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Measurement and Computation of Streamflow: Volume 1. Measurement of Stage and Discharge

By S. E. RANTZ *and others*

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PREFACE

The science and, in part, art of stream gaging has evolved through the years, largely from the collective experiences and innovations of its practitioners. The earliest truly comprehensive manual on stream-gaging procedures and equipment, based on techniques developed up to that time, was published in 1943 by the Geological Survey as Water-Supply Paper 888, "Stream-Gaging Procedures," by D. M. Corbett and others. That report was an instant classic; it was received enthusiastically by the hydraulic-engineering profession throughout the world and became a major training document for at least two generations of stream gagers, hydrologists, and hydraulic engineers, both in the United States and abroad.

The need for updating Water-Supply Paper 888 has been obvious for some time as a result of later developments in stream-gaging techniques and equipment. Furthermore, it has been felt for some time that the scope of that report should be expanded to cover not only the newer field techniques but also the office procedures required to produce a published annual record of stream discharge. In recognition of those needs, the Geological Survey has sporadically produced supplementary reports that update the description of specific techniques and equipment or that describe specific field or office procedures not covered by Water-Supply Paper 888. These reports—some administrative, some open-file, and others in the published series titled "Techniques of Water-Resources Investigations"—are fragmentary in the sense that they deal only with selected aspects of the broad subject of stream gaging. Similar, but less detailed, reports on selected topics have also been produced by international agencies in the form of Technical Notes by the World Meteorological Organization and in the form of Recommendations and Standards by the International Standards Organization.

The present report evolved from that background. Its two volumes provide a comprehensive compilation of time-tested techniques presented as an up-to-date (1980) standardized manual of stream-gaging procedures.

Acknowledgments.—The material presented in the manual is based on the work of many hydraulic engineers and technicians, each of whom has contributed to the current state-of-the-art in the measurement and computation of streamflow. Many of those who contributed directly to the manual are listed in the references appended to each chapter. However, the authors wish to acknowledge a special group of colleagues who have made major contributions to this manual in the form of written (cited) methods and techniques, significant suggestions for correction and revision of the manuscript and illustrations, and all-out efforts to bring about development and publication of the material. These colleagues include:

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[Factors for converting inch-pound to metric units are shown to four significant figures However, in the text the metric equivalents, where shown, are carried only to the number of significant figures consistent with the values for the English units.]

Inch-pound	*Multiply by—*	*Metric*
acres	4.047×10^3	m^2 (square meters)
acre-ft (acre-feet)	1.233×10^3	m^3 (cubic meters)
acre-ft/yr (acre feet per year)	1.233×10^3	m^3/yr (cubic meters per year)
ft (feet)	3.048×10^{-1}	m (meters)
ft/hr (feet per hour)	3.048×10^{-1}	m/hr (meters per hour)
ft/s (feet per second)	3.048×10^{-1}	m/s (meters per second)
ft^3/s (cubic feet per second)	2.832×10^{-2}	m^3/s (cubic meters per second)
in (inches)	2.540×10	mm (millimeters)
lb (pounds)	4.536×10^{-1}	kg (kilograms)
mi (miles)	1.609	km (kilometers)
mi^2 (square miles)	2.590	km^2 (square kilometers)
oz (ounces)	2.835×10^{-2}	kg (kilograms)

MEASUREMENT AND COMPUTATION OF STREAMFLOW

VOLUME 1. MEASUREMENT OF STAGE AND DISCHARGE

By S. E. RANTZ and others

CHAPTER 1.—INTRODUCTION

PURPOSE OF THE MANUAL

The purpose of this manual is to provide a comprehensive description of state–of–the–art standardized stream-gaging procedures, within the scope described below. The manual is intended for use as a training guide and reference text, primarily for hydraulic engineers and technicians in the U.S. Geological Survey, but the manual is also appropriate for use by other stream-gaging practitioners, both in the United States and elsewhere.

SCOPE OF THE MANUAL

The technical work involved in obtaining systematic records of streamflow is discussed, in two volumes, in accordance with the following six major topics:

Volume 1. Measurement of stage and discharge
- a. Selection of gaging-station sites
- b. Measurement of stage
- c. Measurement of discharge

Volume 2. Computation of discharge
- d. Computation of the stage-discharge relation
- e. Computation of daily-discharge records
- f. Presentation and publication of stream-gaging data

In order to make the text as broadly usable as possible, discussions of instrumentation and measurement are aimed at the technician, and discussions of computational procedure are aimed at the junior engineer who has a background in basic hydraulics.

Many of the procedures for determining discharge that are discussed in volume 2 require specialized instrumentation to obtain field data that supplement the observation of stage. The descriptions of such specialized equipment and associated observational techniques are given in appropriate chapters in volume 2 so that the reader may have unified discussions of the methodologies applicable to each type of problem in determining discharge.

In general the authors have attempted to prepare a manual that will stand independently—references are given to supplementary published material, but the reader should find relatively few occasions when there is pressing need to consult those references. There are three notable exceptions to that statement.

1. The subject of indirect determination of peak discharge (v. 1, chap. 9) is treated here only in brief because of space limitations; the subject is treated fully in five reports in the Geological Survey report series, "Techniques of Water-Resources Investigations." The five reports are named in the reference section of chapter 9.
2. Among the methods discussed in this manual for computing the discharge of tidal streams are four mathematical techniques for evaluating the differential equations of unsteady flow (v. 2, chap. 13). The four techniques are given only cursory treatment because a detailed description of the complex mathematical techniques is considered to be beyond the scope of the manual.
3. The processing of streamflow records by digital computer (v. 2, chap. 15) is a subject that is given only generalized treatment here. It was not practicable to include a detailed description of each step in the sequence of operation of an automated computing system because of space limitations, and also because the particulars of each step are somewhat in a state of flux in response to continual improvement in storage and access procedures.

