CHAPTER 5

SURFACE WATER QUANTITY AND SEDIMENT MEASUREMENT

5.1 WATER LEVELS OF RIVERS, LAKES AND RESERVOIRS

5.1.1 General

Water level, or stage, is the elevation of the water surface of a stream, lake or other water body relative to a datum (ISO, 1988*b*), and may be used directly in forecasting flows, to delineate flood hazard areas and to design structures in or near water bodies. When correlated with stream discharge or with the storage volumes of reservoirs and lakes, water levels become the basis for computation of discharge or storage records. An expanded discussion of this topic is given in the *Manual on Stream Gauging* (WMO-No. 519).

The site selected for observation of stage should be governed by the purpose for which the records are collected and by the accessibility of the site. Hydraulic conditions are an important factor in site selection on streams, particularly where water levels are used to compute discharge records. Gauges on lakes and reservoirs are normally located near their outlets, but sufficiently upstream to avoid the influence of drawdown.

5.1.2 Gauges for measurement of stage [HOMS C71]

5.1.2.1 Non-recording gauges

Several types of non-recording gauges for measuring stage are used in hydrometric practice. The common gauges are of the following types:

(a) Graduated vertical staff gauge;
(b) Ramp or inclined gauge;
(c) Wire-weight gauge installed on a structure above the stream;
(d) Graduated rod, tape, wire or point gauge for measuring the distance to the water surface;
(e) Maximum-stage gauge for obtaining the elevation of the flood crest by the adherence of regranulated cork to a graduated staff held in a fixed position with relation to the datum.

5.1.2.2 Recording gauges

Many different types of continuously recording stage gauges are in use. They may be classified according to both mode of actuation and mode of recording.

A commonly used installation consists of a stilling well connected to the stream by pipes and a float in the stilling well connected to a wheel on a recorder by a beaded wire or perforated tape. In high velocity streams, it may be necessary to install static tubes on the end of the intake pipes to avoid drawdown of the water level in the well.

The recorder can either be mechanical or electronic. Recorders with the wheel linked to a pencil or pen and the pencil or pen placed on a strip chart moved by a mechanical clock are still widely used and have proved to be reliable. The timescale and stage scale chosen for a particular station will depend on the range in stage, sensitivity of the stage-discharge relation, and runoff characteristics of the basin. Back in the main office the strip chart can be digitized so that the data can be entered into a computer. The wheel can also be connected directly to an encoder. The encoder will give out analogue or digital values that can be read and stored by a data logger.

Various pressure-actuated recording gauges in common use operate on the principle that static pressure at a fixed point in the stream is directly proportional to the head of liquid above the point. This relation is described by the following equation:

$$\textit{Water level} = (P_{static} - P_{atm})\, C \qquad (5.1)$$

where P_{static} is the pressure in bar on a fixed spot in the water column (one has to make sure that any dynamic pressure from water movement is not measured), P_{atm} is the atmospheric pressure in bar on the surface of the water column, and C is a factor of the water's net weight (C = 10.2 for freshwater at 20°C), which changes with the temperature and salinity of the water. Some gauges use a gas-purge system to transmit the pressure to the gauge. A small quantity of air or inert gas (for example, nitrogen) is allowed to bubble through a pipe or tubing to an orifice in the stream. The pressure of the air or gas that displaces the liquid in the pipe is then measured and recorded. Other gauges use pressure transmitters placed directly into the riverbed.

Compensating for the atmospheric pressure is done by taking air down a small ventilation tube in the cable or by measuring it with another pressure transducer on the surface. The main advantage of pressure-actuated recorders is that they do not require a stilling well, although any unfortunate alignment of the pressure-transducer with respect to flow can cause significant error, and the gas purge systems in particular are not sensitive to sediment if its concentration is in the range normally encountered in a natural setting. Care has to be taken when placing the pressure transducer or bubble gauge on the riverbed. It is important to make sure it does not move and that it is exposed only to static pressure. Compensating for changes in temperature and atmospheric pressure on the surface is also critical.

Two kinds of recording gauge that have come into recent use are those that use ultrasonic or radar sensors. The ultrasonic sensor is based on the speed of transit of a pulse of ultrasonic frequency (>20 kHz), which is emitted by a transmitter located in a structure over the lake or the river. When the pulse hits the surface of the water body, it echoes back to the sensor. The time T which passes from the moment of emission of the pulse and the moment of reception of the echo by the sensor is directly proportional to the distance d between the sensor and the water surface, and inversely proportional to the speed of the pulse in the air. It can be calculated as:

$$T=2d/v \quad (5.2)$$

As sound speed depends on air temperature, it is necessary to compensate with a correction factor to obtain a precise value. The radar sensor is similar to the ultrasonic sensor, but uses high frequencies (around 20 GHz). It has the advantage that at the higher frequency the transit speed of the pulse is not affected by air temperature.

River stage may be recorded on graphical (analogue) recorders. Alternatively the stage can be recorded digitally at fixed or action-triggered intervals.

5.1.3 Procedures for measurement of stage

5.1.3.1 Establishment of gauge datum

To avoid negative readings, the gauge should be set so that a reading of zero is below the lowest anticipated stage. The gauge datum should be checked annually by levelling from local benchmarks. It is important to maintain the same gauge datum throughout the period of record. If feasible, the local gauge datum should be tied to a national or regional datum. The precise locations of the benchmarks should be carefully documented.

5.1.3.2 Recording gauges

The graphical, digital, electronic, or telemetering device recorder is set by reference to an auxiliary tape-float gauge or to a staff gauge located inside the stilling well. In addition, a staff, ramp or wire-weight gauge set to the same datum is necessary to compare the water surface elevation in the stilling well with that of the river. For gauges with gas-purge systems and no stilling well, the staff, ramp or wire-weight gauge in the river should serve as the reference gauge. Small differences usually will occur because of velocity past the ends of the intake pipes. Large differences indicate that the intake pipes may be obstructed.

5.1.3.3 Winter operation of recording gauges

(a) Float-actuated – This type of installation requires a stilling well that must be kept ice-free in winter. This can be done by heating the well with, for example, electricity or gas. Other devices to prevent freezing within a stilling well are a temporary floor within the well at an elevation just below the frost line, and a vertical, open-ended tube, large enough in diameter to receive the float, and containing a layer of fuel oil on the water surface;
(b) Pressure-actuated air bellows and transducers – These types of installations require neither a stilling well nor an operating medium subject to freezing. However, the tube or cable going into water has to be protected from ice.

5.1.4 Frequency of stage measurement

The frequency of recording of water level is determined by the hydrological regime of the water body and by the purposes for collecting the data. At continuous-record gauging stations hourly recordings are normally sufficient for most rivers. For measurement in small or flashy streams and urban catchments, stage has to be recorded more frequently in order to obtain a sufficiently accurate hydrograph. In general, it is recommended to record stage as frequently as possible within the limitations given by the available battery capacity and data memory. Installation of water level recorders is essential for streams where the level is subject to abrupt fluctuations. The non-recording gauge is frequently used as a part of flood forecasting systems, where a local observer is available to report on river stage. For purposes such as flood forecasting or flood management, telemetering systems may be employed to transmit data whenever the stage changes by a predetermined amount.

For some purposes, the recording of only the maximum stages during floods is sufficient and maximum-stage gauges are used. A daily measurement of stage is usually sufficient in lakes and reservoirs for the purpose of computing changes in storage. The recording time interval for a particular station is selected on the basis of the rapidity with which the stage can change and its significance to change in discharge. Flashy streams require shorter time intervals, and large streams allow longer time intervals (ISO, 1981).

Output from pressure transducers, shaft encoders, or other devices that provide electronic outputs representing the stage can also be recorded on electronic data loggers (2.5), or with appropriate interfaces the data can be telemetered from remote locations.

5.2 ICE ON RIVERS, LAKES AND RESERVOIRS

5.2.1 General

Observations of ice conditions on rivers, lakes and reservoirs are of great interest in regions where ice formation affects navigation or results in damage to structures, and where ice jams may form (even to the extent of damming a major river). The obstruction of streamflow by ice can also cause serious local flooding. Long-term data on ice conditions in rivers are extremely valuable in designing various structures, in studying processes of ice formation and dissipation, and in developing methods of ice forecasting.

5.2.2 Elements of ice regime

The most important elements of ice regime to be recorded are the following:

(a) Dates on which flows of floating ice are first observed each winter;
(b) Ratio of the surface area of drifting ice to the open–water surface (ice cover ratio);
(c) Ratio of the surface area of drifting ice to the stationary ice surface;
(d) Dates on which ice becomes immovable;
(e) Thickness of ice;
(f) Features of ice destruction;
(g) Dates of ice break-up;
(h) Dates on which the ice on rivers and reservoirs vanish completely.

5.2.3 Methods of observation

Many of the elements given in 5.2.2 cannot be measured instrumentally and must be evaluated subjectively and recorded in descriptive language. For this reason, it is very important that observers be well trained and that instructions be clearly prepared.

The thickness of ice is measured by means of an auger and a ruler at representative sites. To minimize errors caused by spatial variability in ice thickness, measurements should be made at a minimum of three points spaced over a distance of at least 5 m, and the measurements should be averaged. The depth of any snow on top of the ice should also be measured.

The kilometre signs of navigable rivers or dykes may be used to identify the locations at which ice surveys are routinely conducted. Particularly dangerous conditions (for example, ice jams) must be identified in relation to other landmarks (for example, bridges, river regulation structures and harbours).

Determining some of the characteristics of ice phenomena can be made by means of regular photogrammetric surveys from a location on the shore or by aerial photography. In the case of large rivers, reservoirs or lakes, aircraft observations of ice formation or break-up are of great value. They are also useful in the case of ice gorges when flood warnings are required.

For surveying ice conditions over a reach, a strip width, s, and a flying height, hf, can be determined as a function of focal length, Lf, of the camera being used and the effective width, l, of the film frame, $hf = s\ (Lf/l)$. Because Lf is a camera constant that is approximately equal to 1.0, the strip width is approximately equal to the flying height. By repeat aerial photography at intervals of a few minutes, the velocity of the ice drift can be determined along with the density of cover. If the average ice thickness is known, the ice discharge (throughput) can also be calculated.

Television and IR remote-sensing data from meteorological and Earth-resource satellites are also useful for estimating ice conditions on lakes and reservoirs (Prokacheva, 1975).

5.2.4 Times and frequency of observations

Observations of the state of the ice are made at times when the water level is observed, while ice thickness and snow depth on major rivers, lakes and reservoirs should be measured at intervals of 5 to 10 days during the critical periods of ice formation and break up. Aircraft observations should be made, as required, to meet special purposes.

5.2.5 Accuracy of measurement

The measurement of ice cannot be very accurate because of difficult conditions. However, uncertainty of ice thickness measurement should not exceed 10 to 20 mm or 5 per cent, whichever is greater.

5.3 DISCHARGE MEASUREMENTS AND COMPUTATION

5.3.1 General [HOMS E70]

River discharge, which is expressed as volume per unit time, is the rate at which water flows through a cross-section. Discharge at a given time can be measured by several different methods, and the choice of methods depends on the conditions encountered at a particular site. Normally, the discharge shall be related to a corresponding water stage at a gauging station.

The accuracy of the discharge measurement depends on the length of time required to make the measurement, and the extent to which the stage and the discharge change during the measurement. Changes in the downstream conditions during the measurement can influence the result and should be avoided.

5.3.2 Measurement of discharge by current meters [HOMS C79, C85, C86, C88, E79]

Measurement of discharge by the velocity-area method is explained by reference to Figure I.5.1. The depth of flow in the cross-section is measured at verticals with a rod or sounding line. As the depth is measured, observations of velocity are obtained with a current meter at one or more points in the vertical. The measured widths, depths and velocities permit computation of discharge for each segment of the cross-section. The summation of these segment discharges is the total discharge (ISO, 1979*b*).

