HYDROLOGY PROJECT

Technical Assistance

World Bank & Government of The Netherlands funded

Training module # SWDP - 29

How to establish stage discharge rating curve

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with
HALCROW, TAHAL, CES, ORG & JPS

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1. Module context

While designing a training course, the relationship between this module and the others, would be maintained by keeping them close together in the syllabus and place them in a logical sequence. The actual selection of the topics and the depth of training would, of course, depend on the training needs of the participants, i.e. their knowledge level and skills performance upon the start of the course.

2. Module profile

Title	:	How to establish stage discharge rating curve
Target group	:	
Duration	:	x session of y min
Objectives	:	After the training the participants will be able to*:*
Key concepts	:	•
Training methods	:	Lecture, exercises
Training tools required	:	Board, flipchart
Handouts	:	As provided in this module
Further reading and references	:	

3. Session plan

No	Activities	Time	Tools
1	***General***	10 min	
	Overhead: Text: Establishing stage-discharge relation (1)		OHS 1
	Overhead: Text: Establishing stage-discharge relation (2)		OHS 2
	Overhead: Figure 1.1: Example rating curve		OHS 3
	Overhead: Table 1.1 : Example rating curve computation output		OHS 4
2	***The station control***	15 min	
	Overhead: Text: The station control		OHS 5
	Overhead: Text: Types of station controls		OHS 6
	Overhead: Figure 2.1: Control configuration in natural channel		OHS 7
	Overhead: Figure 2.2: Section control		OHS 8
	Overhead: Figure 2.3: Channel control (1)		OHS 9
	Overhead: Figure: Backwater effect		OHS 10
	Overhead: Text: Channel control (2)		OHS 11
	Overhead: Figure 2.4: Artificial control		OHS 12
	Overhead: Text: Shifting controls		OHS 13
3	***Fitting of rating curve***	120	
3.1	**General**	min	
	Overhead: Text: Fitting rating curves (1)		OHS 14
	Overhead: Text: Fitting rating curves (2)		OHS 15
	Overhead: Figure 3.1: Permanent control		OHS 16
	Overhead: Figure 3.2a: Variable backwater (1)		OHS 17
	Overhead: Figure 3.2b: Variable backwater (2)		OHS 18
	Overhead: Figure 3.3: Unsteady flow		OHS 19
	Overhead: Figure 3.4: River bed changes		OHS 20
	Overhead: Figure 3.5: Effect of vegetation		OHS 21
	Overhead: Text: Fitting rating curves (3)		OHS 22
3.2	**Fitting of single channel rating curve**	120	
	Overhead: Text: Fitting single channel simple rating curve (1)	min	OHS 23
	Overhead: Text: Fitting single channel simple rating curve (2)		OHS 24
	Overhead: Text: Fitting single channel simple rating curve (3)		OHS 25
	Overhead: Text: Fitting single channel simple rating curve (4)		OHS 26
	Overhead: Text: Fitting single channel simple rating curve (5)		OHS 27
	Overhead: Figure 3.7 Trial and error procedure for a		OHS 28
	Overhead: Text: Arithmetic procedure to determine a		OHS 29
	Overhead: Text: Rating curve segments (1)		OHS 30
	Overhead: Figure: Rating curve segments (2)		OHS 31
	Overhead: Figure 3.6: Double logarithmic rating curve plot		OHS 32
	Overhead: Text: Determination of rating curve coefficients (1)		OHS 33
	Overhead: Text: Determination of rating curve coefficients (2)		OHS 34
	Overhead: Text: Determination of rating curve coefficients (3)		OHS 35
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	Overhead: Text: Determination of rating curve coefficients (5)		OHS 37
	Overhead: Text: Determination of rating curve coefficients (6)		OHS 38
	Overhead: Figure 3.8: Example discharge rating curve Khed		OHS 39
	Overhead: Table 3.1: Example output discharge rating Khed		OHS 40

No	Activities	Time	Tools
	Overhead: Text: Standard error of estimate in stage-discharge relation Overhead: Text: Uncertainty in rating curve fit Overhead: Text: Confidence limits of rating curve Overhead: Text: Fitting of rating curve in HYMOS **Exercise:** Develop rating curves for: Chaskman and Khed for 1997 Rakshewa, Khamgaon and Pargaon (Bhima) for 1997 and Continue with Dakor (Sabarmati) for 1991-97		OHS 41 OHS 42' OHS 43 OHS 44
3.3	**<u>Compound channel rating curve</u>** Overhead: Figure: Compound channel rating curve (1) Overhead: Figure 3.10 Compound channel rating curve (2) Overhead: Text: Compound channel rating curve (3) Overhead: Text: Compound channel rating curve (4) Overhead: Figure 3.11: Example rating curve compound channel	60 min	 OHS 45 OHS 46 OHS 47 OHS 48 OHS 49
3.4	**<u>Rating curve with backwater correction</u>** Overhead: Text: Rating curve with backwater correction Overhead: Figure: Backwater effect Overhead: Text: Channel control Overhead: Text: Backwater Overhead: Text: Backwater correction (1) Overhead: Text: Backwater correction (2) Overhead: Text: Constant fall method Overhead: Figure 3.12: Constant fall method Overhead: Figure 3.13: Constant fall rating Overhead: Constant fall computational procedure Overhead: Normal fall method for backwater correction (1) Overhead: Figure 3.14: Normal fall method for backwater correction (2) Overhead: Figure 3.15: Normal fall method for backwater correction (3) Overhead: Figure 3.16: Normal fall method for backwater correction (4) Overhead: Normal fall method for backwater correction (5) Overhead: Normal fall method for backwater correction (6)	60 min	 OHS 50 OHS 51 OHS 52 OHS 53 OHS 54 OHS 55 OHS 56 OHS 57 OHS 58 OHS 59 OHS 60 OHS 61 OHS 62 OHS 63 OHS 64 OHS 65
3.5	**<u>Rating curve with unsteady flow correction</u>** Overhead: Rating curve with unsteady flow correction (1) Overhead: Rating curve with unsteady flow correction (2) Overhead: Rating curve with unsteady flow correction (3) Overhead: Figure 3.15a: Example unsteady flow correction (1) Overhead: Figure 3.15b: Example unsteady flow correction (1) Overhead: Figure 3.15c: Example unsteady flow correction (1) Overhead: Figure 3.15d: Example unsteady flow correction (1) Overhead: Figure 3.15e: Example unsteady flow correction (1) **Exercise:** Apply manually the unsteady flow correction for station Mahemdabad by:	60 min	 OHS 66 OHS 67 OHS 68 OHS 69 OHS 70 OHS 71 OHS 72 OHS 73

No	Activities	Time	Tools
	– assessing the river bed slope from the hydrographs at NSB00I7 and Mahemdabad relative to MSL. – estimating the celerity based on Manning's equation. – determining the rise or fall rate from time derivative of the hydrograph for stages > 28m + MSL		
3.6	**<u>Rating relationships for stations affected by shifting control</u>** Overhead: Text: Shifting control (1) Overhead: Figure 3.16: Shifting control (2), bed configurations Overhead: Figure 3.17: Shifting control (3), indeterminate Q-h Overhead: Figure 3.18: Shifting control (4), alternative: u-R plot Overhead: Text: Shifting control (5), approaches Overhead: Text: Shifting control (6), simple ratings between events Overhead: Text: Shifting control (7), varying shift parameter Overhead: Text: Shifting control (8), Stout’s method (1) Overhead: Figure 3.19: Shifting control (9), Stout’s method (2) Overhead: Text: Shifting control (1), Stout’s method (3) Overhead: Text: Shifting control (1), daily gauging		 OHS 74 OHS 75 OHS 76 OHS 77 OHS 78 OHS 79 OHS 80 OHS 81 OHS 82 OHS 83 OHS 84

4. Overhead/flipchart master

5. Handout

Add copy of Main text in chapter 8, for all participants.

6. Additional handout

These handouts are distributed during delivery and contain test questions, answers to questions, special worksheets, optional information, and other matters you would not like to be seen in the regular handouts.

It is a good practice to pre-punch these additional handouts, so the participants can easily insert them in the main handout folder.

7. Main text

Contents

How to establish stage discharge rating curve

1. General

- **Flow is the variable usually required for hydrological analysis but, continuous measurement of flow past a river section is usually impractical or prohibitively expensive. However, stage can be observed continuously or at regular short time intervals with comparative ease and economy. Fortunately, a relation exists between stage and the corresponding discharge at river section. This relation is termed a stage-discharge relationship or stage-discharge rating curve or simply, rating curve**.

- **A rating curve is established by making a number of concurrent observations of stage and discharge over a period of time covering the expected range of stages at the river gauging section**.

- **At many locations, the discharge is not a unique function of stage**; variables such as surface slope or rate of change of stage with respect to time must also be
- known to obtain the complete relationship in such circumstances.

- **The rating relationship thus established is used to transform the observed stages into the corresponding discharges**. In its simplest form, a rating curve can be illustrated graphically, as shown in Figure 1.1, by the average curve fitting the scatter plot between water level (as ordinate) and discharge (as abscissa) at any river section.

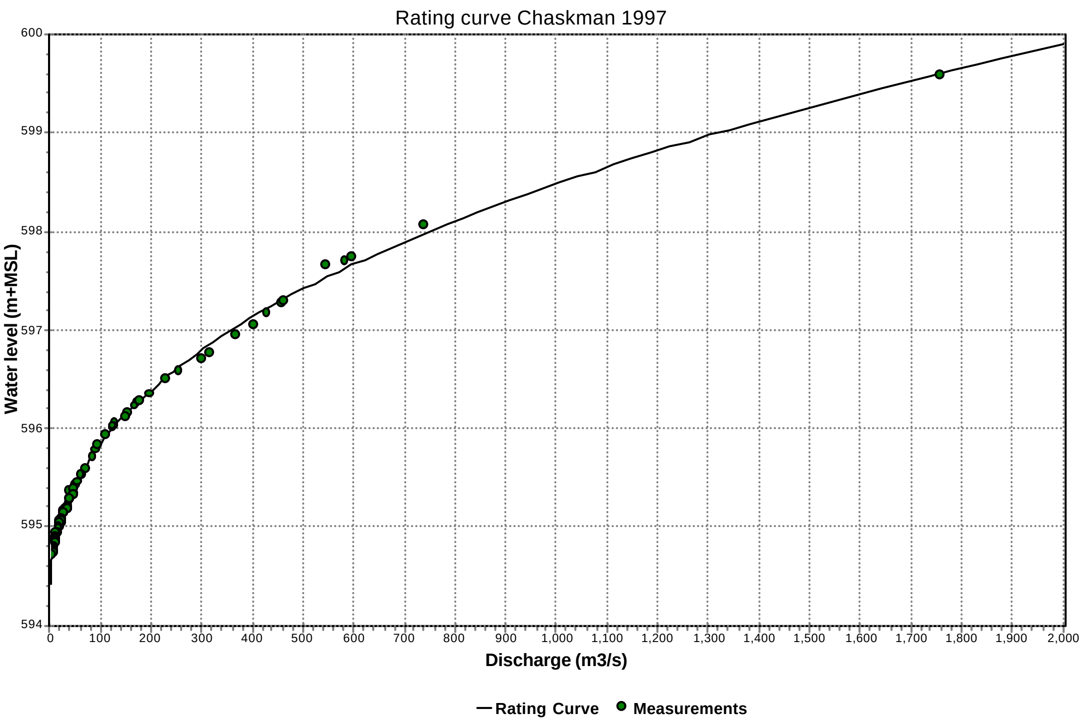

Figure 1.1 Example of stage-discharge rating curve

- If Q and h are discharge and water level, then the relationship can be analytically expressed as:

  $$Q = f(h) \qquad (1)$$

  Where; *f(h)* is an algebraic function of water level. A graphical stage discharge curve helps in visualising the relationship and to transform stages manually to discharges whereas an algebraic relationship can be advantageously used for analytical transformation.