STREAMFLOW RECORDS

Streamflow serves man in many ways. It supplies water for domestic, commercial, and industrial use; irrigation water for crops; dilution and transport for removal of wastes; energy for hydroelectric power generation; transport channels for commerce; and a medium for recreation. Records of streamflow are the basic data used in developing reliable surface-water supplies because the records provide information on the availability of streamflow and its variability in time and space. The records are therefore used in the planning and design of surface-water related projects, and they are also used in the management or operation of such projects after the projects have been built or activated.

Streamflow, when it occurs in excess, can create a hazard—floods cause extensive damage and hardship. Records of flood events obtained at gaging stations serve as the basis for the design of bridges, culverts, dams, and flood-control reservoirs, and for flood-plain delineation and flood-warning systems.

The streamflow records referred to above are primarily continuous records of discharge at stream-gaging stations, a gaging station being a stream-site installation so instrumented and operated that a continuous record of stage and discharge can be obtained. Networks of stream-gaging stations are designed to meet the various demands for streamflow information, including inventory of the total water resource. The networks of continuous-record stations, however, are often augmented by auxiliary networks of partial-record stations to fill a particular need for streamflow information at relatively low cost. For example, an auxiliary network of sites, instrumented and operated to provide only instantaneous peak-discharge data, is often established to obtain basic information for use in regional flood-frequency studies. An auxiliary network of uninstrumented sites for measuring low flow only is often established to provide basic data for use in regional studies of drought and of fish and wildlife maintenance or enhancement.

GENERAL STREAM-GAGING PROCEDURES

After the general location of a gaging station has been determined from a consideration of the need for streamflow data, its precise location is so selected as to take advantage of the best locally available conditions for stage and discharge measurement and for developing a stable stage-discharge relation.

A continuous record of stage is obtained by installing instruments that sense and record the water-surface elevation in the stream. Discharge measurements are initially made at various stages to define the relation between stage and discharge. Discharge measurements are then made at periodic intervals, usually monthly, to verify the stage-discharge relation or to define any change in the relation caused by changes in channel geometry and (or) channel roughness. At many sites the discharge is not a unique function of stage; variables other than stage must also be continuously measured to obtain a discharge record. For example, stream slope is measured by the installation of a downstream auxiliary stage gage at stations where variable backwater occurs. At other sites a continuous measure of stream velocity at a point in the cross section is obtained and used as an additional variable in the discharge rating. The rate of change of stage can be an important variable where flow is unsteady and channel slopes are flat.

Artificial controls such as low weirs or flumes are constructed at some stations to stabilize the stage-discharge relations in the low-flow range. These control structures are calibrated by stage and discharge measurements in the field.

The data obtained at the gaging station are reviewed and analyzed by engineering personnel at the end of the water year. Discharge ratings are established, and the gage-height record is reduced to mean values for selected time periods. The mean discharge for each day and extremes of discharge for the year are computed. The data are then prepared for publication.

SELECTED REFERENCE

Carter, R. W., and Davidian, Jacob, 1968, General procedure for gaging streams: U.S. Geol. Survey Techniques Water-Resources Inv., book 3, chap. A6, p. 1–2.

CHAPTER 2.—SELECTION OF GAGING-STATION SITES

INTRODUCTION

The general location of a gaging station is dependent on the specific purpose of the streamflow record. If the streamflow record is needed for the design or operation of a water project, such as a dam and reservoir, the general location of the gaging station obviously will be in the vicinity of the water project. The selection of a gaging-station site becomes complicated, however, when the station is to be one of a network of stations whose records are required for study of the general hydrology of a region. Such studies are used to inventory the regional water resource and formulate long-range water-development plans. In that situation, attention to hydrologic principles is required in selecting the general locations of the individual stations in the network to ensure that optimum information is obtained for the money spent in data collection.

A discussion of the design of gaging-station networks is beyond the scope of this manual and for the purpose of this chapter we will assume that the general location of a proposed gaging station has been determined. The discussion that follows will be concerned with the hydraulic considerations that enter into the selection of the precise location of the gage to obtain the best locally available conditions for the measurement of stage and discharge and for the development of a stable discharge rating.

CONSIDERATIONS IN SPECIFIC SITE SELECTION

After the general location of a gaging station has been determined, a specific site for its installation must be selected. For example, if the outflow from a reservoir is to be gaged to provide the streamflow data needed for managing reservoir releases, the general location of the gaging station will be along the stretch of stream channel between the dam and the first stream confluence of significant size downstream from the dam. From the standpoint of convenience alone, the station should be established close to the dam, but it should be far enough downstream from the outlet gates and spillway outlet to allow the flow to become uniformly established across the entire width of the stream. On the other hand the gage should not be located so far downstream that the stage of the gaged stream may be affected by the stage of the confluent stream. Between those upstream and downstream limits for locating the gage, the hydraulic features should be investigated to obtain a site that presents the best possible conditions for stage and discharge measurement and for developing a stable stage-discharge relation. If the proposed gaging station is to be established for purely hydrologic purposes, unconnected with the design or operation of a project, the general location for the gage will be the stretch of channel between two large tributary or confluent streams. The same consideration will apply in the sense that the gage should be far enough downstream from the upper tributary so that flow is fairly uniformly established across the entire width of stream, and far enough upstream from the lower stream confluence to avoid variable backwater effect. Those limits often provide a reach of channel of several miles whose hydraulic features must be considered in selecting a specific site for the gage installation.