5.3.2.1 Selection of site

Discharge measurements need not be made at the exact location of the stage gauge because the discharge is normally the same throughout a reach of channel in the general vicinity of the gauge. Sites selected for measurements should ideally have the following characteristics (ISO, 1979*b*):

(a) The velocities at all points are parallel to one another and at right angles to the cross-section of the stream;
(b) The curves of distribution of velocity in the section are regular in the vertical and horizontal planes;

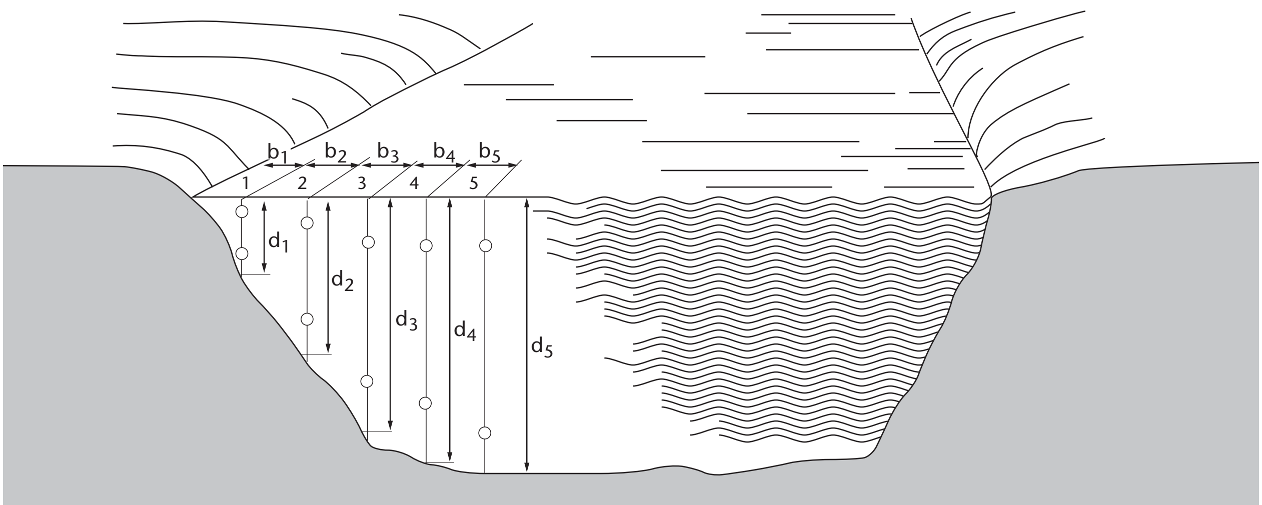

Figure I.5.1. View of a stream cross-section showing the location of points of observation

(c) The velocities are greater than 0.150 m s^{-1};
(d) The bed of the channel is regular and stable;
(e) The depth of flow is greater than 0.300 m;
(f) There is no aquatic growth;
(g) There is minimal formation of slush or frazil ice (5.3.2.5.1).

5.3.2.2 Measurement of cross-section

The accuracy of a discharge measurement depends on the number of verticals at which observations of depth and velocity are obtained. Observation verticals should be located to best define the variation in elevation of the stream bed and the horizontal variation in velocity. In general, the interval between any two verticals should not be greater than 1/20 of the total width and the discharge of any segment should not be more than 10 per cent of the total discharge.

Channel width and the distance between verticals should be obtained by measuring from a fixed reference point (usually an initial point on the bank), which should be in the same plane as the cross-section. Normally, the distance between verticals is determined from graduated tape or beaded wire temporarily stretched across the stream or from semi-permanent marks, for example, painted on a bridge handrail or a suspension cable (ISO, 1979*b*). For large rivers, telemetry systems or triangulation practices can be used for measuring widths.

Depth may be read directly on a graduated rod set on the stream bed if measurement is by wading. If the drum-wire-weight system is used for measurement, the current meter and weight are lowered until the bottom of the weight just touches the water surface, and the depth dial reading is set at zero. The weight is then lowered until it rests on the stream bed, and the depth is read on the dial.

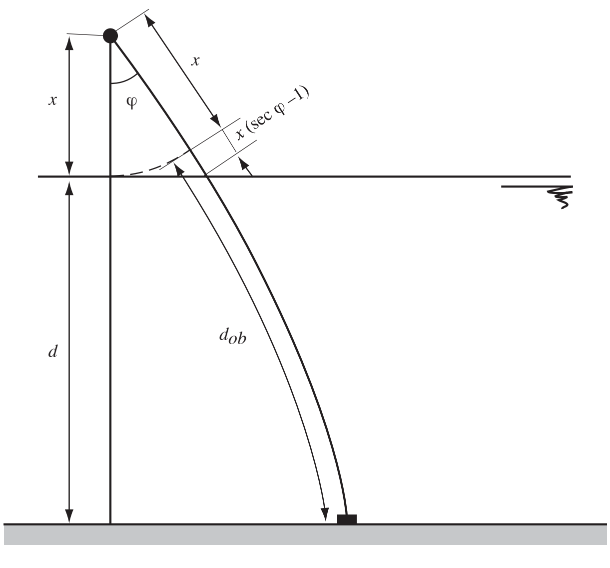

Figure I.5.2. Relationship between correct depth *d* and observed depth d_{ob}

Table I.5.1. Correction factor *k* for given values φ

φ	*k*	φ	*k*	φ	*k*
4°	0.0006	14°	0.0098	24°	0.0256
6°	0.0016	16°	0.0128	26°	0.0350
8°	0.0032	18°	0.0164	28°	0.0408
10°	0.0050	20°	0.0204	30°	0.0472
12°	0.0072	22°	0.0248		

If the weight on the sounding line is not sufficient to keep the line perpendicular to the water surface, the angle between the line and the vertical should be measured to the nearest degree with a protractor. The relationship between the correct depth, *d*, and the observed depth, d_{ob}, based on the observed angle, φ, and the distance from the water surface to the point of suspension of the sounding line, *x*, is shown in Figure I.5.2 and is given below:

$$d = [d_{ob} - x\ (\sec\varphi - l)][1 - k] \qquad (5.3)$$

Values of *k* as given in Table I.5.1 are based on the assumptions that the drag pressure on the weight in the comparatively still water near the bottom can be neglected and that the sounding wire and weight are designed to offer little resistance to the water current. The uncertainties in this estimation are such that significant errors may be introduced if the vertical angle is more than 30°.

5.3.2.3 Measurement of velocity [HOMS C79, E79]

5.3.2.3.1 *Meters for measurement of velocity*

Velocity of flow at a point is usually measured by counting revolutions of a current meter rotor during a short-time period measured with a stop-watch (ISO, 1979*b*). Two types of current meter rotors are in general use: the cup type with a vertical shaft and the propeller type with a horizontal shaft. Both types use a make-and-break contact to generate an electric pulse for indicating the revolutions of the rotor (ISO, 1988*a*). Optical, non-contact type counters are also in use with cup-type meters.

Current meters are calibrated to cover the range in velocity of flow to be measured. Detailed calibration procedures are described in ISO 3455 (ISO, 1976). Current meters may be calibrated individually or a group rating may be used. Individually calibrated meters should be recalibrated after three years or 300 hours of use or if their performance is suspect (*Technical Regulations* (WMO-No. 49), Volume III, Annex).

5.3.2.3.2 *Measurement of velocity using the current meter*

Velocity is observed at one or more points in each vertical by counting revolutions of the rotor during a period of not less than 30 seconds. Where the velocity is subject to large periodic pulsations the exposure time should be increased accordingly (*Technical Regulations* (WMO-No. 49), Volume III, Annex).

For shallow channels, the current meter should be held in the desired position by means of a wading rod. For channels too deep or swift to wade, it should be positioned by suspending it from a wire or rod from a bridge, cableway or boat. When a boat is used, the meter should be held so that it is not affected by disturbances to the natural flow caused by the boat. After the meter has been placed at the selected point in the vertical, it should be allowed to become aligned with the direction of flow before readings are started. If oblique flow is unavoidable, the angle of the direction of the flow normal to the cross-section should be measured and the measured velocity should be corrected. If the measured angle to the normal is γ, then:

$$V_{normal} = V_{measured} \cos \gamma \tag{5.4}$$

The meter on cable suspension will automatically point in the direction of the current owing to the tail vanes built into the meter. In some cases, such as using an oblique bridge as the measuring section, the horizontal distances should be corrected as:

$$d_{normal} = d_{measured} \cos \gamma \tag{5.5}$$

The current meter should be removed from the water at intervals for examination. For measuring very low velocities, special current meters may be used if they have been tested in this range of velocities for repeatability and accuracy.

The horizontal axis of the current meter should not be situated at a distance less than one and one-half times the rotor height from the water surface, nor should it be at a distance less than three times the rotor height from the bottom of the channel. Furthermore, no part of the meter should break the surface of the water (*Technical Regulations* (WMO-No. 49), Volume III, Annex).

5.3.2.3.3 *Determination of mean velocity in a vertical*

The mean velocity of the water in each vertical can be determined by one of the following methods:
(a) Velocity distribution method;
(b) Reduced point methods;
(c) Integration method.

Selection of the appropriate method depends on the time available, the width and depth of the water, the bed conditions, the rate of change of stage, the velocity of the water, the existence of ice cover and the required accuracy.

Velocity distribution method

The measurement of the mean velocity by this method is obtained from velocity observations made at a number of points along each vertical between the surface of the water and the bed of the channel. The velocity observations at each position should be plotted in graphical form and the mean velocity should be determined by dividing the area of this plot by the depth. In developing the graph it may be necessary to estimate the velocities near the stream bed by assuming that the velocity for some distance up from the bed of the channel is proportional to the logarithm of the distance x from that boundary. If the observed velocity at points approaching the bed are plotted against log x, then the best-fitting straight line through these points can be extended to the bed and the velocities close to the bed read from this graph.

The velocity distribution method may not be suitable for discharge measurements made during significant variations of stage because the apparent gain in precision may be more than offset by errors resulting from the longer period required to make the measurement.

The velocity distribution method is valuable in determining coefficients for application to the results obtained by other methods, but it is not generally adapted to routine discharge measurements because of the extra time to compute the mean velocity.

Reduced point methods

(a) One-point method – Velocity observations should be made at each vertical by placing the current meter at 0.6 of the depth below the surface. The value observed should be taken as the mean velocity in the vertical. Where measurements are made under ice cover, this method is applicable with a correction factor of 0.92 for depths shallower than 1 m. Under ice conditions, the current meter may be placed at 0.5 of the depth. A correction factor of 0.88 is then applied to this result;

(b) Two-point method – Velocity observations should be made at each vertical by placing the current meter at 0.2 and 0.8 of the depth below the surface. The average of the two values should be taken as the mean velocity in the vertical;

(c) Three-point method – Velocity observations are made by placing the current meter at each vertical at 0.2, 0.6 and 0.8 of the depth below the surface. The average of the three values may be taken as the mean velocity in the vertical. Alternatively, the 0.6 measurement may be weighted and the mean velocity may be obtained from the equation:

$$\bar{v} = 0.25\ (v_{0.2} + 2v_{0.6} + v_{0.8}) \quad (5.6)$$

(d) Five-point method – It consists of velocity measurements on each vertical at 0.2, 0.6 and 0.8 of the depth below the surface and as near as possible to the surface and the bottom. The mean velocity may be determined from a graphical plot of the velocity profile as with the velocity distribution method or from the equation:

$$\bar{v} = 0.1\ (v_{surface} + 3v_{0.2} + 3v_{0.6} + 2v_{0.8} + v_{bed}) \quad (5.7)$$

(e) Six-point method – Velocity observations are made by placing the current meter at 0.2, 0.4, 0.6 and 0.8 of the depth below the surface and as near as possible to the surface and the bottom. The velocity observations are plotted in graphical form and the mean velocity is determined as with the velocity distribution method or from the equation:

$$\bar{v} = 0.1\ (v_{surface} + 2v_{0.2} + 2v_{0.4} + 2v_{0.6} + 2v_{0.8} + v_{bed}) \quad (5.8)$$

(f) Two-tenths method – In this method, the velocity is observed at 0.2 of the depth below the surface. A coefficient of about 0.88 is applied to the observed velocity to obtain the mean in the vertical;

(g) Surface velocity method – In this method, velocity observations are made as near as possible to the surface. A surface coefficient of 0.85 or 0.86 is used to compute the mean velocity in the vertical.

The two-point method is used where the velocity distribution is normal and depth is greater than about 60 cm. The one-point method is used for shallower depths. The three-point method should be used for measurements under ice or in stream channels overgrown by aquatic vegetation. The five-point method is used where the vertical distribution of velocity is very irregular. The six-point method may be used in difficult conditions, where, for instance, there is aquatic growth, or there is a covering ice. Also it can be used where the vertical distribution of velocity is very irregular. The two-tenths method is principally used when it is not possible to position the meter at the 0.8 or 0.6 of the depth. The surface velocity method may be used for measuring flows of such high velocity that is not possible to obtain depth soundings. In this case a general knowledge of the cross-section at the site or a cross-section measured as soon as possible can be used to obtain the depths.

The accuracy of a particular method should be determined, if possible, by observing the velocity at 6 to 10 points in each vertical for the first few discharge measurements made at a new site.

