LECTURE 4

PROCESSING AND ANALYSIS OF STREAMFLOW DATA

OBJECTIVES

After attending this lecture, the participants would be able to know about the primary and secondary hydrological data processing of streamflow. The participants would also be able to know about the better methods for developing an accurate rating curve at a specific gauge and discharge site. Various methods for the extrapolation of the rating curves are discussed along with their advantages and limitations.

4.1 INTRODUCTION

Hydrological and related meteorological data are required for assessing, developing and managing the water resources of the country and its water related environment. The most important hydrological parameter is stream flow which is required for the efficient day to day management and regulation of a river system. Design, planning and hydrological modelling are some of the important aspects of the water resources projects where the stream flow data are utilized in one form or other. Stream flow data collected from the field as such can not be utilised in hydrological studies Therefore processing of the raw data is extremely essential in order to reduce in a manner to suit it for an analysis. Rainfall is the most important meteorological parameter which determines the quantity of runoff in streams directly as overland flow and indirectly as sub-surface flow and ground water (base flow). Thus, the amount, intensity and areal distribution of rainfall are essential in hydrological study. Preliminary processing of the rainfall data is essential before it is put to further use in analysis. Lecture no. 3 describes the processing and analysis of precipitation data. In this lecture the compilation, processing and analysis of stream flow data are discussed.

4.2 DATA PROCESSING

Data processing is the manipulation of data into a more useful form. Data processing includes not only numerical calculations but also operations such as the classification of data and transmission of data from one place to another. Data processing consists of three basic steps : input, processing and output. These three steps related as in Fig. 4.1 constitute the data processing cycle.

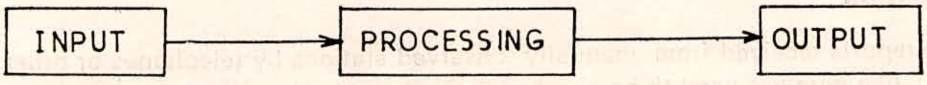

Fig. 4.1 Data Processing

(a) Input : In this step the initial data, or input data are prepared in some convenient form for processing. The form will depend on the processing machine. The input data could be

recorded on any one of several typas of input medium such as cards, tapes and so on if electronic computers are used.

(b) Processing : In this step the input data are changed, and usually combined with other information to produce data in a more useful form. The processing step usually involve a sequence of cetain basic processing operations.

(c) Output : Here the results of the preceeding processing steps are collected. The particular form of the output data depends on the use of the data. The output media may be cards, disk, tape and so on. The output data thus obtained, may be stored for further processing at a later date.

4.3 DATA REQUIREMENTS

Generally the streamflow data are required in the following forms for different hydrological studies :

i. Instantaneous discharges every day, hour or at smaller units.
ii. 3 days, 10 days, monthly, seasonal and yearly mean discharges
iii. Annual maximum flow
iv. Annual minimum flow
v. 1 day, 7 days, 10 days, 30 days, seasonal low flows and volumes.

The length of data for use in hydrological simulation studies vary from 10 years to 40 years depending upon the type of project and their uses.

4.4 COMPILATION AND PROCESSING OF BASIC HYDROLOGICAL DATA

Hydrological investigations specially carried out for the proposed project keeping in view the type and purpose of the project. The details of the specific data collected for the purpose shall be furnished. All the basic/processed hydrological data available from the various sources are relevant to the project shall be collected, compiled and discussed. The source of such data collected shall be indicated at the appropriate place. While processed data is available need or otherwise of further processing of the data shall be indicated.

4.4.1 Preliminary Processing and Scrutiny

Preliminary Processing and scrutiny of the data are essential before the observed data is stored on computer. The preliminary processing includes :

(a) Verification

The reports received from manually observed stations by telephones or other communication channels like wireless need to be checked by a repeat back system.

(b) Valid Status

The station reporting should form part of a standard network accompanied by proper identification with respect to its location i.e. latitude, longitude, district and state to which it belongs.

(c) Reasonable Report

Improper registering of data includes entering against wrong time and dates alteration of figures etc. Also transmission errors occur while sending the data either through telegram or wireless.

