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Liquid flow measurement in open channels — Establishment and operation of a gauging-station and determination of the stage-discharge relation

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FOREWORD

ISO (the International Organization for Standardization) is a worldwide federation of national standards institutes (ISO Member Bodies). The work of developing International Standards is carried out through ISO Technical Committees. Every Member Body interested in a subject for which a Technical Committee has been set up has the right to be represented on that Committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work.

Draft International Standards adopted by the Technical Committees are circulated to the Member Bodies for approval before their acceptance as International Standards by the ISO Council.

Prior to 1972, the results of the work of the Technical Committees were published as ISO Recommendations; these documents are now in the process of being transformed into International Standards. As part of this process, International Standard ISO 1100 replaces ISO Recommendation R 1100-1969, drawn up by Technical Committee ISO/TC 113, *Measurement of liquid flow in open channels*.

The Member Bodies of the following countries approved the Recommendation :

Australia	Ireland	South Africa, Rep. of
Belgium	Israel	Switzerland
Brazil	Italy	Thailand
Chile	Japan	Turkey
Czechoslovakia	Korea, Rep. of	United Kingdom
France	Netherlands	U.S.A.
Germany	Portugal	
India	Romania	

The Member Body of the following country expressed disapproval of the Recommendation on technical grounds :

Canada

Printed in Switzerland

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1 SCOPE AND FIELD OF APPLICATION

This International Standard specifies methods for the continuous measurement of water-level, the determination of the stage-discharge relation by correlating water-levels to discharges and the compilation of records of flow at a gauging-station. It also deals with the establishment and operation of the gauging-station on a river or open channel.

Single-discharge measurements may be made by any of the accepted methods of measurement of liquid flow in open channels in accordance with the relevant International Standards. This International Standard covers only such additional requirements as are necessitated by its wider scope.

Open channels have been grouped into stable and unstable types as the characteristic stage-discharge curves of the two are different.

This International Standard does not cover cases such as those encountered

a) during floods when flow conditions are suddenly or rapidly varying due to abrupt flood-waves;

b) during periods when flow conditions are significantly impeded by the formation or presence of ice.

An Annex is included covering design and practice to assist compliance with this International Standard (Annex A); it also gives relevant statistical tests and procedures for construction of stage-discharge curves.

Further Annexes deal with the correction for discharge in unsteady flow (Annex B) and the family of curves giving the stage-discharge relation (Annex C).

2 REFERENCES

ISO 555, *Liquid flow measurement in open channels — Dilution methods for measurement of steady flow — Constant-rate injection method.*

ISO 748, *Liquid flow measurement in open channels — Velocity-area methods.*

ISO 772, *Liquid flow measurement in open channels — Vocabulary and symbols.*

ISO 1438, *Liquid flow measurement in open channels using thin-plate weir and venturi flumes.*[1)]

3 DEFINITIONS

For the purposes of this International Standard, the definitions given in ISO 772 apply.

4 UNITS OF MEASUREMENT

The units of measurement used in this International Standard are seconds, and metres or feet.

5 PRINCIPLE OF THE METHOD OF MEASUREMENT

The principle of the method is to establish a unique relation between the discharge of a channel and either the water-level in the section of a stream or the readings of water-levels at each end of a reach. Knowledge of this stage-discharge relation will enable the discharge to be determined by simple measurement of the level, during the operating period of the station.

To establish this relation, it is necessary to carry out at the selected site a sufficient number of measurements of the discharge and the corresponding stage simultaneously. Each discharge measurement shall be made by one of the accepted methods.

6 CHOICE OF SITE

6.1 Preliminary survey

A preliminary survey shall be made to ensure that the physical and hydraulic features of the proposed site conform to the requirements for the application of the methods of flow measurement which it is intended to use.

6.2 Selection of site

The site selected shall be such that it is possible to measure the whole range and all types of flow which may be encountered or which it is required to measure. The whole range of measurement, referred to one reference gauge, may be made at a single section, or, for certain ranges of discharge, at two or more sections. Similarly, different

1) At present at the stage of draft.

methods of measurement may be employed for separate parts of the range, the particular conditions relative to each of the methods of measurement being specified in the relevant International Standards for the measurement of liquid flow in open channels.[1)]

Either single- or twin-gauge stations may be employed, depending upon conditions, but the former should be preferred.

The operation of a single-gauge station depends upon the assumption that the elevation of the free surface is a substantially unique function of the discharge. In the case of stations affected by hysteresis, the rise and fall shall be calibrated separately by discharge measurement.

6.2.1 *At a single-gauge station*

a) It is desirable to select a site where the relationship between stage and discharge is substantially consistent and stable. However, this may not be possible on all alluvial rivers. For such rivers, the stage-discharge relation is generally applicable only for the period for which it has been determined.

b) There shall not be any variable backwater effect.

6.2.2 *At any gauging-station (with single or twin gauges)*

a) The site shall be sensitive, i.e. a significant change in discharge, even for the lowest discharges, shall be accompanied by

- a significant change in stage in the case of a single-gauge station;

- a significant change in stage (at one or other of the gauges) and in fall (between the two gauges) in the case of a twin-gauge station.

Otherwise, small errors in stage readings during calibration in a non-sensitive station can result in large errors in the discharges indicated by the curve.

A comparison shall be made between the change in discharge and the corresponding minimum change in stage to ensure that the sensitivity of the station is sufficient for the purpose for which the measurements are required.

b) Sites where weed growth is prevalent shall be avoided.

c) There shall be no vortices, dead water or other abnormalities in flow.

d) Access to the site at all stages and at all times shall be available as far as possible.

7 DESIGN AND CONSTRUCTION OF A GAUGING-STATION

7.1 General

A gauging-station consists of one or more natural or artificial measuring cross-sections (weir or flume), and a reference gauge.

In cases where a general system of river gauges is in existence, it is not absolutely necessary that the position of the measuring cross-section should coincide with the position of the gauge, provided that the discharge is equal in both places for all stages. In all other cases, it is advisable to install the gauge in, or very near to, the chosen cross-section.

Where a desirable site satisfies some but not all of the requirements stated in the relevant International Standards dealing with single-discharge measurement[1)], and in 6.2 of this International Standard, it may be made to do so by appropriate modifications (see Annex A). In general this will only be feasible for smaller rivers.

In the case of a twin-gauge station, the length of the reach shall be sufficient to make any observational error negligible relative to the fall of level between the two gauges. Further, there shall be no additions to the discharge, or withdrawals from it, between the two gauges.

7.2 Devices for measurement of stage

7.2.1 *Reference gauge*

The reference gauge shall be a vertical gauge or an inclined gauge. The markings shall be clear and sufficiently accurate for the purpose for which the measurements are required. The lowest marking and the highest marking on the reference gauge shall be respectively below and above the lowest and highest anticipated water-levels.

The reference gauge shall be securely fixed to an immovable and rigid support in the stream and shall be correlated to a fixed bench-mark by precise levelling to the national datum. It shall have a stilling arrangement, wherever necessary, so that the water-level can be read accurately.

Where a continuous record of water-levels is required, a water-level recorder shall be installed. It is essential, however, to combine such a recorder always with a normal river gauge, placed near the point of measurement of the recorder. In other cases a normal river-gauge will suffice.

NOTE — When possible, an estimate of extreme values should be made by statistical analysis. Care shall be taken to incorporate such extreme values as may be required for the purpose of the station. Possible deepening of the bed shall also be taken into account.

1) See ISO 555, ISO 748, and ISO 1438.

7.2.1.1 Vertical gauge

This staff gauge shall be truly vertical. It shall be of such a shape as not to cause any noticeable heading up of flow.

7.2.1.2 Inclined gauge

The inclined gauge shall fit closely and be solidly anchored to the slope of the natural bank of the water-course. It may be calibrated on the site by precise levelling.

7.2.2 *Continuous liquid-level recorder*

This may consist of a recorder operated by a float in a stilling-well communicating with the channel or a pneumatic recorder or other device. It is essential, however, to combine such a recorder always with a reference gauge, placed near the point of measurement of the recorder. In the case of the float-actuated recorder, an additional gauge shall be installed inside the float-well to serve as a check.

7.2.2.1 Stilling-well

The stilling-well for the accommodation of the float of the float-operated recorder shall meet the following requirements.

a) It shall be vertical and have sufficient height and depth to allow the float to rise and fall over the full range of water-levels.

b) In water-courses with widely fluctuating silt content (i.e. densities), inlet pipes shall be provided at various stages.

c) Joints with any inlet pipe shall be watertight.

d) The dimensions of the inlet pipe(s) or of the channel shall be large enough for the water-level in the well to follow the rise and fall of stage without delay, and also to prevent clogging due to sediment.

e) If the stage cannot be read on the chart with sufficient accuracy because of short-period wave effect, a constriction shall be fitted in the inlet pipe to damp out oscillation.

7.2.2.2 The pneumatic recorder

a) This recorder measures the stage by means of the pressure exerted on a take-off which is immersed and solidly fixed at a known elevation.

b) The recorder shall have a source of compressed gas (air or nitrogen) and a device for adjusting the air flow in the form "bubble to bubble".

c) A device for driving away the gas shall be provided to discharge the pressure take-off, if necessary.

d) The pipe connecting the manometer to the pressure take-off shall have a length less than the limit fixed by the manufacturer. It shall not have low points running the risk of accumulating the condensates of the gas.

e) The device for measuring the pressure shall be sufficiently sensitive and accurate. In case a manometer with a liquid stopper is used, the density of this liquid at various temperatures shall be eventually taken into account and the manufacturer shall indicate the value of the errors.

7.2.2.3 Requirements of the recorder

The recorder shall either provide a continuous graphical record of the changing water-level or register the water-levels digitally at suitably close intervals of time.

The recorded results will depend directly upon the changing water-levels. If they are affected by other phenomena (damping of the stilling-well of the float-operated recorder, loss of head due to the gas flow or the liquid stopper of the manometer, in a pneumatic recorder) the user must know the effects so that he may correct them if necessary.

