# SURFACE WATER DATA ACQUISITION SYSTEMS

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**Summary**

The measurement of water stage is the most basic means to gauge discharge in a stream. Normally, interest centers on the volume of water that has flowed in a stream during a certain time period, i.e. the discharge. The relationship between the stage measured at a section and the discharge is a function of the cross-sectional area of flow, the average flow velocity in a stream, and the time.

Two approaches that can be used to determine discharge from stage measurements in streams are discussed briefly, namely:

- velocity-area methods
- discharge measurements by means of gauging structures

Velocity-area methods involve both the measurement of the area of a stream cross section and the average flow velocity through the section. The product of the two quantities yields the discharge at a particular stage in the stream, and hence a stage-discharge rating curve is obtained. Various techniques are used to determine the average velocity, but it is generally accepted that the use of a current meter is superior in accuracy compared with other velocity-area methods.

In countries with highly variable flow-regime rivers, the construction of permanent measuring structures might be advisable. In addition, if long distances have to be traveled to conduct current meter gauging, it can be difficult to reach rivers in flood, or flowing at high stages, in time. Permanent structures, such as weirs or flumes, have certain advantages for obtaining hydrological data in these circumstances. These structures are capital intensive to construct, but to rate are operationally less labor intensive than natural river sections.



## 1. Introduction

The fluctuations in stage and discharge of stream flow in rivers result from variations in the duration, frequency, intensity, and spatial cover of precipitation and runoff. The characteristics of the catchment, such as plant growth, soil types, topography, geology, and so on, control the rate and amount of runoff. Accurate and reliable information on stream flow in terms of stage and discharge is essential for the assessment, management, and control of water resources, and this information can only be obtained satisfactorily from a network of river gauging stations.

A flow-gauging station can be defined as follows by Lambie (1978):

A gauging station is a site on a river which has been selected, equipped, and operated to provide the basic data from which systematic records of water level and discharge may be derived. Essentially it consists of a natural or artificial river cross section where a continuous record of stage can be obtained and where a relation between stage and discharge can be determined.

From this definition it is obvious that two actions are required to measure discharge, the gauging of stage and the derivation of discharge from stage records.

## 2. Measurement of Stage in Streams

The basic measurement taken to determine flow in a river is the flow depth or "stage." For this purpose, gauge plates can be put up at suitable sites and observed regularly. The water-level measurements can be important in themselves, for example, to determine the height of a bridge deck above the riverbed; or the flow depths can be converted to discharge by means of a discharge table to calculate volumes.

There are indications that our remote ancestors measured flow depths in rivers and fountains in the era preceding 500 BC. During the summer, the Nile River stage gradually increased and the water levels were marked at several places. Records of stage of the Nile River can be traced back to about 3000 BC to 3500 BC from fragments of an ancient monument now in the Palermo Museum in Sicily. As the name indicates, nilometers were used to measure the levels of the Nile River. Today we know of three types of nilometers that were in use. The first type consisted simply of water-level markings on cliffs on the bank of the river. The second made use of a flight of steps that led down to the river. The third and most accurate nilometer used conduits to bring water from the Nile to a well or cistern. The levels were marked either on the walls of the well or on a central column. The longest continuous record of the Nile River is available from the nilometers near Cairo, and records of maximum and minimum levels of the Nile date from AD 641 to AD 1890, according to Biswas (1970).

More information is required than only the maximum and minimum stage of a river every year, and monthly and daily readings are in demand. The next logical step was to use automatic recorders to obtain a continuous record of stage (water level) against time. A variety of recorders are on the market for this purpose. The simplest is a mechanical recorder consisting of a horizontal drum with a sheet of graph paper wrapped around it, which is driven by a clockwork mechanism to make one revolution per week or per month. A float with counterweight, which follows the rising and falling of the water level in a stilling well, measures the stage or water level in the stream at a gauging site.

If it is necessary to record water levels in remote places that can be visited, say, only once every two to six months, roll-chart recorders are available. This type of recorder is often used even if sites are visited frequently. The advantage is that in certain circumstances it facilitates digitizing and storage of data by making a long record in the form of a roll of graph paper.

The punched-tape recorder has become more popular with the advent of the computer. The record of water stage versus time is punched on paper tape in a binary code that is then much more easily accessible by a computer. The disadvantage of this type of recorder is that the routine inspection of a station is not as meaningful because there is no visual record.

The construction of a stilling well for the float-type recorder can be inconvenient and expensive. The so-called bubble recorder solves this problem. The principle according to which this recorder works can be briefly summarized as follows: gas, such as compressed air or nitrogen, is led to an orifice at a specific point below the water surface. The pressure in the pipe is measured; this is a function of the piezometric head, equal to the water depth, above the orifice. A manometer filled with mercury is the obvious apparatus for measuring this pressure.