(d) Quality of Data

i. Methods of measurement/observation of hydrological data, standards followed, instruments used, frequency of observation etc. shall be discussed item wise.

ii. Details of history of station, shift in the location, shift in the rating curves should be identified. Sample calculation for discharge should be furnished. Mention shall be made as to whether discharge data is observed or estimated from the rating curve. Indicate the methods of estimation.

iii. Discuss development of stage discharge curves at discharge site bringing out the extrapolations shall be verified by other methods such as hydraulic calculations etc.

(e) Filling up of short Data gaps

The following are some of techniques which can be used for gap filling :

i. Random choice from values observed for that period.

ii. Interpolation from adjoining values by plotting a smooth hydrograph (for runoff alone).

iii. Double mass curve techniques

iv. Correlation with adjoining station either of the same hydrologic element or different hydrologic elements.

v. Auto correlation with earlier period at the same station.

(f) Consistency of data

i. Internal consistency check : The study of consistency of the observed data at specific control points and corrections if any made shall be checked and discussed. The check can be done by study of stage discharge relationship for different periods. Large variations if any should be investigated, corrected and explained suitably if required.

Trend analysis should be performed :

- To detect a slow continuous variation of meteorological conditions or a long periodic variation of the climate.
- To observe the modification of catchment physiography especially through human activity.

ii. External consistency check ; The consistency of the observed stream flow data should be discussed with reference to the rainfall in the project catchment and observed data in adjacent locations/basins.

Note : The consistency can be checked by :

- Comparing monthly and annual rainfall with corresponding runoff.
- Comparing average annual specific flow expressed in depth unit with corresponding figures at other sites of the same river or adjacent basins.
- Comparing the hydrograph of daily discharge at the control point with adjacent sites etc.
- Use of double mass curve techniques
- Trend analysis

(g) Quality control procedures

Some of the methods for quality control are

- Testing the stage or discharge of a given day within a year against the highest and lowest value of the same date in all the previous years.
- Apply the same test on the difference between the value on the day and the day before.
- Comparing observed data with estimates based on data from adjacent stations. The estimates may be based on regressions. By transforming the data it is possible to increase the weight on high or low values. By plotting the estimates possible errors are easily identified.
- Comparing the observed data with estimates based on a precipitation runoff.
- Checking for negative values during the computation of inflow to a reservoir when the stage storage relationship and the outflow are known.
- Comparing the runoff at a station with runoff at upstream stations.
- Applying double mass curve analysis to identify shift in control.
- Applying time series analysis to detect changes in the homogeneity in time series. This is a valuable supplement to double mass analysis.
- Plotting a graph of the points at which measurements are made and comparison with the original cross section.
- Plotting the graph of the annual regime of specific discharges and regional comparison.
- Regional comparisons of monthly and annual streamflow deficits.

(h) Adjustment of records

The adjustment of flows to natural and virgin conditions for historical uses in the upper reaches and the manner in which this has been done should be discussed duly supported by the withdrawl data, reservoir operation data and irrigation statistics. Where adjustments due to upstream storage are made, such storage changes and evaporation losses are to be properly accounted for. Apart from adding upstream withdrawls return flows have to be subtracted.

Note : 1. The adjustment of the observed flows data may not be necessary if,

- The utilisation by upstream projects has been same throughout the period of observation of flows.
- If the pattern and quantum of usage has not changed appreciably or with a definite trend.

2. Adjustment with the flow records is required in those cases where appreciable changes in land use have taken place.

3. Adjustment of floods and low flows to remove the effect of upstream regulation may be required where this is appreciable.

4.4.2 Secondary Data Processing

Specific tasks in secondary data processing include :

- Calculation of mean velocity and discharge based on stream gaugings.
- Analytical fitting of stage-discharge relations (described in section 4.5 of this lecture).
- Conversion of stages to discharges.
- Preparation of regular time series containing monthly tables of hourly values with means and extremes, annual tables of daily values with means and extremes and miscellaneous graphs showing variations with time.
- Preparation of chronological tables with elementry statistical parameters, daily data tables for spatial comparison, multi-annual summary tables of monthly and annual value (means, totals, extremes or frequencies of occurrence) with elementary statistical parameters, discharge classified into ranges and probability envelope curves (table and graphs) and characteristics discharges and probability envelope curves etc.

