Chapter
4

STREAMFLOW MEASUREMENT

4.1 INTRODUCTION

Streamflow representing the runoff phase of the hydrologic cycle is the most important basic data for hydrologic studies. It was seen in the previous chapters that precipitation, evaporation and evapotranspiration are all difficult to measure exactly and the presently adopted methods have severe limitations. In contrast the measurement of streamflow is amenable to fairly accurate assessment. Interestingly, streamflow is the only part of the hydrologic cycle that can be measured accurately.

A stream can be defined as a flow channel into which the surface runoff from a specified basin drains. Generally, there is considerable exchange of water between a stream and the underground water. Streamflow is measured in units of discharge (m^3/s) occurring at a specified time and constitutes historical data. The measurement of discharge in a stream forms an important branch of *Hydrometry*, the science and practice of water measurement. This chapter deals with only the salient streamflow measurement techniques to provide an appreciation of this important aspect of engineering hydrology. Excellent treatises[1, 2, 4, 5] and a bibliography[6] are available on the theory and practice of streamflow measurement and these are recommended for further details.

Streamflow measurement techniques can be broadly classified into two cate-gories as (i) direct determination and (ii) indirect determination. Under each category there are a host of methods, the important ones are listed below:

1. Direct determination of stream discharge:
   - (a) Area-velocity methods,
   - (b) Dilution techniques,
   - (c) Electromagnetic method, and
   - (d) Ultrasonic method.
2. Indirect determination of streamflow:
   - (a) Hydraulic structures, such as weirs, flumes and gated structures, and
   - (b) Slope-area method.

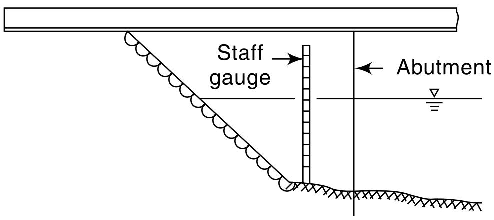
Barring a few exceptional cases, continuous measurement of stream discharge is very difficult. As a rule, direct measurement of discharge is a very time-consuming and costly procedure. Hence, a two step procedure is followed. First, the discharge in a given stream is related to the elevation of the water surface (Stage) through a series of careful measurements. In the next step the stage of the stream is observed routinely in a relatively inexpensive manner and the discharge is estimated by using the previously determined stage–discharge relationship. The observation of the stage is easy, inexpensive, and if desired, continuous readings can also be obtained. This method of discharge determination of streams is adopted universally.

4.2 MEASUREMENT OF STAGE

The stage of a river is defined as its water-surface elevation measured above a datum. This datum can be the mean-sea level (MSL) or any arbitrary datum connected independently to the MSL.

Manual Gauges

Staff Gauge The simplest of stage measurements are made by noting the elevation of the water surface in contact with a fixed graduated staff. The staff is made of a durable material with a low coefficient of expansion with respect to both temperature and moisture. It is fixed rigidly to a structure, such as an abutment, pier, wall, etc. The staff may be vertical or inclined with clearly and accurately graduated permanent markings. The markings are distinctive, easy to read from a distance and are similar to those on a surveying staff. Sometimes, it may not be possible to read the entire range of water-surface elevations of a stream by a single gauge and in such cases the gauge is built in sections at different locations. Such gauges are called *sectional gauges* (Fig. 4.1). When installing sectional gauges, care must be taken to provide an overlap between various gauges and to refer all the sections to the same common datum.



(a) Vertical staff gauge

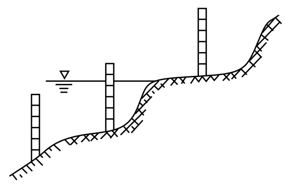

(b) Sectional staff gauge

Fig. 4.1 Staff Gauge

Wire Gauge It is a gauge used to measure the water-surface elevation from above the surface such as from a bridge or similar structure. In this a weight is lowered by a reel to touch the water surface. A mechanical counter measures the rotation of the wheel which is proportional to the length of the wire paid out. The operating range of this kind of gauge is about 25 m.

Automatic Stage Recorders

The staff gauge and wire gauge described earlier are manual gauges. While they are simple and inexpensive, they have to be read at frequent intervals to define the variation of stage with time accurately. Automatic stage recorders overcome this basic objection of manual staff gauges and find considerable use in stream-flow measurement practice. Two typical automatic stage recorders are described below.

Float-Gauge Recorder The Float-operated stage recorder is the most common type of automatic stage recorder in use. In this, a float operating in a stilling well is balanced by means of a counterweight over the pulley of a recorder. Displacement of the float due to the rising or lowering of the water-surface elevation causes an angular displacement of the pulley and hence of the input shaft of the recorder.

Mechanical linkages convert this angular displacement to the linear displacement of a pen to record over a drum driven by clockwork. The pen traverse is continuous with automatic reversing when it reaches the full width of the chart. A clockwork mechanism runs the recorder for a day, week or fortnight and provides a continuous plot of stage *vs* time. A good instrument will have a large-size float and least friction. Improvements over this basic analogue model consists of models that give digital signals recorded on a storage device or transmit directly onto a central data-processing centre.

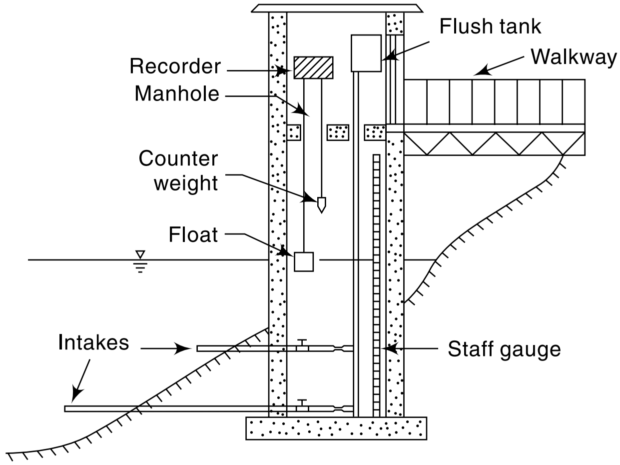


Fig. 4.2 Stilling well Installation

To protect the float from debris and to reduce the water surface wave effects on the recording, *stilling wells* are provided in all float-type stage recorder installations. Figure 4.2 shows a typical stilling well installation. Note the intake pipes that communicate with the river and flushing arrangement to flush these intake pipes off the sediment and debris occasionally. The water-stage recorder has to be located above the highest water level expected in the stream to prevent it from getting inundated during floods. Further, the instrument must be properly housed in a suitable enclosure to protect it from weather elements and vandalism. On account of these, the water-stage-recorder installations prove to be costly in most instances. A water-depth recorder is shown in Fig. 4.3.

Fig. 4.3 Water-depth recorder—Stevens Type F recorder (*Courtesy*: Leupold and Stevens, Inc. Beaverton, Oregon, USA)

Bubble Gauge In this gauge compressed air or gas is made to bleed out at a very small rate through an outlet placed at the bottom of the river [Figs. 4.4, 4.5 and 4.6]. A pressure gauge measures the gas pressure which in turn is equal to the water column above the outlet. A small change in the water-surface elevation is felt as a change in pressure from the present value at the pressure gauge and this in turn is adjusted by a servo-mechanism to bring the gas to bleed at the original rate under the new head. The pressure gauge reads the new water depth which is transmitted to a recorder.

The bubble gauge has certain specific advantages over a float operated water stage recorder and these can be listed as under:

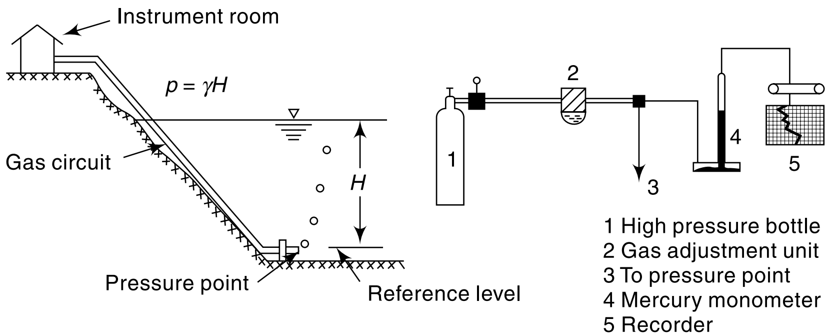


Fig. 4.4 Bubble Gauge

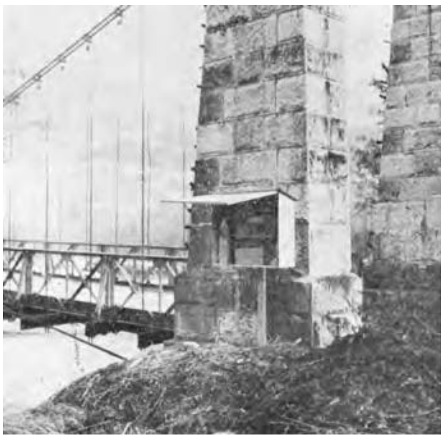


Fig. 4.5 Bubble Gauge Installation—Telemnip
(*Courtesy*: Neyrtec, Grenoble, France)

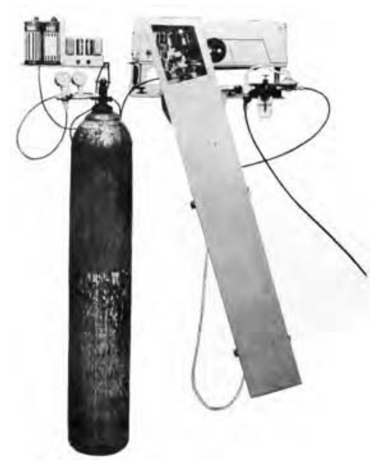


Fig. 4.6 Bubble Gauge—Stevens Manometer Servo
(*Courtesy*: Leupold and Stevens, Inc. Beaverton, Oregon, USA)

1. there is no need for costly stilling wells;
2. a large change in the stage, as much as 30 m, can be measured;
3. the recorder assembly can be quite far away from the sensing point; and
4. due to constant bleeding action there is less likelihood of the inlet getting blocked or choked.

Stage Data

The stage data is often presented in the form of a plot of stage against chrono-logical time (Fig. 4.7) known as *stage hydrograph*. In addition to its use in the determination of stream discharge, stage data itself is of importance in design of hydraulic structures, flood warning and flood-protection works. Reliable long-term stage data corresponding

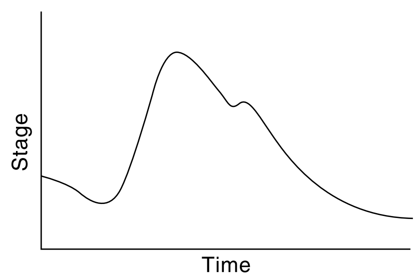


Fig. 4.7 Stage Hydrograph

to peak floods can be analysed statistically to estimate the design peak river stages foruse in the design of hydraulic structures, such as bridges, weirs, etc. Historic flood stages are invaluable in the indirect estimation of corresponding flood discharges. In view of these multifarious uses, the river stage forms an important hydrologic parameter chosen for regular observation and recording.

4.3 MEASUREMENT OF VELOCITY

The measurement of velocity is an important aspect of many direct stream flow measurement techniques. A mechanical device, called *current meter,* consisting essentially of a rotating element is probably the most commonly used instrument for accurate determination of the stream-velocity field. Approximate stream velocities can be determined by *floats.*

Current Meters

The most commonly used instrument in hydrometry to measure the velocity at a point in the flow cross-section is the current meter. It consists essentially of a rotating element which rotates due to the reaction of the stream current with an angular velocity proportional to the stream velocity. Historically, Robert Hooke (1663) invented a propeller-type current meter to measure the distance traversed by a ship. The present-day cup-type instrument and the electrical make-and-break mechanism were invented by Henry in 1868. There are two main types of current meters.

1. Vertical-axis meters, and
2. Horizontal-axis meters.

Vertical-Axis Meters These instruments consist of a series of conical cups mounted around a vertical axis [Figs. 4.8 and 4.9]. The cups rotate in a horizontal plane and a cam attached to the vertical axial spindle records generated signals proportional to the revolutions of the cup assembly. The Price current meter and Gurley current meter are typical instruments under this category. The normal range of velocities is from 0.15 to 4.0 m/s. The accuracy of these instruments is about 1.50% at the threshold value and improves to about 0.30% at speeds in excess of 1.0 m/s. Vertical-axis instruments have the disadvantage that they cannot be used in situations where there are appreciable vertical components of velocities. For example, the instrument shows a positive velocity when it is lifted vertically in still water.

