

MINISTRY OF WATER ENERGY AND MINERALS
TANZANIA

**MANUAL ON PROCEDURES
IN
OPERATIONAL HYDROLOGY**

VOLUME 4

STAGE-DISCHARGE RELATIONS AT STREAM
GAUGING STATIONS

1979

214.0
79 MA

1021

MINISTRY OF WATER
ENERGY AND MINERALS
TANZANIA

NORWEGIAN AGENCY FOR
INTERNATIONAL DEVELOPMENT
(NORAD)

214.0
79mA

MANUAL ON PROCEDURES IN OPERATIONAL HYDROLOGY

VOLUME 4

STAGE-DISCHARGE RELATIONS AT STREAM
GAUGING STATIONS

ØSTEN A. TILREM

1979
Water and Health Centre
for Community Water Supply

1979

PREFACE

This Manual on Procedures in Operational Hydrology has been prepared jointly by the Ministry of Water, Energy and Minerals of Tanzania and the Norwegian Agency for International Development (NORAD). The author is Østen A. Tilrem, senior hydrologist at the Norwegian Water Resources and Electricity Board, who for a period served as the Project Manager of the project *Hydrometeorological Survey of Western Tanzania*. The Manual consists of five Volumes dealing with

1. Establishment of Stream Gauging Stations
2. Operation of Stream Gauging Stations
3. Stream Discharge Measurements by Current Meter and Relative Salt Dilution
4. Stage-Discharge Relations at Stream Gauging Stations
5. Sediment Transport in Streams – Sampling, Analysis and Computation

The author has drawn on many sources for information contained in this Volume and is indebted to these. It is hoped that suitable acknowledgement is made in the form of references to these works. The author would like to thank his colleagues at the Water Resources and Electricity Board for kindly reading and criticising the manuscript. A special credit is due to W. Balaile, Principal Hydrologist at the Ministry of Water, Energy and Minerals of Tanzania for his review and suggestions.

CONTENTS

1	INTRODUCTION	5
2	THE STAGE-DISCHARGE RELATION	5
2.1	General	5
2.2	The Station Control	5
2.3	The Point of Zero Flow.	8
3	ESTABLISHMENT OF THE DISCHARGE RATING CURVE	9
3.1	General	9
3.2	Simple Stage-Discharge Relations	9
3.2.1	Graphical Plot of Discharge Measurements	9
3.2.2	The Series of Differences Method	11
3.2.3	The Logarithmic Method.	12
3.2.3.1	General	12
3.2.3.2	Theory of the Logarithmic Rating Curve.	13
3.2.3.3	Estimating H_o	15
3.2.3.4	Estimating the Constants K and n.	15
3.2.4	Procedure for Establishing the Discharge Rating Curve	19
3.2.5	Rating Tables	25
3.2.6	Verification of the Rating Curve	26
3.2.7	Extrapolation of Rating Curves	26
3.2.7.1	General	26
3.2.7.2	The Stage-Velocity-Area Method.	26
3.2.7.3	The Manning Formula Method	26
3.2.7.4	The Stevens Method	27
3.2.7.5	River-Model Analysis.	27
3.3	Shifting Control	28
3.3.1	General	28
3.3.2	Characteristics of Sand-Bed Channels	28
3.3.3	Discharge Rating of Sand-Bed Channels	28
3.3.4	The Stout Method	30
3.4	Complex Stage-Discharge Relations.	32
3.4.1	General	32
3.4.2	The Constant-Fall Method.	33
3.4.3	The Normal-Fall Method.	36
3.4.4	Rapidly Changing Discharge	37
	REFERENCES	40
	APPENDIX A— GRAPHICAL CURVE FITTING	42
	APPENDIX B.	43
B.1	ERROR OF OBSERVATION OF DISCHARGE MEASUREMENTS	43
B.2	RELIABILITY OF DISCHARGE RATING CURVES.	43
B.2.1	The Standard Deviation of the Rating Curve.	43
B.2.2	Required Number of Discharge Measurements for Establishing a Reliable Rating Curve.	44
B.2.3	Acceptance Limits for the Discharge Measurements	44
B.2.4	Statistical Tests Applied to Rating Curves for Absence of Bias and Goodness of Fit.	44
B.2.4.1	The Paired t-Test.	45
B.2.4.2	The Sign Test	45
B.2.4.3	The Run of Sign Test	46
	APPENDIX C – SHIP DRAFTING CURVES	49
	APPENDIX D – VOCABULARY.	50

Villco Trykkeri A/S, Oslo

1 INTRODUCTION

This Volume describes methods and procedures for the determination of the stage-discharge relation by correlating water-level to discharge. Appendixes covering relevant statistical tests and definitions are included.

A stream gauging station is a selected site on an open channel for making systematic observations for the purpose of determining records of the discharge and/or the stage of the stream. A gauging station can either be a recording (automatic) or a non-recording (manual) station. A non-recording station consists of a staff gauge read regularly by an observer. At recording stations, the staff gauge is supplemented by a float gauge attached to which is a recording device tracing the rise and fall of the water level analogically on a chart or digitally at small time intervals on a tape. The term *gauge height* is often used interchangeably with stage, the former being the more appropriate term when referring to a gauge.

Stage and discharge of a stream both vary most of the time. In general, it is not practicable to measure the discharge continuously. However, to obtain a continuous record of the stage at a site is relatively simple as explained above. Then, if a relation between stage and discharge exists, an observed record of stage can easily be converted into a record of discharge. This two-step operation is the normal procedure for the determination of streamflow records.

The operations necessary to develop the stage-discharge relation at a station include making a sufficient number of discharge measurements and establishing a discharge rating curve and are called the calibration or rating of the station. The rating curve is developed by plotting measured discharge against the corresponding stage and drawing a smooth curve of relation between these two quantities.

2 THE STAGE-DISCHARGE RELATION

2.1 General

When a new river gauging station has been established, the general practice is initially to carry out a series of discharge measurements well-distributed over the range of discharge

variation, in order to establish quickly the discharge rating curve. Usually, there are no difficulties involved in measuring the lower and medium discharges. However, to obtain measurements at the higher stages is often a difficult task and may take time. Thus, at a majority of gauging stations, discharge measurements are not available for the high flood stages and the rating curve must be extrapolated beyond the range of available measurements.

Very few rivers have absolutely stable characteristics. The calibration, therefore, can not 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 relation.

Thus, it is the stability of the stage-discharge relation that governs the number of discharge measurements that are necessary to define the relation at any time and to follow the temporal changes in the stage-discharge relation. If the channel is stable, comparatively few measurements are required. On the other hand, in order to define the stage-discharge relation in sand-bed streams up to several discharge measurements a month may be required because of random shifts in the stream geometry and the station control.

Sound hydrological practice requires that the discharge rating curve is determined as rapidly as possible after the establishment of a new station [1]. Unless the discharge rating curve is properly established and maintained, the record of stage for the station can not be converted into a reliable record of discharge.

References [1], [2], [3]

2.2 The Station Control

A prerequisite for an analysis of the stage-discharge relation and the construction of the rating curve is an insight into and appreciation of the functioning of stage-discharge controls on streams.

In order to have a permanent and stable stage-discharge relation the stream channel at the gauging station must be capable of stabilising and regulating the flow past the station site so that for a given stage the discharge past the station will always be the same. The shape, reliability and stability of the stage-discharge

relation are usually controlled by a section or a reach of channel at or downstream from the gauging station, known as the station control, the geometry of which eliminates the effects of all other downstream features on the velocity of flow at the station site. The channel characteristics forming the control include the cross-sectional area and shape of the stream channel, the channel sinuosity, the expansions and restrictions of the channel, the stability and roughness of the stream bed and banks, and the vegetal cover, all of which collectively constitute the factors determining the channel conveyance.

In terms of open channel hydraulics, a control is a critical depth control, generally termed *section control*, if a critical flow section exists a short distance downstream from the gauging station; or a *channel control* if the stage-discharge relation depends mainly on channel irregularities and channel friction over a reach downstream from the station. A control is *permanent* if the stage-discharge relation it defines does not change with time, otherwise it is *impermanent* and generally called a *shifting* control. From the standpoint of origin, a control is either *artificial* or *natural*, depending on whether it is man-made or not.

Natural controls vary widely in geometry and stability. Some controls consist of a single topographic feature such as a rock ledge crossing the channel at the crest of a rapid or a waterfall, forming a *complete* control independent of all downstream conditions at all stages; some are formed by a combination of two or more features, such as a rock ledge crossing the channel combined with a channel constriction; some are V-shaped and thus sensitive to changes in discharge, some are U-shaped and thus less sensitive. Some consist of two or more interacting controls each effective in a particular range of stage. This is termed a *compound* control, a common situation is that section control is effective at low flow only and is submerged by channel control at the higher discharges. Some controls consist of a long reach of stable bed extending downstream as the stage increases. In general, the distance covered by such a control varies inversely with the slope of the stream and increases as the stage of the stream rises. The tendency for a control to extend farther downstream as the stage rises has a marked effect on the stage-discharge relation. As the

stage increases, low-water and medium-water controlling elements are drowned out and new downstream elements are successively introduced into the station control causing a straightening out of the typical parabola curvature of the rating curve, and at times even causing a reversal of this curvature. In fact, for rivers with very flat slopes the station control may extend so far downstream that backwater complications which do not exist at lower stages are introduced.

The simplest and most satisfactory type of control is formed by a rock ledge at the head of a rapid or at the crest of a waterfall. Firstly, it ensures permanency; secondly, it creates a pool or forebay in which a gauging station is often easily constructed; thirdly, favourable conditions for carrying out discharge measurements may be frequently found within the reach of such a pool; and fourthly, the point of zero flow (Section 2.3) is easily located and surveyed in this situation. Whenever practical this type of control should be utilized for a stream gauging station.

It should be recognized that most natural controls are shifting slightly. However, a *shifting* control is considered to exist where the stage-discharge relation changes frequently, either gradually or abruptly because of changes in the physical features that form the control of the station. The controlling features may be modified by a number of factors. Principal among these are:

- Scour and fill in an unstable channel;
- Growth and decay of aquatic vegetation;
- Formation of an ice cover;
- Variable backwater in a uniform channel;
- Variable backwater submerging a control section;
- Rapidly changing discharge;
- Overflow and ponding in areas adjoining the stream channel.

The corresponding stage-discharge relations are illustrated in Figure 1. A short discussion of each case follows.

PERMANENT CONTROL. Figure 1a. If the control is permanent, occasional discharge measurements need to be made to verify the permanency. Stage-discharge relations for a permanent control can be expressed as a simple exponential function. (Section 3.2).

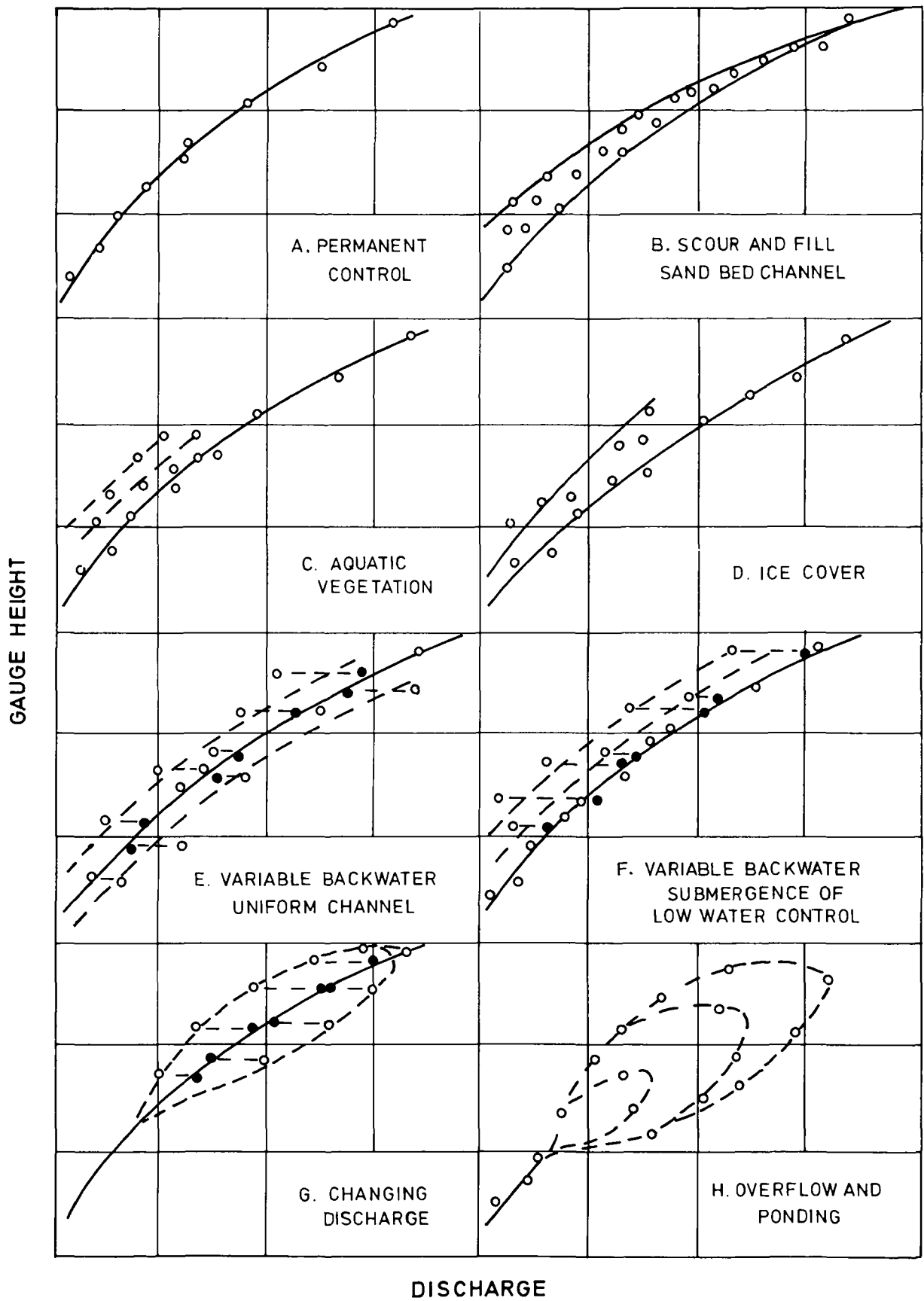


Figure 1. Rating curves for different hydraulic conditions

SAND-BED CHANNEL. Figure 1b. The movement of fluvial sediments, particularly in channels in alluvium, affects the conveyance, the hydraulic roughness, the channel sinuosity, and the energy slope. This makes the determination of a stage-discharge relation difficult. Also, since this movement is erratic, determination of the temporal variation of the stage-discharge relation is also very involved. (Section 3.3).

AQUATIC VEGETATION. Figure 1c. The growth of aquatic vegetation decreases the conveyance and changes the roughness with the result that the stage for a given discharge is increased. The converse is true when it dies, then the stage-discharge relation will gradually return to the previous condition. This change must be observed closely and determined by a series of discharge measurements.

ICE. Figure 1d. Ice in a stream cross section increases the hydraulic radius and the roughness and decreases the cross-sectional area and, as with aquatic vegetation, the stage for a given discharge is increased. The effect of ice formation and thawing is very complex and the temporal stage-discharge relation can only be determined by a series of discharge measurements, using stage, temperature and precipitation records as a guide for interpolation between measurements.

VARIABLE BACKWATER – UNIFORM CHANNEL. Figure 1e. If the control reach for a gauging station has within it a dam, a diversion or a confluent tributary which can increase or decrease the energy gradient for a given discharge, a variable backwater is produced. That is, the slope in a reach is increased or decreased from the normal. In this case, a second gauge is installed below the control section in order to measure the fall for developing a stage-fall-discharge relation (Section 3.4.2).

VARIABLE BACKWATER – SUBMERGENCE. Figure 1f. Some channel reaches below gauging stations contain local control sections such as falls, rapids or a dam, which determine the stage-discharge relation at low flows, but which may be submerged at times by inflow from a confluent tributary downstream or by the operation of a dam. As in the case of rating a station with uniform channel

and variable backwater, a second gauge is installed below the control section in order to measure the fall (Section 3.4.3).

RAPIDLY CHANGING DISCHARGE. Figure 1g. At some gauging stations, generally those of low energy slope, the stage-discharge relation is affected by the rate of change of discharge. If the discharge is increasing rapidly, it will be greater than that for zero rate of change and, conversely, if it is rapidly decreasing it will be less (Section 3.4.4).

OVERFLOW AND PONDING. Figure 1h. At some gauging stations there are large overflow and ponding areas on the flood plains adjacent to the stream channel. During increasing discharge, a part of the flow goes into these areas, increasing the slope and discharge relative to stage. Conversely, when the discharge decreases, water returning to the channel from the flooded areas causes backwater and the discharge for a given stage is markedly decreased; each flood produces its own loop rating. No satisfactory method has been found to develop a single rating under these conditions. A loop rating for each flood is required and must be determined by a series of discharge measurements.

References [3], [4]

2.3 The point of Zero Flow

When constructing discharge rating curves, the gauge height of zero flow, also termed the *point of zero flow*, is an important information especially helpful when shaping the lower part of the curve. The point of zero flow is the gauge height at which the water ceases to flow over the control. This gauge height should be determined by field surveys whenever the flow is sufficiently low to allow an accurate determination.

Stream gauges are usually established at an arbitrary datum. The elevation of gauge zero is decided on the day of establishment and set below the lowest stage anticipated at the site. It is therefore only in a very few cases that the zero of the gauge will correspond by coincidence to the point of zero flow.

The control section is defined by surveying a close grid of spot-levels over a reach of the stream downstream from the station site or

by surveying a sufficient number of cross-sections. The point of zero flow will be the lowest point in the controlling section. In those cases the control is well-defined by a rocky barrier over which the water flows, usually, it is very easy to locate the point of zero flow and obtain its correct gauge height value.

Determination of the point of zero flow from soundings taken during current meter measurements is not possible. These soundings might have been taken in any cross-section of the river in the vicinity of the gauge and will only give the correct point if the soundings happened to be taken in that particular cross-section containing the control.

3 ESTABLISHMENT OF THE DISCHARGE RATING CURVE

3.1 General

The discharge rating curve is established from a graphical analysis of discharge measurements that are plotted on graph paper, either arithmetically or logarithmically ruled. A correct analysis of the proper shape and position of the rating curve requires a knowledge of the channel characteristics at the particular site in question, a knowledge of open channel hydraulics and considerable experience and judgement.

In stream gauging, single-gauge stations and twin-gauge stations are employed. The employment of a single-gauge station depends upon the assumption that the stage in a cross-section of a stream is a unique function of the discharge only. Where variable backwater effects are present, the stage is no longer a single-valued function of the discharge. In these cases a twin-gauge station has to be employed where the stage is observed at each end of a reach.

3.2 Simple Stage-Discharge Relations

3.2.1 Graphical Plot of Discharge Measurements

The rating curve as developed for a single-gauge station will give the value of the normal discharge, that is, the discharge under uniform steady flow conditions for a given stage. Now, the discharge for a particular

level is greater with rising stage, than the normal discharge and lower with falling stage. However, it is possible to compute approximately the true discharge under these conditions using a single-gauge rating curve (Section 3.4.4).

The general procedure in establishing the stage-discharge relation is as follows:

The discharge measurements are plotted on graph paper with discharge on the horizontal scale and the corresponding gauge height on the vertical scale. If a measurement was not made at steady stage, the mean gauge height during the measurement should be used.

The plotted data points should be labelled in their chronological order; rising and falling stage during the measurement should be indicated by distinguishing symbols.

The relation should be defined by a sufficient number of measurements suitably distributed throughout the whole range in stage, taking into account the shape of the stage-discharge relation (Appendix B.2.2). As a rule, the measurements should be spaced closer at the lower end of the range.

Ideally, the number and spacing of the measurements should conform to the relative frequency of flow at the various stages. That is, the number of measurements at various sub-ranges should be in proportion to the probable occurrence of discharge at these same ranges, covering the whole range of discharge for which the relation is plotted.