Electronic data-capturing equipment in the form of data loggers with solid-state memory, encoders, decoders, and so on are available. Real-time data by means of remote sensing via satellite or meteor-burst technology bring together two developments. Electronic equipment does provide many advantages, especially in terms of quality control and improved management (see *Hydrological Data Acquisition Systems; Flow Measurement in Free Surface Flow*).

## 3. Relation Between Stage and Discharge in Streams

In most cases, interest centers on the volume of water that has flowed in a river during a certain time period, referred to as the discharge. The relationship between stage and discharge at a section in a stream is a function of the cross-sectional area, average velocity, and time.

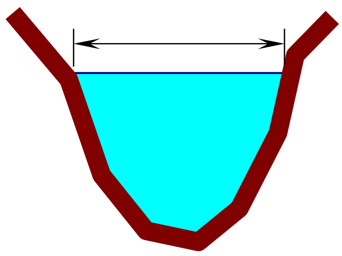
A method whereby flow is directed to a calibrated receptacle is known as the volumetric method of discharge measurement and is usually applied in laboratory tests. However, it is not a practical method to use for routine field measurements. For this purpose, water levels at a gauging station are used as the basis for computation of records of discharges and are referred to as the rating of the site. This is usually presented in the form of a rating table or a graph known as a rating curve.

Any section or point in a stream, at which the discharge is known for a given stage or depth of flow, is defined as a control section. At such a control, the discharge would be a unique function of stage, so that during the rising and falling flood cycles, a given stage would always represent the same discharge. Controls can be classified as section control or channel control and are described in the following sections.

### 3.1. Section Control

Section control occurs in a stream channel where conditions force the flow to change from subcritical flow to supercritical flow. Subcritical flow occurs where the Froude Number is less than unity (Fr<1), and supercritical flow where it is greater than unity (Fr>1). The critical flow condition exists in a section where it equals unity (Fr = 1). Critical flow represents the maximum possible discharge past a section for a certain amount of available energy. The Froude Number is defined as expressed by Eq. (1) below:

$$Fr = \sqrt{\frac{Q^2 B}{g A^3}} \qquad (1)$$



where

Q = discharge in stream in $m^3$ $s^{-1}$
B = top width of stream in meters
g = gravitational acceleration (9.81 m $s^{-2}$)
A = cross-sectional flow area in $m^2$

Section control can result from a local rise in the streambed, in a structure such as a weir or dam, in a constriction in stream width, or at a change from a mild to a steep channel slope as found at the brink of a waterfall or rapids, as shown in Figure 1.

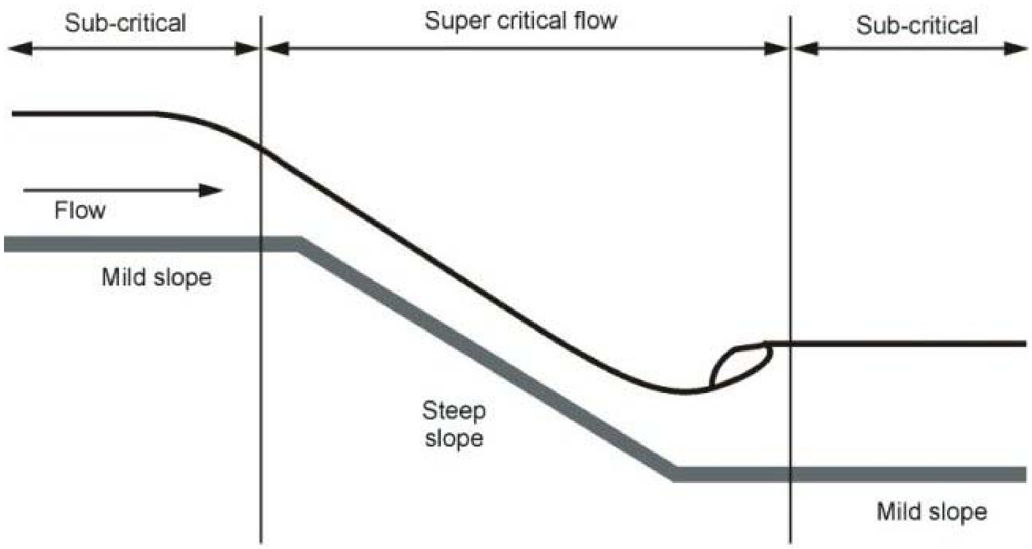



Figure 1. Different flow conditions in a stream with variable slopes

### 3.2. Channel Control

Another form of control section is known as a channel control. This control condition occurs only in long, straight channel reaches with uniform cross section and slope. Geometry, slope, and roughness dictate the relationship between stage and discharge. Uniform flow conditions exist, and flow depths or discharges can be determined by using the Chezy or Manning equations, as expressed in Eqs. (2) and (3):
*Chézy:*