In the case of a recorder giving a graphical chart, the chart sheet shall be positively located on the drum. The scales chosen for time and stage will depend on the characteristics of the river, and shall be such that reading can be made with a degree of accuracy sufficient to show the different phases of the hydrograph.

Any mechanical linkage connecting parts of the recorder shall be as short and direct as possible and there shall be no contact between any moving part of the mechanism and any fixed part of the structure.

The clock mechanism shall maintain accurate time.

The recorder shall be placed out of danger of flooding and be protected against the elements and interference by unauthorized persons.

Precautions shall be taken against the occurrence of errors in records due to

a) lag of the stylus behind the movement of the float;

b) change in the submergence of the float in the water;

c) submergence of the counterweight and the float-line.

7.3 Procedure for observation of gauges

The gauge shall be read from such a position as to avoid all parallax errors. The gauge shall be observed continuously for a minimum period of 2 min or the period of complete oscillation, whichever is longer, and the maximum and minimum readings taken and averaged.

8 SURVEY OF STATION – GENERAL REQUIREMENTS

After a gauging-station has been constructed, a definitive survey shall be made.

The definitive survey shall include the accurate determination of the elevations and relative positions of reference gauges and inlet zeros, the survey of inlet pipes or channel inverts, base of stilling-well in the case of a float-operated recorder, the fixation of the pressure take-off and tightness of the gas-pipes and of all parts under pressure in the case of a pneumatic recorder, cross-section markers and any other key points or significant features of the site.

A periodic check, at least once a year, and on every occasion the gauge is changed, shall also be made of the elevations and relative positions taken at the time of the definitive survey.

9 CALIBRATION OF STATION

9.1 General

The object of a gauging-station is to obtain a knowledge of the discharge of a river or open channel. Once the stage-discharge curve is available, the discharge will be known by reading the gauge or recorder. The operations necessary to obtain this relationship are called the calibration (rating) of the station.

9.1.1 *Measurement of discharge for calibration (rating)*

The discharge shall be measured in accordance with the relevant International Standards[1]. Errors may also be estimated on the basis of those International Standards.

The survey of the site shall be carried out in greater detail than in the case of single-discharge measurements. Special attention shall be given to the likelihood of changes in the channel that may affect the stage-discharge curve.

NOTES

1 Very few rivers have absolutely stable characteristics. The calibration, therefore, cannot be carried out once and for all, but has to be repeated as frequently as required by the rate of change in the stage-discharge curve. It is recommended that measurements at the stages which do not frequently occur should be made as often as possible.

2 In the case of an unstable river, the stage-discharge relationship changes more frequently, especially following floods. Discharge observations have therefore to be made at more frequent intervals during these periods.

9.1.2 *Notches, weirs and flumes*

In the case of notches, weirs and flumes, the operation recommended above would not normally be necessary because the stage-discharge relationship may have been determined by laboratory experiments. However, their operation shall be checked periodically

a) by discharge measurements to ensure that the assumed rating applied and that they actually account for all the flow passing the section;

b) by direct measurement of dimensions to verify stability.

9.2 Construction of stage-discharge curve and rating table

9.2.1 *Single-gauge station*

9.2.1.1 STAGE-DISCHARGE CURVE – STABLE CHANNELS

Discharges shall be plotted as abscissae against the corresponding stages as ordinates and the stage-discharge curve shall be drawn smoothly through the points as plotted. The stage used in plotting shall be the mean stage during the period of discharge measurement.

The curve shall be defined by a sufficient number of measurements suitably distributed throughout the whole range of water-levels, each preferably made at steady stage. The number of measurements to define the curve will depend on the range to be covered, the shape of the stage-discharge curve and the desired accuracy (see A.5.3 of Annex A).

The spacing of the measurements shall be closer at the lower end of the range and the drawing of the curve shall be checked by one of the methods described in Annex A. Where observations are made at rising and falling stages, they shall be indicated by suitable symbols, and there shall be about the same number of each at corresponding steps in order to establish the suitable mean curve.

In order to have at least one measurement at or near the peak discharge, it is desirable to increase the frequency of measurements when the gradient of the hydrograph is becoming significantly flatter at or near the peak.

9.2.1.2 STAGE-DISCHARGE CURVE – UNSTABLE CHANNELS

In the case of unstable channels, the stage-discharge relationship does not remain stable and frequent changes in "control" occur during and after flood-periods. Also in the case of unstable channels, the particular stage-discharge relations prevailing over the different periods are required for the estimation of discharges from stage records for the periods for which no discharge measurements are available. The discharges for the water-year shall be plotted as abscissae against the corresponding stages as ordinates and each point labelled in chronological order. The lie of the points shall be examined for shifts in control with reference to their chronological order. Smooth curves shall be drawn separately for each period having no shift in control. Thus, there may be more than one curve within the rising and falling phases of the same water-year for an unstable channel subject to silting and scouring.

9.2.1.3 METHODS OF TESTING STAGE-DISCHARGE CURVES

The curves shall invariably express the stage-discharge relation objectively and shall therefore be tested for absence from bias and goodness of fit in the periods

1) See ISO 555, ISO 748, and ISO 1438.

between shifts of control, and for the shifts in control. Methods for locating shifts in control in the stage-discharge curves due either to physical changes in the channel features or to changes occurring in course of time are also indicated in A.5.8 of Annex A.

For stable channels, where the control is uniform and remains unchanged, it may be possible to fit a mathematical curve. This may be done as explained in A.5.10 of Annex A. More frequently, even in a stable channel, where the curve has to be drawn by visual estimation for example, when the section is not uniform, the tests described for unstable channels become equally necessary.

In the case of natural unstable channels, different controls come into operation at different stages in different years, so that not only are the curves for the rising and falling stages different from each other and from year to year, but there are also inflexions and discontinuities due to shifts in control within a stage. The inordinate labour involved in fitting the high-degree composite curves rules them out in practice. The best-fitting rising and falling curves have, therefore, to be drawn by visual estimation and shall, therefore, be tested for absence from bias and for goodness of fit, separately for the individual portions between shifts in control.

For absence from bias, there are two tests. In one, the curve is tested to satisfy the basic requirement that a significantly equal number of points are expected to lie above and below an unbiassed curve so that the deviations are not more than those due to chance fluctuations (Test 1, A.5.6.1). In the other, the condition that the algebraic sum of the percentage deviations of the observed discharges from an unbiassed curve should not be significantly different from zero is tested by comparing the mean of the percentage deviations with the standard error (Test 3, A.5.6.3).

For goodness of fit, a test is applied to check that a sign-change in deviations (i.e. observed value minus expected value from the curve) is as likely as a non-change of sign. This test also helps in detecting shifts in control at different stages (Test 2, A.5.6.2).

The above-mentioned tests are described in detail in A.5.6 of Annex A with examples illustrating their application.

9.2.1.4 Rating-table

A rating-table shall be prepared from the stage-discharge curve, or from the equation of the curve, showing the discharges corresponding to stages in ascending order, and with intervals corresponding to the desired accuracy of reading.

9.2.2 *Twin-gauge stations*

9.2.2.1 Stage-discharge curve

The establishment of a single-gauge station is impossible in all cases where the flow in the reach of the river is controlled by conditions existing in another reach (upstream or downstream), if the latter vary owing to natural causes (rise in water-level of tributary, obstruction, etc.), or owing to artificial causes (moving flood-gates of navigational dams, hydro-electric schemes, etc.). It is, however, possible to obtain a measurement of flow with two gauges placed in the same reach by the slope-discharge method. For all pairs of values of levels z_0 and z_1 read off each of the scales, there is a single corresponding value of discharge Q, provided that the topography and roughness of the bed have not changed in the reach between the scales.

The plotting of the stage-discharge observations with the value of fall against each observation will reveal whether the relationship is affected by variable slope at all stages, or is affected only when the fall reduces below a particular value. In the absence of any channel control, the discharge would be affected by the fall at all times, and the correction is applied as indicated in the constant-fall method covered in Annex C. When the discharge is affected only when the fall reduces below a particular value, the normal fall method is applied, which is also given in Annex C.

9.2.2.2 Rating-table

The complexity of the relationship generally makes it difficult to prepare a rating-table and it is recommended that the values be obtained from the relevant graphs.

9.3 Verification of the stage-discharge relationship

If the procedure recommended in A.5.1 is followed, no actual verification is needed. When, after one or more years, a sufficient number of observations is available for the whole range of discharges, the curve shall be drawn. By repeating the procedure it will be possible after a certain period to draw a new curve. When shift is thus detected in an unstable channel, a new curve is drawn which serves as a norm during the period until another shift is detected. Each curve is the calibration curve which serves as the norm during the next period of observations. By comparing successive curves and noting the deviations, it is possible to determine the necessary frequency of observations for the future, and the lengths of the periods during which a certain stage-discharge curve may be regarded as reliable.

In cases where the regularity of observations needed for the method described above cannot be realized, the following method of verification is recommended. The stage-discharge curve relationship should be checked by discharge measurements from time to time at a low stage and at a medium or high stage, and always during and after major floods. If a significant departure from the previously established stage-discharge curve is found, further checks should be made. If the difference is confirmed, sufficient discharge measurements should be made to define the area in which the stage-discharge relationship has altered and a new stage-discharge curve should be drawn.

If a particular change of the stage-discharge curve can be attributed to any definable incident in the history of the station, the new curve should be regarded as having applied from the time of that incident.

Methods of checking the consistency of gaugings are described in Annex A.

For unstable channels, a fresh set of discharge measurements shall be made each water-year and new curves drawn corresponding to periods of no change in control.

10 OPERATION OF GAUGING-STATION AND COMPILATION OF RECORDS

10.1 Operation of gauging-station

Provision should be made to ensure that the station is maintained in full operating order at all times. All instruments shall be in working order and conform to relevant standards and shall be properly and regularly calibrated.

10.2 Compilation of records

The records shall be regularly compiled.

When water-level fluctuates during the period of a day, the discharge may be evaluated from a sufficient number of points to enable the mean daily discharges to be computed. When the value of the difference between the instantaneous discharges at the highest and lowest stages in a day divided by the lowest instantaneous discharge of the same day exceeds 20 %, a discharge hydrograph shall be plotted. The ordinates taken shall be sufficient to define the flow conditions of the day. The total volume of the discharge shall be obtained from the area under the hydrograph for the day and the mean rate of discharge shall be obtained by dividing the total volume by the time.