The ideal gage site satisfies the following criteria:

1. The general course of the stream is straight for about 300 ft (approx. 100 m) upstream and downstream from the gage site.
2. The total flow is confined to one channel at all stages, and no flow bypasses the site as subsurface flow.
3. The streambed is not subject to scour and fill and is free of aquatic growth.
4. Banks are permanent, high enough to contain floods, and are free of brush.
5. Unchanging natural controls are present in the form of a bedrock outcrop or other stable riffle for low flow and a channel constriction for high flow—or a falls or cascade that is unsubmerged at all stages (chap. 3).
6. A pool is present upstream from the control at extremely low stages to ensure a recording of stage at extremely low flow, and to avoid high velocities at the streamward end of gaging-station intakes during periods of high flow.
7. The gage site is far enough upstream from the confluence with another stream or from tidal effect to avoid any variable influence the other stream or the tide may have on the stage at the gage site.
8. A satisfactory reach for measuring discharge at all stages is available within reasonable proximity of the gage site. (It is not nec-

essary that low and high flows be measured at the same stream cross section.)

9. The site is readily accessible for ease in installation and operation of the gaging station.

Rarely will an ideal site be found for a gaging station and judgment must be exercised in choosing between adequate sites, each of which has some shortcomings. Often, too, adverse conditions exist at all possible sites for installing a needed gaging station, and a poor site must be accepted. For example, all streams in a given region may have unstable beds and banks, which result in continually changing stage-discharge relations.

The reconnaissance for a gaging site properly starts in the office where the general area for the gage site is examined on topographic, geologic, and other maps. Reaches having the following pertinent characteristics should be noted: straight alinement, exposed consolidated rock as opposed to alluvium, banks subject to overflow, steep banks for confined flow, divided channels, possible variable backwater effect from a tributary or confluent stream or from a reservoir, and potential sites for discharge measurement by current meter. The more favorable sites will be given critical field examination; they should be marked on the map, access roads should be noted, and an overall route for field reconnaissance should be selected.

In the field reconnaissance the features discussed earlier are investigated. With regard to low flow, a stable well-defined low-water control section is sought. In the absence of such a control, the feasibility of building an artificial low-water control is investigated. If a site on a stream with a movable bed must be accepted—for example, a sand-channel stream—it is best to locate the gage in as uniform a reach as possible, away from obstructions in the channel, such as bridges, which tend to intensify scour and fill. (See page 377.) Possible backwater resulting from aquatic growth in the channel should also be investigated. If the gage is to be located at a canyon mouth where the stream leaves the mountains or foothills to flow onto an alluvial plain or fan, reconnaissance current-meter measurements of discharge should be made during a low-flow period to determine where the seepage of water into the alluvium becomes significant. The station should be located upstream from the area of water seepage in order to gage as much of the surface flow as possible; the subsurface flow or underflow that results from channel seepage is not "lost" water, but is part of the total water resource.

With regard to high stages, high-water marks from major floods of the past are sought and local residents are questioned concerning historic flood heights. Such information is used by the engineer in making a judgment decision on the elevation at which the stage-recorder must be placed to be above any floods that are likely to occur in the future. The recorder shelter should be so located as to be sheltered from waterborne debris during major floods. Evidence is also sought concerning major channel changes, including scour and deposition at streambanks, that occurred during notable floods of the past. That evidence, if found, gives some indication of changes that might be expected from major floods of the future.

The availability of adequate cross sections for current-meter measurement of discharge should also be investigated. Ideally, the measurement cross section should be of fairly uniform depth, and flow lines should be parallel and fairly uniform in velocity throughout the cross section. The measurement section should be in reasonable proximity to the gage to avoid the need for adjusting measured discharge for change in storage, if the stage should change rapidly during a discharge measurement. However a distance of as much as 0.5 mi (approx. 1 km) between gage and measuring section is acceptable if such a distance is necessary to provide both a good stage-measurement site and a good discharge-measurement site. Low-flow discharge measurements of all but the very large streams are made by wading. For flows that cannot be safely waded, the current meter is operated from a bridge, cableway, or boat. It is most economical to use an existing bridge for that purpose, but in the absence of a bridge, or if the measuring section at a bridge site is poor, a suitable site should be selected for constructing a cableway. If construction of a cableway is not feasible because of excessive width of the river, high-water measurements will be made by boat when safe to do so. The cross section used for measuring high flows is rarely suitable for measuring low flows, and wading measurements are therefore made wherever measuring conditions are most favorable.

Consideration should be given to the possibility of variable backwater effect from a stream confluence or reservoir downstream from the general location of the required gaging station. Without knowledge of stage and discharge at a potential gage site and of concurrent stage at the stream confluence or reservoir, the engineer can only conjecture concerning the location on the stream where backwater effect disappears for various combinations of discharge and stage. A safe rule is the following: Given a choice of several acceptable gaging sites on a stream, the gaging site selected should be the one farthest upstream from the possible source of variable backwater. If it is necessary to accept a site where variable backwater occurs, a uniform reach for measurement of slope should be sought, along with a site for the installation of an auxiliary gage. If a gaging station must be placed in a tide-affected reach, the unsteady flow that must be gaged will also require an auxiliary gage, but in addition line power must be available to insure the synchronized recording of stage at the two gages. The availability of line power or telephone lines is also a consideration, where needed for special instrumentation or for the telemetering units that are often used in flood-forecasting and flood-warning systems.