$$\bar{v} = 18 \log \frac{12R}{k} \sqrt{RS} \qquad (2)$$

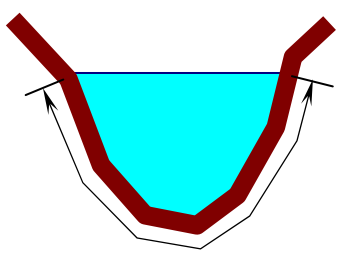
*Manning:*

$$\bar{v} = \frac{R^{2/3} S^{1/2}}{n} \qquad (3)$$

in which

R = hydraulic radius (m) with $R = A/P$

where
A = cross-sectional flow area in $m^2$



P = wetted perimeter in meters
$\bar{v}$ = average flow velocity in m $s^{-1}$
S = hydraulic gradient
k = absolute roughness coefficient in meters
n = Manning roughness coefficient (s $m^{-1/3}$)

If no natural controls are available, artificial controls could be erected to stabilize and sensitize the relation between stage and discharge. Where a small increase in discharge produces a relatively large increase in stage, the measuring point is said to be sensitive.

Two approaches could be followed to rate a gauging site, namely, the construction of permanent structures such as flumes and weirs for discharge measurement purposes; or the measurement of the flow velocity by the use, for instance, of current meters and calculation of the discharge by means of velocity-area integration methods.

In countries with highly variable flow regimes in rivers, construction of permanent measuring structures might be advisable. Where long distances have to be traveled, it can be difficult to reach rivers in flood, or flowing at high stages, for conducting velocity measurements or current meter gauging. Permanent structures have certain advantages under such circumstances: no routine calibrations are needed, they form permanently stable controls, and they sensitize the site. Permanent structures are capital intensive to construct, but are operationally less labor intensive to rate than natural river sections. Natural river sections, on the other hand, seldom offer a permanent control, especially for low-flow conditions. Regular velocity-area measurements must be carried out to confirm the rating. This is, therefore, a labor-intensive approach.

A combination of the two approaches could provide an optimum solution. Depending on the site conditions and the objectives of discharge measurement, a permanent structure could be used for low to medium flows, and the velocity-area integration method used to calibrate the site for high flows. In this manner, some of the disadvantages of each method could be eliminated effectively and economically (see *Measuring Techniques*).

## 4. Velocity-Area Method for Determining Discharge

The velocity-area method involves the measurement of the area of a stream cross section and the mean velocity of flow through it. The product of the two quantities gives the discharge and is expressed as a volume per unit of time. Various methods are used to determine the mean velocity, but it is generally accepted that the current meter is superior in accuracy over other methods. It is important that certain requirements are met to establish a stable stage-discharge relationship when using the velocity-area method. The most important requirements according to Lambie (1970) are as follows:

- The channel should be straight and of uniform cross section and slope to ensure parallel and nonturbulent flow and to reduce the chances of abnormal velocity distributions. Ideally, the straight length should be at least three times the channel width, with the measuring section midway; but where this is not possible, the measuring section should be within the downstream half of the reach. It should, however, be remote from any natural or artificial obstructions on the banks or in the channel that are likely to cause disturbance, distortion, or reversal of flow.

- The depth and velocity of water at minimum flow and the velocity and turbulence at maximum flow should be within the limits imposed by the type of measuring equipment to be used.
- The physical characteristics of the channel should ensure a substantially consistent and stable relation between stage and discharge. The channel itself should be stable, and there should be no variable *backwater* effects such as from tidal influences, downstream tributaries, locks, sluices, off-takes, and other structures.
- The channel, and especially the control, should in all seasons be free from weeds.
- Flows should be confined at all stages to a well-defined channel, or channels, or be contained within an unobstructed floodway having stable boundaries.
- The site should be accessible at all times and at all stages of flow.
- The orientation of the reach should be normal to the prevailing wind, particularly where the reach is long and straight and has a mild surface slope.
- The site should be sensitive, so that a small increase in discharge will produce a relatively large increase in stage.
- The field of view of the measuring section and the upstream reach should be clear and unobstructed.
- A local observer should be available to provide routine attendance.
- There are several different methods whereby the velocity-area approach could be put into practice. Only two methods will be described here, surface velocity measurement and current meter gauging.

