from the gage height of the water surface, G. For simple controls, e is the stage at which discharge ceases. G and e are both measured in feet. By substitution of the gage-height terms for H in equation 2, we obtain the following basic equation for a linear segment of a rating curve plotted on logarithmic graph paper:

$$Q=p(G-e)^{b}. \tag{3}$$

Ordinate scales printed on logarithmic graph paper represent $G-e$; however, ordinate scales can be transformed to gage readings of water surface by adding the value of e to each printed number.

Because the constants in equation 3 are related to the physical characteristics of the stage-discharge control, it is interesting to examine the effects of control changes on the rating curve. If the width of the control increases, p increases, and the new rating curve will be parallel to and to the right of the original curve. If the control scours, e decreases, and the depth for a given gage height increases; the new rating curve will move to the right and will no longer be a straight line but will be concave downward.

This change in shape of the logarithmic rating curve with a change in the value of e is an example of a general rule that is illustrated in figure 1. All three curves in figure 1 represent the same rating. For example, when the gage height, G, is 4 feet, $Q=10$ cfs (cubic feet per second; when the gage height, G, is 8 feet, $Q=90$ cfs If too small a value of e is used, the curve is concave upward; if too large a value of e is used, the curve is concave downward. Consequently, if a curve is concave upward, it can be transformed to a tangent by increasing the value of e. If a curve is concave downward, it can be transformed to a tangent by decreasing the value of e.

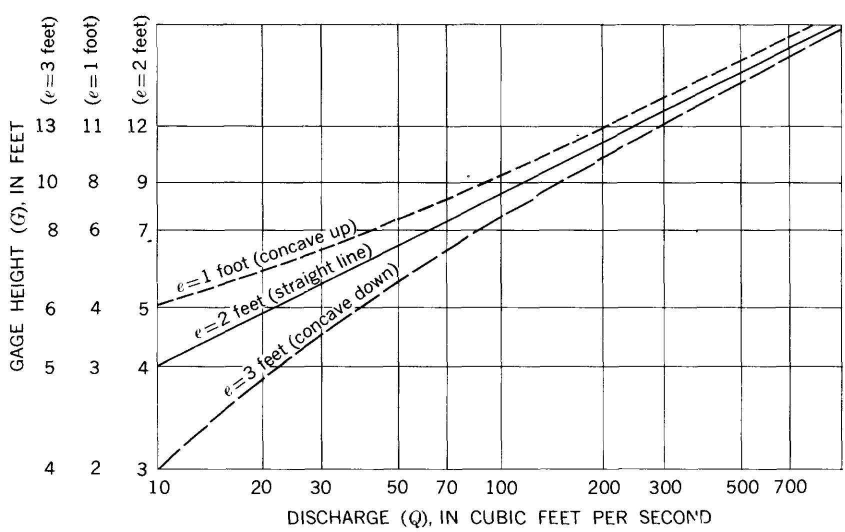

FIGURE 1.—Rating-curve shapes resulting from the use of different values of effective zero flow, e. All curves represent the same rating. The true value of e is 2.

An awareness of these principles of logarithmic curve plotting is necessary for an understanding of the shapes of logarithmic rating curves. The discussion that follows starts with explanations of rating curves for simple controls and progresses to explanations of rating curves for the more complex types.

SECTION CONTROLS OF REGULAR SHAPE

Thin-edged rectangular weir.—For a thin-edged rectangular weir with negligible velocity of approach, the discharge equation (King and Brater, 1963, p. 5–11) is approximately

$$Q=3.3LH^{1.5}, \tag{4}$$

or

$$Q=3.3L(G-e)^{1.5}, \tag{5}$$

where L=length of weir, in feet. If the gage height of the weir crest is used as the value of e in equation 5, the rating curve will be a straight line on logarithmic graph paper with $p=3.3L$ and $b=1.5$.

Thin-edged triangular weir.—For a thin-edged triangular weir with a central angle equal to Θ and a negligible velocity of approach, the discharge equation (King and Brater, 1963, p. 5–16) is

$$Q=2.5 \tan \frac{\Theta}{2} H^{2.5}, \tag{6}$$

or

$$Q=2.5 \tan \frac{\Theta}{2} (G-e)^{2.5}. \tag{7}$$

If the gage height of the bottom of the weir notch is used as the value of e in equation 7, the logarithmic rating curve will be a straight line with $p=2.5 \tan \frac{\Theta}{2}$ and $b=2.5$.

Thin-edged trapezoidal weir.—The discharge equation for a trapezoidal weir is dependent on the geometry of the weir and usually must be determined from discharge measurements. This type of weir has a shape between a rectangle and a triangle, and, if the velocity of approach is negligible, the slope of the logarithmic rating curve will lie between the slope values for a rectangle and a triangle, or between 1.5 and 2.5. The closer the shape is to a rectangle, the closer the slope will be to 1.5.

Broad-crested rectangular weir.—Sharp-crested weirs are seldom used as controls in natural streams. The simplest type of artificial control used is a flat, broad-crested rectangular weir, whose basic discharge equation is

$$Q=CL(G-e)^{1.5}, \quad (8)$$

where C= a variable coefficient.