4.4.3 Analysis of Processed data

The following analysis are normally performed with the processed data :

- Computation of flow duration curves
- Computation of summation and regulation curves
- Computation of natural runoff from a regulated reservoir
- Computation of the inflow to a reservoir
- Routing of flood through reservoir or river channels
- Unit hydrograph analysis
- Flood forecasting
- Computation of flow-frequency curves

- Flood frequency analysis
- Low flow frequency analysis
- Analysis of flood or low water volumes
- Multiple linear regression analysis
- Time series analysis.

4.5 STAGE-DISCHARGE RELATIONSHIP (RATING CURVE)

The primary objective of a gauging station is to provide a record of the stage and discharge of a river. The water level and the volume of water passing a site of river provides useful information about the flow, which can be used for many purposes in water resources planning and management. The water levels are easily measured in comparison to discharge even at very short intervals. The measurement of discharge of a river by direct measurements is laborious and also costly. But the data of the discharge at shorter intervals are needed for unit hydrograph studies. This is achieved by computing the discharge using the data of water level observations. To enable such computation a relationship between stage and discharge is established. Such relationships are also known as the rating curves.

When the measured values of discharges plotted against the corresponding stages give a relationship that represents the integrated eflect of a wide range of channel and flow parameters. The combined effect of these parameters is termed as control. If the stage-discharge relationship for a gauging section is constant and does not change with time, the control is said to be permanent. It is called shifting control if it changes with time. Generally, alluvial rivers pose the problems of shifting control.

4.5.1 Factors Responsible for Shifting Control

At a gauging site the control that exists giving rise to a unique stage-discharge relationship can change due to :

(i) the changing characteristics caused by weed growth, dredging or channel encroachment

(ii) the accumulation of ice.

(iii) aggredation or degradation phenomenon in an alluvial channel,

(iv) variable back water effects affecting the gauging section

(v) the presence of flood plain where the flow characteristics are very much different than main channel

(vi) unsteady flow effects of a rapidly changing stages.

There are no permanent corrective measures to tackle the shifting controls due to causes (i), (ii), (iii) and (v) listed above. The only recourse in such cases is to have frequent current meter gauging and to update the rating curves. However, methods are available to tackle the shifting controls due to causes (iv) and (vi).

4.5.2 Development of Rating Curves

4.5.2.1 Permanent control

Generally non alluvial rivers exhibit permanent control. For such a case, the relationship between the stage and discharge is expressed in the following form :

$$Q = a\,(H - H_o)^b \tag{4.1}$$

where Q = stream discharge (m^3/sec)

H = Gauge height (stage) (metre)

H_o = A constant which represent the gauge reading corresponding to zero discharge

a and b = Rating curve constants

The relationship given by Eq. (4.1) can be graphically expressed by plotting the observed stage against the corresponding values of discharge in an arithmetic or largarithmic plot. Fig. 4.2 and 4.3 illustrate the stage discharge curves on arithmatic and logarithmic plots respectively. Logarithmic plotting is advantageous as Eq. (4.1) plots as a straight line in logarithmic scale. Note that the co-efficients a and b need not be the same for the full range of stages.

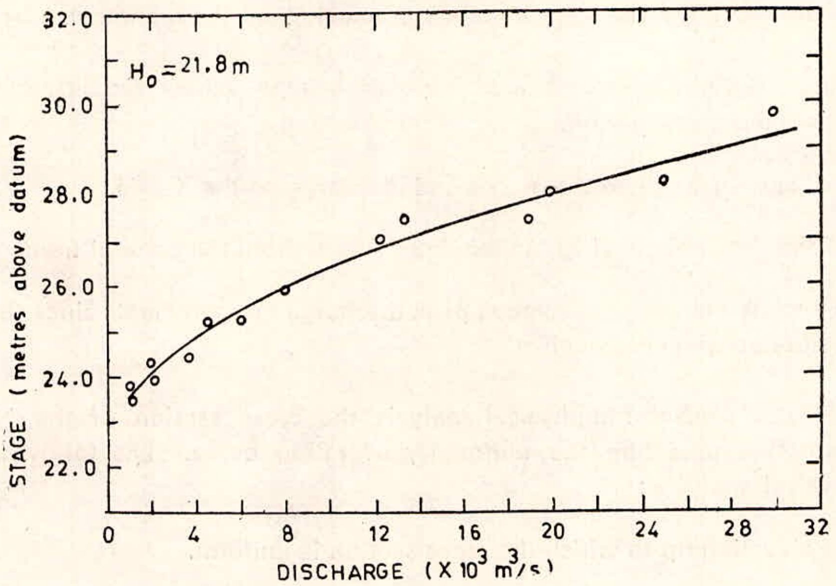

Fig. 4.2 : Stage Discharge Curve-Arithmetic Plot

In case of no shifting controls the rating curves may be developed using the following methods.