Integration method

In this method, the current meter is lowered and raised through the entire depth at each vertical at a uniform rate. The speed at which the meter is lowered or raised should not be more than 5 per cent of the mean velocity of flow in the cross-section, and it should be between 0.04 and 0.10 m s^{-1}. The average number of revolutions per second is determined. Two complete cycles are made in each vertical and, if the results differ by more than 10 per cent, the measurement is repeated. This method is seldom used in water having a depth of less than 3 m and velocities of less than 1 m s^{-1}. The integration method should not be used with a vertical axis current meter because the vertical movement of the meter affects the motion of the rotor.

5.3.2.4 Computations of discharge

Arithmetical methods

(a) Mean-section method – The cross-section is regarded as being made up of a number of segments bounded by two adjacent verticals. If $\bar{v}_1$ is the mean velocity at the first vertical and $\bar{v}_2$ the mean velocity at the second vertical, and if d_1 and d_2 are the total depths measured at verticals 1 and 2, and b is the horizontal distance between verticals, then the discharge q of the segment is:

$$q = \left(\frac{\overline{v}_1 + \overline{v}_2}{2}\right)\left(\frac{d_1 + d_2}{2}\right) b \qquad (5.9)$$

The total discharge is obtained by adding the discharge from each segment;

(b) Mid-section method – The discharge in each segment is computed by multiplying vd in each vertical by a width, which is the sum of half the distances to adjacent verticals. The value of d in the two half-widths next to the banks can be estimated. Referring to Figure I.5.1, the total discharge Q is computed as:

$$Q = \overline{v}_1 d_1 \left(\frac{b_2 + b_1}{2}\right) + \overline{v}_2 d_2 \left(\frac{b_1 + b_2}{2}\right) + \ldots + \overline{v}_n d_n \left(\frac{b_n + b_{n-1}}{2}\right) \qquad (5.10)$$

Graphical methods

(a) Depth-velocity integration method – The first step consists in drawing, for each vertical, the depth velocity curve, the area of which represents the product of the mean velocity and the total depth. The value of this product at each vertical is then plotted versus lateral distance and a curve is drawn through the points. The area defined by this curve is the discharge in the cross-section;

(b) Velocity-contour method – Based on the velocity-distribution curves of the verticals, a velocity distribution diagram for the cross-section is prepared showing curves of equal velocity. Starting with the maximum, areas enclosed by the equal velocity curves and the water surface should be measured and then plotted in another diagram, with the ordinate indicating the velocity and the abscissa indicating the area. The area enclosed by the velocity area curve represents the discharge of the cross-section (ISO, 1979*b*).

5.3.2.5 Measurement of discharge under ice cover

Measurement of discharge under ice cover requires general knowledge of instruments and procedures described in 5.3.2.1 to 5.3.2.4. These sections deal only with equipment and procedures peculiar to the measurement of discharge under ice cover.

5.3.2.5.1 *Selection of site*

It is advisable to select alternate cross-sections during the open water season when channel conditions can be evaluated. At some stations, the same measuring section may be used during winter and summer, but it is more important that winter measurements be made under suitable conditions than it is to use the same measuring section. After initial selection, exploratory holes may be cut at quarter points along the section to detect the presence of slush ice or poor distribution of flow. Frazil ice should be avoided whenever possible because ice particles impede the operation of the meter and because of difficulty in determining ice thickness. Also, a small flow may occur through the frazil ice which cannot be measured by usual methods.

Winter freshets often lead to water breaking through the ice and forming two independent currents, one above and the other below the ice. Such locations should be avoided.

5.3.2.5.2 *Equipment*

(a) Cutting holes – When ice is thick, a mechanical ice auger, drill or chainsaw is desirable for cutting holes. For thin ice, an ice chisel may be used;

(b) Determination of effective depth – Effective depth of water below ice cover is the total depth of water minus the distance from the water surface to the underside of the ice. The distance between the water surface in the ice hole and the underside of the ice may be measured using an ice-measuring stick or "ice stick", which is an L-shaped graduated bar of appropriate length. The short projection of the L-shaped stick is held against the underside of the ice, and the depth to that point is read at the ice surface on the graduated portion of the stick. If there is slush under solid ice at a hole, the depth at which it ends may be determined by suspending the current meter below the slush ice with the meter rotor turning freely and then raising it slowly until the rotor stops. This point is assumed to be the interface between water and slush;

(c) Current meter and weight assembly – If an ice auger or drill is used to cut holes through ice, a special current meter and sounding weight assembly is passed through the ice hole, which is generally about 150 mm in diameter. The assembly may consist of two teardrop-shaped lead weights, one above and one below the meter, or one teardrop-shaped weight below the meter. When the hole can be made large enough, the standard current meter and weight assembly can be used as described in 5.3.2.3.1;

(d) Meter suspension – The meter suspension may be by a rod, handline or sounding reel. If the total depth of water under ice cover is greater than 3 or 4 m, a reel or handline is usually used. The reel is mounted on a collapsible support set on runners. In extremely cold weather, the support may be equipped with a heated water tank or hot air chamber to keep the meter from freezing while moving the equipment from one position to the next. For shallower depths, where a meter without tail vanes is suspended by a rod through a drilled hole, the direction of current must be determined so that the meter can be properly aligned.

5.3.2.5.3 *Discharge measurement*

(a) Spacing of verticals – The information in 5.3.2.2 is also applicable to the spacing of verticals under ice. However, in addition to the variation in elevation of the stream bed, variation in ice cover and slush ice thickness must also be taken into account in selecting the number and location of verticals. If the current is divided into different channels by slush ice, not less than three verticals should be used in each channel;

(b) Measurement of velocity – Ideally, velocity curves should be determined from velocity observations at every tenth of the effective depth in at least two verticals to determine what coefficients, if any, are necessary to convert the average velocity obtained by any standard open-water method of observation to an average velocity in a vertical under the ice cover. In shallow water, velocity may be observed at one point at either 0.5 or 0.6 of the effective depth, but a coefficient is normally required to convert the observed velocity to mean velocity. In deeper water (1 m or more), velocity observations could include two observations at 0.2 and 0.8 of the effective depth, three observations at 0.15, 0.5 and 0.85 of the effective depth, six observations at 0.2, 0.4, 0.6 and 0.8 of the effective depth, and at points close to the top and bottom. The average velocity observed in the two- and three-point methods may be used as the mean in the vertical. For the six-point method, see 5.3.2.3.3;

(c) General notes – When measuring discharge from an ice cover, appropriate safety precautions should be observed. For example, the safety of ice should always be tested by probing ahead with an ice chisel while moving across the ice. If the velocity measured under ice conditions is less than the accepted lower limit of the current meter, the cross-section should be moved to another reach of the river where the velocity is higher. Care must be taken to ensure that the meter is rotating freely and is not impeded by ice that can accumulate on the meter and freeze while moving from one vertical to another. At the time the measurements are taken, a record should be kept of a complete description of weather and ice conditions on the river, particularly at the control sections. This will aid in the later computation of discharge between measurements.

5.3.2.5.4 *Computation of discharge*

The computation of discharge under ice cover is the same as for open-water conditions described in 5.3.2.4 except that effective depth is used instead of total depth of water.

5.3.2.6 Accuracy of measurement

The accuracy of discharge measurements depends on the reliability of the meter rating, on the conditions of flow, on the skill of the hydrometrist, and on the number of observations of depth and velocity obtained (ISO, 1981; 1985). Measurements are normally made by observing the depth and the velocity at two points, in 20 to 25 verticals in the cross-section. For this type of measurement, under the flow conditions that are usually encountered, the standard error at the 95 per cent confidence level is about 5 per cent (ISO, 1979*b*).

5.3.3 **Measurement of discharge by the float method** [HOMS C86]

This method should be used in the following instances: it is impossible to use a current meter because of unsuitable velocities or depths, or where there is the presence of a large amount of material in suspension, or when a discharge measurement must be made in a very short time.

5.3.3.1 Selection of sections

Three cross-sections should be selected along a reach of straight channel. The cross-sections should be spaced far enough apart for the time that the float takes to pass from one cross-section to the next to be measured accurately. A travel time of 20 seconds is recommended, but a shorter time may have to be used on small rivers with high velocities where it is often impossible to select an adequate length of straight channel.

5.3.3.2 Floats

Surface floats or rod floats may be used. A surface float has a depth of immersion of less than one quarter the depth of the water. Surface floats should not be used when they are likely to be affected by wind. A rod float has a depth of immersion exceeding one quarter the depth of the water. Rod floats must not touch the channel bed. Floating trees or ice cakes may serve as natural floats during periods when it is unsafe to be on the river.

5.3.3.3 Measuring procedure

Float observations must be uniformly distributed over the width of the stream. The float should be released far enough above the upper cross-section to attain a constant velocity before reaching the first cross-section. The time at which the float crosses each of the three cross-sections should be noted with a stopwatch. This procedure should be repeated with the floats at several locations across the stream. The width of the channel should be divided into segments of equal width or of approximately equal discharge. The number of segments should be not less than three, but where possible a minimum of five should be used. Distances of the float from the bank as it passes each cross-section may be determined by suitable optical means, for example, a theodolite.

The depth of flow at points in the cross-section may be determined by surveying methods.

5.3.3.4 Computation of velocity

The velocity of the float is equal to the distance between cross-sections divided by the time of travel. At least five values of the float velocity should be taken at each segment and the mean of these values should be multiplied by a coefficient to obtain the mean water velocity for each segment. This coefficient is based on the shape of the vertical velocity profile and the relative depth of immersion of the float. The coefficient to be applied to the measured velocity should be determined, if possible, for each site by an analysis of discharge measurements that have been made by current meter. When such measurements are not available, an adjustment factor, F, from Table I.5.2 may be used for rough estimation.

Alternatively the float velocity may be plotted as a function of the corresponding distance from the bank, and the mean surface velocity across the river should be determined from this plot. The mean velocity of flow in the cross-section is equal to the mean surface velocity multiplied by a coefficient, K, the value of which is deduced, if possible, from preceding measurements made with a current meter for smaller discharges.

Table I.5.2. Float velocity adjustment factor *F* as a function of *R*, the ratio of the immersed depth of float to depth of water

R	*F*
0.10 or less	0.86
0.25	0.88
0.50	0.90
0.75	0.94
0.95	0.98

5.3.3.5 Computation of discharge

Discharge in each segment is computed by multiplying the average area of the cross-section of the segment by the mean velocity of flow in the segment. The total discharge is the sum of these discharges (ISO, 1979*b*).

5.3.4 Measurement of discharge by dilution methods [HOMS E73]

The measurement of discharge by this method depends on determining the degree of dilution by the flowing water of an added tracer solution. The method is recommended for sites with excessive turbulence flows. The two principal tracer methods used for discharge measurements are the constant-rate-injection method and the sudden-injection method. The general requirements (5.3.4.1) for both methods are the same (ISO, 1973*a*; 1987).

The dilution method is a fully acceptable method for discharge measurement at sites where the conditions for this method are good.

5.3.4.1 General requirements

A solution of a stable tracer is injected into the stream at either a constant rate or all at once. Computation of the stream discharge requires knowledge of the following factors:

(a) The rate of injection for the constant-rate-injection method or the total amount injected for the sudden-injection method;
(b) The concentration of the tracer in the injected solution;
(c) The calibrated relationship between tracer concentration and the recorded property (for example, conductivity, colour and radioactivity) at the measuring site after it has been well mixed laterally.

The accuracy of these methods critically depends upon:

(a) Adequate mixing of the injected solution throughout the stream cross-section at the sampling section. If the tracer solution is continuously injected, the concentration of the tracer should be essentially constant throughout the sampled section. If the tracer is injected all at once, $\int_0^T c\,dt$ should essentially be the same at all points in the section, where c is the concentration and T is the time for all of the tracer to pass a particular point in the section;

(b) No absorption or adsorption of the added tracer by stream bottom materials, sediments, plants or organisms, and no decomposition of the added tracer in the stream water. The concentration should be determined at the sampling section and at least one other cross-section downstream to verify that there is not a systematic difference in the mean concentration from one sampling section to another.

5.3.4.2 Selection of site

The primary criterion for the selection of sites for measurement of discharge by dilution is adequate mixing of the injected solution with the stream water in a short length of channel. Mixing is enhanced by high boundary roughness and features that cause the channel flow to be highly turbulent, such as at waterfalls, bends or abrupt constrictions. A small injection of rhodamine dye or fluorescein can help to assess the mixing condition at the measuring site. Large dead-water zones between the injection site and the sampling site will often affect the mixing so that the tracer will not be adequately mixed in the cross-section at the sampling site.

