CHAPTER 12—DISCHARGE RATINGS USING A VELOCITY INDEX AS A PARAMETER

INTRODUCTION

Chapter 11 discussed the use of a slope parameter for developing discharge ratings at gaging stations where the use of stage alone was inadequate for rating purposes. However, it is not feasible to use a slope parameter for all stations for which no simple stage-discharge relation can be developed. Often slopes are so flat that the available reach of channel for developing slope is too short to give sufficiently accurate values of fall in the reach. At other sites, as on tidal streams or on some streams used for hydroelectric power generation, the acceleration head (p. 391) in the equations of unsteady flow is of such magnitude that it cannot be ignored as was done in chapter 11. In those situations it is often possible to develop a discharge rating by using a velocity index in a stage-velocity-discharge relation.

The principle behind a stage-velocity-discharge relation is simple enough. A continuous stage record provides a means of obtaining a continuous record of cross-sectional area from a relation of area to stage. If a continuously recorded velocity index, at a point or in a transverse line, can be related to stage and mean velocity in the cross section, the product of cross sectional area and mean velocity gives the discharge at any time. The calibration of the velocity relation—that is, the relation of recorded index velocity to stage and mean velocity—requires discharge measurements for the determination of mean velocity. The discharge measurements also furnish the values of cross-sectional area to be used in the stage-area relation.

Four types of instrumentation have been used to provide an index of mean velocity in a measurement cross section. They are:

1. standard current meter,
2. deflection meter,
3. acoustic velocity meter, and
4. electromagnetic velocity meter.

The simplest instruments for recording velocity at a fixed point in the cross section are the standard current meter and the deflection meter. Their use is limited to the smaller streams and canals where the hazard of damage by boats or debris is minimal. The acoustic velocity meter integrates the velocity along a transverse line in the stream. It has been used in large rivers to provide an index to mean velocity in the measurement cross section. The use of an electromagnetic velocity meter is still (1980) in the experimental stage, and its use has been limited mostly to the smaller streams. Experimental work in the U.S.A. with the electromagnetic current meter has been largely in the use of the meter to obtain a continuous record of velocity at a point; in several European countries the experimental work has been largely in the use of the meter to obtain a continuous record of an index value of integrated mean velocity in the entire measurement cross section.

STANDARD CURRENT-METER METHOD

The use of an unattended standard current meter, securely anchored in a fixed position in the stream below the minimum expected stage, is attractive because of the simplicity of the device. The most desirable location for the meter will be in the central core of the flow, away from the influence of the banks or any other impediment to flow, where streamlines are parallel and at right angles to the measurement cross section. For streams of irregular alignment or cross section, it may be necessary to experiment with meter location to determine the most suitable site for the meter.

Any of several schemes may be used for recording revolutions of the current meter. For example, one might use a modification of the system for recording velocity that was described earlier for the moving-boat method of measuring discharge (see section in chapter 6 titled, "Rate Indicator and Counter"). In that system a clock-activated moving chart is automatically marked after each occurrence of a predetermined number of meter revolutions. In another system that might be used, the current meter would be connected to a digital recorder and at predetermined time intervals—say, 15 minutes—the number of revolutions that occurred in the preceding 15 minutes would be punched. In either system the current-meter rating equation would be used to convert revolutions per time interval to average velocity during the time interval.

As mentioned earlier, discharge measurements would be used to calibrate the stage-velocity-discharge relation. The cross-sectional areas shown by the discharge measurements would be used with stage to define the stage-area relation, which could be extrapolated by the use of data obtained in a field survey. The mean velocities shown by the discharge measurements would be used in a graphical relation of mean velocity to stage and to the index velocities indicated by the fixed current meter. Extrapolation of that relation would be aided if a vertical-velocity curve were obtained at the site of the index current meter at the time of each discharge measurement, and if the mean velocity in the vertical at the index meter site, as computed from each vertical velocity curve, were related to mean velocity in the measurement cross section. The use of such relations is illustrated in the hypothetical example that follows where, for simplicity, it is assumed that the relations can be expressed mathematically.

Assume that the vertical-velocity curves at the index site can consistently be defined by the equation,

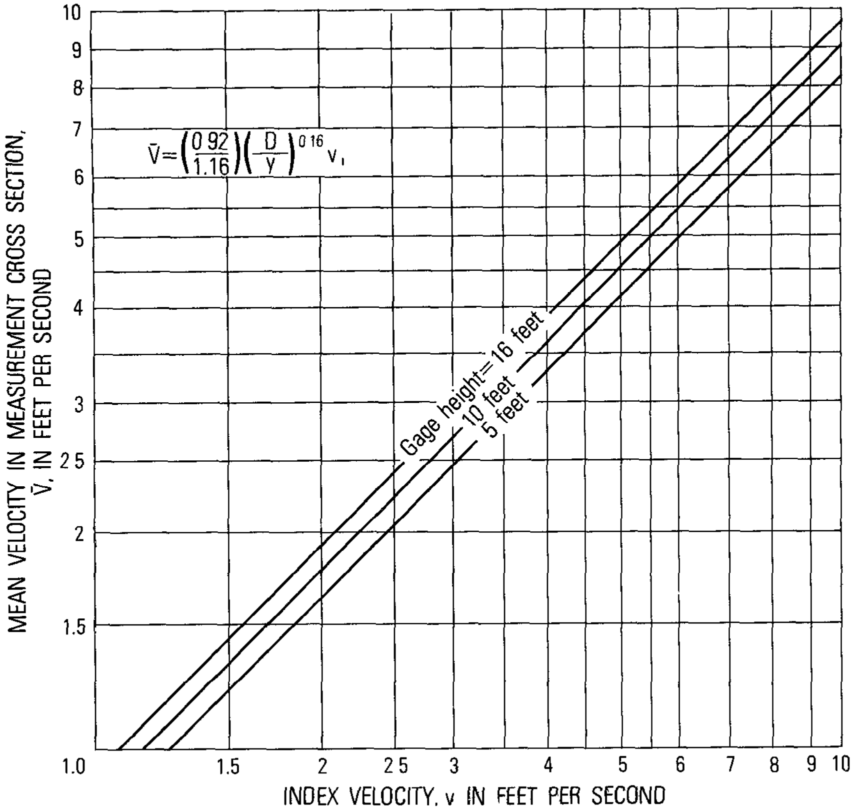


FIGURE 201.—Hypothetical relation of mean velocity in measurement cross section to stage and index velocity.

$$v_i = 1.16\, V_m\, (y/D)^{0.16},$$

where

V_m is the mean velocity in the vertical,

D is the depth, and

v_i is the velocity at a height, y, above the streambed.

Assume further that the ratio of mean velocity in the measurement cross section to mean velocity in the vertical at the index-meter site is consistently 0.92. It is also assumed that gage height and depth are equivalent, that stage is expected to range from 6 to 16 ft, and that the index meter is set at an elevation 5 ft above the streambed. Under those assumptions, the relation of mean velocity in the cross section to stage and index velocity would be that shown in figure 201. The mean velocity obtained by the use of figure 201 would be multiplied by the appropriate cross-sectional area to obtain the required discharge.

The utilization of a standard current meter to obtain an index of mean velocity has certain disadvantages that inhibit its use. The meter is susceptible to damage or impairment by submerged drift, but even where that hazard is negligible, there is a strong tendency for the meter to become fouled, after long immersion, by algae and other aquatic growth that becomes attached to the meter. Stoppage or impaired operation of the meter invariably results from the attachment of such growth, and constant servicing of the meter is usually a necessity. Suspended sediment in the stream also adversely affects the operation of an unattended current meter.

DEFLECTION-METER METHOD

GENERAL

Deflection meters are used to provide a velocity index in small canals and streams where no simple stage-discharge relation can be developed. The inability to develop a simple stage-discharge relation usually results from tide effect or from downstream gate operations to regulate the flow. At such gaging stations a recording stage-gage is operated in conjunction with the deflection meter.

The deflection meter has a submerged vane that is deflected by the force of the current. The amount of deflection, which is roughly proportional to the velocity of the current impinging on the vane, is transmitted either mechanically or electrically to a recorder. Values of the mean velocity of the stream are determined from discharge measurements, and mean velocity is then related to deflection and stage.

The ideal location for a deflection meter is in midchannel of a straight reach. However, it seldom is feasible to install the meter in midchannel; a site close to the bank of a straight reach is usually used.

Through the years, two basic types of deflection vane have evolved—the vertical-axis and the horizontal-axis types. The vertical-axis type has been most commonly used. Both types are described in the sections that follow.

VERTICAL-AXIS DEFLECTION VANE

The vertical-axis deflection vane is attached to a vertical shaft that is free to pivot about its vertical axis. Figure 202 shows two variations of the vertical-axis deflection vane. Vane A on the left is designed to sample a "point" or local velocity; vane B on the right is designed to integrate velocities throughout the greater part of a vertical. Vane B is used particularly in tidal streams where at times during a tidal cycle, stratification and density currents occur. At those times the denser salt water at the bottom of the channel flows upstream while fresh water in the upper zone starts to flow seaward.

Vane B extends from about 6 inches above the streambed to an elevation just below the water surface at low tide. While vane B is used in other circumstances, it cannot be used in a narrow channel where velocities are high, because a hydraulic jump may occur on the downstream side of the vane and affect the meter rating.

The force of the current acting on a vertical-axis vane turns the vertical shaft and the motion is transmitted to a graphic or digital

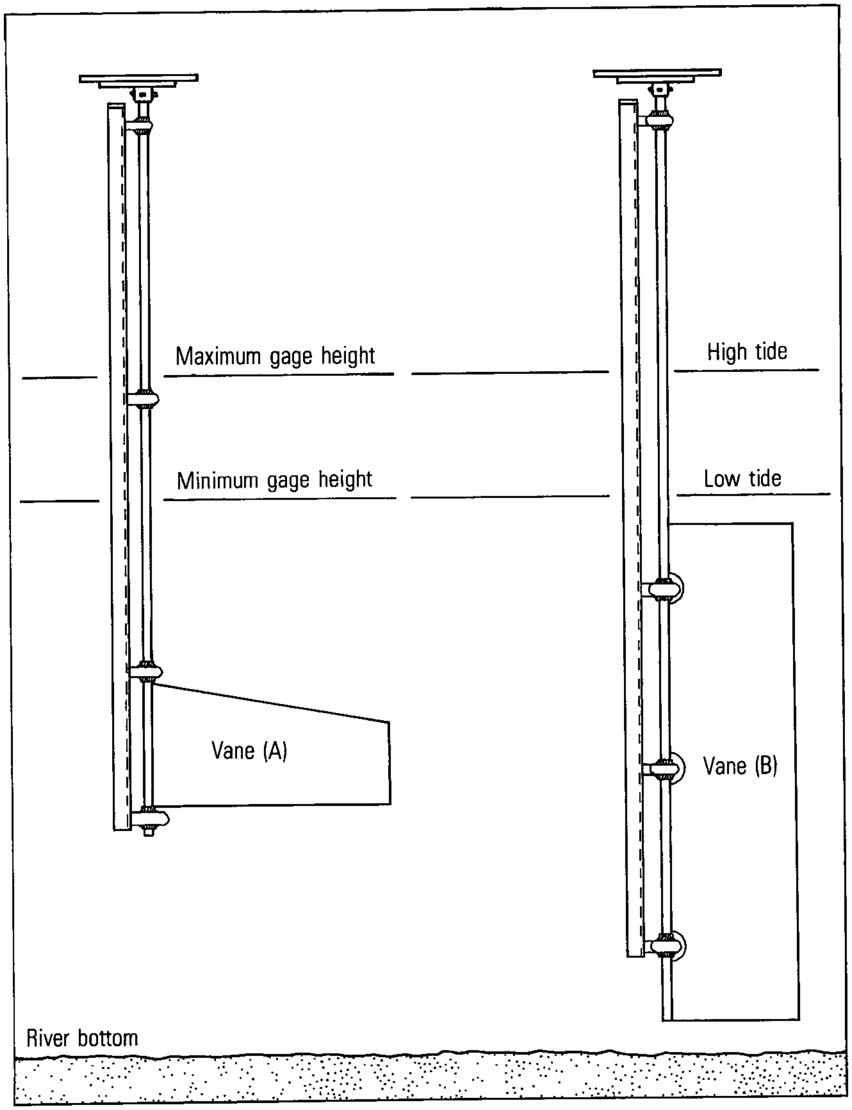


FIGURE 202.—Sketch of two types of vertical-axis deflection vanes.

recorder. A graphic recorder is shown in the system in figure 203. The vertical shaft also has an index plate fastened to it, and to the index plate is attached a counterweighted cable. When the velocity is zero, no lateral force is exerted on the vane and the counterweight will hold the vane in a position that is perpendicular to the direction of flow. A 15- to 20-pound counterweight is generally used with most vanes, but high velocities and (or) the use of a large vane may necessitate the use of a heavier counterweight in order to provide the counter-torque necessary to resist the rotary movement of the vane.