- **Because it is difficult to measure flow at very high and low stages due to their infrequent occurrence and also to the inherent difficulty of such measurements, extrapolation is required to cover the full range of flows.** Methods of extrapolation are described in a later module.

2. The station control

- **The shape, reliability and stability of the stage-discharge relation are controlled by a section or reach of channel at or downstream from the gauging station and known as the station control**. The establishment and interpretation of stage discharge relationships requires an understanding of the nature of controls and the types of control at a particular station.

- **Fitting of stage discharge relationships must not be considered simply a mathematical exercise in curve fitting**. Staff involved in fitting stage discharge relationships should have familiarity with and experience of field hydrometrics.

The channel characteristics forming the control include the cross-sectional area and shape of the stream channel, expansions and restrictions in the channel, channel sinuosity, the stability and roughness of the streambed, and the vegetation cover all of which collectively constitute the factors determining the channel conveyance.

2.1 Types of station control

The character of the rating curve depends on the type of control which in turn is governed by the geometry of the cross section and by the physical features of the river downstream of the section. Station controls are classified in a number of ways as:

- section and channel controls
- natural and artificial controls
- complete, compound and partial controls
- permanent and shifting controls

2.1.1 Section and channel controls

When the control is such that any change in the physical characteristics of the channel downstream to it has no effect on the flow at the gauging section itself then such control is termed as section control. In other words, any disturbance downstream the control will not be able to pass the control in the upstream direction. Natural or artificial local narrowing of the cross-section (waterfalls, rock bar, gravel bar) creating a zone of acceleration are some examples of section controls (Figs. 2.1 and 2.2). The section control necessarily has a critical flow section at a short distance downstream.

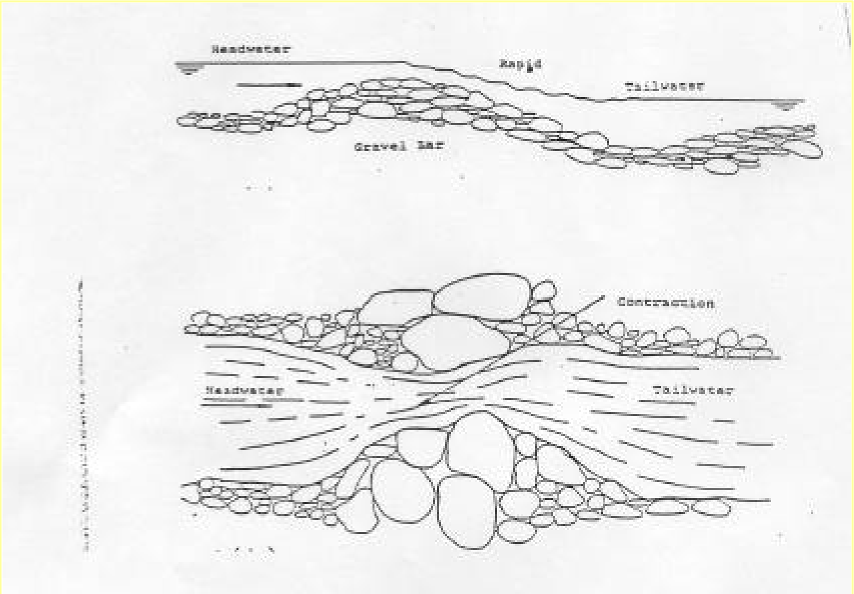

Figure 2.1 Example of section control

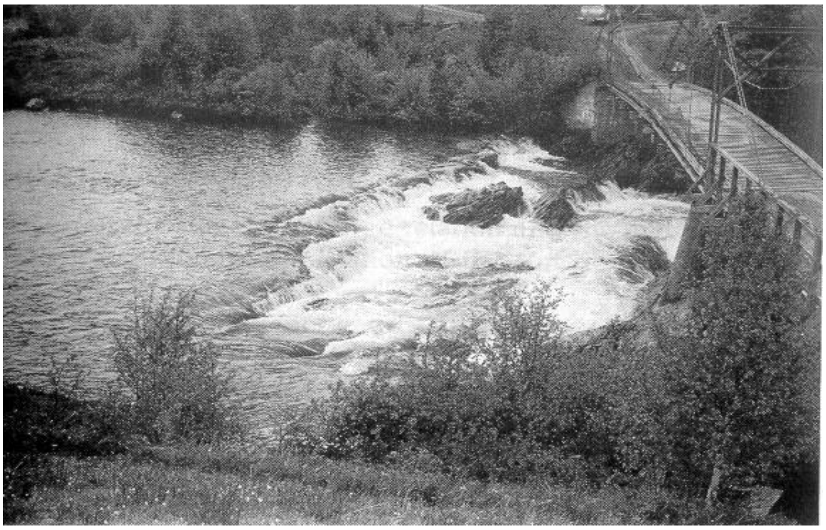

Figure 2.2 Example of section control. (low-water part is sensitive, while high-water part is non-sensitive)

A cross section where no acceleration of flow occurs or where the acceleration is not sufficient enough to prevent passage of disturbances from the downstream to the upstream direction then such a location is called as a channel control. The rating curve in such case depends upon the geometry and the roughness of the river downstream of the control (Fig. 2.3). The length of the downstream reach of the river affecting the rating curve depends on the normal or equilibrium depth h_e and on the energy slope S ($L \propto h_e/S$, where h_e follows from Manning $Q=K_mBh_e^{5/3}S^{1/2}$ (wide rectangular channel) so $h_e = (Q/K_mS^{1/2})^{3/5}$). The length of channel effective as a control increases with discharge. Generally, the flatter the stream gradient, the longer the reach of channel control.

Figure 2.3 Example of channel control

2.1.2 Artificial and natural controls

An artificial section control or structure control is one which has been specifically constructed to stabilise the relationship between stage and discharge and for which a theoretical relationship is available based on physical modelling. These include weirs and flumes, discharging under free flow conditions (Fig. 5). Natural section controls include a ledge of rock across a channel, the brink of a waterfall, or a local constriction in width (including bridge openings). All channel controls are 'natural'.

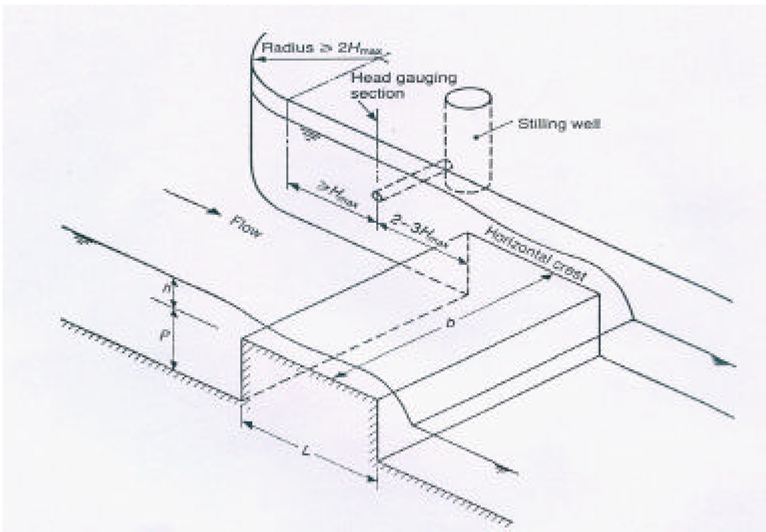

Figure 2.4 Example of an artificial control

2.1.3 Complete, compound and partial controls

Natural controls vary widely in geometry and stability. Some consist of a single topographical feature such as a rock ledge across the channel at the crest of a rapid or waterfall so forming a complete control. Such a complete control is one which governs the stage-discharge relation throughout the entire range of stage experienced. However, in many cases, station controls are a combination of section control at low stages and a channel control at high stages and are thus called compound or complex controls. A partial control cases, station controls are a combination of section control at low stages and a is one which operates over a limited range of stage when a compound control is present, in the transition between section and channel control. The section control begins to drown out with rising tailwater levels so that over a transitional range of stage the flow is dependent both on the elevation and shape of the control and on the tailwater level.

2.1.4 Permanent and shifting controls

Where the geometry of a section and the resulting stage-discharge relationship does not change with time, it is described as a stable or permanent control. Shifting controls change with time and may be section controls such as boulder, gravel or sand riffles which undergo periodic or near continuous scour and deposition, or they may be channel controls with erodible bed and banks. **Shifting controls thus typically result from**:

- scour and fill in an unstable channel
- growth and decay of aquatic weeds
- overspilling and ponding in areas adjoining the stream channel.

The amount of gauging effort and maintenance cost to obtain a record of adequate quality is much greater for shifting controls than for permanent controls. Since rating curves for the unstable controls must be updated and/or validated at frequent intervals, regular and frequent current meter measurements are required. In contrast, for stable controls, the rating curve can be established once and needs validation only occasionally. Since stage discharge observations require significant effort and money, it is always preferred to select a gauging site with a section or structure control. However, this is not practicable in many cases and one has to be content with either channel control or a compound control.

3. Fitting of rating curves

3.1 General

A simple stage discharge relation is one where discharge depends upon stage only. A complex rating curve occurs where additional variables such as the slope of the energy line or the rate of change of stage with respect to time are required to define the relationship. The need for a particular type of rating curve can be ascertained by first plotting the observed stage and discharge data on a simple orthogonal plot. The scatter in the plot gives a fairly good assessment of the type of stage-discharge relationship required for the cross section. Examples of the scatter plots obtained for various conditions are illustrated below.

If there is negligible scatter in the plotted points and it is possible to draw a smooth single valued curve through the plotted points then a simple rating curve is required. This is shown in Fig. 3.1.

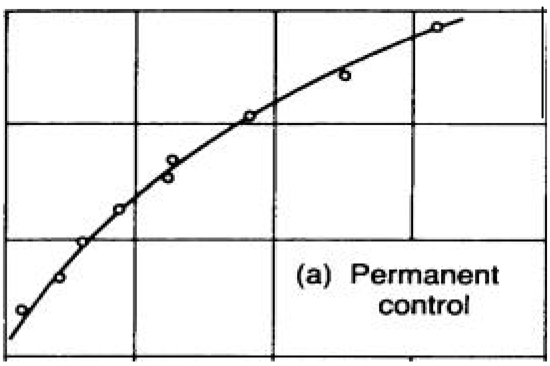

Figure 3.1 Permanent control

However, if scatter is not negligible then it requires further probing to determine the cause of such higher scatter. There are four distinct possibilities:

- **The station is affected by the variable backwater conditions** arising due for example to tidal influences or to high flows in a tributary joining downstream. In such cases, if the plotted points are annotated with the corresponding slope of energy line (≈surface slope for uniform flows) then a definite pattern can be observed. A smooth curve passing through those points having normal slopes at various depths is drawn first. It can then be seen that the points with greater variation in slopes from the corresponding normal slopes are located farther from the curve. This is as shown in Fig. 3.2a and b.