Nevertheless, in actual practice, it is desirable to have as many measurements as possible at the extreme ranges, both at the low flow and at the high flood stages.

The curve of relation, the rating curve, should be drawn evenly and smoothly through the scatter of plotted data points.

Although all discharge measurements have been checked and considered correct before plotting, measurements which plot more than 4 percent in discharge off the curve should again be checked for possible errors. Look especially for the need to adjust or weigh the gauge height, for the use of the correct current meter calibration table, and for errors in the computation of the discharge measurement. With respect to the latter, it is suggested that a plot is made of the cross-sectional area and

Table 1. Smoothing and extrapolation of the discharge rating curve

(1)	(2)	(3)	(4)	(5)	(6)	(7)
Gauge Height m	Discharge, m ³ /sec					
	From curve			Smoothed		
	Q	ΔQ	$\Delta^2 Q$	ΔQ	$\Delta^2 Q$	Q
.20	0.800					0.800
.30	3.10	2.30	1.40	2.30	1.30	3.10
.40	6.80	3.70	1.30	3.60	1.20	6.70
.50	11.8	5.00	1.00	4.80	1.30	11.50
.60	17.8	6.00	1.20	6.10	1.20	17.60
.70	25.0	7.20	1.30	7.30	1.20	24.90
.80	33.5	8.50	1.50	8.50	1.10	33.40
.90	43.5	10.0	0.50	9.60	1.10	43.00
1.00	54.0	10.5	0.50	10.7	1.10	53.70
1.10	65.0	11.0	1.00	11.8	1.0	65.50
1.20	78.0	13.0	0.00	12.8	1.0	78.30
1.30	91.0	13.0	2.00	13.8	0.9	92.10
1.40	106.0	15.0	1.00	14.7	0.8	106.8
1.50	122.0	16.0	0.00	15.5	0.8	122.3
1.60	138.0	16.0	0.00	16.3	0.7	138.6
1.70	154.0	16.0	2.00	17.0	0.6	155.6
1.80	172.0	18.0		17.6	(0.6)	173.2
1.90				(18.2)	(0.5)	(191.4)
2.00				(18.7)	(0.5)	(210.1)
2.10				(19.2)		(229.3)

Figures in parentheses are extrapolated

mean velocity against gauge height for the measurements. Such plots will reveal the presence of an error and where it is located in the computation, either in the velocity or in the cross-sectional area. If no apparent error is found to be caused by the above, then the measurement be discarded or shift correction applied if applicable (Section 3.3.4).

There are several methods of fitting a curve to observed or measured data points. This may be done quite satisfactorily simply by a visual estimation of the plot with the aid of drafting curves. Ship drafting curves are useful in this respect as these curves are designed to conform to parabolic equations. Very often, the trend of discharge measurements plotted on graph paper will closely follow a particular drafting curve due to the fact that the discharge of a stream tends to vary as some power of the depth of the water.

The criterion used when fitting a curve to plotted data points by visual estimation is that there should be about the same number of plus and minus deviations (a deviation being negative for a measurement lying above the curve and positive when lying below). In other words, one is developing a median curve. In general, at least 10 discharge measurements

well-distributed over the range in stage are considered desirable when constructing the initial rating curve. Assuming that these measurements were properly made under reasonably steady flow conditions and that they apply to a stable stage-discharge relation, it is then reasonable to expect that it should be possible to fit a mean curve from which any individual discharge measurement will not deviate more than 5 percent, 5 percent being about the maximum error of observation likely to occur under these conditions. Using group averages when fitting a curve is also quite useful, the method is illustrated in Appendix A.

Reference [3]

3.2.2 The series of Differences Method

A method often used in fitting a smooth curve to observed or measured data and of extrapolating the curve, is by use of series of differences. The discharge measurements are plotted on ordinary graph paper. A mean curve is fitted to the data points by visual estimation (Figure 2). At equal gauge height increments, say every 0.05 m or 0.10 m, the

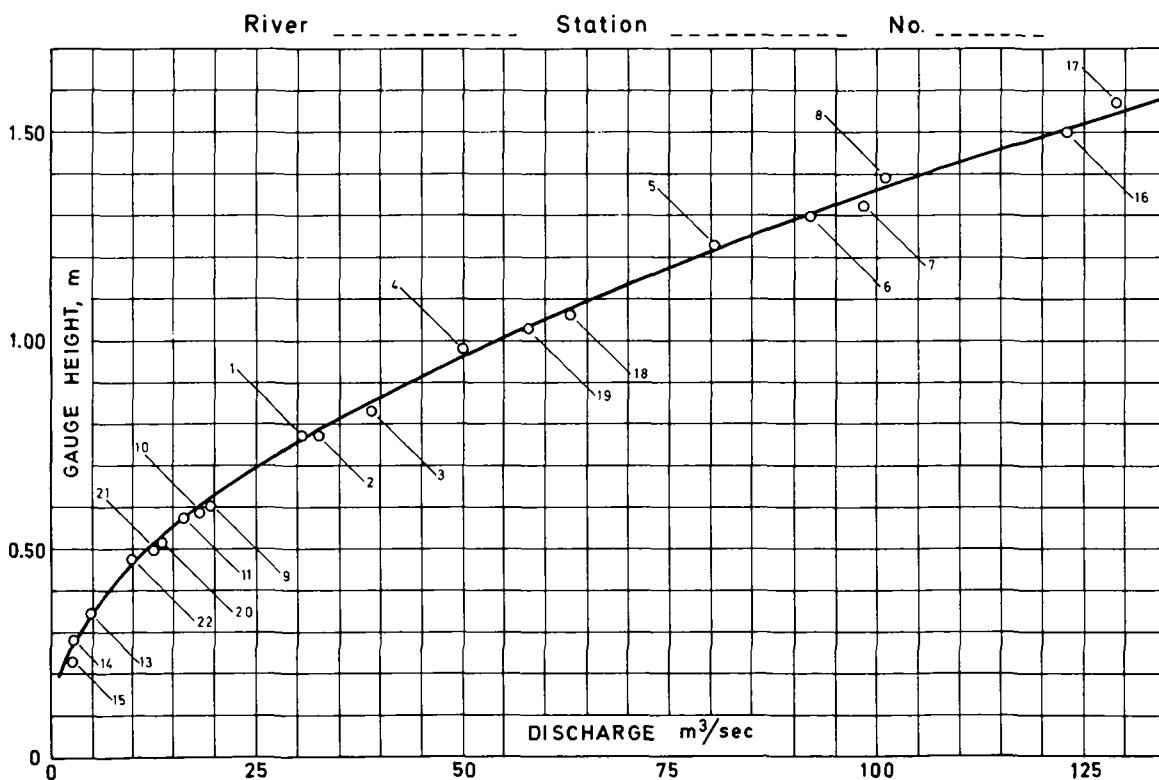


Figure 2. Discharge rating curve, first plotting

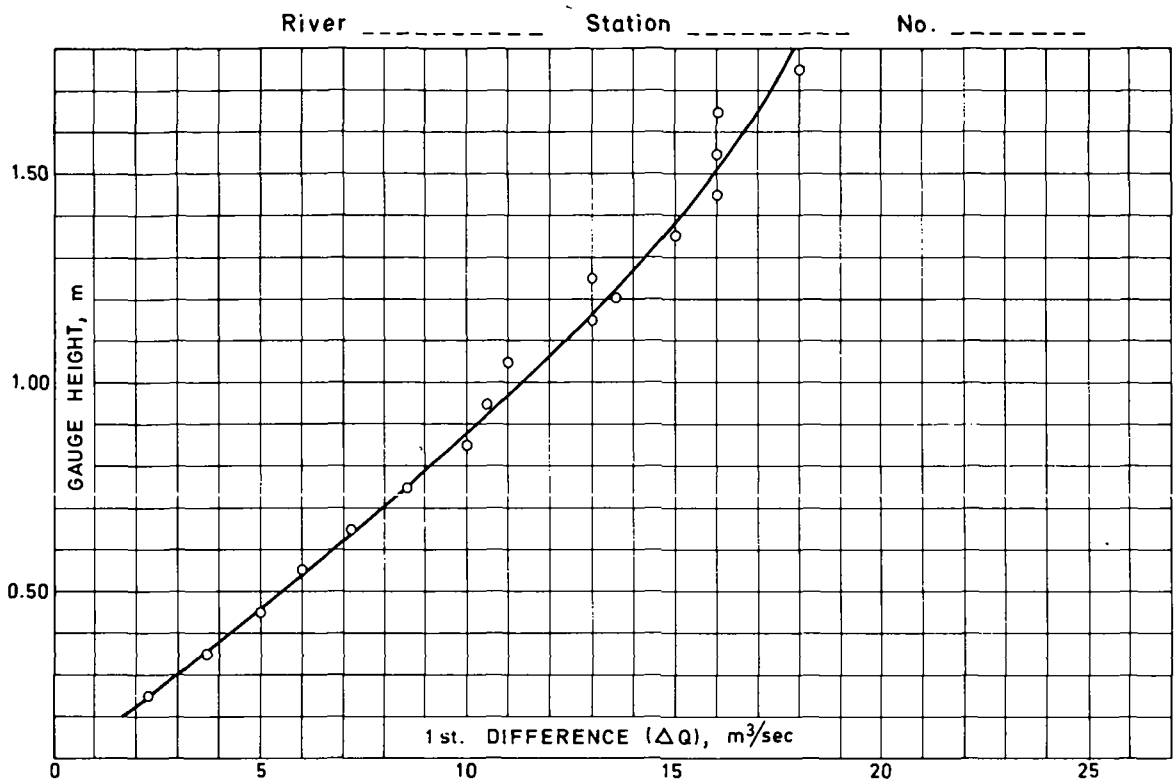


Figure 3. Smoothing graph for series of differences

discharge is read from the curve and tabulated as illustrated in Table 1, columns 1 and 2.

The series of 1st differences, that is, the differences between adjacent discharges, is computed and entered on the form (column 3). The 1st differences should increase evenly or remain the same as the preceding difference. The series of differences is graphically smoothed as illustrated in Figure 3, each difference is plotted against its corresponding gauge height, the plotting position being the mid-interval of gauge height.

A mean curve is fitted to the plotted points and the smoothed differences are read from this curve and entered on the form (column 5). An adjusted version of the original discharge series is thereafter calculated by successively adding the smoothed differences starting from the top (column 7). The first value, $0.800 \text{ m}^3/\text{sec}$, is taken from column 2.

The method may be refined by also introducing the series of 2nd differences (Table 1, columns 4 and 6). The 2nd differences must also progress evenly between adjacent figures but unlike the 1st differences, they may progress both upward or downward, or remain constant. When the 2nd differences change

to a downward progression, this indicates a reversal in the rating curve, which is often the case when a section control is drowned out by a downstream control for the higher stages.

The rating curve as established by this method may be extrapolated to a certain extent if the station control does not have any sharp breaks in the cross-sectional contour or is of a different character at the higher stages. The series of differences is extended by following the apparent trend of the series and the rating curve is calculated accordingly.

Reference [5]

3.2.3 The Logarithmic Method

3.2.3.1 General

The logarithmic representation of the stage-discharge relation is commonly used because it produces the best graphical form of a standard rating curve and readily adapts to the use of ship drafting curves. Also, the logarithmic form of the rating curve can be made to approach a straight line, or straight line segments, by adding or subtracting a constant value to the gauge height scale on the logarithmic

graph paper. There are several other advantages that the logarithmic form has, as: 1) A percentage distance off the curve is always the same regardless of where it is located. Thus, a measurement that is 10 percent off the curve at high stage will be the same distance away from the curve as a measurement that is 10 percent off at low stage, 2) halving, doubling or adding a percentage to the gauge height has no effect, the curve will merely shift position but retain the same shape, 3) it is easy to identify the range in stage for which different controls are effective, 4) the logarithmic form may be described by a simple mathematical equation that is easily handled by electronic computers, 5) the curve can easily be extrapolated.

Regarding extrapolations, however, one has to be careful. If the control does not change character at the higher stages, the same discharge equation will cover the whole range in stage and the rating curve can be extrapolated up to the highest observed water level. If the control changes either shape or character as the stage increases, the rating curve will consist of more than one segment. In these cases, an extrapolation of the first segment up to the higher stages will of course introduce serious errors.

3.2.3.2 Theory of the Logarithmic Rating Curve

According to the Chezy uniform flow formula

$$V = C (RS)^{1/2} \quad (3.1)$$

in which V is the mean velocity, C is a factor of flow resistance, R the hydraulic radius, and S the slope of the energy line.

The discharge is given by

$$Q = AC (AS/P)^{1/2} \quad (3.2)$$

in which Q is the discharge, A the cross-sectional area, and P the wetted perimeter. In rectangular cross-sections, width (W) x depth (D) can be substituted for A , and for P , $W + 2D$; of which follows

$$Q = CWD (WDS / (W + 2D))^{1/2} \quad (3.3)$$

or

$$Q = CWS^{1/2} D^{3/2} \left(\frac{W}{W + 2D} \right)^{1/2} \quad (3.4)$$

For very wide channels ($W + 2D$) is approximately equal to W and therefore equation (3.4) reduces to

$$Q = CWS^{1/2} D^{3/2} \quad (3.5)$$

Regarding $CWS^{1/2}$ as a constant K , which is approximately correct in most cases, equation (3.5) can be written as

$$Q = KD^{3/2} \quad (3.6)$$

Here D is effective head, or depth to zero flow.

For gauge height H and for point of zero flow H_o , equation (3.6) can be written as

$$Q = K(H - H_o)^{3/2} \quad (3.7)$$

Similarly, it can be shown for sections of other shapes that

$$Q = K(H - H_o)^{(2m + 1)/2} \quad (3.8)$$

where

- $m = 1$ for a rectangular section
- $m = 3/2$ for a concave section of parabolic shape
- $m = 2$ for a triangular section
- $m = 2$ for a semicircular section.

The general equation of the relation between stage and discharge is therefore

$$Q = K (H - H_o)^n \quad (3.9)$$

Equation (3.9) is a parabolic equation which plots as a straight line on double logarithmic graph paper.

Equation (3.9) will apply to cross-sections of rectangular, triangular, trapezoidal, parabolic and other geometrically simple sections. Many natural streams approximate to these shapes making equation (3.9) a general discharge equation.

The approximation that W equals $(W + 2D)$ in determining equation (3.6) is valid only for very wide streams. For deep narrow streams W is much smaller than $(W + 2D)$, which has the effect of increasing the exponent in equation (3.6). Changes in the factor of flow resi-

stance C and slope S with stage will also affect the exponent. The net result of all these factors is that the exponent in equation (3.9) for relatively wide rivers with channel control will generally vary from 1.3 to 1.8 and rarely exceed 2.0. For relatively deep narrow rivers with section control, the exponent n will almost always be greater than 2.0 and may often exceed a value of 3.0. [6].

However, for very irregular channels or for flow not uniform, equation (3.9) can not be expected to apply throughout the range of stage. Sometimes the curve changes from a parabolic to an odd curve or vice versa, sometimes the constants and exponents vary throughout the range.

In fact, the logarithmic discharge equation is seldom a straight line or a gentle curve for the entire range in stage at a gauging station. Even if the same channel cross-section is the control for all stages, a sharp break in the contour of the cross-section causes a break in the slope of the rating curve. Also, the other constants in equation (3.9) are related to the physical characteristics of the stage-discharge control.

If the control section changes at various stages, it may be necessary to fit two or even more equations, each corresponding to the portion of the range over which the control is the same. If, however, too many changes in the parameters are necessary in order to define

the relationship, then possibly the logarithmic discharge equation may not be suitable and a curve fitted by visual estimation would be better.

The first derivative of equation (3.9) is a measure of the change in discharge per unit change in gauge height, that is, the first derivative gives the first order differences of the discharge series.

The first derivative is:

$$dQ/dH = Kn(H - H_o)^{n-1} \quad (3.10)$$

Second order differences are obtained by differentiating again.

The second derivative is:

$$d^2Q/dH^2 = Kn(n-1)(H - H_o)^{n-2} \quad (3.11)$$

An examination of the second derivative shows that the second order differences increase with stage when n is greater than 2.0, i.e. for section control, and decrease with stage when n is less than 2.0, i.e. for channel control. [6].

An examination of the 2nd differences, column 6 in Table 1, will reveal that the illustrated rating is for a compound control. This rating represents the condition of section control at the lower stages drowned out by channel control at the higher stages. Inspection of the 2nd differences column shows the 2nd differences to be increasing at the low-water end, i.e. section control, and decreasing at the high-water end, i.e. channel control [6].

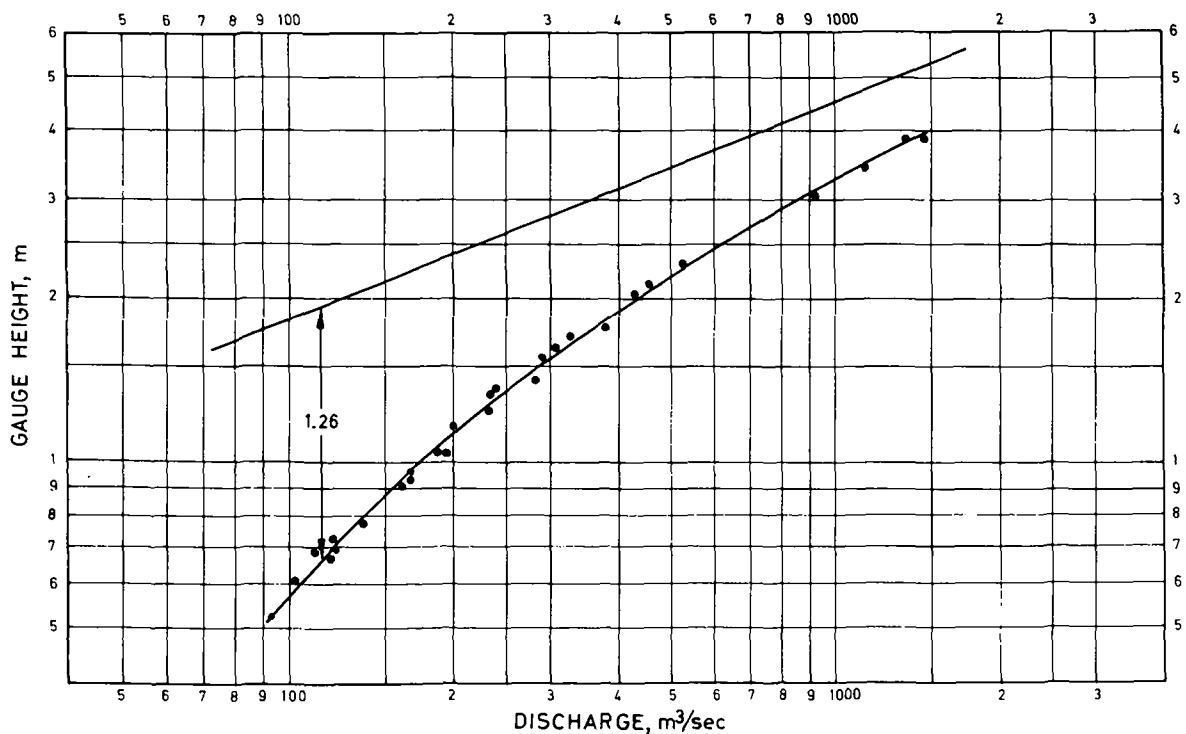


Figure 4. Trial and error method of finding H_o

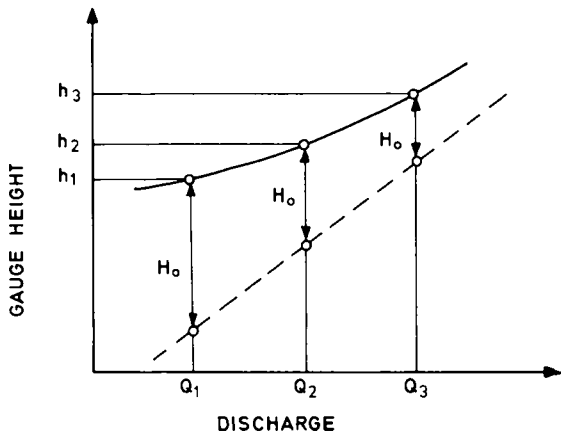


Figure 5. Schematic illustration of how a curved line is transformed into a straight line on logarithmic paper

3.2.3.3 Estimating H_0

There are three methods of estimating the point of zero flow apart from making a field survey. However, if at all possible, the estimates should always be sought verified by field investigations.