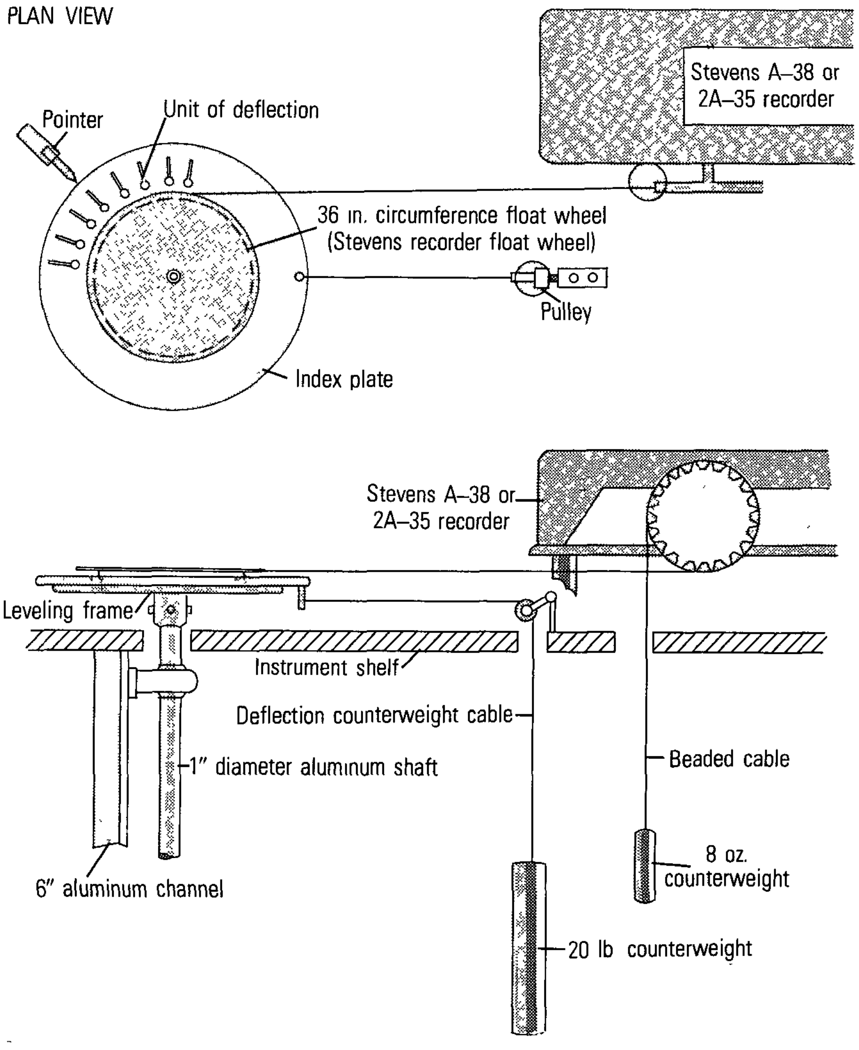


FIGURE 203.—Plan and front elevation views of a vertical-axis deflection meter attached to a graphic recorder.

A pointer for indicating the units of deflection on the index plate is attached to the instrument shelf. The index plate is calibrated by placing the recorder pen at zero position on the recorder and locking it there. The index plate is then scribed with a mark opposite the pointer. The index plate is rotated until the pen moves 1 inch on the recorder chart and another mark is scribed opposite the pointer. This process is repeated until marks for the full range of deflection have been scribed on the index plate and numbered. These units of deflection on the calibrated index plate are the reference marks for checking and resetting the recorder pen on future inspections of the deflection meter.

The vertical-axis deflection vane does have several drawbacks, the most serious of which is its tendency to collect floating debris which, in turn, affects the calibration of the vane. Another problem is the high degree of bearing friction resulting from the weight and bearing system of the vane assembly; the friction causes insensitivity at low velocities. In addition, removal of the vane for service and repair is difficult because of the weight involved. Furthermore, the projection of the vane assembly above the water surface makes it susceptible to damage by ice.

HORIZONTAL-AXIS DEFLECTION VANE

A recent development is the horizontal-axis or pendulum type deflection vane. This type is designed to overcome many of the difficulties mentioned in connection with the vertical-axis vane. For example, the pendulum vane can be installed with the mount totally submerged, thus reducing the possibility of collecting debris at or near the water surface where such debris is usually found. Its light weight and simplified bearing design greatly reduce the bearing friction, thus improving its low-velocity characteristics. Because no parts protrude from the water, there is little danger of damage by ice.

The pendulum-type vane consists of a flat triangular plate, suspended from above, that pivots about a horizontal axis located at the apex of the triangle (fig. 204). Interchangeable weights are available for attachment to the base of the triangular plate, thereby providing for optimum adjustment to the desired veolcity range. The location and design of the weights serve the additional purpose of reducing fluctuations caused by eddy shedding.

The force of the current acting on the horizontal-axis vane causes it to deflect. The angle formed by the vane itself and a small reference pendulum sealed within the pivot chamber is the angle of deflection. A potentiometer is positioned to generate an electrical signal that is proportional to the angle of deflection. The voltage that is generated is converted to a proportional shaft position for recording by a digital or graphic recorder.

It can be demonstrated that when the horizontal-axis vane is deflected by flowing water and the system is in mechanical equilibrium, the following relation exists between velocity of the water, angle of deflection, and the physical properties of the vane:

$$V^2 = \left(\frac{2WL_M}{\rho AL_A}\right)\left(\frac{\sin\Theta}{C_D\cos^2\Theta + C_L\sin^2\Theta}\right),$$

where V is horizontal velocity of the water,
W is weight of the pendulum in water,

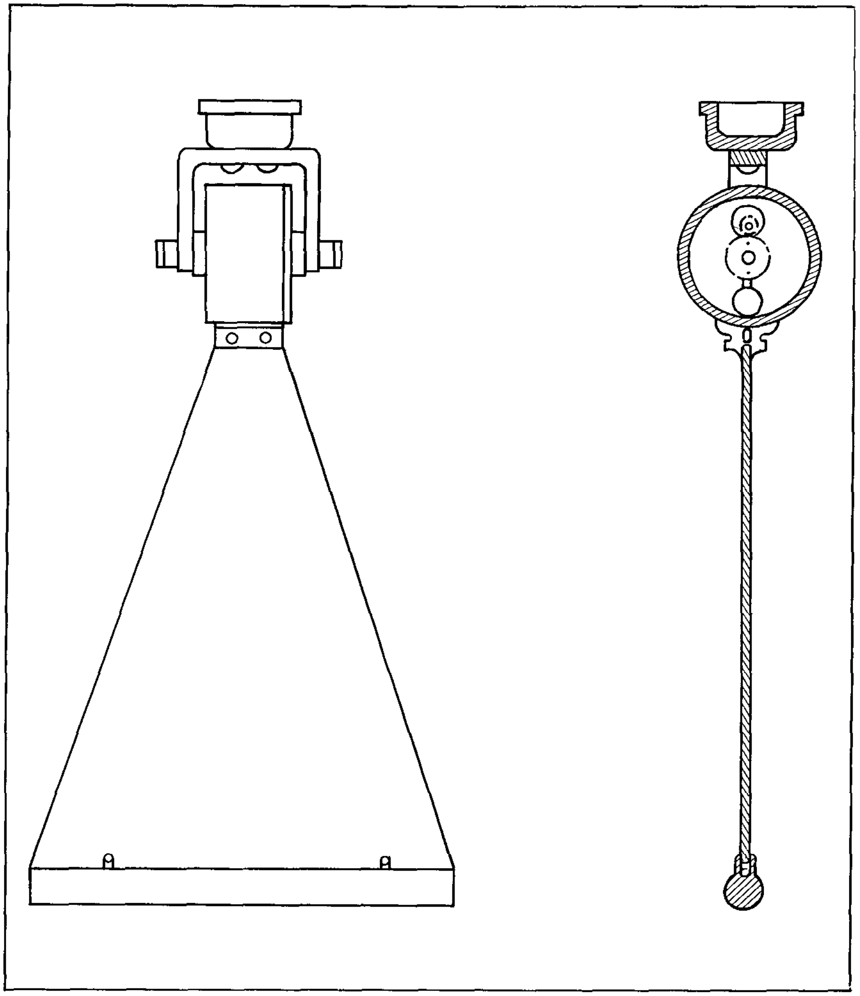


FIGURE 204.—Sketch of a pendulum-type deflection vane.

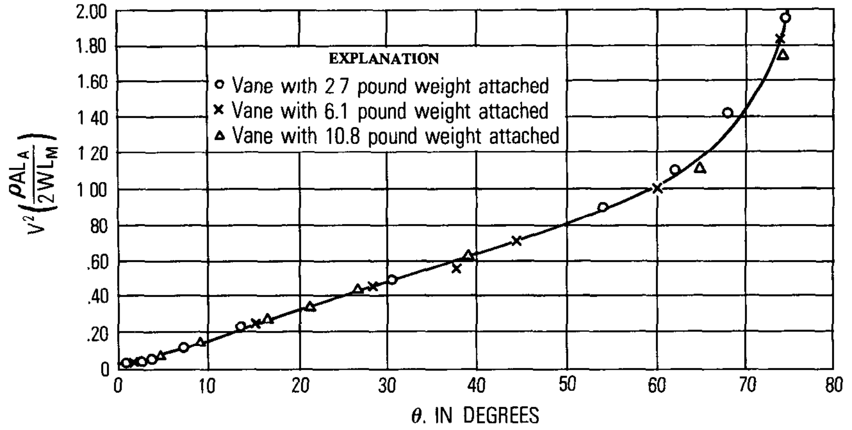


FIGURE 205.—Calibration curve for pendulum-type deflection vane.

ρ is the density of water,
A is the area of the vane,
L_M is the distance from the pivot point to the center of mass,
L_A is the distance from the pivot point to the center of the area,
Θ is the angle of deflection,
C_D is the coefficient of drag, and
C_L is the coefficient of lift.

Figure 205 is a graphical presentation of the above relation that can be used for selecting the weight needed for a given velocity range.

EXAMPLES OF STAGE-VELOCITY-DISCHARGE RELATIONS BASED ON DEFLECTION-METER OBSERVATIONS

Figure 206 shows a graphic-recorder chart for a gaging station in Florida where tidal flow reverses direction. The upper pen trace shows the stage at various times during the tide cycle for the period May 4–6, 1962. The lower pen trace shows the deflection units recorded during the same period. Zero flow is represented by a reading of four units on the deflection scale. Flow is in the seaward direction when the deflection is less than 4 units (hachured part of deflection graph in fig. 206); flow is in the inland direction when the deflection is greater than four units.

The rating curves shown in figure 207 were derived from discharge measurements. The units of deflection are indicative of velocity in a single vertical in the channel, having been obtained from a vertical-axis deflection meter equipped with vane B (fig. 202). The velocity curve shows the relation of deflection units to measured mean velocity in the channel; stage was not a factor in the relation because of the limited range (2 ft) in stage. For deflections of less than four units, velocity is negative, meaning that flow is in the seaward direction.

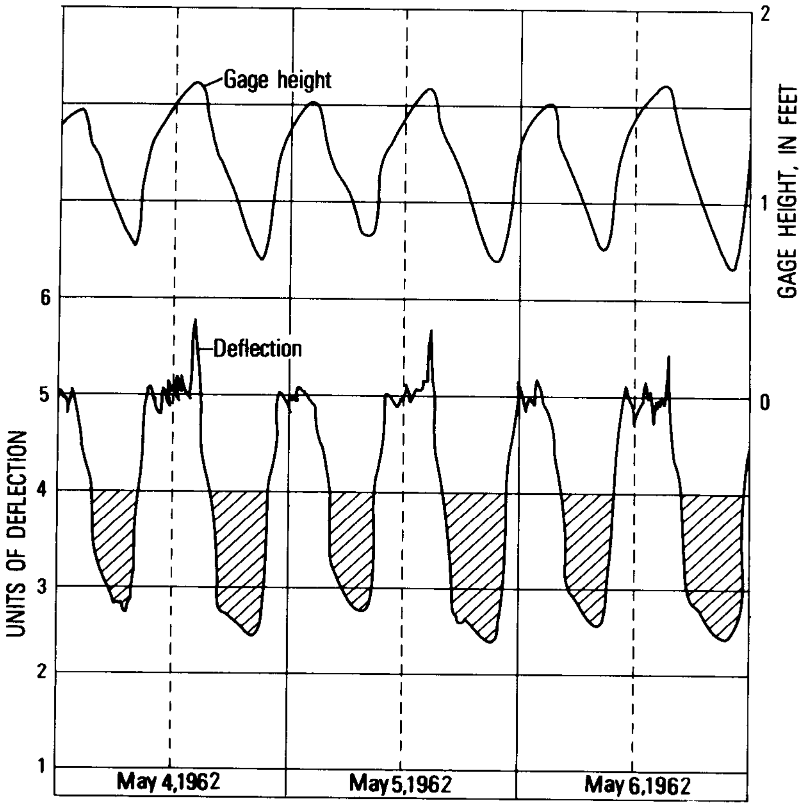


FIGURE 206.—Recorder chart for a deflection-meter gaging station on a tidal stream.