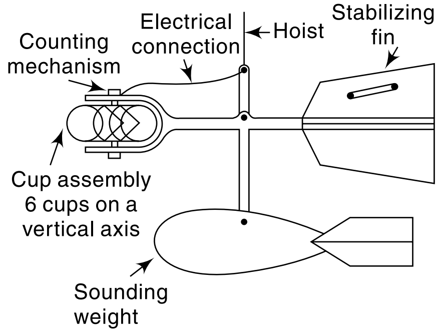


Fig. 4.8 Vertical-axis Current Meter

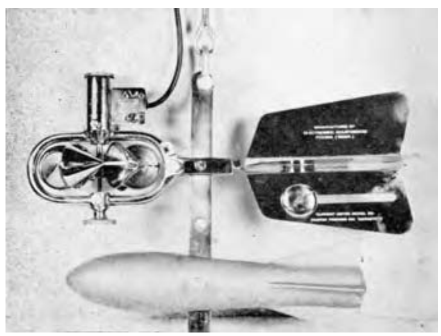


Fig. 4.9 Cup-type Current Meter with Sounding Weight—'Lynx' Type
(*Courtesy*: Lawrence and Mayo (India) New Delhi)

HORIZONTAL-AXIS METERS These meters consist of a propeller mounted at the end of horizontal shaft as shown in Fig. 4.10 and Fig. 4.11. These come in a wide variety of size with propeller diameters in the range 6 to 12 cm, and can register velocities in the range of 0.15 to 4.0 m/s. Ott, Neyrtec [Fig. 4.12] and Watt-type meters are typical instruments under this kind. These meters are fairly rugged and are not affected by oblique flows of as much as 15°. The accuracy of the instrument is about 1% at the threshold value and is about 0.25% at a velocity of 0.3 m/s and above.

Fig. 4.10 Propeller-type Current Meter—Neyrtec Type with Sounding Weight

A current meter is so designed that its rotation speed varies linearly with the stream velocity v at the location of the instrument. A typical relationship is

$$v = aN_s + b \qquad (4.1)$$

where v = stream velocity at the instrument location in m/s, N_s = revolutions per second of the meter and a, b = constants of the meter. Typical values of a and b for a standard size 12.5 cm diameter Price meter (cup-type) is $a = 0.65$ and $b = 0.03$. Smaller meters of 5 cm diameter cup assembly called *pigmy meters* run faster and are useful in measuring small velocities. The values of the meter constants for them are of the order of $a = 0.30$ and $b = 0.003$. Further, each instrument has a threshold velocity below which Eq. (4.1) is not applicable. The instruments have a provision to count the number of revolutions in a known interval of time. This is usually accomplished by the making and breaking of an electric circuit either mechanically or electro-magnetically at each revolution of the shaft. In older model instruments the breaking of the circuit would be counted through an audible sharp signal ("tick") heard on a headphone. The revolutions per second is calculated by counting the number of such signals in a known interval of time, usually about 100 s. Present-day models employ electro-magnetic counters with digital or analogue displays.

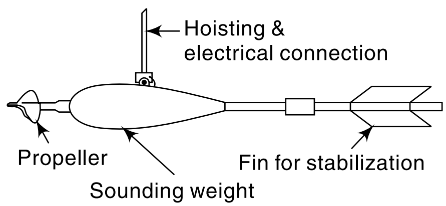


Fig. 4.11 Horizontal-axis Current Meter

CALIBRATION

The relation between the stream velocity and revolutions per second of the meter as in Eq. (4.1) is called the *calibration equation*. The calibration equation is unique to each instrument and is determined by towing the instrument in a special tank. A *towing tank* is a long channel containing still water with arrangements for moving a carriage

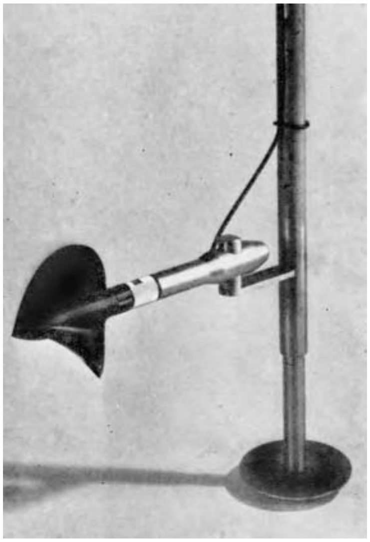


Fig. 4.12(a) Neyrtec Type Current Meter for use in Wading (*Courtesy:* Neyrtec, Grenoble, France)

Fig. 4.12(b) Neyrtec Type Meter in a Cableway

longitudinally over its surface at constant speed. The instrument to be calibrated is mounted on the carriage with the rotating element immersed to a specified depth in the water body in the tank. The carriage is then towed at a predetermined constant speed (v) and the corresponding average value of revolutions per second (N_s) of the instruments determined. This experiment is repeated over the complete range of velocities and a best-fit linear relation in the form of Eq. (4.1) obtained. The instruments are designed for rugged use and hence the calibration once done lasts for quite some time. However, from the point of view of accuracy it is advisable to check the instrument calibration once in a while and whenever there is a suspicion that the instrument is damaged due to bad handling or accident. In India excellent towing-tank facilities for calibration of current meters exist at the Central Water and Power Research Station, Pune and the Indian Institute of Technology, Madras.

Field Use

The velocity distribution in a stream across a vertical section is logarithmic in nature. In a rough turbulent flow the velocity distribution is given by

$$v = 5.75\, v_* \log_{10}\left(\frac{30\, y}{k_s}\right) \tag{4.2}$$

where v = velocity at a point y above the bed, v_* = shear velocity and k_s = equivalent sand-grain roughness. To accurately determine the average velocity in a vertical section, one has to measure the velocity at a large number of points on the vertical. As it is time-consuming, certain simplified procedures have been evolved.

- In shallow streams of depth up to about 3.0 m, the velocity measured at 0.6 times the depth of flow below the water surface is taken as the average velocity $\bar{v}$ in the vertical,

$$\bar{v} = v_{0.6} \quad (4.3)$$

This procedure is known as the single-point observation method.

- In moderately deep streams the velocity is observed at two points; (i) at 0.2 times the depth of flow below the free surface ($v_{0.2}$) and (ii) at 0.8 times the depth of flow below the free surface ($v_{0.8}$). The average velocity in the vertical $\bar{v}$ is taken as

$$\bar{v} = \frac{v_{0.2} + v_{0.8}}{2} \quad (4.4)$$

- In rivers having flood flows, only the surface velocity (v_s) is measured within a depth of about 0.5 m below the surface. The average velocity $\bar{v}$ is obtained by using a reduction factor K as

$$\bar{v} = Kv_s \quad (4.5)$$

The value of K is obtained from observations at lower stages and lie in the range of 0.85 to 0.95.

In small streams of shallow depth the current meter is held at the requisite depth below the surface in a vertical by an observer who stands in the water. The arrangement, called *wading* is quite fast but is obviously applicable only to small streams.

In rivers flowing in narrow gorges in well-defined channels a cableway is stretched from bank to bank well above the flood level. A carriage moving over the cableway is used as the observation platform.

Bridges, while hydraulically not the best locations, are advantageous from the point of view of accessibility and transportation. Hence, railway and road bridges are frequently employed as gauging stations. The velocity measurement is performed on the downstream portion of the bridge to minimize the instrument damage due to drift and knock against the bridge piers.

For wide rivers, boats are the most satisfactory aids in current meter measurement. A cross-sectional line is marked by distinctive land markings and buoys. The position of the boat is determined by using two theodolites on the bank through an intersection method. Use of total station simplifies the work considerably.

Sounding Weights

Current meters are weighted down by lead weights called *sounding weights* to enable them to be positioned in a stable manner at the required location in flowing water. These weights are of streamlined shape with a fin in the rear (Fig. 4.8) and are connected to the current meter by a hangar bar and pin assembly. Sounding weights come in different sizes and the minimum weight is estimated as

$$W = 50\ \bar{v}\ d \quad (4.6)$$

where W = minimum weight in N, $\bar{v}$ = average stream velocity in the vertical in m/s and d = depth of flow at the vertical in metres.

Velocity Measurement by Floats

A floating object on the surface of a stream when timed can yield the surface velocity by the relation

$$v_s = \frac{S}{t} \quad (4.7)$$

where S = distance travelled in time t. This method of measuring velocities while primitive still finds applications in special circumstances, such as: (i) a small stream in flood, (ii) small stream with a rapidly changing water surface, and (iii) preliminary or exploratory surveys. While any floating object can be used, normally specially made leakproof and easily identifiable floats are used (Fig. 4.13). A simple float moving on stream surface is called *surface float.* It is easy to use and the mean velocity is obtained by multiplying the observed surface velocity by a reduction coefficient as in Eq. (4.5). However, surface floats are affected by surface winds. To get the average velocity in the vertical directly, special floats in which part of the body is under water are used. *Rod float* (Fig. 4.13), in which a cylindrical rod is weighed so that it can float vertically, belongs to this category.

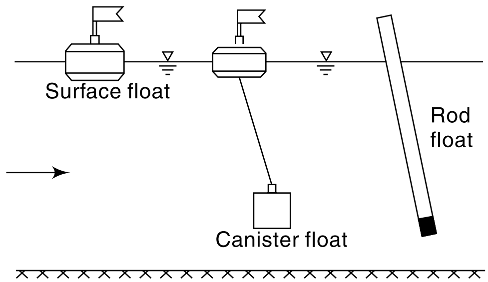


Fig. 4.13 Floats

In using floats to observe the stream velocity a large number of easily identifiable floats are released at fairly uniform spacings on the width of the stream at an upstream section. Two sections on a fairly straight reach are selected and the time to cross this reach by each float is noted and the surface velocity calculated.

4.4 AREA-VELOCITY METHOD

This method of discharge measurement consists essentially of measuring the area of cross-section of the river at a selected section called the *gauging site* and measuring the velocity of flow through the cross-sectional area. The gauging site must be selected with care to assure that the stage-discharge curve is reasonably constant over a long period of about a few years. Towards this the following criteria are adopted.

- The stream should have a well-defined cross-section which does not change in various seasons.
- It should be easily accessible all through the year.
- The site should be in a straight, stable reach.
- The gauging site should be free from backwater effects in the channel.

At the selected site the section line is marked off by permanent survey markings and the cross-section determined. Towards this the depth at various locations are measured by sounding rods or sounding weights. When the stream depth is large or when quick and accurate depth measurements are needed, an electroacoustic instrument called *echo-depth recorder* is used. In this a high frequency sound wave is sent down by a transducer kept immersed at the water surface and the echo reflected by the bed is also picked up by the same transducer. By comparing the time interval between the transmission of the signal and the receipt of its echo, the distance to the bed is obtained and is indicated or recorded in the instrument. Echo-depth recorders are particularly advantageous in high-velocity streams, deep streams and in streams with soft or mobile beds.

For purposes of discharge estimation, the cross-section is considered to be divided into a large number of subsections by verticals (Fig. 4.14). The average velocity in these subsections are measured by current meters or floats. It is quite obvious that the

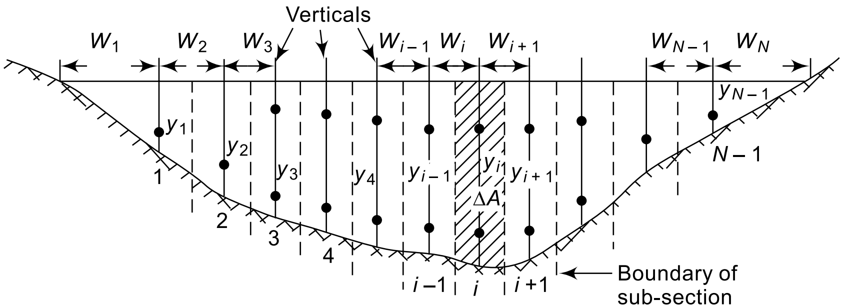


Fig. 4.14 Stream Section for Area-velocity Method

accuracy of discharge estimation increases with the number of subsections used. However, the larger the number of segments, the larger is the effort, time and expenditure involved. The following are some of the guidelines to select the number of segments.

- The segment width should not be greater than 1/15 to 1/20 of the width of the river.
- The discharge in each segment should be less than 10% of the total discharge.
- The difference of velocities in adjacent segments should not be more than 20%.