In cold regions the formation of ice always presents a problem in obtaining reliable winter records of streamflow. However in regions that are only moderately cold, and therefore subject to only moderate ice buildup, forethought in the selection of gage sites may result in streamflow records that are free of ice effect. Gage sites that are desirable from that standpoint are as follows:

1. Below an industrial plant, such as a paper mill, steel mill, thermal powerplant, or coal mine. "Waste" heat may warm the water sufficiently or impurities in the water may lower the freezing point to the extent that open-water conditions always prevail.
2. Immediately downstream from a dam with outlet gages. Because the density of water is maximum at a temperature of 4°C, the water at the bottom of a reservoir is commonly at or near that temperature in winter. Most outlet gates are placed near the bottom of the dam, and the water released is therefore approximately 4°C above freezing. It would take some time for that water to lose enough heat to freeze.
3. On a long fairly deep pool just upstream from a riffle. A deep pool will be a tranquil one. Sheet ice will form readily over a still pool, but the weather must be extremely cold to give complete cover on the riffle. At the first cold snap, ice will form over the pool and act as an insulating blanket between water and air. Under ice cover the temperature of the streambed is generally slightly above the freezing point and may, by conduction and convection, raise the water temperature slightly above freezing, even though water enters the pool at 0°C. That rise in temperature will often be sufficient to prevent ice formation on the riffle.

After the many considerations discussed on the preceding pages have been weighed, the precise sites for the recording stage gage and for the cableway for discharge measurements (if needed) are selected. Their locations in the field are clearly marked and referenced. The maximum stage at which the low-water control will be effective should be estimated; the intakes to the stage recorder should be located upstream from the low-water control, a distance equal to at least three times the depth of water on the control at that estimated maximum stage. If the intakes are located any closer than that to the control, they may lie in a region where the streamlines have vertical curvature; intake location in that region is hydraulically undesirable.

The gaging station on the Kaskaskia River at Bondville, Ill., shown in figure 1, satisfies most of the requirements discussed in this chapter. Low-flow measurements are made by wading upstream from the control. The bridge site provides accessibility, convenience to power lines, and a good location for an outside reference gage, which is shown on the downstream parapet wall of the bridge.

Up to this point there has been no discussion of specific site location for crest-stage gages. Those gages provide peak-discharge data only. Where possible they should be installed upstream from road culverts, which act as high-water controls. The specific site for a gage is at a distance of one culvert width upstream from the culvert inlet. In the absence of such control structures, the crest-stage gage should be installed in a straight reach of channel that can be utilized in computing peak discharge by the slope-area method (chap. 9).

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Carter, R. W., and Davidian, Jacob, 1968, General procedure for gaging streams: U.S. Geol. Survey Techniques Water-Resources Inv., book 3, chap. A6, p. 2–3.

World Meteorological Organization, 1974, Guide to hydrometeorological practices [3d ed.]: WMO-no. 168, p. 3.1–3.4, 3.13–3.16.

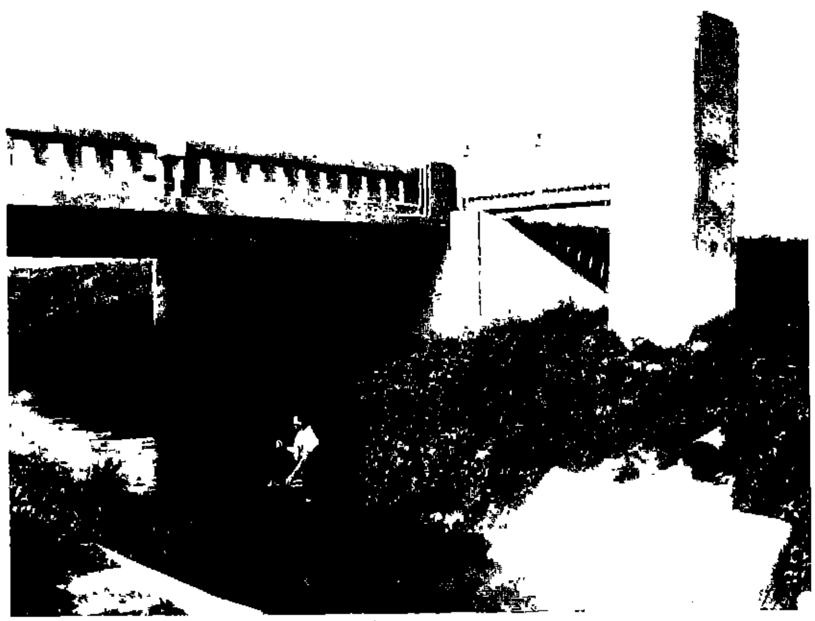

FIGURE 1.—Gage, concrete control, outside gage on bridge, and an engineer making a wading measurement, Kaskaskia River at Bondville, Ill.

CHAPTER 3.—GAGING-STATION CONTROLS

TYPES OF CONTROL

The conversion of a record of stage to a record of discharge is made by the use of a stage-discharge relation. The physical element or combination of elements that controls the relation is known as a control. The major classification of controls differentiates between section controls and channel controls. Another classification differentiates between natural and artificial controls. (Artificial controls are structures built for the specific purpose of controlling the stage-discharge relation; a highway bridge or paved floodway channel that serves incidentally as a control is not classed as an artificial control.) A third classification differentiates between complete, partial, and compound controls.

Section control exists when the geometry of a single cross section a short distance downstream from the gage is such as to constrict the channel, or when a downward break in bed slope occurs at the cross section. The constriction may result from a local rise in the streambed, as at a natural riffle or rock ledge outcrop, or at a constructed weir or dam; or it may result from a local constriction in width, which may occur naturally or be caused by some manmade channel encroachment, such as a bridge whose waterway opening is considerably narrower than the width of the natural channel. Examples of a downward break in bed slope are the head of a cascade or the brink of a falls.

Channel control exists when the geometry and roughness of a long reach of channel downstream from the gaging station are the elements that control the relation between stage and discharge. The length of channel that is effective as a control increases with discharge. Generally speaking, the flatter the stream gradient, the longer the reach of channel control.