5.3.4.3 Tracers and detection equipment

Any substance may be used as a tracer if:

(a) It dissolves readily in the stream's water at ordinary temperatures;

(b) It is absent in the water of the stream or is present only in negligible quantities;

(c) It is not decomposed in the stream's water and is not retained or absorbed by sediment, plants or organisms;

(d) Its concentration can be measured accurately by simple methods;

(e) It is harmless to humans, animals and vegetation in the concentration it assumes in the stream.

The cheapest tracer is common salt. Where the tracer is instantaneously injected into the stream, the required quantity is not particularly large and detection by conductivity methods is relatively simple.

Sodium dichromate is used extensively in the dilution method. Its solubility in water is relatively high (600 kg m^{-3}), and the salt satisfies most requirements of 5.3.4.1. Colourimetric analysis (ISO, 1987) permits the measurement of very low concentrations of sodium dichromate.

Lithium chloride has solubility in water of 600 kg m^{-3} and its concentrations down to 10^{-4} kg m^{-3} can be detected using flame photometric analysis.

Other chemicals used for dilution gauging are sodium iodide, sodium nitrite and manganese sulphate.

Rhodamine WT dye is widely used in the United States in the dilution method. Its absorptive characteristics are much better than those of other rhodamine dyes. The concentration of the dye can be measured using commercially available fluorometers that can measure concentrations of 5 to 10 parts per billion.

Radioactive elements such as bromine-82, gold-198, iodine-131 and sodium-24 have been used as tracers. Concentrations of these elements as low as 10^{-9} may be determined accurately with a counter or count rate meter with the sensing probe suspended in the stream or in a standard counting tank. Although radioactive elements are ideal tracers for the dilution method, the health hazards may limit their use in measurement of stream discharge in some localities.

5.3.4.4 Computation of discharge

Equations used to compute the stream discharge, Q, are based on the principle of continuity of the tracer:

$$Q = \frac{Q_{tr} c_i}{c_s} \quad \text{(continuous injection)} \tag{5.11}$$

and

$$Q = \frac{c_i V}{\int_0^\infty c_s \, dt} \quad \text{(sudden injection)} \tag{5.12}$$

where Q_{tr} is the rate of injection, c_i is the concentration of injection solution, c_s is the concentration in the stream at the sampling section, V is the volume of injected solution and t is time.

5.3.5 Computations of discharge by indirect methods [HOMS E70]

5.2.5.1 General

During flood periods, it may be impossible to measure discharge directly because of the excessive rate of change of discharge, excessive velocities, debris, depths or widths, or because flooded conditions make roads impassable or measuring structures inaccessible. When such conditions occur, the peak discharge may be determined after the flood has subsided by computations that combine well-established hydraulic principles with field observations of channel conditions and flood profiles. All the methods involve the simultaneous solution of continuity of mass and energy equations. Such computations may be made for reaches of river channel, through roadway culverts and bridge openings, and over dams and highway embankments. Although the hydraulic formulae differ for each type of waterway, all the methods involve the following factors:

(a) Geometry and physical characteristics of the channel and boundary conditions of the reach used;
(b) Water-surface elevations at time of peak stage to define the cross-sectional areas and the head difference between two significant points;
(c) Hydraulic factors, such as roughness coefficients based on physical characteristics.

5.3.5.2 Field survey

A reconnaissance study, from maps, by air or by travel in the region, is made to select the most favourable site for determining discharge by one of the indirect methods. The site should be as close as possible to the desired measuring point, and large intervening tributaries or diversions should be avoided. The site must contain good high-water marks defining the water-surface profile during the peak.

A detailed survey is made to define channel geometry adjacent to and within the selected reach, the channel cross-sections, the dimensions and details of culverts, bridges, dams, roadways or other artificial structures, and the positions and locations of high-water marks left by the flood. All factors that affect channel roughness are noted and roughness coefficients are selected. Photographs should be taken of the cross-sections and reach to facilitate office evaluations of site conditions.

From the field survey notes, drawings are made showing the plan, the profiles of the channel bottom and high-water surface on both banks, the cross-sectional areas and details of any artificial structures. Computations are made of hydraulic factors and the discharge is computed.

5.3.5.3 Slope-area measurements

Slope-area measurements require a reach of river channel that is selected for uniformity or uniform variation in hydraulic properties (ISO, 1973*b*). Discharge is computed on the basis of a uniform flow equation, such as the Manning equation, involving channel characteristics, water-surface profiles and roughness coefficients.

5.3.5.4 Measurement of flow through culverts

Peak discharge through culverts can be determined from high-water marks that define the headwater and tailwater elevations, culvert geometry and slopes, and cross-sections that define approach conditions. The head-discharge relationships of culverts have been defined by laboratory investigations and field verification. Peak discharge is determined by the application of continuity and energy equations between the approach section and a section within the culvert barrel. For convenience in computation, culvert flow has been classified into six types on the basis of the location of the control section and the relative heights of the headwater and tailwater elevations.

5.3.5.5 Measurement of flow through width contractions

The contraction of a stream channel by a roadway crossing creates an abrupt drop in water surface elevation between an approach section and the contracted section under the bridge. The contracted section formed by bridge abutments and the channel bed may be used as a discharge control to compute flood flows. The head on the contracted section is defined by high-water marks (upstream and downstream), and the geometry of the channel and bridge is defined by field surveys. The discharge equation results from a combination of the energy and continuity equations for the reach between these two sections.

5.3.5.6 Measurement of flow over weirs, dams and highway embankments

A weir, dam or embankment generally forms a control section at which the discharge may be related to the upstream water-surface elevation. The peak discharge at the control section can be determined on the basis of a field survey of high-water marks and the geometry of the structure. The methods are derived from laboratory and field studies of the discharge characteristics of weirs, dams and embankments.

The fieldwork consists of a survey of headwater and tailwater elevations from high-water marks, an approach cross-section to define velocity of approach, and an exact determination of the profile of the control structure to assign the proper discharge coefficient. Coefficients are available for:
(a) Thin-plated weirs, either discharging freely or submerged;
(b) Broad-crested weirs, not submerged;
(c) Ogee or design-head dams, submerged or not submerged;
(d) Many irregular shapes.

5.3.6 Measurement of discharge under difficult conditions

General discussion on the measurement of discharge under difficult conditions is provided in the *Level and Discharge Measurements under Difficult Conditions* (WMO-No. 650).

5.3.6.1 Unstable channels

Channel instability is characterized by systematic shifts of the bed, high silt content and the presence of various kinds of debris in the flow. Channel instability is a hindrance to the operation of a permanent gauging structure and/or measurement section. This problem can be minimized by selecting a site midway along a straight reach of the river with a uniform section remote from various obstructions (bridges, etc.). The greatest stability in the banks is usually found at places where the channel narrows. On small rivers, the site should be convenient for the construction of a permanent measurement section.

On small streams, where there is no transport of large stones and debris, portable or permanently installed flumes may be used to measure flow. On small rivers, it is desirable, in some cases, to have an artificial section for measurements to improve the stage-discharge relationship. Improvements may take the form of a low weir or flume depending on the specific conditions at the site. The structure should be high enough to remove variable back-water from downstream but not so high as to cause excessive disturbances downstream. At low water, the structure should provide a sensitive relationship between discharges and water levels. To clean the crests of large structures and to provide a means for making current-meter measurements, a foot-bridge may be provided. Because of the large silt content of unstable channels, it is desirable to use current meters with a sealed contact chamber. Sounding rods should be provided with a foot to prevent them from sinking into the silt.

When measuring discharge by the velocity-area method, the depth is usually determined before and after measurement of the velocity. When the velocity is high, the presence of various kinds of debris in the stream may lead to external damage to the current meter. In such cases, it is advisable to compare the current-meter readings, before and after measuring the discharge, with the readings from a separate current meter not used in the measurement.

In rivers with intensive channel shifts, the distribution of velocity in a cross-section varies periodically. The choice of velocity verticals must be made by taking into account the velocity distribution at the time of measurement. The use of permanent verticals may lead to systematic errors. If there is intensive shifting of the channel, it is also desirable to use a reduced point method of velocity measurement and a reduced number of verticals (ISO, 1979*b*).

If soundings have been made twice (before and after velocity measurements), the area of water cross-section is computed on the basis of the mean depths from the two soundings. On wide rivers, where the location of sounding verticals usually is determined by distances from an initial point on the shore, the verticals obtained on the two runs may not coincide. In this case, an average cross-section profile of the measurement site is used to select depth values for the discharge computation.

5.3.6.2 Mountain streams

Mountain streams are characterized by high flow velocities, shallow and uneven beds blocked by boulders and debris, transverse and uneven water-surface slopes, and transport of large but varying quantities of stones and pebbles. Measurement or gauging locations with these characteristics should be avoided if possible.

Due to very turbulent flows, it is desirable to use one of the dilution methods of flow measurement on small mountain streams (5.3.4).

Improvements in the channel to make better measurements may be advisable. It may also be desirable to equip the site with a gauging bridge (5.3.2). If it is possible to build a reach with acceptable conditions for current-meter measurements these should be comprised of at least 20 verticals. Measurement of depth by wading rod in mountain streams does not lead to systematic errors. However, the use of a sounding weight with tailfin may lead to underestimates of the depth if the depth is small. For depths of about 1 m, these differences from measurements made by wading rod may amount to about 2.5 to 3 per cent, while for depths of 0.4 to 0.8 m, the difference may be as much as 10 to 15 per cent.

It is best to use the two-point method to measure velocities by current meter. The discharge is calculated as explained in 5.3.2.4.

5.3.6.3 Measurement of unsteady flow

5.3.6.3.1 *Measurement of discharge during floods and on large rivers*

Flood measurements are best made from bridges, cableways or boats. Portable electromechanical winches are available, which can be set up on special trucks, motorcars and tractors. On large rivers, where there are no bridges or cableways, boats, large vessels or ferries are used. Optical or telemetric equipment may be set up on board the vessel and on the bank to determine the position in the channel. Ferries using a cable for the crossing are equipped with electric or mechanical engines for traction by the cable and for lifting and lowering the equipment. Generally, sounding weights of up to 200 kg are necessary because maximum velocities on large rivers may be as great as 3 to 5 m s^{-1}. Soundings of depth also may be made by echo sounder.

For flood measurements on small rivers, remote control or bank-operated traversing systems are particularly suitable. These systems may be portable and can be used at several sites, which need merely to be equipped with a main carrying cable across the river. If such systems are not available, easily transportable duraluminium boats or inflatable rubber rafts with outboard motors and equipment platforms can be used. Locations that are difficult to access may have to be reached by helicopter.

For very high velocities, surface floats or stroboscopic instruments for measuring velocities may be used. The stroboscope has a telescope that is directed towards the surface of the water and a number of rotating mirrors. The speed of rotation of the mirrors is chosen so that a stationary image of the surface of the water is obtained. The velocity of the flow is determined from the speed of rotation of the mirrors. The maximum speed measurable by this method is 15 m s^{-1}, but this maximum is dependent on the height of the observation point above the water surface. Measurements by stroboscope can be made in very turbid flow with floating ice and other solid matter preventing the use of a current meter. The coefficient for converting the surface velocity to the mean velocity at a vertical, determined by similar measurements under less difficult conditions, is usually equal to 0.85–0.90. Measurement of depth is commonly made by echo sounder or a standard cross-section is used.

For wide rivers (3 to 20 km) with several subchannels, measurements by current meter become extremely difficult. In this case, the moving boat method (5.3.7.2) or discharge measurement by acoustic Doppler instruments (5.3.7.5) may be used. Moreover, these are convenient methods when there are short breaks in the ice run or if there is debris. If there is ice or debris in some particular part of the flow, measurements may be made by the float method and by current meter during breaks in occurrence of such debris. Aerial photography using floats may also be employed for wide river measurements.

5.3.6.3.2 *Measurement of discharge in tidal reaches*

Where a measurement section is affected by ocean tides, the following effects must be taken into account:

(a) Continuous change of water level, with and without change of direction of the current;
(b) Continuous change of velocity with time, even at a single point in a vertical with considerable velocity gradients;
(c) Change in the time-distribution of velocity;
(d) Change of direction of the current for the tidal cycle with zero velocity;
(e) Presence of stratified flow with varying density and direction of flows;
(f) Considerable change in the width and cross-section of the flow;
(g) Presence of large-scale turbulence (for example, fluctuations with a period of more than 30 seconds and the amplitude of velocity variations up to 50 per cent) and of seiches.