At the lower stages C varies with stage approximately according to the equation

$$C=K(G-e)^{0.15}, \quad (9)$$

where K= a coefficient.

By substituting the value of C from equation 9 into equation 8, the following equation is obtained:

$$Q=C_p(G-e)^{1.65}, \quad (10)$$

where $C_p=KL$.

In equation 10, C_p is used as a term to indicate a general constant that has the same function as p in equation 3. In later equations differently derived constants, if they serve the same function, will be labeled C_p.

Because the rate of change of velocity of approach increases with higher stages, the slope of the logarithmic rating curve for the control increases and the exponent of $(G-e)$ also increases. If, as at most controls, width of the stream also increases with stage, the exponent of $(G-e)$ becomes even greater and may exceed a value of 3. Therefore, the value of the exponent for the entire range of stage is considerably greater than 1.5, which at first thought might be considered the expected value for the slope of the rating curve.

Because the rating curve for an unsubmerged natural riffle has many of the characteristics of the rating curve for a broad-crested weir, the above remarks are applicable to the rating curve for a natural riffle.

Notched broad-crested control.—Figure 2 shows a cross section of a notched broad-crested control and the rating curves for the gaging station. Because there is a sharp break in the cross section of the control at a gage height of 1.4 feet, a break occurs in the slope of the rating curve at that stage. For stages between 0.0 and 1.4 feet, the gage height of zero flow is 0.0 feet; for stages above 1.4 feet, the gage height of effective zero flow is at some stage between 0.0 and 1.4 feet.

If the low end of the rating curve is made a tangent, the gage height of zero flow is 0.0 feet; and the slope of this tangent turns out to be 2.5, which is expectedly greater than the theoretical slope of 1.5 for a broad-crested weir. The upper part of this rating curve is concave upward because the value of e used (0.0 feet) is lower than the gage height of effective zero flow for high stages.

If the upper end of the rating is made a tangent, it is found that the value of e, or effective zero flow, must be increased to 0.6 feet. Because

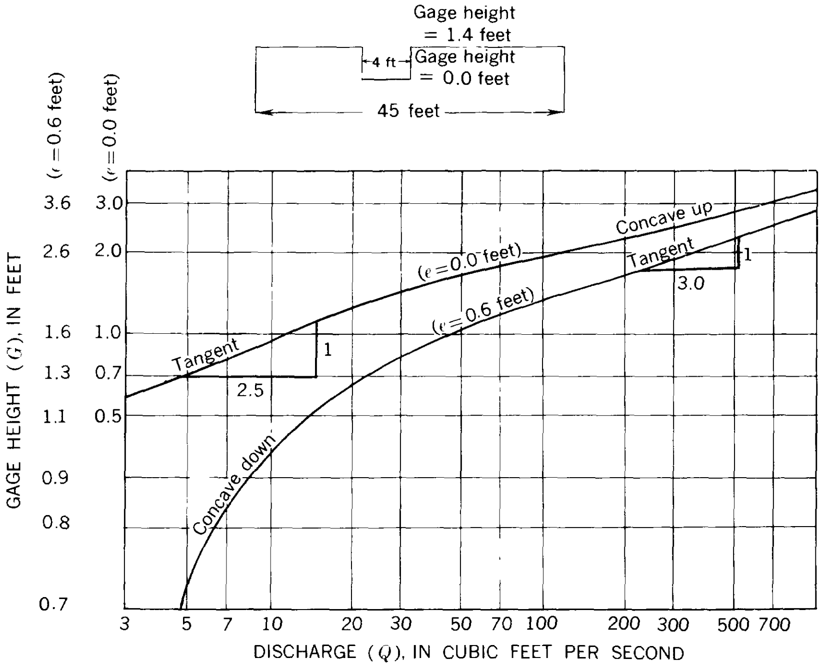

FIGURE 2.—Cross section of notched artificial broad-crested control at the gaging station on Great Trough Creek near Marklesburg, Pa., and rating curves for the station. Cross section not to scale.

the value of e is increased, the low-water end of the curve becomes concave downward. The high-water tangent of the curve, principally because of increased rate of change of velocity of approach, has a slope greater than the slope of the low-water tangent of the curve. The slope of the high-water tangent is found to be 3.0.

COMPOUND SECTION CONTROL

Figure 3 shows the rating curves for a compound section control and a profile of the control. The control consists of two rock-ledge riffles. Zero flow, e, for very low stages is at gage height 1.3 feet and for higher stages is at gage height 1.2 feet. If the low end of the rating curve is made a tangent, it means that too large a value of e is used for the high end of the rating curve—1.3 feet instead of 1.2 feet—and the high-water end of the curve is concave downward. Conversely, if the high end of the curve is made a tangent, the low-water end of the curve is concave upward.

The high-water tangent of the one curve has a greater slope than the low-water tangent of the other curve. The differences in slope reflect the differences in the geometries of the two controls as well as the effect of the increased rate of change of approach velocity at the higher stages. The slopes of the two tangents are 2.9 and 2.2. Both values are greater than the theoretical slope of 1.5 for a broad-crested control.