(c) Data analysis
(d) Physical analysis
(c) Double log plot
(d) Least Square method

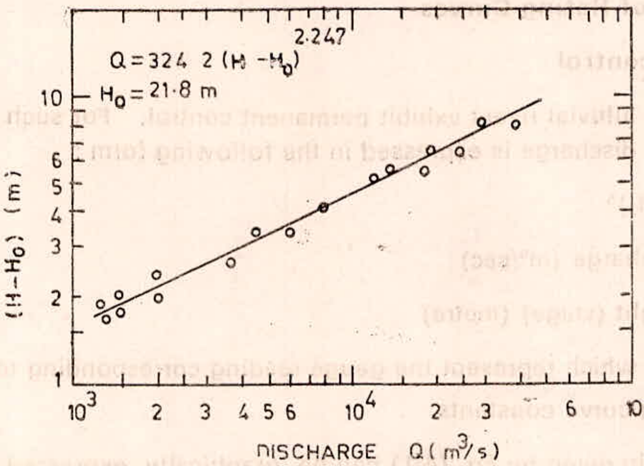

Fig. 4.3 : Stage Discharge Curve-Logarithmic Plot

(a) Data analysis : The steps involved in developing the rating curve by this method are :

(i) Group the measured discharge and corresponding stage values for different years pertaining to the site under investigation.

(ii) Plot the data with stage on the Y-axis and discharge on the X-axis.

(iii) Mark off the data points which are obviously away from the general trend.

(iv) Do not be misled however to remove peak discharge measurements since the deviation could be a possible physical mechanism.

(b) Physical analysis : In physical analysis the cross section of the river reveals certain important information regarding the uniformity of rating curve. The following steps may be followed in physical analysis :

(i) Note the elevation up to which the cross section is uniform.

(ii) Choose the exponent b in the Eq. (4.1) as follows :

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

(iii) Take the average bed level as the value for H_o in Eq. (4.1).

(iv) Compute the value of the co-efficient as appeared in Eq. (4.1) using the following relationship

$$a = \frac{1}{n} W S^{1/2} \tag{4.2a}$$

where,

W is the top width of the channel,

S is the bed slope, and

n is Manning's co-efficient.

In Eq. (4.2a) W and S would be known from the available cross section of the river at the gauging site and longitudinal section of the river. Fig. 4.4 shows a typical cross section of a river at the gauging site. The value of n can be evaluated as follows :

— For gravel bed rivers the emperical equation given by Strickler may be used. The equation is :

$n = 0.034\ d^{1/6}$ ......(4.2b)

where d is median size of the bed materials in mm.

— Typical values of 'n' for natural rivers are : (Henderson (1966))

clean and straight river channel 0.025—0.03

winding with pools and shoals 0.033—0.04

very weedy, winding and overgrown 0.075—0.15

(c) Double log plot

The grouped data obtained from step (i) of the data analysis are plotted on a double logarithmic paper. The advantage of using double logarithmic plot is two fold. Firstly, the plot would produce straight lines. Since general form of rating curve is parabolic. Secondly, different straight lines allow to further grouping of data. A part or the entire range of the stage may form a straight line. It gives an indication about the stage at which the slope of the straight lines changes if more than one straight lines are used for re-presenting the rating curve. Use of different symbols for different periods (years) of data would enable one to identify the uniform deviations if any present from the mean. In case of such deviations either different rating curves should be developed for each year or use the methods discussed in later part of this lecture for correcting the observed stages depending upon the factors responsible for shifting control.

While plotting the data on double log plot a prior knowledge about the value of H_o in Eq. (4.1) is necessary. As a first approximation the value of H_o is assumed to be the level of the bottom of the channel as determined from the cross section of the gauging site. Marginal adjustment in the value of H_o may be required in order to produce a straight line giving better fit to the plotted points. In case if a single straight line could not be fitted inspite of trials with various values of H_o, it should be concluded that the data need grouping for different relations and dealt accordingly as explained in the previous paragraph.