Trial and Error Procedure

All discharge measurements available are plotted on log-log paper and a median line balanced through the scatter of data points. Usually, this line will be a curved line. Various trial values, one value for each trial, are added or subtracted to the gauge heights of the measurements until the plot obtained forms a straight line. The trial value forming the straight line is the value of H_0 (Figure 4).

All the plotted data points may be used in the trial operation. However, it is better to use only a few points selected from the median line first fitted to the points. [7].

Note that when a quantity has to be added to the gauge height readings of the measurements in order to obtain a straight line, then H_0 will have a negative value, and vice versa. That is, the zero of the gauge is in this case positioned at a level above the point of zero flow and the point of zero flow will consequently give a negative gauge reading.

Arithmetical Procedure

All discharge measurements are plotted on log-log paper (Figure 5). An average line drawn through the scatter of points has resulted in the solid curved line. Three values of discharge Q_1 , Q_2 , and Q_3 are selected in geometric

progression, that is, two values Q_1 and Q_3 are chosen from the curve, the third value Q_2 is then computed according to

$$Q_2^2 = Q_1 Q_3 \quad (3.12)$$

The corresponding gauge heights read from the plot are H_1 , H_2 , and H_3 . It is now possible to verify that [8]

$$H_0 = \frac{H_1 H_3 - H_2^2}{H_1 + H_3 - 2H_2} \quad (3.13)$$

The solid curved line may now be transformed into a straight line by subtracting H_0 from each value of the gauge height H and replotting the new values.

Graphical Procedure

As above, three values of discharge in geometric progression are selected, but this time from a plot on arithmetical graph paper. The points are A, B, and C as illustrated in Figure 6.

Vertical lines are drawn through A and B and horizontal lines are drawn through B and C intersecting the verticals at D and E respectively. Let DE and AB meet at F. Then the ordinate of F is the value of H_0 . [8].

The last two methods are based on the assumption that the lower part of the stage-discharge relation including the selected points is a part of a parabola. In most cases this assumption holds and the method will give acceptable results on the condition that there are enough discharge measurements available to satisfactorily define the curvature of the lower part of the rating curve.

3.2.3.4 Estimating the Constants K and n

After a straight line plot of the discharge measurements on double logarithmic graph paper has been obtained, the constant K and n of flow equation (3.9) can be worked out in three ways; namely, arithmetically, statistically and graphically.

The stage-discharge relation must first be analyzed from a plot on log-log graph paper in order to establish whether the rating curve is composed of one or several straight line segments, each having its own constants K and n. The constants for each separate segment must be calculated separately.

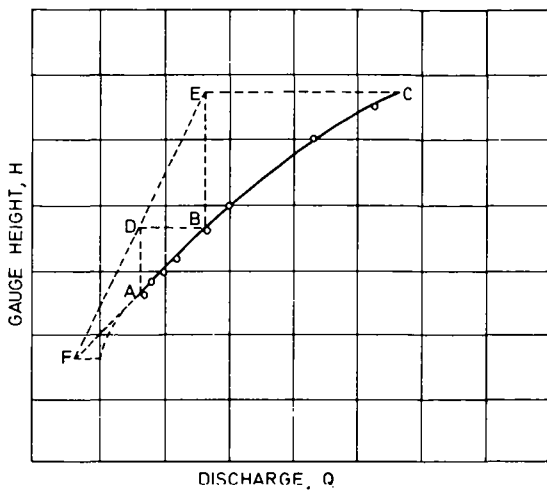


Figure 6. Graphical determination of H_0 . [8]

Arithmetical procedure

A series of discharge measurements at a gauging station has been obtained as given below. By a field survey, the point of zero flow, H_0 , has been found to equal -1.26 m. The constants K and n of flow equation (3.9) shall be determined. The data are given in metres and m^3/sec .

Table 2. Discharge Measurements (River Karun at Ahwaz, Iran)

No.	H	Q	No.	H	Q
1	1.55	300	15	3.87	1374
2	1.44	287	16	2.33	540
3	1.26	235	17	3.49	1152
4	1.05	193	18	3.93	1452
5	0.73	125	19	2.03	440
6	0.69	113	20	1.61	306
7	0.70	124	21	2.13	469
8	1.70	340	22	1.37	246
9	0.96	169	23	1.05	189
10	0.94	168	24	0.91	163
11	1.35	240	25	0.79	139
12	1.17	202	26	0.68	120
13	1.79	387	27	0.61	104
14	3.09	930	28	0.53	94.6

To the gauge heights of the measurements given in Table 2, 1.26 m is added. The measurements are thereafter plotted on log-log graph paper, the gauge height on the vertical scale

and the discharge on the horizontal scale. The plot seems to define a straight line (Figure 7).

Select two points on this line as far from each other as possible but within the range of measured discharges. Let the two selected points, (Q, H) , be given in m^3/sec and metres as $(97, 1.80)$ and $(1300, 5.00)$.

In general, the equation of a straight line passing through two points (x_1, y_1) and (x_2, y_2) in a rectangular coordinate system is written as follows:

$$\frac{y - y_1}{x - x_1} = \frac{y_2 - y_1}{x_2 - x_1} \quad (3.14)$$

Similarly, a logarithmic linear function can be drawn as a straight line on log-log paper, of which follows:

$$\frac{\log y - \log y_1}{\log x - \log x_1} = \frac{\log y_2 - \log y_1}{\log x_2 - \log x_1} \quad (3.15)$$

In the present case, after changing the notations, equation (3.15) can be written as:

$$\frac{\log Q - \log Q_1}{\log (H - H_0) - \log H_1} = \frac{\log Q_2 - \log Q_1}{\log H_2 - \log H_1} \quad (3.16)$$

Substituting the given values in equation (3.16), obtains:

$$\frac{\log Q - \log 97}{\log (H + 1.26) - \log 1.80} = \frac{\log 1300 - \log 97}{\log 5.00 - \log 1.80}$$

$$\frac{\log Q - 1.9868}{\log (H + 1.26) - 0.2553} = \frac{3.1139 - 1.9868}{0.6990 - 0.2553} = 2.54$$

$$\log Q = 2.54 \log (H + 1.26) + 1.3383$$

$$Q = 21.79 (H + 1.26)^{2.54} \quad (3.17)$$

Equation (3.17) is the discharge formula for the rating curve as illustrated in Figure 7.

As already discussed, it is often found that the discharge measurements do not plot as one straight line all through but will diverge at

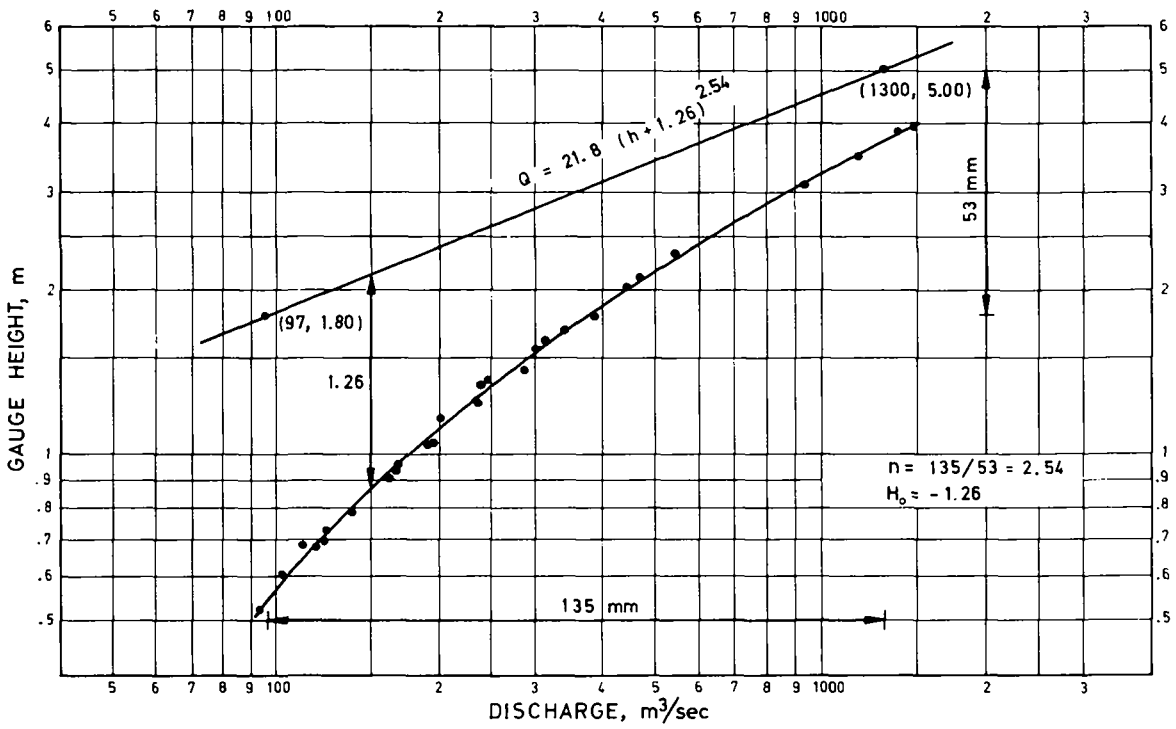


Figure 7. Discharge rating curve established by the logarithmic method

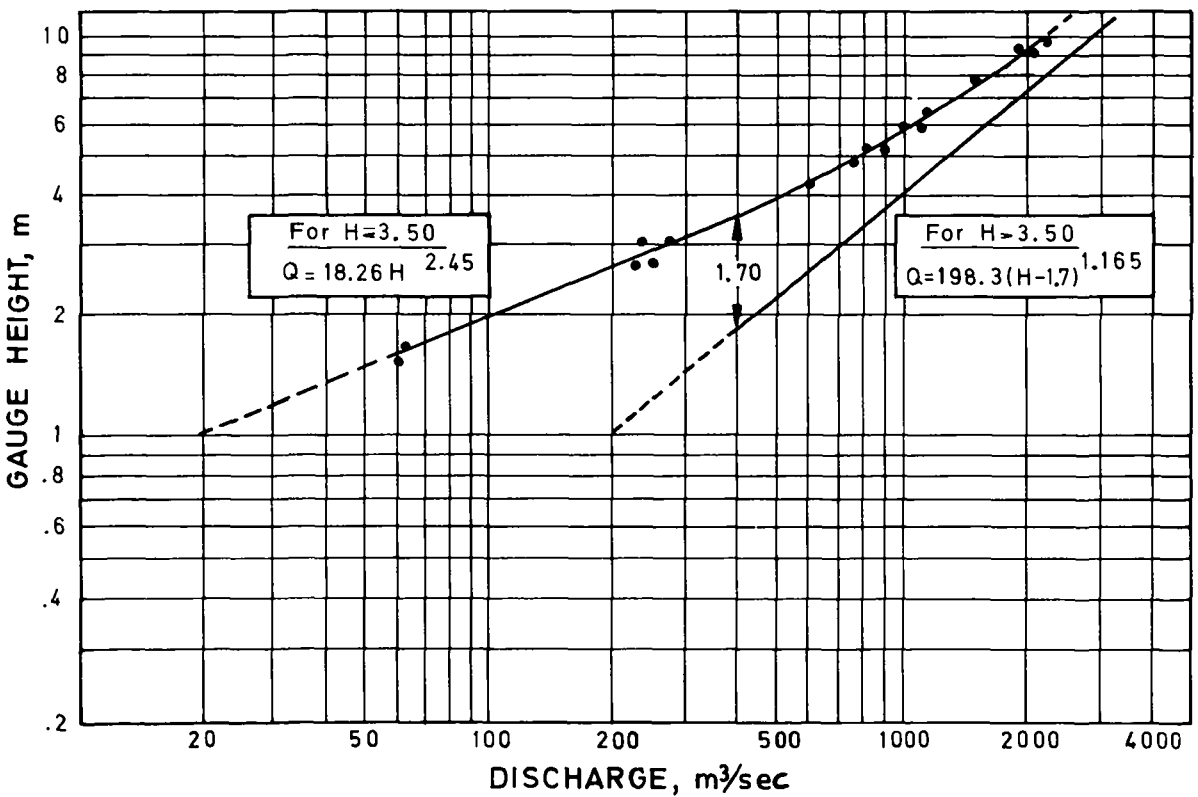


Figure 8. Discharge rating curve composed of two segments of different slope. [5]

a certain stage. In such cases, the rating curve will be composed of two, or even more, straight line segments differing in slope and each segment having its own particular equation as illustrated in Figure 8. Here it appears that the logarithmic plot has a curvature above 3.50 m on the gauge and that the upper part of the curve has to be moved down 1.70 m in order to plot as a straight line.

At this station the zero of the gauge seems to be set at the point of zero flow since the lower part of the curve is a straight line on log-log graph paper and at about 3.50 m a high water control downstream is taking effect decreasing the rate of increase in channel conveyance with stage.

Reference [5]

Statistical Procedure

The values of K and n may be worked out statistically according to the Method of the Least Squares. That is, the sum of the squares of the deviations between the logarithms of the discharges measured and estimated by a mean curve should be a minimum.

According to this the values of K and n are obtained from the following equations:

$$\Sigma(X) - m \log K - n \Sigma(X) = 0 \quad (3.18)$$

$$\Sigma(XY) - \Sigma(X) \log K - n \Sigma(X^2) = 0 \quad (3.19)$$

where

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

$\Sigma(X)$ = the sum of all values of
log (H-H_o)

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

$\Sigma(XY)$ = the sum of all values
of the product of (X) and (Y)

m = the number of observations

In order to illustrate the method the data of Table 2 are prepared as shown in Table 3.

Substituting the calculated values of Table 3 into equations (3.18) and (3.19) obtains:

$$68.0506 - 28 \log K - n 12.0182 = 0$$

$$30.4351 - 12.0182 \log K - n 5.6430 = 0$$

From these two equations it follows that n = 2.53 and K = 22.10 which is in close agreement with equation (3.17) of the arithmetical procedure.

A word of caution. It is a common practice when using the Method of Least Squares to give all the discharge measurements an equal statistical weight in spite of the fact that most of the measurements available for defining the relation will always be located at the low and medium stages. Thus, an extrapolation of the discharge formula to the higher stages, where at best very few and usually no data points are available, will be biased by the greater number of low-lying data points [9]. It follows that extrapolation of discharge formulas developed by use of the Method of Least Squares should be done carefully and always checked against other methods of extrapolation.

References [9], [10]

Graphical procedure

The dependent variable Q in equation (3.9) is conventionally plotted as the abscissa and the independent variable H as the ordinate. Then, from a straight line plot on log-log graph paper of equation (3.9), the slope n of the line is calculated as the ratio of the horizontal projection of the line to the vertical projection (Figure 7).

The factor K equals the numerical value of the discharge Q when the head (H-H_o) equals 1.00, K is constant for a given control condition. Note that H_o must be larger than -1.00 in order to solve for K using the graphical procedure.

Table 3. Tabulation of data for determination of the constants K and n

No.	H	Q	H-H ₀	log Q = (Y)	log (H-H ₀) = (X)	(XY)	(X ²)
1	1.55	300	2.81	2.4771	0.4487	1.1115	0.2013
2	1.44	287	2.70	2.4579	0.4314	1.0603	0.1861
3	1.26	235	2.52	2.3711	0.4014	0.9518	0.1611
4	1.05	193	2.31	2.2856	0.3636	0.8310	0.1322
5	0.73	125	1.99	2.0969	0.2989	0.6268	0.0893
6	0.69	113	1.95	2.0531	0.2900	0.5954	0.0841
7	0.70	124	1.96	2.0934	0.2923	0.6119	0.0854
8	1.70	340	2.96	2.5315	0.4713	1.1931	0.2221
9	0.96	169	2.22	2.2279	0.3464	0.7717	0.1200
10	0.94	168	2.20	2.2253	0.3424	0.7619	0.1172
11	1.35	240	2.61	2.3802	0.4166	0.9916	0.1736
12	1.17	202	2.43	2.3054	0.3856	0.8890	0.1487
13	1.79	387	3.05	2.5877	0.4843	1.2532	0.2345
14	3.09	930	4.35	2.9685	0.6385	1.8954	0.4077
15	3.87	1374	5.13	3.1380	0.7101	2.2283	0.5042
16	2.33	540	3.59	2.7324	0.5551	1.5168	0.3081
17	3.49	1152	4.75	3.0615	0.6767	2.0717	0.4579
18	3.93	1452	5.19	3.1620	0.7152	2.2615	0.5115
19	2.03	440	3.29	2.6435	0.5172	1.3672	0.2675
20	1.61	306	2.87	2.4857	0.4579	1.1382	0.2097
21	2.13	469	3.39	2.6712	0.5302	1.4163	0.2811
22	1.37	246	2.63	2.3909	0.4200	1.0039	0.1764
23	1.05	189	2.31	2.2765	0.3636	0.8277	0.1322
24	0.91	163	2.17	2.2122	0.3365	0.7444	0.1132
25	0.79	139	2.05	2.1430	0.3118	0.6682	0.0972
26	0.68	120	1.94	2.0792	0.2828	0.5984	0.0828
27	0.61	104	1.87	2.0170	0.2718	0.5482	0.0739
28	0.53	94.6	1.79	1.9759	0.2529	0.4997	0.0640
			Sum	68.0506	12.0182	30.4351	5.6430

$m = 28$

$H_0 = -1.26$

3.2.4 Procedure for Establishing the Discharge Rating Curve

In actual practice, the two techniques presented in Sections 3.2.2 and 3.2.3, the Series of Differences method and the Logarithmic method, are not regarded as two separate methods but rather worked into a single procedure.

The following steps have been found practicable:

1. All discharge measurements are plotted on ordinary arithmetical graph paper, gauge height on vertical scale and discharge on horizontal scale. If the point of zero flow has been obtained by an actual field

survey, this point must also be included in the plot. The scales should be so selected that the mean direction of the plot approximately follows the diagonal of the graph sheet from left to right. Uncommon odd scales should not be used; suggested scales for the gauge height are 1:5, 1:10, and 1:20, preferably 1:10.

A curve is fitted to the data points by visual estimation (Section 3.2.1).

2. At equal gauge height increments, the discharge is selected from the curve and tabulated together with its gauge height (Section 3.2.1). Usually, increments in gauge height of 0.10 m are practical, however, at the lower part of the curve where the curvature is greatest, it may sometimes be better to use increments of 0.05 m; at the upper part of the curve increments of 0.20 m may often be preferable.
3. The 1st and 2nd series of differences of the discharges are calculated and smoothed. From the smoothed series of 1st differences, adjusted values of the discharge are calculated (Section 3.2.1). Replot adjusted discharge values on arithmetical graph sheet. Inspect the plot, adjust if necessary.

When the rating curve is of a fairly regular shape, it is not considered necessary to use the 2nd differences in order to smooth the 1st differences.

4. Plot final adjusted discharges against their corresponding gauge height on double logarithmic graph paper; draw a smooth curve through the data points by means of ship drafting curves.
5. Estimate H_o by trial and error (Section 3.2.3.3). That is, add or subtract trial values for H_o to the gauge height until the curve drawn on log-log graph paper becomes transformed into a straight line, or into two or more straight line segments. Usually, the following instances will occur:
 - a) One single straight line. Produced by a complete section control of regular shape, often the crest of a rapid or a waterfall.

- b) One single broken line consisting of two straight line segments, each with a different slope but the same H_o . Produced by a complete section control having a sharp break in the cross-sectional contour but otherwise of regular shape.
- c) Two or more disconnected straight line segments each with its own slope n and H_o . Produced by a compound control of various combinations, usually section control at low stage. This case is the most common.
- d) Sometimes it happens that the plotted curve can not be transformed into straight line segments, or rather, the segments will be so short and numerous that the logarithmic representation of the curve would not be practical. Produced by a very irregular control.