The stage at the time of discharge measurements was used to construct the area curve, which relates stage to cross-sectional area. Discharge is computed by multiplying area by mean velocity; negative values of discharge indicate seaward flow and positive values indicate inland flow.

Figure 208 shows the rating for a gaging station at the outlet of a large natural lake, immediately downstream from which are gates that regulate the flow for hydroelectric-power generation farther downstream. The deflection meter at the station is of the vertical-axis type and is equipped with vane A (fig. 202) to measure deflection at a "point" in the rectangular channel. Instead of deriving separate relations of stage versus cross-sectional area and deflection versus mean velocity, a single graphical relation, in the form of a family of curves, was derived for discharge versus stage and deflection. A preliminary study had shown that mean velocity was related to a combination of deflection and stage. The ratings for values of deflection other than

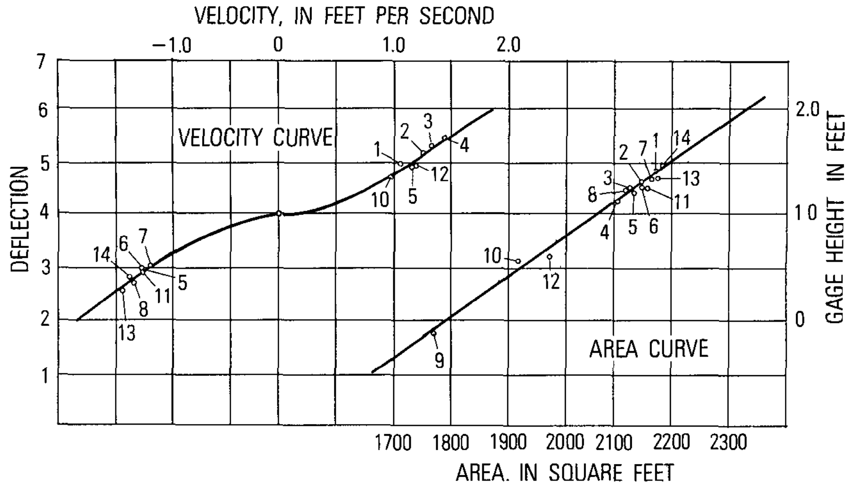


Figure 207.—Rating curves for a deflection-meter gaging station on a tidal stream.

those shown by the individual curves in figures 208 were obtained by interpolation between curves. Most of the 40 discharge measurements, which are shown by the small circles in figure 208, depart from the interpolated ratings by no more than 2 percent.

The use of separate relations for area and mean velocity is considered preferable to the use of a single compound relation for discharge, as was done in figure 208, because separate analysis of two components of discharge is simpler. Shifts in the discharge rating—that is, differences between measured and computed discharge—are also more easily analyzed when separate relations for area and mean velocity are prepared.

ACOUSTIC VELOCITY-METER METHOD

DESCRIPTION

Acoustic velocity meters are particularly advantageous in obtaining a continuous record of the discharge of large rivers in those situations where neither a simple stage-discharge relation nor a stage-fall-discharge relation can be applied satisfactorily. Those situations, as mentioned in the first section of this chapter, usually involve tidal flow or flow affected by hydroelectric-power generation, where the acceleration head in the equations of unsteady flow (p. 391) cannot be ignored. Acoustic velocity meters operate on the principle that the velocity of sound propagation through a fluid in motion is the algebraic sum of the fluid velocity and the acoustic propagation rate through the fluid. Thus acoustic pulses transmitted in the direction of flow will traverse a given path in shorter time than will acoustic pulses transmitted in opposition to the flow. The difference in transit

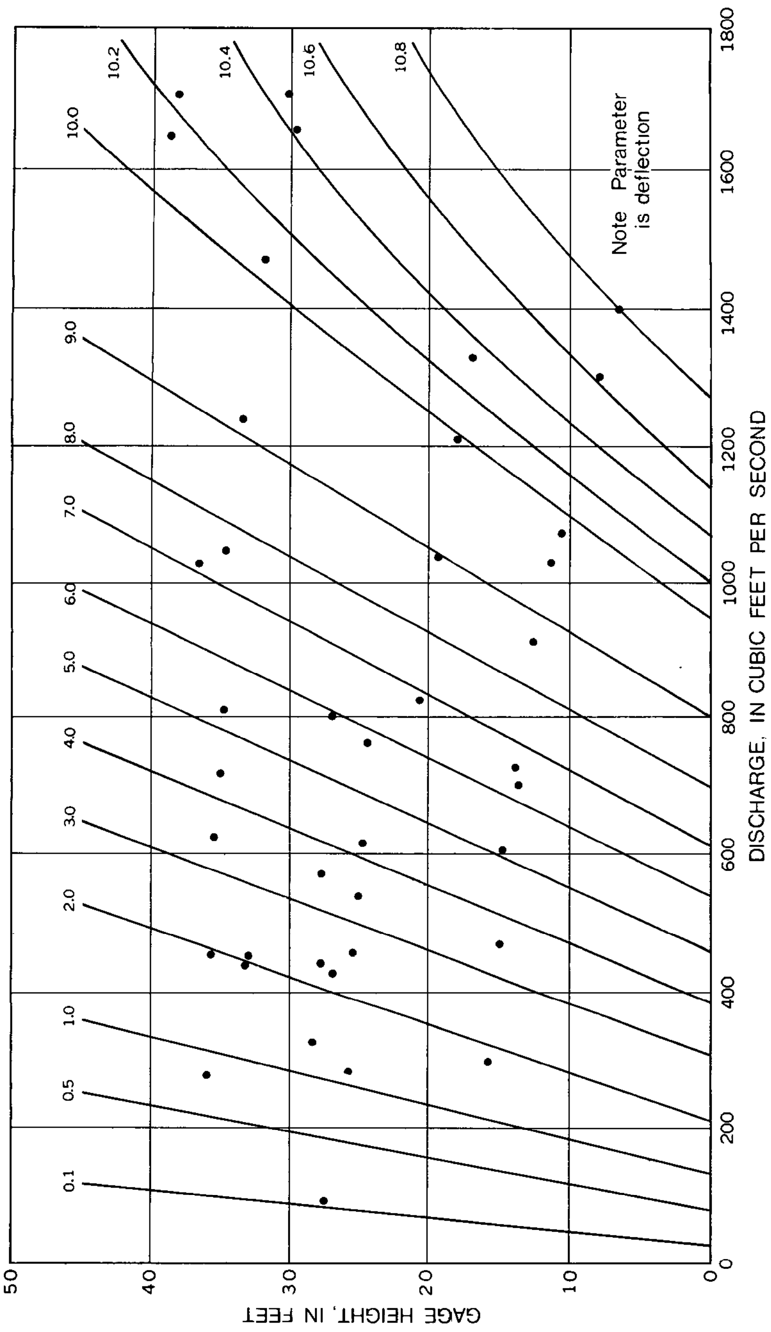


FIGURE 208.—Rating curves for a deflection-meter gaging station on Lake Winnipesaukee outlet at Lakeport, N.H.

times provides a measure of the line velocity—that is, the average value of the water velocity at the elevation of the acoustic path—and the line velocity is a satisfactory index of mean velocity in the channel. Because the transducers that transmit and receive the acoustic pulses are installed in the stream at a fixed elevation, the relation of line velocity to mean velocity varies with stage. The stage data required for the velocity relation are obtained from the stage recorder, which also provides an index of cross-sectional area.

Differences exist among the various acoustic-velocity metering systems that are commercially available, but the differences are not vital, and only one system will be briefly described. The major components of the acoustic monitoring system are two submerged transducers (fig. 209) and a console (fig. 210) housed on the streambank and electrically connected to both transducers. The two transducers, one on each side of the channel, are installed at the same elevation—an elevation that is below the lowest expected stage of the stream—on a diagonal path across the stream. The transducers convert electrical impulses generated in the console into sound pulses that travel through the water. They also convert the received sound pulses back into electrical signals. The console contains: the operating controls, the signal-generating and -receiving circuits (acoustic unit), the system clock that provides the basic timing pulses for the system and also furnishes the time-of-day readout, the digital processor (digital unit) that controls the transmission of acoustic pulses and performs the computations of the velocity index, and the velocity-index display. The velocity index is a measure of the line velocity. In the U.S.A., power for the system is usually furnished by a 110-volt alternating-current power supply.

Although acoustic-velocity meter systems are currently (1980) operational, the techniques and instrumentation are relatively new and are continually being improved. The cost of an acoustic-velocity meter installation is roughly 10 times that of a conventional gaging station. For that reason the acoustic-velocity method is limited to those sites where an accurate record of discharge is unattainable by the more conventional methods, but is of great value for water-management purposes.

THEORY

Measurement of the water velocity is possible because the velocity of a sound pulse in moving water is the algebraic sum of the acoustic propagation rate and the component of velocity parallel to the acoustic path. Reference is made to figure 211 in the following derivation of the mathematical relations of the system.

The traveltime of an acoustic pulse originating from a transducer at *A* and traveling in opposition to the flow of water along the path

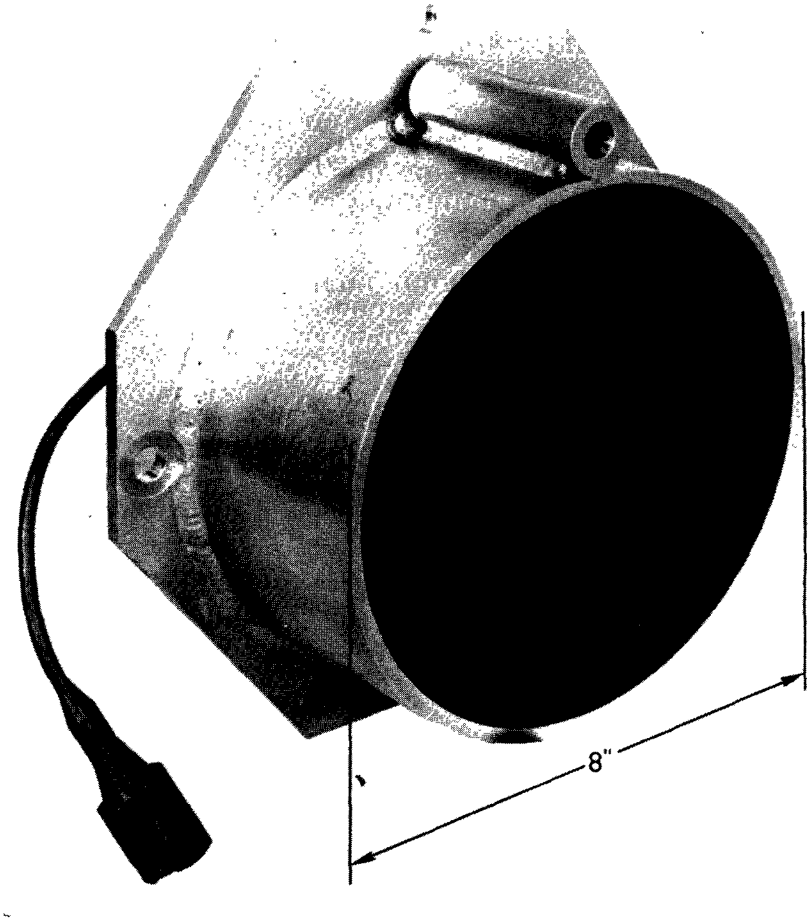


FIGURE 209.—Transducer.

A–C can be expressed as

$$T_{AC} = \frac{B}{c - V_p} , \qquad (91)$$

where

c is the propagation rate of sound in still water,
B is the length of the acoustic path from A to C,
T_{AC} is traveltime from A to C, and
V_p is average component of water velocity parallel to the acoustic path.