The discharge of tidal river is generally determined by one of the following methods (ISO, 1974): velocity-area method, volumetric method, or by solving the equation for unsteady flow. The moving boat method (5.3.7.2) or the acoustic Doppler method (5.3.7.5) may also be used, particularly at times when the distribution curve of velocities is close to its usual shape. Other methods, such as the ultrasonic method (5.3.7.3), may also be suitable.

In the method of computation of discharge by the velocity-area method, the velocity is measured during the entire flood-ebb cycle. Measurements are usually made at several points to be able to account for the different directions of flow. At the same time, the water level and the depths at verticals are measured continuously. Then, all measurements are reduced to a single time for which the discharge is calculated.

The accuracy of the velocity-area method is greater if:
(a) The tidal cycle during which the measurement is made is periodic or nearly periodic;
(b) Currents, particularly during the period of maximum flow, are parallel to each other and at right angles to the gauging site at all points;
(c) Curves of horizontal and vertical velocity distributions are of the regular shape encountered at the gauging site;
(d) The transverse profile of the gauging site is uniform and lacks shallow areas.

The site selected should meet as closely as possible the following requirements:
(a) The river bed section should be straight and of regular shape;
(b) The depth of the water at the site should be such that current meters can be used effectively;
(c) The channel section should be stable during the tidal cycle;
(d) The discharge should be concentrated within channels the cross-sections of which can be determined with a fair degree of accuracy;
(e) The site should not be near artificial or natural obstacles causing non-parallel flows;
(f) The gauging site should be clear of vegetation;
(g) Oblique flow, backflow and dead zones should be avoided.

The site should be conspicuously marked on both banks.

To determine discharge during the rise and recession of floods, measurements are made at each vertical during the entire tidal cycle. To determine accurately the moment of zero velocity, measurements begin and end half an hour before and after the tidal cycle. Depending on the equipment available and on the physical characteristics of the selected site, different procedures can be adopted for velocity measurements:
(a) If a sufficient number of boats are available, measurements are made simultaneously at all verticals during the entire tidal cycle;
(b) If only a limited number of boats are available, the chosen verticals are marked by anchored buoys. One or two boats are necessary to carry out the measurements, proceeding successively from one vertical to the next, at intervals of not more than one hour between each vertical. At least one additional boat remains permanently at one reference vertical, carrying out measurements continuously during the entire tidal cycle. In this case, the curves of velocity changes occurring over time at each vertical are plotted by using the concurrent velocities at the reference vertical as a basis of comparison;
(c) If the shape of the tidal curve does not change considerably from day to day and if at least two boats are available, then one of the boats is stationed at the reference vertical to carry out measurements during the whole tidal cycle for each day. The other boat carries out measurements during the whole cycle at each vertical, moving to a new vertical each day. In this case, the number of days required for the whole cycle of observations is equal to the number of velocity verticals;
(d) If there are different tidal amplitudes and if it is not possible to make measurements in many verticals, measurements are carried out at each vertical for the entire cycle at different tidal amplitudes during a lunar month and at spring and neap tides;
(e) If there is considerable pulsation, measurements should be carried out at each vertical with the aid of several current meters set at different heights for periods of 10 to 15 minutes. The mean velocity is determined for the mean period of time;
(f) In the case of oblique currents, use must be made of direct reading current meters or of instruments capable of measuring the angle of deviation.

Where rapid velocity changes occur, the velocity values at the various points in the vertical must be adjusted to a specific time. For this purpose, velocity measurements are either repeated at all points in the vertical by moving from the bottom to the surface, or are measured only at one point at the surface.

For the computation of the discharge at each vertical, a curve of velocity changes with time is plotted, from which the value for a specified time is taken.

For the computation of discharge by the volumetric method, synchronous measurements of the water level are made at the boundaries of the measuring section or sections after their geometrical characteristics (cross-sections, lengths and flooded areas) are determined. An additional gauging station is located on the river above the area of tidal effects so that the discharge attributable to the river can be determined. Where there are transverse slopes in wide estuaries, levels are measured at both banks. The difference in volumes of the tidal prisms during the accounting interval is computed from the change in mean depths and areas of water surface between the boundaries. To determine the mean discharge, the difference in the volume of the total prism is divided by the accounting period minus the inflow into the river.

In the method of computation of discharge from equations of unsteady motion, the solution of the equations of unsteady motion for the section under consideration is simplified by certain assumptions, such as parallel flow and uniform density, and that the channel is prismatic. Measurements are usually made for two typical (high and low) tidal cycles. The measurements are used to calibrate the parameters of the equations.

5.3.6.4 Weed growth in stream channels

Weed growth in rivers can cause relatively large errors. For small rivers, it is advisable, if possible, to construct artificial controls. If this is not possible, discharges should be measured by the velocity area method. For this purpose, a reach of the river 6 to 10 m long should be kept clear of weed growth during the entire season. In addition, the banks should be kept clear of shrubs and high grass over a somewhat larger reach.

The use of toxic substances to impede the growth of vegetation is effective for a short time only. Frequent clearing of the bed may be the most practical method. The weeds growing in the bed may be cut by a special machine attached to a mechanized chainsaw or by the aid of an ordinary scythe.

Flow velocity in each vertical should be measured at three points (at depths of 0.15, 0.5 and 0.85). Where the depth of the vertical is less than 0.40 m, velocity is measured by the single-point method.

In the discharge measurement notes, a short description of the actual state of weed growth should be given.

Because algae and weeds could become entwined in the propeller of the current meter, the instrument should be inspected and cleaned frequently during the measurement process. Where measurements are made at one point only, the regularity with which signals are received must be carefully checked. Experience has been acquired with the use of the electromagnetic method for gauging under such conditions (5.3.7.4).

5.3.7 Non-traditional methods of stream gauging

5.3.7.1 General

Determination of discharge by the velocity-area method, the dilution method and by means of a hydraulic structure (5.4) have certain limitations and are not applicable in some instances. Four relatively new methods of flow measurement in open channels are the moving boat method, the ultrasonic method, the electromagnetic method and the Acoustic Doppler method.

5.3.7.2 Moving-boat method [HOMS E79]

In this method, a boat is fitted with a specially designed component current-meter assembly that indicates an instantaneous value of velocity. A measurement is made by traversing the stream along a preselected path that is normal to the flow. During the traverse, which is made without stopping, an echo sounder records the geometry of the cross-section, and the continuously operating current meter measures the combined stream and boat velocities. These data, collected at some 30 to 40 observation points (verticals) across the path, are converted to discharge. The velocity recorded at each of the observation points in the cross-section is a vector quantity that represents the relative velocity of flow past the meter assembly. This assembly consists of a vane attached to a stainless steel shaft, which, at its upper end, incorporates a dial and pointer for reading the angle between the direction of the vane and the true course of the boat. This is performed by sighting on carefully located markers on the banks. About six runs, in alternate directions, are usually taken and the measurements are averaged to give the discharge (ISO, 1979*a*; Smoot and Novak, 1969).

The discharge is calculated in a similar manner to the conventional velocity-area method by summing the products of the segment areas and average velocities. Because the current meter is located about 1 m below the surface, a coefficient is required to adjust the measured velocity. In large rivers, the coefficient is usually uniform across the section. Investigations on several rivers have shown that the coefficient generally lies between 0.85 and 0.95. The moving boat method provides a single measurement of discharge, and an accuracy of ±5 per cent is claimed at the 95 per cent confidence level.

5.3.7.3 Ultrasonic (acoustic) method [HOMS C73]

The principle of the ultrasonic method is to measure the velocity of flow at a certain depth by simultaneously transmitting sound pulses through the water from transducers located on either side of the river. The transducers, which are designed both to transmit and receive sound pulses, are located on opposite banks, so that the angle between the pulse path and the direction of flow is between 30° and 60°. The difference between the time of travel of the pulses crossing the river in an upstream direction and those travelling downstream is directly related to the average velocity of the water at the depth of the transducers. This velocity can be related to the average velocity of flow of the whole cross-section. The incorporation of an area computation into the electronic processor allows the system to output discharge.

Ideally, the transducers are set at a depth such that they measure the average velocity of flow. In practice, they are ultimately fixed in position so that for any change in stage, they probably will not be at the point of average velocity, and a coefficient is necessary to adjust the measured velocity.

There are two types of ultrasonic systems commonly in use, the first where the transducers are fixed in position and the station is calibrated by current meter, and the second where the transducers are designed to slide on either a vertical or inclined assembly. In the latter method, the system is self-calibrating and therefore no current-meter measurements are necessary. By moving the transducers through a number of paths in the vertical (generally 7 to 10), velocity readings are obtained along these paths. From each set of the readings, vertical velocity curves are established over as large a range in stage as possible. It is then possible first, to estimate a suitable position for the fixing of the transducers in the vertical and, second, to establish a curve of stage against the coefficient of discharge as in the first method.

In rivers with small range in stage, a single-path transducer system may be acceptable. For rivers with large variations in stage, a multipath system with several pairs of transducers may be necessary.

The accuracy of the ultrasonic method depends on the precision with which the travel times can be measured. The several techniques available at the present time are capable of measuring time to very high accuracy (Smoot and Novak, 1969; Herschy and Loosemore, 1974; Smith, 1969; 1971; 1974; Botma and Klein, 1974; Kinosita, 1970; Holmes and others, 1970; Halliday and others, 1975; Lenormand, 1974).

5.3.7.4 Electromagnetic method

The motion of water flowing in a river cuts the vertical component of the Earth's magnetic field, and an electromotive force (emf) is induced in the water that can be measured by two electrodes. This emf, which is directly proportional to the average velocity in the river, is induced along each traverse filament of water as the water cuts the line of the Earth's vertical magnetic field.

Figure I.5.3 shows diagrammatically an electromagnetic gauging station where the coil is placed in the

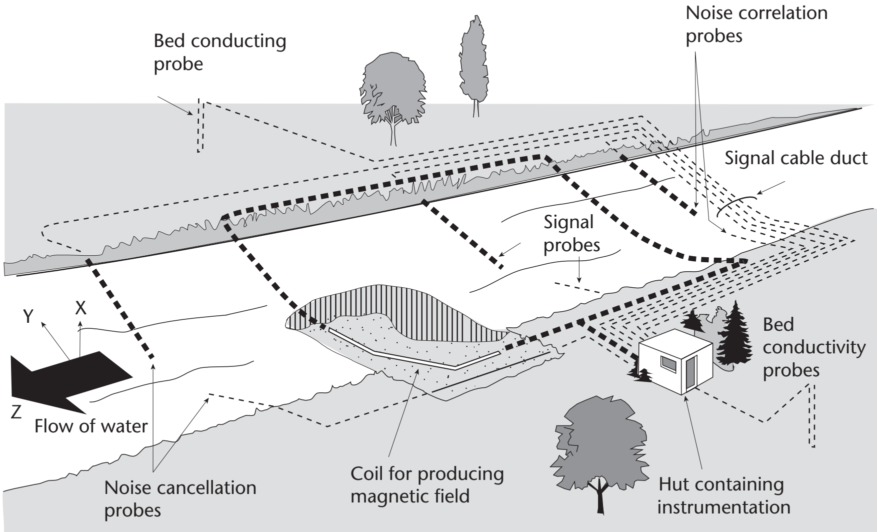

Figure I.5.3. Basic system of the electromagnetic method

bed and the magnetic field is in the *x* direction, the emf is in the *y* direction and the streamflow is in the *z* direction. Faraday's law of electromagnetic induction relates the length of a conductor moving in a magnetic field to the emf generated by the equation (Herschy and Newman, 1974).

In practice, most river beds have significant electrical conductivity that will allow electric currents to flow in the bed. From practical considerations, the induced field will be spatially limited and electric currents flowing in the area outside the field will have the effect of reducing the output potential. Both of the above factors have the effect of reducing the signal and hence the voltage recorded. At an electromagnetic gauging station, it is necessary to measure both the bed and water conductivity.

The most suitable current for the coil is a direct current, the direction of which is reversed a few times per second and an alternating square wave with a frequency of about 1 Hz should be used. A typical installation may have a coil of 12 turns, each of 16 mm^2 double PVC insulated cable, and be supplied with 25 A with a voltage across the coil of about 20 V (Herschy and Newman, 1974).

The electromagnetic method will be suitable for use in rivers with weed growth, high sediment concentration or unstable bed conditions. It gives a continuous record of the average velocity in the cross-section that can be combined with stage to give an on-site output of discharge.

The accuracy depends on the signal processing equipment detecting and measuring small potentials sensed at the voltage probes. It is possible to detect a signal of 100 nV, which represents a velocity of approximately 1 mm s^{-1}. The electromagnetic gauging station requires on-site calibration by current meter or other means and a relation established between discharge and output.