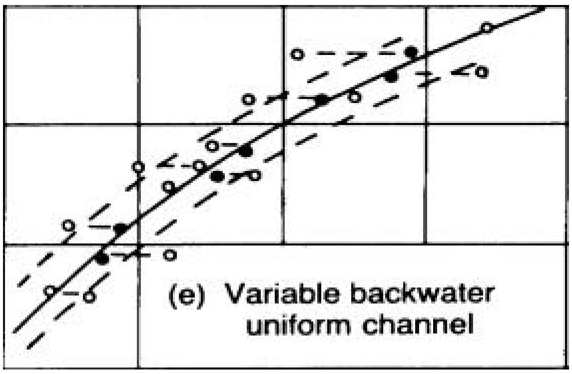

Figure 3.2a Rating curve affected by variable backwater (uniform channel)

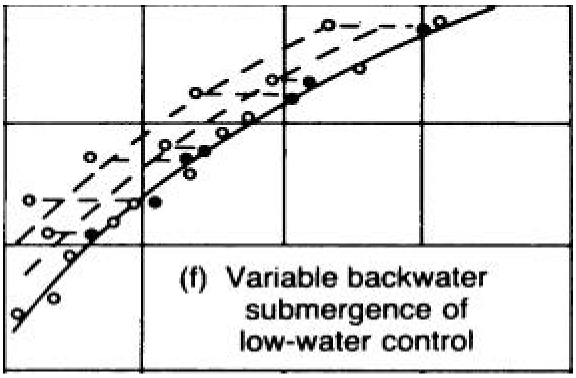

Figure 3.2b Rating curve affected by variable backwater (submergence of low-water control)

- **The stage discharge rating is affected by the variation in the local acceleration due to unsteady flow**. In such case, the plotted points can be annotated with the corresponding rate of change of slope with respect to time. A smooth curve (steady state curve) passing through those points having the least values of rate of change of stage is drawn first. It can then be seen that all those points having positive values of rate of change of stage are towards the right side of the curve and those with negative values are towards the left of it. Also, the distance from the steady curve increases with the increase in the magnitude of the rate of change of stage. This is as shown in Fig. 3.3.

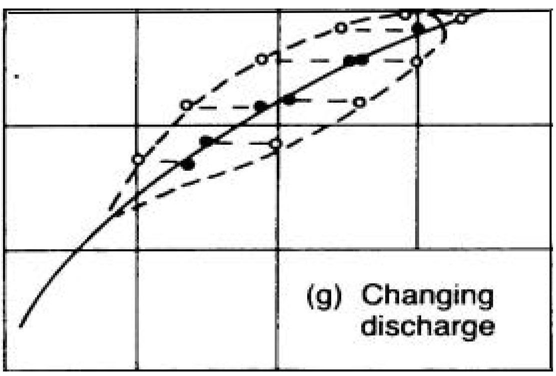

Figure 3.3 Rating curve affected by unsteady flow

- **The stage discharge rating is affected by scouring of the bed or changes in vegetation characteristics**. A shifting bed results in a wide scatter of points on the graph. The changes are erratic and may be progressive or may fluctuate from scour in one event and deposition in another. Examples are shown in Fig. 3.4.

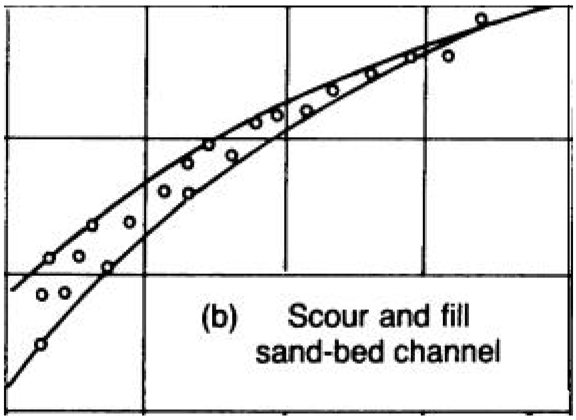

Figure 3.4 Stage-discharge relation affected by scour and fill

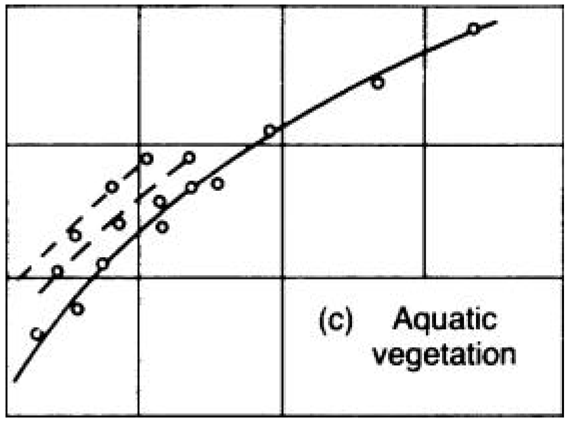

Figure 3.5 Stage-discharge relation affected by vegetation growth

- **If no suitable explanation can be given for the amount of scatter present in the plot, then it can perhaps be attributed to the observational errors**. Such errors can occur due to non-standard procedures for stage discharge observations.

Thus, based on the interpretation of scatter of the stage discharge data, the appropriate type of rating curve is fitted. There are four main cases:

- **Simple rating curve**: If simple stage discharge rating is warranted then either single channel or compound channel rating curve is fitted according to whether the flow occur essentially in the main channel or also extends to the flood plains.
- **Rating curve with backwater corrections**: If the stage discharge data is affected by the backwater effect then the rating curve incorporating the backwater effects is to be established. This requires additional information on the fall of stage with respect to an auxiliary stage gauging station.
- **Rating curve with unsteady flow correction**: If the flows are affected by the unsteadiness in the flow then the rating curve incorporating the unsteady flow effects is established. This requires information on the rate of change of stage with respect to time corresponding to each stage discharge data.
- **Rating curve with shift adjustment**: A rating curve with shift adjustment is warranted in case the flows are affected by scouring and variable vegetation effects.

3.2 Fitting of single channel simple rating curve

Single channel simple rating curve is fitted in those circumstances when the flow is contained the main channel section and can be assumed to be fairly steady. There is no indication of any backwater affecting the relationship. The bed of the river also does not significantly change so as create any shifts in the stage discharge relationship. The scatter plot of the stage and discharge data shows a very little scatter if the observational errors are not significant. The scatter plot of stage discharge data in such situations, typically is as shown in Fig. 1.1. **The fitting of simple rating curves can conveniently be considered under the following headings**:

- equations used and their physical basis
- determination of datum correction(s)
- number and range of rating curve segments
- determination of rating curve coefficients
- estimation of uncertainty in the stage discharge relationship

3.2.1 Equations used and their physical basis

Two types of algebraic equations are commonly fitted to stage discharge data are:

1. Power type equation which is most commonly used:

$$Q = c\,(h + a)^b \qquad (2)$$

2. Parabolic type of equation

$$Q = c_2\,(h_w + a)^2 + c_1\,(h_w + a) + c_0 \qquad (3)$$

where: Q = discharge (m^3/sec)
h = measured water level (m)
a = water level (m) corresponding to Q = 0
c_i = coefficients derived for the relationship corresponding to the station characteristics

It is anticipated that the power type equation is most frequently used in India and is recommended. Taking logarithms of the power type equation results in a straight line relationship of the form:

$$\log(Q) = \log(c) + b\log(h + a) \qquad (4)$$

or

$$Y = A + B\,X \qquad (5)$$

That is, if sets of discharge (Q) and the effective stage (h + a) are plotted on the double log scale, they will represent a straight line. Coefficients A and B of the straight line fit are functions of a and b. Since values of a and b can vary at different depths owing to changes in physical characteristics (effective roughness and geometry) at different depths, one or more straight lines will fit the data on double log plot. This is illustrated in Fig. 3.6, which shows a distinct break in the nature of fit in two water level ranges. A plot of the cross section at the gauging section is also often helpful to interpret the changes in the characteristics at different levels.

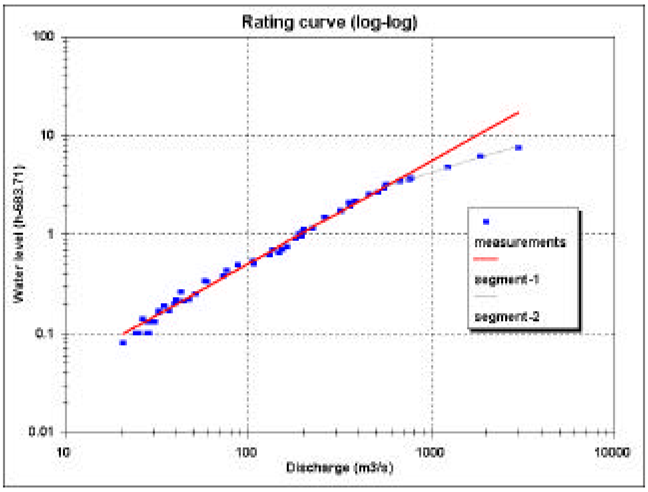

Figure 3.6 Double logarithmic plot of rating curve showing a distict break

The relationship between rating curve parameters and physical conditions is also evident if the power and parabolic equations are compared with Manning's equation for determining discharges in steady flow situations. The Manning's equation can be given as:

$$Q_m = \frac{1}{n} AR^{2/3} S^{1/2} \quad = \quad (\frac{1}{n} S^{1/2})(AR^{2/3}) \qquad (6)$$
$$= \textit{function of } (\textit{roughness} \ \& \ \textit{slope}) \ \& \ (\textit{depth} \ \& \ \textit{geometry})$$

Hence, the coefficients a, c and d are some measures of roughness and geometry of the control and b is a measure of the geometry of the section at various depths. **The value of coefficient b for various geometrical shapes are as follows:**

For rectangular shape	:	about 1.6
For triangular shape	:	about 2.5
For parabolic shape	:	about 2.0
For irregular shape	:	1.6 to 1.9

Changes in the channel resistance and slope with stage, however, will affect the exponent b. The net result of these factors is that the exponent for relatively wide rivers with channel control will vary from about 1.3 to 1.8. For relatively deep narrow rivers with section control, the exponent will commonly be greater than 2 and sometimes exceed a value of 3. Note that for compound channels with flow over the floodplain or braided channels over a limited range of level, very high values of the exponent are sometimes found (>5).

3.2.2 Determination of datum correction (a)

The datum correction (a) corresponds to that value of water level for which the flow is zero. **From eq. (2) it can be seen that for Q = 0, (h + a) = 0 which means: a = -h.**

Physically, this level corresponds to the zero flow condition at the control effective at the measuring section. The exact location of the effective control is easily determined for artificial controls or where the control is well defined by a rock ledge forming a section control. For the channel controlled gauging station, the level of deepest point opposite the gauge may give a reasonable indication of datum correction. In some cases identification of the datum correction may be impractical especially where the control is compound and channel control shifts progressively downstream at higher flows. Note that the datum correction may change between different controls and different segments of the rating curve.