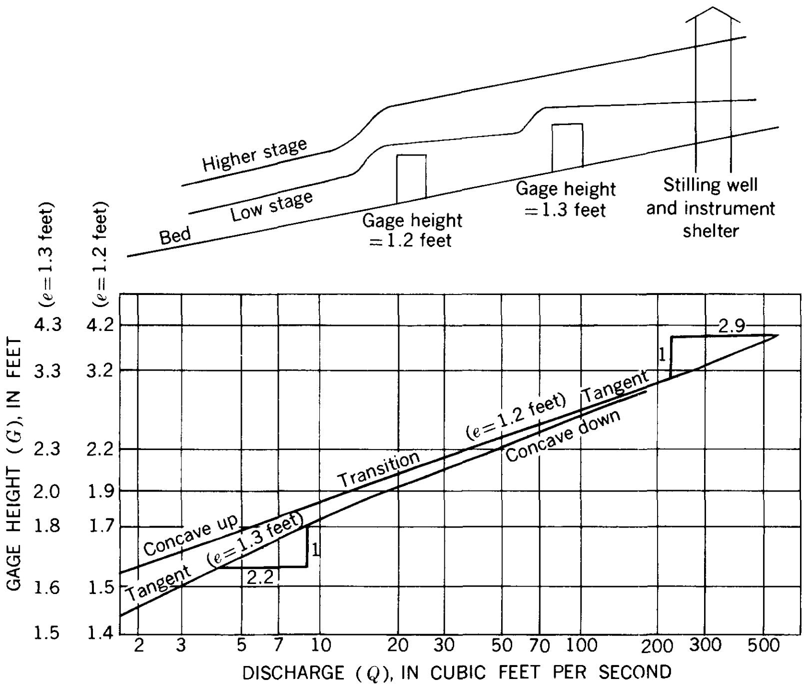

FIGURE 3.—Profile of compound section control at the gaging station on Muncy Creek near Sonestown, Pa., and rating curves for the station. Profile not to scale.

CHANNEL CONTROL

Up to this point there has been little mention of rating curves for channel controls. The discharge equation for the condition of channel control is the familiar Manning equation (King and Brater, 1963, p. 7–13),

$$Q=\frac{1.486}{n}AR^{\frac{2}{3}}S^{\frac{1}{2}}, \tag{11}$$

where n= the Manning roughness coefficient,

A= the cross-sectional area, in square feet,

R= the hydraulic radius, in feet,

and S= the slope of the energy gradient.

However, A is approximately equal to the depth of water in feet on the control, H, multiplied by width in feet, W; and the value of S at high stages frequently approaches a constant value. Therefore, equation 11 can be rewritten as follows:

$$Q=C_1HWR^{2/3}, \tag{12}$$

where $C_1=\frac{1.486}{n}S^{1/2}$.

If W is considered a constant, as in a rectangular channel, and if R is considered equal to H, equation 12 becomes

$$Q=C_pH^{1.67}, \tag{13}$$

where $C_p=C_1W$.

By substituting $G-e$ for H, equivalent expressions, equation 13 becomes

$$Q=C_p(G-e)^{1.67}. \tag{14}$$

Compare equation 14 with equation 10 and with equation 3.

The assumption that R is equal to H, used in deriving equation 14, is valid only for an extremely wide stream. If the stream is not extremely wide, R, is smaller than H. For a deep narrow stream, R is much smaller than H. For most streams the difference between R and H has the effect of reducing the exponent in equation 14. The exponent reduction may be offset, however, by an increase in S or W as discharge increases. Changes in roughness, n, with stage will also affect the value of the exponent. The net result of all these factors is that the channel control discharge equation can be put into the general form

$$Q=p(G-e)^b, \tag{3}$$

where b=from 1.3 to 1.8 and rarely reaches a value as high as 2.0.

Stage-discharge relations are shown in figure 4 for a gaging station with the common situation of a compound control—section control at low stages and channel control at high stages. The low-water control is a low weir with gage height of effective zero flow, e, at 2.2 feet. At a stage of 3.9 feet the weir starts to "drown out," and channel control becomes effective. If the low end of the rating curve is made a tangent, a value for e of 2.2 feet must be used. Because the value of e for the upper end of the rating curve is something less than 2.2 feet, the high end becomes concave downward. If the high end of the curve is made a tangent, the value of e is found to be 0.0 feet, which is too low a value of e for the lower end of the curve. The low end becomes concave upward.

Where the rating for a section control (low end of the curve) is a tangent, the slope, b, is expected to be greater than 2.0. In figure 4, b is 2.3. Where the rating for a channel control (high end of the curve) is a tangent, the value of b is expected to be less than 2.0 and probably between 1.3 and 1.8. In figure 4, b is 1.3 for the channel-control tangent. Should overbank flow occur at higher stages, the rating curve bends to the right to reflect an accelerated increase in discharge with stage.