5.3.7.5 Measurement of discharge by acoustic Doppler instruments

5.3.7.5.1 *General*

Developments in acoustic Doppler technology have made these instruments a viable alternative for making measurements of discharge in rivers and large streams. During recent years the instruments and techniques have changed appreciably and it has become possible to use Dopper instruments in small and shallow rivers. All instruments use the Doppler principle to measure velocity from particles (scatters) suspended in the water in order to compute discharge. An acoustic Doppler instrument contains transducers and temperature sensors that are made for operating in water. None of the instruments requires periodic calibrations, unless there is physical damage to the instrument.

5.3.7.5.2 *Doppler principle*

An acoustic Doppler instrument (see Figure I.5.4) measures the velocity of the water using a physical principle called the Doppler shift. This states that if a source of sound is moving relative to the receiver, the frequency of the sound at the receiver is shifted from the transmit frequency. The instrument transmits an acoustic pulse of energy into the water much like a submarine's sonar but at much higher frequencies. This energy is reflected off particles suspended in, and moving with, the water and some of it returns to the instrument. The instrument measures the Doppler shift (change in frequency) of the reflected energy and uses this to compute the velocity of the water relative to the instrument. The reflected pulses have a frequency (Doppler) shift proportional to the velocities of the scatterers they are travelling in along the acoustic beam:

$$V = \left(\frac{F_d}{2\,F_0}\right) C \qquad (5.13)$$

where F_d is the Doppler shifted frequency received at the transducer, F_0 is the transducer transmit frequency, C is the sound speed, and V is the scatterer (water) velocity.

All Doppler instruments operate within a pre-set frequency. The frequency determines under which conditions they are best equipped to measure. An instrument that operates on a lower frequency has

Figure I.5.4. Transducer of an acoustic Doppler instrument installed on a boat

a greater range of distance than an instrument with a higher frequency. The amount and type of particles in the water will also determine the range of the instrument and the quality of the measurements. If there are too few particles in the water, the range will be noticeably shorter and the quality of the data might be compromised.

These principles are true for all of the acoustic Doppler instruments, but different instruments compute discharge in different ways.

5.3.7.5.3 *Acoustic Doppler Current Profilers*

The use of Acoustic Doppler Current Profilers (ADP/ADCP™) has become a common method of measuring river discharge. There are a handful of instruments on the market today designed for use in larger or smaller rivers. They have several traits in common.

ADCP instruments can be mounted on a moving vessel, such as an inflatable boat (see Figure I.5.5). The instrument measures water velocity, depth and vessel path simultaneously to compute discharge. This method computes the discharge as the vessel is crossing the river. The total discharge measurement (ΣQ_1) is completed in a few minutes. The result from one measurement is not enough to give an accurate value of the water flow/discharge; it only gives a freeze-frame picture of the flow. To get an accurate value of the discharge of the river, it is important to take the average of several transects. At least four transects are recommended to calculate the discharge at a site. The actual river discharge estimate will then be the average of the *N* individual transects discharge values:

$$\sum Q = \frac{\left(\sum Q_1 + \sum Q_2 + \sum Q_3 + \sum Q_4 + \ldots\right)}{N} \qquad (5.14)$$

There is need for the instrument to communicate with a computer that computes the discharge. As an ADCP instrument processes the signal reflected off the particles in the water, it divides the water column into a number of discrete segments stacked in the vertical. These segments are called depth cells. An ADCP instrument determines the velocity and direction of each depth cell. At the same time the signal from the bottom, called bottom-track, measures the speed and direction of the boat. This means that the boat does not have to cross perpendicularly to the flow.

The procedures for collecting good data are becoming more standardized worldwide. The number of transects depends on the difference between the discharge measurements. If the discharge for any of four transect differs more than 5 per cent, a minimum of four additional transects should be obtained and the average of all eight transects will be the measured discharge. Sometimes even more transects are made to reduce potential directional

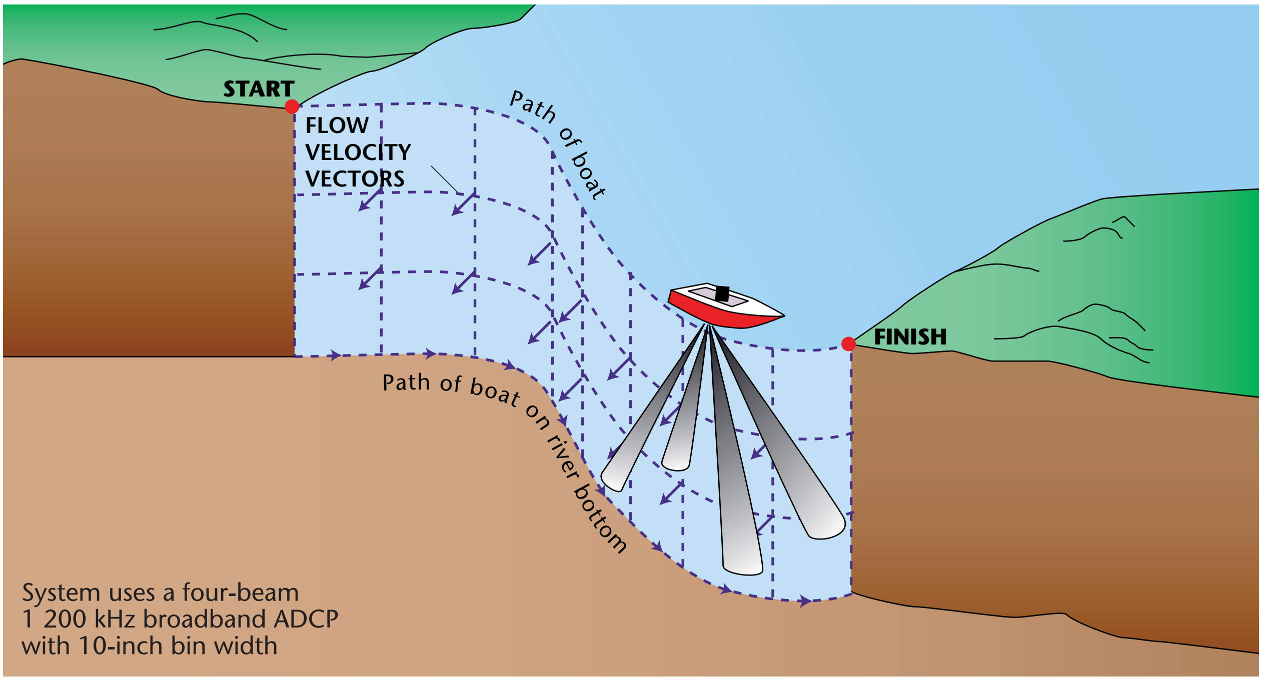

Figure I.5.5. The layout of a typical acoustic Doppler measurement
(Source: United States Geological Survey, http://www.usgs.gov)

biases. The user must configure the instruments before starting the measurements. The choice among different modes of configuration is based on the conditions at the site (water depth, water speed, etc.) at the time of measurement. Use of the correct mode is important for greater accuracy in discharge measurements. The user has to set proper ADCP depth, distance to the banks and make sure that the pitch and roll and the speed of the boat/instrument is within acceptable limits during the measurements. A bias in any of these can result in a significant bias in the resulting measured discharges.

Another kind of acoustic Doppler profiler instrument makes discharge measurements without using a bottom track. Instead, it measures by use of sections or "verticals". Depending on the characteristics of the river, the instrument takes 10–20 verticals, each measured for 30–60 seconds, to make a discharge measurement. Such instruments measure the full vertical velocity profile and can easily be suspended from a bridge or suspended with a tag line across the river.

The beams are all oriented in the direction of a two-dimensional (2D) system that makes it possible to measure close to the banks of the river (channel). The user has to set the distance from the bank and the software calculates the cross-sectional area. Since there is no bottom tracking, the instrument must be oriented in the direction of the flow and move across the river in pre-defined segments/verticals. Failure to do this results in inaccurate discharge measurements.

5.3.7.5.4 *Acoustic Doppler Velocimeter*

An Acoustic Doppler Velocimeter (ADV) is a single-point current meter designed specifically for low-power measurements in slow-moving water. These meters require much smaller water sampling volumes than traditional current meters.

One type of ADV is Flowtracker, which is currently the only hand-held ADV on the market. The instrument is an alternative to mechanical current meters for making wading discharge measurements. The Flowtracker consists of a probe head attached to a top-setting wading rod with an interface. The interface allows entering the basic parameters required to make a discharge measurement: station, distance, depth and vertical location of the measurements (0.6, or 0.2 and 0.8 of the depth). By using the velocity-area method, it computes discharge by multiplying the channel area and the mean channel velocity.

True 2D or 3D velocity data are output in Cartesian coordinates (XYZ) relative to probe orientation. Only the X component of velocity (V_x) is used for river discharge measurements. The probe direction has to be perpendicular to the tag line to ensure proper discharge calculations. The operator does not have to estimate the flow angle as is required for 1D current meters.

5.3.7.5.5 *Discharge measurements from fixed platform*

In addition to use for vessel mounted discharge measurements, an acoustic Doppler instrument can be used on fixed platforms to compute the discharge in rivers. The instrument is normally mounted from an underwater structure facing perpendicular to the river flow, and measures water velocity in a two-dimensional plane at multiple points. These instruments are often called Acoustic Doppler Velocity Meters (ADVM) (Gotvald, 2005).

The water velocity meaured by the ADVM is used to compute the mean velocity of the river channel. This is called the index velocity of the river. By using the index velocity, the discharge can be computed in different ways. This is called the index-velocity method. An ADVM gives the opportunity to measure discharge in a river with no or poor stage/discharge relationship. The index-velocity method is basically computing the discharge from the equation $Q = VA$, where Q is the total discharge, V is the mean velocity and A is the channel area. Use of ADVMs on fixed platforms to provide index velocity measurements for river discharge has increased recently.

5.4 STREAM-GAUGING STATIONS

5.4.1 Purpose of stream-gauging stations

The purpose of stream-gauging stations is to provide systematic records of stage and discharge. Continuous streamflow records are necessary in the design of water supply and waste systems, in designing hydraulic structures, in the operations of water management systems, and in estimating the sediment or chemical loads of streams, including pollutants.

Since continuous measurement of discharge is not usually feasible, unless one of the methods in 5.3.7.3 and 5.3.7.4 is used, records of discharge are computed from the relationship between stage and discharge, as defined by periodic discharge measurements and a systematic record of stage, or from a measuring structure that has been calibrated in either a laboratory or the field.

5.4.2 Selection of site

The selection of streams to be gauged should be governed by the principles of network design (2.4) and the proposed use of the data. The selection of a particular site for the gauging station on a given stream should be guided by the following criteria for an ideal gauge site:

(a) The general course of the stream is straight for about 100 m upstream and downstream from the gauge site;
(b) The total flow is confined to one channel at all stages and no flow bypasses the site as subsurface flow;
(c) The stream bed is not subject to scour and fill and is free of weeds;
(d) Banks are permanent, high enough to contain floods, and free of brush;
(e) Unchanging natural controls are present in the form of a bedrock outcrop or other stable riffle during low flow, and a channel constriction for high flow, or a fall or cascade that is unsubmerged at all stages to provide a stable relationship between stage and discharge. If no satisfactory natural low-water control exists, then installation of an artificial control should be considered;
(f) A site is available, just upstream from the control, for housing the stage recorder where the potential for damage by drifting ice or water-borne debris is minimal during flood stages. The elevation of the stage recorder itself should be above any flood likely to occur during the life of the station;
(g) The gauge site is far enough upstream from the confluence with another stream or from tidal effect to avoid any variable influences which the other stream or the tide may have on the stage at the gauge site;
(h) A satisfactory reach for measuring discharge at all stages is available within reasonable proximity of the gauge site. It is not necessary that low and high flows be measured at the same stream cross-section;
(i) The site is readily accessible for ease in the installation and operation of the gauging station;
(j) Facilities for telemetry or satellite relay can be made available, if required;
(k) If ice conditions occur, it would still be possible to record stage and measure discharge;
(l) The flow in the channel section containing the gauging site is subcritical at all stages;
(m) There are no waves and ripples on the water surface in the vicinity of the gauging site.

In many instances, it may be impossible to meet all of these criteria. Judgement is then required to select the most suitable site for the gauge.

5.4.3 Stage-discharge controls

The physical element or combination of elements that control the stage-discharge relationship is known as a control. The major classification of controls differentiates between section control and channel control. Another classification differentiates between natural and artificial controls.