H_o as obtained from a field survey or by the arithmetical and graphical techniques presented in Section 3.2.3.3 is valid for the lowest segment only, and for one single line. The "trial and error" technique has to be used for the upper segment or segments. The trial and error technique is not too time-consuming, after some practice it will be found that only a few trials are necessary in order to find the correct H_o . It is not necessary to plot all the incremental data points of the table during the trials, only a few. For a final check of the H_o value selected, however, all the points should be used.

6. Inspect the straight line plot; one last adjustment of the tabulated discharges may prove necessary.
7. When the curve has been found acceptable, the mathematical equation for each segment is calculated (Section 3.2.3.4).
8. Finally, each segment is tested for bias and goodness of fit as illustrated in Appendix B.

ILLUSTRATION

At a gauging station, a series of discharge measurements has been obtained, chronologically arranged as given in Table 4 below. It is desired

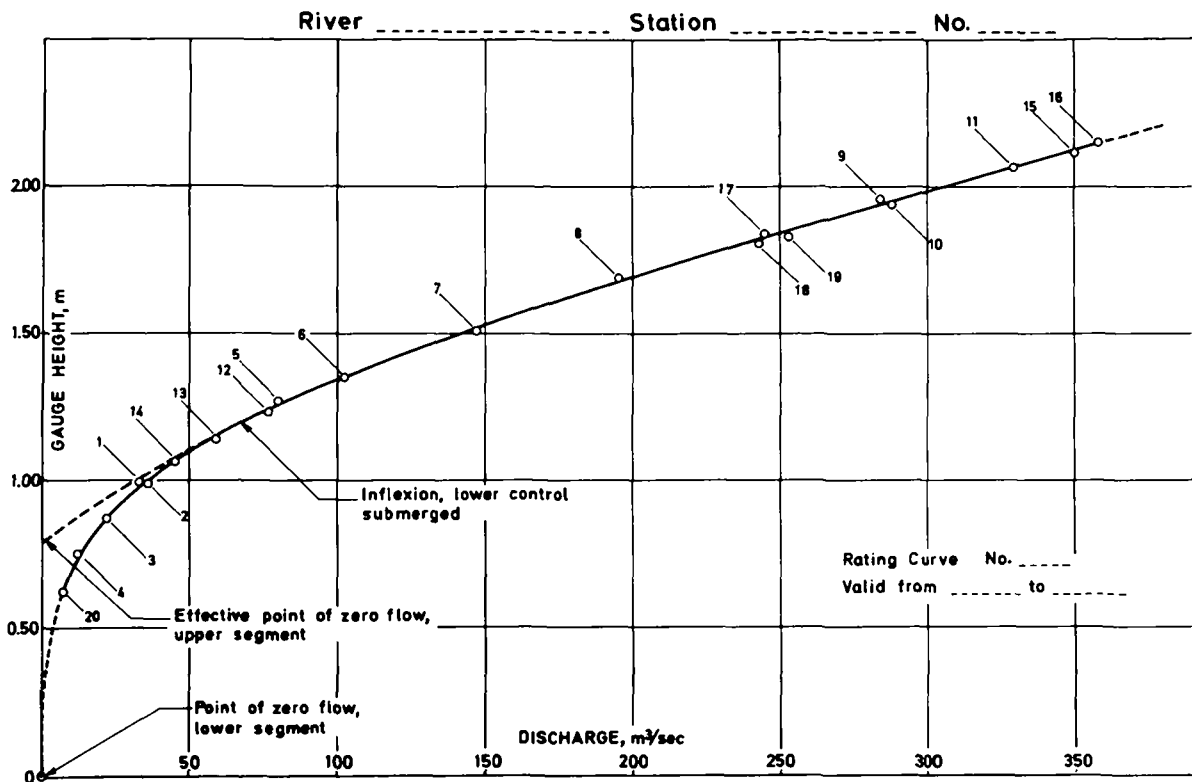


Figure 9. First plotting of discharge measurements and visual estimation of rating curve

to establish a rating curve for the station. The point of zero flow is not known.

Table 4. Discharge measurements

No.	H	Q	No.	H	Q
1	0.99	33.0	11	2.07	330.0
2	0.99	36.0	12	1.23	77.0
3	0.87	22.0	13	1.15	57.0
4	0.75	12.5	14	1.10	46.0
5	1.27	80.0	15	2.12	350.0
6	1.35	102.5	16	2.15	358.0
7	1.51	147.0	17	1.84	245.0
8	1.69	195.0	18	1.81	243.0
9	1.96	284.0	19	1.83	253.0
10	1.94	288.0			

1. Plot the measurements on ordinary graph paper and fit a curve to the data points by visual estimation as illustrated in Figure 9 (Section 3.2.1).
2. For equal gauge height increments of 0.10 m select from the curve the corresponding discharges and tabulate on calculation form as illustrated in Figure 10, columns 1 and 2 (Section 3.2.2).

3. Calculate the 1st differences from the discharges in column 2 and enter in column 3 of the calculation form. Plot and smooth the 1st differences as illustrated in Figure 11. Enter smoothed 1st differences in column 4 of calculation form (Section 3.2.2).
4. Calculate an adjusted discharge series by successively adding the 1st differences in column 4 from the top, start with first value in column 2. The adjusted discharges are entered in column 6.
5. Plot the adjusted discharge values of column 6 against their corresponding gauge height on log-log graph paper, gauge height on vertical scale and discharge on horizontal scale. Draw a smooth curve through the data points by means of ship drafting curves (Figure 12).
6. Determine the point of zero flow (H_0) by trial and error. If the trial value of H_0 is less than actual, the curve will bend upward, if it is greater than actual, the curve will bend downward.

CALCULATION FORM FOR RATING CURVE

(1)	(2)	(3)	(4)	(5)	(6)
Gauge height m	Discharge, m ³ /sec				
	Visual estimate		Smoothed		Adjusted Q
	Q	ΔQ	ΔQ	$\Delta^2 Q$	
0.50	3.0				3.0
0.60	6.0	3.0	2.8		5.8
0.70	10.0	4.0	4.2		10.0
0.80	16.1	6.1	6.0		16.0
0.90	24.5	8.4	8.2		24.2
1.00	35.5	11.0	11.0		35.2
1.10	50.5	15.0	14.3		49.5
1.20	68.0	17.5	18.0		67.5
1.30	90.0	22.0	22.0		89.5
1.40	115.0	25.0	25.0		114.5
1.50	142.0	27.0	27.0		141.5
1.60	171.0	29.0	29.0		170.5
1.70	202.0	31.0	31.0		201.5
1.80	235.0	33.0	33.0		234.5
1.90	270.0	35.0	35.0		269.5
2.00	305.0	35.0	35.0		304.5
2.10	340.0	35.0	35.0		339.5
2.20	375.0	35.0	35.0		374.5

Figure 10.

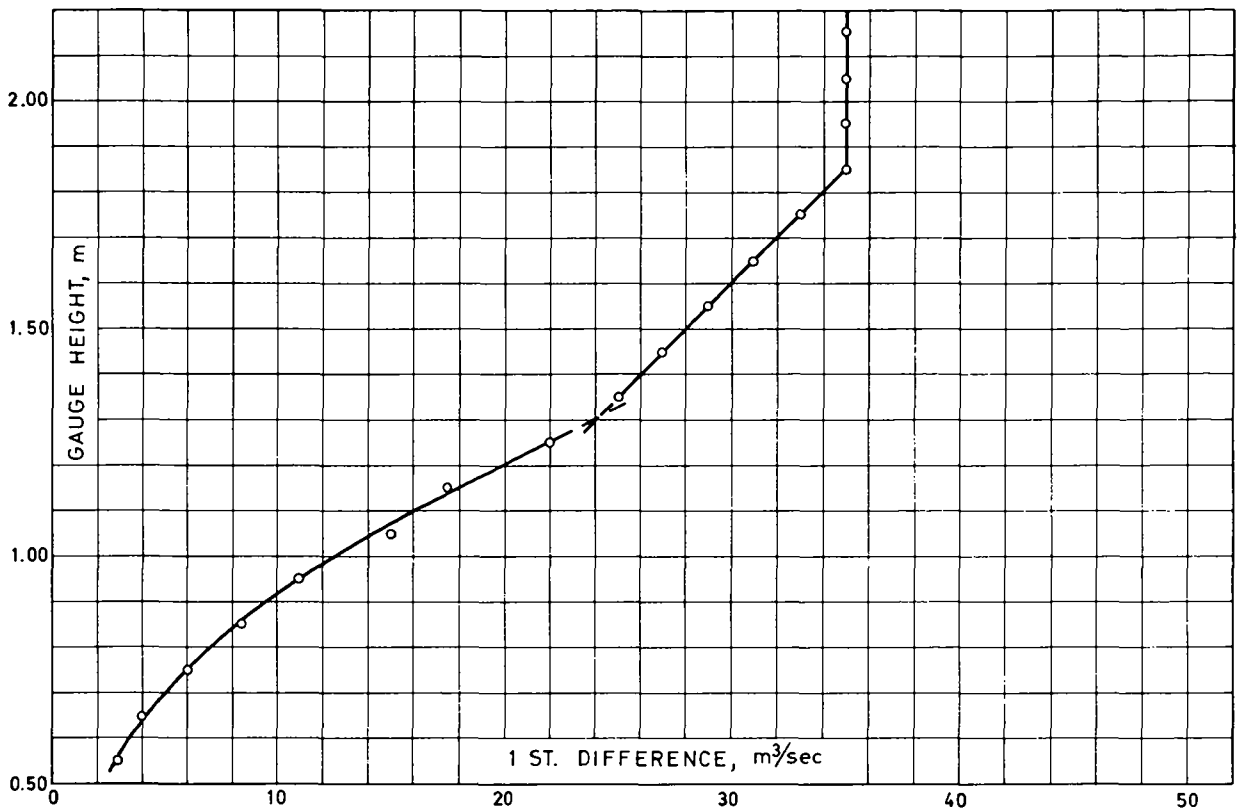


Figure 11. Smoothing graph for series of differences

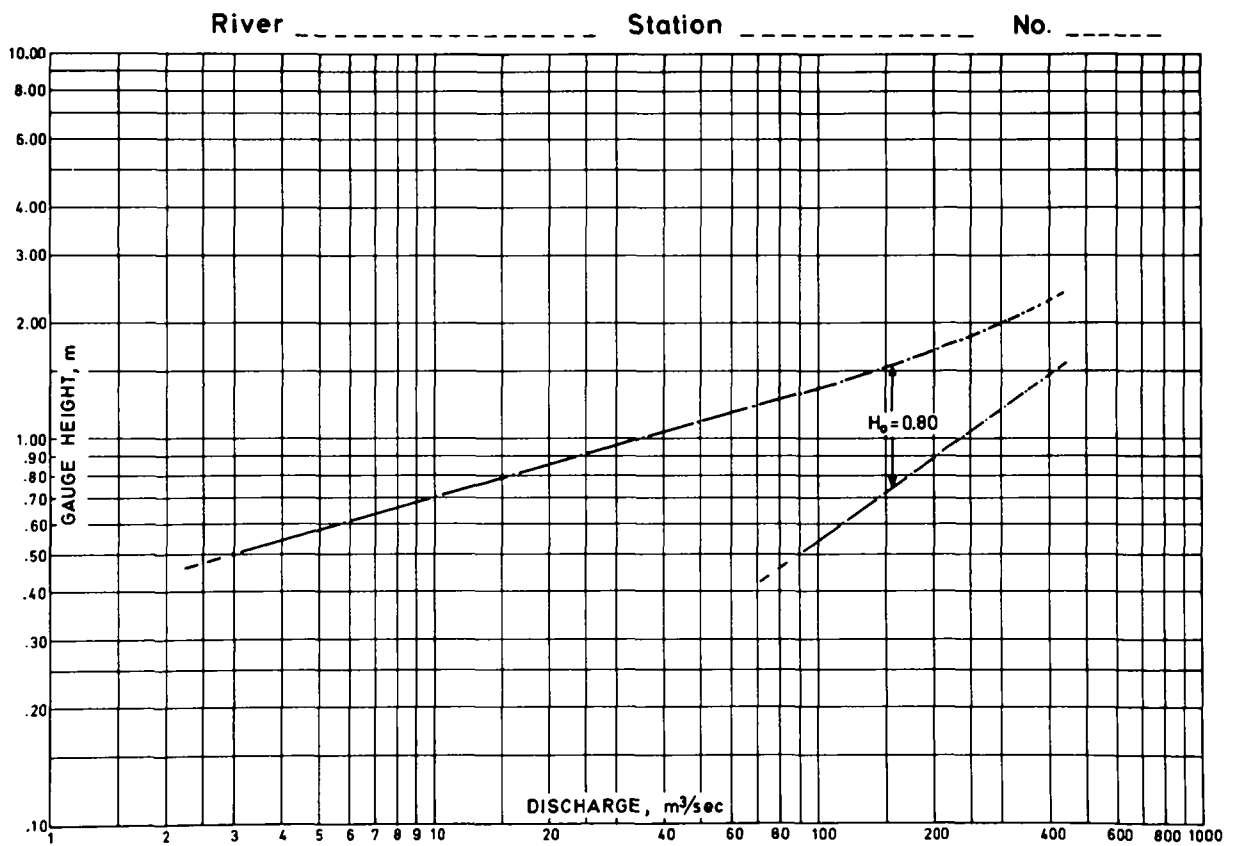


Figure 12. Second plotting and development of rating curve

The lower part of the plotted curve up to a gauge height of 1.30 m appears to be a straight line, therefore, nothing should be added or subtracted to the gauge height for this range. This means that the point of zero flow has an elevation equal to the zero of the gauge, and that around 1.30 m on the gauge the low water control is drowned out by a downstream high water control becoming effective.

The upper part of the rating curve, above approximately 1.30 m, is bending upward.

By successive trials, it is found that the curve will approach a straight line for a value of H_o equal to 0.80 m.

The rating curve consists of two straight line segments, the one below and the other above a stage of approximately 1.30 m. H_o for the lower segment is equal to 0.00, and for the upper segment equal to 0.80 m.

- Develop the flow equations for the two segments as follows:

Lower segment

Select two points on the lower straight line segment, the points should be as far as possible from each other and within the range of the measured discharges. Let the coordinates (Q, H) of the points be (3.0, 0.50) and (89.5, 1.30). Using equation (3.16) obtains:

$$\frac{\log Q - \log Q_1}{\log(H - H_o) - \log H_1} = \frac{\log Q_2 - \log Q_1}{\log H_2 - \log H_1}$$

$$\frac{\log Q - \log 3.0}{\log(H - 0) - \log 0.50} = \frac{\log 89.5 - \log 3.0}{\log 1.30 - \log 0.50}$$

$$\frac{\log Q - 0.4771}{\log H + 0.3010} = \frac{1.9518 - 0.4771}{0.1139 + 0.3010} = 3.5543$$

$$\text{Log } Q = (\log H + 0.3010)3.5543 + 0.4771$$

$$\log Q = 3.5543 \log H + 1.5469$$

$$Q = 35.2 H^{3.554}$$

which is the discharge equation for the lower segment, i.e. for H less than, or equal to, 1.30 m.

Upper segment

H_o has been determined by trial and error to equal 0.80 m. Select two points on the upper straight line segment, let the coordinates be (89.5, 0.50) and (339.5, 1.30). Substituting in equation (3.16) obtains:

$$\frac{\log Q - \log 89.5}{\log(H - 0.80) - \log 0.50} = \frac{\log 339.5 - \log 89.5}{\log 1.30 - \log 0.50}$$

$$\frac{\log Q - 1.9518}{\log(H - 0.80) + 0.3010} = \frac{2.5308 - 1.9518}{0.1139 + 0.3010} = 1.3956$$

$$\log Q = (\log(H - 0.80) + 0.3010) 1.3956 + 1.9518$$

$$\log Q = 1.3956 \log(H - 0.80) + 2.3718$$

$$Q = 235.4 (H - 0.80)^{1.40}$$

which is the discharge equation for the upper segment, i.e. for H greater than 1.30 m.

- Check the flow equations if they give satisfactory results as illustrated next.

Test of lower segment using data point (24.2, 0.90):

$$Q = 35.2 \cdot 0.90^{3.55} = 24.2$$

Test of upper segment using data point (269.5, 1.90):

$$Q = 235.4 \cdot 1.10^{1.40} = 269.0$$

It is seen that both of the equations give good results as compared with the data in Figure 10.

Each segment should be checked using three data points, one data point each for a low stage, a medium stage, and a high stage. The reason for checking with three points is the possibility that only a part of the curve is represented by the equation within acceptable limits of accuracy. If

the result of the check is not satisfactory, adjustments of the straight line plot are made and the procedure repeated.

9. Check the rating curve for bias and goodness of fit as illustrated in Appendix B.

3.2.5 Rating Tables

The rating table is a tabular representation of the rating curve and is a useful tool for converting gauge height readings into discharges when this is done manually (Figure 13).

The discharges entered in the .00-column are copied from the final adjusted values of Figure 10, column 6, and give the discharge for every 0.10 m increments in gauge height. Intermediate values are obtained by interpolating between the values of the .00-column, the difference between adjacent discharges should increase smoothly or be the same as the preceding difference.

With a modern pocket calculator the rating table is easily established by means of the discharge equation.

RATING TABLE

River _____ Station _____ No. _____
 From _____ to _____; from _____ to _____

G. H. m	Discharge, m ³ /sec										Δ Q
	.00	.01	.02	.03	.04	.05	.06	.07	.08	.09	
.0											
.1											
.2											
.3											
.4											
.5											
.6											
.7											
.8											
.9											
.0											
.1											
.2											
.3											
.4											
.5											
.6											
.7											
.8											
.9											
.0											
.1											
.2											
.3											
.4											
.5											
.6											
.7											
.8											
.9											
.0											

Figure 13.

3.2.6 Verification of the Rating Curve

The stage-discharge relation is checked from time to time by discharge measurements at a low stage and at a medium or high stage, and always during and after major floods. If a significant departure from the established rating curve is found, further checks are made. If the difference is confirmed, sufficient discharge measurements are made to redefine the curve in the range in which the relation has altered and a new rating curve is made (Appendix B 2.3 and B. 2.4).

If a particular change of the rating curve can be attributed to a definable incident in the history of the station, the new curve should apply from the time of that incident.

3.2.7 Extrapolation of Rating Curves

3.2.7.1 General

Extrapolation of the rating curve in both directions is often necessary. If the point of zero flow has been obtained, the curve may be interpolated between this point and the lowest discharge measurements without much error. But, if the point of zero flow is not available, it is not advisable to extrapolate far in this direction.

In the upper part of the curve extrapolation is almost always necessary. Only in very few cases have discharge measurements been obtained at about the highest flood peak observed.

Two methods of extrapolation have already been mentioned. The series of differences method can be used if the control does not change at the higher stages. This also applies for a logarithmic extrapolation which has proved to be a reliable method for shorter extensions. If, however, extended extrapolations have to be made, special methods must be used, some of which will be described in the following. [5]. [11].

3.2.7.2 The Stage-Velocity-Area Method

The best method to use is the extension of the stage against the mean velocity curve. A plot with stage as the ordinate and the mean velocity as the abscissa gives a curve which, if the cross-section is fairly regular and no bank overflow occurs, tends to become asymptotic

to the vertical at higher stages. That is, the rate of increase in the velocity at the higher stages diminishes rapidly and this curve can therefore be extended without much error. Further, by plotting the stage-area curve (stage as ordinate, area as abscissa) for the same cross-section as that from which the mean velocity was obtained, the area can be read off at any stage desired. Multiplication of the area by the mean velocity gives the discharge (Figure 14).

The area is obtained by a field survey up to the highest stage required and is therefore a known quantity.