Quantities derived from extrapolation of the stage-discharge curve shall be indicated by the letter "e" and the limits beyond which extrapolation has taken place shall be defined and indicated in an appropriate note accompanying the data. The discharges which have been estimated by interpolation due to failure of the recorder or lack of observer's readings shall be indicated by the letter "i".

The accuracy (number of decimals) of the figures published shall not exceed the accuracy with which they have been determined. The day of record shall extend from a fixed time in the morning on one day to the same time on the next day, quantities measured for that period being credited to the day on which the record started.

10.3 Extrapolation of the stage-discharge curve

Extrapolation of the stage-discharge curve shall be avoided. Whether it is permissible in a given case, and to what extent, depends on the accuracy of the curve (number of observations, natural scatter) and on the characteristics of the channel (see section A.6 of Annex A).

11 OBSERVATION ERROR AND RELIABILITY OF THE STAGE-DISCHARGE CURVE

The stage-discharge curve obtained from the observations gives the mean relationship between the stage and the discharge. The ideal stage-discharge curve would be obtained if measurements were made without errors of observation and where the control remained constant. All points would then fall exactly on the curve. Since these ideal conditions are unattainable in practice, there will be deviations of observations from the curve. These deviations of the measured discharges from the curve give, within limits of the reliability of the curve, an estimate of the observational error. The reliability of the mean curve and of the deviations of the measured discharges from the discharges estimated from the curve may generally be assessed by one or more of the concepts of "Standard error of the mean (the stage-discharge curve)", "Acceptance limits of the observations", and "Confidence limits of the mean stage-discharge curve", as indicated in the following clauses.

11.1 Standard error of the stage-discharge curve

From the points that have been used to determine the stage-discharge curve, all or a certain number shall be chosen, well spaced along the curve. For observations within small intervals of the stage of the selected points taken as the central value, the *standard deviation* from the curve, s_D (i.e. the square root of the mean of the squares of the residuals of the discharge figures from the curve) shall be computed. The intervals shall be selected so that

a) there are a sufficient number of observations in each interval;

b) the error of observation in each interval could be considered as independent of discharge.

The *standard error* of the mean (the stage-discharge curve) is

$$s_E = \frac{s_D}{\sqrt{m}} \qquad \ldots (1)$$

where

m is the number of observations used to determine the stage-discharge curve;

s_D is the standard deviation.

The standard error s_E is usually expressed as a percentage of the estimated discharge from the stage-discharge curve. It is to be noted that the standard error is worked out only for the range over which the control remains invariant.

Where the standard deviation s_D cannot be computed because the number of observations is too small, the value of s_D may be taken to equal X_Q, i.e. the *percentage standard error* of the single discharge measurement in accordance with ISO 748.

NOTE — All calculations of standard deviations are strictly applicable only if care has been taken to randomize the systematic errors by interchanging, as often as possible, the instruments used for the measurements and by changing the observer.

11.2 "Acceptance limits" of the stage-discharge observations

A pair of curves, one on each side of the stage-discharge curve at a distance of twice the *standard deviation,* are called the "control curves" and define the *95 % acceptance limits* of the discharges at the corresponding stages.

On average, in nineteen out of every twenty measurements, results should be within these limits. Any points lying far outside (say, beyond three times the standard deviation) can be regarded as the result of faulty measurement, except in those cases where two or more consecutive points, either chronologically or over a range of stage, appear to be well on one side of one of the limits. Where this occurs, a change of the stage-discharge curve is probable, which means that the calibration of the station has to be repeated, or a different stage-discharge curve is required owing to a shift in control.

Usually, the two postulates made for a valid estimate of the standard deviation in 11.1 are not available; that is, there are not a sufficient number of observations over small intervals of stage and the errors are known to be porportional to discharge over a range having the same control. Therefore, a pooled estimate of the percentage standard deviation may be worked out from the individual percentage deviations of discharge

$$\left(\text{i.e. } \frac{\text{observed discharge} - \text{estimated discharge}}{\text{estimated discharge}} \times 100\ \%\right),$$

taking all the observations together. From this overall percentage standard deviation, the "95 % acceptance limit" may be drawn over the entire range of control.

11.3 95 % confidence limits of the mean (the stage-discharge curve)

Where the pair of curves are drawn to pass through points at a distance of twice the *standard error* s_E of the mean (the stage-discharge curve) (NOT at twice the standard deviation of the observations) on either side of the stage-discharge curve, the pair of curves are called the *95 % confidence limits* of the curve, and the error should be regarded as representative for the corresponding region of the stage-discharge curve.

These limits define the band-width for which there is a probability of 95 % that the true curve lies within these limits.

11.4 Alternative method of determining "acceptance limits of observations" and "confidence limits of the stage-discharge curve"

Another method of determining the "acceptance limits" for discharges and the "confidence limits of the mean (stage-discharge curve)" is to plot the data on log-log paper. The discharges are taken along the abscissae and the stages (referred to datum G_0 for nil discharge – see A.5.10 of Annex A) along the ordinates. The plotted points within the range having the same control will generally fall on a straight line. The "acceptance limits" based on the standard deviation and the "confidence limits" based on the standard error of the mean shall be worked out from the horizontal distances of the observed points from this line.

ANNEX A

DESIGN, CONSTRUCTION AND OPERATION OF A GAUGING-STATION

A.1 PRELIMINARY SURVEY

The topographic survey shall include a plan of the site indicating the width of the water-surface at a stated level, the edges of the natural banks of the channel(s), the line of any definite discontinuity of the slope of these banks and the toe and crest of any artificial floodbank. All obstructions in the channel(s) or floodway shall be indicated. A longitudinal section of the channel shall be drawn extending from below a control, where this exists, to the upstream limits of the reach, showing the level of the deepest part of the bed and water-surface gradients at low and high stages. Cross-sections shall be surveyed in the proposed measuring-section and upstream and downstream of this section. At least five cross-sections shall be taken in a measuring-reach or two cross-sections above a measuring-section and the same below that point, covering a minimum distance equal to one bank-full width of the channel in each direction. The control section should be defined, wherever possible, by surveying a close grid of spot-levels over the area or by a sufficient number of cross-sections. All cross-sections shall be taken normal to the direction of flow and should be extended through the floodway to an elevation well above the highest anticipated stage of flood. The spacing of levels or soundings shall be close enough to reveal any abrupt change in the contour of the channel. The bed shall be carefully examined for the presence of rocks or boulders between the cross-sections, particularly in the vicinity of a measuring-section.

Where velocities are to be measured by a current-meter, exploratory measurements of velocities shall be made in the proposed measuring-section and in the cross-sections immediately upstream and downstream. When possible, the method of velocity distribution should be used for these measurements. When floats are to be used for velocity measurements, trial runs of floats shall be closely spread across the width of the channel to ensure that any abnormality of flow will be detected. These measurements shall be repeated at more than one value of discharge.

A.2 DESIGN OF STATION

The design of the station shall be based on the features disclosed by the preliminary survey.

The control section which determines the water stages at low flows at the gauging-point shall be situated at the downstream end of the measuring-reach, and the operating cross-section nearest to the control (i.e. the measuring-section in the case of current-meter measurement or the terminal section in the case of any other method) shall be sufficiently remote from it to avoid any distortion of flow which might occur in that vicinity, but close enough to ensure that a variable stage-discharge relation will not be introduced through the effect of wind or weed growth in the channel.

Higher flows are usually controlled by the general characteristics of the channel for a considerable distance downstream.

The reference gauge and the recorder shall be located as closely as possible to the measuring-section in the case of a current-meter station, or near the mid-point of the measuring-reach in the case of any other method of measurement.

The important requirements specified as necessary for a suitable gauging-site shall be naturally present, for example a sufficient length of reasonably straight and regular channel free from variable backwater. Where other desirable features are not present, conditions may be improved to some extent by rectification work.

The loss of water from the main channel by spillage can be avoided by constructing floodbanks to confine the flow in a defined floodway. This, however, can only be done for small channels.

It is advisable to protect unstable banks and such protection shall, in the case of current-meter measuring-sections, extend upstream and downstream from the section a distance equal to at least one-fourth the bank-full width of the channel in each direction or, in the case of float measurement, throughout the whole of the measuring-reach.

Instability of the bed may sometimes be corrected by introducing an "artificial control" (see below), which may also serve to improve the stage-discharge relationship (sensitivity), or to create sufficient depth in the measuring-section for instruments to be effectively used. Occasionally, it may be possible to eliminate variable backwater effect by introducing an artificial control.

An "artificial control" is a structure built for the reasons given above. It may be a low dam, or a contraction similar to a flume. The structure is seldom designed to function as a control throughout the entire range of stage. Each "artificial control" structure shall be designed in accordance with the conditions at the site where it is to be built. In the design of controls, the following four major points shall be borne in mind :

a) the shape of the structure shall permit the passage of water without creating undesirable disturbances in the channel above or below the control;

b) the structure shall be of sufficient height to eliminate from the measuring cross-section the effects of variable conditions immediately downstream;

c) the profile of the crest of a control shall be designed so that a small change in discharge at low stages will cause a measurable change in the stage;

d) the control shall have structural stability and shall be permanent.

NOTES

1 Artificial controls are not practicable in the case of large alluvial rivers.

2 Where, in the normal measuring-section, there is insufficient depth or excessively low velocity at low stages, the discharges may often be measured in the same general reach of the stream at another section which is more suitable under these conditions, but which may not be satisfactory for higher flows.

3 It should be noted that if any alterations to natural conditions are made, the subsequent re-establishment of stability will take some time.

A.3 CONSTRUCTION OF STATION

The "reference gauge" is the most important item of equipment at the station. Safe and convenient access shall be provided so that an observer may approach closely to the gauge and make readings accurately from a suitable angle. Readings made from a distance or from an awkward angle may be considerably inaccurate.

In order to avoid velocity effects which may hinder accurate reading, a staff-gauge shall be sited if possible in a bay, where it will not be exposed to the force of the current.