Section control exists when the geometry of a single cross-section is such as to constrict the channel, or when a major downward break in bed slope occurs at a cross-section. The constriction may result from a local rise in the stream bed, as at a natural riffle or rock ledge outcrop or at a constructed weir or dam. It may also result from a local constriction in width, which may occur naturally or may be caused by some man-made channel encroachment, such as a bridge with a waterway opening that is considerably narrower than the width of the natural channel.

Channel control exists when the geometry and roughness of a long reach of channel downstream from the gauging station are the elements that control the relationship between stage and discharge. The length of channel that is effective as a control increases with discharge. Generally, flatter stream gradients will result in longer reaches of channel control.

A low dam, weir or flume is often built in the channel to provide an artificial control. Such controls are usually submerged by high discharges, but they provide a stable stage-discharge relationship in the low to medium flow range.

The two attributes of a good control are resistance to change – ensuring stability of the stage-discharge relationship – and sensitivity, whereby a small change in discharge produces a significant change in stage.

5.4.4 Measuring structures

At some gauging sites it is feasible to utilize an artificial control of such shape that head-discharge relationships can be determined without calibration, that is, by the application of a discharge formula. There is a set of weirs and flumes that have well-established relationships between head and discharge. However, only under favourable field conditions can the established formulae for some types of weirs and flumes be applied accurately. If these structures are used to measure flow directly from water level readings, it is important that care be taken in their construction and operation and that the most suitable formulae be used (WMO, 1986*b*; ISO, 1977*b*, 1980, 1983, 1984, 1989).

Under less favourable conditions, in situ calibration is necessary to establish the extent of the departures from the standard formulae or to develop the head-discharge relationship. It is particularly important at low flow to measure periodically the discharge by other means in order to detect changes in the discharge coefficient caused by sediment deposits in the pool or growth of algae on the weir or flume.

The material in this Guide is limited to the general considerations involved in the selection and use of weirs and flumes at gauging stations. Specific information on their geometries and head-discharge formulae are presented in the *Use of Weirs and Flumes in Stream Gauging* (WMO-No. 280).

5.4.4.1 Scope

Weirs and flumes for use at gauging stations may be catalogued into three groups:

(a) Thin-plate weirs generally used on small, clear-flowing streams or small research watersheds;
(b) Flumes used on small streams and canals conveying sediment and debris or in other situations where the head loss associated with thin-plate weirs is unacceptable;
(c) Broad-crested, triangular-profile and round-shaped weirs used on larger streams.

Weirs and flumes may be free-flowing or submerged. In the first case, the discharge is a function of the headwater elevation, and accurate calibrations are possible. For submerged conditions, the discharge is a function of both the headwater and tailwater elevations, and less accuracy is obtained by use of laboratory calibrations. At many sites, weirs or flumes are used to measure only the lower range of discharge, and the stage-discharge relationship for the upper range of discharges is determined by direct methods.

5.4.4.2 Selection of structure

The choice of a measuring structure depends on costs, the characteristics of the stream and channel at the site, the range of discharges, the accuracy desired and the potential head loss. Criteria to be considered in choosing a structure include:

(a) Cost is usually the major factor in deciding whether or not a measuring structure is to be built. The cost of the structure is affected most by the width of the stream and the type or condition of the bed and bank material. Stream width governs the size of the structure, and bed and bank material govern the type of construction that must be used to minimize leakage under and around the structure;
(b) Channel characteristics and flow conditions influence the design of the measuring structure. Factors controlling velocity or Froude number, sediment loads and the stability of the bed need to be considered in the structure design;
(c) The range of discharge, range of stage, desired sensitivity and allowable head loss must also be considered in structure design and positioning. Submergence by high flows or from backwater influence both the design and elevations of the structure. The sensitivity, that is, the change in stage corresponding to change in discharge at very low flows, may dictate whether a V-crest or flat crest is appropriate;
(d) Cheap, portable weirs made of canvas and light metal plates, for example, may be used on small rivers for limited periods of time.

5.4.4.3 Measurement of head

The head over the structure is usually measured at a distance upstream from the structure equal to about three times the depth of water, h_{max}, on the control at the maximum stage for which the section control is effective. Some special weir shapes and all flumes require that stage be measured at specific distances from the control section that differ from the general rule of $3 \times h_{max}$. The locations for the gauge or gauge intake for these special cases are described in the *Use of Weirs and Flumes in Stream Gauging* (WMO-No. 280). The zero of the gauge should be set at crest elevation and should be checked regularly.

5.4.4.4 Operation of measuring structures

Both the channel and structure are subject to changes with time that may affect the head-discharge relationship. Sand, rocks or debris may be deposited in the approach section or on the structure itself. Algae may grow directly on the crest of the structure during summer and ice may form on the structure during winter.

For optimum accuracy the approach channel to weirs should be kept clean and free of any accumulation of silt or vegetation. The structure must be kept clean and free of debris, algae and ice. Damage to critical parts of the structure should be repaired.

The datum of the gauge should be checked periodically. Periodic discharge measurements should also be made to define possible changes in the original calibration.

5.4.5 Stage-discharge relationships

5.4.5.1 General

The stage-discharge relationship for most gauging stations is defined by plotting the measured discharges as the abscissa and the corresponding stage as the ordinate (ISO, 1981). The shape of the stage-discharge relationship is a function of the geometry of the downstream elements of the channel that act as the control. When plotted on rectangular coordinate paper, the relationship is generally concave downwards (depends on the exponent value) since discharge often can be described by a power function of the flow depth. Hence, when plotted on logarithmic coordinate paper, the medium- and high-stage sections of the relationship are often approximately linear if the stage represents the effective head on the control for medium and high stages. If this is not linear, the stage-discharge relationship is typically comprised of two or more segments because of shifts in geometry and/or channel resistance. The stage-discharge relationship can readily be expressed by a mathematical equation derived from the available measurements. This equation can be determined by graphical methods or regression methods. Independent of what method is used for deriving the stage-discharge relationship, its accuracy is determined by:
(a) The number of available measurements;
(b) The spread of the measurements;
(c) The average discharge measurement uncertainty.

An estimated stage-discharge relationship should not be extrapolated. Where it is desirable to extrapolate, the application of indirect methods based on the physical conditions of the actual channel and hydraulic control is recommended.

At many sites, the discharge is not a unique function of stage, and additional variables must be measured continuously to obtain a discharge record. For example, in situations where variable backwater at the gauge is caused by a downstream tributary, by tidal effect or by downstream reservoir operation, an auxiliary stage gauge must be installed to measure continuously the fall of the water surface in the gauged reach of the channel. Where flow is unsteady and the channel slopes are flat, the rate of change of stage can be an important variable, and a given discharge that occurs on a rising stage will have a lower gauge height than the same discharge occurring on a falling stage.

5.4.5.2 Stability of stage-discharge relationships

The stability of a stage-discharge relationship is directly related to the stability of the control. For natural section controls, a rock-ledge outcrop will be unaffected by high velocities. Boulder, gravel and sandbar riffles are likely to shift. Boulder riffles are the most resistant to movement, and sandbars are the least. Of the natural channel controls, those found in sand-channel streams are the most likely to change as a result of velocity-induced scour and deposition.

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

Ice cover also affects the stage-discharge relationship of a stream by causing backwater that varies in effect with the quantity and nature of the ice. If the section control remains open and if the gauge is not too far from the control, there probably will be little or no backwater effect even though the entire pool is ice covered. The only effect of the ice cover will be to slow the velocity of approach, and that effect probably will be minor. However, if the gauge is a considerable distance upstream from the riffle, surface ice on the pool may cause backwater when the covered reach of the pool becomes a partial channel control.

Surface ice forming below a section control may jam and dam water sufficiently to cause backwater effects at the control. Anchor ice may build up the bed or control to the extent that a higher than normal stage results from a given discharge. The magnitudes of ice effects can be determined accurately only by measuring the discharges, observing the corresponding stages and analysing the differences between the observed stage and the discharge corresponding to the open-water stage-discharge relationship.

The various additional conditions that have to be taken into account in making discharge measurements under ice conditions and the procedures for making such measurements are described in 5.3.2.5.

Artificial controls eliminate or alleviate many of the undesirable characteristics of natural section controls. Not only are they physically stable, but also they are less subject to the cyclic or progressive growth of aquatic vegetation. Algal slimes that sometimes form on artificial controls can be removed with a wire brush, and the controls can be self-cleaning with regard to fallen leaves. In moderately cold climates, artificial controls are less likely to be affected by the formation of winter ice than are natural controls. However, even when the artificial control structure is unchanged, the stage-discharge relationship may be affected by changes in the velocity of approach caused by scour and/or fill, or by vegetal growth in the approach channel.

5.4.5.3 Frequency of discharge measurements

Factors to be considered in scheduling the number and distribution of discharge measurements throughout the year include:

(a) Stability of stage-discharge relationship;
(b) Seasonal discharge characteristics and variability;
(c) Accessibility of the gauge in various seasons.

Many discharge measurements are necessary at a new station to define the stage-discharge relationship throughout the entire range of the stage. Periodic measurements are then necessary to define changes in the stage-discharge relationship. A minimum of 10 discharge measurements per year is recommended.

Adequate definition of discharge during flood and under ice conditions is of prime importance. It is essential that the measurement programme provides for non-routine measurement of discharge at these times.

Where it is important to record streamflow continuously throughout the year, discharge measurements should generally be made more frequently when the stream is under ice cover.

During freeze-up and break-up periods, measurements should be obtained as often as possible because of the extreme variability of flow. In midwinter, the frequency of the measurements will depend on climate, accessibility, size of stream, winter runoff characteristics and the required accuracy. In very cold climates, where discharge follows a smooth recession curve, fewer measurements are required than for a stream in a climate of alternate freezing and melting.

5.4.6 Computation of mean gauge height of a discharge measurement [HOMS E71]

Stage and corresponding time should be noted at intervals to identify segments of total discharge with time and stage. Usually the stage at the mid-time of the measurement or the average of the stage at the beginning and end of the measurement can be used as the mean stage corresponding to the measured discharge. If the stage does not change linearly with time the following weighting procedure should be used, where $\overline{h}$ is the weighted stage and $Q_1, Q_2, \ldots Q_N$ are segments of discharge corresponding to stages $h_1, h_2, \ldots h_N$:

$$\overline{h} = \frac{Q_1 h_1 + Q_2 h_2 + \ldots + Q_N h_N}{Q_1 + Q_2 + \ldots + Q_N} \qquad (5.15)$$

5.5 SEDIMENT DISCHARGE AND YIELD

5.5.1 General [HOMS E09]

Sediment is transported by flowing water in different ways. The sediment grains may be moved by saltation, rolling or sliding on or near the bed or may be swept away from it and kept in suspension. The type of movement experienced by the grains depends upon their physical characteristics (size and form of particles, specific weight, etc.) and upon the grain-size composition of the sediment, as well as upon flow velocities and depths. The different phases of sediment transportation generally occur simultaneously in natural streams, and there is no sharp line of demarcation between them. For convenience, sediment discharge is divided into two categories: suspended-sediment and bed-material discharge. The latter consists of grains sliding, rolling or saltating on or near the bed.

This chapter provides guidance on the collection of sediment-discharge data. For each phase of transport, a more in-depth discussion of this topic can be found in the *Manual on Operational Methods for Measurement of Sediment Transport* (WMO-No. 686).

5.5.2 Selection of site

The same criteria used for the selection of a site for a water-discharge measurement should be used in selecting a site for measuring sediment transport (5.3.2.1 and 5.4.2).

5.5.3 Measurement of suspended-sediment discharge

5.5.3.1 Sampling instruments and in situ gauges [HOMS C10]

Several types of suspended-sediment samplers are in use, for example, instantaneous, bottle, pumping or integrating. However, only some of these are designed so that the velocity within the cutting circle of the sampler intake is equal to the ambient stream velocity. This feature is essential so that the samples obtained are truly representative of the suspended-sediment discharge at the point of measurement. The well-designed sampler faces the approaching flow, and its intake protrudes upstream from the zone of disturbance caused by the presence of the sampler.

Instantaneous samples are usually taken by trap samplers consisting of a horizontal cylinder equipped with end valves that can be closed suddenly to trap a sample at any desired time and depth. The very simple bottle sampler is corked or provided with an orifice of variable diameter, or wide open. As soon as the bottle is opened and air within the bottle is being displaced by the sample, bubbling takes place at the mouth, which slows the filling process. Consequently, bottle-sampling is not actually instantaneous.