A complete control is one that governs the stage-discharge relation throughout the entire range of stage experienced at the gaging station. More commonly, however, no single control is effective for the entire range of stage, and so the result is a compound control for the gaging station. A common example of a compound control is the situation where a section control is the control for low stages and channel control is effective at high stages. The compound control sometimes includes two section controls, as well as channel control. In that situation the upstream section control is effective for the very low stages, a section control farther downstream is effective for intermediate stages, and channel control is effective at the high stages.

With regard to complete controls, a section control may be a complete control if the section control is a weir, dam, cascade, or falls of such height that it does not become submerged at high discharges. A channel control may be a complete control if a section control is absent, as in a sand channel that is free of riffles or bars, or in an artificial channel such as a concrete-lined floodway.

A partial control is a control that acts in concert with another control in governing the stage-discharge relation. That situation exists over a limited range in stage whenever a compound control is present. As an example consider the common situation where a section control is the sole control for low stages and channel control is solely operative at high stages. At intermediate stages there is a transition from one control to the other, during which time submergence is "drowning out" the section control. During that transition period the two controls act in concert, each as a partial control. In effect we have a dam (low-flow control) being submerged by tailwater; before complete submergence (channel control), the upstream stage for the particular discharge is dependent both on the elevation of the dam and on the tailwater elevation. Where the compound control includes two section controls, the degree of submergence of the upstream section control will be governed by the downstream section control, during a limited range in stage. When that occurs, each of the section controls is acting as a partial control. A constriction in channel width, unless unusually severe, usually acts as a partial control, the upstream stage being affected also by the stage downstream from the constriction.

ATTRIBUTES OF A SATISFACTORY CONTROL

The two attributes of a satisfactory control are permanence (stability) and sensitivity. If the control is stable, the stage-discharge relation will be stable. If the control is subject to change, the stage-discharge relation is likewise subject to change, and frequent discharge measurements are required for the continual recalibration of the stage-discharge relation. That not only increases the operating cost of a gaging station, but results in impairment of the accuracy of the streamflow record.

The primary cause of changes in natural controls is the high velocity associated with high discharge. Of the natural section controls, a rock ledge outcrop will be unaffected by high velocities, but boulder, gravel, and sand-bar riffles are likely to shift, boulder riffles being the most resistant to movement and sand bars the least resistant. Of the natural channel controls those with unstable bed and banks, as found in sand-channel streams, are the most likely to change as a result of velocity-induced scour and deposition.

Another cause of changes in natural controls is vegetal growth. The growth of aquatic vegetation on section controls increases the stage for a given discharge, particularly in the low-flow range. Vegetal growth on the bed and banks of channel controls also affects the stage-discharge relation by reducing velocity and the effective waterway area. In the temperate climates, accumulations of water-logged fallen leaves on section controls each autumn clog the interstices of alluvial riffles and raise the effective elevation of all natural section controls. The first ensuing stream rise of any significance usually clears the control of fallen leaves.

Controls, particularly those for low flow, should be sensitive; that is, a small change in discharge should be reflected by a signficant change in stage. To meet that requirement it is necessary that the width of flow at the control be greatly constricted at low stages. In a natural low-water control such constriction occurs if the control is in effect notched, or if the controlling cross section roughly has a flat V-shape or a flat parabolic shape. Those shapes will ensure that the width of flow over the control decreases as discharge decreases. Generally speaking, a low-water control is considered to be sensitive if a change of no more than 2 percent of the total discharge is represented by a change of one unit of recorded stage. For example, in the U.S.A., stage is recorded in units of hundredths of a foot; therefore, for the low-water control to be regarded as sensitive, a change in stage of 0.01 ft (0.003 m) should represent a change of no more than about 2 percent of the total discharge.

In the interest of economy a gaging station should be located upstream from a suitable natural control (fig. 2). However, where natural conditions do not provide the stability or the sensitivity required, artificial controls should be considered. The artificial controls are all section controls; it is not feasible to pave or otherwise improve a long reach of channel solely for the purpose of stabilizing the stage-discharge relation.

ARTIFICIAL CONTROLS

An artificial control is a structure built in a stream channel to stabilize and constrict the channel at a section, and thereby simplify the procedure of obtaining accurate records of discharge. The artificial controls built in natural streams are usually broad-crested weirs that conform to the general shape and height of the streambed. (The term "broad-crested weir," as used in this manual, refers to any type of weir other than a thin-plate weir.) In canals and drains, where the range of discharge is limited, thin-plate weirs and flumes are the controls commonly built. Thin-plate weirs are built in those channels whose flow is sediment free and whose banks are high enough to accommodate the increase in stage (backwater) caused by the installation of a weir (fig. 3). Flumes are largely self cleaning and can critical-flow flume (Parshall flume) it is also desirable that the minimum discharge to be gaged have a head of at least 0.2 ft (0.06 m) to eliminate the effects of surface tension and viscosity.

Stage-discharge relations for the several controls under consideration are next prepared for the anticipated range in discharge. A structure is then selected that best meets the demands of the site in acting as a control for as much of the range as possible, without exceeding the maximum allowable backwater (head loss) at the higher stages and with minor submergence effect and acceptable sensitivity at lower stages. In other words, a high crest elevation minimizes submergence but maximizes backwater effect which may cause or aggravate flooding; a low crest elevation maximizes submergence but minimizes backwater effect; and where flumes are concerned, the attainment of the desired range of discharge may require some sacrifice of sensitivity at extremely low discharges. The engineer must use judgment in selecting a control design that is optimum for the local conditions. For example, to design a flume whose throat is sufficiently wide to accommodate the desired range of discharge, it may be necessary to relax the 2-percent sensitivity criterion at extremely low flows; in that situation the engineer may accept a sensitivity such that a change in stage of 0.01 ft (0.003 m) results in as much as a 5-percent change in discharge.