### 4.1. Surface Velocity Measurement

Surface velocity measurement is probably the simplest method for determining discharge. Only two quantities need to be measured, namely, the cross-sectional area and the surface velocity of the stream. The velocity of water flowing in an open channel varies in both a vertical and a horizontal direction across the section as shown in Figure 2. To establish the average velocity across a section and hence calculate the discharge, it is necessary to measure the surface velocity at various distances from the bank to determine the mean surface velocity across the horizontal plane.

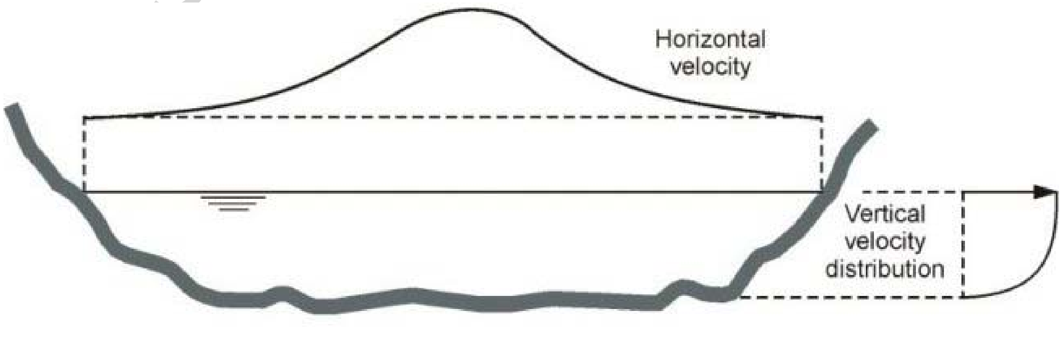



Figure 2. The horizontal and vertical velocity distribution across a natural stream

To determine the surface velocity, the following procedure must be carried out:

- Select a section of the river or stream that is fairly straight.
- Peg out a fixed distance along the riverbank. For a small stream 10 m would suffice, but for a major river, the distance should not be less than 50 m.
- Measure the time with a stopwatch for an object (tree trunk, orange, float, and so on) to travel the distance between the two pegs, and calculate the surface velocity.
- In a natural channel, the average velocity in the stream varies between 0.85 times and 0.86 times the calculated surface velocity. In an artificial channel, the average velocity is taken as 0.9 times the surface velocity.

The velocity of water flowing in an open channel varies in both vertical and horizontal directions across the section, as shown in Figure 2. To establish the average velocity across a section, and hence calculate the discharge, it is necessary to measure the surface velocity at various distances from the bank to determine the mean surface velocity across the horizontal plane. The arithmetic mean would give a first approximation. A better approximation would be to attach more weight to the surface velocity at midstream, because the major portion of the volume passes through this section. The cross section could also be divided into panels and the velocity measured in each panel, in m $s^{-1}$. The velocity multiplied by the panel area in $m^2$ gives the discharge in $m^3$ $s^{-1}$ through each panel. The total discharge in the stream is the sum of all the individual discharges calculated for the various panels (see *Flow Measurement in Free Surface Flow*).

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**Bibliography**

Ackers P., White W.R., Perkins J.A. and Harrison A.J.M. (1978). *Weirs and Flumes for Flow Measurement*, 327 pp. Chichester: John Wiley & Sons. [Comprehensive guide and handbook on all aspects of free-surface flow measurement by means of gauging structures of many kinds, under ideal as well as adverse flow conditions; contains information on the development of the Crump weir and dimension data on Parshall Flumes.]

Beach M.H. (1984). *Fish Pass Design—Criteria for the Design and Approval of Fish Passes and Other Structures to Facilitate the Passage of Migratory Fish in Rivers.* Fisheries Research Technical Report 78. Lowestoft, UK: Ministry of Agriculture, Fisheries and Food. [Useful reference on all aspects of fish-passage design and associated environmental considerations.]

Biswas A.K. (1970). *History of Hydrology*, 336 pp. Amsterdam: North-Holland Publishing Company. [Useful reference on the origins of hydrometry and on the background and development of hydrology.]

BSI (1986). *Measurement of Liquid Flow in Open Channels—Triangular Profile Weirs.* BS3680: Part 4B. London: British Standards Institute. [Precise flow measurement standards to be observed to ensure accuracy and reliability of data.]

ISO (1980). *Water Flow Measurement in Open Channels Using Weirs and Venturi Flume—Thin-plate Weirs.* ISO 1438/1: Part 1. Geneva: International Standards Organization. [Accurate guidelines on flow gauging structures and their principles and operation, and information on the Carter-Kindsvater and IMFT formulae.]