An inclined gauge may be constructed to one continuous slope or may be a compound of two or more slopes. It is often convenient to construct a flight of steps alongside the inclined gauge to facilitate taking readings. The accuracy of readings of an inclined gauge may be improved if a portable stilling-box is used.

The stilling-well shall either be carried on a solid foundation slab below the bottom of the well or, when pipe construction is adopted, the well-pipe may be hung from an under-floor located below the point where the pipe emerges from the bank. The under-floor shall extend well beyond the limit of the intake pipe trench on both sides and shall be solidly bedded on undisturbed ground. The well dimensions shall be large enough (say 60 cm × 90 cm or 24 in × 36 in) to permit the bottom of the well to be cleaned. The smallest dimension of the well, however, shall be not less than twice the diameter of the float of the recorder. It is an advantage to fit more than one intake pipe to the well, the lowest being situated below the lowest anticipated level of flow and the others at suitable levels below normal water-level.

In this way, if during the season of high water the lower pipe(s) becomes obstructed and it is not possible to clean it (them) owing to the depth of water, the recorder will continue to operate on the upper intake(s) until the water-level falls sufficiently to allow access to the lower pipe(s). The upper pipe(s) will usually be accessible for cleaning. It is convenient to provide valves in the intake pipes and install flushing systems to clear silt from the pipes and if this arrangement is impracticable, means for cleaning with flexible sewer-rods should be provided. Further, silt-traps may be provided near the outer end of the intake pipe, in order to retard silting. When appreciable fluctuation occurs in the density of the water it is all the more important that the well should be connected to the channels at various levels to prevent deviation from the water-level in the channel and the well resulting from differences in density.

The diameter of the intake pipe should generally be 10 cm (4 in). If use is made of larger pipes or an open intake, a valve or penstock shall be fitted to control surge in the well. Intake pipes shall be laid level throughout their length. If they exceed 20 m (60 ft) in length, an intermediate inspection man-hole shall be constructed. The bottom of the well shall be carried at least about 30 cm (12 in) below the level of the lowest intake pipe so that there may be no danger of the float grounding when the stream falls to its minimum level.

It is preferable that the recorder should be housed in a ventilated, weatherproof and lock-fast hut, constructed on a thoroughly stable foundation and of such dimensions as will permit the entry of the observer and give him protection from the weather during the operations of changing the chart and servicing the instrument. The recorder shall be mounted on a rigid stool or table firmly fixed to the foundation of the hut and independent of the main structure of the building. There shall be provision for heating the hut in extreme winter conditions. All operating equipment shall be inside the hut.

All key points at the site shall be permanently marked on the ground by markers sunk to such a depth below the surface as will secure them against movement. Cross-section markers shall be set at definite points in the cross-section to facilitate the repetition of levels or soundings when the section is checked.

A.4 DEFINITIVE SURVEY

For current-meter measurements, a standard profile of the measuring cross-section shall be drawn, indicating the position of the cross-section markers. On this standard drawing, the positions selected for the velocity-verticals shall be recorded. The bed-levels of the cross-section shall be checked and the profile revised frequently. A copy of the standard profile (most recent revision) shall be kept in the instrument hut at all times.

For float-stations, a standard plan shall be prepared on which the lines of the selected float-runs and the release points for floats shall be indicated. A copy of this plan shall be kept in the instrument hut at all times.

A.5 STAGE-DISCHARGE CURVE

A.5.1 Trial curves

For purposes of rough estimates, the graphical record obtained by plotting the measured discharges on arithmetically divided graph paper may be sufficient. But where a more critical examination or application of the results is desired, or when a rating-table is to be prepared, it is necessary to ensure that the curve (or curves) drawn are close fits and free from personal bias. If it were possible to fit a mathematical curve, some such procedure as the method of least squares would be adequate. But, in natural rivers, separate controls coming into operation at different stages cause varying and composite curves with undefinable inflexions to which it may not be possible to fit a single mathematical curve. For such rivers, the following procedure may be adopted to ensure that the curves drawn are the best fits and are free from personal bias.

When the observations are plotted, the points shall be labelled with reference to their chronological order, rising and falling points being indicated by distinguishing symbols. A smooth curve (or curves, for example if the rising and falling points indicate distinctly different trends) may be drawn by visual estimation to pass as evenly as possible through the points. If the section is not uniform, or the low- and high-water controls are different, there may be one or two inflexions or discontinuities in the curve. In cases of acute inflexions or discontinuities, more than one curve may be preferable.

These curves shall be tested for "number of signs" (Test 1 – A.5.6.1) and "change of sign" (Test 2 – A.5.6.2) and modified as may be necessary to satisfy these tests.

A.5.2 Rejection of freak observations or incorrect measurements

Incorrect values may have come into the record due to instrumental, computational or copying errors, or for some other reasons. A comparative examination of the stage hydrograph and the discharge hydrograph (of observed discharges), plotted one above the other, will at once spotlight freak values. The data for these dates shall be checked with the original record, and computational and copying errors, if any, rectified.

After correction of the data, there may still be some values which may lie very far away from the trial curves. Such observations shall be pruned down so as to secure homogeneous data for correct stage-discharge relation. Either a limit depending upon the desired accuracy of discharge measurements, or a criterion based on the standard deviation of the observed discharges, as outlined in 11.2, may be adopted for the rejection of freak observations.

A.5.3 Determination of number of observations necessary for establishing a reliable stage-discharge relation

The reliability of the mean relation is measured by the standard error of the percentage deviations (see 11.1) which is given by

$$s_E = \frac{s_D}{\sqrt{m}} \qquad \ldots (1)$$

If the acceptable shift at a confidence level of 95 % is set at P %, then $2\,s_E$ should not exceed P.

But $s_E = \frac{s_D}{\sqrt{m}}$; therefore $\frac{2\,s_D}{\sqrt{m}}$ should not exceed P, from which it follows that m should not be less than $\left(\frac{2\,s_D}{P}\right)^2$.

s_D shall be calculated separately for each range of stage having separate control, and the m-test shall be applied to each s_D separately to obtain the number of observations necessary to attain a specified precision.

In practice, the test may be conveniently applied with sufficient accuracy in the following way :

For this example, P is taken as 5 %. All observations shall first be plotted on double-log paper and the independent controlled ranges of flow identified. They lie between, or to either side of, angular changes in direction of the scatter band. For each independent range, the points shall be replotted on double-log paper on as large a scale as possible, to an appropriate datum. The curve of the relationship will then be a substantially straight line, and, given a reasonable number of well-distributed observations, its position and direction in relation to the points can be established quite accurately by visual examination. Perhaps the most satisfactory estimate will be given by a median line, to either side of which lie an equal number of observed points. Thus, two-thirds of the total number of points are included between two outer lines. At any selected gauge-height, the interval between the two outer lines, measured in discharge units, is equal to $2\,s_D$, and this is expressed as a percentage of the discharge, at this gauge-height, read from the curve of relationship. It may be noted that since these are straight parallel lines on double-log paper, the value of $2\,s_D$, expressed as a percentage, will be the same, no matter at what gauge-height the value is determined. From the value of $2\,s_D$ thus obtained, the value of $\left(\frac{2\,s_D}{5}\right)^2$ shall be calculated and compared with m, the number of observations. If m is less than $\left(\frac{2\,s_D}{5}\right)^2$ more stage-discharge observations shall be taken, after which the test shall be applied again.

It is suggested arbitrarily that m should never be less than 6 for any one section of the range.

Figure 1 illustrates that part of the above example relating to the test on a single section of the range. The following table illustrates the variation in the necessary number of observations with variation in width of scatter band, P being taken as 5 %.

$2\,s_D$ %	10	15	20	25	30
m minimum	6	9	16	25	36

A.5.4 Stable channels

In the case of stable channels, it is generally found that one curve for the rising and falling stages is adequate, unless the river has a steep slope or is flashy; sometimes, one curve is applicable with a narrow belt of dispersion for some years.

Test 3 (see A.5.6.3) shall be applied to the trial curve and if this test is satisfied in addition to Tests 1 and 2, the curve may be considered as free from bias. With practice, one would be able to draw a curve satisfying all the three tests with a single trial.

Of the alternative curves satisfying all the three tests, the one that gives the least standard error shall be taken as the best. The curve shall, of course, be smooth. The standard deviation of the percentage difference of the observed discharges from the curve shall not be greater than the percentage standard deviation of the discharge observations for the method of measurement used.

A.5.5 Unstable channels

In addition to the shift in control at some particular stage due to a different control coming into operation as exhibited by some stable channels, the unstable channels manifest another peculiarity, that is, a shift of control with reference to time or intensity of floods, and the consequential seasonal scour and fill phenomena. There are significant differences in the gauge-heights for the same discharge in the rising and falling stages, and a complete change in regime occurs after the maximum flood of the year. Minor freshets, specially during the clear-water season, may also cause shifts in control.

Channels which are subject to freezing or which have features like aquatic growth and vegetal cover also exhibit shifts in control with reference to time.

Such shifts in control may be detected by following the deviations (positive and negative) of the observed discharges from the trial curves in chronological order as indicated in A.5.8.

The water-year shall be subdivided into periods over which the same stage-discharge relation prevails, and separate curves shall be drawn for each period. These curves shall, in addition, satisfy Tests 1, 2 and 3 of A.5.6. Further, the standard deviation of the percentage differences for each curve shall be reasonably small, as stated in the case of stable channels.

A.5.6 Tests for absence from bias and goodness of fit

All the tests enumerated below may be applied to portions of curves, each individual portion being tested for bias separately.

A.5.6.1 *Test 1 – Absence from bias (signs)*

The number of positive and negative deviations of the observed values from the stage-discharge curve drawn by visual estimation (see A.5.1) shall be evenly distributed, i.e. the difference in number between the two shall not be more than can be explained by chance fluctuations.