For upper segments the datum correction is effectively the level of zero flow had that control applied down to zero flow; it is thus a nominal value and not physically ascertainable. **Alternative analytical methods of assessing "a" are therefore commonly used and methods for estimating the datum correction are as follows:**

- trial and error procedure
- arithmetic procedure
- computer-based optimisation

However, where possible, the estimates should be verified during field visits and inspection of longitudinal and cross sectional profiles at the measuring section:

Trial and error procedure

This was the method most commonly used before the advent of computer-based methods. The stage discharge observations are plotted on double log plot and a median line fitted through them. This fitted line usually is a curved line. However, as explained above, if the stages are adjusted for zero flow condition, i.e. datum correction a, then this line should be a straight line. This is achieved by taking a trial value of "a" and plotting (h + a), the adjusted stage, and discharge data on the same double log plot. It can be seen that if the unadjusted stage discharge plot is concave downwards then a positive trial value of "a" is needed to make it a straight line. And conversely, a negative trial value is needed to make the line straight if the curve is concave upwards. A few values of "a" can be tried to attain a straight line fit for the plotted points of adjusted stage discharge data. The procedure is illustrated in Fig.3.7. This procedure was slow but quite effective when done earlier manually. However, making use of general spreadsheet software (having graphical provision) for such trial and error procedure can be very convenient and faster now.

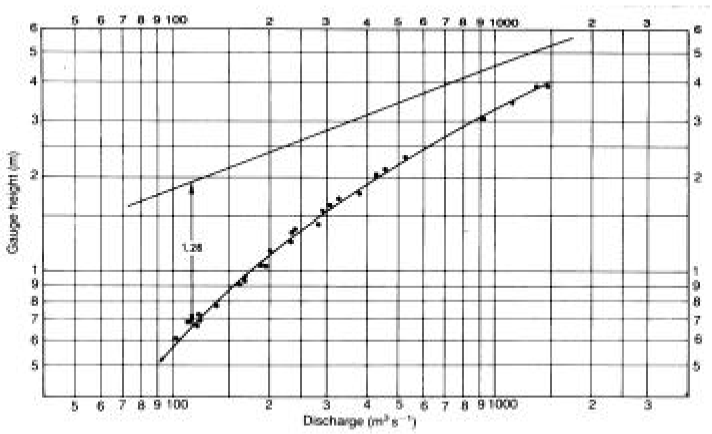

Figure 3.7 Determination of datum correction (a) by trial and error

Arithmetic procedure:

This procedure is based on expressing the datum correction "a" in terms of observed water levels. This is possible by way elimination of coefficients b and c from the power type equation between gauge and discharge using simple mathematical manipulation. From the median curve fitting the stage discharge observations, two points are selected in the lower and upper range (Q1 and Q3) whereas the third point Q2 is computed from $Q_2^2 = Q_1 . Q_3$, such that:

$$\frac{Q_1}{Q_2} = \frac{Q_2}{Q_3} \qquad (7)$$

If the corresponding gauge heights for these discharges read from the plot are h_1, h_2 and h_3 then using the power type, we obtain:

$$\frac{c\ (h_1 + a)}{c\ (h_2 + a)} = \frac{c\ (h_2 + a)}{c\ (h_3 + a)} \tag{8}$$

Which yields:

$$a = \frac{h_2^2 - h_1 h_3}{h_1 + h_3 - 2h_2} \tag{9}$$

From this equation an estimated value of "a" can be obtained directly. This procedure is known as Johnson method which is described in the WMO Operational Hydrology manual on stream gauging (Report No. 13, 1980).

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Optimisation procedure:

This procedure is suitable for automatic data processing using computer and "a" is obtained by optimisation. The first trial value of the datum correction "a" is either input by the user based on the field survey or from the computerised Johnson method described above. Next, this first estimate of "a" is varied within 2 m so as to obtain a minimum mean square error in the fit. This is a purely mathematical procedure and probably gives the best results on the basis of observed stage discharge data but it is important to make sure that the result is confirmed where possible by physical explanation of the control at the gauging location. The procedure is repeated for each segment of the rating curve.

3.2.3 Number and ranges of rating curve segments:

After the datum correction "a" has been established, the next step is to determine if the rating curve is composed of one or more segments. This is normally selected by the user rather than done automatically by computer. It is done by plotting the adjusted stage, (h-a) or simply "h" where there are multiple segments, and discharge data on the double log scale. This scatter plot can be drawn manually or by computer and the plot is inspected for breaking points. Since for (h-a), on double log scale the plotted points will align as straight lines, breaks are readily identified. The value of "h" at the breaking points give the first estimate of the water levels at which changes in the nature of the rating curve are expected. The number and water level ranges for which different rating curves are to be established is thus noted. For example, Fig. 3.6 shows that two separate rating curves are required for the two ranges of water level – one up to level "h_1" and second from "h_1" onwards. The rating equation for each of these segments is then established and the breaking points between segments are checked by computer analysis (See below).

3.2.4 Determination of rating curve coefficients:

A least square method is normally employed for estimating the rating curve coefficients. **For example, for the power type equation, taking $\mathbf{a}$ and $\mathbf{b}$ as the estimates of the constants of the straight line fitted to the scatter of points in double log scale**, the estimated value of the logarithm of the discharge can be obtained as:

$$\hat{Y} = \mathbf{a} + \mathbf{b}\ X \tag{10}$$

The least square method minimises the sum of square of deviations between the logarithms of measured discharges and the estimated discharges obtained from the fitted rating curve. Considering the sum of square the error as E, we can write:

$$E = \sum_{i=1}^{N} (Y_i - \hat{Y}_i)^2 = \sum_{i=1}^{N} (Y_i - \mathbf{a} - \mathbf{b}\ X_i)^2 \tag{11}$$

Here i denotes the individual observed point and N is the total number of observed stage discharge data.

Since this error is to be minimum, the slope of partial derivatives of this error with respect to the constants must be zero. In other words:

$$\frac{\partial E}{\partial a} \quad = \quad \frac{\partial \{\sum_{i=1}^{N} (Y_i - a - b \ X_i)^2\}}{\partial a} \quad = \quad 0 \qquad (12)$$

and

$$\frac{\partial E}{\partial b} \quad = \quad \frac{\partial \{\sum_{i=1}^{N} (Y_i - a - b \ X_i)^2\}}{\partial b} \quad = \quad 0 \qquad (13)$$

This results in two algebraic equations of the form:

$$\sum_{i=1}^{N} Y_i \quad - \quad a \, N \quad - \quad b \sum_{i=1}^{N} X_i \quad = \quad 0 \qquad (14)$$

and

$$\sum_{i=1}^{N} (X_i \ Y_i) \quad - \quad a \sum_{i=1}^{N} X_i \quad - \quad b \sum_{i=1}^{N} (X_i)^2 \quad = \quad 0 \qquad (15)$$

All the quantities in the above equations are known except α and β. Solving the two equations yield:

$$b \quad = \quad \frac{N \sum_{i=1}^{N} (X_i \ Y_i) \quad - \quad (\sum_{i=1}^{N} X_i)(\sum_{i=1}^{N} Y_i)}{N \sum_{i=1}^{N} (X_i)^2 \quad - \quad (\sum_{i=1}^{N} X_i)^2} \qquad (16)$$

and

$$a \quad = \quad \frac{\sum_{i=1}^{N} Y_i \quad - \quad b \sum_{i=1}^{N} X_i}{N} \qquad (17)$$

The value of coefficients c and b of power type equation can then be finally obtained as:

$b = \beta$ and $c = 10^{\alpha}$ (18)

<u>Reassessment of breaking points</u>

The first estimate of the water level ranges for different segments of the rating curve is obtained by visual examination of the cross-section changes and the double log plot. However, exact limits of water levels for various segments are obtained by computer from the intersection of the fitted curves in adjoining the segments.

Considering the rating equations for two successive water level ranges be given as $Q = f_{i-1}(h)$ and $Q = f_i\,(h)$ respectively and let the upper boundary used for the estimation of f_{i-1} be denoted by hu_{i-1} and the lower boundary used for the estimation of f_i by hl_i . To force the intersection between f_{i-1} and f_i to fall within certain limits it is necessary to choose: $hu_{i-1} > hl_i$. That is, the intersection of the rating curves of the adjoining segments should be found numerically within this overlap. This is illustrated in Fig. 3.8 and Table 3.1. If the intersection falls outside the selected overlap, then the intersection is estimated for the least difference between $Q = f_{i-1}(h)$ and $Q = f_i\,(h)$. Preferably the boundary width between hu_{i-1} and hl_i is widened and the curves refitted.

It is essential that a graphical plot of the fit of the derived equations to the data is inspected before accepting them.

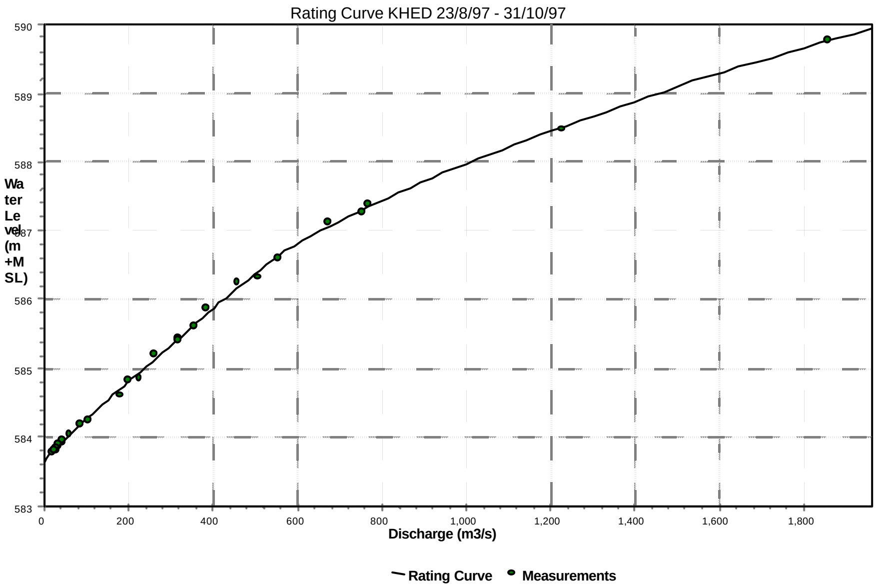


Figure 3.8 Fitted rating curve using 2 segments

3.2.5 Estimation of uncertainty in the stage discharge relationship:

With respect to the stage discharge relationship the standard error of estimate (Se) is a measure of the dispersion of observations about the mean relationship. The standard error is expressed as:

$$S_e = \sqrt{\frac{\sum(\Delta Q_i - \overline{\Delta Q})^2}{N-2}} \tag{19}$$

Here, ΔQ_i is the measure of difference between the observed (Q_i) and computed (Q_c) discharges and can be expressed in absolute and relative (percentage) terms respectively as:

$$\Delta Q_i = Q_i - Q_c \tag{20}$$

or

$$\Delta Q_i = \frac{Q_i - Q_c}{Q_i} \times 100\% \tag{21}$$

Table 3.1 Results of stage-discharge computation for example presented in Figure 3.8

```
Analysis of stage-discharge data

Station name :  KHED
Data from 1997  1  1 to 1997 12 31

Single channel

Gauge Zero on  1997  7 30 =       .000 m

Number of data =  36
h minimum =    583.79 meas.nr =  44
h maximum =    589.75 meas.nr =  49
q minimum =    20.630 meas.nr =  44
q maximum =  1854.496 meas.nr =  49

Given boundaries for computation of rating curve(s)
interval lower bound upper bound  nr. of data
       1     583.000     587.000           31
       2     586.500     590.000            6

Power type of equation q=c*(h+a)**b is used

Boundaries / coefficients
lower bound upper bound         a         b         c

     583.00      586.68  -583.650     1.074   .1709E+03
     586.68      590.00  -581.964     2.381   .1401E+02

Number   W level    Q meas    Q comp      DIFf  Rel.dIFf      Semr
               M      M3/S      M3/S      M3/S       0/0       0/0

     2   584.610   181.500   163.549    17.951     10.98      3.08
     3   587.390   768.820   785.226   -16.406     -2.09      3.54
     5   586.240   457.050   475.121   -18.071     -3.80      4.93
     6   585.870   386.020   402.597   -16.577     -4.12      4.60
     7   585.440   316.290   319.452    -3.162      -.99      4.16
     9   585.210   261.650   275.570   -13.920     -5.05      3.89
    10   584.840   200.850   206.013    -5.163     -2.51      3.41
..................................................................
    48   583.870    32.490    33.574    -1.084     -3.23      3.35
    49   589.750  1854.496  1854.988     -.492      -.03      6.02
    50   588.470  1228.290  1209.632    18.658      1.54      3.48
    51   587.270   753.580   744.518     9.062      1.22      3.79
    52   587.120   673.660   695.381   -21.721     -3.12      4.14
    53   586.600   553.930   546.431     7.499      1.37      5.21
    54   586.320   509.230   490.911    18.319      3.73      4.99
    55   585.620   357.030   354.093     2.937       .83      4.35
    56   585.410   319.860   313.697     6.163      1.96      4.12
    57   584.870   226.080   211.593    14.487      6.85      3.45
    62   584.040    59.020    62.120    -3.100     -4.99      2.69

    Overall standard error =     6.603

    Statistics per interval
    Interval Lower bound Upper bound Nr.of data Standard error
       1     583.000     586.680         31           7.11
       2     586.680     590.000          5           2.45
```

Standard error expressed in relative terms helps in comparing the extent of fit between the rating curves for different ranges of discharges. The standard error for the rating curve can be derived for each segment separately as well as for the full range of data.

Thus 95% of all observed stage discharge data are expected to be within t x S_e from the fitted line where:

Student's $t \cong 2$ where $n > 20$, but increasingly large for smaller samples.

The stage discharge relationship, being a line of best fit provides a better estimate of discharge than any of the individual observations, but the position of the line is also subject to uncertainty, expressed as the Standard error of the mean relationship (S_{mr}) which is given by:

$$S_{mr} \quad = \quad S_e \sqrt{\frac{1}{n} + \frac{(P_i - \overline{P})^2}{S_P^2}} \qquad and \quad CL_{95\%} = \pm t S_{mr} \tag{22}$$

where t = Student t-value at 95% probability

P_i = $ln\,(h_i + a)$

S^2_P = variance of P

$CL_{95\%}$ = 95% confidence limits

The S_e equation gives a single value for the standard error of the logarithmic relation and the 95% confidence limits can thus be displayed as two parallel straight lines on either side of the mean relationship. By contrast S_{mr} is calculated for each observation of $(h + a)$. The limits are therefore curved on each side of the stage discharge relationship and are at a minimum at the mean value of $ln\,(h + a)$ where the S_{mr} relationship reduces to:

$$S_{mr} = \pm Se / n^{1/2} \tag{23}$$

Thus with n = 25, S_{mr}, the standard error of the mean relationship is approximately 20% of *Se* indicating the advantage of a fitted relationship over the use of individual gaugings.

3.3 Compound channel rating curve

If the flood plains carry flow over the full cross section, the discharge (for very wide channels) consists of two parts:

$$Q_{river} \quad = \quad (h\, B_r)\,(K_{mr}\ h^{2/3}\ S^{1/2}) \tag{24}$$

and

$$Q_{floodplain} = (h - h_1)\,(B - B_r)\,[K_{mf}\ (h - h_1)^{2/3}\ S^{1/2}] \tag{25}$$

assuming that the floodplain has the same slope as the river bed, **the total discharge becomes:**

$$Q_{total} = h\,B_r\,(K_{mr}\,h^{2/3}\,S^{1/2}) + (h-h_1)(B-B_r)[K_{mf}\,(h-h_1)^{2/3}\,S^{1/2}] \tag{26}$$

This is illustrated in Fig. 3.9. The rating curve changes significantly as soon as the flood plain at level h-h_1 is flooded, especially if the ratio of the storage width B to the width of the river bed B_r is large. **The rating curve for this situation of a compound channel is determined by considering the flow through the floodplain portion separately. This is done to avoid large values of the exponent b and extremely low values for the parameter c in the power equation for the rating curve in the main channel portion.**

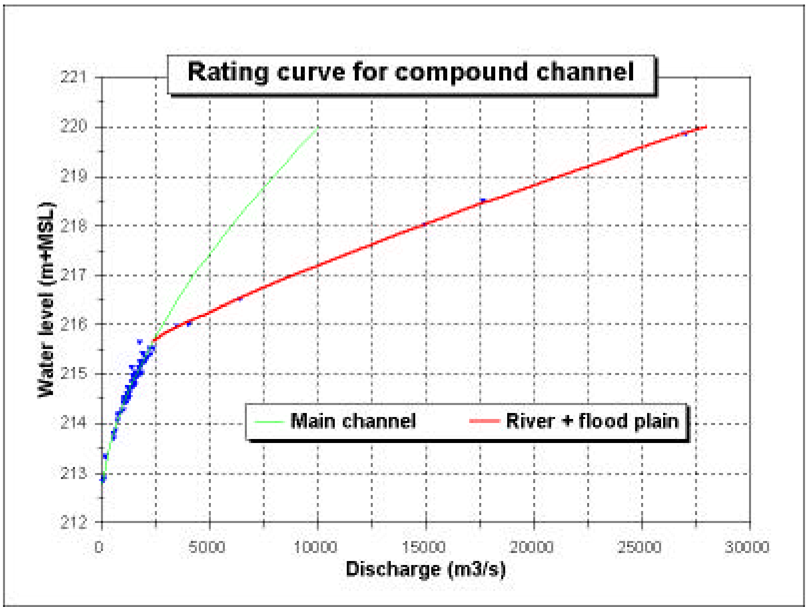


Figure 3.9 Example of rating curve for compound cross-section

The last water level range considered for fitting rating curve is treated for the flood plain water levels. First, the river discharge Q_r will be computed for this last interval by using the parameters computed for the one but last interval. Then a temporary flood plain discharge Q_f is computed by subtracting Q_r from the observed discharge (O_{obs}) for the last water level interval, i.e.

$$Q_f = Q_{obs} - Q_r. \tag{27}$$

This discharge Q_f will then be separately used to fit a rating curve for the water levels corresponding to the flood plains. The total discharge in the flood plain is then calculated as the sum of discharges given by the rating curve of the one but last segment applied for water levels in the flood plains and the rating curve established separately for the flood plains.

The rating curve presented in Figure 3.9 for Jhelum river at Rasul reads:

For h < 215.67 m + MSL: $Q = 315.2(h-212.38)^{1.706}$

For h > 215.67 m + MSL: $Q = 315.2(h-212.38)^{1.706} + 3337.4(h-215.67)^{1.145}$

Hence the last part in the second equation is the contribution of the flood plain to the total river flow.

3.4 Rating curve with backwater correction

When the control at the gauging station is influenced by other controls downstream, then the unique relationship between stage and discharge at the gauging station is not maintained. Backwater is an important consideration in streamflow site selection and sites having backwater effects should be avoided if possible. However, many existing stations in India are subject to variable backwater effects and require special methods of discharge determination. **Typical examples of backwater effects on gauging stations and the rating curve are as follows:**

- by regulation of water course downstream.
- level of water in the main river at the confluence downstream
- level of water in a reservoir downstream
- variable tidal effect occurring downstream of a gauging station
- downstream constriction with a variable capacity at any level due to weed growth etc.
- rivers with return of overbank flow

Backwater from variable controls downstream from the station influences the water surface slope at the station for given stage. When the backwater from the downstream control results in lowering the water surface slope, a smaller discharge passes through the gauging station for the same stage. On the other hand, if the surface slope increases, as in the case of sudden drawdown through a regulator downstream, a greater discharge passes for the same stage. The presence of backwater does not allow the use of a simple unique rating curve. **Variable backwater causes a variable energy slope for the same stage. Discharge is thus a function of both stage and slope and the relation is termed as slope-stage-discharge relation.**

The stage is measured continuously at the main gauging station. The slope is estimated by continuously observing the stage at an additional gauge station, called the auxiliary gauge station. The auxiliary gauge station is established some distance downstream of the main station. Time synchronisation in the observations at the gauges is necessary for precise estimation of slope. The distance between these gauges is kept such that it gives an adequate representation of the slope at the main station and at the same time the uncertainty in the estimation is also smaller. When both main and auxiliary gauges are set to the same datum, the difference between the two stages directly gives the fall in the water surface. Thus, **the fall between the main and the auxiliary stations is taken as the measure of surface slope. This fall is taken as the third parameter in the relationship and the rating is therefore also called stage-fall-discharge relation.**

Discharge using Manning's equation can be expressed as:

$$Q \;=\; K_m\, R^{2/3}\, S^{1/2}\, A \tag{28}$$

Energy slope represented by the surface water slope can be represented by the fall in level between the main gauge and the auxiliary gauge. **The slope-stage-discharge or stage-fall-discharge method is represented by:**

$$\frac{Q_m}{Q_r} \;=\; \left(\frac{S_m}{S_r}\right)^p \;=\; \left(\frac{F_m}{F_r}\right)^p \tag{29}$$

where Q_m is the measured (backwater affected) discharge
Q_r is a reference discharge
F_m is the measured fall
F_r is a reference fall
p is a power parameter between 0.4 and 0.6

From the Manning's equation given above, the exponent "p" would be expected to be ½. The fall (F) or the slope (S = F/L) is obtained by the observing the water levels at the main and auxiliary gauge. Since, there is no assurance that the water surface profile between these gauges is a straight line, the effective value of the exponent can be different from ½ and must be determined empirically.

An initial plot of the stage discharge relationship (either manually or by computer) with values of fall against each observation, will show whether the relationship is affected by variable slope, and whether this occurs at all stages or is affected only when the fall reduces below a particular value. In the absence of any channel control, the discharge would be affected by variable fall at all times and the correction is applied by the **constant fall method.** When the discharge is affected only when the fall reduces below a given value the **normal (or limiting) fall** method is used.