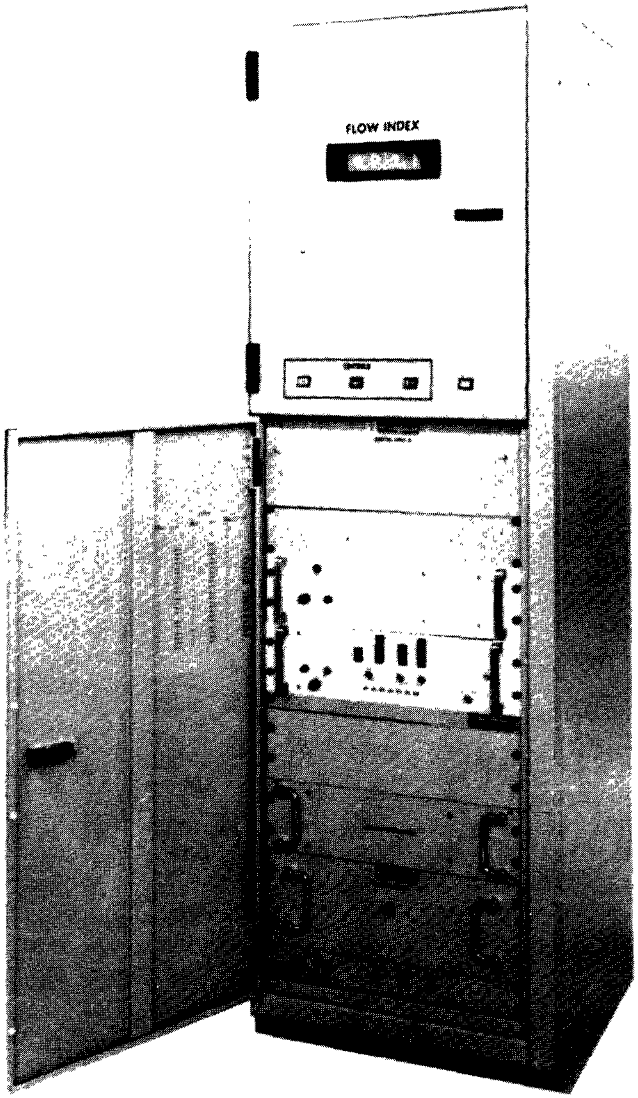


FIGURE 210.—Console.

Similarly, the traveltime for a pulse traveling with the current from C to A is

$$T_{CA} = \frac{B}{c + V_P}, \tag{92}$$

where T_{CA} is traveltime from C to A.

ΔT is the difference between $T_{AC}$and T_{CA}; therefore,

$$\Delta T = \frac{B}{c - V_P} - \frac{B}{c + V_P} = \frac{2BV_P}{c^2 - V_P{}^2} \quad ; \tag{93}$$

and since $V_P{}^2 <<< c^2$,

$$\Delta T \cong \frac{2BV_P}{c^2} \quad , \tag{94}$$

or

$$V_P \cong \frac{\Delta T c^2}{2B} \quad . \tag{95}$$

Both ΔT and c in equation 95 can be defined by measurement of the traveltimes of acoustic signals transmitted in each direction between transducers, c being computed by solving equations 91 and 92 simultaneously. The digital processor in the console can be scaled to produce a velocity index (I) that is equal to V_P. In some of the older systems used in the U.S.A. the velocity index was not scaled to equal V_P, but instead the velocity index was directly proportional to V_P, so that

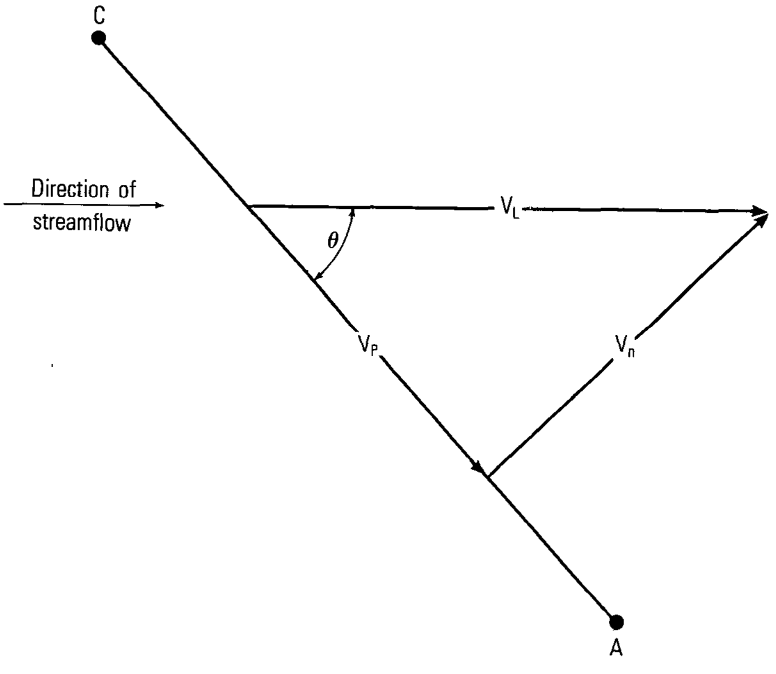


FIGURE 211.—Sketch to illustrate operating principles of the acoustic velocity meter.

$$V_P = C_1 I, \tag{96}$$

where C_1 is a constant of proportionality.

In the continuing discussion of "Theory", equation 96 will be used with the understanding that $C_1 = 1.00$ in some of the acoustic-velocity meter systems.

Figure 211 shows that

$$V_L = \frac{V_p}{\cos \Theta}, \tag{97}$$

where V_L is the average water velocity at the elevation of the acoustic path, and Θ is the acute angle between the streamline of flow and the acoustic path, AC.

By combining equations 96 and 97,

$$V_L = \left(\frac{C_1}{\cos\Theta}\right) I \tag{98}$$

Experimentation has shown V_L to be a stable index of $\overline{V}$, the mean velocity in the cross section at right angles to the streamlines of flow. The relation between V_L and $\overline{V}$ can be expected to vary with stage because V_L is a measure of the mean velocity along a line at a fixed elevation in the cross section. As the stage rises, the position of this line is moved downward in the cross section relative to the total depth, and resultant changes in the velocity distribution in the vertical column cause a change in the ratio between V_L and $\overline{V}$. Correlation of the ratio $V_L/\overline{V}$ with stage is accordingly necessary, and $\overline{V}$ can be expressed as follows:

$$\overline{V} = C_2 V_L, \tag{99}$$

where C_2 is a function of stage.

The basic equation for discharge (Q) is

$$Q = \overline{V} A, \tag{100}$$

where A is area of the cross section.

By substituting in equation 100, terms given in equations 98 and 99, the following equation is obtained:

$$Q = I \left(\frac{C_1 C_2}{\cos \Theta}\right) A. \tag{101}$$

When the symbol K is substituted for $\frac{(C_1 C_2)}{\cos \Theta}$ in equation 101, the result is

$$Q = KIA. \tag{102}$$

K varies with stage including, as it does, C_2 which is a function of stage.

To calibrate the system, discharge measurements are made to obtain measured values of A and $\overline{V}$. The measured values of A are correlated with stage to obtain a graphical stage-area relation. Measured values of $\overline{V}$ are divided by concurrent values of I, recorded by the console digital processor, to obtain concurrent values of K. Those values of K are correlated with stage to obtain an empirical graphical relation of K to stage. Such a relation is shown in figure 212.

To compute the discharge for any given value of I, the concurrent value of stage is first read. That value of stage is then used in the above grapnical relations to obtain the corresponding values of A and K. In a final step the values of K, I, and A are multiplied together, in accordance with equation 102, to obtain the required value of discharge.

Newer acoustic-meter velocity systems that have been designed provide a readout of discharge after the calibration coefficients have been determined. The additional calibration coefficients needed are provided by substituting mathematical relations of A to stage and K to stage, in place of the graphical relations discussed above. The computation of discharge is based on the following two assumptions:

1. The relation between area (A) and stage (H) is stable and can be adequately defined by the second-order equation,

$$A = C_1 + C_2H + C_3H^2, \tag{103}$$

where C_1, C_2, and C_3 are constants.

2. The ratio (K) between mean stream velocity ($\overline{V}$) and the velocity index (I), which is equal to, or linearly related to, the line velocity (V_p), can be defined by the second-order equation,

$$K = \overline{V}/I = C_4 + C_5H + C_6H^2, \tag{104}$$

where C_4, C_5, and C_6 are constants.

If sufficient data from discharge measurements are available, the "best" values of C in equations 103 and 104 can be computed from a least-squares solution of each of the equations. Usually, however, the C values in the two equations are obtained from the graphical relations of A versus H and K versus H. That is done by first selecting the coordinates of three significant points on one of the graphical relations, and then substituting those values in the appropriate equation—equation 103 when the area relation is used. The three resulting simultaneous equations are solved to produce the required C values. The process is then repeated, using equation 104 for the K relation. The six C values so obtained are then entered in the program for computing discharge. Discharge is computed as before, in

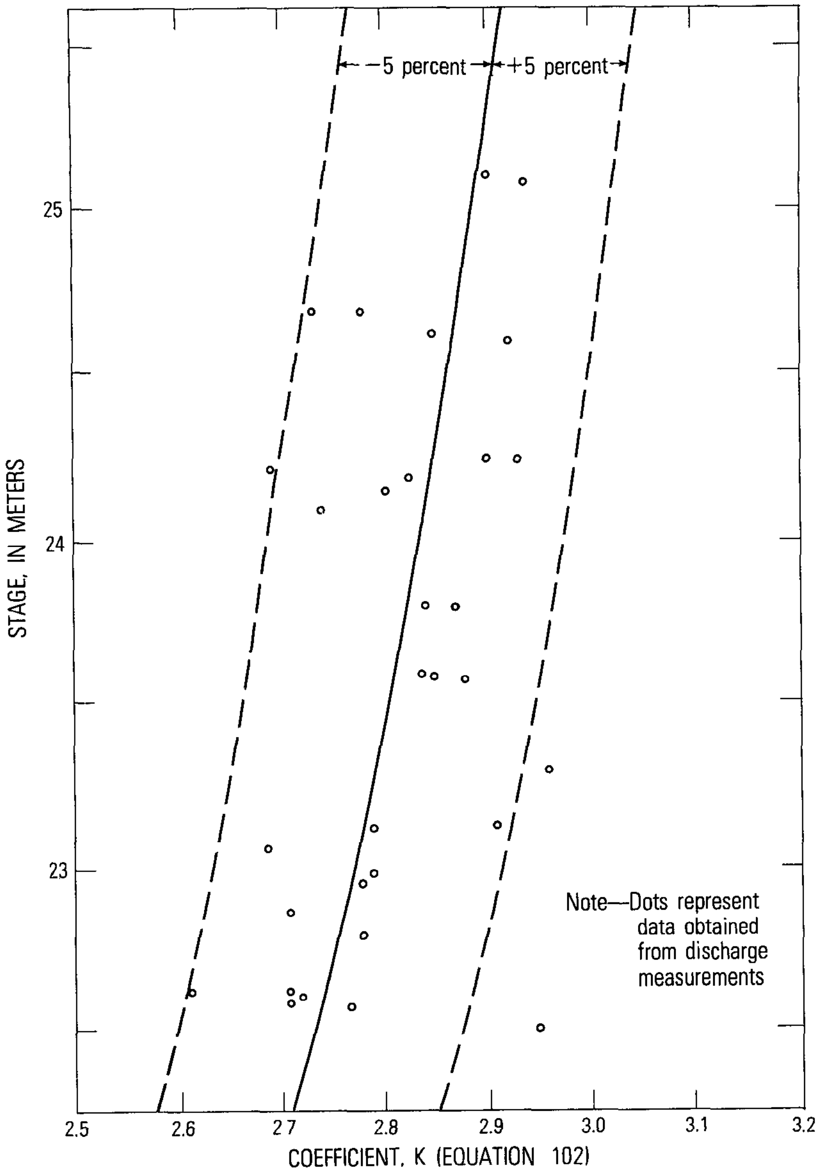


FIGURE 212.—Relation between stage and mean-velocity coefficient, K, for the acoustic-velocity meter (AVM) system, Columbia River at The Dalles, Oreg.

accordance with equation 102, except that the computations are performed in the console digital processor. The digital processor uses the C values, along with concurrent values of I and H, to make the required computations and provide a readout of K, I, A, H, and Q.

It would be simple, of course, to multiply I by the product of equations 103 and 104 and thereby obtain a single equation for Q. The result would be a fourth order equation of the form,

$$Q = I(k_1+k_2H+k_3H^2+k_4H^3+k_5H^4), \tag{105}$$

in which the k constants represented combinations of the C constants from equations 103 and 104. The "best" values of the constants could be obtained by a least-squares solution of equation 105, using measured values of Q and concurrent values of I and H. The use of equation 105 would simplify the computation of discharge, but the analyst would then lose much of his ability to analyze error sources in the calibration of shifts in the basic relations. It is therefore recommended that equations 103 and 104 be used rather than equation 105.