The test is applied to find out if the curve has been drawn in a sufficiently balanced manner so that the two sets of discharge values, observed and estimated (from the curve), may be reasonably supposed to represent the same population. This is a very simple test and can be performed by counting the observed points falling on either side of the curve. If Q_o is the observed value and Q_E the estimated value, then $Q_o - Q_E$ should have an equal chance of being positive or negative. In other words, the probability of $Q_o - Q_E$ being positive is 1/2. Hence, assuming the successive signs to be independent of each other, the sequence of the differences may be considered as distributed according to the binomial law $(p+q)^m$, where m is the number of observations, and p and q, the probabilities of occurrence of positive and negative values, are 1/2 each.[1)]

1) The test as performed on the 1959-1960 Farakka stage-discharge (see Figure 2) yielded the following results :

Particulars	Symbol	Rising-stage curve	Falling-stage curve
1) Number of positive signs, i.e. points lying to the right of the curve	m_1	42	67
2) Total number of observation	m	83	122
3) Probability of a sign being positive	p	1/2	1/2
4) Probability of a sign being negative	q	1/2	1/2
5) Expected number of positive signs	mp	41,5	61
6) Standard deviation of 5)	$\sqrt{mpq}$	4,56	5,52
7) $\dfrac{\lvert m_1 - mp\rvert - 0{,}5^*}{\sqrt{mpq}}$	**t**	0,00	1,00
* Continuity correction			

NOTE – Tables giving values of **t** for different levels of significance are available and values exceeding these would denote bias. For m greater than 30, a value lower than 1,96 (say lower than 2) indicates that the difference is not statistically significant at the 5 % level. Since the values for both the rising- and falling-stage curves are considerably less than 2, the curves are free of bias when judged by this test. For small values of m (say less than 25), the exact probability of the above difference or a greater difference between the actual and expected signs has to be worked out from the binomial distribution to assess the freedom from bias.

A.5.6.2 *Test 2 – Goodness of fit*

This test is carried out for long runs of positive and negative deviations of the observed values from the stage-discharge curve.

This test is designed to ensure a balanced fit in reference to the deviations over different stages.

This test is based on the number of changes of sign in the series of deviations (observed value minus expected value). Write down the signs of deviations in discharge measurements in ascending order of stage, and, starting from the second sign of the series, write under each a "0" if the sign agrees or "1" if it does not agree with the sign immediately preceding. For example :

+ – + + + – – + +
1 1 0 0 1 0 1 0

If there are m observations in the original series, there will be $(m-1)$ numbers in the derived series 11 001 010 ... ...

If the observed values could be regarded as arising from random fluctuations about the values estimated from the curve, the probability of a change in sign could be taken to be 1/2. It should be noted that this assumes that the estimated value is a median rather than a mean. If m is fairly large (say 25 or more), a practical criterion may be obtained by assuming successive signs to be independent (i.e. by assuming that they arise only from random fluctuations), so that the number of "1"s (or "0"s) in the derived sequence of $(m-1)$ members may be judged as a binomial variable with parameters $(m-1)$ and 1/2.[1)]

Further, for goodness of fit, the standard deviation of the percentage deviations should be as low as possible, consistent with the smoothness of curve. No simple test is possible to check the smoothness of curve (see A.5.7). As a rule, this should not be greater than the percentage standard deviation of the error of discharge measurements by the method used.

1) The test as applied to the curves in Figure 2 is shown below :

Particulars	Symbol	Rising-stage curve	Falling-stage curve
1) Number of observations	m	83	122
2) Number of changes of sign	m'	34	53
3) Probability of change in sign	p	1/2	1/2
4) Probability of no change in sign	q	1/2	1/2
5) Expected number of changes in sign	$(m-1)\,p$	41	60,5
6) $\dfrac{\lvert m'-(m-1)\,p\rvert - 0{,}5}{\sqrt{(m-1)\,pq}}$	t	1,44	1,27

NOTE – Since the value of t is less than 1,96, the difference is not significant at the 5 % level, i.e. the assumption of random fluctuations is not disproved. Therefore, there is no abnormal variation in the number or order of the signs of deviations. Since it has been already tested for the number of signs of deviations due to random fluctuations, the present test confirms that there is no systematic trend in the deviations.

A.5.6.3 *Test 3 – Absence from bias (values)*

The third test is designed to determine whether a particular stage-discharge curve, on average, yields significant under-estimates or over-estimates as compared to the actual observations on which it is based. The percentage differences,

$$\frac{(Q_o - Q_E) \times 100}{Q_E} = P \qquad \ldots (2)$$

are worked out and averaged. If there are m observations and $P_1, P_2 \ldots P_i \ldots P_m$ are the percentage differences, and if $\bar{P}$ is the average of these differences, the standard error s_E of $\bar{P}$ is given by :

$$s_E = \sqrt{\frac{\Sigma (P_i - \bar{P})^2}{m(m-1)}} \qquad \ldots (3)$$

The average percentage $\bar{P}$ is tested against its standard error to see if it is significantly different from zero.

The percentage differences have been taken as they are somewhat independent of the discharge volume and are approximately normally distributed about a zero mean value for an unbiased curve.

A.5.7 Smoothness of curve

Smoothness of a relation curve is also important, but it is a property which cannot be exactly defined. The criterion frequently accepted is that the first and second-order differences should progress smoothly, and higher-order differences should become very small. But acceptance of such a criterion is tantamount to accepting that the curve should approximately be a third or higher-order polynomial. The higher-order derivatives should show a tendency to diminish, but no test can be imposed in regard to smoothness for stage-discharge relation curves, as irregularities at some stages due to changes in control and irregularities of cross-section are inherent features of these relation curves.

A.5.8 Methods for locating shift in control

To locate shifts in control in curves already drawn and to check whether subsequent gaugings indicate any change in the established relationship, one of the following two simple procedures may be adopted according to whether the shift in control is due to channel features or due to change occurring in course of time.

a) As the stage rises, shifts in control may occur owing to different channel features. Inflexions and discontinuities in the stage-discharge relations usually mark these shifts. These shifts in control may be located conveniently by means of a deviation diagram in which the amounts (positive or negative) by which each check-gauging deviates from the curve are plotted around a central ordinate which represents the established curve. The deviations are plotted as abscissae against the appropriate stages as ordinates.

If the acceptable limits of deviation (positive and negative) of individual gauges are drawn on the diagram, it is readily seen whether any check-gauging falls outside the limits. This also shows whether, within the prescribed limits, there is any tendency for the relationship to drift to one side or the other.

b) A similar procedure may be used to detect shift in control which occurs in course of time owing to a change in the river regime, following floods or freshets or any other natural phenomena. In this case, the positive and negative deviations may be plotted along the ordinate against time along the abscissa. When the deviations of the same sign exhibit long runs, a shift is suspected. Generally, when seven or more consecutive observations spread over sufficiently long periods have the same sign, the stage and discharge hydrographs should be checked to find out if there is any likelihood or assignable cause of a shift in control.

A.5.9 Check on subsequent shifts in control

Once a gauging-station has been calibrated and the stage-discharge curve has been drawn, a careful watch shall be kept to ascertain whether subsequent check-gaugings indicate any departure from the established relationship. The method for locating the shift in control is indicated in A.5.8.

Changes in bed conditions over long periods may also be detected from a study of the specific stage-discharge curves. In this method, the observed stages with respect to specific discharges (say 500, 1 000 or 2 500 m³/s or 20 000, 50 000 or 100 000 ft³/s) are plotted against time for a number of years. If the plot of the stages for the same discharge is more or less horizontal with reasonable degree of scatter, then the channel may be taken as fairly stable, as it may be assumed that there are no significant changes with time in the bed conditions on account of erosion or silting action. If, on the other hand, the alignment of points shows consistent falling or rising trends for any specific discharges, this leads to the inference that the bed shows a definite tendency to fall or rise, as the case may be, in course of time. This procedure will throw considerable light not only on the presence, but also on the pattern, of bed changes and, consequently, on the kind of shift expected in the stage-discharge relation.

A.5.10 Fitting of a mathematical curve

In some rare cases, where the control section is uniform and remains unchanged, it may be possible to fit a mathematical curve. Usually, the relationship may be expressed by the equation

$$Q = C_1 (G - G_0)^{C_2} \qquad \ldots (4)$$

where

Q and G are the discharge and the gauge reading respectively;

G_0 is the gauge reading corresponding to zero discharge;

C_1 and C_2 are station constants.

The values of Q plotted against $G - G_0$ on log-log scale would therefore, between shifts in control, lie about a straight line. For this purpose, it would be necessary to determine G_0. This may be done by trial and error. If the value of G_0 selected is less than actual, the curve on log-log scale will be concave upwards. But if it is greater than actual, the curve will be the reverse. A more objective method of determining G_0 is given below.

A.5.10.1 *Determination of G_0*

The points are plotted on ordinary (arithmetical) scale and a smooth curve is drawn by visual estimation. Three values of discharges, Q_1, Q_2 and Q_3, are selected in geometric progression, i.e.

$$Q_2{}^2 = Q_1 \times Q_3 \qquad \dots (5)$$

If the corresponding values of the gauge readings from the curve are G_1, G_2 and G_3, it is possible to verify that, if equation (4) holds, then

$$G_0 = \frac{G_1 G_3 - G_2{}^2}{G_1 + G_3 - 2\,G_2} \qquad \dots (6)$$

A graphical method of determining G_0 is described below.

As above, three values of discharges in geometric progression are selected. Let the corresponding points on the curve be A, B and C (see Figure 3).

Through A and B vertical lines are drawn, and through B and C horizontal lines are drawn intersecting the verticals at D and E respectively. Let DE and AB meet at F. Then the ordinate of F is the value of G_0.

A.5.10.2 *Determination of C_1 and C_2*

After having established the value of G_0, the constants C_1 and C_2 may be determined from the logarithmic plot of Q against $G - G_0$. The values of the constants C_1 and C_2 can also be worked out statistically so that sum of the squares of the deviations between log Q and log $(G - G_0)$ is a minimum.

Values of C_1 and C_2 may then be obtained from the equations :

$$\Sigma\,(Y) - m \log C_1 - C_2 \Sigma\,(X) = 0 \qquad \dots (7)$$

$$\Sigma\,(XY) - \Sigma\,(X) \log C_1 - C_2 \Sigma\,(X^2) = 0 \qquad \dots (8)$$

where

$\Sigma\ (Y)$ is the sum of all values of log Q;

$\Sigma\ (X)$ is the sum of all values of log $(G - G_0)$;

$\Sigma\ (X^2)$ is the sum of all values of the square of (X);

$\Sigma\ (XY)$ is the sum of all values of the products of (X) and (Y);

m is the number of observations.