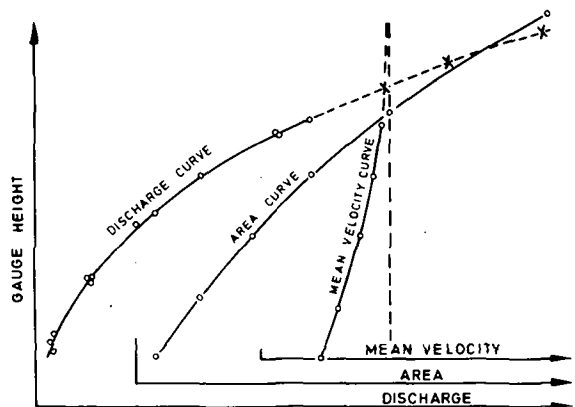


Figure 14. Discharge rating curve extrapolated by the stage-area/stage-velocity method. [5]

3.2.7.3 The Manning Formula Method

The uniform flow formula as developed by Manning can be expressed as

$$Q = NAR^{2/3} S^{1/2} \quad (3.20)$$

where

- N = a constant
- A = area of cross-section
- R = hydraulic radius
- S = slope of water surface
- Q = discharge

may be used for extrapolation of rating curves. In terms of mean velocity the formula may be written

$$V = NR^{2/3} S^{1/2} \quad (3.21)$$

For the higher stages, the factor $NS^{1/2}$ becomes approximately constant. Equations (3.20) and (3.21) can therefore be rewritten as

$$Q = KAR^{2/3} \quad (3.22)$$

and

$$V = KR^{2/3} \quad (3.23)$$

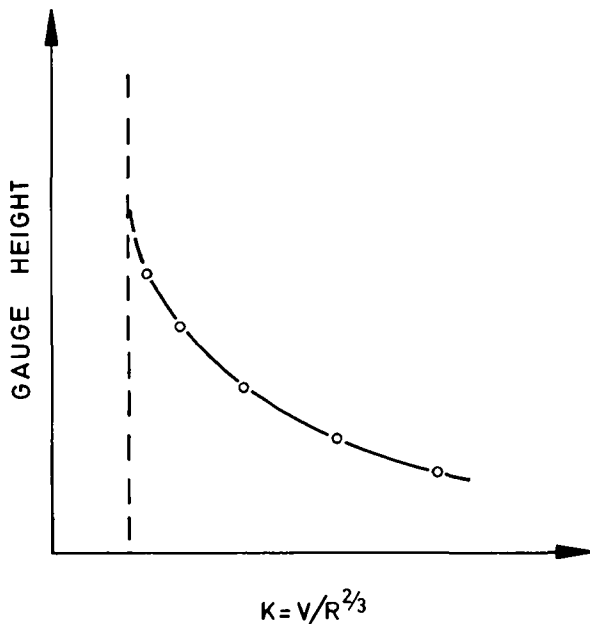


Figure 15. Extrapolation of K . [11]

By using various values of V from the known portion of the stage against mean-velocity curve and the corresponding values of R , values of K can be computed by equation (3.23) for the range in stage for which the velocity is known. By plotting these values of K against the gauge height, a curve is obtained that should asymptotically approach a vertical line for the higher stages (Figure 15). This K -curve may then be extended without much error and values of K obtained from it for the higher stages. These high stage values of K combined with their respective values of A and $R^{2/3}$ using equation (3.22) will give values of the discharge Q which may be used to extrapolate the rating curve.

A and R are obtained by field surveys and are known for any stage required.

3.2.7.4 The Stevens Method

The so-called Stevens Method is a variation of the method described above. It is based on the Chezy formula for uniform flow

$$Q = AC(RS)^{1/2} \quad (3.24)$$

For shallow streams with a relatively small depth-width ratio, the mean depth D does not differ much from the hydraulic radius R . Then, by substituting D for R , equation (3.24) may be written

$$Q = CS^{1/2}AD^{1/2} \quad (3.25)$$

At higher stages, the slope S in most cases may be considered constant. Then, by plotting $AD^{1/2}$ against Q in equation (3.25), an approximately straight line is obtained which is readily extended.

As illustrated in Figure 16, values of $AD^{1/2}$ are plotted both against gauge height H and discharge Q , and the latter curve extended up to the higher stages.

Both A and D are obtained by field surveys and are therefore known factors.

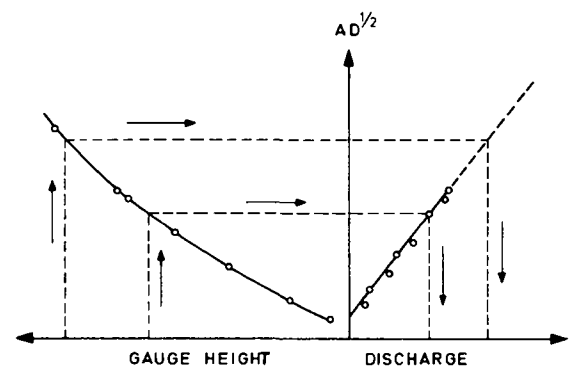


Figure 16. Discharge rating curve extrapolated by the Stevens method. [5]

3.2.7.5 River-Model Analysis

A method for extrapolation of the stage-discharge relation that has proved very useful is the technique of hydraulic model testing carried out in a hydraulic laboratory.

A hydraulic model is in principle an exact replica of the prototype in all significant details at a reduced scale.

Based on accurate field data, a model is built of the stream at the gauging station including all the controlling features. Some field measurements of the discharge at low and medium stage must be available in order to adjust (calibrate) the model to conform exactly to the prototype at the lower discharges. By now observing the model when its discharge is

further increased, the stage-discharge relation for the prototype can be derived quite accurately for the high flood stages.

3.3 Shifting Control

3.3.1 General

Shifts in the control features occur especially in alluvial sand-bed streams. However, even in solid stable stream channels shifts will occur, particularly at low flow because of aquatic and vegetal growth in the channel, or due to debris caught in the control section.

In alluvial sand-bed streams, the stage-discharge relation usually changes with time, either gradually or abruptly, due to scour and silting in the channel and because of moving sand dunes and bars. These variations will cause the rating curve to vary with both time and the magnitude of flow. Nevertheless, runoff records at a particular location may be of great importance and observations and measurements have to be carried out the best way possible.

3.3.2 Characteristics of Sand-Bed Channels

In sand-bed channels, the configuration of the bed varies with the magnitude of the flow of water. The bed configurations occurring with increasing discharge are ripples, dunes, plane bed, standing waves, antidunes, and chute and pool (Figure 17). The bed forms are associated with a particular mode of sand movement and with a particular range of resistance to the flow of water. The resistance to the flow is greatest in the dunes range. When the dunes are washed out and the sand is rearranged to form a plane bed, there is a marked decrease in bed roughness and resistance to the flow causing an abrupt discontinuity in the stage-discharge relation.

The sequence of bed configurations shown in Figure 17 is arranged as developed by increasing discharge. The bed configurations are grouped into two regimes. The lower regime, A–C, occurs with lower discharges; the upper regime, E–H, with higher discharges; an unstable discontinuity, D, in the depth-discharge relation appears between these more stable regimes.

Fine sediment present in the water influences the configuration of the sand-bed and thus the resistance to flow. It has been demonstrated that a concentration of fine sediments in the order of 40,000 ppm may reduce the resistance to flow in the dune regime as much as 40 percent. Thus, the stage-discharge relation for a stream may vary with the sediment concentration if the water is heavily loaded with fine sediments.

Changes in water temperature may also alter the bed form, and hence roughness and resistance to flow in sand-bed channels. The viscosity of the water will increase with lower temperature and thereby the mobility of the sand will increase.

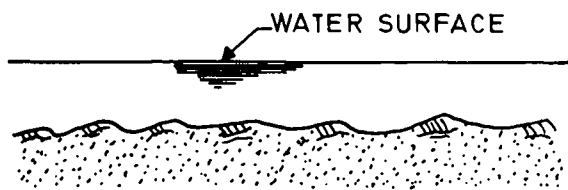
References [12], [13]

3.3.3 Discharge Rating of Sand-Bed Channels

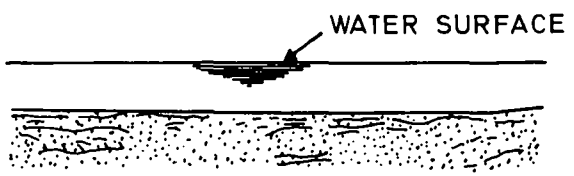
For sand-bed streams where neither bottom nor sides are stable, a plot of stage against discharge will very often scatter widely and thus be indeterminate (Figure 18). By changing variables, however, a hydraulic relationship will become apparent. The effect of variation in bottom elevation is eliminated by replacing stage by mean depth (hydraulic radius). The effect of variation in width is eliminated by using mean velocity instead of discharge.

Plots of mean depth against mean velocity are very useful in the analysis of stage-discharge relations, provided the measurements are referred to one and the same cross-section. These plots will identify the bed-form regime associated with each individual discharge measurement (Figure 19). Thus, only the measurements associated with the upper flow regime should be used to define the upper part of the rating curve, and similarly, only measurements identified with the lower flow regime should be used to define the lower part. Measurements made in the transition zone will scatter widely and should not be taken as representing shifts in the more stable parts of the rating.

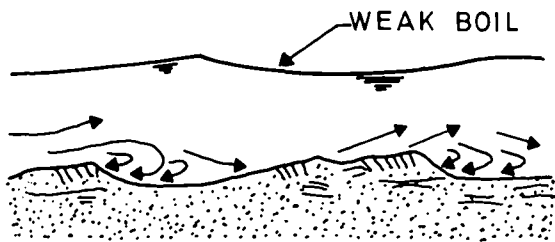
Knowledge of the bed-form which existed at the time of the individual discharge measurements is helpful in developing discharge ratings. Indication of bed-forms may be obtained by visual observation of the water surfaces.



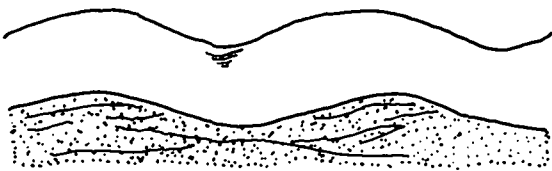
A. Ripples



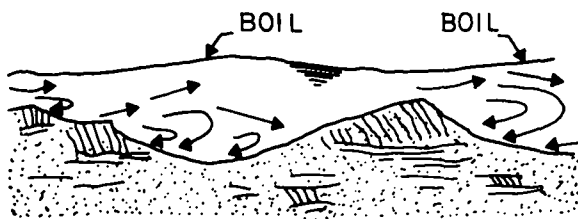
E. Plane bed



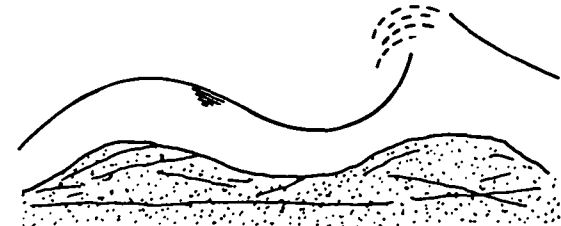
B. Dunes with ripples



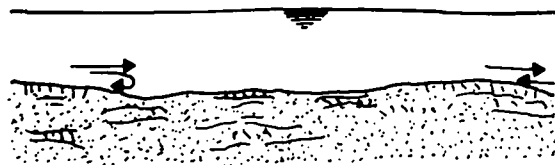
F. Standing waves



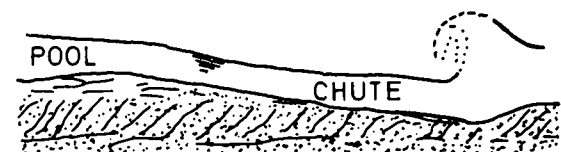
C. Dunes



G. Antidune, braking waves



D. Transition (washed out dunes)



H. Chute and pool

Figure 17. Diagramme of bed and surface configurations found in sand-bed channels. [13]

A very smooth surface indicates a plane bed, large boils and eddies indicate dunes, standing waves indicate smooth bed waves in phase with surface waves, and breaking waves indicate antidunes. The visual observations of the water surfaces should be recorded on the note sheet when making discharge measurements in sand-bed channels.

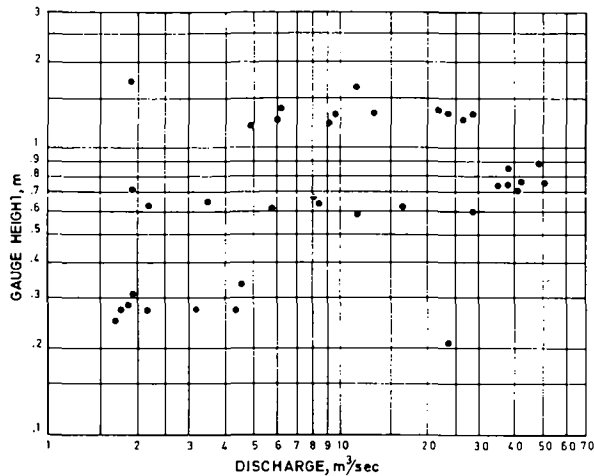


Figure 18. Plot of discharge against gauge height for a sandbed channel with indeterminate stage-discharge relation. [12]

The upper part of the stage-discharge relation associated with the upper flow regime for a sand-bed channel is usually comparatively stable. The middle part of the stage-discharge relation associated with the transition zone between the upper and lower regime varies almost randomly with time, and frequent discharge measurements are necessary in order to define this part of the relation.

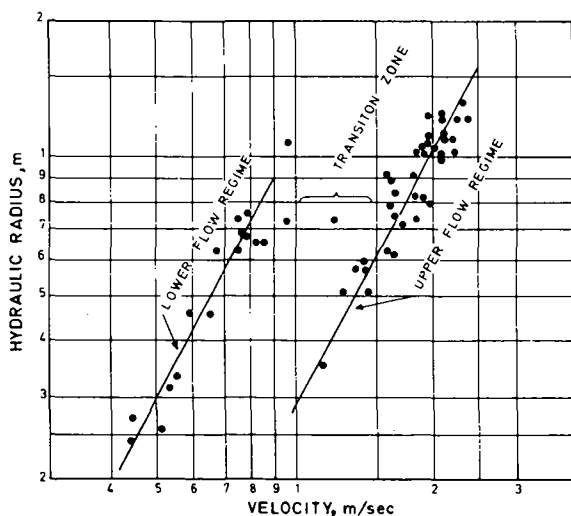


Figure 19. Relation of mean velocity to hydraulic radius for same channel as in Figure 18. [12]

At low flow when the water is not covering the whole width of a sand-bed channel, the flow tends to meander in the course of time. Under this condition, it is not possible to observe a systematic gauge height and a record of the discharge can therefore not be obtained.

A continuous definition of the stage-discharge relation for a sand-bed stream at low flow is difficult. If at all feasible, a permanent control structure for the lower flow should be considered in these cases.

Reference [12]

3.3.4 The Stout Method

For making adjustment for shifting control the Stout Method is commonly used. In this method, the gauge heights corresponding to discharge measurements taken at intervals are corrected so that the discharge values obtained from the established rating curve may be the same as the measured values. From the plot of these corrections against the chronological dates of measurements, a gauge height correction curve is made. Corrections from this

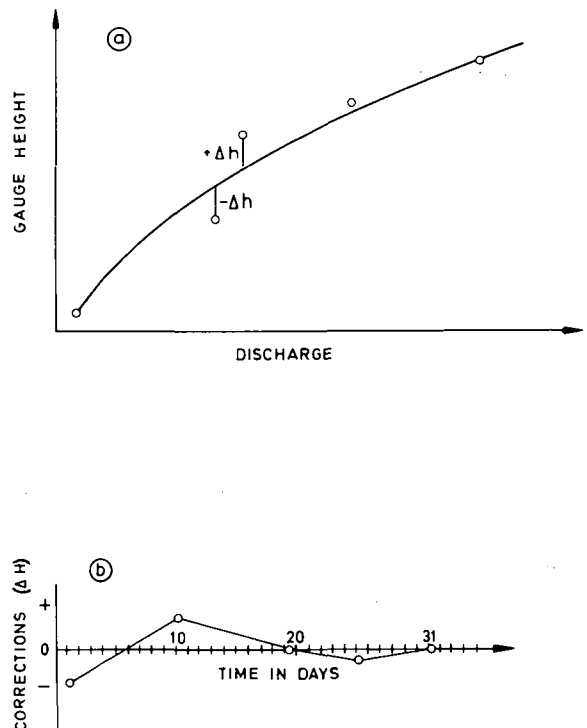


Figure 20. The Stout Method of correcting gauge height readings when control is shifting. [5]

CALCULATION FORM FOR THE STOUT METHOD

River _____ Station _____ No. _____
 Month _____ 19__

DATE.	Observed Gauge Height	Measured Discharge	Shift Correction	Corrected Gauge Height	Corrected Discharge	Remarks
1						
2						
3						
4						
5						
6						
7						
8						
9						
10						
TOTAL	—	—	—		—	
11						
12						
13						
14						
15						
16						
17						
18						
19						
20						
TOTAL	—	—	—		—	
21						
22						
23						
24						
25						
26						
27						
28						
29						
30						
31						
TOTAL	—	—	—		—	
MONTHLY TOTAL		—	—		—	

Figure 21.

curve are applied to the recorded gauge heights for the intervening days between the discharge measurements.

An ordinary staff gauge is established at the best available site on the river and readings taken at appropriate intervals, say once a day. Discharge measurements are made as often as found necessary, and may be required as often as once or twice a week. How often discharge measurements need to be taken depends on several factors, such as the hydraulic conditions in the river, the accuracy and the feasibility based on economic and other factors.

The measurements are plotted against observed gauge height on ordinary graph paper and a median curve is fitted to the points. Most of the subsequent discharge measurements will deviate from the established curve. For points lying above the curve, a small height, Δh , must be subtracted from the observed gauge height in order to make these points lie on the curve. That is, minus corrections are applied to all points above the curve, plus corrections are applied to points lying below the curve (Figure 20a).

Next, a correction graph is made as shown in Figure 20b. The plus and minus corrections are plotted on the date of measurement and the points connected by straight lines or a smooth curve. Gauge height corrections for each day are now obtained directly from this correction graph, remembering that the parts of the graph below the abscissa axis give minus corrections and the parts above give plus corrections.

When discharge measurements plot within 5 percent of the rating curve, with some plus and some minus deviations, it is acceptable to use the curve directly without adjustment for shifting control.

For computation purposes special forms may be made. Forms are made for each month as shown in Figure 21.

It is not too important how the median curve is drawn between the measurements. Different curves will give different corrections and the final result will be approximately the same. Extrapolation of the curve, however, has to be done with care.

A rating of this type requires much work in order to obtain good results. The accuracy depends on the hydraulic conditions in the river and on the number and accuracy of the discharge measurements and the gauge height readings. The reliability is much less than for a station with a permanent control.

The Stout Method presupposes that the deviations of the measured discharges from the established stage-discharge curve are due only to a change or shift in the station control, and that the corrections applied to the observed gauge heights vary gradually and systematically between the days on which the check measurements are taken.

In fact, the deviation of a discharge measurement from an established rating curve may be due to 1) gradual and systematic shifts in the control, 2) abrupt random shifts in the control, and 3) error of observation and systematic errors of both instrumental and personal nature.

The Stout Method is strictly appropriate for making adjustments for the 1st type of errors only. If the check measurements are taken frequently enough, fair adjustments may be made for the 2nd type of error also. However, the drawback of the Stout Method is that the error of observation and the systematic errors are disregarded as such and simply mixed with the errors due to shift in control, although the former errors may be at times of a higher magnitude than the latter. This means that "corrections" may be applied to a discharge record when in reality the rating is correct. The apparent error is not due to shifting control but to faulty equipment or careless measuring procedure.

Reference [5]

3.4 Complex Stage-Discharge Relations

3.4.1 General

If variable backwater or highly unsteady flow occurs at a gauging station, a single-valued stage-discharge relation does not exist. A third variable, fall or rate of change of stage (also slope or rate of change of discharge may be used) will have to be included in order to define the discharge rating.