(d) Least Square Method

The best values of a and b in Eq. (4.1) for a given range of stage are obtained by the least square error method. Thus by taking logarithms of Eq. (4.1).

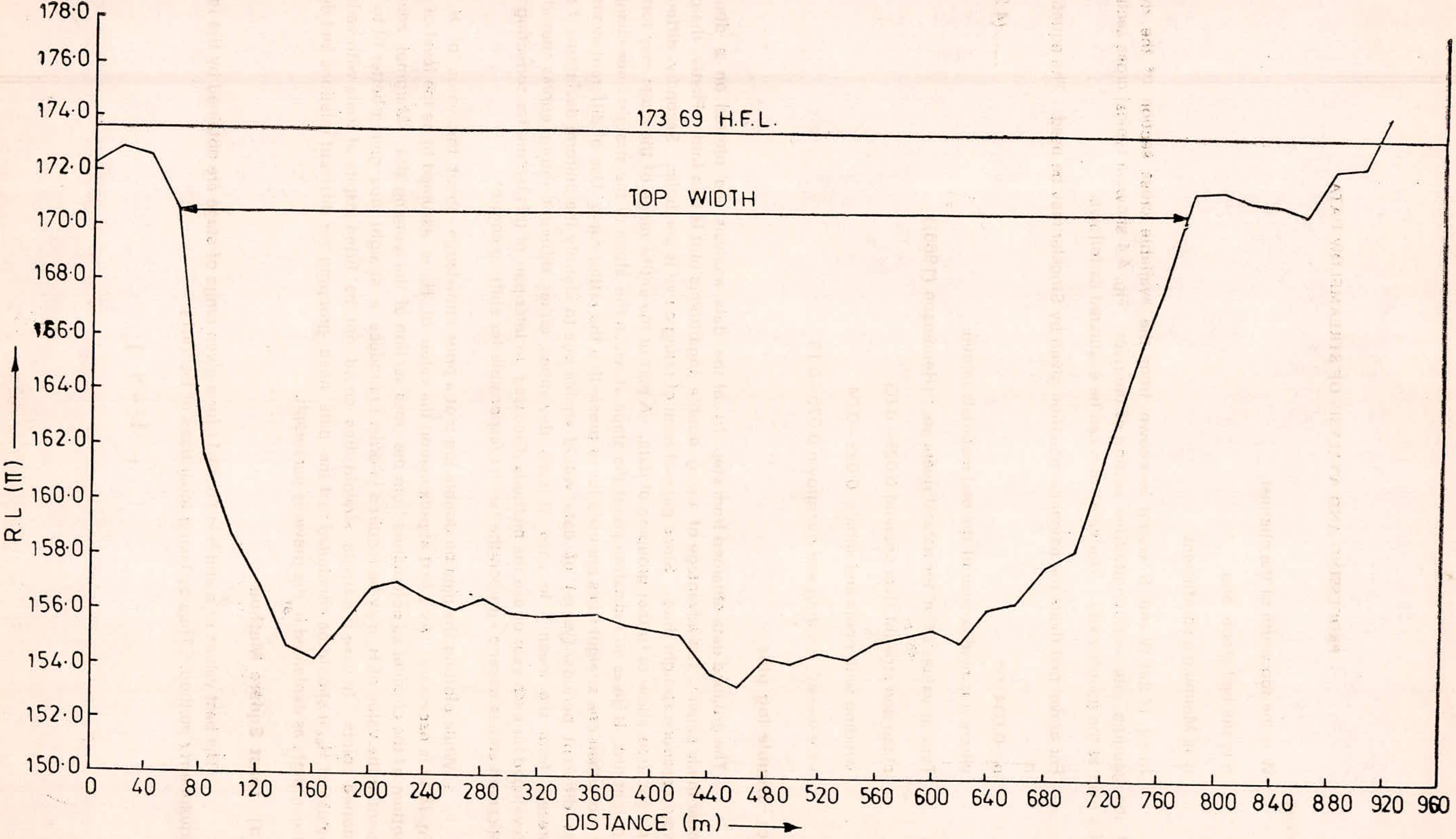

Fig. 4.4 : Cross Section of A Typical Gauging Site

$$\log_e Q=\log_e a+b\ \log_e (H-H_o) \tag{4.3}$$

or $$Y=\alpha+\beta X \tag{4.4a}$$

where $$Y=\log_e Q \tag{4.4b}$$

$$X=\log_e (H-H_o) \tag{4.4c}$$

$$\alpha=\log_e a \tag{4.4d}$$

$$\beta=b \tag{4.4e}$$

For the best fit straight line or N observations of X and Y

$$\beta=\frac{N(\Sigma XY)-(\Sigma X)\quad(\Sigma Y)}{N(\Sigma X^2)\ -(\Sigma X)^2} \tag{4.5}$$