The preparation of the data and solution of the equation may be simplified by employing a tabulation as shown in Table 1. The corresponding tabulation for determining plotting points or a rating-table is shown in Table 2.

If the controlling section changes at various stages, it may be necessary to fit two or more similar equations, each relating to the portion of the range over which the control has remained the same. If, however, too many changes in parameters are necessary to define the relationship, then possibly the mathematical form assumed may not be suitable and a curve fitted by visual estimation would be better.

TABLE 1 – **Example of tabulation of calculation to determine stage-discharge relationship**

Observation Ref. No.	Q	G	$(G - G_0)$ $G_0 = +0,2$	$\log Q$ $= (Y)$	$\log (G - G_0)$ $= (X)$	(XY)	(X^2)
1	65	0,95	0,75	1,813	− 0,125	− 0,227	0,015 6
2	177	1,45	1,25	2,248	0,097	0,218	0,009 4
3	159	1,35	1,15	2,201	0,061	0,134	0,003 7
4	63	0,90	0,70	1,799	− 0,155	− 0,279	0,024 0
5	49	0,80	0,60	1,690	− 0,222	− 0,375	0,049 3
6	341	1,90	1,70	2,533	0,230	0,583	0,052 9
7	61	0,90	0,70	1,785	− 0,155	− 0,277	0,024 0
8	114	1,10	0,90	2,057	− 0,046	− 0,095	0,002 1
9	172	1,35	1,15	2,236	0,061	0,136	0,003 7
10	202	1,45	1,25	2,305	0,097	0,224	0,009 4
11	225	1,55	1,35	2,352	0,130	0,306	0,016 9
12	255	1,62	1,42	2,407	0,152	0,366	0,023 1
			Σ	25,426	+ 0,125	+ 0,714	0,234 1

From the results of Table 1,

$$25{,}43 - 12 \log C_1 - 0{,}125\, C_2 = 0 \qquad \text{(using equation 7)}$$

$$0{,}714 - 0{,}125 \log C_1 - 0{,}234\, C_2 = 0 \qquad \text{(using equation 8)}$$

From these two equations it follows that $C_2 = 1{,}93$ and $C_1 = 125{,}6$

By substituting for C_2 and C_1 in equation (4), it follows that

$$Q = 125{,}6\ (G - 0{,}2)^{1{,}93}$$

TABLE 2 – **Tabulation of calculation to determine the points for plotting stage-discharge curve and constructing rating-table**

With $Q = 125{,}6\ (G - 0{,}2)^{1{,}93}$ and $\log 125{,}6 = 2{,}099$ the following table can be established :

G	$(G - 0{,}2)$	$\log (G - 0{,}2)$	$\log (G - 0{,}2) \times 1{,}93$ $= (A)$	$(A) + 2{,}099$	Q	ΔQ	ΔG	Increment for 0,01 unit
0,2					0			
						12,3	0,3	0,41
0,5	0,3	− 0,523	− 1,009	1,090	12,3			
						27,2	0,25	1,09
0,75	0,55	− 0,260	− 0,502	1,597	39,5			
						42,1	0,25	1,68
1,00	0,80	− 0,097	− 0,187	1,912	81,6			
						56,4	0,25	2,26
1,25	1,05	0,021	0,041	2,140	138,0			
						70,0	0,25	2,80
1,50	1,30	0,114	0,220	2,319	208,0			

A.6 EXTRAPOLATION OF STAGE-DISCHARGE CURVE

The stage-discharge relation curves are primarily intended for interpolation, and their extrapolation beyond the highest-recorded high water or the lowest-recorded low water may be subjected to risk and indefinite errors. Physical factors like overbank spills at high stages, shifts in controls at very low and very high stages, changes in rugosity coefficients at different stages, etc., materially affect the nature of the relationship at the extreme ends and should be taken account of in the extrapolations. Extrapolation should be avoided as far as possible, but where extrapolation beyond the range of actual measurements is necessary, such extrapolation shall be checked by the results obtained by more than one method. The physical conditions of the channel, that is, whether the channel has defined banks over the entire range, or only up to a stage and overbank spill above that stage, as well as whether the channel has fixed of shifting controls, should govern the methods to be used in the extrapolation. There are a number of methods; those given below are suitable for a channel with defined banks and fixed controls, as well as for a channel with spill.

a) If the control does not change beyond a particular stage, it may be possible to fit a mathematical curve as indicated in clause A.5.10 and obtain the values in the range at the upper or lower end of the stage-discharge curve to be extrapolated.

b) Another simple method would be the separate extensions of the stage-area curve and the stage mean velocity curve. The latter has little curvature under normal conditions and can be extended without error. The product of the corresponding values of A and $\bar{v}$ may be used for extending the discharge (Q) curve.

c) The mean velocity curve may also be extended by adopting the following procedure :

The hydraulic mean depth (R_h) can be found for all stages from the cross-section.

A logarithmic plot of $\bar{v}$ against R_h generally shows a linear relationship for the higher measurements and the values of $\bar{v}$ for the range to be extrapolated may be obtained therefrom.

d) A variation of the last method is by the use of Manning's formula :

$$Q = A\bar{v} = \frac{AR_h{}^{2/3}S^{1/2}}{n} \quad \text{(in metric units)} \quad \ldots (9)$$

or

$$Q = \frac{1{,}5\, AR_h{}^{2/3}S^{1/2}}{n} \quad \text{(in foot and second units)} \ldots (10)$$

Assuming $\dfrac{S^{1/2}}{n}$ remains constant and substituting $\bar{D}$ for R_h a curve can be prepared for Q against $A\bar{D}^{2/3}$.

After the full-bank stage, the discharge of the spill portion will have to be worked out separately by assuming an appropriate value of n. If accurate gauges do not exist for computing the slope, it may roughly be estimated from the flood-marks.

e) Chezy's formula can be used in the same way in place of Manning's formula. In this case the slope of the $\log \bar{v} - \log R_h$ line is taken as 1/2.

f) Yet another method that may be used, when another discharge site exists on the same stream, upstream or downstream, is to assess the relation between the rating-curves of the two stations and find out the discharge at the required station. This presumes that corresponding discharge at the other station is either known or can be worked out correctly taking additions, withdrawals, channel and valley storage into consideration.

A.7 OPERATION OF STATION

The production of satisfactory records depends upon efficient attendance on the recorder and proper maintenance of the station, its equipment and its calibration.

Where a station is only fitted with a gauge or gauges (staff, inclined, or hook) and no continuous water-level recorder, the local observer shall be required to furnish for each day one or more readings of all the gauges in his care. Preferably the readings should be made at fixed hours. The intervals between the readings shall be determined by the rate at which the water-level at the site usually changes, but arrangements shall be made to have additional readings when the water-level is changing more abruptly than usual. It is essential that for all gauge readings the time at which the observation was made should be recorded.

When a recorder is provided, the local observer shall visit the station at the appropriate intervals to ensure regular servicing of the recorder. If possible, additional visits should be made throughout the period to verify that the recorder is operating satisfactorily. The local observer shall be required to record observations of the water-level "reference gauge" and also the time for comparison with the recorder chart and clock. To relate the readings to the chart trace, the observer may mark the chart by slightly raising or lowering the float-wire. At all stations the local observer shall record any obstruction of the channel by weeds or ice, shall note any casual obstruction of the channel by flood-debris or from any other cause, and shall keep the site and equipment generally clean and tidy, paying particular attention to the legibility of the "reference gauge". He shall be required to despatch all records or charts to the record office for computation immediately they have been completed, together with any relevant notes or observations.

Every gauging-station shall be inspected by a superior officer, whenever any incident which might affect its accuracy is notified by the local observer.

Recorders which are otherwise in good working order shall be thoroughly cleaned (on the site if necessary) at least annually. Clocks shall be removed for overhaul by a clockmaker at intervals not greater than two years.

The elevation of all key points (including particularly zero of reference gauge) which were surveyed in the definitive survey shall be checked by reference to the station bench-mark at least annually or following any flood when equipment might have been damaged or disturbed by debris or by ice. At the same time, any staff-gauge shall be tested for verticality. The connection of the station bench-mark with ordnance survey datum shall be checked at intervals not greater than 5 years.

A.8 COMPILATION OF RECORDS

The collection of field data in the form of records of gauge readings or of charts taken from water-level recorders and of velocity measurements is only the first step in the compilation of a station record. While it is important that field observation should be made accurately, no less importance should be attached to the work of reducing and transcribing information. Both operations must be performed with meticulous care as negligence at either stage can vitiate the value of the record.

All field data shall be examined critically with the object of uncovering any anomalies which may exist or rejecting data which is evidently erroneous and beyond valid correction.

Where autographic recorders are installed, readings of water-levels from instrument charts shall be taken at such intervals as may be necessary to define the hydrograph adequately.

The conversion from water-level to discharge by the use of the stage-discharge curve and station rating-table shall be made for each water-level after making all necessary corrections and the daily means of discharge shall be computed independently. For the computation of daily means of discharge, the assumption shall be made that changes in water-level which take place between readings, whether these are observations of a gauge or readings from an instrument chart, vary directly with time. The water-levels so obtained shall be converted to discharge by use of the station rating-tables. The daily means of discharge shall be computed separately. No discharges shall be calculated from a daily mean water-level.

The daily mean discharge shall then be entered on the office record of the station, and all significant flood-peaks shall also be entered on the record. Annotations on the record shall also indicate any day on which the flow suffered interference through weed growth, ice or flood-debris.

ANNEX B

CORRECTION FOR DISCHARGE IN UNSTEADY FLOW

The stage-discharge curve for a single-gauge station gives the value of the normal discharge, i.e. the discharge under uniform steady-flow conditions for a given stage. The discharge for a particular level is greater with rising stage than the normal discharge and the reverse is the case with the falling stages.