It should be noted that in natural rivers the verticals for velocity measurement are not necessarily equally spaced. The area-velocity method as above using the current meter is often called as the *standard current meter method.*

Calculation of Discharge

Figure 4.14 shows the cross section of a river in which $N-1$ verticals are drawn. The velocity averaged over the vertical at each section is known. Considering the total area to be divided into $N-1$ segments, the total discharge is calculated by the *method of mid-sections* as follows.

$$Q = \sum_{i=1}^{N-1} \Delta Q_i \tag{4.8}$$

where ΔQ_i = discharge in the ith segment

$$= (\text{depth at the } i\text{th segment}) \times \left(\frac{1}{2} \text{ width to the left} + \frac{1}{2} \text{ width to right}\right) \times (\text{average velocity at the } i\text{th vertical})$$

$$\Delta Q_i = y_i \times \left(\frac{W_i}{2} + \frac{W_{i+1}}{2}\right) \times v_i \qquad \text{for } i = 2 \text{ to } (N-2) \tag{4.9}$$

For the first and last sections, the segments are taken to have triangular areas and area calculated as

$$\Delta A_1 = W_1 \cdot y_1$$

where $\bar{W}_1 = \dfrac{\left(W_1 + \dfrac{W_2}{2}\right)^2}{2W_1}$ and $\Delta A_N = \bar{W}_{N-1} \cdot y_{N-1}$

where $\overline{W}_{N-1} = \dfrac{\left(W_N + \dfrac{W_{N-1}}{2}\right)^2}{2W_N}$

to get

$$\Delta Q_1 = \bar{v}_1 \cdot \Delta A_1 \text{ and } \Delta Q_{N-1} = \bar{v}_{N-1}\ \Delta A_{N-1} \tag{4.10}$$

Example 4.1 *The data pertaining to a stream-gauging operation at a gauging site are given below.*

The rating equation of the current meter is $v = 0.51\ N_s + 0.03$ m/s *where* N_s = *revolutions per second. Calculate the discharge in the stream.*

Distance from left water edge (m)	0	1.0	3.0	5.0	7.0	9.0	11.0	12.0
Depth (m)	0	1.1	2.0	2.5	2.0	1.7	1.0	0
Revolutions of a current meter kept at 0.6 depth	0	39	58	112	90	45	30	0
Duration of observation (s)	0	100	100	150	150	100	100	0

Solution: The calculations are performed in a tabular form.
For the first and last sections,

Average width, $\overline{W} = \dfrac{\left(1 + \dfrac{2}{2}\right)^2}{2 \times 1} = 2.0$ m

For the rest of the segments,

$$\overline{W} = \left(\frac{2}{2} + \frac{2}{2}\right) = 2.0 \text{ m}$$

Since the velocity is measured at 0.6 depth, the measured velocity is the average velocity at that vertical ($\bar{v}$).

The calculation of discharge by the mid-section method is shown in tabular form below:

Distance from left water edge (m)	**Average width $\overline{W}$ (m)**	**Depth y (m)**	**N_s = Rev./second**	**Velocity $\bar{v}$ (m/s)**	**Segmental discharge ΔQ_i (m^3/s)**
0	0	0			0.0000
1	2	1.10	0.390	0.2289	0.5036
3	2	2.00	0.580	0.3258	1.3032
5	2	2.50	0.747	0.4110	2..0549
7	2	2.00	0.600	0.3360	1.3440
9	2	1.70	0.450	0.2595	0.8823
11	2	1.00	0.300	0.1830	0.3660
12	0	0.00			0.0000
				Sum =	**6.45393**

Discharge in the stream = 6.454 m^3/s

Moving-Boat Method

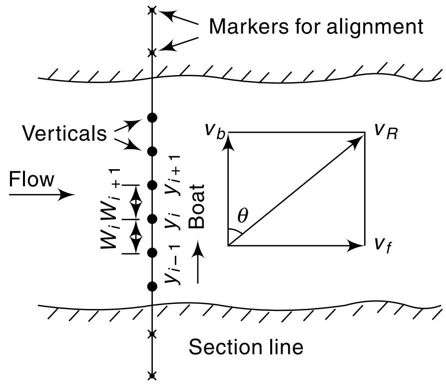


Fig. 4.15 Moving-boat Method

Discharge measurement of large alluvial rivers, such as the Ganga, by the standard current meter method is very time-consuming even when the flow is low or moderate. When the river is in spate, it is almost impossible to use the standard current meter technique due to the difficulty of keeping the boat stationary on the fast-moving surface of the stream for observation purposes. It is in such circumstance that the moving-boat techniques prove very helpful.

In this method a special propeller-type current meter which is free to move about a vertical axis is towed in a boat at a velocity v_b at right angles to the stream flow. If the flow velocity is v_f the meter will align itself in the direction of the resultant velocity v_R making an angle θ with the direction of the boat (Fig. 4.15). Further, the meter will register the velocity v_R. If v_b is normal to v_f,

$$v_b = v_R \cos\theta \quad \text{and} \quad v_f = v_R \sin\theta$$

If the time of transit between two verticals is Δt, then the width between the two verticals (Fig. 4.15) is

$$W = v_b\, \Delta t$$

The flow in the sub-area between two verticals i and $i + 1$ where the depths are y_i and y_{i+1} respectively, by assuming the current meter to measure the average velocity in the vertical, is

$$\Delta Q_i = \left(\frac{y_i + y_{i+1}}{2}\right) W_{i+1}\, v_f$$

i.e.

$$\Delta Q_i = \left(\frac{y_i + y_{i+1}}{2}\right) v_R^2 \sin\theta \cdot \cos\theta \cdot \Delta t \qquad (4.11)$$

Thus by measuring the depths y_i, velocity v_R and θ in a reach and the time taken to cross the reach Δt, the discharge in the sub-area can be determined. The summation of the partial discharges ΔQ_i over the whole width of the stream gives the stream discharge

$$Q = \Sigma\, \Delta Q_i \qquad (4.12)$$

In field application a good stretch of the river with no shoals, islands, bars, etc. is selected. The cross-sectional line is defined by permanent landmarks so that the boat can be aligned along this line. A motor boat with different sizes of outboard motors for use in different river stages is selected. A special current meter of the propeller-type, in which the velocity and inclination of the meter to the boat direction θ in the horizontal plane can be measured, is selected. The current meter is usually immersed at a depth of 0.5 m from the water surface to record surface velocities. To mark the various vertical sections and know the depths at these points, an echo-depth recorder is used.

In a typical run, the boat is started from the water edge and aligned to go across the cross-sectional line. When the boat is in sufficient depth of water, the instruments are lowered. The echo-depth recorder and current meter are commissioned. A button on the signal processor when pressed marks a distinctive mark line on the depth vs time chart of the echo-depth recorder. Further, it gives simultaneously a sharp audio signal to enable the measuring party to take simultaneous readings of the velocity v_R and the inclination θ. A large number of such measurements are taken during the traverse of the boat to the other bank of the river. The operation is repeated in the return journey of the boat. It is important that the boat is kept aligned along the cross-sectional line and this requires considerable skill on the part of the pilot. Typically, a river of about 2 km stretch takes about 15 min for one crossing. A number of crossings are made to get the average value of the discharge.

The surface velocities are converted to average velocities across the vertical by applying a coefficient [Eq. (4.5)]. The depths y_i and time intervals Δt are read from the echo-depth recorder chart. The discharge is calculated by Eqs. (4.11) and (4.12). In practical use additional coefficients may be needed to account for deviations from the ideal case and these depend upon the actual field conditions.

4.5 DILUTION TECHNIQUE OF STREAMFLOW MEASUREMENT

The *dilution method* of flow measurement, also known as the *chemical method* depends upon the continuity principle applied to a tracer which is allowed to mix completely with the flow.

Consider a tracer which does not react with the fluid or boundary. Let C_0 be the small initial concentration of the tracer in the streamflow. At Section 1 a small quantity (volume $\forall_1$)" of high concentra-tion C_1 of this tracer is added as shown in Fig. 4.16. Let Section 2 be sufficiently far away on the downstream of Section 1 so that the tracer mixes thoroughly with the fluid due to the turbulent mixing process while passing through the reach. The concentration profile taken at Section 2 is schematically shown in Fig. 4.16. The concentration will have a base value of C_0, increases from time t_1 to a peak value and gradually reaches the base value of C_0 at time t_2. The stream flow is assumed to be steady. By continuity of the tracer material

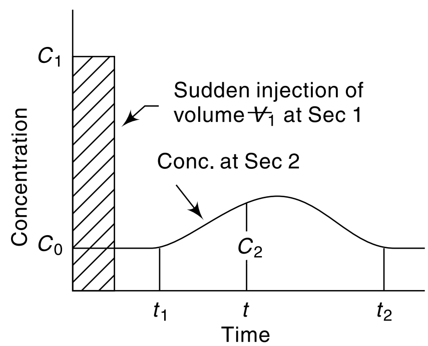


Fig. 4.16 Sudden-injection Method

$$M_1 = \text{mass of tracer added at Section 1} = \forall_1 C_1$$

$$= \int_{t_1}^{t_2} Q(C_2 - C_0)\, dt + \frac{\forall_1}{t_2 - t_1} \int_{t_1}^{t_2} (C_2 - C_0)\, dt$$

Neglecting the second term on the right-hand side as insignificantly small,

$$Q = \frac{\forall_1 C_1}{\int_{t_1}^{t_2} (C_2 - C_0)\, dt} \tag{4.13}$$

Thus the discharge Q in the stream can be estimated if for a known M_1 the variation of C_2 with time at Section 2 and C_0 are determined. This method is known as *sudden injection* or *gulp* or *integration method*.

Another way of using the dilution principle is to inject the tracer of concentration C_1 at a constant rate Q_t at Section 1. At Section 2, the concentration gradually rises from the background value of C_0 at time t_1 to a constant value C_2 as shown in Fig. 4.17. At the steady state, the continuity equation for the tracer is

$$Q_tC_1 + QC_0 = (Q + Q_t)C_2$$

i.e., $$Q = \frac{Q_t(C_1 - C_2)}{(C_2 - C_0)} \quad (4.14)$$

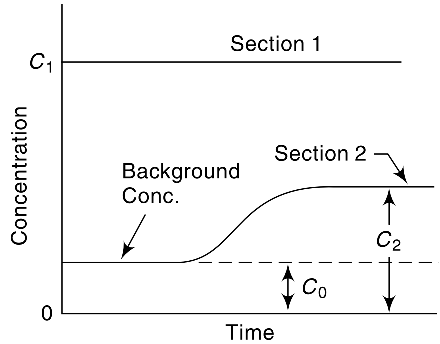


Fig. 4.17 Constant Rate Injection Method

This technique in which Q is estimated by knowing C_1, C_2, C_0 and Q_t is known as *constant rate injection method* or *plateau gauging*.

It is necessary to emphasise here that the dilution method of gauging is based on the assumption of steady flow. If the flow is unsteady and the flow rate changes appreciably during gauging, there will be a change in the storage volume in the reach and the steady-state continuity equation used to develop Eqs. (4.13) and (4.14) is not valid. Systematic errors can be expected in such cases.

Tracers

The tracer used should have ideally the following properties

1. It should not be absorbed by the sediment, channel boundary and vegetation. It should not chemically react with any of the above surfaces and also should not be lost by evaporation.
2. It should be non-toxic.
3. It should be capable of being detected in a distinctive manner in small concentrations.
4. It should not be very expensive.

The tracers used are of three main types

1. Chemicals (common salt and sodium dichromate are typical)
2. Fluorescent dyes (Rhodamine-WT and Sulpho-Rhodamine B Extra are typical)
3. Radioactive materials (such as Bromine-82, Sodium-24 and Iodine-132).

Common salt can be detected with an error of ±1% up to a concentration of 10 ppm. Sodium dichromate can be detected up to 0.2 ppm concentrations. Fluorescent dyes have the advantage that they can be detected at levels of tens of nanograms per litre (~1 in 10^{11}) and hence require very small amounts of solution for injections. Radioactive tracers are detectable up to accuracies of tens of picocuries per litre (~1 in 10^{14}) and therefore permit large-scale dilutions. However, they involve the use of very sophisticated instruments and handling by trained personnel only. The availability of detection instrumentation, environmental effects of the tracer and overall cost of the operation are chief factors that decide the tracer to be used.

Length of Reach The length of the reach between the dosing section and sampling section should be adequate to have complete mixing of the tracer with the flow. This length depends upon the geometric dimensions of the channel cross-section, discharge and turbulence levels. An empirical formula suggested by Rimmar (1960) for estimation of mixing length for point injection of a tracer in a straight reach is

$$L = \frac{0.13\, B^2\, C(0.7\, C + 2\sqrt{g})}{gd} \tag{4.15}$$

where L = mixing length (m), B = average width of the stream (m), d = average depth of the stream (m), C = Chezy coefficient of roughness and g = acceleration due to gravity. The value of L varies from about 1 km for a mountain stream carrying a discharge of about 1.0 m^3/s to about 100 km for river in a plain with a discharge of about 300 m^3/s. The mixing length becomes very large for large rivers and is one of the major constraints of the dilution method. Artificial mixing of the tracer at the dosing station may prove beneficial for small streams in reducing the mixing length of the reach.

Use The dilution method has the major advantage that the discharge is estimated directly in an absolute way. It is a particularly attractive method for small turbulent streams, such as those in mountainous areas. Where suitable, it can be used as an occasional method for checking the calibration, stage-discharge curves, etc. obtained by other methods.

Example 4.2 *A 25 g/l solution of a flourescent tracer was discharged into a stream at a constant rate of 10 cm³/s. The background concentration of the dye in the stream water was found to be zero. At a downstream section sufficiently far away, the dye was found to reach an equilibrium concentration of 5 parts per billion. Estimate the stream discharge.*

Solution: By Eq. (4.14) for the constant-rate injection method,

$$Q = \frac{Q_t(C_1 - C_2)}{C_2 - C_0}$$

$$Q_t = 10 \text{ cm}^3/\text{s} = 10 \times 10^{-6} \text{ m}^3/\text{s}$$

$$C_1 = 0.025,\ C_2 = 5 \times 10^{-9},\ C_0 = 0$$

$$Q = \frac{10 \times 10^{-6}}{5 \times 10^{-9}}(0.025 - 5 \times 10^{-9}) = 50 \text{ m}^3/\text{s}$$

4.6 ELECTROMAGNETIC METHOD

The electromagnetic method is based on the Faraday's principle that an emf is induced in the conductor (water in the present case) when it cuts a normal magnetic field. Large coils buried at the bottom of the channel carry a current I to produce a controlled vertical magnetic field (Fig. 4.18). Electrodes provided at the sides of the channel section measure the small voltage produced due to flow of water in the channel. It has been found that the signal output E will be of the order of millivolts and is related to the discharge Q as

$$Q = K_1\left(\frac{Ed}{I} + K_2\right)^n \tag{4.16}$$

where d = depth of flow, I = current in the coil, and n, K_1 and K_2 are system constants.