and $$\alpha=\frac{\Sigma Y-\beta\ (\Sigma X)}{N} \tag{4.6}$$

In the above it should be noted that H_o is an unknown and its determination poses some difficulties. The following alternate methods are available for its determination :

(i) Plot Q VS H on an arithmatic graph paper and draw a best fit curve. By extrapolating the curve by eye judgement find H_o as the value of H corresponding to $Q = 0$. Using this value of H_o, plot log Q VS log $(H—H_o)$ and verify whether the data plots as a straight line. If not, select another value in the neighbourhood of previously assumed value and by trial and error find an acceptable value of H_o which gives a straight line plot of log Q VS log $(H-H_o)$. In order to avoid the plotting for each trial value of H_o the least square method discussed earlier in this lecture is used and the value of a fitting parameter 'r' which may be computed using Eq. 4.7 are compared for each trial run. That value of H_o is finally accepted which gives the fitting parameter closest to one.

$$r=\sqrt{1-\frac{F_1}{F_o}} \tag{4.7a}$$

where $$F_o=\sum_{i=1}^{N}(Y_i-\overline{Y})^2\ /\ (N-1) \tag{4.7b}$$

$$F_1=\sum_{i=1}^{N}(Y_i-\hat{Y}_i)^2\ /\ (N-2) \tag{4.7c}$$

Y_i = logarithms of observed discharge values

$\overline{Y}$ = Mean of the logarithms of observed discharge values

$\hat{Y}_i$ = logarithms of computed discharge values obtained from Eq. (4.4a)

(ii) A graphical method due to Running is as follows : (Wisler and Brater (1959)).

The Q VS H data are plotted to arithmatic scale and smooth curve through the plotted points are drawn. Three points A, B and C on the curve are selected such that their discharges are in geometric progression (Fig. 4.5) i.e.

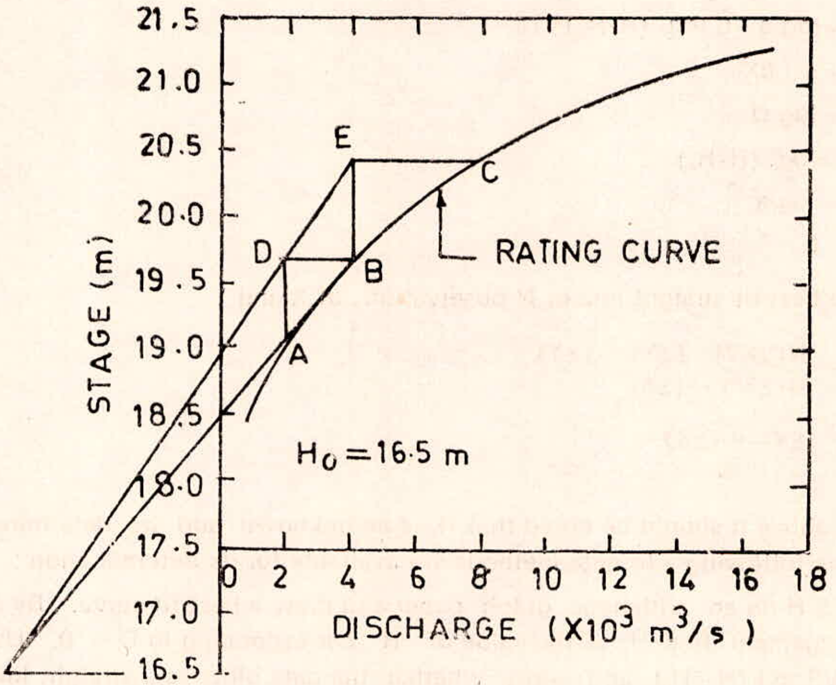

Fig. 4.5 : Running's Method for Estimation of the Constant H_0

$$\frac{Q_A}{Q_B} = \frac{Q_B}{Q_C} \tag{4.8}$$

At A and B vertical lines are drawn and then horizontal lines are drawn at B and C to get D and E as intersection point with the verticals. Two straight lines ED and BA are drawn intersect at F. The ordinate at F is the required value of H_{or} the gauge height corresponding to zero discharge. This method assumes the lower part of the stage-discharge curve to be a parabola.