Under certain conditions, it is possible to compute approximately the true discharge (Q) of an unsteady flow from the normal discharge (Q_o) obtained from the stage-discharge curve by using the following formula :

$$Q = Q_o \sqrt{1 + \frac{1}{S_o v_w} \times \frac{dz}{dt}} \qquad \ldots (11)$$

where

S_o is the normal slope corresponding to steady discharge;

v_w is the velocity of flood-wave;

$\frac{dz}{dt}$ is the time rate of change of stage.

The slope S_o may be determined from observation of gauges during conditions of steady flow. Alternatively, it may be approximately computed from Manning's or Chezy's formula.

The rate of change of stage $\frac{dz}{dt}$ may be obtained from observation of the gauge installed for the purpose.

The wave velocity is given by the formula

$$v_w = \frac{dQ}{dA} = \frac{1}{b} \times \frac{dQ}{dz} \qquad \ldots (12)$$

where

A is the cross-sectional area;

b is the surface-width at the cross-section;

$\frac{dQ}{dz}$ can be approximately taken from the stage-discharge curve. The assumption is valid when the rise or fall of the flood is gradual, i.e. the rate of change of velocity or the acceleration head can be neglected.

Another condition for the formula to be applicable is that the velocity is not very high so that the velocity head can also be neglected.

When a sufficient number of field measurements of discharge are available, it may be possible to establish an acceptable family of calibration curves empirically by evaluating the effect of the rate of change in stage measured at one gauge, as a parameter.

ANNEX C

FAMILY OF CURVES GIVING THE STAGE-DISCHARGE RELATION

C.1 GENERAL

The plotting of the stage-discharge measurements, with the value of fall $(z_0 - z_1)$, where z_0 and z_1 are the upstream and downstream stages, respectively, marked against each measurement, will reveal whether the relationship is affected by variable slopes at all stages or is affected only when the fall reduces below a particular value. In the absence of any channel control, the discharge would be affected by the fall at all times and a correction is applied by the fixed or the "constant-fall" method (see section C.2 below); on the other hand, however, when the discharge is affected only when the fall reduces below a particular value, the "normal-fall" method is applied (see section C.3 below).

C.2 CONSTANT-FALL METHOD

The calibration curve $Q = f(z)$ (equation 13) of single gauge stations is here replaced by a calibration surface which is a function of z_0 and z_1 and which may be theoretically determined by measuring the discharges corresponding to a large number of pairs of conjugate values z_0, z_1.

It can, nevertheless, be pointed out that for the same elevation z_0 on the upstream scale, the discharge is a function of the fall $H = z_0 - z_1$ (equation 14), that is :

$$Q = Q_n \, f\left(\frac{H}{H_n}\right) \qquad \ldots (15)$$

where

Q is the measured discharge;

Q_n is the constant-fall discharge at the same stage;

H is the fall corresponding to the measured stage;

H_n is the selected constant fall (arbitrary).

It would, therefore, be easy to trace

a) the calibration curve $Q_n = f(z_0)$ (equation 16) of the upstream scale for a constant arbitrary value H_n of the fall H between the two scales;

b) the correction curve $\dfrac{Q}{Q_n} = f\left(\dfrac{H}{H_n}\right)$ (equation 17) of "relative discharges" in relation to "relative falls".

In practice, the calibration and correction curves may be determined by successive approximations, by means of the following procedure :

On a graph, record the measured discharges Q in terms of the elevation on the upstream scale z_0, then adapt a reference fall H_n, chosen as far as possible from among the most frequent ones, and then by guesswork trace among the experimental points the curve $Q_n = f(z_0)$ (see Figure 4) corresponding to this fall, and passing through the experimental points.

This may be aided by the fact that as a first approximation

$$\frac{Q}{Q_n} = f\left(\frac{H}{H_n}\right) = \left(\frac{H}{H_n}\right)^{1/2} \qquad \ldots (18)$$

From this curve, it will be possible to determine the ratio

$$\frac{Q}{Q_n} = f\left(\frac{H}{H_n}\right) \qquad \text{(see Figure 5)}$$

and thus, by successive attempts, the calibration curve $Q_n = f\,(z_0)$ can be adjusted (see Figure 6).

Direct measurements of discharge should as far as possible cover simultaneously the whole range of discharges and stages.

C.3 NORMAL-FALL METHOD

This method is useful if the usual simple rating is applicable at sufficient falls when backwater effect is absent, while for low falls the discharge is affected by backwater. Critical values of the fall dividing these two regions are termed the "normal fall". The value of "normal fall" at any discharge can be determined by studying the plot of stage against discharge. The points at which backwater has no effect will group at the extreme right. This is the simple rating curve (see Figure 7). A plot of the normal-fall values from this curve is made and the corresponding stages are derived (see Figure 8). This permits of drawing a curve of discharge ratios where normal fall is used in place of constant fall (see Figure 9). The rest of the procedure is similar to that of the constant fall method (section C.2).

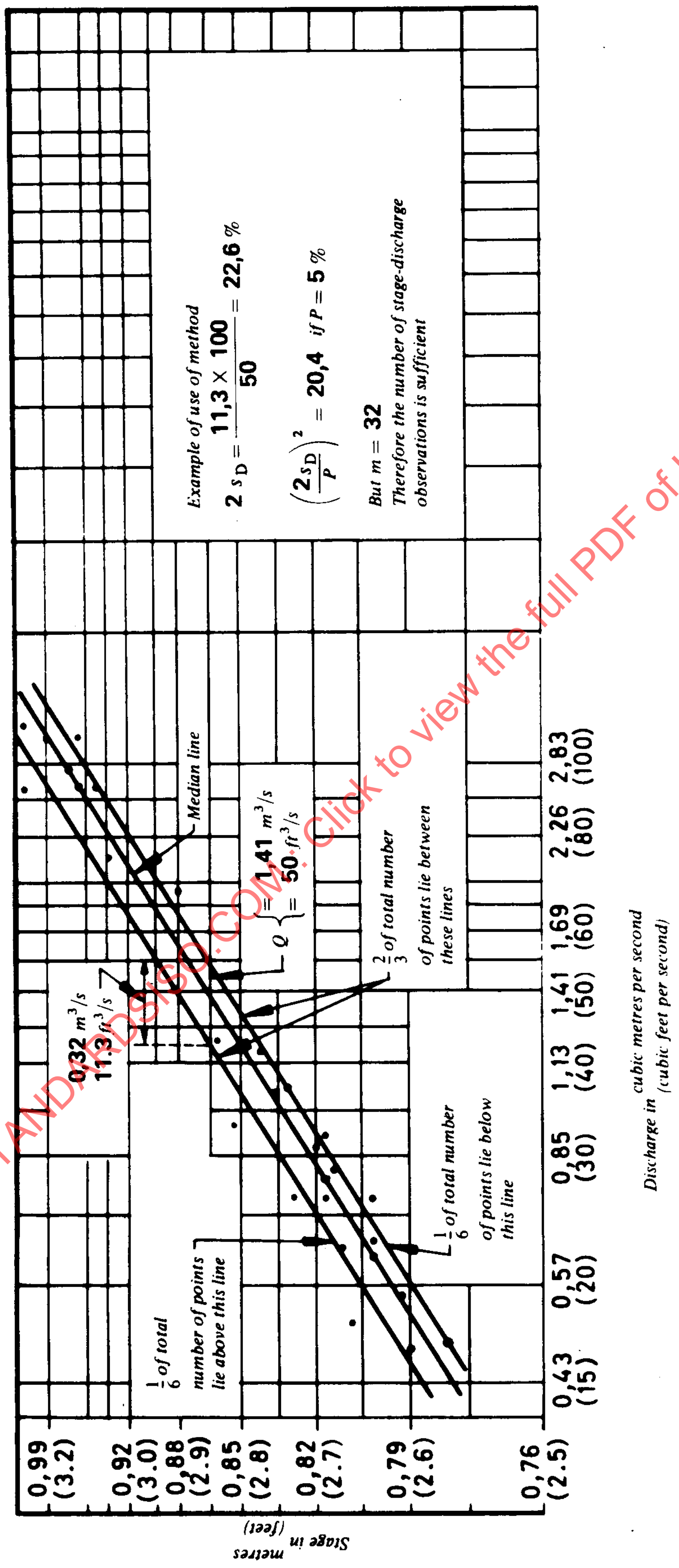

FIGURE 1 — Determination of number of observations necessary for establishing a reliable stage-discharge relationship