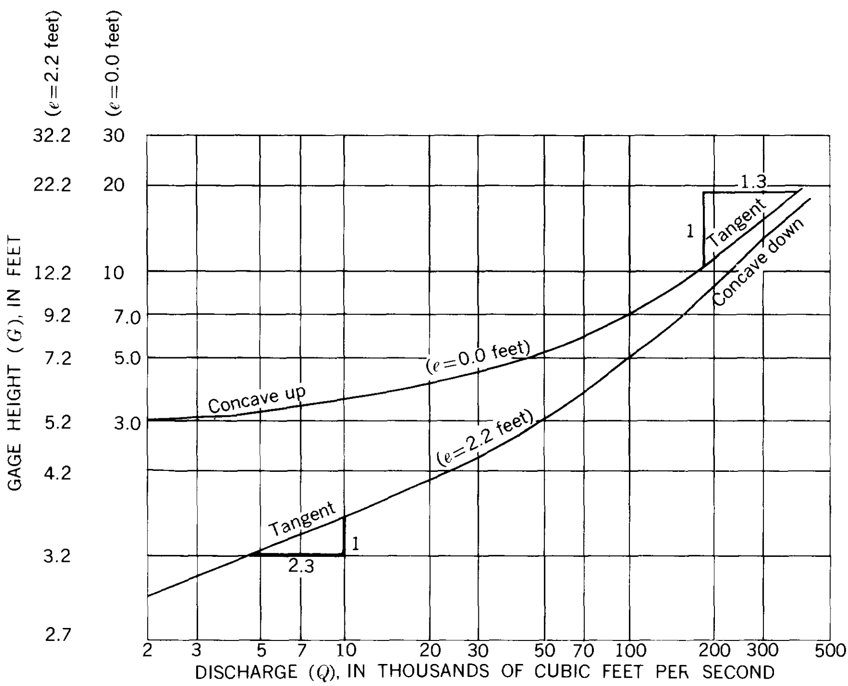

FIGURE. 4.—Rating curves for section control at low stages and channel control at high stages for a compound control at the gaging station on the Susquehanna River at Harrisburg, Pa.

A GENERAL NOTE ON THE SLOPE OF LOGARITHMIC RATING CURVES

It can be demonstrated, nonrigorously, that logarithmic straight-line rating curves for section controls almost always have slopes greater than 2 and that rating curves for channel controls generally have slopes less than 2. To illustrate this, first examine the equation

$$Q=pH^{b}, \tag{2}$$

a general equation for a straight-line rating curve on logarithmic graph paper. If equation 2 is differentiated with respect to H, an equation is obtained for computing the change in discharge per tenth of a foot change in stage, or $\frac{\Delta Q}{\Delta H}$, which is usually obtained graphically. This first derivative obtained from equation 2 is

$$\frac{dQ}{dH}=pbH^{b-1}. \tag{15}$$

If we differentiate again, we obtain an equation for computing the change in $\frac{\Delta Q}{\Delta H}$ per tenth of a foot change in stage, commonly referred to as the second difference of the rating table. The second derivative of equation 2 is

$$\frac{d^2Q}{dH^2}=pb(b-1)H^{b-2}. \tag{16}$$

Examination of equation 16 shows that the second difference increases with stage when b, the slope of the straight-line rating curve, is greater than 2; the second difference decreases with stage when b is less than 2.

Now examine the rating shown in table 1 for a hypothetical stream having compound control. This rating table represents the common condition of section control at the lower stages and channel control at the higher stages. Where two values of discharge are shown for an item in the table, the figure in parentheses is exact and the other figure is the rounded value that normally would be used in a rating table. Experienced hydrographers will recognize this rating as being typical of ratings for the most streams. Inspection of the second difference column shows that the second differences increase as gage height increases at the low-water end (section control, $b>2$) and decrease as gage height increases at the high-water end (channel control, $b<2$). These are the results that one would predict from the preceding discussion.

TABLE 1.—*Hypothetical stage-discharge rating table*

[If two figures are given under one heading, the figure in parentheses is exact and the other figure is the rounded value that would normally be used in a rating table]

Gage height, in feet	Discharge, in cfs	Change in discharge per 0.1 ft change in gage height $\left(\frac{\Delta Q}{\Delta H}\right)$	Change in $\frac{\Delta Q}{\Delta H}$ per 0.1 ft change in gage height [1]
1.0	100		
		20	
1.1	120		1
		21	
1.2	141		1
		22	
1.3	163		2
		24	
1.4	187		2
		26	
1.5	213		3
		29	
1.6	242		3
		32	
1.7	274		4
		36	
1.8	310		3
		40 (39)	
1.9	350 (349)		2
		40 (41)	
2.0	390		2
		45 (43)	
2.1	435 (433)		2
		45 (45)	
2.2	480 (478)		2
		45 (47)	
2.3	525		1
		50 (48)	
2.4	575 (573)		1
		50 (49)	
2.5	625 (622)		1
		50 (50)	
2.6	675 (672)		1
		50 (51)	
2.7	725 (723)		1
		50 (52)	

[1] Second difference.

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INTERPRETATION OF FLOOD-FREQUENCY DATA

By J. R. CRIPPEN and S. E. RANTZ

ABSTRACT

The conventional flood-frequency curve is an excellent tool for studying the economics of planned flood-control measures, but the curve presents an incomplete picture of flood risk. That is, the flood-frequency curve shows the probability of an annual peak discharge being exceeded in any one year, but does not show the probability for a sequence of years. A family of curves is presented that overcomes the deficiency. These curves have universal use in studies of flood risk because they are based on fundamental probability principles and are independent of both the flood data and the statistical distribution represented by the conventional flood-frequency curve.