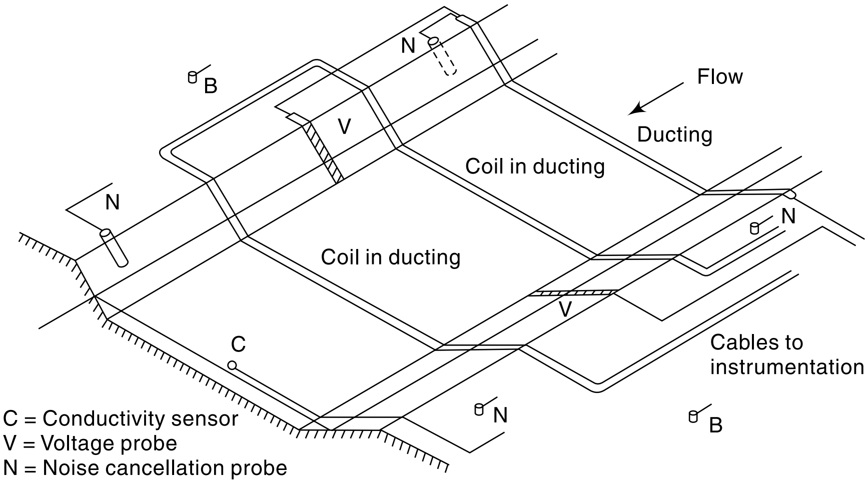


Fig. 4.18 Electromagnetic Method

The method involves sophisticated and expensive instrumentation and has been successfully tried in a number of installations. The fact that this kind of set-up gives the total discharge when once it has been calibrated, makes it specially suited for field situations where the cross-sectional properties can change with time due to weed growth, sedimentation, etc. Another specific application is in tidal channels where the flow undergoes rapid changes both in magnitude as well as in direction. Present, day commercially available electromagnetic flowmeters can measure the discharge to an accuracy of ±3%, the maximum channel width that can be accommodated being 100 m. The minimum detectable velocity is 0.005 m/s.

4.7 ULTRASONIC METHOD

This is essentially an area-velocity method with the average velocity being measured by using ultrasonic signals. The method was first reported by Swengel (1955), since then it has been perfected and complete systems are available commercially.

Consider a channel carrying a flow with two transducers *A* and *B* fixed at the same level *h* above the bed and on either side of the channel (Fig. 4.19). These transducers can receive as well as send ultrasonic signals. Let *A* send an ultrasonic signal to be received at *B* after an elapse time t_1 Similarly, let *B* send a signal to be received at *A* after an elapse time t_2. If C = velocity of sound in water,

$$t_1 = L/(C + v_p) \tag{4.17}$$

where L = length of path from *A* to *B* and v_p = component of the flow velocity in the sound path = $v \cos \theta$. Similarly, from Fig. 4.19 it is easy to see that

$$t_2 = \frac{L}{(C - v_p)} \tag{4.18}$$

Thus $$\frac{1}{t_1} - \frac{1}{t_2} = \frac{2 v_p}{L} = \frac{2 v \cos \theta}{L}$$

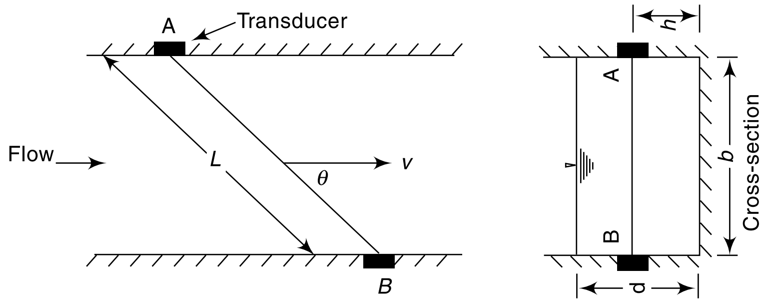


Fig. 4.19 Ultrasonic Method

or $$v = \frac{L}{2\cos\theta}\left(\frac{1}{t_1} - \frac{1}{t_2}\right) \quad (4.19)$$

Thus for a given L and θ, by knowing t_1 and t_2, the average velocity along the path AB, i.e., v can be determined. It may be noted that v is the average velocity at a height h above the bed and is not the average velocity V for the whole cross-section. However, for a given channel cross-section v can be related to V and by calibration a relation between v/V and h can be obtained. For a given set-up, as the area of cross-section is fixed, the discharge is obtained as a product of area and mean velocity V. Estimation of discharge by using one signal path as above is called *single-path gauging*. Alternatively, for a given depth of flow, multiple single paths can be used to obtain v for different h values. Mean velocity of flow through the cross-section is obtained by averaging these v values. This techniques is known as *multi-path gauging*.

Ultrasonic flowmeters using the above principal have frequencies of the order of 500 kHz. Sophisticated electronics are involved to transmit, detect and evaluate the mean velocity of flow along the path. In a given installation a calibration (usually performed by the current-meter method) is needed to determine the system constants. Currently available commercial systems have accuracies of about 2% for the single-path method and 1% for the multipath method. The systems are currently available for rivers up to 500 m width.

The specific advantages of the ultrasonic system of river gauging are

1. It is rapid and gives high accuracy.
2. It is suitable for automatic recording of data.
3. It can handle rapid changes in the magnitude and direction of flow, as in tidal rivers.
4. The cost of installation is independent of the size of rivers.

The accuracy of this method is limited by the factors that affect the signal velo-city and averaging of flow velocity, such as (i) unstable cross-section, (ii) fluctuating weed growth, (iii) high loads of suspended solids, (iv) air entrainment, and (v) salinity and temperature changes.

4.8 INDIRECT METHODS

Under this category are included those methods which make use of the relationship between the flow discharge and the depths at specified locations. The field measurement is restricted to the measurements of these depths only.

Two broad classifications of these indirect methods are

1. Flow measuring structures, and
2. Slope area method.

Flow-Measuring Structures

Use of structures like notches, weirs, flumes and sluice gates for flow measurement in hydraulic laboratories is well known. These conventional structures are used in field conditions also but their use is limited by the ranges of head, debris or sediment load of the stream and the back-water effects produced by the installations. To overcome many of these limitations a wide variety of flow measuring structures with specific advantages are in use.

The basic principle governing the use of a weir, flume or similar flow-measuring structure is that these structures produce a unique *control section* in the flow. At these structures, the discharge Q is a function of the water-surface elevation measured at a specified upstream location,

$$Q = f(H) \tag{4.20}$$

where H = water surface elevation measured from a specified datum. Thus, for example, for weirs, Eq. (4.20) takes the form

$$Q = KH^n \tag{4.21}$$

where H = head over the weir and K, n = system constants. Equation (4.20) is applicable so long as the downstream water level is below a certain limiting water level known as the *modular limit*. Such flows which are independent of the downstream water level are known as *free flows.* If the tail water conditions do affect the flow, then the flow is known as *drowned* or *submerged flow*. Discharges under drowned, condition are obtained by applying a reduction factor to the free flow discharges. For example, the submerged flow over a weir [Fig. 4.20(b)] is estimated by the Villemonte formula,

$$Q_s = Q_1\left[1 - \left(\frac{H_2}{H_1}\right)^n\right]^{0.385} \tag{4.22}$$

where Q_s = submerged discharge, Q_1 = free flow discharge under head H_1, H_1 = upstream water surface elevation measured above the weir crest, H_2 = downstream water surface elevation measured above the weir crest, n = exponent of head in the free flow head discharge relationship [Eq. (4.21)]. For a rectangular weir n = 1.5.

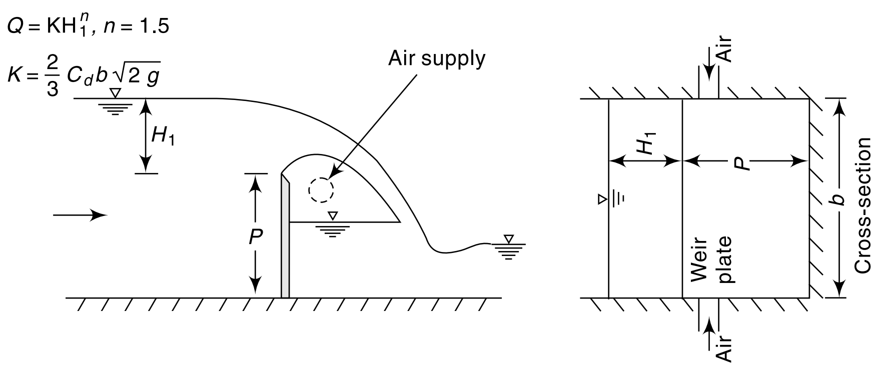


Fig. 4.20(a) Flow over a Weir: (a) Free Flow

The various flow measuring structures can be broadly considered under three categories:

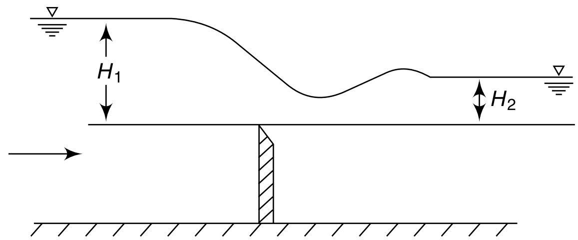


Fig. 4.20(b) Submerged Flow

THIN-PLATE STRUCTURES are usually made from a vertically set metal plate. The V-notch, rectangular full width and contracted notches are typical examples under this category.

LONG-BASE WEIRS also known as *broad-crested weirs* are made of concrete or masonry and are used for large discharge values.

FLUMES are made of concrete, masonry or metal sheets depending on their use and location. They depend primarily on the width constriction to produce a control section.

Details of the discharge characteristics of flow-measuring structures are available in Refs. 1, 2 and 7.

SLOPE-AREA METHOD

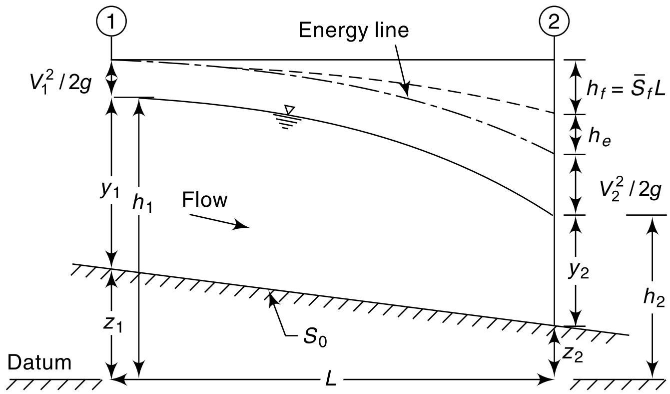


Fig. 4.21 Slope-area Method

The resistance equation for uniform flow in an open channel, e.g. Manning's formula can be used to relate the depths at either ends of a reach to the discharge. Figure 4.21 shows the longitudinal section of the flow in a river between two sections, 1 and 2. Knowing the water-surface elevations at the two sections, it is required to estimate the discharge. Applying the energy equation to Sections 1 and 2,

$$Z_1 + y_1 + \frac{V_1^2}{2g} = Z_2 + y_2 + \frac{V_2^2}{2g} + h_L$$

where h_L = head loss in the reach. The head loss h_L can be considered to be made up of two parts (i) frictional loss h_f and (ii) eddy loss h_e. Denoting $Z + y = h$ = water-surface elevation above the datum,

$$h_1 + \frac{V_1^2}{2g} = h_2 + \frac{V_2^2}{2g} + h_e + h_f$$

or

$$h_f = (h_1 - h_2) + \left(\frac{V_1^2}{2g} - \frac{V_2^2}{2g}\right) - h_e \qquad (4.23)$$

If L = length of the reach, by Manning's formula for uniform flow,

$$\frac{h_f}{L} = S_f = \text{energy slope} = \frac{Q^2}{K^2}$$

where K = conveyance of the channel = $\frac{1}{n} AR^{2/3}$

In nonuniform flow an average conveyance is used to estimate the average energy slope and

$$\frac{h_f}{L} = \bar{S}_f = \frac{Q^2}{K^2} \tag{4.24}$$

where $K = \sqrt{K_1 K_2}$; $K_1 = \frac{1}{n_1} A_1 R_1^{2/3}$ and $K_2 = \frac{1}{n_2} A_2 R_2^{2/3}$

n = Manning's roughness coefficient

The eddy loss h_e is estimated as

$$h_e = K_e \left| \frac{V_1^2}{2g} - \frac{V_2^2}{2g} \right| \tag{4.25}$$

where K_e = eddy-loss coefficient having values as below.