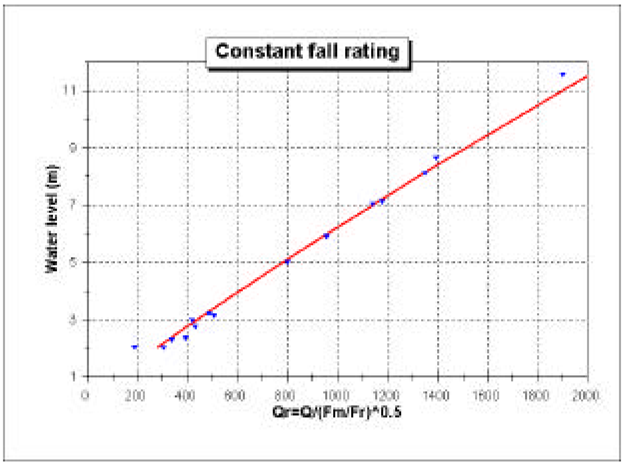
3.4.1 Constant fall method:

The constant fall method is applied when the stage-discharge relation is affected by variable fall at all times and for all stages. The fall applicable to each discharge measurement is determined and plotted with each stage discharge observation on the plot. If the observed falls do not vary greatly, an average value (reference fall or constant fall) F_r is selected.

Manual computation

For manual computation an iterative graphical procedure is used. Two curves are used (Figs. 3.10 and 3.11):

- All measurements with fall of about F_r are fitted with a curve as a simple stage discharge relation (Fig.3.10). This gives a relation between the measured stage h and the reference discharge Q_r.
- A second relation, called the adjustment curve, either between the measured fall, F_m, or the ratio of the measured fall for each gauging and the constant *fall* (F_m / F_r), and the discharge ratio (Q_m / Q_r) (Fig. 3.11)
- This second curve is then used to refine the stage discharge relationship by calculating Q_r from known values of Q_m and F_m/F_r and then replotting h against Q_r .
- A few iterations may be done to refine the two curves.



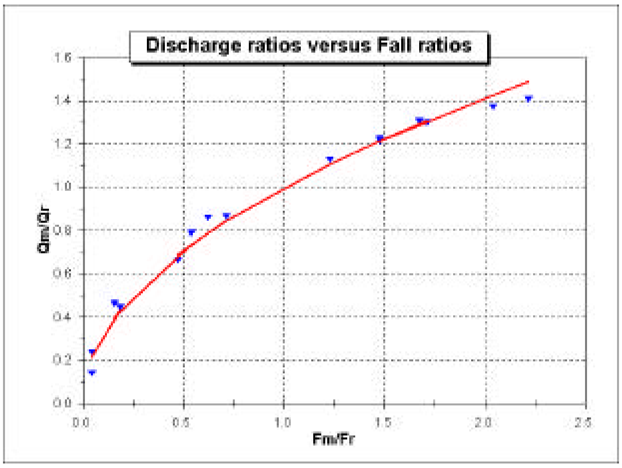


Figure 3.10 Q_r=f(h) in constant fall rating **Figure 3.11 Q_m/Q_r = f(F_m/F_r)**

The discharge at any time can be then be computed as follows:

- For the observed fall (F_m) calculate the ratio (F_m/F_r)
- read the ratio (Q_m / Q_r) from the adjustment curve against the calculated value of (F_m/F_r)
- multiply the ratio (Q_m / Q_r) with the reference discharge Q_r obtained for the measured stage *h* from the curve between stage *h* and reference discharge Q_r.

<u>Computer computation</u>

For computer computation, this procedure is simplified by mathematical fitting and optimisation. First, as before, a reference (or constant) fall (F_r) is selected from amongst the most frequently observed falls.

A rating curve, between stage *h* and the reference discharge (Q_r), is then fitted directly by estimating:

$$Q_r = Q_m \left(\frac{F_r}{F_m} \right)^p \tag{30}$$

where *p* is optimised between 0.4 and 0.6 based on minimisation of standard errors.

The discharge at any time, corresponding to the measured stage *h* and fall F_m , is then calculated by first obtaining Q_r from the above relationship and then calculating discharge as:

$$Q = Q_r \left(\frac{F_m}{F_r} \right)^p \tag{31}$$

A special case of constant fall method is the unit fall method in which the reference fall is assumed to be equal to unity. This simplifies the calculations and thus is suitable for manual method.

3.4.2 *Normal Fall Method*:

The normal or limiting fall method is used when there are times when backwater is not present at the station. Examples are when a downstream reservoir is drawn down or where there is low water in a downstream tributary or main river.

<u>Manual procedure</u>

The manual procedure is as follows:

- Plot stage against discharge, noting the fall at each point. The points at which backwater has no effect are identified first. These points normally group at the extreme right of the plotted points. This is equivalent to the simple rating curve for which a Q_r -*h* relationship may be fitted (where Q_r in this case is the reference or normal discharge) (Fig. 3.12).

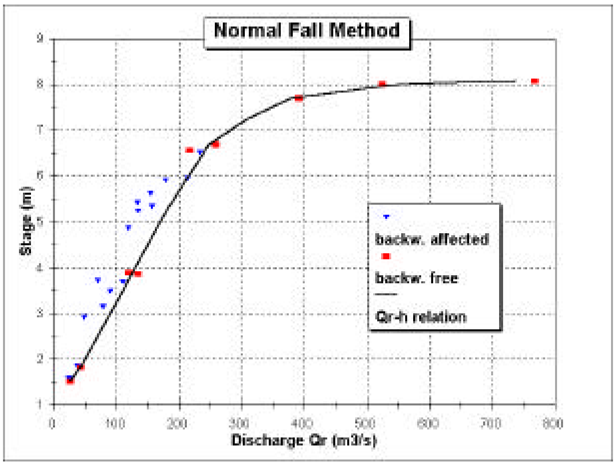


Figure 3.12 Q_r-*h* relationship for Normal Fall Method

- Plot the measured fall against stage for each gauging and draw a line through those observations representing the minimum fall, but which are backwater free. This represents the normal or limiting fall F_r (Fig. 3.13). It is observed from Figure 3.13 that the line separates the backwater affected and backwater free falls.

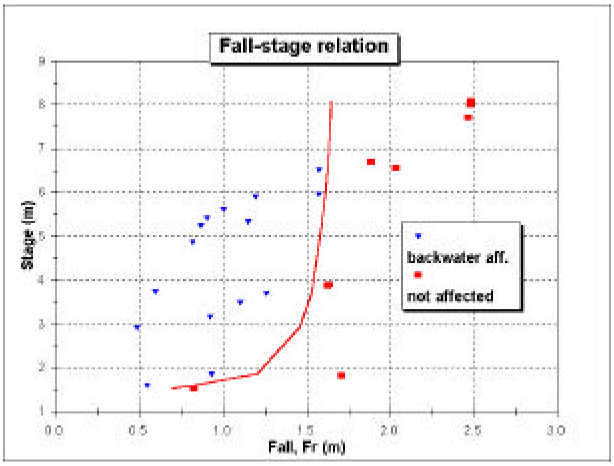


Figure 3.13 F_r-*h* relationship

- For each discharge measurement derive Q_r using the discharge rating and F_r , the normal fall from the fall rating.
- For each discharge measurement compute Q_m/Q_r and F_m/F_r and draw an average curve (Fig. 3.14).

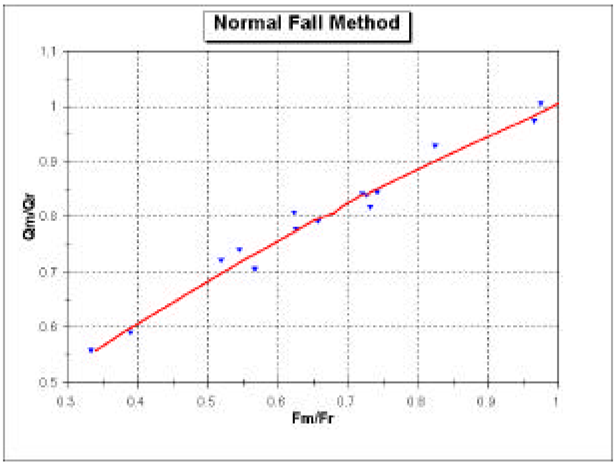


Figure 3.14 Q_m/Q_r - F_m/F_r relationship

- As for the constant fall method, the curves may be successively adjusted by holding two graphs constant and re-computing and plotting the third. No more than two or three iterations are usually required.

The discharge at any time can be then be computed as follows:

- From the plot between stage and the normal (or limiting) fall (F_r), find the value of F_r for the observed stage h
- For the observed fall (F_m), calculate the ratio (F_m/F_r)
- Read the ratio (Q_m / Q_r) from the adjustment curve against the calculated value of (F_m/F_r)
- Obtain discharge by multiplying the ratio (Q_m / Q_r) with the reference discharge Q_r obtained for the measured stage h from the curve between stage h and reference discharge Q_r.

<u>Computer procedure</u>

The computer procedure considerably simplifies computation and is as follows:

- Compute the backwater-free rating curve using selected current meter gaugings (the Q_r -h relationship).
- Using values of Q_r derived from (1) and F_r derived from:

$$F_r = F_m \left(\frac{Q_r}{Q_m} \right)^{1/p} \qquad (32)$$

a parabola is fitted to the reference fall in relation to stage *(h)* as:

$$F_r = a + b\,h + c\,h^2 \qquad (33)$$

The parameter p is optimised between 0.4 and 0.6.

The discharge at any time, corresponding to the measured stage *h* and fall F_m , is then calculated by:

- obtaining F_r for the observed *h* from the parabolic relation between *h* and F_r
- obtaining Q_r from the backwater free relationship established between *h* and Q_r
- then calculating discharge corresponding to measured stage *h* as:

$$Q = Q_r \left(\frac{F_m}{F_r} \right)^p \qquad (34)$$

3.5 Rating curve with unsteady flow correction

Gauging stations not subjected to variable slope because of backwater may still be affected by variations in the water surface slope due to high rates of change in stage. This occurs when the flow is highly unsteady and the water level is changing rapidly. At stream 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 the passing flood wave. During the rising stage, the velocity and discharge are normally greater than they would be for the same stage under steady flow conditions. Similarly, during the falling stage the discharge is normally less for any given gauge height than it is when the stage is constant. This is due to the fact that the approaching velocities in the advancing portion of the wave are larger than in a steady uniform flow at the corresponding stages. In the receding phase of the flood wave the converse situation occurs with reduced approach velocities giving lower discharges than in equivalent steady state case.

Thus, the stage discharge relationship for an unsteady flow will not be a single-valued relationship as in steady flow but it will be a looped curve as shown in the example below. The looping in the stage discharge curve is also called hysteresis in the stage-discharge relationship. From the curve it can be easily seen that at the same stage, more discharge passes through the river during rising stages than in the falling ones.

3.5.1 Application

For practical purposes the discharge rating must be developed by the application of adjustment factors that relate unsteady flow to steady flow. **Omitting the acceleration terms in the dynamic flow equation the relation between the unsteady and steady discharge is expressed in the form:**

$$Q_m = Q_r \sqrt{\left(1 + \frac{1}{c\,S_0}\frac{dh}{dt}\right)} \qquad (35)$$

where Q_m is measured discharge
Q_r is estimated steady state discharge from the rating curve
c is wave velocity (celerity)
S_0 is energy slope for steady state flow
dh/dt is rate of change of stage derived from the difference in gauge height at the beginning and end of a gauging (+ for rising ; - for falling)

Q_r is the steady state discharge and is obtained by establishing a rating curve as a median curve through the uncorrected stage discharge observations or using those observations for which the rate of change of stage had been negligible. Care is taken to see that there are sufficient number of gaugings on rising and falling limbs if the unsteady state observations are considered while establishing the steady state rating curve.