From a practical viewpoint the use of artificial controls is limited to streams with stable channels. Artificial controls seldom operate satisfactorily in sand channels having highly mobile beds. The transport of sediment as bedload continually changes the characteristics of the approach channel, and the control itself may be buried or partially buried by the movement of sand dunes.

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CHAPTER 4.—MEASUREMENT OF STAGE

GENERAL

The stage of a stream or lake is the height of the water surface above an established datum plane. The water-surface elevation reity observations are made in each vertical at 0.2, 0.4, 0.6, and 0.8 of the depth below the surface, and also close to the surface and to the streambed. The criteria for surface and streambed observations are those given in the discussion above.

The velocity observations at the six meter positions are plotted in graphical form and the mean velocity in the vertical is determined by planimetering the area bounded by the vertical-velocity curve and the ordinate axis, as explained on page 132. The mean velocity may also be computed mathematically from the equation,

$$V_{mean} = 0.1(V_{surface} + 2V_{0.2} + 2V_{0.4} + 2V_{0.6} + 2V_{0.8} + V_{bed}).$$

PROCEDURE FOR CONVENTIONAL CURRENT-METER MEASUREMENT OF DISCHARGE

The first step in making a conventional current-meter measurement of discharge is to select a measurement cross section of desirable qualities. If the stream cannot be waded, and high-water measurements are made from a bridge or cableway, the hydrographer has no choice with regard to selection of a measurement cross section. If the stream can be waded, the hydrographer looks for a cross section of channel with the following qualities:

1. Cross section lies within a straight reach, and streamlines are parallel to each other.
2. Velocities are greater than 0.5 ft/s (0.15 m/s) and depths are greater than 0.5 ft (0.15 m).
3. Streambed is relatively uniform and free of numerous boulders and heavy aquatic growth.
4. Flow is relatively uniform and free of eddies, slack water, and excessive turbulence.
5. Measurement section is relatively close to the gaging-station control to avoid the effect of tributary inflow between the measurement section and control and to avoid the effect of storage between the measurement section and control during periods of rapidly changing stage.

It will often be impossible to meet all of the above criteria, and when that is the case, the hydrographer must exercise judgment in selecting the best of the sites available for making the discharge measurement.

If the stream cannot be waded and the measurement must be made from a boat, the measurement section selected should have the attributes listed above, except for those listed in item 2 concerning depth and velocity. Depth is no consideration in a boat measurement; if the stream is too shallow to float a boat, the stream can usually be waded. However, velocity in the measurement section is an important consideration. If velocities are too slow, meter registration may be affected by an oscillatory movement of the boat, in which the boat, even though fastened to the tag line, moves upstream and downstream as a result of wind action; or, where a vertical-axis meter is used, meter registration may be affected by vertical movement of the boat as a result of wave action (p. 180–181). If velocities are too fast, it becomes difficult to string the tag line across the stream.

Regardless of the type of measurement that is to be made, if the gaging station is downstream from a hydroelectric powerplant, the stage will be changing too rapidly, most of the time, to assure a satisfactory discharge measurement. The hydrographer should obtain a schedule of operations from the powerplant operator, or determine the operating schedule from the gage-height chart, and plan to make his discharge measurements near the crest or trough of the stage hydrograph, or during periods of near-constant discharge from the powerplant.

After the cross section has been selected, the width of the stream is determined. A tag line or measuring tape is strung across the measurement section for measurements made by wading, from a boat, from ice cover, or from an unmarked bridge. Except where a bridge is used, the line is strung at right angles to the direction of flow to avoid horizontal angles in the cross section. For cableway or bridge measurements, use is made of the graduations painted on the cable or bridge rail as described on page 110. Next the spacing of the verticals is determined to provide about 25 to 30 subsections. If previous discharge measurements at the site have shown uniformity of both the cross section and the velocity distribution, fewer verticals may be used. The verticals should be so spaced that no subsection has more than 10 percent of the total discharge. The ideal measurement is one in which no subsection has more than 5 percent of the total discharge, but that is seldom achieved when 25 subsections are used. (The discharge measurement notes in figure 42 show that the subsection with the greatest discharge had 6.2 percent of the total discharge.) It is not recommended that all observation verticals be spaced equally unless the discharge is evenly distributed across the stream. The spacing between verticals should be closer in those parts of the cross section that have the greater depths and velocities.

After the stationing of the observation verticals has been determined, the appropriate equipment for the current-meter measurement is assembled and the measurement note sheets for recording observations are prepared. (See fig. 42.) The following information will be recorded for each discharge measurement:

1. Name of stream and location to correctly identify the established gaging station; or name of stream and exact location of site for a miscellaneous measurement.

2. Date, party, type of meter suspension, and meter number.
3. Time measurement was started using military time (24-hr clock system).
4. Bank of stream that was the starting point.
5. Control conditions.
6. Gage heights and corresponding times.
7. Water temperature.
8. Other pertinent information regarding the accuracy of the discharge measurement and conditions which might affect the stage-discharge relation.

The streambank is identified by the letters LEW or REW (left edge of water or right edge of water, respectively, when facing downstream). The time is recorded periodically in the notes during the course of the measurement. If the gaging station is equipped with a digital recorder it is advantageous to synchronize the time observations with the punch cycle of the recorder. (See fig. 42.) The time observations are important for computing the mean gage height of the discharge measurement, if the measurement is made during a period of appreciable change in stage. (See p. 170–173.) When the discharge measurement is completed, the time is recorded along with the streambank (LEW or REW) where the measurement ended.