EFFECT OF TIDAL FLOW REVERSAL ON RELATION OF MEAN VELOCITY TO LINE VELOCITY

The value of C_2 in equation 99, $\overline{V} = C_2V_l$, varies only with stage in unidirectional flow. In streams where the direction of flow reverses in response to tide, the value of C_2 may vary not only with stage, but also with the four phases of the tide cycle. For such streams numerous discharge measurements, preferably by the moving-boat method (chap. 6), are required to evaluate C_2 for each of the tide phases. In using the moving-boat method of discharge measurement, it is necessary to determine a velocity coefficient for each individual discharge measurement and that is done by continuously defining the vertical-velocity distribution at several strategically located verticals that are representative of the main portion of streamflow. (See section in chapter 6 titled, "Adjustment of Mean Velocity and Total Discharge.")

The results of an evaluation of C_2 for a particular cross section in the Sacramento River in California are given in table 22 (Smith, 1969, p. 11–18). Column heading, $\overline{C}_2$, in table 22 refers to the mean values of C_2; column heading, s, refers to the standard deviations of C_2 values. Figure 213 is a plot of the data from columns headed, $\overline{V}$ and $\overline{C}_2$, in table 22.

ORIENTATION EFFECTS AT ACOUSTIC-VELOCITY METER INSTALLATIONS

EFFECT OF ACOUSTIC-PATH ORIENTATION ON ACCURACY OF COMPUTED LINE VELOCITY (V_l)

The basic accuracy or resolution of a given acoustic-velocity meter (AVM) system is controlled principally by the accuracy with which the arrival times of the acoustic pulses can be discriminated and by the accuracy of the timing circuitry used to measure elapsed times. A related factor that affects the accuracy of results obtained with a par-

TABLE 22.—*Variation of* C_2 *with tidal phase*

[$\overline{C}_2$ are mean values of C_2; s are standard deviations of C_2 values]

Velocity range (ft/s)	Increasing ebb			Decreasing ebb			Increasing flood			Decreasing flood		
	$\overline{V}$ (ft/s)	$\overline{C}_2$	s	$\overline{V}$ (ft/s)	$\overline{C}_2$	s	$\overline{V}$ (ft/s)	$\overline{C}_2$	s	$\overline{V}$ (ft/s)	$\overline{C}_2$	s
<1.00	0.90	0.961	(1)	0.84	1.030	0.031	0.87	1.005	0.030	----	----	----
1.00–1.40	1.16	.957	0.035	----	----	----	1.21	1.006	(1)	1.11	0.983	(1)
1.41–1.80	1.52	.965	(1)	1.41	1.040	(1)	1.75	.982	(1)	1.58	.997	0.022
1.81–2.20	1.96	.981	.011	2.02	1.019	.017	2.09	.970	(1)	2.08	.991	.020
2.21–2.60	2.44	.978	.014	2.46	1.019	.018	2.43	.985	.011	2.43	.992	.009
>2.60	2.75	.985	.009	2.76	.990	.014	2.92	.982	.007	2.84	.982	.009

[1] Not computed, only one or two values of C_2 available for determining $\overline{C}_2$

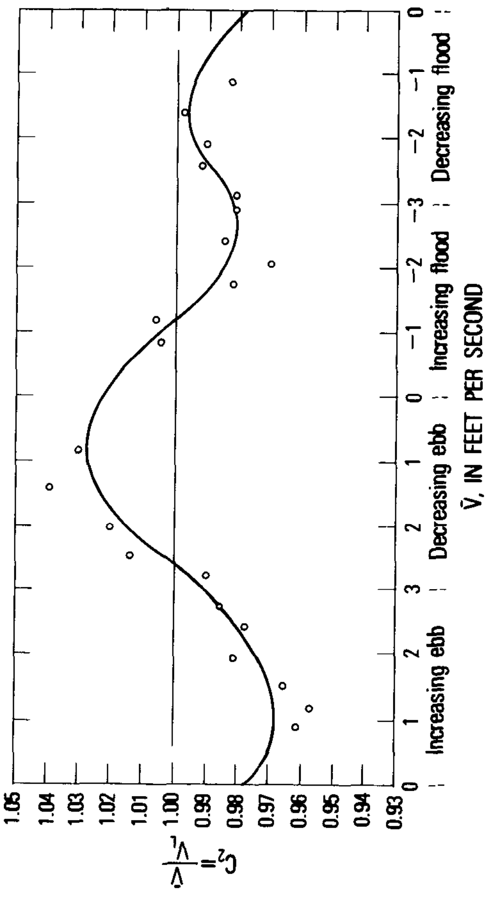


FIGURE 213.—Relation between C_2 and velocity and tide phase.

ticular *AVM* system is the orientation of the acoustic path with respect to the streamlines of flow. The effect of path orientation will now be examined for one of the *AVM* systems used in the U.S.A. It is assumed that no changes in the basic circuitry are made for operations over acoustic paths of various orientations, that the streamlines at all times and stages are parallel and their direction is invariant, and that acoustic performance is thoroughly reliable.

From figure 211

$$V_P = V_L \cos \Theta \tag{97a}$$

Insertion of the resolution error (R_e) for the system in equation 97a yields

$$V_P = V_L \cos \Theta \pm R_e$$

or,

$$V_L = \frac{V_P}{\cos \Theta} \pm \frac{R_e}{\cos \Theta}\,. \tag{106}$$

The last term in equation 106 represents the error (E) in computed values of V_L, meaning that

$$E = \pm \frac{R_e}{\cos \Theta} \tag{107}$$

In other words, for a given *AVM* system, the error in computed values of V_L decreases as Θ decreases.

According to the claim of the manufacturer of the *AVM* system under discussion, inaccuracy (E) attributable to the resolution error is ±0.05 ft/s when angle Θ is 45°. From equation 107, the implication is that the resolution error (R_e) equals $\pm 0.05 \cos \Theta$, or ±0.035 ft/s. Table 23 was computed from equation 107 using the above value of R_e. Because the error in computed values of V_L is independent of the magnitude of V_L, the greatest percentage errors in computed velocity occur at low velocities for any given orientation of the acoustic path.

EFFECT OF VARIATION IN STREAMLINE ORIENTATION

If an *AVM* system were located a short distance downstream from the confluence of two streams, as shown in figure 214, the direction of

TABLE 23.—*Error in computed* V_L, *attributable to resolution error, for various acoustic-path orientations, for a given* AVM *system*

Path-orientation angle Θ, in degrees	Error in V_L, in ft/s
30	±0.04
45	± .05
60	± .07
70	± .10
80	± .20

the streamlines of flow at the gage site could be expected to vary with the proportion of total discharge contributed by the tributary stream. When the tributary flow is low, the angle between streamlines and acoustic path is Θ, V_L is the velocity normal to the cross section whose area is A, and a value of V_p is recorded by the *AVM*;

$$V_L = \frac{V_p}{\cos \Theta} \quad , \tag{108}$$

and

$$Q_{AVM} = AV_L \tag{109}$$

If stage and discharge remain constant, but the proportion of flow from the tributary increases significantly, the angle Θ between the streamlines of flow and the acoustic path will increase by an increment ϕ, but V_L will remain constant because the discharge and stage remain constant. A value of V'_p will now be recorded by the *AVM*, where

$$V'_p = V' \cos(\Theta+\phi) \tag{110}$$

But,

$$V' = \frac{V_L}{\cos \phi} \tag{111}$$

Therefore,

$$V'_p = \frac{V_L \cos(\Theta+\phi)}{\cos \phi} \tag{112}$$

However the discharge has not changed. If the *AVM* system had been calibrated under conditions where, for the given discharge and given stage, the angle between streamlines and acoustic path was Θ, the *AVM* system will be unaware of the increase in angle from Θ to $(\Theta+\phi)$, and the discharge will be computed as

$$Q'_{AVM} = \frac{AV'_p}{\cos \Theta} = \frac{AV_L \cos(\Theta+\phi)}{\cos \Theta \cos \phi} \tag{113}$$

But the true *AVM* discharge (line velocity times area) is that shown by equation 109. Therefore the ratio between computed *AVM* discharge for the condition of the angle being $(\Theta+\phi)$ and the true *AVM* discharge is,

$$\frac{Q'_{AVM}}{Q_{AVM}} = \frac{\left(\frac{AV_L \cos(\Theta+\phi)}{\cos \Theta \cos \phi}\right)}{AV_L} \tag{114}$$

$$= \frac{\cos(\Theta+\phi)}{\cos \Theta \cos \phi}$$

$$= 1 - \tan\Theta \tan\phi \tag{115}$$

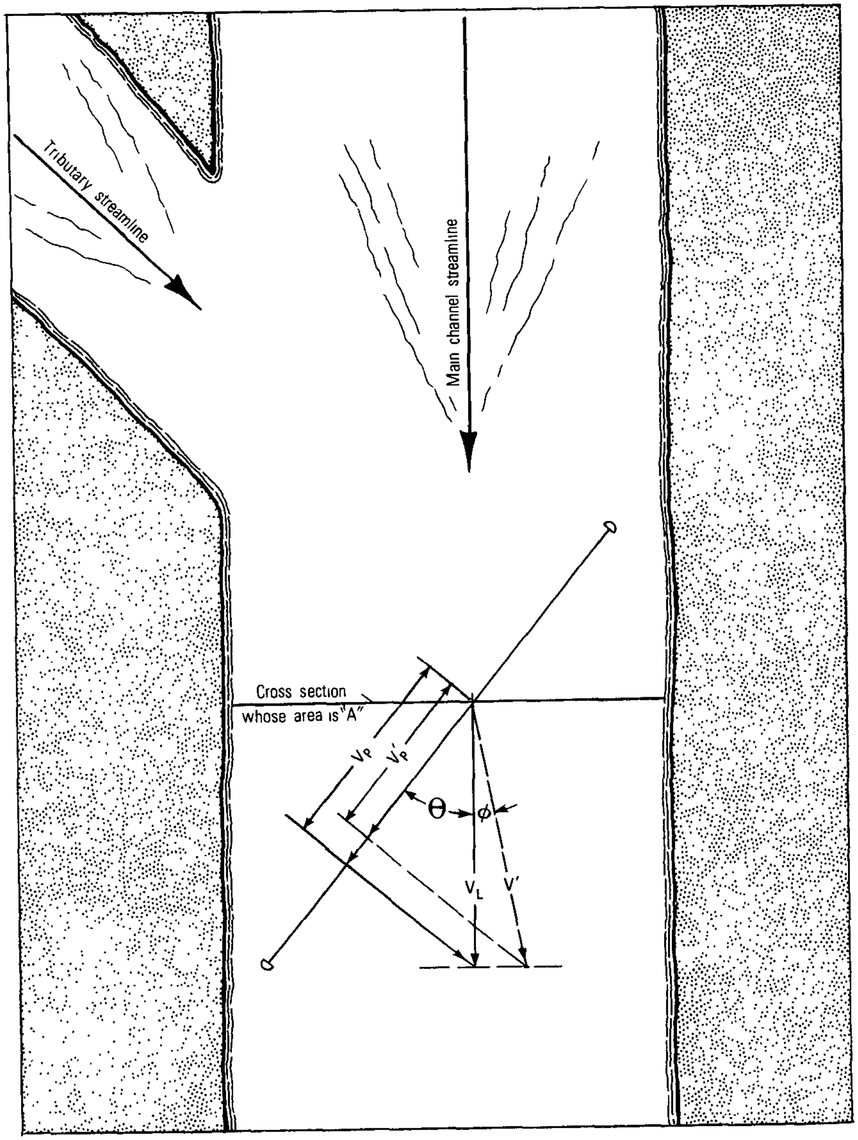


FIGURE 214.—Possible variation in streamline orientation.

Equation 115 is evaluated in table 24 for acoustic path orientations (Θ) ranging from 30° to 60°, and for streamline variations (φ) ranging from −4° to +4°.

As a general rule one should avoid installing an *AVM* system immediately downstream from the confluence of two streams. It is true

TABLE 24.—*Ratio of computed discharge to true discharge for various combinations of* Θ *and* ϕ

Θ	Ratios for the values of ϕ indicated below								
	−4°	−3°	−2°	−1°	0°	+1°	+2°	+3°	+4°
30°	1.040	1.030	1.020	1.010	1.000	0.990	0.980	0.970	0.960
45°	1.070	1.052	1.035	1.017	1.000	.983	.965	.948	.930
50°	1.083	1.062	1.042	1.021	1.000	.979	.958	.938	.917
60°	1.121	1.091	1.060	1.030	1.000	.970	.940	.909	.879

that calibration of the system will be unaffected if, for each value of total discharge, there exists a particular ratio of tributary discharge to mainstream discharge. However, if that ratio is not constant for a given total discharge, error will be introduced in the calibration of the system, and therefore, in the computation of discharge.