Rearranging the above equation gives:

$$\frac{1}{c\,S_0} = \frac{(Q_m / Q_r)^2 - 1}{dh/dt} \tag{36}$$

The quantity (*dh/dt*) is obtained by knowing the stage at the beginning and end of the stage discharge observation or from the continuous stage record. Thus the value of factor ($1/cS_0$) can be obtained by the above relationship for every observed stage. The factor ($1/cS_0$) varies with stage and a parabola is fitted to its estimated values and stage as:

$$\frac{1}{c\,S_0} = a + b\,h + ch^2 \tag{37}$$

A minimum stage h_{min} is specified beyond which the above relation is valid. A maximum value of factor ($1/cS_0$) is also specified so that unacceptably high value can be avoided from taking part in the fitting of the parabola.

Thus unsteady flow corrections can be estimated by the following steps:

- Measured discharge is plotted against stage and beside each plotted point is noted the value of *dh/dt* for the measurement (+ or -)
- A trial Q_s rating curve representing the steady flow condition where *dh/dt* equals zero is fitted to the plotted discharge measurements.
- A steady state discharge Q_r is then estimated from the curve for each discharge measurement and Q_m, Q_r and *dh/dt* are together used in the Equation 35 to compute corresponding values of the adjustment factor $1 / cS_0$
- Computed values of $1 / cS_0$ are then plotted against stage and a smooth (parabolic) curve is fitted to the plotted points

For obtaining unsteady flow discharge from the steady rating curve the following steps are followed:

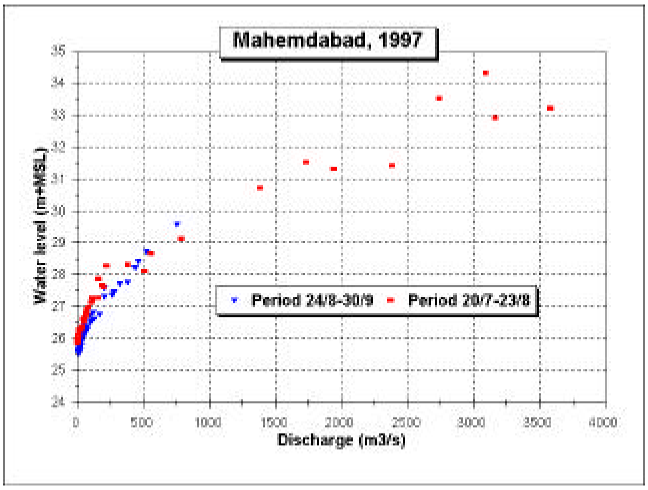
- obtain the steady state flow Q_r for the measured stage *h*
- obtain factor ($1/cS_0$) by substituting stage *h* in the parabolic relation between the two
- obtain (*dh/dt*) from stage discharge observation timings or continuous stage records
- substitute the above three quantities in the Equation 35 to obtain the true unsteady flow discharge

The computer method of analysis using HYMOS mirrors the manual method described above.

It is apparent from the above discussions and relationships that the effects of unsteady flow on the rating are mainly observed in larger rivers with very flat bed slopes (with channel control extending far downstream) together with significant rate change in the flow rates. For rivers with steep slopes, the looping effect is rarely of practical consequence. **Although there will be variations depending on the catchment climate and topography, the potential effects of rapidly changing discharge on the rating should be investigated in rivers with a slope of 1 metre/ km or less. Possibility of a significant unsteady effect (say more than 8–10%) can be judged easily by making a rough estimate of ratio of unsteady flow value with that of the steady flow value.**

Example

The steps to correct the rating curve for unsteady flow effects is elaborated for station MAHEMDABAD on WAZAK river. The scatter plot of stage discharge data for 1997 is shown in Figure 3.15a. From the curve is apparent that some shift has taken place, see also Figure 3.15b. The shift took place around 24 August.



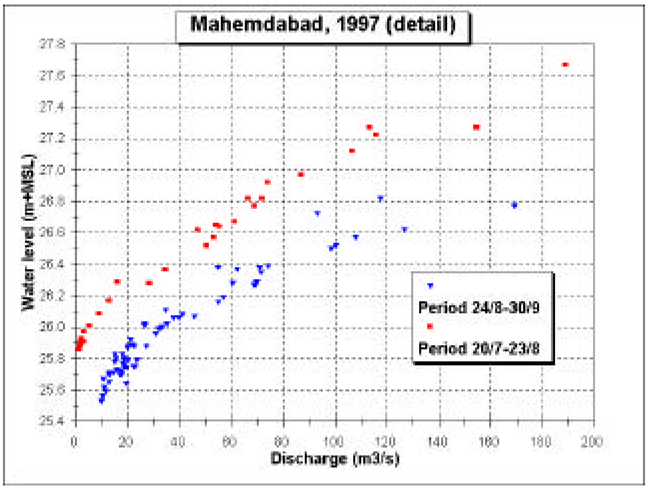


Figure 3.15a Stage-discharge data of station Mahemdabad on Wazak river, 1997

Figure 3.15 b Detail of stage discharge data for low flows, clearly showing the shift

In the analysis therefore only the data prior that date were considered. The scatter plots clearly show a looping for the higher flows. To a large extent, this looping can be attributed to unsteady flow phenomenon. The Jones method is therefore applied. The first fit to the scatter plot, before any correction, is shown in Figure 3.15c.

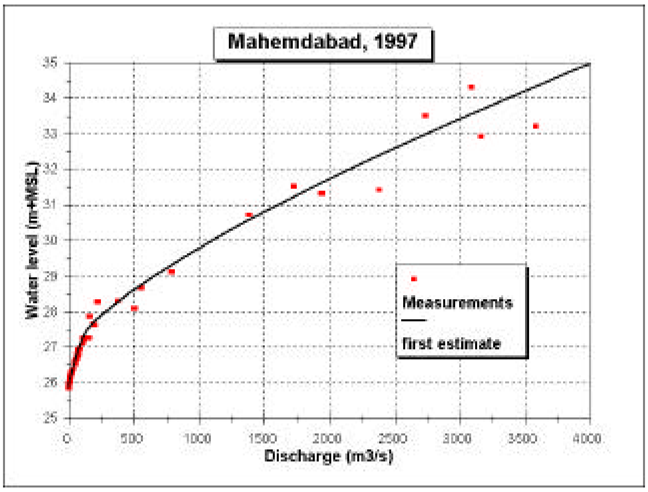


Figure 3.15c First fit to stage-discharge data, prior to adjustment

Based on this relation and the observed discharges and water level changes values for $1/cS_0$ were obtained. These data are depicted in Figure 3.15d. The scatter in the latter plot is seen to be considerable. An approximate relationship between $1/cS_0$ and h is shown in the graph.

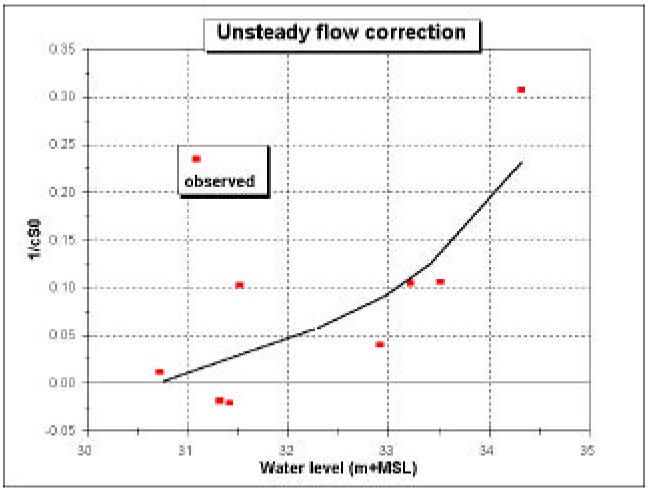


Figure 3.15 d Scatter plot of $1/cS_0$ as function of stage, with approximate relation.

With the values for $1/cS_0$ taken from graph the unsteady flow correction factor is computed and steady state discharges are computed. These are shown in Figure 3.15e, together with the uncorrected discharges. It is observed that part of the earlier variation is indeed removed. A slightly adjusted curve is subsequently fit to the stage and corrected flows.

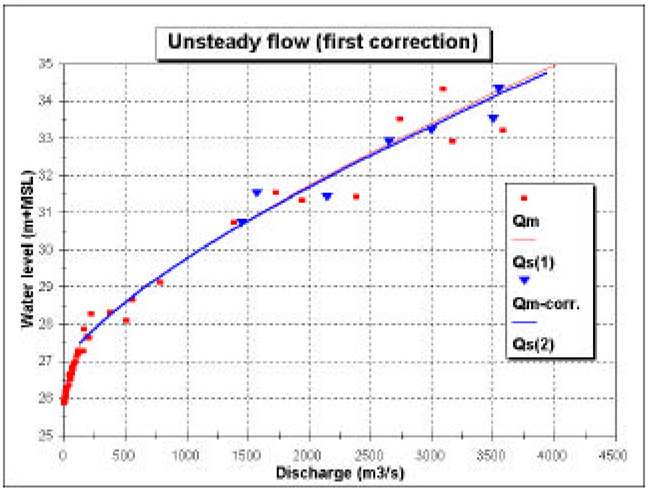


Figure 3.15e Rating curve after first adjustment trial for unsteady flow.

Note that the looping has been eliminated, though still some scatter is apparent.

3.6 Rating relationships for stations affected by shifting control

For site selection it is a desirable property of a gauging station to have a control which is stable, but no such conditions may exist in the reach for which flow measurement is required, and the selected gauging station may be subject to shifting control. Shifts in the control occur especially in alluvial sand-bed streams. However, even in stable stream channels shift will occur, particularly at low flow because of weed growth in the channel, or as a result of 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. The extent and frequency with which changes occur depends on typical bed material size at the control and velocities typically occurring at the station. In the case of controls consisting of cobble or boulder sized alluvium, the control and hence the rating may change only during the highest floods. In contrast, in sand bed rivers the control may shift gradually even in low to moderate flows. Intermediate conditions are common where the bed and rating change frequently during the monsoon but remain stable for long periods of seasonal recession.

For sand bed channels the stage-discharge relationship varies not only because of the changing cross section due to scouring or deposition but also because of changing roughness with different bed forms. Bed configurations occurring with increasing discharge are ripples, dunes, plane bed, standing waves, antidunes and chute and pool (Fig. 3.16). The resistance of 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. Fine sediment present in water also influences the configuration of sand-bed and thus the resistance to flow. Changes in water temperature may also alter bed form, and hence roughness and resistance to flow in sand bed channels. The viscosity of water will increase with lower temperature and thereby mobility of the sand will increase.