Data on the peak discharges of flood events have been gathered from many sites over many years. These data are frequently studied in efforts to arrive at a more complete understanding of the hydrologic and climatic phenomena that are involved. The data are also examined for more obvious and immediately practical purpose of planning construction features that must be related to the hydraulic characteristics of the streams during flood periods. For both purposes the flood data must be considered as a sample from a parent population whose characteristics are inferred by the statistical concepts of sampling theory and probability distribution.

When flood data are to be analyzed statistically, the assumptions, postulates, and hypotheses involved should not only be recognized but should also be specifically stated. Most analyses of flood data include the following assumptions:

1. The data studied consist either of annual flood peaks (on a water-year basis) or of peaks above a predetermined magnitude (a partial-duration series).
2. The sample (that is, the data chosen) is a random sample from a parent distribution with characteristics that can be estimated by graphical or mathematical means.
3. Other samples (specifically, flood events during the period of future concern) will be from the same parent distribution and will occur within limits that can be defined by probability methods.

With regard to the first assumption, the probabilities or the recurrence intervals of all but the smaller flood peaks on a stream are usually almost identical whether determined from either the annual-flood series or the partial-duration series. Because of this similarity and because the annual-flood series is more easily manipulated statistically, annual floods are generally used in flood-frequency analysis.

As for the second assumption, several theoretical distributions—for example, logarithmic normal, extreme value (Gumbel), Pearson type III, and gamma distributions—are widely used in flood-frequency studies; other nonstandard distributions are derived from the flood data by graphical or semigraphical techniques. Whatever the distribution or technique used, the cumulative distribution of flood magnitudes at a site is the conventional flood-frequency curve, as illustrated in figure 1. The ordinate of any point on the curve is discharge; the corresponding abscissa is recurrence interval, or the average number of

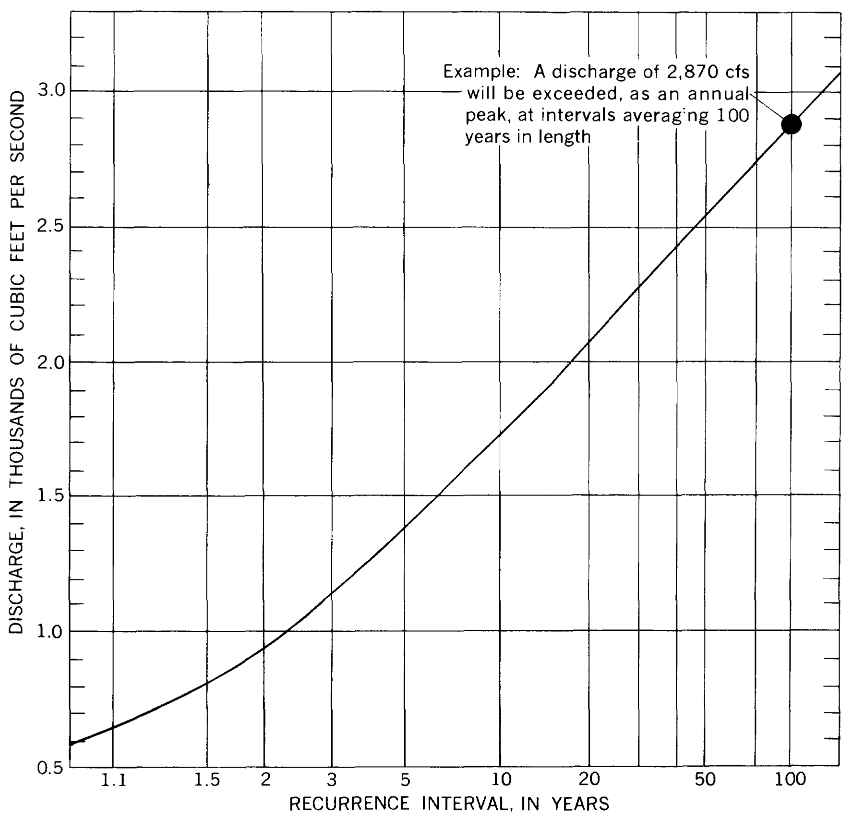

FIGURE 1—Typical flood-frequency curve showing avearge number of years between floods greater than the indicated magnitude.

years between occurrences of an annual peak flow greater than that discharge.

The third assumption concerning the distribution of future flood events in effect states that our only clue to flood experience in the future lies in our experience of the past.

The traditional wording related to the coordinates of the flood-frequency curve includes the phrase "discharge equal to or greater than * * *." Because the flood-frequency curve is a continuous function rather than discrete, the probability of a specific, precisely defined discharge is infinitesimal and the words "equal to" are therefore unnecessary and are not used in this paper.

The conventional flood-frequency curve is widely used to compute average annual flood damage in studying the economics of planned flood-control measures (Eckstein, 1958, p. 121–126; Maass and others, 1962, p. 230–232). In these studies it is necessary to know the stage-discharge relation at the study site and the relation of monetary damage to stages. With this knowledge the frequency curve of flood peak discharge can be transformed to a frequency curve of monetary damage which, when integrated, gives the average annual flood damage. Figures of average annual damage are needed for computing cost-benefit ratios.