Cross-section characteristic of the reach	**Value of K**	
	Expansion	**Contraction**
Uniform	0	0
Gradual transition	0.3	0.1
Abrupt transition	0.8	0.6

Equation (4.23), (4.24) and (4.25) together with the continuity equation $Q = A_1 V_1 = A_2 V_2$ enable the discharge Q to be estimated for known values of h, channel cross-sectional properties and n.

The discharge is calculated by a trial and error procedure using the following sequence of calculations

1. Assume $V_1 = V_2$. This leads to $V_1^2/2g = V_2^2/2g$ and by Eq. (4.23) $h_f = h_1 - h_2 = F$ = fall in the water Surface between Sections 1 and 2
2. Using Eq. (4.24) calculate discharge Q
3. Compute $V_1 = Q/A_1$ and $V_2 = Q/A_2$. Calculate velocity heads and eddy-loss h_e
4. Now calculate a refined value of h_f by Eq. (4.23) and go to step (2). Repeat the calculations till two successive calculations give values of discharge (or h_f) differing by a negligible margin.

This method of estimating the discharge is known as the *slope-area method.* It is a very versatile indirect method of discharge estimation and requires (i) the selection of a reach in which cross-sectional properties including bed elevations are known at its ends, (ii) the value of Manning's n and (iii) water-surface elevations at the two end sections.

Example 4.3 *During a flood flow the depth of water in a 10 m wide rectangular channel was found to be 3.0 m and 2.9 m at two sections 200 m apart. The drop in the water-surface elevation was found to be 0.12 m. Assuming Manning's coefficient to be 0.025, estimate the flood discharge through the channel.*

Solution: Using suffixes 1 and 2 to denote the upstream and downstream sections respectively, the cross-sectional properties are calculated as follows:

Section 1	Section 2
$y_1 = 3.0$ m $A_1 = 30$ m^2 $P_1 = 16$ m $R_1 = 1.875$ m $K_1 = \frac{1}{0.025} \times 30 \times (1.875)^{2/3}$ $= 1824.7$	$y_2 = 2.90$ m $A_2 = 29$ m^2 $P_2 = 15.8$ m $R_2 = 1.835$ m $K_2 = \frac{1}{0.025} \times 29 \times (1.835)^{2/3}$ $= 1738.9$

Average K for the reach = $\sqrt{K_1 K_2} = 1781.3$
To start with h_f = fall = 0.12 m is assumed.
Eddy loss $h_e = 0$
The calculations are shown in Table 4.1.

$$\bar{S}_f = h_f/L = h_f/200 \qquad Q = K\sqrt{\bar{S}_f} = 1781.3\sqrt{\bar{S}_f}$$

$$\frac{V_1^2}{2g} = \left(\frac{Q}{30}\right)^2/19.62, \frac{V_2^2}{2g} = \left(\frac{Q}{29}\right)^2/19.62$$

$$h_f = (h_1 - h_2) + \left(\frac{V_1^2}{2g} - \frac{V_2^2}{2g}\right)$$

$$h_f = \text{fall} + \left(\frac{V_1^2}{2g} - \frac{V_2^2}{2g}\right) = 0.12 + \left(\frac{V_1^2}{2g} - \frac{V_2^2}{2g}\right) \qquad \text{(E–1)}$$

Table 4.1 Calculations for Example 4.3

Trial	h_f (trial)	S_f (units of 10^{-4})	Q (m^3/s)	$V_1^2/2g$ (m)	$V_2^2/2g$ (m)	h_f by Eq. (E–1) (m)
1	0.1200	6.000	43.63	0.1078	0.1154	0.1124
2	0.1124	5.622	42.24	0.1010	0.1081	0.1129
3	0.1129	5.646	42.32	0.1014	0.1081	0.1129

(The last column is h_f by Eq. (E–1) and its value is adopted for the next trial.)
The discharge in the channel is 42.32 m^3/s.

Flood Discharge by Slope-Area Method The slope-area method is of particular use in estimating the flood discharges in a river by past records of stages at different sections. Floods leave traces of peak elevations called high-water marks in their wake. Floating vegetative matter, such as grass, straw and seeds are left stranded at high water levels when the flood subsides and form excellent marks. Other high-water marks include silt lines on river banks, trace of erosion on the banks called *wash lines* and silt or stain lines on buildings. In connection with the estimation of very high floods, interviews with senior citizens living in the area, who can recollect from memory certain salient flood marks are valuable. Old records in archives often provide valuable information on flood marks and dates of occurrence of those floods. Various such information relating to a particular flood are cross-checked for consistency and only reliable data are retained. The slope-area method is then used to estimate the magnitude of the flood.

The selection of the reach is probably the most important aspect of the slope-area method. The following criteria can be listed towards this:

- The quality of high-water marks must be good.
- The reach should be straight and uniform as far as possible. Gradually contracting sections are preferred to an expanding reach.
- The recorded fall in the water-surface elevation should be larger than the velocity head. It is preferable if the fall is greater than 0.15 m.
- The longer the reach, the greater is the accuracy in the estimated discharge. A length greater than 75 times the mean depth provides an estimate of the reach length required.

The Manning's roughness coefficient n for use in the computation of discharge is obtained from standard tables[7]. Sometimes a relation between n and the stage is prepared from measured discharges at a neighbouring gauging station and an appropriate value of n selected from it, with extrapolation if necessary.

4.9 STAGE-DISCHARGE RELATIONSHIP

As indicated earlier the measurement of discharge by the direct method involves a two step procedure; the development of the stage-discharge relationship which forms the first step is of utmost importance. Once the stage-discharge $(G - Q)$ relationship is established, the subsequent procedure consists of measuring the stage (G) and reading the discharge (Q) from the $(G - Q)$ relationship. This second part is a routine operation. Thus the aim of all current-meter and other direct-discharge measurements is to prepare a stage-discharge relationship for the given channel gauging section. The stage-discharge relationship is also known as the *rating curve.*

The measured value of discharges when plotted against the corresponding stages gives relationship that represents the integrated effect of a wide range of channel and flow parameters. The combined effect of these parameters is termed *control.* If the $(G - Q)$ relationship for a gauging section is constant and does not change with time, the control is said to be *permanent.* If it changes with time, it is called *shifting control*.

Permanent Control

A majority of streams and rivers, especially nonalluvial rivers exhibit permanent control. For such a case, the relationship between the stage and the discharge is a single-valued relation which is expressed as

$$Q = C_r\,(G - a)^{\beta} \tag{4.26}$$

in which Q = stream discharge, G = gauge height (stage), a = a constant which represent the gauge reading corresponding to zero discharge, C_r and β are rating curve constants. This relationship can be expressed graphically by plotting the observed relative stage $(G - a)$ against the corresponding discharge values in an arithmetic or logarithmic plot [Fig. 4.22(a) and (b)]. Logarithmic plotting is advantageous as Eq. (4.26) plots as a

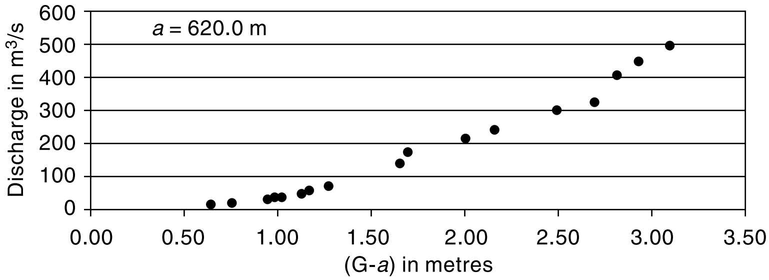


Fig. 4.22(a) Stage-Discharge Curve: Arithmetic Plot

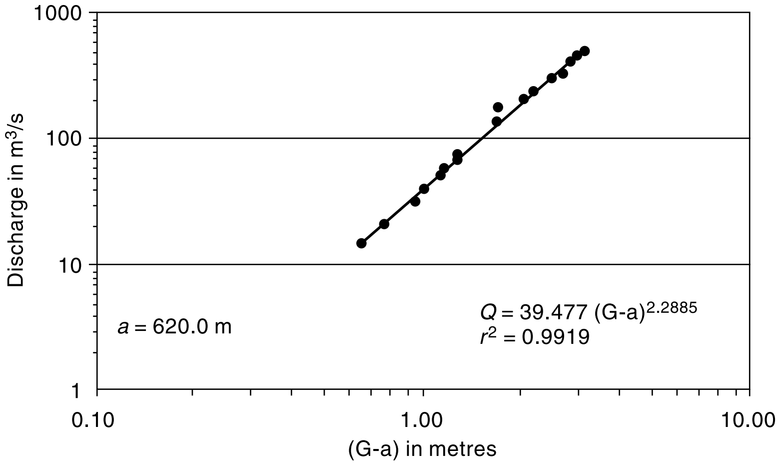


Fig. 4.22(b) Stage-Discharge Curve: Logarithmic Plot

straight line in logarithmic coordinates. In Fig. 4.22(b) the straight line is drawn to best represent the data plotted as Q *vs* $(G - a)$. Coefficients C_r and β need not be the same for the full range of stages.

The best values of C_r and β in Eq. (4.26) for a given range of stage are obtained by the least-square-error method. Thus by taking logarithms,

$$\log Q = \beta \log (G - a) + \log C_r \tag{4.27}$$

or

$$Y = \beta X + b \tag{4.27a}$$

in which the dependent variable $Y = \log Q$, independent variable $X = \log (G - a)$ and $b = \log C_r$. For the best-fit straight line of N observations of X and Y, by regressing $X = \log (G - a)$ on $Y = \log Q$

$$\beta = \frac{N(\Sigma XY) - (\Sigma X)(\Sigma Y)}{N(\Sigma X^2) - (\Sigma X)^2} \tag{4.28a}$$

and

$$b = \frac{\Sigma Y - \beta(\Sigma X)}{N} \tag{4.28b}$$

Pearson product moment correlation coefficient

$$r = \frac{N(\Sigma XY) - (\Sigma X)(\Sigma Y)}{\sqrt{[N(\Sigma X^2) - (\Sigma X)^2][N(\Sigma Y^2) - (\Sigma Y)^2]}} \tag{4.29}$$

Here r reflects the extent of linear relationship between the two data sets.

For a perfect correlation $r = 1.0$. If r is between 0.6 and 1.0 it is generally taken as a good correlation. It should be noted that in the present case, as the discharge Q increases with $(G - a)$ the variables Y and X are positively correlated and hence r is positive. Equation (4.26), viz.

$$Q = C_r(G - a)^{\beta}$$

is called the *rating equation* of the stream and can be used for estimating the discharge Q of the stream for a given gauge reading G within range of data used in its derivation.

STAGE FOR ZERO DISCHARGE, a In Eq. (4.26) the constant a representing the stage (gauge height) for zero discharge in the stream is a hypothetical parameter and cannot be measured in the field. As such, its determination poses some difficulties. The following alternative methods are available for its determination:

1. Plot Q *vs* G on an arithmetic graph paper and draw a best-fit curve. By extrapolating the curve by eye judgment find a as the value of G corresponding to $Q = 0$. Using the value of a, plot log Q *vs* log $(G - a)$ and verify whether the data plots as a straight line. If not, select another value in the neighbourhood of previously assumed value and by trial and error find an acceptable value of a which gives a straight line plot of log Q *vs* log $(G - a)$.
2. A graphical method due to Running[8] is as follows. The Q *vs* G data are plotted to an arithmetic scale and a smooth curve through the plotted points are drawn. Three points A, B and C on the curve are selected such that their discharges are in geometric progression (Fig. 4.23), i.e.

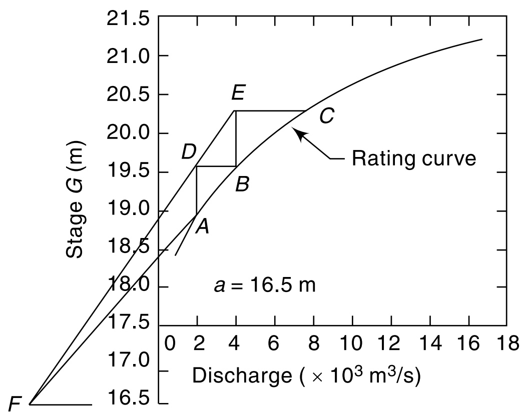


Fig. 4.23 Running's Method for Estimation of the Constant *a*

$$\frac{Q_A}{Q_B} = \frac{Q_B}{Q_C}$$

At A and B vertical lines are drawn and then horizontal lines are drawn at B and C to get D and E as intersection points with the verticals. Two straight lines ED and BA are drawn to intersect at F. The ordinate at F is the required value of a, the gauge height corresponding to zero discharge. This method assumes the lower part of the stage-discharge curve to be a parabola.
3. Plot Q *vs* G to an arithmetic scale and draw a smooth good-fitting curve by eye-judgement. Select three discharges Q_1, Q_2 and Q_3 such that $Q_1/Q_2 = Q_2/Q_3$ and note from the curve the corresponding values of gauge readings G_1, G_2 and G_3. From Eq. (4.26)

$$(G_1 - a)/(G_2 - a) = (G_2 - a)/(G_3 - a)$$

i.e.
$$a = \frac{G_1 G_3 - G_2^2}{(G\ + G_3) - 2G_2} \qquad (4.30)$$

4. A number of optimization procedures are available to estimate the best value of *a*. A trial-and-error search for *a* which gives the best value of the correlation coefficient is one of them.