Backwater is caused by constrictions such as narrow reaches of a stream channel or artificial structures such as dams or bridges. If the backwater from fixed obstructions is always the same at a given stage, the discharge rating is a function of stage only.

If the reach downstream from a gauging station has within it a dam, a diversion, or a confluent stream, which can increase or decrease the energy gradient for a given discharge, a variable backwater is produced. That is, the slope in a reach is increased or decreased from the normal. Under this condition, a third parameter, fall over a channel reach, is introduced in order to develop a stage-fall-discharge relation.

Stage-fall-discharge ratings are established from observation of 1) stage at a base gauge, 2) the fall of the water surface between the base gauge and an auxiliary gauge downstream, and 3) the discharge.

The plotting of the discharge measurements with the fall marked against each measurement, will reveal whether the relationship is affected by variable slopes at all stages or is affected only when the stage rises above a particular level. If the relationship is affected by variable backwater at all stages, a correction is applied by the *constant-fall* method, on the other hand, however, when the relation is affected only when the stage rises above a particular value, the *normal-fall* method is applied.

In order to observe the fall, an auxiliary gauge is established a distance L downstream from the base gauge at the station and set to the same datum as the base gauge. With a difference in gauge reading of F (fall), the surface slope is approximated by

$$S \sim \frac{F}{L} \quad (3.26)$$

3.4.2 The Constant-Fall Method

The Manning uniform flow formula may be written in the form

$$Q = NAR^a S^b \quad (3.27)$$

where

N = a constant

A = area of cross-section

R = hydraulic radius

S = slope of water surface

a, b = two exponents

Substituting for S , equation (3.27) will read

$$Q = NAR^a \left(\frac{F}{L}\right)^b \quad (3.28)$$

The roughness factor N and the conveyance AR^a are functions of stage, then for a given stage the relation between discharge and fall can be developed, thus

$$\frac{Q_m}{Q_r} = \left(\frac{F_m}{F_c}\right)^b \quad (3.29)$$

in which Q_m and F_m are the measured discharge and fall, and Q_r and F_c are the adjusted discharge from the rating curve and a selected constant fall on which the rating curve is based.

From fluid mechanics, the exponent b in equation (3.28) would be expected to equal 0.5. However, the slope S is only approximated by F/L , the exponent b would then not necessarily equal 0.5 and must be determined empirically, this is done by a graphical plot of Q_m/Q_r against F_m/F_c as explained below.

The procedure of the constant-fall method in developing a stage-fall-discharge relation is as follows:

1. Plot the discharge measurements against stage in the usual manner and indicate the observed fall beside each point. Select a constant fall for which a rating curve can be drawn through the measurements and draw the curve by visual estimation; for curve a) in Figure 22 a constant fall of 0.50 m has been selected.
2. Read the discharge Q from the rating curve for each measurement and compute the ratios Q_m/Q_r and F_m/F_c . Plot these ratios and draw a smooth curve through them, i.e. curve b) in Figure 22. Note that curve b) expresses the exponent b in equation (3.29).
3. From the curve of relation between discharge ratios and fall ratios, curve b) in Figure 22, select the smoothed discharge ratio for each measurement.

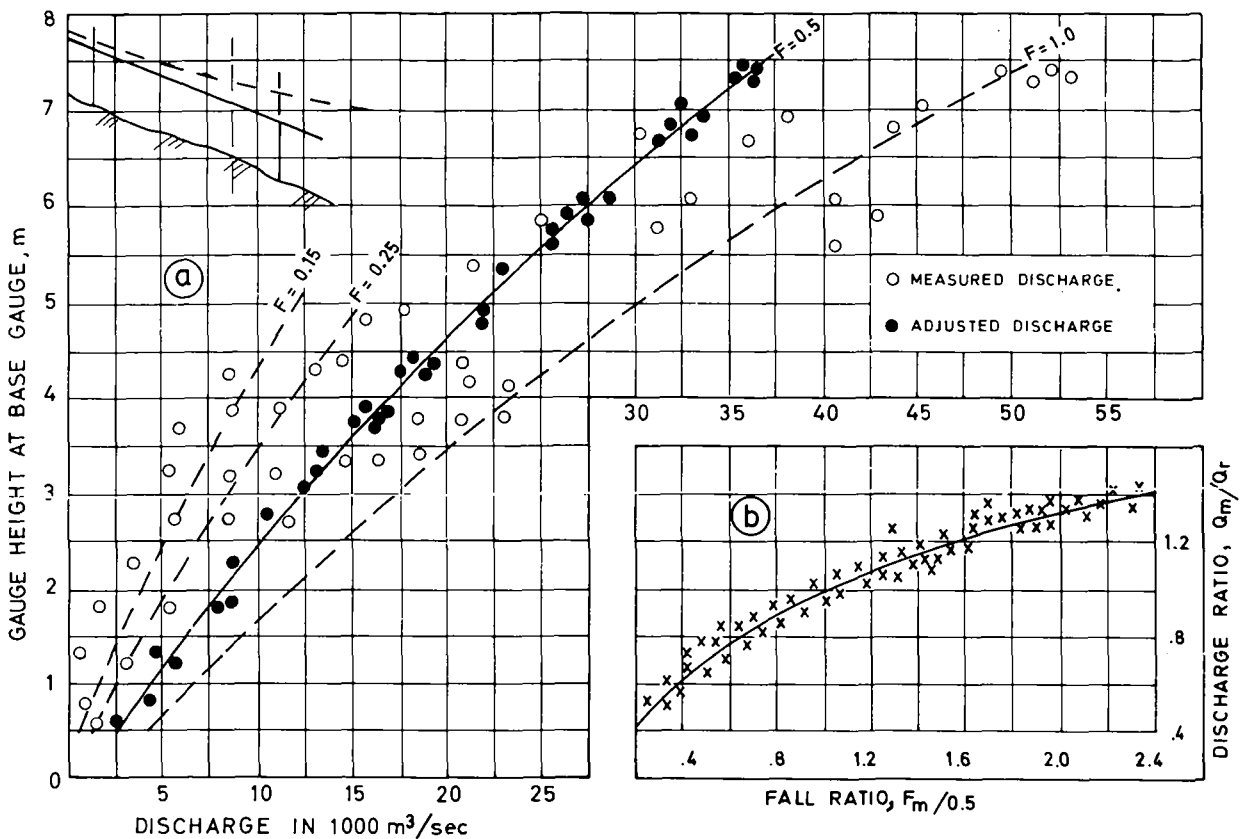


Figure 22. Stage-fall-discharge rating for variable backwater, nearly uniform channel

Adjust each measurement by dividing it by its smoothed discharge ratio, then replot the adjusted discharge measurements. Examine the plot. If the first approximation of the rating curve does not appear to be well-balanced among the adjusted discharge measurements, then adjust the rating curve and repeat the procedure. Usually, not more than one repeat is necessary.

A constant-fall rating is not the usual case in natural streams. However, if discharge measurements cover the whole range of flow and if the measurements conform to a constant-fall rating, the constant-fall method is sufficient and there is no need to use a more complicated technique. If the stream geometry is not too far from uniform and the velocity head increments are negligible, the relation between the discharge ratio and fall ratio should approach a single curve.

Reference [4]

ILLUSTRATION

See Table 5 and Figure 23.

14 discharge measurements are available at a twin-gauge station. In columns 2, 3, and 5 of Table 5, values of observed gauge height (H), measured discharge (Q_m), and measured fall (F_m) are shown. It is desired to develop a stage-fall-discharge relation for this station.

1. Plot the discharge measurements in the usual manner indicating measured fall beside each point. Select a constant fall for which a rating curve can be drawn. Here a suitable fall would be $F_c = 0.30$ m. Draw the curve (Figure 23 a).
2. Compute the fall ratios F_m/F_c and enter in column 6.
3. Read the discharge Q_r from the rating curve for each measurement and enter in column 4. Compute the discharge ratio Q_m/Q_r and enter in column 7.

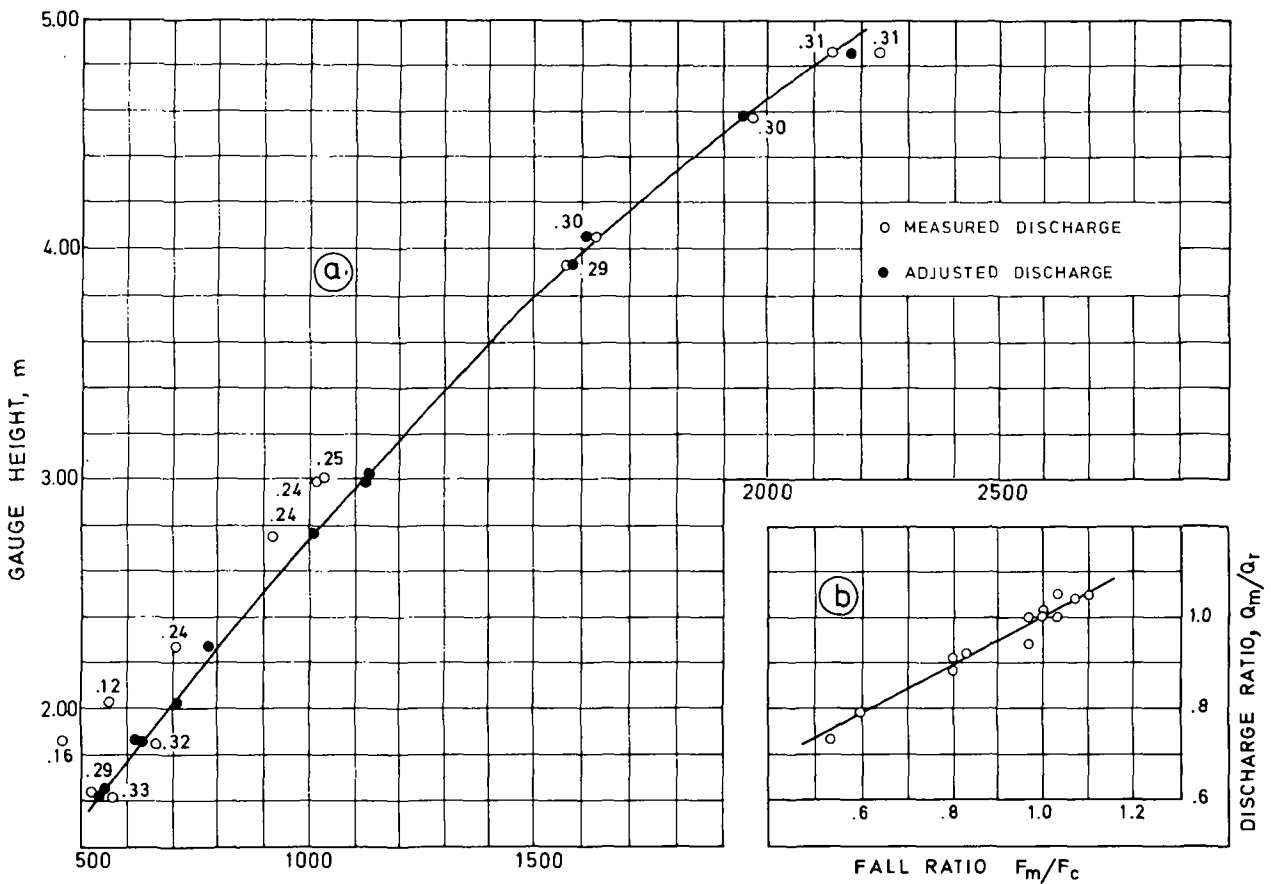


Figure 23.

4. Plot the fall ratios F_m/F_c against the discharge ratios Q_m/Q_r and draw a smooth mean curve of relation. Here it appears that the curve of relation approaches a straight line. Usually this curve bends downward (Figure 23 b).
5. Entering the curve of relation with the fall ratios, adjusted values of the discharge ratios are obtained and entered in column 8.
6. Now, divide each value in column 3 by its corresponding value in column 8 obtaining adjusted values for Q_r which are entered in column 9.
7. Replot the adjusted values of Q_r . It appears that in this case the original rating curve has a well-balanced fit to the new adjusted values of Q_r , therefore, no repeat is necessary.

The procedure of converting observed gauge height and fall to discharge by means of the stage-fall-discharge relation as developed in Figure 23 is as follows:

Observed gauge height	$H = 3.40$ m
Observed fall	$F_m = 0.22$ m
Selected constant fall	$F_c = 0.30$ m
Computed fall ratio, $0.22/0.30$	$= 0.73$
Discharge ratio corresponding to a fall ratio of 0.73 (curve b)	$= 0.86$
Discharge of rating curve corresponding to a gauge height of 3.40 m	$= 1300$ m ³ /sec
True discharge, 1300 m ³ /sec x 0.86	$= 1118$ m ³ /sec

Table 5. Developing a stage-fall-discharge relation

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
No.	H	Q_m m ³ /sec	Q_r m ³ /sec	F_m m	F_m/F_c	Q_m/Q_r	Adjusted Q_m/Q_r	Adjusted Q_r m ³ /sec
1	1.62	580	550	0.33	1.10	1.05	1.05	552
2	1.64	526	560	0.29	0.97	0.94	0.99	531
3	1.85	668	642	0.32	1.07	1.04	1.04	642
4	1.86	468	645	0.16	0.53	0.73	0.75	642
5	2.02	568	715	0.18	0.60	0.79	0.79	719
6	2.26	710	810	0.24	0.80	0.88	0.90	789
7	2.75	922	1015	0.24	0.80	0.91	0.90	1024
8	2.98	1018	1115	0.24	0.80	0.91	0.90	1131
9	3.00	1035	1125	0.25	0.83	0.92	0.91	1140
10	3.92	1562	1560	0.29	0.97	1.00	0.99	1578
11	4.05	1620	1625	0.30	1.00	1.00	1.00	1620
12	4.56	1960	1935	0.30	1.00	1.01	1.00	1960
13	4.85	2130	2125	0.31	1.03	1.00	1.02	2088
14	4.85	2230	2125	0.31	1.03	1.05	1.02	2186

$F_c = 0.30$ m

3.4.3 The Normal-Fall Method

At some stations, a simple single-gauge rating is applicable at low discharge when the surface slope is comparatively steep, while at higher discharges when the slope becomes

more flat the discharge is affected by variable backwater. Critical values of the fall (or slope) dividing these two regions are termed the normal-fall. The value of normal-fall at any discharge can be defined by studying the plot of stage against discharge (Figure 24). The points

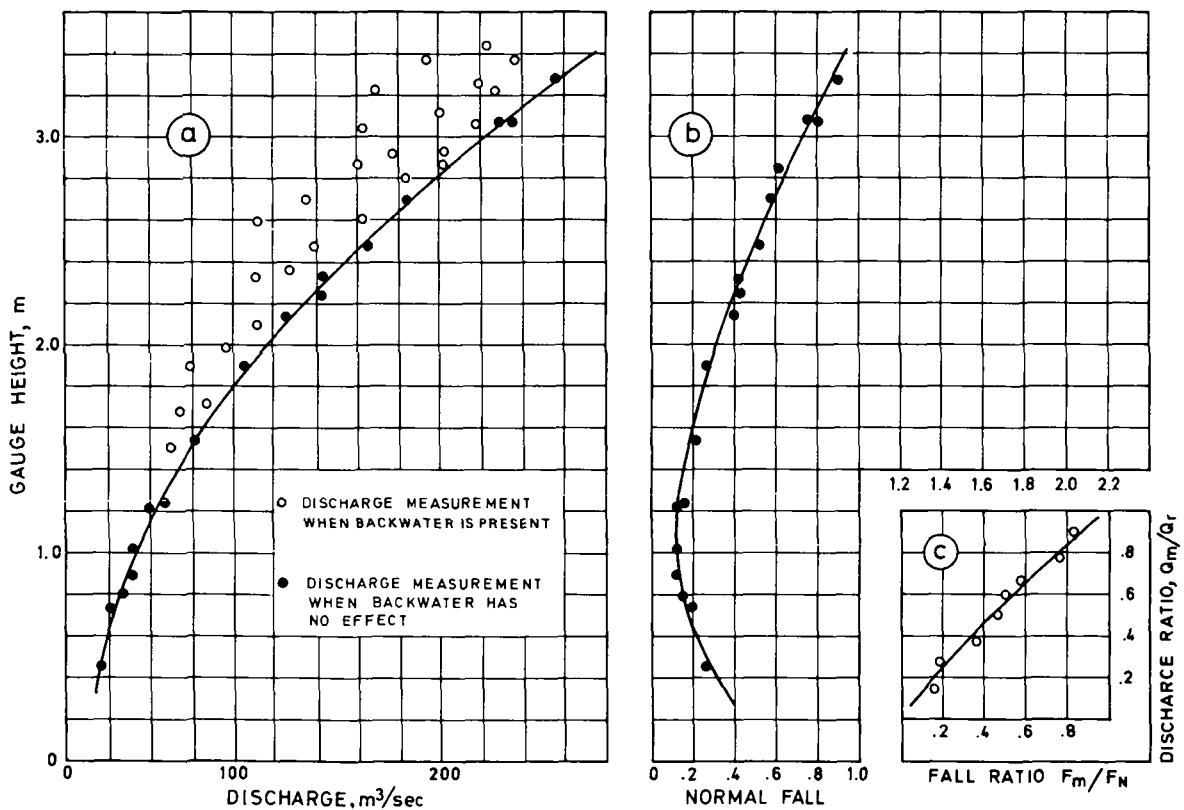


Figure 24. Stage-fall-discharge rating, submergence of low-flow control

at which backwater has no effect will group to the extreme right. This is the simple single-gauge rating with no backwater effects. A plot of the normal-fall values from this curve is made against the corresponding stage and a curve of normal-fall obtained. This permits drawing a curve of discharge ratios against fall ratios when normal-fall is used in place of constant-fall. The rest of the procedure is similar to that of the constant-fall method (Figure 24).

The normal-fall procedure in developing a stage-fall-discharge rating is as follows:

1. Plot the discharge measurements and write the fall beside each as indicated in Figure 24a (the fall values are not shown in the figure). A smooth curve is fitted to the measurements grouped to the extreme right. This curve is the stage-discharge relation for a condition of no backwater effects at the base gauge.
2. The fall for the measurements used to fit the rating curve are plotted against stage as illustrated in Figure 24b, a curve is fitted to the plotted points. This curve, the normal-fall curve, shows the fall at which backwater begins at any stage. That is, there are no backwater effects at a fall value to the right of the normal-fall curve, for fall values to the left of the curve there is backwater present.
3. Each fall ratio F_m/F_n is plotted against its corresponding discharge ratio Q_m/Q_r and

a smooth curve of relation drawn (Figure 24c).

The rest of the procedure is identical to that of the constant-fall method. The only difference is that a normal-fall value varying with stage is used instead of a constant-fall value.

Reference [4]

3.4.4 Rapidly Changing Discharge

At river gauging stations located in a reach where the slope is very flat, the stage-discharge relation is frequently affected by the superimposed slope of the rising and falling limb of a passing flood wave. During the rising stage, the velocity and discharge are greater than they would be for the same stage at steady flow conditions. Similarly, during the falling stage, the discharge is less for any given gauge height than it is when the discharge is constant.