Although the conventional flood-frequency curve is an excellent and necessary tool for such economic studies, it presents an incomplete picture of the flood risk (Riggs, 1961, p. 21). If we compute the reciprocal of the recurrence interval of a given peak discharge, the flood-frequency curve gives us the probability of that discharge being exceeded in any year. It is equally important to know the probability of that discharge being exceeded during a sequence of years. This probability can be computed on the basis of fundamental statistical principles that are independent of the distribution represented by the flood-frequency curve.

If the flood-frequency curve shows that a peak discharge of magnitude y has a recurrence interval of T years, then $py=\frac{1}{T}$, where py is the probability of an annual flood, y, being exceeded in any 1 year. The probability of y not being exceeded in any 1 year is therefore $1-py$, and the probability of y not being exceeded in a period of n years is $(1-py)^n$. This logic is general and is independent of the nature of the flood-frequency graph. It follows then that the probability, Py, of y being exceeded in a sequence of n years is computed by the equation

$$Py=1-(1-py)^n \tag{1}$$

or, substituting $\frac{1}{T}$ for py,

$$Py=1-\left(1-\frac{1}{T}\right)^n. \tag{2}$$

For example, to determine the probability of a flood of 100-year recurrence interval being exceeded in the next 25 years, substitute into equation 2 as follows:

$$\begin{aligned} Py &= 1-\left(1-\frac{1}{100}\right)^{25} \\ &= 1-(0.99)^{25} \\ &= 1-0.778 \\ &= 0.222. \end{aligned}$$

The probability is 22 percent that the 100-year flood will be exceeded in any 25-year period (see fig. 2).

Similar computations can be made for various values of T and n, and the results are presented in the family of curves in figure 2. Used with figure 1 the curves indicate, for example, a 22-percent probability that a flood peak greater than 2,870 cfs (cubic feet per second) will occur during any 25-year period. Figure 2, a graphic presentation of a basic probability principle, has universal use in studies of flood risk because it is independent of both the flood data and the statistical distribution represented by flood-frequency curves.

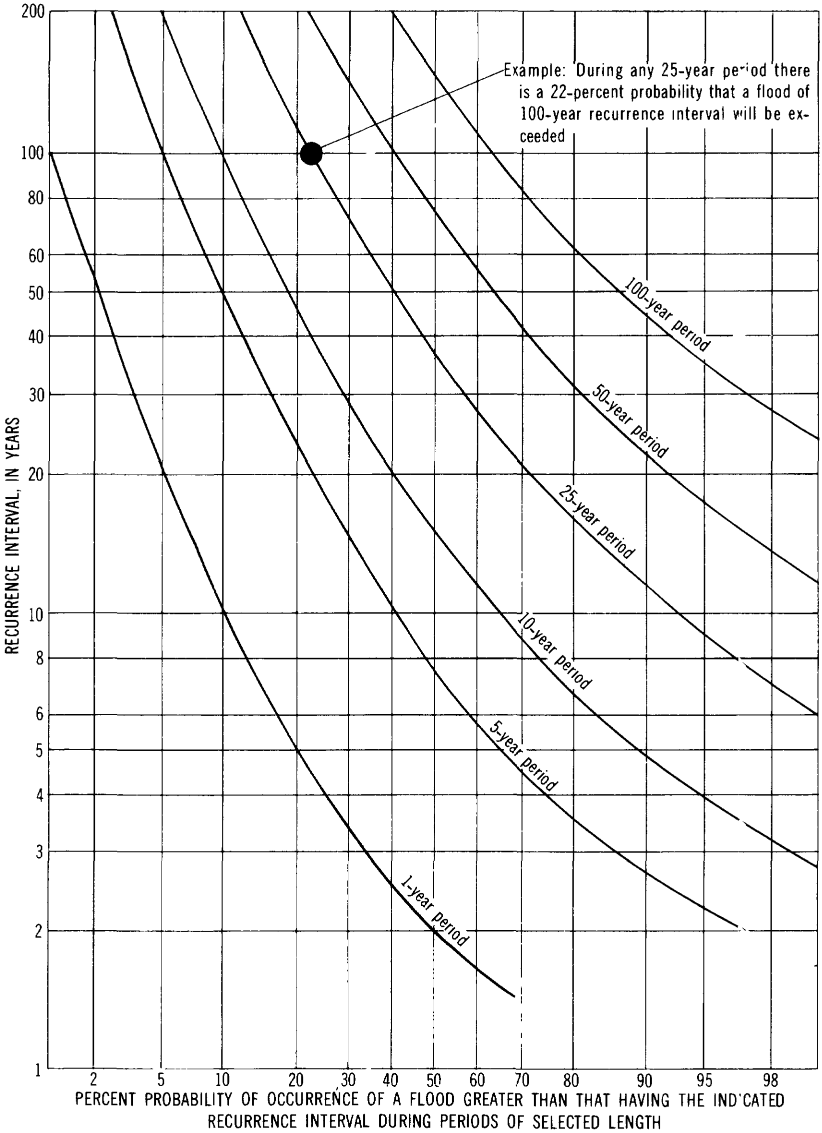

FIGURE 2.—Relation between recurrence interval and probability of exceedence during periods of selected length.