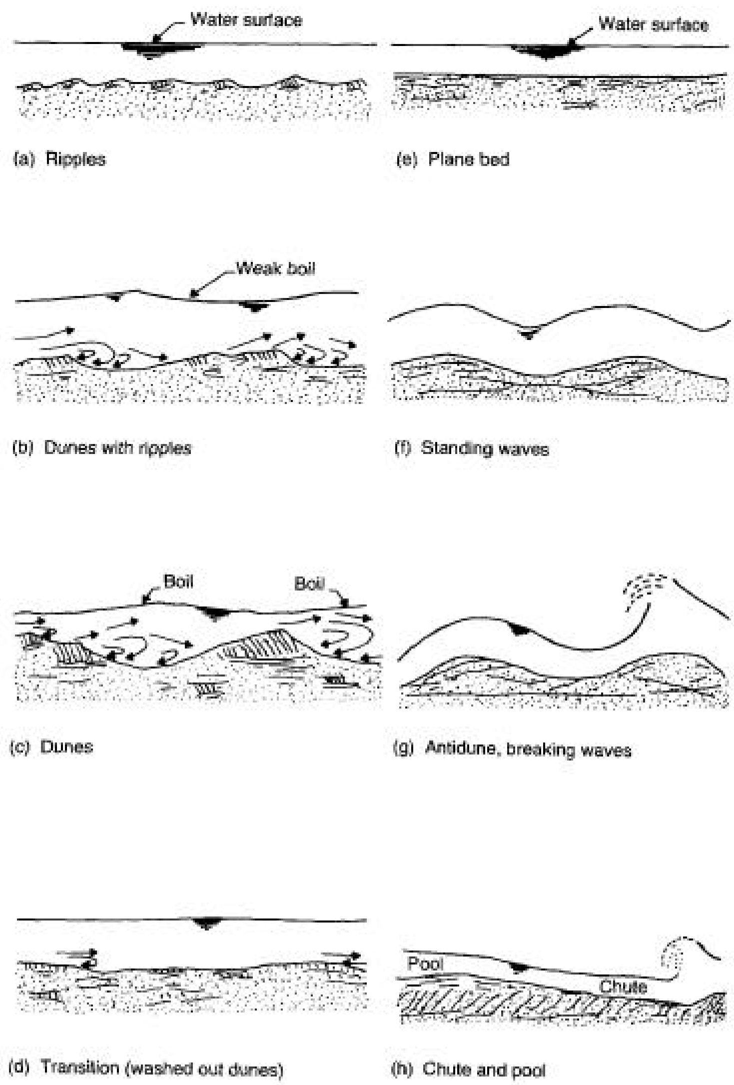


Figure 3.16 Bed and surface configurations configurations in sand-bed channels

For alluvial streams where neither bottom nor sides are stable, a plot of stage against discharge will very often scatter widely and thus be indeterminate (Fig. 3.17) However, the hydraulic relationship becomes apparent by changing the variables. The effect of variation in bottom elevation and width is eliminated by replacing stage by mean depth (hydraulic radius) and discharge by mean velocity respectively. Plots of mean depth against mean velocity are useful in the analysis of stage-discharge relations, provided the measurements are referred to the same cross-section.

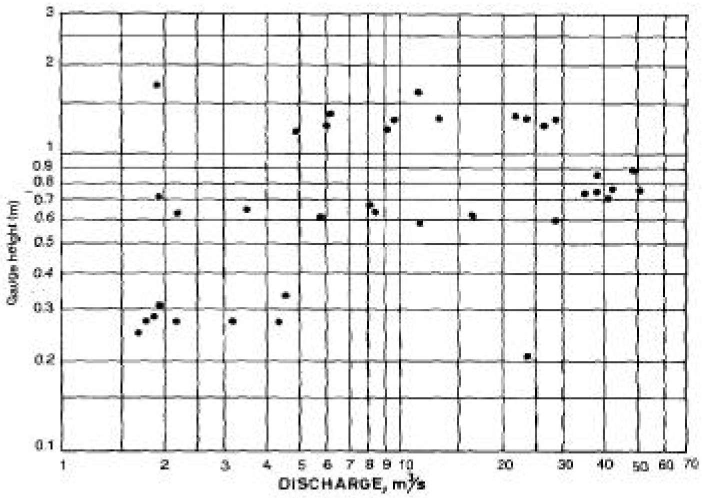


Figure 3.17 Plot of discharge against stage for a sand-bed channel with indeterminate stage-discharge relation

These plots will identify the bed-form regime associated with each individual discharge measurement. (Fig. 3.18). Thus measurements associated with respective flow regimes, upper or lower, are considered for establishing separate rating curves. Information about bed-forms may be obtained by visual observation of water surfaces and noted for reference for developing discharge ratings.

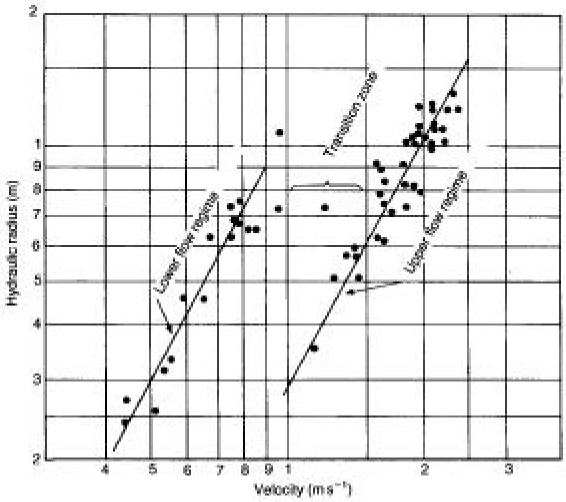


Figure 3.18 Relation of mean velocity to hydraulic radius of channel in Figure 3.17

There are four possible approaches depending on the severity of scour and on the frequency of gauging:

- Fitting a simple rating curve between scour events
- Varying the zero or shift parameter
- Application of Stout's shift method
- Flow determined from daily gauging

3.6.1 Fitting a simple rating curve between scour events

Where the plotted rating curve shows long periods of stability punctuated by infrequent flood events which cause channel adjustments, the standard procedure of fitting a simple logarithmic equation of the form $Q = c_1(h + a_1)^{b1}$ should be applied to each stable period. This is possible only if there are sufficient gaugings in each period throughout the range of stage.

To identify the date of change from one rating to the next, the gaugings are plotted with their date or number sequence. The interval in which the change occurred is where the position of sequential plotted gaugings moves from one line to the next. The processor should then inspect the gauge observation record for a flood event during the period and apply the next rating from that date.

Notes from the Field Record book or station log must be available whilst inspection and stage discharge processing is carried out. This provides further information on the nature and timing of the event and confirms that the change was due to shifting control rather than to damage or adjustment to the staff gauge.

3.6.2 Varying the zero or shift parameter

Where the plotted rating curve shows periods of stability but the number of gaugings is insufficient to define the new relationship over all or part of the range, then the parameter 'a' in the standard relationship $Q = c_1(h + a_1)^{b1}$ may be adjusted. The parameter 'a_1' represents the datum correction between the zero of the gauges and the stage at zero flow. Scour or deposition causes a shift in this zero flow stage and hence a change in the value 'a_1'..

The shift adjustment required can be determined by taking the average difference (Δa) between the rated stage (h_r) for measured flow (Q_m) and measured stage (h_m) using the previous rating. i.e.

$$\Delta a = \sum_{i=1}^{n} (h_r - h_m) / n \qquad (39)$$

The new rating over the specified range then becomes:

$$Q = c_1(h + a_1 + \Delta a)^{b1} \qquad (40)$$

The judgement of the processor is required as to whether to apply the value of Δa over the full range of stage (given that the % effect will diminish with increasing stage) or only in the lower range for which current meter gauging is available. If there is evidence that the rating changes from unstable section control at low flows to more stable channel control at higher flows, then the existing upper rating should continue to apply.

New stage ranges and limits between rating segments will require to be determined. The method assumes that the channel hydraulic properties remain unchanged except for the level of the datum. Significant variation from this assumption will result in wide variation in (h_r - h_m) between included gaugings. If this is the case then Stout's shift method should be used as an alternative.

3.6.3 *Stout's shift method (Not Recommended to be Applied)*

For controls which are shifting continually or progressively, Stout's method is used. In such instances the plotted current meter measurements show a very wide spread from the mean line and show an insufficient number of sequential gaugings with the same trend to split the simple rating into several periods. **The procedure is as follows:**

- Fit a mean relationship to (all) the points for the period in question.
- Determine h_r (the rated stage) from measured Q_m by reversing the power type rating curve or from the plot:

$$h_r = (Q_m / c)^{1/b} - a \qquad (41)$$

- Individual rating shifts (Dh), as shown in Fig. 3.19, are then:

$$Dh = h_r - h_m \qquad (42)$$

- These Dh stage shifts are then plotted chronologically and interpolated between successive gaugings (Fig. 3.19) for any instant of time t as Dh_t.
- These shifts, Dh_t ,are used as a correction to observed gauge height readings and the original rating applied to the corrected stages, i.e.

$$Q_t = c_1(h_t + Dh_t + a_1)^{b1} \qquad (43)$$

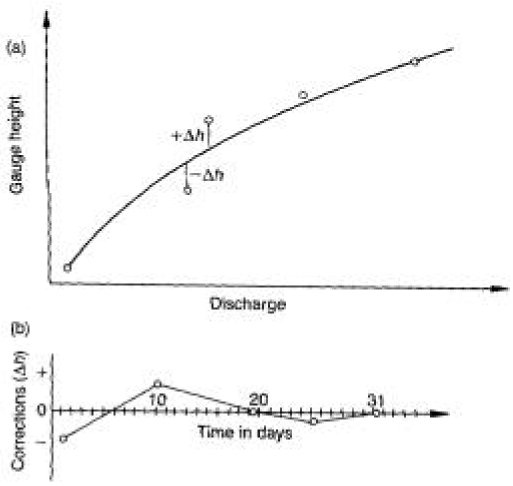


Figure 3.19 Stout's method for correcting stage readings when control is shifting

The Stout method will only result in worthwhile results where:

(a) Gauging is frequent, perhaps daily in moderate to high flows and even more frequently during floods.
(b) The mean rating is revised periodically - at least yearly.

The basic assumption in applying the Stout's method is 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. However, the deviation of a discharge measurement from an established rating curve may be due to:

(a) gradual and systematic shifts in the control,
(b) abrupt random shifts in the control, and
(c) error of observation and systematic errors of both instrumental and a personnel nature.

Stout's method is strictly appropriate for making adjustments for the first type of error only. If the check measurements are taken frequently enough, fair adjustments may be made for the second type of error also. **The drawback of the Stout's method is that all the errors in current meter observation are mixed with the errors due to shift in control and are thus incorporated in the final estimates of discharge. The Stout method must therefore never be used where the rating is stable, or at least sufficiently stable to develop satisfactory rating curves between major shift events; use of the Stout method in such circumstances loses the advantage of a fitted line where the standard error of the line S_{mr} is 20% of the standard error of individual gaugings (S_e). Also, when significant observational errors are expected to be present it is strongly recommended not to apply this method for establishing the rating curve.**

3.6.4 Flow determined from daily gauging

Stations occur where there is a very broad scatter in the rating relationship, which appears neither to result from backwater or scour and where the calculated shift is erratic. A cause may be the irregular opening and closure of a valve or gate in a downstream structure. Unless there is a desperate need for such data, it is recommended that the station be moved or closed. If the station is continued, a daily measured discharge may be adopted as the daily mean flow. This practice however eliminates the daily variations and peaks in the record.

It is emphasised that even using the recommended methods, the accuracy of flow determination at stations which are affected by shifting control will be much less than at stations not so affected. Additionally, the cost of obtaining worthwhile data will be considerably higher. At many such stations uncertainties of ± 20 to 30% are the best that can be achieved and consideration should be given to whether such accuracy meets the functional needs of the station.