The method used in developing rating curves at single-gauge stations is, as discussed in Section 3.2.1 to draw a median curve through a scatter of plotted discharge measurements. This procedure gives a correct result when all discharge measurements are made at steady or nearly steady flow conditions. In fact, if each plotted measurement had been tagged as to whether it had been measured on a rising or falling stage, the curve would have taken the shape of a loop (Figure 25). This effect

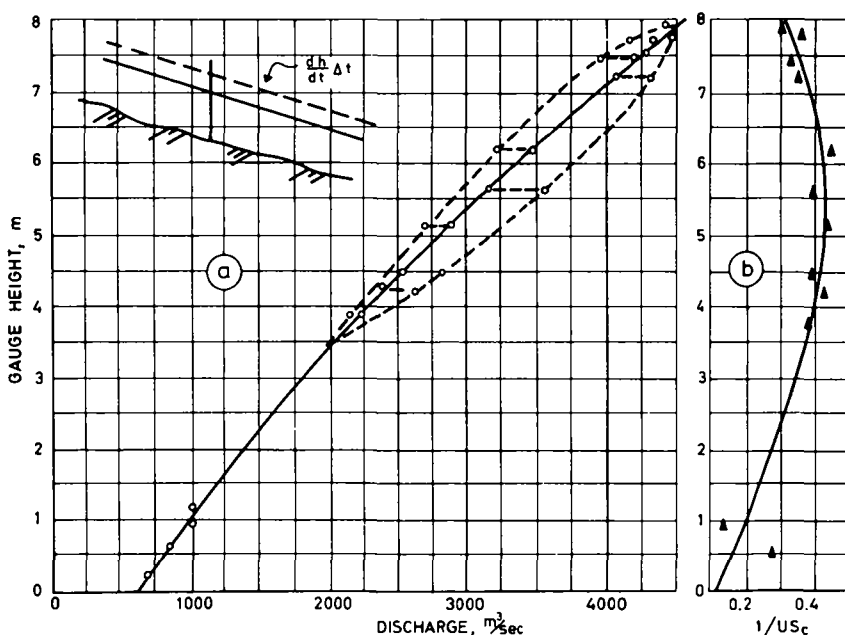


Figure 25. Stage-discharge relation, rapidly changing flow

is especially noticeable for larger rivers having very flat slopes with channel control extending far downstream. For smaller rivers having section control or steeper slopes and the measuring site is not too far from the site where the stage is observed, the looping effect is seldom of such a magnitude as to have any practical consequence. The looping effect is due to several causes. The first of them is channel storage. If a discharge measurement is made at some distance from the station control during a period of rising or falling stage, the discharge passing the measuring section will not be the same as the discharge at the control. A correction for the channel storage has to be applied to the measured discharge by adding or subtracting from the measured discharge a quantity equal to the product obtained by multiplying the water surface area between the measuring section and the control by the average rate of change in stage in the same river reach. If the measurement is made above the control, the correction will be plus for falling stages and minus for rising stages. If made below the control, it will be minus for falling and plus for rising stages.

ILLUSTRATION

A measurement is made 1000 m upstream of the control; average width of channel in reach is 100 m; average rate of rise of water surface in reach during measurement is 0.15 m/hr.; measured discharge is 120 m³/sec.

Then, the rate of change of storage in the reach is given by

$$\begin{aligned} ds &= 1000 \times 100 \times 0.15 = 15000 \text{ m}^3/\text{hr.} \\ &= 4.2 \text{ m}^3/\text{sec.} \end{aligned}$$

The discharge measurement should be plotted as 120 m³/sec - 4 m³/sec = 116 m³/sec (rounded) since this is the discharge passing the control and to which the mean gauge height during the measurement corresponds.

The second reason for the looping of rating curves is the variation in surface slope which occurs as a flood wave passes a river gauging station. Discharge measurements taken on either side of a flood wave may be corrected to the theoretical steady state condition by application of the following equation:

$$Q_m/Q_r = \left(1 + \frac{1}{US_c} \frac{dh}{dt}\right)^{1/2} \quad (3.30)$$

where

- Q_m = measured discharge
- Q_r = estimated steady state discharge from rating curve
- U = wave velocity (celerity)
- S_c = energy slope for steady state flow
- dh/dt = rate of change of stage, positive for rising stage and negative for falling stage.

Rearranging equation (3.30) obtains:

$$1/US_c = \frac{(Q_m/Q_r)^2 - 1}{dh/dt} \quad (3.31)$$

If a sufficient number of measurements have been made at a gauging station during both rising and falling stage and at steady state conditions, equation (3.31) may be solved by a graphical method, the so-called Boyer method, without having to compute the energy slope and the velocity of the flood wave.

The discharge measurements are plotted in the usual manner and a rating curve is drawn as a median curve through the uncorrected values (Figure 25a). The steady state discharge Q_r is estimated from this median curve. Q_m and dh/dt have been measured and are therefore known quantities, then by substituting in Equation (3.31) the term $1/US_c$ is obtained for each discharge measurement. The term $1/US_c$ is plotted against stage and a mean curve fitted to the plotted points (Figure 25b). From the $1/US_c$ against stage relation, new smoothed values of $1/US_c$ are obtained and inserted in Equation (3.31) in order to obtain the steady state Q_r . The new values of Q_r are then plotted against stage to obtain a corrected steady state rating curve.

For gauging stations situated in tidal reaches with significant unsteady flow, calculation of the discharge is generally carried out by special methods, the *method of cubature* and *unsteady flow mathematical modelling*.

The method of cubature is based on the law of continuity. The rate of rise and fall of the water surface is used to determine the rate of gain and loss of channel storage in a reach. The discharge at the downstream end of the channel reach is calculated from the known

inflow to the reach and the computed gain or loss in channel storage during the time required for the water surface to rise and fall. [18].

Unsteady flow mathematical models are based on assumptions of moderately unsteady, homogeneous, and one-dimensional flow and prismatic channel geometry. On these assump-

tions, a system of unsteady flow equations can readily be set up to describe the tidal flow. Initial and boundary conditions are determined by field measurements. The actual computation of discharge is performed by digital computer. [18].

References [4], [18]

REFERENCES

1. Klaeboe, H.
1962: Grunntrekk av hydrologien, særlig Norges hydrologi. – Universitetsforlaget, Oslo; p. 177.
2. Trestmann, A.G.
1960: New aspects of River Runoff Calculations. – GIMIZ, Leningrad; p. 26–47. (Translated from Russian; Israel Program for Scientific Translations, 1964)
3. Grover, N.C. and Harrington, A.W.
1966: Stream Flow; Measurements, Records and Their Uses. – Dover Publications, Inc., New York; 363 p.
4. Corbett, Don M. and others
1945: Stream-Gauging Procedure. – U.S. Geol. Survey Water-Supply Paper 888; 245 p.
5. Otnes, J.
1969: Instruments, Methods of Observation and Processing of Basic Data and Water Levels and Streamflow. Contribution to "Hydrometeorological Observations and Networks in Africa". – WMO Secretariat Geneva; p. 93–98 and p. 114–116.
6. Rantz, S.E.
1968: Characteristics of Logarithmic Rating Curves. – U.S. Geol. Survey Water-Supply Paper 1892; p. 142–152.
7. Schenck Jr., H.
1961: Theories of Engineering Experimentation. – McGraw-Hill Book Co., New York; p. 184.
8. Framji, K.K.; Madan M.L. and Nag, S.K.
1962: Determination of Stage-Discharge Relations for Estimation of Discharge from Gauges. Contribution to "Field Methods and Equipment Used in Hydrology and Hydrometeorology". – United Nations Secretariat, New York; p. 90–95.
9. Gerhard, H.
1971: Extrapolation von Abflusskurven aus den Geschwindigkeitflächen. – Die Wasserwirtschaft 9 (1971), Stuttgart; p. 261–265.
10. International Organization for Standardization (ISO)
1973: Liquid flow measurements in open channels – Establishment and operation of a gauging-station and determination of the stage-discharge relation. Ref. No. ISO 1100–1973 (E). – Geneva; 29 p.
11. Skofteland, E.
1974: Lectures on Hydrology. – Ministry of Water Development and Power, Tanzania, Dar es Salaam; p. 105–106.
12. Carter, R.W. and Davidian, J.
1965: Discharge Ratings at Gauging Stations. – Techniques of Water-Resources Investigations of the United States Geological Survey, Book 1, chapter 12; 36 p.

13. Guy, H.P.
1970: Fluvial Sediment Concepts. – Techniques of Water-Resources Investigations of the United States Geological Survey, Book 3, Chapter C1; 51 p.
14. Ezekiel, M. and Fox, K.A.
1966: Methods of Correlation and Regression Analysis. – John Wiley and Sons, Inc., New York; p. 254–278.
15. WMO/UNESCO
1974: International Glossary of Hydrology. – WMO Secretariat, Geneva; 393 p.
16. Langbein, W.B. and Iseri, K.T.
1960: General Introduction and Hydrologic Definitions. – U.S. Geol. Survey Water-Supply Paper 1541; 29 p.
17. Nelson, A. and Nelson, K.D.
1973: Dictionary of Water and Water Engineering. – Butterworth and Company Ltd., London; 271 p.
18. International Organization for Standardization (ISO)
1974: Measurement of flow in tidal channels. Ref. No. ISO 2425–1974 (E). – Geneva; 15 p.

APPENDIX A

GRAPHICAL CURVE FITTING

The simplest way of fitting a curve to plotted data points would be to draw a continuous and smooth median curve through the scatter of the points. Where the nature of the relation is indicated and the points are not too scattered, this might give a quite satisfactory result. In other cases, however, the points might be more widely scattered and the underlying relation might be more difficult to determine so that different persons drawing in the curve by free hand might draw rather different curves. Some method is therefore needed to ensure a greater degree of precision and stability to the result. This is obtained by determining average coordinates for groups of points. The general nature of the relation is then expressed by an irregular line connecting the several

group averages, and a continuous and smooth curve is derived from this irregular line.

The group averages are estimated graphically by first estimating two-point averages, that is, halfway between two and two of the plotted points. The four-point averages are halfway between each pair of the two-point averages, etc., (Figure 1.A). The points are grouped with respect to the independent variable. If upon inspection of the group averages (two-point, four-point, etc.) it is decided that the relation is curvilinear, then a curve can be fitted to the average points with the aid of drafting curves. If the curve is a straight line, this line must pass through the centre of gravity of all the points.

References [7], [14]

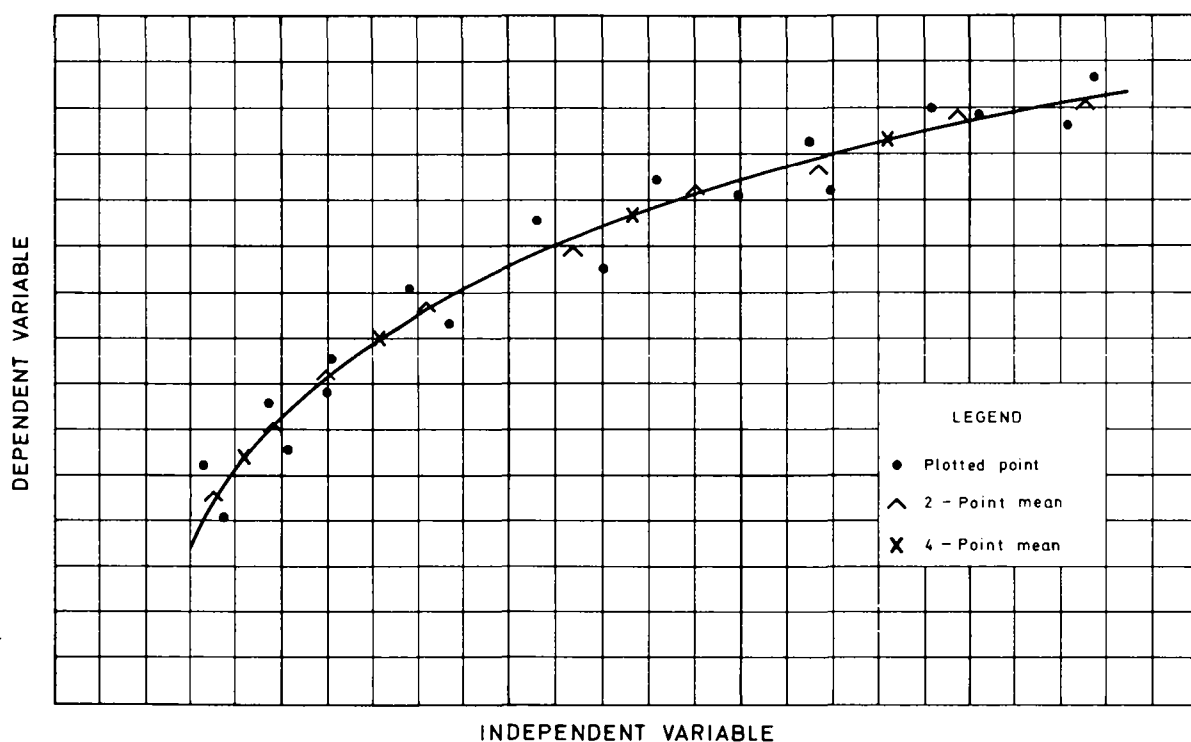


Figure A.1 Graphical determination of group means of points and curve fitted to the means

APPENDIX B

B. 1 ERROR OF OBSERVATION OF DISCHARGE MEASUREMENTS

A rating curve based on discharge measurements is developed by balancing it through a scatter-plot of measurements. If the measurements were made without error and if the station control remained absolutely constant, all points would fall on a smooth curve. Such ideal conditions are not attainable in practice and there will always be deviations from the curve.

In fact, it is well-known that measurements and observations of all kind are invariably subject to error of observation. The error of observation is generally composed of several independent errors associated with the operational procedure of making the observation and with the performance of the measuring equipment.

In a discharge measurement, errors may be associated more or less with all of the following operations: 1) Measurement of depth, 2) measurement of width, 3) number of verticals in the cross section, 4) number of points in the vertical, 5) time of each observation, 6) drift of instrument, 7) obliquity of current, 8) determination of the gauge height for the measurement, 9) sensitivity of the current meter, 10) the precision of the timer, and others. All these operations may be considered independent of each other and the associated errors may therefore be regarded as random variables. Consequently, it follows from the Central Limit Theorem that the resulting composite error, i.e. the error of observation, should be approximately normally distributed. (The Central Limit Theorem states that a sum of random variables tends to normal distribution as the number of variables increases).

Investigations confirm that the error of observation in discharge measurements is, in fact, normally distributed.

Therefore, a rating curve fitted to a plot of discharge measurements in a balanced way is likely to give the best estimate of discharges corresponding to observed stages, and the deviation from this curve by the measurements is a measure of the error of observation. Investigations show further that with a proper

measuring procedure it should be possible to keep the error of observation in the order of 3–5 percent of the measured discharge.

Regarding the distribution of the error of observation of discharge measurements, it is important not to forget the restriction on this kind of observations. That is, the error of observation is normally distributed around the mean for measurements made at one and the same gauge height only. The error of observation is not independent, that is, it depends on the magnitude of the discharge measured. It has been demonstrated that the absolute error of observation is proportional to the magnitude of the measured discharge over a range having the same station control.

There may also be systematic errors in a discharge measurement caused by faulty measuring instruments, or by human factors. Such errors can not be eliminated by repeated measurements, but only by checks against proven instruments by different observers. With today's current meters, the systematic error due to meter performance might not be expected to exceed one percent, if the meter is functioning properly.

B.2 RELIABILITY OF DISCHARGE RATING CURVES

B.2.1 The Standard Deviation of the Rating Curve

The Standard Deviation – also known as the mean square deviation from the mean, which actually explains how it is calculated – is a measure of the degree of scatter or dispersion of observed values around their arithmetic mean. It is one of the important statistical measures.

The basic assumptions for a valid estimation of the standard deviation (i.e. the standard deviation of the error of observation) are that the error of observation be 1) normally distributed, and 2) independent. The latter is achieved by a simple transformation: a percentage standard deviation is calculated between the differences (of the measured discharges and the corresponding discharges estimated by the rating curve) and the average

or mean difference, as illustrated in the following.

Thus,

$$P = \frac{Q_m - Q_r}{Q_r} 100\% \quad (B.1)$$

$$s_D = \sqrt{\frac{\Sigma(P - \bar{P})^2}{n - 1}} \quad (B.2)$$

where

- P = percentage deviation
- \bar{P} = mean percentage deviation
- Q_m = measured discharge
- Q_r = discharge estimated by rating curve
- s_D = percentage standard deviation
- n = number of discharge measurements

B.2.2 Required Number of Discharge Measurements for Establishing a Reliable Rating Curve

The required number of discharge measurements in order to obtain a reliable rating curve may be calculated from the formula

$$n > \left(\frac{2s_D}{E}\right)^2 \quad (B.3)$$

where

- n = number of required measurements
- s_D = standard deviation in percent ($2s_D$ is allowable width of scatter band)
- E = a specified precision expressed as a percentage, usually 5%

s_D is calculated separately according to Formulae (B.2) for each range of stage having a separate station control, and the test is applied separately to each range.

The following table indicates the variation in the required number of measurements with variation in width of scatter band, E being taken as 5%.

Width of scatter band $2s_D$ (%)	Minimum number of measurements, n
10%	6
15%	9
20%	16
25%	25
30%	36

It is recommended that n should never be less than 6 for any one interval of the range.

B.2.3 Acceptance Limits for the Discharge Measurements

The reliability of the estimated rating curve and of the deviations of the measured discharges from the rating curve may generally be assessed by the concept of the *Acceptance region for the observations*.

A pair of curves drawn one on each side of the rating curve and each at a distance of two standard deviations from the rating curve, are called control curves and define the 95% acceptance region. That is, 95 out of every hundred (or nineteen out of every twenty) measurements should be between the control curves. A single measurement lying far outside (say beyond three standard deviations) is most probably the result of faulty gauging equipment or of poor measuring practices.

However, in those cases where two or more consecutive points, either chronologically or over a range in stage, appear to be well on one side of a control curve, a change of the stage-discharge relation has probably occurred. This means that owing to shift in the station control, a new rating curve is required and the calibration of the station must be repeated.

B.2.4 Statistical Tests Applied to Rating Curves for Absence of Bias and Goodness of Fit

The following two criteria are commonly used to test a rating curve for *absence of bias*:

1. The average of the percentage differences between the measured discharges and the discharges estimated by means of the rating curve should not be significantly different from zero. This is tested by the *t-test*.
2. The number of positive and negative deviations of the measured discharges from the rating curve should be evenly distributed, i.e. the difference in number of

pluses and minuses should not be more than can be explained by chance fluctuations. This is tested by the *sign test*.

These two tests are only applicable for stations where the stage-discharge relation is permanent and not effected by variable backwater or highly unsteady flow conditions.

After the rating curve has been checked for absence of bias, it should next be checked for shifts in control. The errors due to shifting control would be of a systematic nature. The difference between Q_m and Q_r , the measured discharge and the estimated discharge by the rating curve, is checked for the same sign in long runs. This is tested by the *run of sign test*. The *goodness of fit* may also be checked by this test.

B.2.4.1 The Paired t-Test

A paired t-test of the differences between the discharges measured and the discharges estimated by the rating curve is used to check whether a rating curve, on an average, gives significant overestimates or underestimates as compared with the discharge measurements on which the curve is based. The mean difference in percent, \bar{P} , is tested against its standard error to see if it is significantly different from zero.

The assumptions underlying this test are that the percentage differences between the measured values and the values estimated by the curve are independent of the magnitude of the discharge and normally distributed around a mean value of zero.

In Table B.1 are tabulated 28 discharge measurements. The *test statistic t* has been calculated and is equal to 0.23.

Tables of the t-distribution giving values of *t* for different levels of significance are available, values of the calculated *t* exceeding these tabulated values would indicate bias (Table B.2).

The tabulated value of *t* at the 5 percent significance level and for a sample size of 28 is found to equal 2.052 (two-tailed test, $(n-1) = 27$ degrees of freedom).

Conclusion: Since the calculated value of *t* is less than 2.052, the rating curve is free of bias as judged by this method.

(Strictly speaking, this test would be more appropriate if the number of discharge measurements at the various ranges of discharge were in proportion to the probable occurrence of these discharges, covering the whole range of discharge for which the curve is estimated).

B.2.4.2 The Sign Test

The number of positive and negative deviations of the measurements from the estimated rating curve shall be evenly distributed. That is, the difference in number between the two shall not be more than can be explained by chance fluctuations.

The test is used to check if the curve has been drawn in a sufficiently balanced manner so that the two sets of discharge values, those measured and those estimated from the curve, may be reasonably supposed to represent the same population. This is a simple test and is performed by counting the observed points falling on either side of the curve. If Q_m is the measured value and Q_r the estimated value, then $(Q_m - Q_r)$ should have an equal chance of being positive or negative, that is, the probability of $(Q_m - Q_r)$ being positive is 0.5. Then, assuming the successive signs to be independent of each other, the sequence of the differences may be considered distributed according to the binomial law $(p+q)^n$ where *n* is the number of observations, and *p* and *q*, the probabilities of occurrence of positive and negative values, are 0.5 each.