EXAMPLE 4.4 *Following are the data of gauge and discharge collected at a particular section of the river by stream gauging operation. (a) Develop a gauge-discharge relationship for this stream at this section for use in estimating the discharge for a known gauge reading. What is the coefficient of correlation of the derived relationship? Use a value of a = 7.50 m for the gauge reading corresponding to zero discharge. (b) Estimate the discharge corresponding to a gauge reading of 10.5 m at this gauging section.*

Gauge reading (m)	Discharge (m^3/s)	Gauge reading (m)	Discharge (m^3/s)
7.65	15	8.48	170
7.70	30	8.98	400
7.77	57	9.30	600
7.80	39	9.50	800
7.90	60	10.50	1500
7.91	100	11.10	2000
8.08	150	11.70	2400

SOLUTION: (a) The gauge–discharge equation is $Q = C_r(G - a)^{\beta}$

Taking the logarithms $\log Q = \beta \log (G - a) + \log C_r$

or $Y = \beta X + b$

where $Y = \log Q$ and $X = \log (G - a)$.

Values of *X*, *Y* and *XY* are calculated for all the data as shown in Table 4.2.

Table 4.2 Calculations for Example 4.4

$a = 7.5$ m $N = 14$

Stage (*G*) (metres)	(*G* – *a*) (m)	Discharge (*Q*)(m^3/s)	log (*G* – *a*) = *X*	log *Q* = *Y*	*XY*	X^2	Y^2
7.65	0.15	15	–0.824	1.176	–0.969	0.679	1.383
7.70	0.20	30	–0.699	1.477	–1.032	0.489	2.182
7.77	0.27	57	–0.569	1.756	–0.998	0.323	3.083
7.80	0.30	39	–0.523	1.591	–0.832	0.273	2.531
7.90	0.40	60	–0.398	1. 778	–0.708	0.158	3.162
7.91	0.41	100	–0.387	2.000	–0.774	0.150	4.000
8.08	0.58	150	–0.237	2.176	–0.515	0.056	4.735
8.48	0.98	170	–0.009	2.230	–0.020	0.000	4.975
8.98	1.48	400	0.170	2.602	0.443	0.029	6.771
9.30	1.80	600	0.255	2.778	0.709	0.065	7.718
9.50	2.00	800	0.301	2.903	0.874	0.091	8.428
10.50	3.00	1500	0.477	3.176	1.515	0.228	10.088
11.10	3.60	2000	0.556	3.301	1.836	0.309	10.897
11.70	4.20	2400	0.623	3.380	2.107	0.388	11.426
		Sum	**–1.262**	**32.325**	**1.636**	**3.239**	**81.379**

From the above table:

$\Sigma X = -1.262$ $\Sigma Y = 32.325$ $\Sigma XY = 1.636$

$\Sigma X^2 = 3.239$ $\Sigma Y^2 = 81.379$

$(\Sigma X)^2 = 1.5926$ $(\Sigma Y)^2 = 1044.906$ $N = 14$

By using Eq. (4.28a)

$$\beta = \frac{N(\Sigma XY) - (\Sigma X)(\Sigma Y)}{N(\Sigma X^2) - (\Sigma X)^2} = \frac{(14 \times 1.636) - (-1.262)(32.325)}{(14 \times 3.239) - (-1.262)^2} = 1.4558$$

By Eq. (4.28b)

$$b = \frac{\Sigma Y - \beta(\Sigma X)}{N} = \frac{(32.325) - 1.4558 \times (-1.262)}{14} = 2.440$$

Hence $C_r = 275.52$

The required gauge–discharge relationship is therefore

$$Q = 275.52\,(G - a)^{1.456}$$

By Eq. 4.29 coefficient of correlation

$$r = \frac{N(\Sigma XY) - (\Sigma X)(\Sigma Y)}{\sqrt{[N(\Sigma X^2) - (\Sigma X)^2][N(\Sigma Y^2) - (\Sigma Y)^2]}}$$

$$= \frac{(14 \times 1.636) - (-1.262)(32.325)}{\sqrt{[(14 \times 3.239) - (1.5926)][(14 \times 81.379) - (1044.906)]}} = 0.9913$$

As the value of r is nearer to unity the correlation is very good.

The variation of discharge (Q) with relative stage ($G - a$) is shown in Fig. 4.24(a)—arithmetic plot and in Fig. 4.24(b)—logarithmic plot.

(b) when $G = 10.05$: as $a = 7.5$ m

$$G = 275.52\,(10.05 - 7.50)^{1.456} = 1076 \text{ m}^3/\text{s}$$

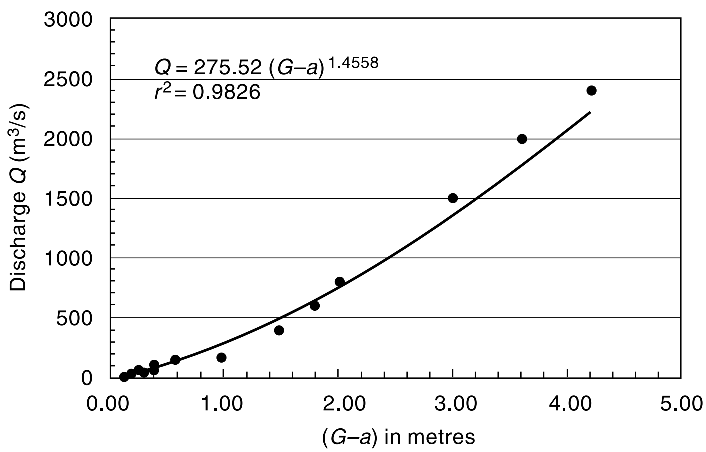


Fig. 4.24(a) Stage-discharge Relation (Arithmetic Plot)—Example 4.4

SHIFTING CONTROL

The control that exists at a gauging section giving rise to a unique stage-discharge relationship can change due to: (i) changing characteristics caused by weed growth,

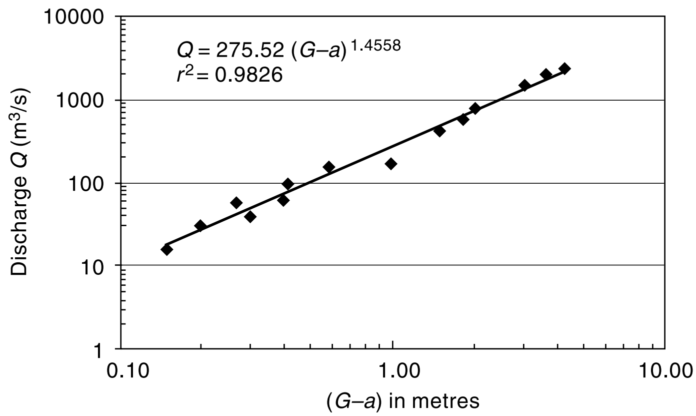


Fig. 4.24(b) Stage-discharge Relationship (Logarithmic Plot)—Example 4.4

dredging or channel encroachment, (ii) aggradation or degradation phenomenon in an alluvial channel, (iii) variable backwater effects affecting the gauging section and (iv) unsteady flow effects of a rapidly changing stage. There are no permanent corrective measure to tackle the shifting controls due to causes (i) and (ii) listed above. The only recourse in such cases is to have frequent current-meter gaugings and to update the rating curves. Shifting controls due to causes (iii) and (iv) are described below.

BACKWATER EFFECT If the shifting control is due to variable backwater curves, the same stage will indicate different discharges depending upon the backwater effect. To remedy this situation another gauge, called the *secondary gauge* or *auxiliary gauge* is installed some distance downstream of the gauging section and readings of both gauges are taken. The difference between the main gauge and the secondary gauge gives the *fall* (F) of the water surface in the reach. Now, for a given main-stage reading, the discharge under variable backwater condition is a function of the fall F, i.e.

$$Q = f(G, F)$$

Schematically, this functional relationship is shown in Fig. 4.25. Instead of having a three-parameter plot, the observed data is normalized with respect to a constant fall value. Let F_0 be a normalizing value of the fall taken to be constant at all stages and F the actual fall at a given stage when the actual discharge is Q. These two fall values are related as

$$\frac{Q}{Q_0} = \left(\frac{F}{F_0}\right)^m \qquad (4.31)$$

in which Q_0 = normalized discharge at the given stage when the fall is equal to F_0 and m = an

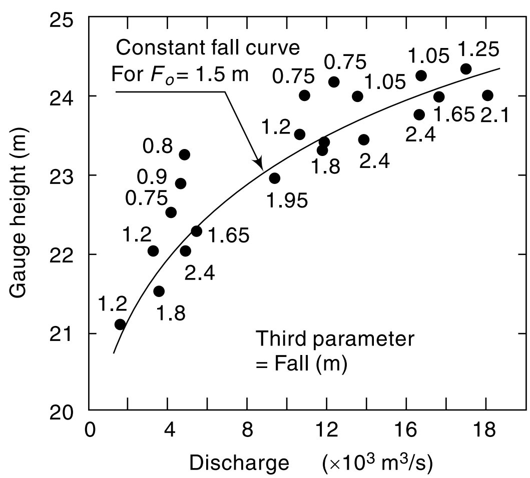


Fig. 4.25 Backwater Effect on a Rating Curve—Normalised Curve

exponent with a value close to 0.5. From the observed data, a convenient value of F_0 is selected. An approximate Q_0 *vs* G curve for a constant F_0 called *constant fall curve* is drawn. For each observed data, Q/Q_0 and F/F_0 values are calculated and plotted as Q/Q_0 *vs* F/F_0 (Fig. 4.26). This is called the *adjustment curve*. Both the constant fall curve and the adjustment curve are refined, by trial and error to get the best-fit curves. When finalized, these two curves provide the stage-discharge information for gauging purposes. For example, if the observed stage is G_1 and fall F_1, first by using the adjustment curve the value of Q_1/Q_0 is read for a known value of F_1/F_0. Using the constant fall-rating curve, Q_0 is read for the given stage G_1 and the actual discharge calculated as $(Q_1/Q_0) \times Q_0$.

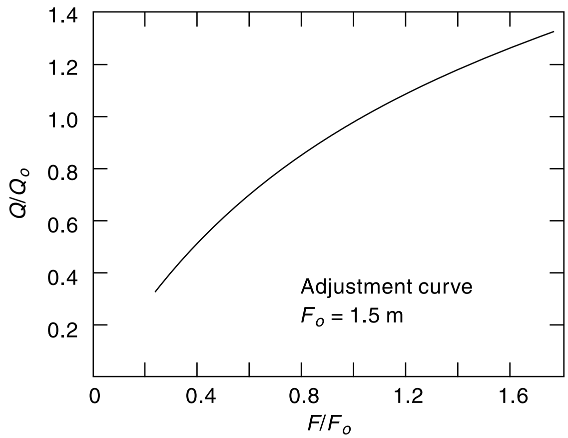


Fig. 4.26 Backwater Effect on a Rating Curve—Adjustment Curve

UNSTEADY-FLOW EFFECT When a flood wave passes a gauging station in the advancing portion of the wave the approach velocities are larger than in the steady flow at corresponding stage. Thus for the same stage, more-discharge than in a steady uniform flow occurs. In the retreating phase of the flood wave the converse situation occurs with reduced approach velocities giving lower discharges than in an equivalent steady flow case. Thus the stage-discharge relationship for an unsteady flow will not be a single-valued relationship as in steady flow but it will be a looped curve as in Fig. 4.27. It may be noted that at the same stage, more discharge passes through the river during rising stages than in falling ones. Since the conditions for each flood may be different, different floods may give different loops.

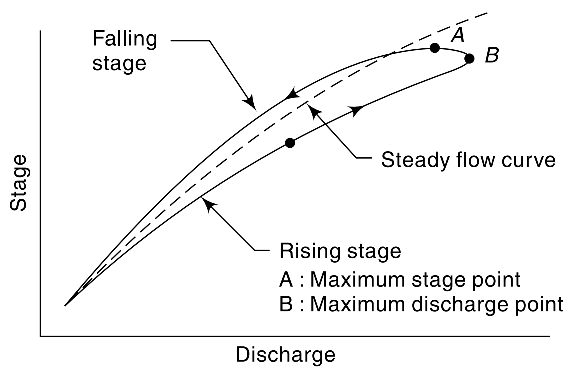


Fig. 4.27 Loop Rating Curve

If Q_n is the normal discharge at a given stage under steady uniform flow and Q_M is the measured (actual) unsteady flow the two are related as[7]

$$\frac{Q_M}{Q_n} = \sqrt{1 + \frac{1}{V_w S_0}\frac{dh}{dt}} \tag{4.32}$$

where S_0 = channel slope = water surface slope at uniform flow, dh/dt = rate of change of stage and V_w = velocity of the flood wave. For natural channels, V_w is usually assumed equal to 1.4 V, where V = average velocity for a given stage estimated by applying Manning's formula and the energy slope S_f. Also, the energy slope is used in place of S_0 in the denominator of Eq. (4.32). If enough field data about the flood magnitude and dh/dt are available, the term $(1/V_w S_0)$ can be calculated and plotted against the stage for use in Eq. (4.32). For estimating the actual discharge at an observed stage, Q_M/Q_n is calculated by using the observed data of dh/dt. Here Q_n is the discharge corresponding to the observed stage relationship for steady flow in the channel reach.