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AN OUTLINE OF GEOPHYSICAL LOGGING METHODS AND THEIR USES IN HYDROLOGIC STUDIES

By A. I. Johnson

ABSTRACT

Information on the depth, thickness, extent, and structure of an aquifer may be obtained for use of the hydrologist by judicious choice of the proper geophysical logging methods. To assist in making this choice, the various methods of borehole logging, the uses that may be made of each log, and the recommended borehole conditions are summarized. However, proper use of borehole logs requires some knowledge of the geology of the area and considerable experience in log interpretation.

When the Schlumberger brothers made their first electrical survey of a borehole in France more than a quarter of a century ago, only one simple curve—resistivity—was recorded. The early equipment was very simple but signaled the beginning of a whole new industry that has provided many useful tools in the solution of hydrologic problems.

The hydrologist has the problem of selecting the logging methods most efficient, technically and economically, for answering his particular need. Information on aquifer depth, thickness, extent and structure, as well as details of permeability, porosity, moisture content, and the chemical quality of the contained water, are often needed in hydrologic studies. Borehole geophysical logging methods now are available to provide the hydrologist with the data needed to give (through interpretation) all the above information, if the logging is properly supplemented by driller's logs, some knowledge of the local geology, and considerable experience in interpretation of the geophysical logs.

If funds are not to be wasted on unnecessary data, the logging methods must be chosen with due regard for the problem at hand. When there is doubt as to what type of log will give the information desired, logging experts in the hydrologist's organization or in the technical service centers of commercial logging companies should be consulted. In addition to a knowledge of the type of information desired from the logs, those logging experts probably would desire information on the following borehole conditions: depth, size, and condition or borehole; type of fluid in hole; classification and general thickness of formations; and quantity of fluid lost into formations. The technical consultation would be of even greater assistance if requested before drilling the boreholes.

It is the purpose of this paper to list various methods available for the geophysical logging of boreholes, and to briefly summarize the use that may be made of each log, as well as the specific borehole characteristics that provide conditions for optimum use of each method. The information was compiled from the references at the end of this paper and does not necessarily represent the opinions of the author. For more detailed information than that presented in table 1, the reader is referred to the references.

TABLE 1.—*Borehole geophysical logging methods*

Method	Uses	Recommended conditions
Electric logging:		
Single-electrode resistance.	Determining depth and thickness of thin beds. Identification of rocks, provided general lithologic information is available, and correlation of formations. Determining casing depths.	Fluid-filled hole. Fresh mud required. Hole diameter less than 8 to 10 inches. Log only in uncased holes.
Short normal (electrode spacing of 16 inches).	Picking tops of resistive beds. Determining resistivity of the invaded zone. Estimating porosity of formations (deeply invaded and thick interval). Correlation and identification, provided general lithologic information is available.	Fluid-filled hole. Fresh mud. Ratio of mud resistivity to formation-water resistivity should be 0.2 to 4. Log only in uncased part of hole.
Long normal (electrode spacing of 64 inches).	Determining true resistivity in thick beds where mud invasion is not too deep. Obtaining data for calculation of formation-water resistivity.	Fluid-filled hole. Ratio of mud resistivity to formation-water resistivity should be 0.2 to 4. Log only in uncased part of hole.
Deep lateral (electrode spacing approximately 19 feet).	Determining true resistivity where mud invasion is relatively deep. Locating thin beds.	Fluid-filled uncased hole. Fresh mud. Formations should be of thickness different from electrode spacing and should be free of thin limestone beds.
Limestone sonde (electrode spacing of 32 inches).	Detecting permeable zones and determining porosity in hard rock. Determining formation factor in situ.	Fluid-filled uncased hole. May be salty mud. Uniform hole size. Beds thicker than 5 feet.

TABLE 1.—*Borehole geophysical logging methods*—Continued

Method	Uses	Recommended conditions
Electric logging—Con.		
Laterolog	Investigating true resistivity of thin beds. Used in hard formations drilled with very salty muds. Correlation of formations, especially in hard-rock regions.	Fluid-filled uncased hole. Salty mud satisfactory. Mud invasion not too deep.
Microlog	Determining permeable beds in hard or well-consolidated formations. Detailing beds in moderately consolidated formations. Correlation in hard-rock country. Determining formation factor in situ in soft or moderately consolidated formations. Detailing very thin beds.	Fluid required in hole. Log only in uncased part of hole. Bit-size hole (caved sections may be logged, provided hole enlargements are not too great).
Microlaterolog	Determining detailed resistivity of flushed formation at wall of hole when mudcake thickness is less than three-eighths inch in all formations. Determining formation factor and porosity. Correlation of very thin beds.	Fluid-filled uncased hole. Thin mud cake. Salty mud permitted.
Spontaneous potential.	Helps delineate boundaries of many formations and the nature of these formations. Indicating approximate chemical quality of water. Indicate zones of water entry in borehole. Locating cased interval. Detecting and correlating permeable beds.	Fluid-filled uncased hole. Fresh mud.
Radiation logging:		
Gamma ray	Differentiating shale, clay, and marl from other formations. Correlations of formations. Measurement of inherent radioactivity in formations. Checking formation depths and thicknesses with reference to casing collars before perforating casing. For shale differentiation when holes contain very salty mud. Radioactive tracer studies. Logging dry or cased holes. Locating cemented and cased intervals. Logging in oil-base muds. Locating radioactive ores. In combination with electric logs for locating coal or lignite beds.	Fluid-filled or dry cased or uncased hole. Should have appreciable contrast in radioactivity between adjacent formations.