The statistics for the sign test applied to the curve of Table B.1 are:

1. Total number of observations $n = 28$
2. Number of positive signs $n_1 = 15$
3. Probability of sign being positive $p=0.5$
4. Probability of sign being negative $q=0.5$
5. Expected number of positive signs $np=14$
6. Standard error of np $s_E = \sqrt{npq}$
7. Test criterion

$$t = \frac{|n_1 - np - 0.5^*|}{\sqrt{npq}} = 0.189$$

*) Continuity correction.

The tabulated value of t at the 5 percent significance level and for a sample size of 28 is equal to 2.052 (two-tailed test, $n = 28$ degrees of freedom). Table B.2.

Conclusion: Since the calculated value of t is less than the tabulated value, the rating curve is free of bias as judged by this method.

B.2.4.3 The run of Sign Test

This test is based on the number of changes of sign in the series of deviations of measured discharges from the established rating curve. It is carried out by detecting the presence of possible abnormally long runs of positive or negative deviations.

From Table B.1 write down the signs of deviations in chronological order.

Starting from the second number of the series, we write under each a "0" if the sign is the same or "1" if the sign is not the same as the immediate preceding sign. If there are n deviations in the original series, there will be $(n-1)$ numbers in the derived series, thus:

-+++--+--+---++---+-----++++-+
 10011110101010101000100011

Assuming the deviations can be regarded as arising from random fluctuations about the estimated values from the curve, the probability for a change in sign may be taken to be 0.5. If n is fairly large, say 25 or more, this will be a reasonable assumption and the derived series may be assumed to follow the

binomial distribution. The test is carried out as follows:

1. Number of deviations $n = 27$
2. Number of changes in sign $n_1 = 13$
3. Probability of change in sign $p = 0.5$
4. Probability of no change in sign $q = 0.5$
5. Expected number of changes in sign $(n-1)p = 13$
6. Standard error of $(n-1)p$ $s_E = \sqrt{(n-1)pq}$
7. Test criterion

$$t = \frac{|n_1 - (n-1)p - 0.5|}{\sqrt{(n-1)pq}} = 1.96$$

The tabulated value of t at the 5 percent significance level and for a sample size of 27 is equal to 2.056 (two-tailed test, $(n-1) = 26$ degrees of freedom). Table B.2.

Conclusion: As the calculated value of t is less than the tabulated value, the assumption of random fluctuations has not been disproved.

The test shows that there is no systematic trend in the deviations with time, indicating that the curve as drawn does not need any adjustment for shift in control.

This test may also be used to test for goodness of fit. In this case the discharge measurements will have to be arranged in an ascending order.

References [8], [10]

Table B.1. Statistics for the paired t-test

No.	Measurements		Rating Q_r	Percentage deviation, P				$(P-\bar{P})^2$
	H	Q_m		P		$P-\bar{P}$		
				+	-	+	-	
1	1.55	300	303	-	0.99	-	1.13	1.28
2	1.44	287	274	4.74	-	4.60	-	21.16
3	1.26	235	231	1.73	-	1.59	-	2.53
4	1.05	193	185	4.32	-	4.18	-	17.47
5	0.73	125	125	-	-	-	0.14	0.10
6	0.69	113	118	-	4.24	-	4.38	18.49
7	0.70	124	120	3.33	-	3.19	-	10.18
8	1.70	340	344	-	1.16	-	1.30	1.69
9	0.96	169	166	1.81	-	1.67	-	2.79
10	0.94	168	162	3.70	-	3.56	-	12.67
11	1.35	240	252	-	4.76	-	4.90	24.01
12	1.17	202	211	-	4.27	-	4.41	19.45
13	1.79	387	372	4.03	-	3.89	-	15.13
14	3.09	930	916	1.53	-	1.39	-	1.93
15	3.87	1374	1395	-	1.51	-	1.65	2.72
16	2.33	540	558	-	3.23	-	3.37	12.74
17	3.49	1152	1135	1.50	-	1.36	-	1.85
18	3.93	1452	1430	1.54	-	1.40	-	1.96
19	2.03	440	452	-	2.65	-	2.79	7.78
20	1.61	306	319	-	4.08	-	4.22	19.54
21	2.13	469	488	-	3.89	-	4.03	16.24
22	1.37	246	257	-	4.28	-	4.42	19.54
23	1.05	189	185	2.16	-	2.02	-	4.08
24	0.91	163	156	4.49	-	4.35	-	18.92
25	0.79	139	135	2.96	-	2.82	-	7.95
26	0.68	120	117	2.56	-	2.42	-	5.86
27	0.61	104	106	-	1.89	-	2.03	4.12
28	0.53	94.6	95.2	0.60	-	0.46	-	0.21
			Sum	41.00	36.95	38.90	38.77	272.39

$$\text{Percentage deviation, } P = \frac{Q_m - Q_r}{Q_r} \cdot 100$$

$$\text{Mean deviation, } \bar{P} = \frac{P_1 + P_2 + \dots + P_n}{n} = \frac{41.00 - 36.95}{28} = 0.14\%$$

$$\text{Standard deviation of } \bar{P}, s_D = \left(\frac{\sum (P - \bar{P})^2}{n - 1} \right)^{1/2} = \left(\frac{272.39}{27} \right)^{1/2} = 3.17\%$$

$$\text{Standard error of } \bar{P}, s_E = \frac{s_D}{n^{1/2}} = \frac{3.17}{28^{1/2}} = 0.60\%$$

$$\text{Test statistic, } t = \frac{\bar{P}}{s_E} = \frac{0.14}{0.60} = 0.23$$

Table B.2

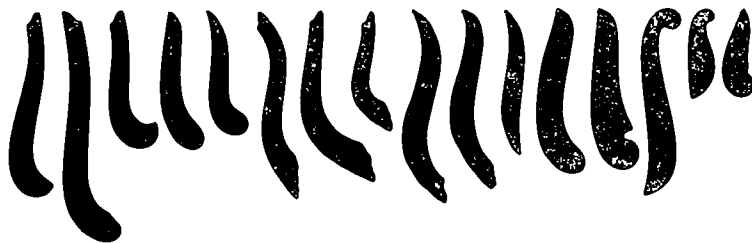
Table of the *t* distribution

Probability of a larger value of <i>t</i> , sign ignored (two-tail test)												
d.f.	.9	.8	.7	.6	.5	.4	.3	.2	.1	.05	.02	.01
1	.158	.325	.510	.757	1.000	1.376	1.963	3.078	6.314	12.706	31.821	63.657
2	.142	.289	.445	.617	.816	1.061	1.386	1.886	2.920	4.303	6.965	9.925
3	.137	.277	.424	.584	.765	.978	1.250	1.638	2.353	3.182	4.541	5.841
4	.134	.271	.414	.569	.741	.941	1.190	1.533	2.132	2.776	3.747	4.604
5	.132	.267	.408	.559	.727	.920	1.156	1.476	2.015	2.571	3.365	4.032
6	.131	.265	.404	.553	.718	.906	1.134	1.440	1.943	2.447	3.143	3.707
7	.130	.263	.402	.549	.711	.896	1.119	1.415	1.895	2.365	2.998	3.499
8	.130	.262	.399	.546	.706	.889	1.108	1.397	1.860	2.306	2.896	3.355
9	.129	.261	.398	.543	.703	.883	1.100	1.383	1.833	2.262	2.821	3.250
10	.129	.260	.397	.542	.700	.879	1.093	1.372	1.812	2.228	2.764	3.169
11	.129	.260	.396	.540	.697	.876	1.088	1.363	1.796	2.201	2.718	3.106
12	.128	.259	.395	.539	.695	.873	1.083	1.356	1.782	2.179	2.681	3.055
13	.128	.259	.394	.538	.694	.870	1.079	1.350	1.771	2.160	2.650	3.012
14	.128	.258	.393	.537	.692	.868	1.076	1.345	1.761	2.145	2.624	2.977
15	.128	.258	.393	.536	.691	.866	1.074	1.341	1.753	2.131	2.602	2.947
16	.128	.258	.392	.535	.690	.865	1.071	1.337	1.746	2.120	2.583	2.921
17	.128	.257	.392	.534	.689	.863	1.069	1.333	1.740	2.110	2.567	2.898
18	.127	.257	.392	.534	.688	.862	1.067	1.330	1.734	2.101	2.552	2.878
19	.127	.257	.391	.533	.688	.861	1.066	1.328	1.729	2.093	2.539	2.861
20	.127	.257	.391	.533	.687	.860	1.064	1.325	1.725	2.086	2.528	2.845
21	.127	.257	.391	.532	.686	.859	1.063	1.323	1.721	2.080	2.518	2.831
22	.127	.256	.390	.532	.686	.858	1.061	1.321	1.717	2.074	2.508	2.819
23	.127	.256	.390	.532	.685	.858	1.060	1.319	1.714	2.069	2.500	2.807
24	.127	.256	.390	.531	.685	.857	1.059	1.318	1.711	2.064	2.492	2.797
25	.127	.256	.390	.531	.684	.856	1.058	1.316	1.708	2.060	2.485	2.787
26	.127	.256	.390	.531	.684	.856	1.058	1.315	1.706	2.056	2.479	2.779
27	.127	.256	.389	.531	.684	.855	1.057	1.314	1.703	2.052	2.473	2.771
28	.127	.256	.389	.530	.683	.855	1.056	1.313	1.701	2.048	2.467	2.763
29	.127	.256	.389	.530	.683	.854	1.055	1.311	1.699	2.045	2.462	2.756
30	.127	.256	.389	.530	.683	.854	1.055	1.310	1.697	2.042	2.457	2.750
∞	.12566	.25335	.38532	.52440	.67449	.84162	1.03643	1.28155	1.64485	1.95996	2.32634	2.57582
d.f.	.45	.40	.35	.3	.25	.2	.15	.1	.05	.025	0.01	.005
Probability of a larger value of <i>t</i> , sign considered (one -tail test)												

APPENDIX C

SHIP DRAFTING CURVES

Approx. Scale 1:7



APPENDIX D

VOCABULARY

ALLUVIUM. A fine-grained deposit, composed mainly of mud and silt, deposited by a river.

ALLUVIAL RIVER. A river which flows in a channel, carved in its own deposits of alluvium.

BACKWATER. Water backed up or retarded in its course as compared with its normal or natural conditions.

BANK. The margins of a channel. Banks are called right or left as viewed facing in the direction of the flow.

BANKFUL STAGE. Stage at which a stream just overflows its natural banks.

BIASED ESTIMATE. A positive bias gives estimates that are on the whole too high, a negative bias, too low.

BOIL. A vertical eddy developed in a river during a flood. It produces an upthrow of water to the surface, causing it to "boil".

CALIBRATION. See RATING.

CELERITY (WAVE VELOCITY). Speed of propagation of a wave relative to the moving or still water surface.

CHANNEL. A natural, or artificial, clearly distinguished, water-way which periodically or continuously contains moving water, or which forms a connecting link between two bodies of water.

CHANNEL CONVEYANCE. The water carrying capacity of a channel reach.

CHANNEL ROUGHNESS. The unevenness, irregularity, or texture of the channel surface in contact with the flowing water.

CHANNEL STORAGE. The volume of water that can be stored in a channel by increasing the water-level.

CHEZY FORMULA. An empirical formula expressing the relation between mean velocity of flow V , hydraulic mean depth R , hydraulic gradient or slope S , and roughness coefficient C . Thus,

$$V = C \sqrt{RS}$$

CONFLUENCE. The joining, or the place of junction, of two or more streams.

CONTROL. The morphologic features of the open channel (or of a section in the open channel) which determine the stage of the river at a given point for a certain discharge.

CRITICAL FLOW. The flow in which the total energy head is a minimum for a given discharge, under this condition the effect of changes in downstream water-surface elevation can not be transmitted upstream.

CROSS-SECTION. A section of the stream at right angles to the main direction of flow.

CURRENT. General term to designate the movement of water.

DEBRIS. Any accumulation of loose material arising from the wasting away of rocks.

DISCHARGE. The volume of fluid, e.g. water, flowing through a cross-section in a unit of time.

DISCHARGE MEASUREMENT. The operation of measuring the discharge of water in an open channel.

DISCHARGE RATING CURVE. A curve showing the relation between the gauge height, plotted as ordinate and the amount of water flowing in a channel expressed as volume per second (m^3/sec), plotted as abscissa.

DOWNSTREAM. In the direction of the flow.

EDDY. A small whirlpool moving in a circular direction in flowing water; caused by irregularities or obstructions in the bed and banks of the stream.

ENERGY GRADIENT (ENERGY SLOPE). The gradient or slope of the energy line.

ENERGY HEAD (total). The sum of the elevation of the free surface above the horizontal datum of a section, and the velocity head based on the mean velocity at the section.

ENERGY LINE. A line joining elevations of energy heads of an open conduit.

FALL. The difference of the water-levels at two points on a stream.

FALLING LIMB. The part of the hydrograph in which the discharge is decreasing.

FALLING STAGE. The water-level of a stream which drops continuously during a certain period.

FLOOD. (See also **HIGH WATER**)

- a) A rapid rise in the water-level in a stream to a peak from which the water level recedes at a slower rate.
- b) A relative high flow as measured by stage or discharge.

FLOOD PLAIN. Land adjoining the open channel which is inundated only during floods.

FLOOD WAVE. A distinct rise in stage culminating in a crest and followed by recession to lower stages.

GAUGE. The device installed at the gauging station for measuring the level of the surface of the water relative to a datum.

GAUGE DATUM. The zero of the gauge to which the level of the water surface is related. The elevation of the zero of the gauge is normally related to a datum or bench mark.

GAUGE HEIGHT. The water surface elevation referred to some arbitrary gauge datum. Gauge height is often used interchangeably with the more general term stage although gauge height is more appropriate when used with a reading on a gauge.

GAUGING STATION. A selected site on an open channel for making systematic observations for the purpose of determining the discharge and/or water level.

HYDRAULIC RADIUS (HYDRAULIC MEAN DEPTH). The value obtained by dividing the cross-sectional area of a stream by the wetted perimeter.

HYDROGRAPH. Graph showing stage, discharge, velocity or some other characteristics of the water flow relative to time.

INFLOW. Water flowing into the reach of a stream, into a lake or a reservoir.

LOOP OF THE RATING CURVE. The double-valued part of the rating curve, in which the highest values of the discharge apply when the river is rising and the lower values when the river is falling.

LOW WATER. The low water levels reached during minimum stream flow conditions.

MEAN VELOCITY AT A CROSS-SECTION. The velocity at a given cross-section of a stream obtained by dividing the discharge by the cross-sectional area of the stream at that section.

MEASURING SECTION. The section in which discharge measurements are taken.

MEDIAN. The central value in a series of ranked values.

MODEL ANALYSIS. The study of scale models of hydraulic structures, the measurement of the heads and discharges of water, and finally the interpretation of the results to predict the characteristics of the full-size or actual structures. Model analyses is used for dam spillways, river improvement works, harbours, and so on.

NATURAL CONTROL. A section or a reach of a stream channel where natural conditions exist that make the water level above it a stable index of the discharge.

OPEN CHANNEL. The longitudinal boundary surface consisting of the bed and banks or sides within which the water flows with a free surface.

OVERFLOW. The excess water which overflows the ordinary limits.

POINT OF ZERO FLOW. The gauge height at which water ceases to flow over the control.

PONDING. The natural formation of a pond in a watercourse.

POOL. A deep reach of a stream. The reach of a stream between two riffles. Natural streams often consists of a succession of pools and riffles.

PROTOTYPE. An original on which a thing is modelled.

RANGE. The difference between the largest and the smallest values of a variate.

RAPIDS. A stretch of a stream where the flow is very swift and shooting and where the surface is usually broken by obstructions, but has no actual waterfall or cascade.

RATING. In general, the relationship between two mutually dependent quantities. In hydraulics, e.g. the relationship between the water level and the discharge of stream or channel, or between current meter revolutions and water velocity.

RATING CURVE. See DISCHARGE RATING CURVE

REACH. A length of open channel between two defined cross-sections.

RECORDS. A tabulation of observed hydrological characteristics, e.g. stages or discharges at a given site on a stream.

REGIMEN (of a stream). The habits of a stream with respect to velocity and volume, form of and changes in channel, capacity to transport sediment, and amount of material supplied for transportation.

RIVER (see also STREAM, WATERCOURSE)
A large stream which serves as the natural drainage channel for a drainage basin.

RIVER BED. The lowest part of a river valley shaped by the flow of water and along which most of the sediment and runoff moves.

RIVER STAGE. The height of the water surface related to a fixed datum.

RIPPLES (BED RIPPLES). Small, undulating ridges and furrows or crests and troughs on water, or formed by the action of the flow of water on the bed of a channel.

RISING LIMB. The part of the hydrograph in which the discharge is increasing.

RISING STAGE. A water stage in a stream which increases continuously during a certain period.

SCOUR. The erosive action particularly pronounced local erosion, of water in streams, in excavating and carrying away materials from the bed and banks.

SEDIMENT. Fragmental material transported by water from the place of origin to the place of deposition. In watercourses sediment is the alluvial material carried in suspension or as bed-load.

SHIFTING BED. A bed whose topography changes with time.

SHIFTING CONTROL (UNSTABLE CONTROL). The change in the course of time of the stage-discharge relationship at a control section in a stream, resulting from physical changes in the stream.

SINUOSITY. The meanders and loops in the course of a river flowing over relatively flat valley areas.

SITE OF A STATION. Location of a station from the point of view of geography, orientation and position of shelter and various instruments.

SLOPE (of water surface). Inclination of the water surface expressed as the difference in elevation of two points divided by their horizontal distance.

STABLE CHANNEL. Channel in which the bed and the sides remain reasonably stable over a substantial period of time in the control reach, and in which scour and deposition during the rising and falling floods is inappreciable.

STAFF GAUGE. A graduated scale used to indicate the height of the water surface in a stream channel.

STAGE. See RIVER STAGE.

STAGE-DISCHARGE RELATION. Relation between stage and discharge of a stream at a given site.

STANDARD DEVIATION. A measure of dispersion of a frequency distribution equal to the square root of the mean squared deviation of n individual measurements of a variate x from their mean, $s = \sqrt{\Sigma(x-\bar{x})^2/(n-1)}$

STEADY FLOW. Flow in which the mean velocity vector at any point remains constant with respect to time.

STREAM. A body of water flowing in a natural open channel.

STREAM GAUGING. The operation of measuring the velocity and area in a cross-section of a stream for the purpose of determining the discharge.

STREAM GAUGING STATION. A gauging station where a record of discharge of a stream is obtained.

TIDAL RIVERS. A river whose flow and water surface elevation is affected by the tides.

TREND. A statistical term referring to the direction or rate of change in magnitude in the average value of a hydrological variable.

UNIFORM FLOW. A flow of water which is steady and continuous and the streamlines more or less parallel at all points.

UNSTABLE CHANNEL. Channel in which there is frequent and significant changing control.

UNSTABLE CONTROL. See **SHIFTING CONTROL.**

UNSTEADY FLOW. Flow in which the velocity changes in magnitude or direction with respect to time.

UPSTREAM. In the direction opposite to the main current.

VARIATE. An individual observation.

VELOCITY. Rate of movement past a point in a specified direction.

VELOCITY HEAD. The head obtained by dividing the square of the velocity by twice the acceleration of free fall.

VELOCITY OF APPROACH. The mean velocity in an open channel at a specified distance upstream from a measuring device.

WATERCOURSE. A natural or artificial channel through which water flows either continuously or intermittently.

WATER LEVEL (see also **STAGE**). The elevation of the free watersurface of a body of water relative to a datum level.

WETTED PERIMETER. The length of the wetted contact between a stream of flowing water and its containing channel, measured in a direction normal to flow.

References [15], [16], [17]