Lambie J.C. (1978). Measurement of Flow—Velocity-Area Methods. *Hydrometry Principles and Practices* (ed. R.W. Herschy), 511 pp. Chichester: Wiley Interscience, John Wiley & Sons. [Systematic review of the state of the art of discharge measurement by direct methods.]

Parshall R.L. (1925). The Improved Venturi Flume. Proceedings of ASCE **51** No. 7, Sept., 1340–1349). New York: American Society of Civil Engineers. [The original paper describing the development of the critical-flow discharge measuring flume structure, later to become known as the Parshall Flume].

Parshall R.L. (1936). *The Parshall Measuring Flume*, Bulletin 423. Fort Collins, CO: Colorado Experimental Station. [The development of the critical flow measuring flume structure that has become well-known as the Parshall flume.]

Parshall R.L. (1961). *Parshall Flumes of Large Size*, Bulletin 426 A. Department of Agriculture. Fort Collins: Colorado State University. [The further development of large size Parshall flume structures for flow measurement.]

USBR (1985). *Design of Small Dams*, Third Edition, 860 pp. Washington, DC, US: US Department of the Interior, Bureau of Reclamation (Denver, CO). [A comprehensive textbook and design manual on all aspects of the design of dams of moderate height.]

WMO (1980). *Operational Hydrology Report 13, Manual on Stream Gauging*, **Vol. 1**, Fieldwork, WMO 519. Geneva: World Meteorological Organization. [Authoritative reference on stream-flow gauging, describing precisely the various methods used and the standards to be observed.]

WMO (1994). *Guide to Hydrological Practices—Data Acquisition and Processing, Analysis, Forecasting and Other Applications*, WMO 168. Geneva: World Meteorological Organization. [Standard reference on the collection of hydrological data and its processing, storage, and dissemination.]



**Biographical Sketches**

**Stéfan van Biljon** obtained his B.Sc. (physics and chemistry) in 1966 and B.Sc. (Hons.) (physics) in 1968 at the University of Stellenbosch, South Africa. He joined the Directorate of Hydrology of the Department of Water Affairs and Forestry in 1968 as a hydrologist and furthered his knowledge by attending various international short courses on hydrology. His initial experience concentrated on flood studies and water resource studies in South Africa. He undertook developmental work on stochastic hydrology from the mid-1970s to the mid-1980s, after which he applied himself to optimization techniques on reservoir systems. Mr. van Biljon developed a deterministic rainfall-runoff model in 1990, which was applied to forecasting and management of the Vaal River System in South Africa. He was appointed as director of Hydrology (Surface Water) in 1989 and assumed responsibility for monitoring the water resources of South Africa, undertaking water resource and reservoir systems analysis for selected basins and flood-related studies. Special initiatives to optimize the hydrological gauging network for surface water hydrology and measures to assure the quality of data were due to his work. He was responsible for modernizing the instrumentation for stream-flow gauging in South Africa and by 1999 upgraded almost 70% of the network to electronic data-logging. He played a leading role in the establishment of a network of 60 data-collection platforms, transmitting data via METEOSAT satellite as part of the WMO-proposed World Hydrological Cycle Observing System (WHYCOS). The Directorate of Hydrology, in which he is Director: Surface Water, hosts the Pilot Regional Center for the HYCOS Project of the Regional Southern African Development Community (SADC), funded by the European Commission. This has the objective, under the direction of Mr. Van Biljon, of installing 50 METEOSAT Data-Collection Points in 10 SADC member countries. The Directorate, under his leadership, has the responsibility for capacity building in hydrology within the SADC region.

**Pieter Wessels** completed his B.Eng. (Civil) studies at the University of Pretoria during 1978 and joined the Department of Water Affairs and Forestry (DWAF) of South Africa as an engineer in the same year. During 1984 he began his M.Eng. (water engineering) studies at the University of Pretoria, South Africa, on a part-time basis and obtained his Master’s degree at the end of 1986. He joined the Directorate of Hydrology in DWAF during 1985 and is employed as a specialist engineer responsible for the design of gauging structures and related installations in the Republic of South Africa. At the end of 1996, he obtained his Ph.D. (engineering) after completing his studies at the University of Stellenbosch, South Africa, on the calibration of compound Crump and sharp-crested gauging weirs in South Africa. Dr. Wessels is involved in the reinstatement of about 84 flow-gauging stations in South Africa that were damaged by the disastrous floods of February 2000 over the eastern parts of southern Africa. All the early flood-warning stations as far as Mozambique have been severely damaged and have to be reconstructed or replaced.