Example 4.5 *An auxiliary gauge was used downstream of a main gauge in a river to provide corrections to the gauge-discharge relationship due to backwater effects. The following data were noted at a certain main gauge reading.*

Main gauge (m above datum)	Auxiliary gauge (m above datum)	Discharge (m^3/s)
86.00	85.50	275
86.00	84 80	600

If the main gauge reading is still 86.00 m and the auxiliary gauge reads 85.30 m, estimate the discharge in the river.

Solution: Fall (F) = main gauge reading – auxiliary gauge reading.

When $F_1 = (86.00 - 85.50) = 0.50$ m $\quad Q_1 = 275$ m^3/s

$F_2 = (86.00 - 84.80) = 1.20$ m $\quad Q_2 = 600$ m^3/s

By Eq. (4.31) $(Q_1/Q_2) = (F_1/F_2)^m$ or $(275/600) = (0.50/1.20)^m$

Hence $m = 0.891$

When the auxiliary gauge reads 85.30 m, at a main gauge reading of 86.00 m,

Fall $F = (86.00 - 85.30) = 0.70$ m and

$$Q = Q_2\,(F/F_2)^m = 600\,(0.70/1.20)^{0.891} = 371 \text{ m}^3/\text{s}$$

4.10 EXTRAPOLATION OF RATING CURVE

Most hydrological designs consider extreme flood flows. As an example, in the design of hydraulic structures, such as barrages, dams and bridges one needs maximum flood discharges as well as maximum flood levels. While the design flood discharge magnitude can be estimated from other considerations, the stage-discharge relationship at the project site will have to be used to predict the stage corresponding to design-flood discharges. Rarely will the available stage-discharge data include the design-flood range and hence the need for extrapolation of the rating curve.

Before attempting extrapolation, it is necessary to examine the site and collect relevant data on changes in the river cross-section due to flood plains, roughness and backwater effects. The reliability of the extrapolated value depends on the stability of the gauging section control. A stable control at all stages leads to reliable results. Extrapolation of the rating curve in an alluvial river subjected to aggradation and degradation is unreliable and the results should always be confirmed by alternate methods. There are many techniques of extending the rating curve and two well-known methods are described here.

Conveyance Method

The conveyance of a channel in nonuniform flow is defined by the relation

$$Q = K\sqrt{S_f} \tag{4.33}$$

where Q = discharge in the channel, S_f = slope of the energy line and K = conveyance. If Manning's formula is used,

$$K = \frac{1}{n} AR^{2/3} \tag{4.34}$$

where n = Manning's roughness, A = area of cross-section and, R = hydraulic radius. Since A and R are functions of the stage, the values of K for various values of stage are calculated by using Eq. (4.34) and plotted against the stage. The range of the stage should include values beyond the level up to which extrapolation is desired. Then a smooth curve is fitted to the plotted points as shown in Fig. 4.28(a). Using the available discharge and stage data, values of S_f are calculated by using Eq. (4.33) as $S_f = Q^2/K^2$ and are plotted against the stage. A smooth curve is fitted through the plotted points as shown in Fig. 4.28(b). This curve is then extrapolated keeping in mind that S_f approaches a constant value at high stages.

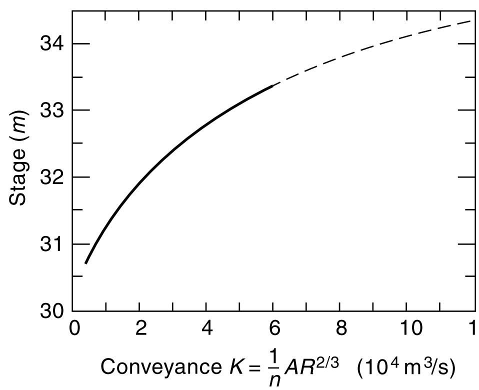


Fig. 4.28(a) Conveyance Method of Rating Curve Extension: K *vs* Stage

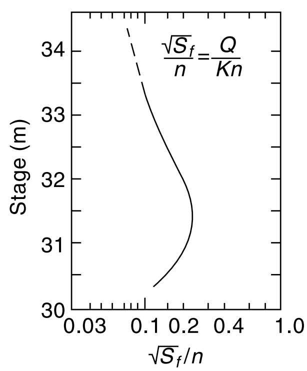


Fig. 4.28(b) Conveyance Method of Rating Curve Extension: S_f *vs* Stage

Using the conveyance and slope curves, the discharge at any stage is calculated as $Q = K\sqrt{S_f}$ and a stage-discharge curve covering the desired range of extrapolation is constructed. With this extrapolated-rating curve, the stage corresponding to a design-flood discharge can be obtained.

Logarithmic-Plot Method

In this technique the stage-discharge relationship given by Eq. (4.26) is made use of. The stage is plotted against the discharge on a log–log paper. A best-fit linear relationship is obtained for data points lying in the high-stage range and the line is extended to cover the range of extrapolation. Alternatively, coefficients of Eq. (4.26) are obtained by the least-square-error method by regressing X on Y in Eq. (4.27a). For this Eq. (4.27a) is written as

$$X = \alpha Y + C \tag{4.35}$$

where the dependent variable $X = \log (G - a)$ and $Y = \log Q$. The coefficients α and C are obtained as,

$$\alpha = \frac{N(\Sigma XY) - (\Sigma Y)(\Sigma X)}{N(\Sigma Y^2) - (\Sigma Y)^2} \tag{4.35a}$$

and
$$C = \frac{(\Sigma X) - \alpha(\Sigma Y)}{N} \tag{4.35b}$$

The relationship governing the stage and discharge is now

$$(G - a) = C_1 Q^{\alpha} \tag{4.36}$$

where C_1 = antilog C.

By the use of Eq. (4.36) the value of the stage corresponding to a design flood discharge is estimated.

EXAMPLE 4.6 *For the stage-discharge data of Example 4.4, fit a regression equation for use in estimation of stage for a known value of discharge. Use a value of 7.50 m as the gauge reading corresponding to zero discharge. Determine the stage for a discharge of 3500 m³/s.*

SOLUTION: The regression equation is $X = \alpha Y + C$ (Eq. 4.35)
where $X = \log(G - a)$ and $Y = \log Q$. The value of α is given by Eq. (4.35a) as

$$\alpha = \frac{N(\Sigma XY) - (\Sigma Y)(\Sigma X)}{N(\Sigma Y^2) - (\Sigma Y)^2}$$

Values of X, Y and XY are the same as calculated for the data in Table 4.3. Thus

$\Sigma X = -1.262$ $\Sigma Y = 32.325$ $\Sigma XY = 1.636$
$\Sigma X^2 = 3.239$ $\Sigma Y^2 = 81.379$
$(\Sigma X)^2 = 1.5926$ $(\Sigma Y)^2 = 1044.906$ $N = 14$

Substituting these values in Eq. (4.35)

$$\alpha = \frac{(14 \times 1.636) - (32.325)(-1.262)}{(14 \times 81.379) - (1044.906)} = 0.675$$

The coefficient C is given by Eq. (4.35b) as

$$C = \frac{(\Sigma X) - \alpha(\Sigma Y)}{N} = \frac{(-1.262) - 0.675(32.325)}{14} = -1.6486$$

C_1 = antilog $C = 0.02246$ leading to the gage-discharge equation as

$$(G - a) = 0.02246\, Q^{0.675}$$

The variation of relative stage $(G - a)$ with discharge (Q) is shown in Fig. 4.29(a)—arithmetic plot and in Fig. 4.29(b)—logarithmic plot.

(b) When $Q = 3500$ m³/s and given that $a = 7.50$ m

$$(G - 7.50) = 0.02246\,(3500)^{0.675} = 5.540 \text{ m}$$
$$G = 13.04 \text{ m}$$

4.11 HYDROMETRY STATIONS

As the measurement of discharge is of paramount importance in applied hydrologic studies, considerable expenditure and effort are being expended in every country to collect and store this valuable historic data. The WMO recommendations for the minimum number of hydrometry stations in various geographical regions are given in Table 4.3.

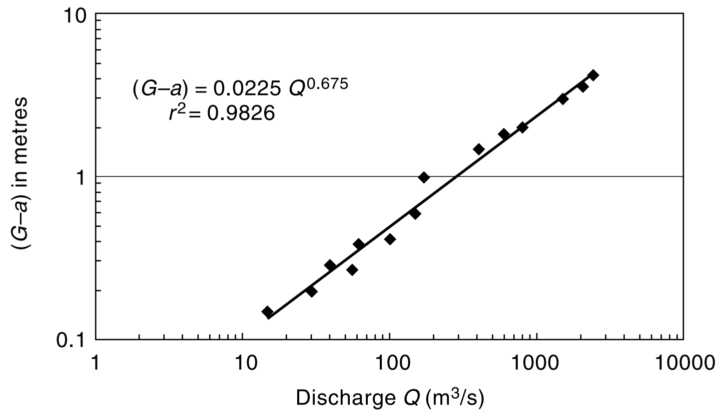


Fig. 4.29(a) Discharge-stage Relationship: Example 4.6 (Logarithmic Plot)

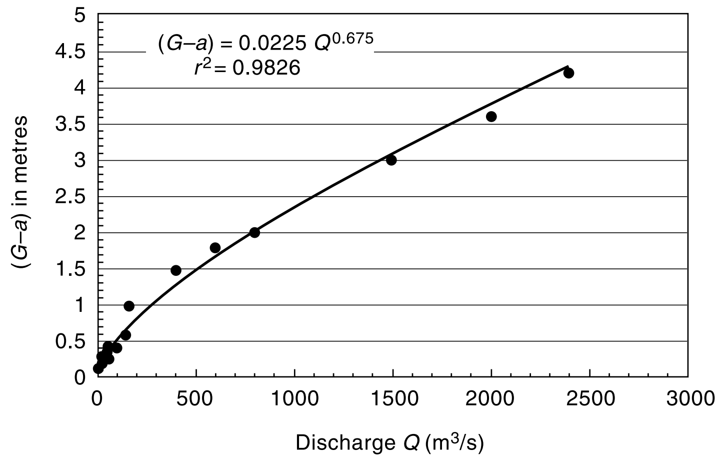


Fig. 4.29(b) Discharge-stage Relationship: Example 4.6 (Arithmetic Plot)

Table 4.3 WMO Criteria for Hydrometry Station Density

S. No.	Region	Minimum density (km^2/station)	Tolerable density under difficult conditions (km^2/station)
1.	Flat region of temperate, mediterranean and tropical zones	1,000 – 2,500	3,000 – 10,000
2.	Mountainous regions of temperate mediterranean and tropical zones	300 – 1,000	1,000 – 5,000
3.	Arid and polar zones	5,000 – 20,000	

Hydrometry stations must be sited in adequate number in the catchment area of all major streams so that the water potential of an area can be assessed as accurately as possible.

As a part of hydrological observation activities CWC operates a vast network of 877 hydrological observation stations on various state and interstate rivers for collection of gauge, discharge, silt and water quality data which are stored after analysis in central data bank. In addition to observation of river flow, CWC is also monitoring water quality, covering all the major river basins of India. The distribution of various kinds of CWC hydrological observation stations is as follows:

Type of Station	Number
Gauge observation only	236
Gauge—Discharge	281
Gauge—Discharge and Silt	41
Gauge—Discharge and water quality	80
Gauge—Discharge, water quality and Silt	239

In a few gauging stations on major rivers, moving boat method facilities exist. Reports containing the gauge, discharge, sediment and water quality data are brought out by CWC every year as *Year books*. In addition to the above, the state governments maintain nearly 800 gauging stations. Further, in most of the states institutional arrangements exist for collection, processing and analysis of hydrometric and hydrometeorological data and publication of the same.

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Revision Questions

4.1 Explain the various commonly used methods of measurement of stage of a river. Indicate for each method its specific advantage and the conditions under which one would use it.

4.2 What factors should be considered in selecting a site for a stream gauging station?

4.3 Explain the salient features of a current meter. Describe briefly the procedure of using a current meter for measuring velocity in a stream.

4.4 List the qualities of a good tracer for use in dilution technique of flow measurement.

4.5 Explain briefly the dilution method of flow measurement.

4.6 Explain the streamflow measurement by area-velocity method.

4.7 Describe briefly the moving boat method of stream flow measurement.

4.8 Describe the slope-area method of measurement of flood discharge in a stream.

4.9 Explain the procedure for obtaining the stage-discharge relationship of a stream by using the stage-discharge data from a site with permanent control.