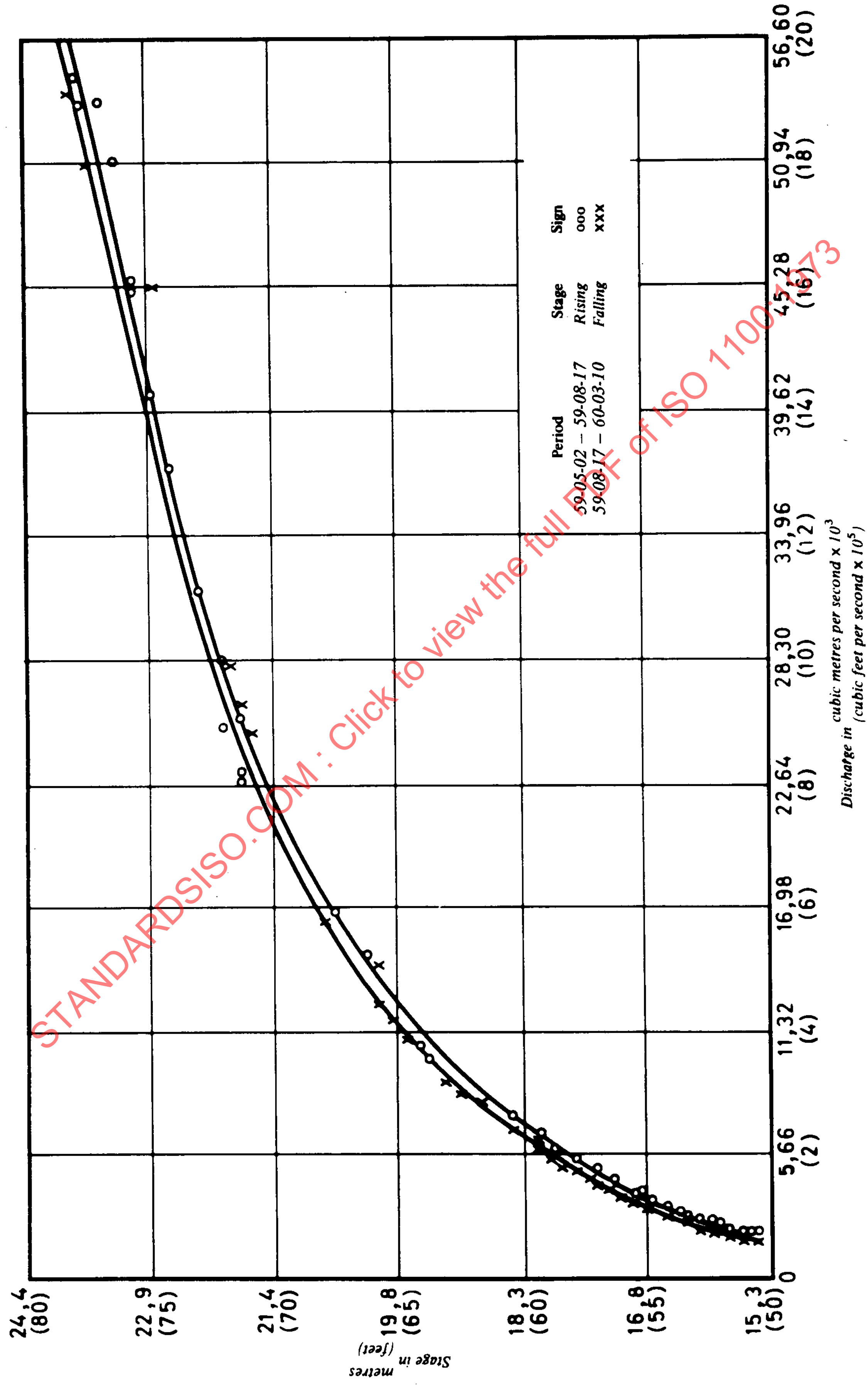

FIGURE 2 — Testing of stage-discharge curves (See also Tests 1 and 2 of A.5.6)

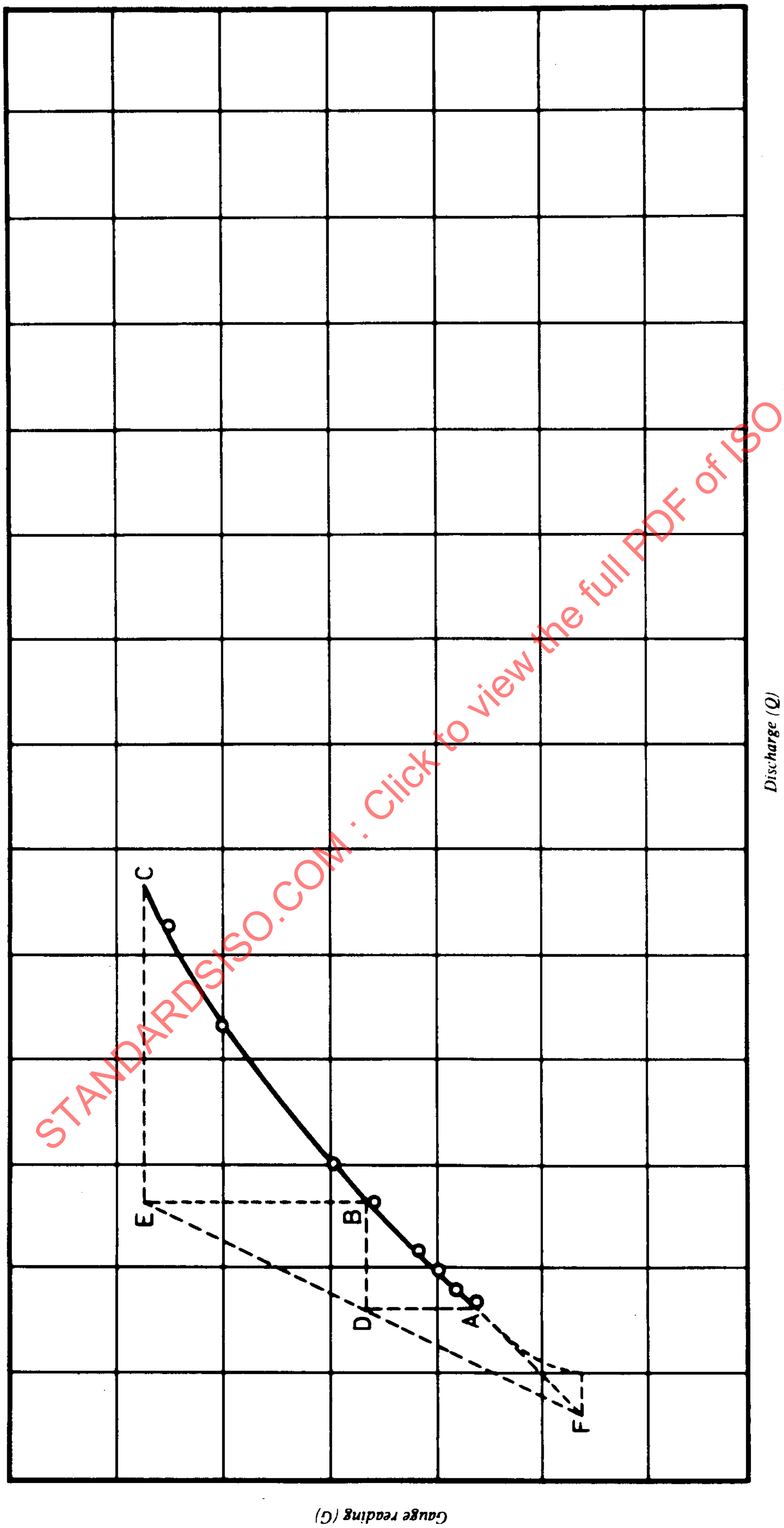

FIGURE 3 — Determination of G_0 — Gauge reading for zero discharge

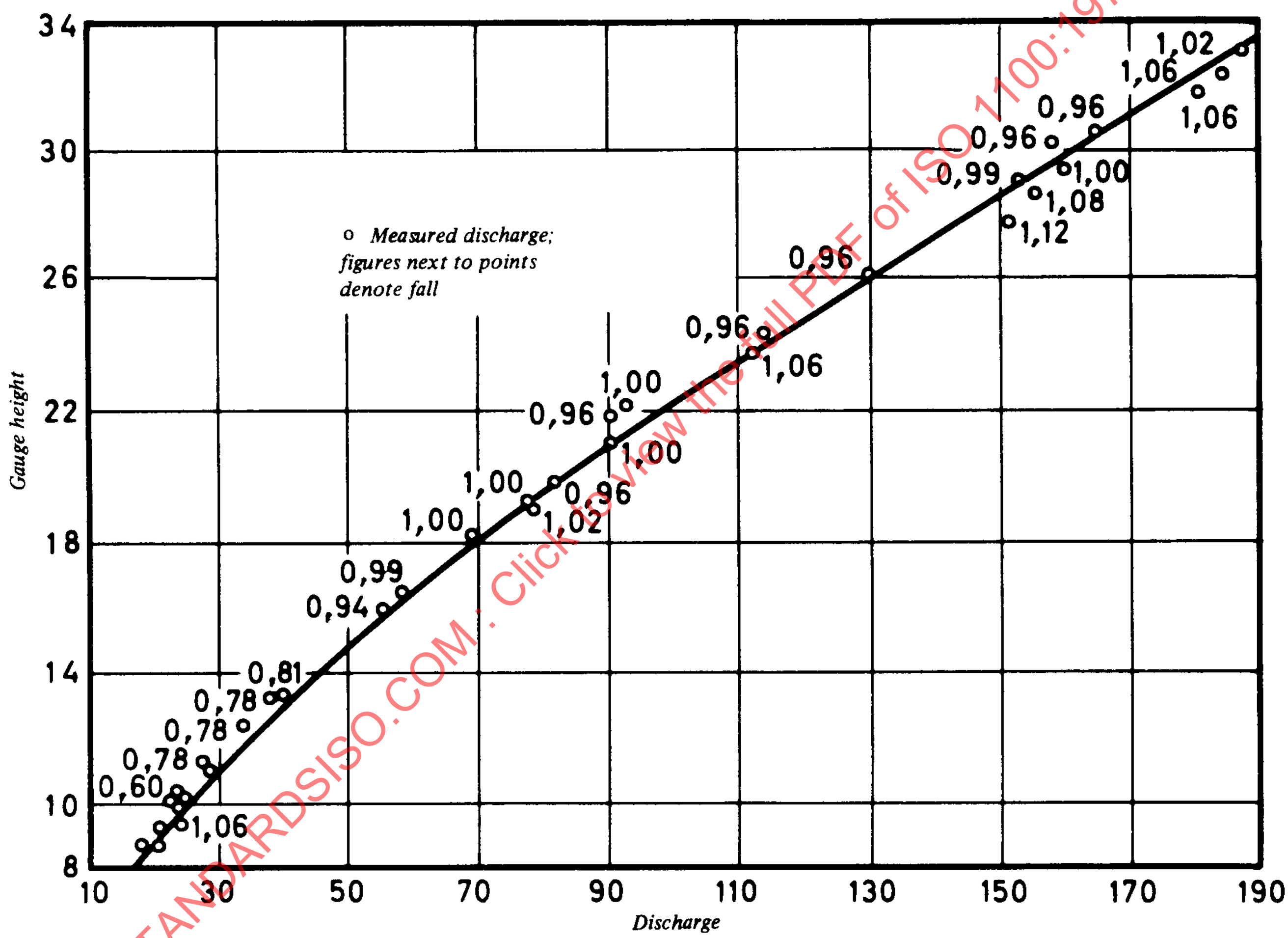

FIGURE 4 — **Relationship $Q_n = f(z_0)$ for unit fall $H_n = 1$**