The pumping sampler sucks the water-sediment mixture through a pipe or hose, the intake of which is placed at the sampling point. By regulating the intake velocity, the operator can obtain a sample that is representative of the sediment concentration at the point of measurement. The integrating sampler consists of a metallic streamlined body equipped with tail fins to orient it into the flow. The sample container is located in the body of the sampler. An intake nozzle of variable diameter projects into the current from the sampler head. An exhaust tube, pointing downstream, permits the escape of air from the container. Valve mechanisms enclosed in the head are electrically operated by the observer to start and stop the sampling process.

A relatively new method of in situ determination of suspended-sediment concentration is the use of optical or nuclear gauges. The working principle of these instruments is that a visible light of X-ray emitted by a source with constant intensity is scattered and/or absorbed by the suspended-sediment particles. The decrease of intensity measured by a photoelectric or nuclear detector situated at constant distance from the source is proportional to the sediment concentration, if other relevant characteristics of water and sediment (chemical, mineral composition, etc.) remain unchanged.

The overall design of suspended-sediment samplers should be checked by towing them in still water at a known velocity or by holding them in flowing water of known velocity. The optical and nuclear gauges must be calibrated by simultaneous and repeated sampling in sediment-laden flumes and natural streams.

5.5.3.2 Measurement procedure

Samples of suspended sediment in streams are taken in the discharge-measuring cross-sections, but not necessarily in the velocity-measuring verticals. In lakes, the locations of sampling verticals are scattered over an area, because here the measurements are usually aimed at the determination of distribution of sediment concentration in time and space. The samplers are suspended in the water on a rod or on a wire.

In streams, there are two methods that give comparative results:

(a) Equal discharge increment (EDI) method: The cross-section is divided into 3 to 10 subsections of about equal discharge. A depth-integrated sample is taken at each vertical in the centroid of each subsection by lowering the sampler from the stream surface to the bed and back at a uniform transit rate. This gives a discharge-weighted sample for each centroid;
(b) Equal transit rate (ETR) method: The stream width is divided into 6 to 10 equal distances separated by the verticals and one depth-integrated sample is taken at each vertical at a constant transit rate. In the latter case, all samples can be composited into a single representative discharge-weighted sample (ISO, 1977*b*).

By using a point sampler, samples may also be taken at evenly spaced points at each vertical mentioned above, and the sediment concentrations obtained are weighted by the ratio of the velocity at the given point to the mean velocity in the vertical. In practice this procedure can be combined with the mid-section method of discharge measurement

(5.3.2.4) because the velocity measuring and sampling verticals coincide.

The optical and nuclear sediment gauges may be used both for point- and depth-integrating measurements, provided the electrical signals from the detector are summarized by a scalar. Depending upon the statistical characteristics of counting by a particular instrument, the usual counting period is three to five minutes.

5.5.3.3 Determination of sediment concentration

Suspended-sediment samples are usually processed and analysed in special laboratories for the determination of the sediment concentration. Evaporation, filtration or displacement methods are generally used for this purpose. In general, the evaporation method is suitable for use with low concentrations. Filtering may be used for samples with medium to high concentrations. The displacement method, however, is suitable only when the concentration is high (WMO, 1989). The sample is usually allowed a settling time of one to two days, the water is then carefully drained off and the remaining sediment is oven dried at a temperature of about 110°C, and weighted. If the sediment is separated by evaporation, a correction must be made for dissolved solids. The concentration of suspended sediment is the weight of dried sediment contained in a unit volume of the sediment-water mixture and is expressed in mgl^{-1}, gl^{-1} m^{-3} or in kg m^{-3}.

Sediment samplers have been standardized in some countries to have a container capacity of one litre or less. In such cases, sampling should be repeated until the required volume of sediment sample is obtained (ISO, 1977*b*).

The intensities of light or X-ray indicated by the submerged photoelectric or nuclear probes of in situ gauges should be divided by the intensity measured in clear water and the sediment concentration corresponding to this ratio is read from the calibration curves of these instruments.

5.5.3.4 Computation of suspended-sediment discharge

For the EDI method, the weighted mean sediment concentration, $\overline{c_s}$, in kg m^{-3} for the entire cross-section is computed as:

$$\overline{c_s} = \frac{\sum c_q q_p}{\sum q_p} \qquad (5.16)$$

where q_p is the partial discharge in the subsection in $m^3 s^{-1}$, and c_q is the discharge weighted concentration in the vertical at the centroid of the subsection in kg m^{-3} (ISO, 1977*b*).

For the ETR method the concentration of the composite sample is the weighted mean concentration in the entire cross-section. The suspended sediment discharge, Q_s, is computed as:

$$Q_s = \overline{c}_s Q \qquad (5.17)$$

where Q_s is in kg s^{-1} and Q is the stream discharge in $m^3 s^{-1}$.

5.5.3.5 Continuous record of suspended-sediment discharge

A continuous record of suspended-sediment discharge may be computed from a record of stream discharges and systematic samples of suspended-sediment concentration. The samples should be taken daily during periods of low and mean flow and more frequently during floods. The most valuable information concerning the time-variation of concentration and its peak values can be obtained by the continuous recording of signals supplied by the photoelectric or nuclear suspended-sediment gauges during flood periods. The peak in concentration usually precedes peak flow, and loops can be observed on plots of the water discharge versus sediment discharge, similar to those in stage-discharge rating curves during floods.

The samples or observation records are collected at a single vertical in the cross-section, preferably using the depth-integrating procedure. The relation between the concentration at this vertical and the mean concentration in the section must be established by detailed measurements of the distribution of sediment in the cross-section, as outlined in 5.5.3.2. This relation is not necessarily linear and constant throughout the year, nor in all ranges of sediment concentration.

5.5.3.6 Use of remote-sensing techniques

The determination of the amount of sediment in water is based on the reflectance of radiation in the visible and IR parts of EMS (WMO, 1972). In general, reflection is a non-linear function of the concentration of suspended sediments with maximum reflectance dependent on wavelength and suspended sediment concentration. Because turbidity and suspended sediments are closely linked in most water bodies, estimates of turbidity can also be made. A limitation on the use of this technique is the need to collect field data to calibrate the relationship between suspended sediments and reflectance. Furthermore, scanner data can be used without calibration data to map relative suspended sediment concentrations in river plumes and draw conclusions about sediment deposition patterns in lakes and estuaries. A good review of applications of remote-sensing to estimation of suspended sediments can be found in Dekker and others (1995).

5.5.4 Measurement of bed-material discharge

5.5.4.1 Instrumentation [HOMS C12]

The field measurement of bed-material discharge is difficult because of the stochastic nature of the sediment movement and because the phenomenon takes place in the form of ripples, dunes and bars. No single apparatus has proved to be completely adequate for trapping the largest and smallest sediment particles with the same efficiency, while remaining in a stable, flow-oriented position on the stream bed, and still not altering the natural flow pattern and sediment movement. Available samplers can be classified into three types: basket, pan and pressure-difference (ISO, 1977*c*). Another type of sampler is the slot or pit-type sampler which is adaptable for use mainly in relatively small rivers and particularly for experimental study or calibration of samplers (Emmett, 1981).

Basket samplers are generally made of mesh material with an opening on the upstream end, through which the water-sediment mixture passes. The mesh should pass the suspended material but retain the sediment moving along the bed.

Pan samplers are usually wedge-shaped in longitudinal section and are located so that the point of the wedge cuts the current. The pan contains baffles and slots to catch the moving material.

Pressure-difference samplers are designed to produce a pressure drop at the exit of the sampler which is sufficient to overcome energy losses and to ensure an entrance velocity equal to that of the undisturbed stream. A perforated diaphragm within the sampler forces the flow to drop its sediment into the retaining chamber and to leave through the upper exit.

It is necessary, because of several uncertainties involved in sampling, to determine an efficiency coefficient for each type of sampler. The calibration generally takes place in a laboratory flume, where the bed-material discharge can be directly measured in a sump at the end of the flume, although uniform-transport conditions over the width and length of the flume are difficult to maintain. Even under favourable conditions, efficiency factors are not easily determined because they vary according to, among others, the grain-size composition of the bed material and the degree of fullness of the sampler. An efficiency of 60 to 70 per cent can be regarded as satisfactory.

5.5.4.2 Measurement procedure

Bed-material discharge is determined from the amount of sediment trapped per unit time in a sampler located at one or more points on the stream bed. There should generally be 3 to 10 measurement points in a cross-section, depending on the width of the cross-section and the sediment concentration distribution. In determining the distribution of sampling points, it should be noted that, except during flood periods, bed-material transport takes place only in a part of the stream width.

The inclusion of a zero measurement in the computation of bed-material discharge can lead to uncertainties in the result even though the sampling point may be situated between two moving strips of the stream bed. Uncertainties can also occur if a measured rate of transport is extended over a segment of the cross-section with low or zero sediment movement.

On gravel-bed streams, of which partial bed-material movement is most characteristic, different types of acoustic detectors can help to solve this problem. Submerged to a depth near the bed, these detectors pick up the sound of moving gravel, indicating the movement of bed material at this particular point. Moreover, the intensity of the sound and that of the sediment transport may be correlated.

The samplers (see, for example, Figure I.5.6) are lowered to the bottom and held in position by a rod or a wire. The duration of the sampling period is usually a few minutes, depending on the dimensions of the sampler and on the intensity of the sediment transport. When low-flow velocities exist near the bed, the downstream forces are reduced and the sampler tends to dive into the stream bed and scoop up bed material that is not in transport. A similar tendency can develop during an abrupt or incautious lifting of the sampler.

Measurements should be made at various stream discharges so that a rating may be prepared showing the relationship between stream discharge and bed-material discharge. Owing to the highly complex mechanism and random nature of sediment transport and to the errors of sampling, one single catch at a measuring point can provide a very uncertain estimate of the true bed-material transport. Therefore, repeated sampling should be carried out at each point. The number of repetitions depends on the local circumstances. However, statistical analyses of field data resulting from up to 100 repetitions have shown that only the bed-material discharge can be measured with restricted accuracy, unless an impracticably large number of samples are taken at each point.

5.5.4.3 Computation of bed-material discharge

The sediment collected in the sampler is dried and weighed. The dry weight, when divided by the time taken for the measurement and the width of the sampler, gives the bed-material discharge per unit width of stream at the point of measurement, q_b. A curve showing the distribution of q_b in the stream width can be constructed based on data obtained at the sampled points. The area enclosed between this curve and the water-surface line represents the total daily bed-material discharge over the entire cross-section Q_b. The value of Q_b can also be computed by using the measured q_b data as:

$$Q_b = \frac{q_{b1}}{2} x_1 + \frac{q_{b1} + q_{b2}}{2} x_2 + \ldots + \frac{q_{bn-1} + q_{bn}}{2} x_{n-1} + \frac{q_{bn}}{2} x_n \quad (5.18)$$

where Q_b is in kg s^{-1}, q_b is in kg s^{-1} m^{-1} and x is in metres. The variable x represents the distance between sampling points, between a marginal point and the edge of the water surface, or that of the moving strip of stream bed.

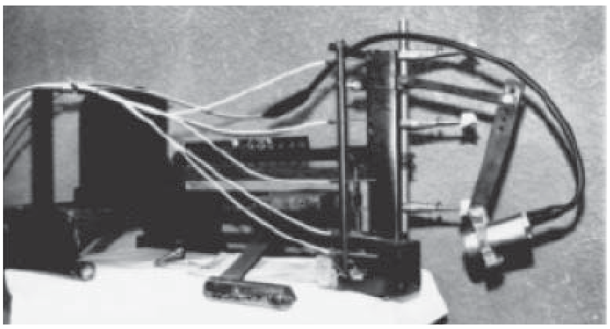

Figure I.5.6. Delft Nile sampler consisting of a bed-load and suspended-load sampler as well as an underwater video camera

The existence of dams trapping most of the sediment transported by upstream river reaches offers the possibility of estimating the annual or seasonal sediment discharge by successively surveying suitable selected profiles of the reservoir and by computing the volumes occupied by the trapped sediment. This method, combined with regular suspended-sediment sampling upstream and downstream of the dam, can provide acceptable estimates of bed-material discharge.

5.5.4.4 Continuous record of bed-material discharge

A continuous record of bed-material discharge can be obtained by relating bed-material discharge to stream discharge or other hydraulic variables with available records. This relationship can be assumed approximately linear for water discharges above the limiting value corresponding to the beginning of sediment movement because the tractive force of the flow increases in direct proportion to the increase in stream discharge. Bed-material transport is of primary interest in all investigations concerning stream bed-changes.

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