FACTORS AFFECTING ACOUSTIC-SIGNAL PROPAGATION

In the installation of an *AVM* system, consideration must be given to the factors that affect the propagation of the acoustic signal through the water. Refraction or reflection of the acoustic beam away from the selected path or attenuation of the acoustic signal may result from:

1. temperature gradients in the stream,
2. boundary proximity,
3. air entrainment,
4. sediment concentration, and
5. aquatic vegetation.

TEMPERATURE GRADIENTS

Periodic loss of signal at some *AVM* installations where the transducers were relatively close to the water surface of a deep stream have led engineers to theorize that the development of even extremely small temperature gradients in the water column may cause refraction of the acoustic signal. In streams where mixing is poor, changes in solar radiation and air temperature could conceivably cause such gradients to develop. It has been reasoned that location of the acoustic path near mid-depth of the stream should minimize temperature gradients caused by variations in temperature or possibly by heat exchange between the water and channel perimeter.

BOUNDARY PROXIMITY

When the acoustic path is located near the water surface or near the streambed, part of the acoustic signal will be reflected from the boundary (air-water interface or streambed). The reflected component may arrive at the receiving transducer almost simultaneously with, but out of phase with, the primary pulse. In extreme cases, signals may be almost completely blanked out. This phenomenon is related to the ratio of path length to distance to a boundary and to the frequency of the transmitted signal.

The above considerations, combined with the possibility of the thermal effects discussed above, have led the designers of some *AVM* systems to develop the criteria curves for *AVM* site selection shown in figure 215. The curves indicate the performance that can probably be expected from some systems in a given channel geometry when the transducer elevation is set at mid-depth. The terms "excellent" and "acceptable" are relative, and their significance is dependent upon the reliability requirements at the site. The curves show that the depth of water required increases as the path length increases. For example, for a path length of 500 ft, excellent acoustic performance would be expected for depths greater than 18 ft and acceptable performance would be anticipated for depths between 10 and 18 ft, but for depths less than 10 ft, on-site investigation of the characteristics of acoustic transmission would be necessary. For a path length of 1,000 ft, these depth ranges change to 34 ft or more for excellent transmission and from 19 to 34 ft for acceptable transmission. On-site studies would be required for depths less than 19 ft. The curves in figure 215 should not be construed as providing all the information

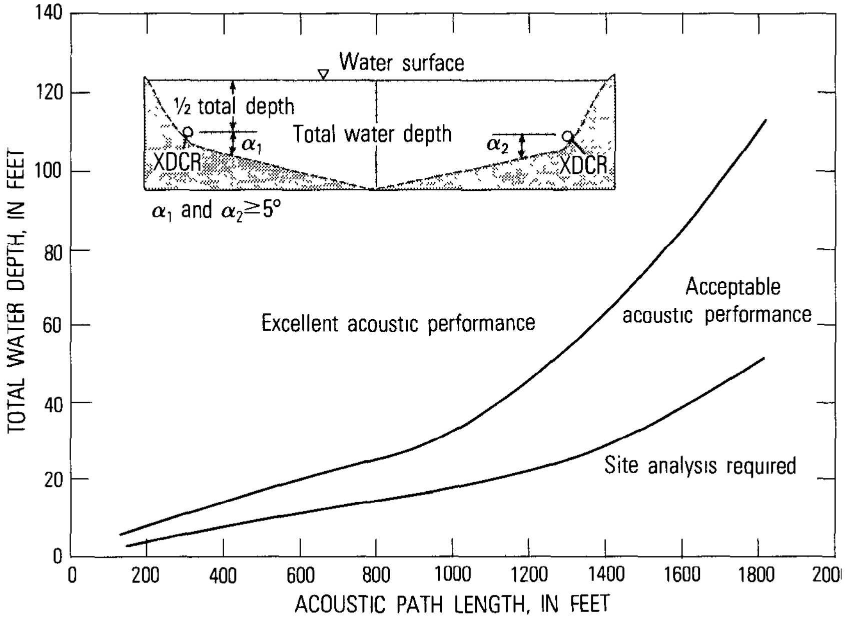


FIGURE 215 —Curves used as a preliminary guide for AVM site selection, based solely on consideration of channel geometry.

required for assessment of the potential for utilizing an *AVM* system. By these criteria, broad, shallow channels would seem to be questionable sites, but it is possible that further developments in transducer design and system characteristics may provide reliable performance in such channels also.

AIR ENTRAINMENT

Little quantitative information is available concerning the attenuation of acoustic signals by air bubbles entrained in the water, but the effect of air entrainment has been observed downstream from dams where the falling water becomes highly aerated. Bubbles formed at such sites may remain entrained in the water for a considerable distance downstream, and they absorb and reflect the acoustic signal much as fog absorbs and reflects a beam of light. The highly absorptive characteristics of water with entrained air precludes satisfactory operation of *AVM* systems, and locations close to spillways or other sources of air entrainment should consequently be avoided.

SEDIMENT CONCENTRATION

The degree of attenuation of signal strength caused by the reflection and scatter of the acoustic signals from sediment particles suspended in the stream has not been fully documented. The attenuation is influenced not only by suspended-sediment concentration, but also by the size of the sediment particles, water temperature, and length of the acoustic path. Equations given by Flammer (1962) for the evaluation of energy loss are:

$$E = E_0 10^{-0.1 \alpha x}, \tag{116}$$

where

E = sound energy flux at a given point, if sediment is suspended in the transmitting fluid;
E_0 = sound-energy flux at the same point, if no sediment were present;
α = attenuation coefficient that is due to sediment alone, measured in decibels per inch; and
x = distance from the point of measurement to the sound source.

The attenuation coefficient α can be evaluated as

$$\alpha = C\left[\frac{K(\gamma-1)^2 S}{S^2+(\gamma+\tau)^2} + \frac{K^4 r^3}{6}\right]\frac{22.05}{2} \quad , \tag{117}$$

where

C = concentration (1,000 mg/L = 0.001),
$K = 2\pi/\lambda$,
$\gamma = \rho_1/\rho_2$,
$S = [9/(4\beta r)]\,[1+1/(\beta r)]$,
$\tau = \frac{1}{2} + 9/(4\beta\tau)$, and

r = particle radius, in centimeters;

in which

λ = wave length of sound in water, in centimeters; ρ_1 and ρ_2 = densities of particle and fluid, respectively;

$\beta = [\omega/2v]^{1/2}$

$\omega = 2\pi f$;

v = kinematic viscosity of water, in stokes; and

f = frequency of sound wave.

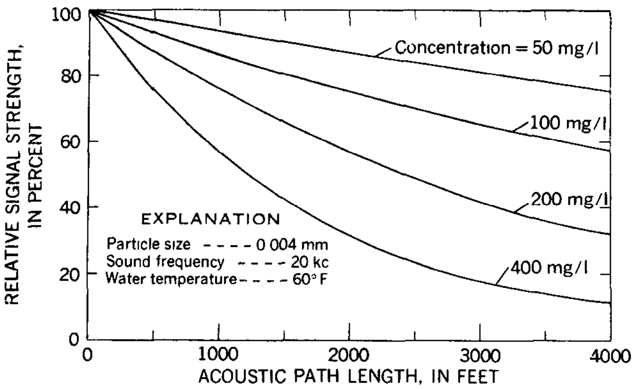
An example of the evaluation of equations 116 and 117 for an *AVM* site investigated in central California is shown in figure 216. Pertinent site and *AVM* characteristics were as follows:

Particle size—0.004 mm
Sediment concentration—20-100 mg/L
Water temperature—60°F(15.6°C)
Sonic-path length—4,000 ft (1219 m)
Sound frequency—20 kc

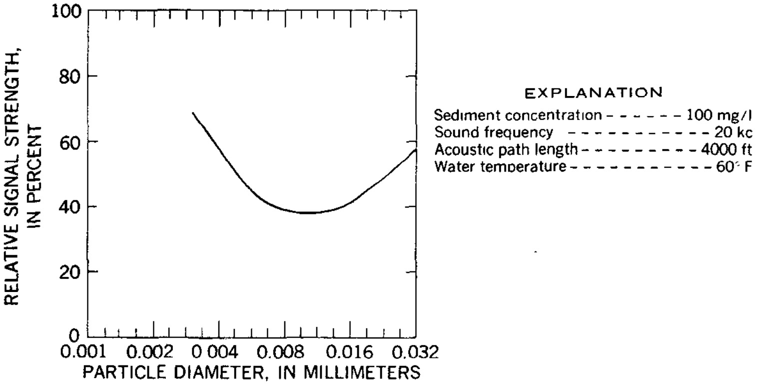
Figure 216*A* illustrates the general problem and shows the reduction in signal strength resulting from sediment concentrations ranging from 50 mg/L to 400 mg/L over acoustic paths as long as 4,000 ft. Figure 216*B* shows the signal loss for a given concentration and path length, as affected by particle size, and relates signal loss, for a path length of 4,000 ft, to sediment size when the sediment concentration is held constant at 100 mg/L. Figure 216*C* relates signal loss, for a path length of 4,000 ft, to sediment concentration when the sediment size is held constant at 0.004 mm. Figure 216*C* is of particular significance; it indicates that for the probable range in suspended-sediment concentrations at the site under consideration (20–100 mg/L), signal strength will vary from 90 to 56 percent of the levels possible in clear water. One of the requirements of an *AVM* designed for use at this site would be that no calibration changes should result from signal strength variations of that magnitude.

AQUATIC VEGETATION

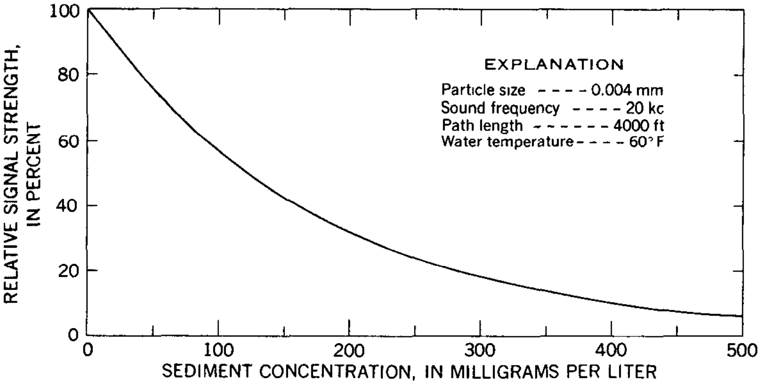
The effect of aquatic weeds in the acoustic path is variable, depending on the location and density of the weed growth. Dense growth may cause complete blockage of the signal. It has been found, in experiments in the United Kingdom, that the removal of only a small amount of weeds will increase the amplitude of the received signal. Further experimentation (Green and Ellis, 1974) has shown that weeds growing close to the transducer may actually cause the *AVM* system to overregister the velocity; the weeds reflect and scatter the wave train and the extra scattered signals are detected by the transducer. On the other hand, weeds in the midchannel result in a widely variable registration of velocity, in which the velocity is underestimated. In short, aquatic weeds in the acoustic path interfere with



A. Relation between signal strength, sediment concentration, and path length



B. Variation in signal strength with particle size



C. Relation between signal strength and sediment concentration

FIGURE 216.—Interrelation between signal strength, sediment concentration, particle size, and acoustic-path length.

the operation of an *AVM* system, but the quantitative results of experimentation with weed growths are not transferable from the experimental sites to other *AVM* sites.

It should also be noted that there has been no experimentation to relate attenuation caused by weed growth to sonic frequency. It appears probable that operation at a low frequency might reduce the attenuation; however, that would also reduce the basic accuracy of the *AVM* system.

SUMMARY OF CONSIDERATIONS FOR ACOUSTIC-VELOCITY METER INSTALLATIONS

The foregoing discussions of factors that influence *AVM* operation demonstrate that the interrelation of those factors must be considered in site selection of the acoustic path of an *AVM* system in a given stream. The most important consideration is to ensure reliable acoustic transmission and reception, and from that standpoint the acoustic path should be as short as possible to minimize acoustic refraction and attenuation losses. On the other hand, consideration of the hydraulic aspects of the system suggests use of a long path at a small angle of incidence (Θ in fig. 211) to the streamlines to achieve the best resolution of velocity and to reduce the effect of variations in streamline direction. These are opposing restraints on the system configuration, therefore compromise is often required. For most installations, the desired resolution can be attained by utilizing a path at the mid-depth position and at an angle of 45° to the streamlines. Narrow deep sections of a river are to be preferred over broad shallow sections, and locations influenced by tributary inflow should be avoided. On-site investigation of acoustic-propagation characteristics will be desirable at sites where the depth-to-path length criteria of figure 215 indicate possible problems.