We have digressed somewhat in discussing the measurement notes and now return to the details of the discharge measurement. After the note sheet is readied, the meter assembly is checked. The meter should balance on the hanger used and should spin freely; the electric circuit through the meter should operate satisfactorily; and the stopwatch should check satisfactorily in a comparison with the hydrographer's watch. After recording on the note sheet the station (distance from initial point) of the edge of water, the actual measurement is ready to be started.

Depth (if any) at the edge of water is measured and recorded. The depth determines the method of velocity measurement to be used, normally the two-point method (p. 134) or the 0.6-depth method (p. 134). The setting of the meter for the particular method to be used is then computed, and the meter position is recorded, using a designation such as 0.8 or 0.6 or 0.2, as the case may be. After the meter is placed at the proper depth and pointed into the current, the rotation of the rotor is permitted to become adjusted to the speed of the current before the velocity observation is started. The time required for such adjustment is usually only a few seconds if velocities are greater than 1 ft/s (0.3 m/s), but for slower velocities, particularly if the current meter is suspended on a cable, a longer period of adjustment is needed. After the meter has become adjusted to the current, the number of revolutions made by the rotor is counted for a period of 40 to 70 s. The stopwatch is started simultaneously with the first signal or click, which is counted as "zero," and not "one." The count is ended on a convenient number coinciding with one of those given in the column headings of the meter rating table. The stopwatch is stopped on that count and is read to the nearest second or to the nearest even second if the hand of the stopwatch is on a half-second mark. That number of seconds and the number of revolutions are then recorded.

If the velocity is to be observed at more than one point in the vertical, the meter setting for the additional observation is determined, the revolutions are timed, and the data are recorded. The hydrographer moves to each of the observation verticals and repeats the above procedure until the entire cross section has been traversed. For each vertical he records distance from initial point, water depth, meter-position depth, revolutions of the meter, and the time interval associated with those revolutions (fig. 42).

Consideration must be given to the direction of flow, because it is the component of velocity normal to the measurement section that must be determined. The discussion that follows concerns currents that approach the measurement section obliquely, at angle α (fig. 47). If, in a wading measurement, the meter used is a horizontal-axis meter with a component propellor, such as the Ott meter, the propellor should be pointed upstream at right angles to the cross section, but only if α is less than 45°. Such a meter will register the desired component of velocity normal to the cross section, when α is less than 45°. If α is greater than 45°, the component meter should be pointed into the current. All other meters on a wading-rod suspension should likewise be pointed into the current. Any meter on a cable suspension, as is used for the higher stages, will automatically point into the current because of the effect of the meter vanes. When the meter is pointed into an oblique current the measured velocity must be multiplied by the cosine of the angle (α) between the current and a perpendicular to the measurement section in order to obtain the desired normal component of the velocity.

In the U.S.A., either of two methods is used to obtain cosine α (fig. 47). In the first method, use is made of the field notes which have a point of origin (*o*) printed on the left margin and cosine values on the right margin (fig. 42). The cosine of the angle of the current is measured by holding the note sheet in a horizontal position with the point of origin on the tag line, bridge rail, cable rail, or any other feature parallel to the cross section (fig. 90). With the long side of the note sheet parallel to the direction of flow, the tag line or bridge rail will intersect the value of cosine α on the top, bottom, or right edge of the note sheet. The direction of the current will be apparent from the direction of movement of floating particles. If the water is clear of floating material, small bits of floating material are thrown into the stream and the edge of the note sheet is alined parallel to the direction of movement. If no such material is available, the inelegant, but time-honored method of spitting into the stream is used to obtain an indicator of the direction of flow. The measured velocity is multiplied by the cosine of the angle to determine the velocity component normal to the measurement section.

The second, and more reliable, method of obtaining cosine α involves the use of a folding foot-rule. These rules, which are either 3 or 6 ft long, are graduated in hundredths of a foot and are jointed every half foot. The first 2 ft of the rule is extended, the 2.00-ft marker is placed on the tag line or bridge rail (fig. 91), and the rule is alined with the direction of the current. The rule is folded at the 1-ft mark so that the first foot of the rule is normal to the tag line or bridge rail. That reading, subtracted from 1.00, is cosine α. For example, if the reading on the rule is 0.09 ft, cosine α equals 0.91.

Details peculiar to each of the various types of current-meter measurement are described in the sections of the manual that follow.

CURRENT-METER MEASUREMENT BY WADING

Current-meter measurements are best made by wading, if conditions permit. (See fig. 92.) Wading measurements have a distinct advantage over measurements made from cableways or bridges in that it is usually possible to select the best of several available cross sections for the measurement. The type AA or pygmy meter is used for wading measurements in the U.S.A. Table 3 lists the type of meter and velocity method to be used for wading measurements at various depths.

Some departure from table 3 is permissible. For example, if a type

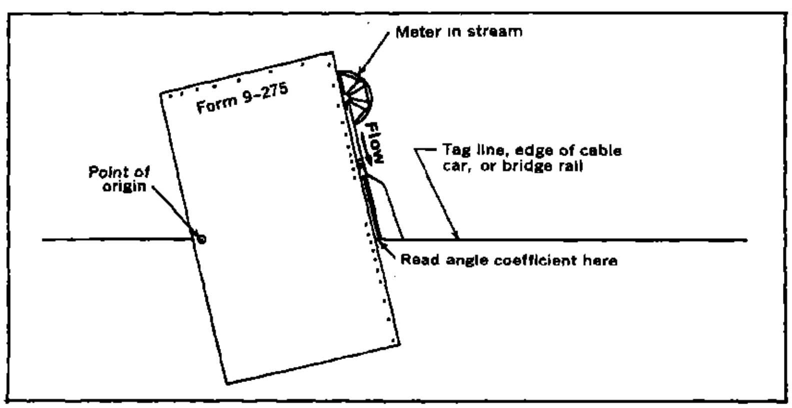

FIGURE 90.—Measurement of horizontal angle with measurement-note sheet.