TABLE 1.—*Borehole geophysical logging methods*—Continued

Method	Uses	Recommended conditions
Radiation logging—Con.		
Neutron	Delineating formations and correlation in dry or cased holes. Qualitative determination of shales, tight formations, and porous sections in cased wells. Determining porosity and water content of formations, especially those of low porosity. Distinguishing between water- or oil-filled and gas-filled reservoirs. Combining with gamma-ray log for better identification of lithology and correlation of formations. Indicating cased intervals. Logging in oil-base muds.	Fluid-filled or dry cased or uncased hole. Formations relatively free from shaly material. Diameter less than 6 inches for dry holes. Hole diameter similar throughout.
Induction logging	Determining true resistivity, particularly for thin beds (down to about 2 feet thick) in wells drilled with comparatively fresh mud. Determining resistivity of formations in dry holes. Logging in oil-base muds. Defining lithology and bed boundaries in hard formations. Detection of water-bearing beds.	Fluid-filled or dry uncased hole. Fluid should not be too salty.
Sonic logging	Logging acoustic velocity for seismic interpretation. Correlation and identification of lithology. Reliable indication of porosity in moderate to hard formations; in soft formations of high porosity it is more responsive to the nature rather than quantity of fluids contained in pores.	Not affected materially by type of fluid, hole size, or mud invasion.
Temperature logging	Locating approximate position of cement behind casing. Determining thermal gradient. Locating depth of lost circulation. Locating active gas flow. Used in checking depths and thickness of aquifers. Locating fissures and solution openings in open holes and leaks or perforated sections in cased holes. Reciprocal-gradient temperature log may be more useful in correlation work.	Cased or uncased hole. Can be used in empty hole if logged at very slow speed, but fluid preferred in hole. Fluid should be undisturbed (no circulation) for 6 to 12 hours minimum before logging; possibly several days may be required to reach thermal equilibrium.

TABLE 1.—*Borehole geophysical logging methods*—Continued

Method	Uses	Recommended conditions
Fluid-conductivity logging.	Locating point of entry of different quality water through leaks or perforations in casing or opening in rock hole. (Usually fluid resistivity is determined and must be converted to conductivity.) Determining quality of fluid in hole for improved interpretation of electric logs. Determining fresh-water–salt-water interface.	Fluid required in cased or uncased hole. Temperature log required for quantitative information.
Fluid-velocity logging	Locating zones of water entry into hole. Determining relative quantities of water flow into or out of these zones. Determine direction of flow up or down in sections of hole. Locating leaks in casing. Determine approximate permeability of lithologic sections penetrated by hole, or perforated section of casing.	Fluid-filled cased or uncased hole. Injection, pumping, flowing, or static (at surface) conditions. Flange or packer units required in large diameter holes. Caliper (section gage) logs required for quantitative interpretation.
Casing-collar locator	Locating position of casing collars and shoes for depth control during perforating. Determining accurate depth references for use with other types of logs.	Cased hole.
Caliper (section gage) survey.	Determining hole or casing diameter. Indicates lithologic character of formations and coherency of rocks penetrated. Locating fractures, solution openings, and other cavities. Correlation of formations. Selection of zone to set a packer. Useful in quantitative interpretation of electric, temperature, and radiation logs. Used with fluid-velocity logs to determine quantities of flow. Determining diameter of underreamed section before placement of gravel pack. Determining diameter of hole for use in computing volume of cement to seal annular space. Evaluating the efficiency of explosive development of rock wells. Determining construction information on abandoned wells.	Fluid-filled or dry cased or uncased hole. (In cased holes does not give information on beds behind casing.)

TABLE 1.—*Borehole geophysical logging methods*—Continued

Method	Uses	Recommended conditions
Dipmeter survey	Determining dip angle and dip direction (from magnetic north) in relation to well axis in the study of geologic structure. Correlation of formations.	Fluid-filled uncased hole. Carefully picked zones needing survey, because of expense and time required. Directional survey required for determination of true dip and strike (generally obtained simultaneously with dipmeter curves).
Directional (inclinometer) survey.	Locating points in a hole to determine deviation from the vertical. Determining true depth. Determining possible mechanical difficulty for casing installation or pump operation. Determining true dip and strike from dipmeter survey.	Fluid-filled or dry uncased hole.
Magnetic logging	Determining magnetic field intensity in borehole and magnetic susceptibility of rocks surrounding hole. Studying lithology and correlation, especially in igneous rocks.	Fluid-filled or dry uncased hole.

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U.S. GOVERNMENT PRINTING OFFICE: 1968 O—312-670