Weed-covered sites and sites where air bubbles are entrained in the water should be avoided in selecting an acoustic path because of the likelihood of signal attenuation. For that same reason, the use of *AVM* systems may not be practical in streams that frequently carry large sediment loads.

ELECTROMAGNETIC VELOCITY-METER METHOD

GENERAL

The electromagnetic method of measuring velocity in stream-gaging operations will be discussed only briefly because it is still (1980) in the experimental stage. Experimental work in the U.S.A. has been largely in the use of the electromagnetic meter to obtain a continuous record of velocity at a point. The observed point velocities are then used as indexes of mean velocity in the stream, precisely as explained in earlier sections of this chapter, where the standard current meter and the deflection meter were the instruments used for continuously measuring point velocities. In several European countries, notably the United Kingdom, experimental work in electromagnetic stream-gaging has been largely in the use of an electromagnetic meter to obtain a continuous record of an index value of integrated mean velocity in the entire measurement cross section.

The operation of an electromagnetic velocity meter is based on the principle that an electromotive force, or voltage, is induced in an electrical conductor moving through a magnetic field. For a given field strength the magnitude of the induced voltage is proportional to the velocity of the conductor. In the electromagnetic velocity meter, the conductor is the flowing water whose velocity is to be measured. Although all devices for measuring water velocity electromagnetically are based on the above principle, the actual instrumentation for measuring point velocities differs greatly from that used for integrating the mean velocity in a cross section.

POINT-VELOCITY INDEX

INSTRUMENTATION

A variety of electromagnetic meters for measuring point velocity are available commercially. The meters differ in details of construction and performance, but essentially there are two general types.

One type of meter consists of the following elements: a nonmagnetic tube or pipe through which the water flows; two magnetic coils, one on each side of the pipe; electrodes in the walls of the pipe between the magnetic coils; and suitable electrical circuits to transform the induced voltage into a velocity indication on a meter dial. The other type of meter consists of a probe, or cylinder, containing an electromagnet internally and two pairs of external electrodes in contact with the water. Flow around the cylindrical probe intersects magnetic flux lines causing voltages to be generated that are detected by the electrodes. Electrical circuitry is provided to transform the induced voltage into a velocity indication on a meter dial.

For either type of meter, a source of electrical power is needed to activate the magnetic field and a transmitter is used to record the velocity signals on digital tape or to send the signals to desired stations. The meters used in the U.S.A. generally require an alternating-current source of 110 volts, but many are battery powered. The meters cause negligible head loss; accuracy claimed by the manufacturers is generally in the range of ±2 to ±3 percent or ±0.005 to ±0.007 ft/sec, whichever is larger. In other words, from a standpoint of percentage error, the higher velocities are more accurately measured than low velocities.

At the gage site the unattended electromagnetic velocity meter is securely anchored in a fixed position in the stream below the minimum expected stage. The considerations governing the precise location of the meter in the stream are identical with those discussed for the standard current meter when it is used to provide a point-velocity index (see section titled "Standard Current-Meter Method"). A recording stage-gage is operated in conjunction with the velocity meter. Velocity and stage are usually recorded on digital tape.

ANALYSIS OF POINT-VELOCITY DATA

The point-velocity data from the electromagnetic meter are analyzed in the same manner as discussed earlier in this chapter for the fixed standard current meter. Mean velocity for the measurement cross section, as obtained from discharge measurements, is correlated with concurrent stage and point velocity. Cross-sectional area is related to stage. The product of mean velocity and cross-sectional area gives the required discharge. Experimentation in the U.S.A. in the use of an unattended electromagnetic meter as a point-velocity index for gaging open-channel flow had lagged, primarily because of problems in suppressing electrical noise and in preventing the contamination of electrodes, but experimentation has recently been renewed. A description of a gaging-station operation in which point-velocity data are being obtained from an electromagnetic probe follows.

The gaging site on the Alabama River near Montgomery, Ala. is at a pool formed by a dam 43 miles downstream. The river is 600 ft wide and 40 ft deep, and the flow is largely controlled by the operation of hydroelectric-power dams upstream. The flow of the river is thus highly unsteady and in addition the water-surface slope varies because of operations at the downstream dam. The discharge of the river could not be related to stage or to stage and slope. Consequently, an electromagnetic meter was installed to provide point-index velocities.

The meter is of the portable probe type, is battery powered, and features solid-state electronics in a durable field housing. The form and size of the probe are shown in figure 217. The electromagnetic probe is mounted on a structure attached to the upstream end of a bridge pier in the center of the stream. The probe was positioned to sense the velocity at a point 6 ft upstream from the nose of the pier and 6 ft below the minimum stage of the water surface. The recorder and electronic package are installed in the gage house on the pier, about 35 feet above the mean high-water stage. The Geological Survey developed the electronics necessary to average the continuously generated velocity signal over 30-minute intervals and to record this average velocity on a digital recorder.

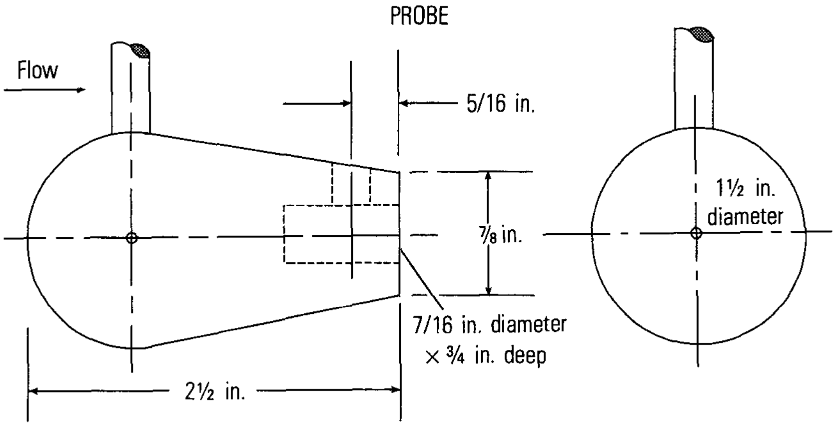


FIGURE 217.—Electromagnetic probe, model 201, Marsh-McBirney.

A series of current-meter discharge measurements was made to calibrate the relation of point velocity, as indicated by the probe, to the average velocity of the stream, as determined from the discharge measurements. Because of the unsteady flow, it was necessary that the discharge measurements be completed as quickly as possible. For that reason the measurements were made by defining the variation of velocity with time at a number of verticals in the stream-measurement cross section, as described in the section in chapter 5 titled, "Measurement Procedures During Rapidly Changing Stage—Case B. Small Streams." The relation between recorded point-index velocity and mean stream velocity determined from the discharge measurements is shown in figure 218. Although several of the plotted points scatter widely, the relation appears to be adequately defined over the range of velocity that was experienced. An attempt to improve the relation by the use of stage as an additional parameter, as in figure 201, was unsuccessful. A continuous record of discharge is computed at the gaging station by using the records of stage and point velocity, stage being an index of the cross-sectional area and point velocity an index of mean stream velocity.

Experience with the electromagnetic probe at the Alabama River gaging station has been very encouraging. The instrumentation appears to have wide application for gaging streams at sites where simpler rating methods such as stage-discharge or stage-slope-discharge are not adequate. The system has the sensitivity and accuracy required even at low velocities, is relatively inexpensive, has flexibility with regard to location because it is powered by dry-cell batteries, and can probably be used even at sites where the direction of flow reverses. The use of the system for gaging streams is consid-

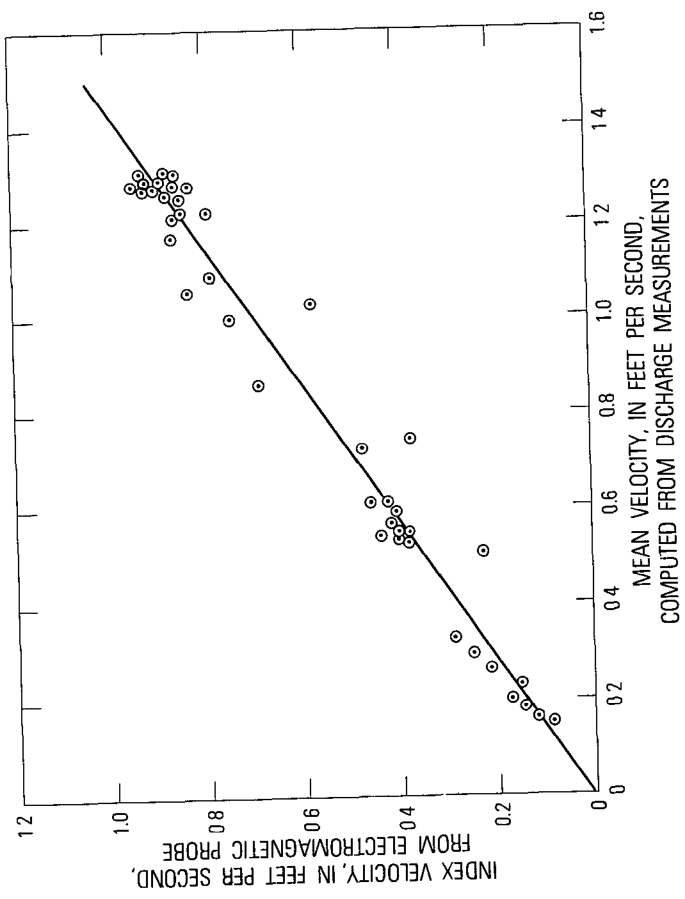


FIGURE 218.—Relation between point-index velocity and mean stream velocity for Alabama River near Montgomery, Ala.

ered to be in the experimental stage (1980), but it is hoped that further testing and development will result in the perfection of a reliable tool for gaging streams.

INTEGRATED-VELOCITY INDEX

THEORY

The discussions that follow have been extracted from British publications (Herschy and Newman, 1974; Newman, 1974; Plessey Radar, 1974).

If a conductor moves through a magnetic field, an electromotive force (voltage) is generated in the conductor. That principle can be applied to stream gaging. An electric current, flowing through a coil placed on a streambed at right angles to the flow, generates a magnetic field in the vertical direction. The flowing water is the conductor moving through the field, and the electromotive force (emf) generated in the water is at right angles to the flow. In accordance with Faraday's law of electromagnetic induction, the equation relating the length of the conductor moving in the magnetic field to the emf that is generated, is

$$E = HVb, \tag{118}$$

where

E is emf generated, in volts;

H is magnetic field intensity, in Tesla;

V is average velocity of the river water, in meters per second, and

b is river width, in meters.

In practice most streambeds will have some significant electrical conductivity that will allow electric currents to flow in the bed. The electric currents have the effect of attenuating the signal, predicted from equation 118, by a theoretically predictable factor called the conductivity-attenuation factor δ,

$$\delta = \frac{1}{1 + \left(\frac{b\sigma_0}{2h\sigma_1}\right)} \tag{119}$$

where

b is stream width,

h is stream depth,

σ_0 is streambed conductivity, and

σ_1 is river-water conductivity.

Equation 118 then becomes

$$E = HVb\delta \tag{120}$$

In an operational electromagnetic gaging station, the river and streambed conductivity should be continuously monitored and the output signal corrected accordingly.

When an electromagnetic gaging station uses an artificially produced magnetic field, that is, a magnetic field produced by a current-carrying coil, the field must, from practical considerations, be spatially limited. This means that electric currents flow in the areas outside the magnetic field, thereby reducing the output potential by a factor β, the end-shorting factor. That factor is a constant for a given coil size and configuration. Equation 120 now becomes

$$E = HVb\delta\beta. \tag{121}$$

For a given electromagnetic gaging station the magnetic-field intensity H, and the end-shorting factor β, are constants. The streambed resistivity attenuation factor, δ, is a function of the river-aspect ratio (the stage, if the river width is constant) and of the river-to-streambed conductivity ratio, σ_0/σ_1. Therefore, to insert the correct value of δ in equation 121 it is necessary to have measurements of the stage and the river-to-streambed conductivity ratio. The mean velocity of the river can then be computed. To obtain the discharge, the velocity is multiplied by the river cross-sectional area.

INSTRUMENTATION

An electromagnetic system for integrating stream velocity can be installed anywhere in a river or canal where the conductivity of the water is uniform but not necessarily constant. At present, installations have been confined to small streams. Measuring sections that are bounded by heavily reinforced concrete or by steel pilings are not suitable because of the relatively high electrical conductivity of those boundary elements. Although the signal-recovery techniques that are used make the system immune to ambient electrical noise, sites close to overhead or buried powerlines should be avoided if possible.