(iii) Plot Q VS H to an arithematic scale and draw a smooth good fitting curve by eye judgement. Select three discharges Q_1, Q_2 and Q_3 such that $Q_1/Q_2 = Q_2/Q_3$ and note from the curve the corresponding values of gauge reading H_1, H_2 and H_3. From Eq. (4.3]

$$(H_1 - H_0) \,/\, (H_2 - H_0) = (H_2 - H_0) \,/\, (H_3 - H_0)$$

$$\text{i.e. } H_0 = \frac{H_1 H_3 - H_2^2}{(H_1 + H_3) - 2H_2} \tag{4.9}$$

(iv) A number of optimisation procedures that are based on the use of computers are available to estimate the best value of H_0. A trial and error search for H_o which gives the best value of the correlation co-efficient (fitting parameter 'r' as expressed by Eq. (4.7) is one of them.

The following example illustrates the development of rating curve using Least Square Method.

Example 4.1

The values of observed stage and corresponding discharge are given below for a gauging site :

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

Develop the rating curve in the form of $Q = a\,(H - H_0)^b$ for the gauging site assuming H_0, the value of the gauge corresponding to zero discharge, equal to 21.00 metre. Also compute the correlation co-efficient 'r' for the rating curve equation.

Solution :

(i) Table 4.1 shows the computation of various terms involved in Eq. (4.5) and (4.6) which provide the solution for α and β for the above example. Hence from Table 4.1.

$\Sigma X = 14.203$

$\Sigma Y = 90.478$

$\Sigma XY = 97.004225$

$\Sigma X^2 = 17.4143$

$N = 14$

Putting the above values in Eq. (4.5) and (4.6) one will get

$$\beta = \frac{14 \times 97.004225 - 14.203 \times 90.478}{14 \times 17.443 - (14.203)^2}$$

$$\beta = \frac{73.000116}{42.476791}$$

$$\beta = 1.718$$

$$\alpha = \frac{90.478 - 1.718 \times 14.203}{14} = 4.719$$

Thus the rating curve equation in log domain will be written as :

$$Y = 4.719 + 1.718\,X$$

and the above equation in real domain will be written as :

$$Q = e^{4.719}\,(H - 21)^{1.718}$$

$$= 112.06\,(H - 21)^{1.718}$$

Here $H_o = 21.0$ metre

(ii) Various terms used in Eq. (4.7 a) which computes the correlation coefficient are evaluated in Table 4.2 and given below :

$$\sum_{i=1}^{14} (Y_i - \overline{Y})^2 = 9.146, \qquad \text{where } \overline{Y} = \Sigma\, Y/N = 90.478/14 = 6.463$$

$$\sum_{i=1}^{14} (\hat{Y} - Y_i)^2 = 0.10$$

$$\therefore \text{Fo} = \frac{9.146}{14-1} = 0.704$$

$$F_1 = \frac{0.10}{14-2} = 0.008$$

$$\therefore r = \sqrt{1 - \frac{0.008}{0.704}}$$

$$= 0.994$$

Hence the required co-efficient of correlation is equal to 0.994.

Table 4.1 Development of Rating curve using Least Square Method

No.	H (metre)	$H-H_o$ (metre)	Q (m^3/S)	$X=\ln(H-H_o)$	$Y=\ln Q$	X^2	XY
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
1.	21.95	0.95	100	—0.051	4.605	0.002601	—0.234855
2.	22.45	1.45	220	0.372	5.394	0.138384	2.006568
3.	22.80	1.80	295	0.588	5.687	0.345744	3.343956
4.	23.00	2.00	400	0.693	5.991	0.480249	4.151763
5.	23.40	2.40	490	0.875	6.194	0.765625	5.41975
6.	23.75	2.75	500	1.012	6.215	1.024144	6.28958
7.	23.65	2.65	640	0.975	6.461	0.950625	6.299475
8.	24.05	3.05	780	1.115	6.659	1.243225	7.424785
9.	24.55	3.55	1010	1.267	6.918	1.605289	8.765106
10.	24.85	3.85	1220	1.348	7.107	1.817104	9.580236
11.	25.40	4.40	1300	1.482	7.170	2.196324	10.62594
12.	25,15	4.15	1420	1.423	7.258	2.024929	10.328134
13.	25.55	4.55	1550	1.515	7.346	2.295225	11.12919
14.	25.90	4.90	1760	1.589	7.473	2.524921	11.874597
				14.203	90.478	17.4143	97.004225