4.10 Describe briefly:
(a) Backwater effect on a rating curve.
(b) Unsteady flow effect on a rating curve

4.11 Describe a procedure for extrapolating a rating curve of a stream.

4.12 Discuss the advantages and disadvantages of the following relative to the flow measurement by using current meters:
(a) Electromagnetic method (b) Ultrasound method

4.13 Explain briefly the important aspects relating to the following instruments
(a) Float-gauge recorder (b) Bubble gauge
(c) Echo-depth recorder (d) Current meter

Problems

4.1 The following data were collected during a stream-gauging operation in a river. Compute the discharge.

Distance from left water edge (m)	Depth (m)	Velocity (m/s)	
		at 0.2 *d*	at 0.8 *d*
0.0	0.0	0.0	0.0
1.5	1.3	0.6	0.4
3.0	2.5	0.9	0.6
4.5	1.7	0.7	0.5
6.0	1.0	0.6	0.4
7.5	0.4	0.4	0.3
9.0	0.0	0.0	0.0

4.2 The velocity distribution in a stream is usually approximated as $v/v_a = (y/a)^m$, where v and v_a are velocities at heights y and a above the bed respectively and m is a coefficient with a value between 1/5 to 1/8. (i) Obtain an expression for $v/\bar{v}$, where $\bar{v}$ is the mean velocity in terms of the depth of flow. (ii) If $m = 1/6$ show that (a) the measured velocity is equal to the mean velocity if the velocity is measured at 0.6 depth from the water surface and (b) $\bar{v} = \frac{1}{2}(v_{0.2} + v_{0.82})$, where $v_{0.2}$ and $v_{0.82}$ are the velocities measured at 0.2 and 0.82 depths below the water surface respectively.

4.3 The following are the data obtained in a stream-gauging operation. A current meter with a calibration equation $V = (0.32N + 0.032)$ m/s, where N = revolutions per second was used to measure the velocity at 0.6 depth. Using the mid-section method, calculate the discharge in the stream.

Distance from right bank (m)	0	2	4	6	9	12	15	18	20	22	23	24
Depth (m)	0	0.50	1.10	1.95	2.25	1.85	1.75	1.65	1.50	1.25	0.75	0
Number of revolutions	0	80	83	131	139	121	114	109	92	85	70	0
Observation Time (s)	0	180	120	120	120	120	120	120	120	120	150	0

4.4 In the moving-boat method of discharge measurement the magnitude (V_R) and direction (θ) of the velocity of the stream relative to the moving boat are measured. The depth of the stream is also simultaneously recorded. Estimate the discharge in a river that gave the following moving-boat data. Assume the mean velocity in a vertical to be 0.95 times the surface velocity measured by the instrument.

Section	V_R (m/s)	θ (degrees)	Depth (m)	Remark
0	—	—	—	Right bank.
1	1.75	55	1.8	
2	1.84	57	2.5	
3	2.00	60	3.5	θ is the angle made by V_R
4	2.28	64	3.8	with the boat direction
5	2.30	65	4.0	
6	2.20	63	3.8	The various sections are
7	2.00	60	3.0	spaced at a constant
8	1.84	57	2.5	distance of 75 m apart
9	1.70	54	2.0	
10	—	—	—	Left bank

4.5 The dilution method with the sudden-injection procedure was used to measure the discharge of a stream. The data of concentration measurements are given below. A fluorescent dye weighing 300 N used as a tracer was suddenly injected at station *A* at 07 h.

Time (h)	07	08	09	10	11	12	13	14	15	16	17	18
Concentration at station *B* in parts per 10^9 by weight	0	0	3.0	10.5	18.0	18.0	12.0	9.0	6.0	4.5	1.5	0

Estimate the stream discharge.

4.6 A 500 g/*l* solution of sodium dichromate was used as chemical tracer. It was dosed at a constant rate of 4 *l*/s and at a downstream section. The equilibrium concentration was, measured as 4 parts per million (ppm). Estimate the discharge in the stream.

4.7 A 200 g/*l* solution of common salt was discharged into a stream at a constant rate of 25 *l*/s. The background concentration of the salt in the stream water was found to be 10 ppm. At a downstream section where the solution was believed to have been completely mixed, the salt concentration was found to reach an equilibrium value of 45 ppm. Estimate the discharge in the stream.

4.8 It is proposed to adopt the dilution method of stream gauging for a river whose hydraulic properties at average flow are as follows: width = 45 m, depth = 2.0 m, discharge = 85 m^3/s, Chezy coefficient = 20 to 30. Determine the safe mixing length that has to be adopted for this stream.

4.9 During a high flow water-surface elevations of a small stream were noted at two sections *A* and *B*, 10 km apart. These elevations and other salient hydraulic properties are given below.

Section	Water-surface elevation (m)	Area of cross-section (m^2)	Hydraulic radius (m)	Remarks
A	104.771	73.293	2.733	*A* is upsteam of *B*
B	104.500	93.375	3.089	$n = 0.020$

The eddy loss coefficients of 0.3 for gradual expansion and 0.1 for gradual contraction are appropriate. Estimate the discharge in the stream.

4.10 A small stream has a trapezoidal cross section with base width of 12 m and side slope 2 horizontal: 1 vertical in a reach of 8 km. During a flood the high water levels record at the ends of the reach are as follows.

Section	Elevation of bed (m)	Water surface elevation (m)	Remarks
Upstream	100.20	102.70	Manning's n = 0.030
Downstream	98.60	101.30	

Estimate the discharge in the stream.

4.11 The stage-discharge data of a river are given below. Establish the stage-discharge relationship to predict the discharge for a given stage. Assume the value of stage for zero discharge as 35.00 m. (2) What is the correlation coefficient of the relationship established above? (3) Estimate the discharge corresponding to stage values of 42.50 m and 48.50 m respectively.

Stage (m)	Discharge (m^3/s)	Stage (m)	Discharge (m^3/s)
35.91	89	39.07	469
36.90	230	41.00	798
37.92	360	43.53	2800
44.40	3800	48.02	5900
45.40	4560	49.05	6800
46.43	5305	49.55	6900
		49.68	6950

4.12 Downstream of a main gauging station, an auxiliary gauge was installed and the following readings were obtained.

Main gauge (m)	Auxiliary gauge (m)	Discharge (m^3/s)
121.00	120.50	300
121.00	119.50	580

What discharge is indicated when the main gauge reading is 121.00 m and the auxiliary gauge reads 120.10 m.

4.13 The following are the coordinates of a smooth curve drawn to best represent the stage-discharge data of a river.

Stage (m)	20.80	21.42	21.95	23.37	23.00	23.52	23.90
Discharge (m^3/s)	100	200	300	400	600	800	1000

Determine the stage corresponding to zero discharge.

4.14 The stage discharge data of a river are given below. Establish a stage-discharge relationship to predict the stage for a known discharge. Assume the stage value for zero discharge as 20.50 m. Determine the stage of the river corresponding to a discharge of 2600 m^3/s.

Stage (m)	Discharge (m^3/s)	Stage (m)	Discharge (m^3/s)
21.95	100	24.05	780
22.45	220	24.55	1010
22.80	295	24.85	1220
23.00	400	25.40	1300
23.40	490	25.15	1420
23.75	500	25.55	1550
23.65	640	25.90	1760

(**Hint:** Use Eq. 4.35)

4.15 During a flood the water surface at a section in a river was found to increase at a rate of 11.2 cm/h. The slope of the river is 1/3600 and the normal discharge for the river stage read from a steady-flow rating curve was 160 m^3/s . If the velocity of the flood wave can be assumed as 2.0 m/s, determine the actual discharge.

Objective Questions

4.1 The science and practice of water flow measurement is known as
(a) Hypsometry (b) Hydro-meteorology
(c) Fluvimetry (d) Hydrometry

4.2 The following is *not* a direct stream flow determination technique
(a) Dilution method (b) Ultrasonic method
(c) Area-velocity method (d) Slope-area method

4.3 A stilling well is required when the stage measurement is made by employing a
(a) bubble gauge (b) float gauge recorder
(c) vertical staff gauge (d) inclined staff gauge

4.4 In a river carrying a discharge of 142 m^3/s, the stage at a station *A* was 3.6 m and the water surface slope was 1 in 6000. If during a flood the stage at *A* was 3.6 m and the water surface slope was 1/3000, the flood discharge (in m^3/s) was approximately
(a) 100 (b) 284 (c) 71 (d) 200

4.5 In a triangular channel the top width and depth of flow were 2.0 m and 0.9 m respectively. Velocity measurements on the centre line at 18 cm and 72 cm below water surface indicated velocities of 0.60 m/s and 0.40 m/s respectively. The discharge in the channel (in m^3/s) is
(a) 0.90 (b) 1.80 (c) 0.45 (d) none of these.

4.6 In the moving-boat method of stream-flow measurement, the essential measurements are:
(a) the velocity recorded by the current meter, the depths and the speed of the boat.
(b) the velocity and direction of the current meter, the depths and the time interval between depth readings
(c) the depth, time interval between readings, speed of the boat and velocity of the stream
(d) the velocity and direction of the current meter and the speed of the boat.

4.7 Which of the following instruments in *not* connected with stream flow measurement
(a) hygrometer (b) Echo-depth recorder
(c) Electro-magnetic flow meter (d) Sounding weight

4.8 The surface velocity at any vertical section of a stream is
(a) not of any use in stream flow measurement
(b) smaller than the mean velocity in that vertical
(c) larger than the mean velocity in that vertical section
(d) equal to the velocity in that vertical at 0.6 times the depth.

4.9 If a gauging section is having shifting control due to backwater effects, then
(a) a loop rating curve results
(b) the section is useless for stream-gauging purposes
(c) the discharge is determined by area-velocity methods
(d) a secondary gauge downstream of the section is needed.

4.10 The stage discharge relation in a river during the passage of a flood wave is measured. If Q_R = discharge at a stage when the water surface was rising and Q_F = discharge at the same stage when the water surface was falling, then
(a) $Q_F = Q_R$ (b) $Q_R > Q_F$
(c) $Q_R < Q_F$ (d) Q_R/Q_F = constant at all stages

4.11 A large irrigation canal can be approximated as a wide rectangular channel and Manning's formula is applicable to describe the flow in it. If the gauge (*G*) is related to discharge (*Q*) as

$$Q = C_r(G - a)^{\beta}$$

where a = gauge height at zero discharge, the value of β is
(a) 1.67 (b) 1.50 (c) 2.50 (d) 0.67

4.12 The dilution method of stream gauging is ideally suited for measuring discharges in
(a) a large alluvial river
(b) flood flow in a mountain stream
(c) steady flow in a small turbulent stream
(d) a stretch of a river having heavy industrial pollution loads.

4.13 A 400 g/*l* solution of common salt was discharged into a stream at a constant rate of 45 *l*/s. At a downstream section where the salt solution is known to have completely mixed with the stream flow the equilibrium concentration was read as 120 ppm. If a background concentration of 20 ppm is applicable, the discharge in the stream can be estimated to be, in m^3/s, as
(a) 150 (b) 180 (c) 117 (d) 889

4.14 In the gulp method of stream gauging by dilution technique, 60 litres of chemical *X* with concentration of 250 g/litre is introduced suddenly in to the stream at a section. At a downstream monitoring section the concentration profile of chemical *X* that crossed the section was found to be a triangle with a base of 10 hours and a peak of 0.10 ppm. The discharge in the stream can be estimated to be about
(a) 83 m^3/s (b) 180 m^3/s (c) 15000 m^3/s (d) 833 m^3/s

4.15 The slope-area method is extensively used in
(a) development of rating curve
(b) estimation of flood discharge based on high-water marks
(c) cases where shifting control exists.
(d) cases where backwater effect is present.

4.16 For a given stream the rating curve applicable to a section is available. To determine the discharge in this stream, the following-data are needed
(a) current meter readings at various verticals at the section
(b) slope of the water surface at the section
(c) stage at the section
(d) surface velocity at various sections.

4.17 During a flood in a wide rectangular channel it is found that at a section the depth of flow increases by 50% and at this depth the water-surface slope is half its original value in a given interval of time. This marks an approximate change in the discharge of
(a) –33% (b) +39% (c) +20% (d) no change.

4.18 In a river the discharge was 173 m^3/s, the water surface slope was 1 in 6000 and the stage at the station *X* was 10.00 m. If during a flood, the stage at station *X* was 10.00 and the water surface slope was 1/2000, the flood discharge was approximately
(a) 100 m^3/s (b) 519 m^3/s (c) 300 m^3/s (d) 371 m^3/s

4.19 During a flood, the water surface at a section was found to decrease at a rate of 10 cm/h. The slope of the river is 1/3600. Assuming the velocity of the flood wave as 2 m/s, the actual discharge in the stream can be estimated as
(a) 2.5% larger than the normal discharge
(b) 5% smaller than the normal discharge
(c) 2.5% smaller than the normal discharge
(d) Same as the normal discharge
where normal discharge is the discharge at a given stage under steady, uniform flow.