A description of one of the operational systems for integrating the stream velocity electromagnetically follows. In that system a large coil (fig. 219) is buried under the streambed and banks to a depth of about 0.5 m (1.5 ft, approx.). The trench in which the coil is laid roughly follows the contours of the bed and banks to minimize the effect of variation in the velocity profile. A magnetic field is produced by an electric current flowing through the coil.

Two signal probes placed in the magnetic field are fixed against the banks (fig. 219) or are driven vertically into the banks (fig. 220). The probes are used to detect the electromotive force induced in the moving water and to define precisely the cross section of the measurement area. The purpose of driving the signal probes vertically into the bank, as in figure 220, is to define a cross section whose area is rectangular. Such materials as aquatic vegetation and bed and bank sediments streamward from the probes are included in the size of the

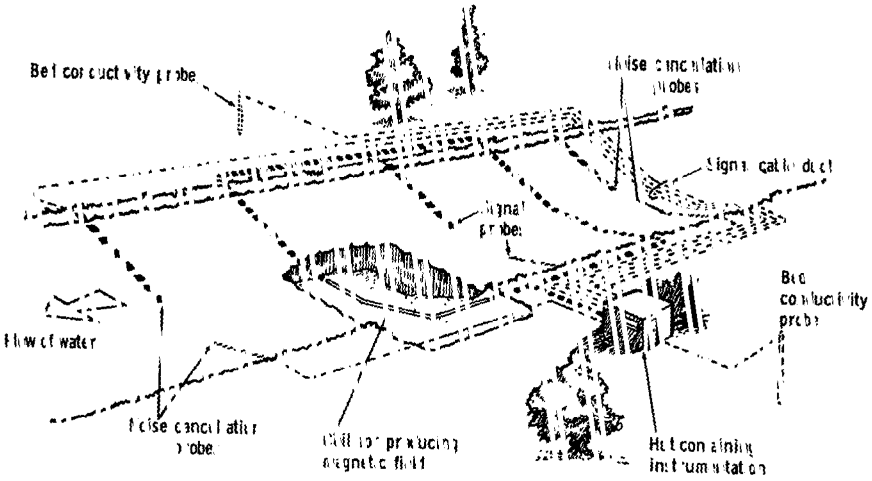


FIGURE 219.—Instrumentation for an electromagnetic stream-gaging station. (After Herschy and Newman, 1974.)

cross-sectional area; the velocity of the extraneous material is zero and its effect on the system is therefore as innocuous as that of stagnant water.

Four noise-cancellation probes (fig. 219) outside the influence of the induced magnetic field are used to detect the ambient electrical noise which is later subtracted from the signal induced by the coil. These probes are mounted in a manner similar to the signal probes, with one pair upstream and one pair downstream from the measurement area.

Two bed-conductivity probes (fig. 219) are placed on each side of the stream, at a distance back from the bank that is approximately equal to the width of the stream. The probes and their cables may be buried sufficiently deep to avoid damage by agricultural work or other ground-disturbing activities. By the use of the bed-conductivity probes and the signal probes, the conductivity of the streambed is measured.

The power-supply unit provides a direct-current source that is connected to the coil through a switching unit. The switching unit, in response to timing pulses from the data-processor unit described below, reverses the direction of the current flowing through the coil at half-second intervals. That causes a synchronous change in the polarity of the electrical potential induced in the moving water by the magnetic field, with the result that the signal can be detected by the signal probes in the presence of electrical noise. At the signal-recovery unit, the probe voltage is amplified, and after filtering and conversion, a digital signal is provided to the data-processor unit.

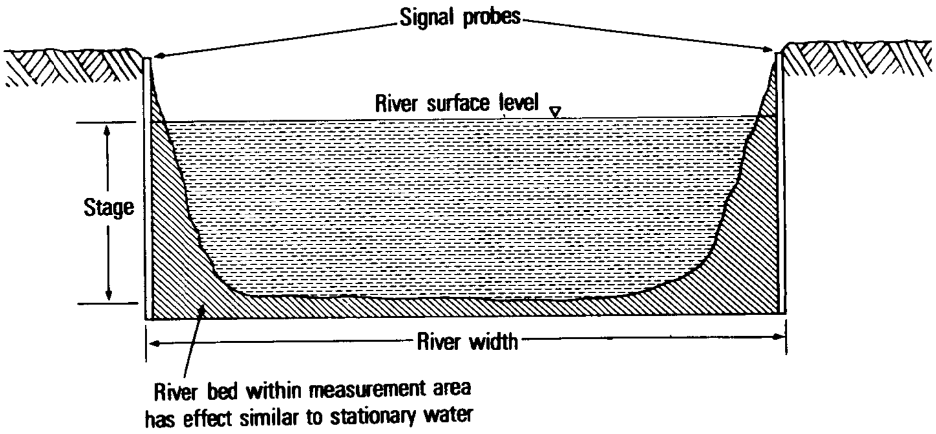


FIGURE 220.—Schematic diagram showing inclusion of bed and bank material in stream cross section. (After Herschy and Newman, 1974)

Additional instrumentation in the system includes a stage sensor and a power-operated pump that delivers continuous samples of water to a conventional conductivity sensor. The stage sensor, usually operating in a stilling well, provides a digital signal of stage to the data processor.

The block diagram in figure 221 shows the function of the data processor. In the data processor, the information from the probes is combined with that from the sensors for conductivities and stage. The latest information received is combined with similar prior information to provide a weighted average value. The weighted average value is then scaled, using preprogramed constants, to give an output of discharge in conventional units. The principles underlying the computation of discharge have been discussed in the subsection on theory of the integrated-velocity index. However, in the system described here, no separate computations of area and mean velocity are made. The two computations are easily combined because the cross-sectional area is a simple function of stage, the area bounded by the signal probes being a simple rectangle (fig. 220) or a trapezoid. The time constant in the process of averaging values is normally 15 minutes, which is also the time interval used in logging the data.

Information relating to discharge, stage, and water and streambed conductivities may be recorded locally on computer-compatible punched paper tape or on magnetic tape. Alternatively, the data may be transmitted to a control center over telephone lines or by a radio link. The transmission can be incorporated in a wider telemetry system for flood or pollution warning.

An initial field calibration, using discharge measurements, is required for the system. However, because the relation of electromagnetic output to discharge is linear, few discharge measurements are required to define the relation.

APPRAISAL OF METHOD

Studies to date (1980) indicate that the technique of electromagnetic stream gaging is feasible although there are still problems to be resolved. The method would probably have its principal use in gaging those streams that are not amenable to the more conventional methods of stream gaging—sand-channel streams with movable beds (see section in chapter 10 titled "Sand-Channel Streams,") and streams with profuse growths of aquatic weeds.

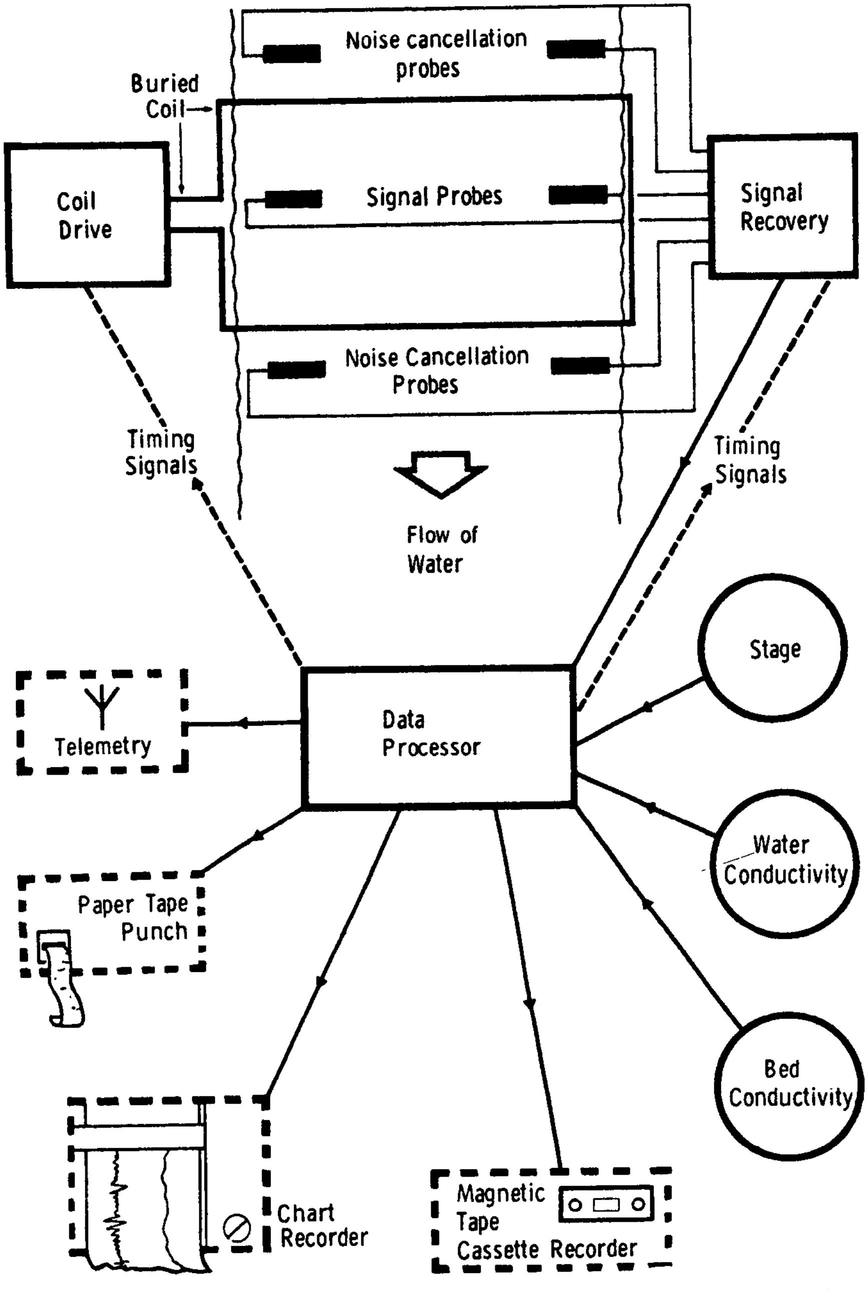


FIGURE 221.—Block diagram showing the function of the data processor. (After Plessey Radar, 1974. Reprinted by permission of the Plessey Company, Ltd.)

SELECTED REFERENCES

Flammer, G. H., 1962, Ultrasonic measurement of suspended sediment: U.S. Geol. Survey Bull. 1141–A, 48 p.

Green, M. H., and Ellis, J. C., 1974 Knapp Mill ultrasonic gauging station on the River Avon, Christchurch, Dorset, art. 2 *in* Analysis of Gauging Results: Water Research Centre symposium on river gauging by ultrasonic and electromagnetic methods, Sess. 2, Reading, England, Dec. 1974, p. 28–65.

Herschy, R. W., and Newman, J. D., 1974. Electromagnetic river gauging: Water Research Centre symposium on river gauging by ultrasonic and electromagnetic methods, Sess. 2, Reading, England, Dec. 1974, 23 p.

Newman, J. D., 1974, Princes Marsh electromagnetic gauging station on the River Rother, Liss, Hants, art. 1 *in* Analysis of Gauging Results: Water Research Centre symposium on river gauging by ultrasonic and electromagnetic methods, Sess. 2, Reading, England, Dec. 1974, p. 1–27.

Plessey Radar, 1974, The electromagnetic flow gauge, advance information: Addlestone, Weybridge, Surrey, England, 5 p.

Smith, Winchell, 1969, Feasibility study of the use of the acoustic velocity meter for measurement of net outflow from the Sacramento-San Joaquin Delta in California: U.S. Geol. Water-Supply Paper 1877, 54 p

——— 1971, Techniques and equipment required for precise stream gaging in tide-affected fresh-water reaches of the Sacramento River, California: U.S. Geol. Water-Supply Paper 1869–G, 46 p.

——— 1974. Experience in the United States of America with acoustic flowmeters: Water Research Centre symposium on river gauging by ultrasonic and electromagnetic methods, Sess. 3, Reading, England, Dec. 1974, 13 p.

Smith, Winchell, Hubbard, L L., and Laenen, Antonious, 1971, The acoustic streamflow-measuring system on the Columbia River at The Dalles, Oreg.: U.S. Geol. Survey open-file report, 59 p.

U.S. Bureau of Reclamation, 1971, Water measurement manual (2d ed): Water Resources Tech. Pub., p. 208–209.