AA meter is being used in a measurement section that has almost all its depths greater than 1.5 ft (0.46 m), the pygmy meter should not be substituted for the few depths that are less than 1.5 ft, or vice versa. With regard to the use of the type AA meter in depths less than 1.5 ft, strictly speaking, that meter should not be used in depths less than 1.25 ft (0.38 m). A depth of 1.25 ft will accommodate the 0.6-depth method without causing the meter to be set closer than 0.5 ft from the streambed; if the meter is set any closer to the streambed it will underregister the velocity (p. 132). However, if the hydrographer is using the type AA meter in a measurement section that has only few verticals shallower than 1.25 ft, he may use that meter for depths that are even as shallow as 0.5 ft (0.15 m) without changing to a pygmy meter. The hydrographer must make a judgment decision. He knows that his meter is underregistering the velocity by some unknown percentage in the depths shallower than 1.25 ft, but if that shallow-depth flow represents less than 10 percent of the total discharge, his total measured discharge should not be too greatly in error.

Neither the type AA meter nor the pygmy meter should be used for measuring velocities slower than 0.2 ft/s, unless absolutely necessary.

If depths or velocities under natural conditions are too low for a dependable current-meter measurement, the cross section should be modified, if practical, to provide acceptable conditions. It is often pos-

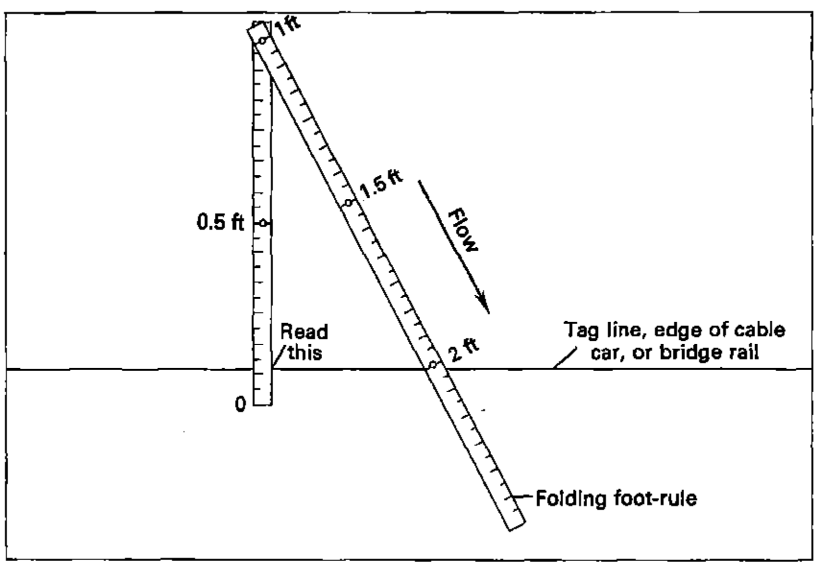

FIGURE 91.—Measurement of horizontal angle with folding foot-rule.

sible to build temporary dikes to eliminate slack water or shallow depths in a cross section, or to improve the cross section by removing rocks and debris within the section and in the reach of channel im-

FIGURE 92.—Wading measurement using top-setting rod.

TABLE 3.—*Current-meter and velocity-measurement method for various depths (wading measurement)*

Depth (ft)	Depth (m)	Meter	Velocity method
2.5 or more	0.76 or more	Type AA (or type A)	0.2 and 0.8
1.5–2.5	0.46–0.76	---- do ----	.6
.3–1.5	.09– .46	Pygmy[1]	.6

[1]Used when velocities are less than 2 5 ft/s (0 76 m/s)

mediately upstream and downstream from the section. After the cross section has been modified, the flow should be allowed to stabilize before starting the discharge measurement.

The hydrographer should stand in a position that least affects the velocity of the water passing the current meter. That position is usually obtained by facing the bank so that the water flows against the side of the leg. The wading rod is held at the tag line by the hydrographer who stands about 3 in (0.07 m) downstream from the tag line and at least 1.5 ft (0.46 m) from the wading rod. He should avoid standing in the water if his feet and legs occupy a significantly large percentage of a narrow cross section. In small streams where the width permits, the hydrographer stands on an elevated plank or other support, rather than in the water.

The wading rod should be held in a vertical position with the meter parallel to the direction of flow while the velocity is being observed. If the flow is not at right angles to the tag line, the angle coefficient should be carefully measured (figs. 90 and 91).

When measuring streams having shifting beds, the soundings or velocities can be affected by the scoured depressions left by the hydrographer's feet. For such streams, the meter should be placed ahead of and upstream from the feet. For such streams, too, the hydrographer's notes should accurately describe the configuration of the streambed and water surface. (See p. 376–379.)

A measurement should be made of the depth of water over the lowest point of the control, either before or after the discharge measurement. The gage height corresponding to this lowest point (gage height of zero flow) is very useful in analyzing the stage-discharge relation for the gaging station. (See p. 333–334).

When the flow is too low for a reliable measurement of discharge by current meter, the discharge is determined by use of (1) a volumetric method of measurement, (2) a portable Parshall flume, or (3) a portable weir plate. Those three methods of discharge determination are discussed in chapter 8.

CURRENT-METER MEASUREMENTS FROM CABLEWAYS

The equipment assemblies for use on cableways are described on pages 110–117.

The size of the sounding weight used in current-meter measurements depends on the depth and velocity in the measurement cross section. A rule of thumb generally used is that the size of the weight (lb) should be greater than the maximum product of velocity (ft/s) and depth (ft) in the cross section. If insufficient weight is used, the meter assembly will be dragged downstream. If debris or ice is flowing or if the stream is shallow and swift, the weight used should