Table 4.2 Computation of correlation co-efficient

H (Metre) (1)	$(H-H_o)$ (Metre) (2)	Q $(m^{3/5})$ (3)	$X=\ln(H-H_o)$ (4)	$Y=\ln Q$ (5)	$\hat{Y}$ (6)	$(Y-\bar{Y})^2$ (7)	$(\hat{Y}-Y)^2$ (8)
21.95	0.95	100	—0.051	4.605	4.631	3.452	0.0007
22.45	1.45	220	0.372	5.394	5.358	1.143	0.0013
22.80	1.80	295	0.588	5.687	5.729	0.602	0.0018
23.00	2.00	400	0.693	5.991	5.910	0.223	0.0066
23.40	2.40	490	0.875	6.194	6.222	0.072	0.0008
23.75	2.75	500	1.012	5.215	6.458	0.062	0.0590
23.65	2.65	640	0.975	6.461	6.394	0.000	0.0045
24.05	3 05	780	1.115	6.659	6.635	0.038	0.0006
24 55	3.55	1010	1.267	6.918	6.896	0.207	0.0005
24.85	3.85	1220	1.348	7.107	7.035	0.415	0.005
25.40	4.40	1300	1.482	7.170	7.265	0.500	0.009
25.15	4.15	1420	1.423	7.258	7.164	0.632	0.009
25 55	4.55	1550	1 515	7.346	7.322	0.780	0.0006
25.90	4.90	1760	1.589	7.473	7.449	1.020	0.0006
				90.478		9.146	0.100

4.5.2.2 Shifting control

As discussed earlier, the stage-discharge curve do change with time due to various factors. This section describes some of the method for appling the shifting control corrections with time and/or stage. The choice of the methods depends upon the factors responshible for shifting control.

(a) Correction for systematic shift

(b) Correction for back water effect

(c) Correction for unsteady flow effect

(a) Correction for systematic shift : Shift is defined as the difference between the observed stage and calculated stage from rating curve with the same discharge. On many sandy rivers it is not possible to find or construct a stable control. The sites used for constructing the controls are generally subjected to scour and deposit in irregular pattern. If the shift in control follow some systematic pattern, then the observed stages may be corrected for those shifts and a median rating curve developed based on permanent control concept may be used for the estimation of correct discharge values corresponding to the corrected stage values. The steps to be followed for applying the corrections for the systematic shifts are :

(i) Prepare a median rating curve

(ii) Calculate shift in stage values by subtracting the stage values obtained from the median rating curve and the observed stage with same discharge.

(iii) Plot the shift values obtained from step (ii) Vs time.

(iv) Based on the systematic pattern observed in shifting control, draw a curve through the points plotted at step (iii).

(v) Use the curve of step (iv) to compute the shift corrections in stage values observed at different times.

The following example illustrates the above procedure.

Example 4.2 :

The rating table for a small river is defined by :

H=0.1	0.2	0.3	0.4	0.5	0.6	0.7	0 8	0.9	1.0
Q=1.1	1.8	2.7	3.8	5.0	6.4	8.0	9.8	11 8	14.0

Where H in metres and Q in m^3/S. The control section has a gravel bed which is known to shift. During March 1975, reliable gaugings were taken as :

March	1	10	19	26	31	
Gauge Height	0.85	0.50	0.10	0.98	1.16	m
Discharge	8.0	6.8	1.1	12 5	17.9	m^3/s

The mean daily gauge heights for March were consecutively :

0.85	0.84	0.82	0 75	0.70	0.66	0.61
0.57	0.54	0.50	0.45	0.41	0.36	0.29
0,24	0.20	0.16	0.13	0.10	0 09	0.13
0.30	0.72	0 88	0.98	1.10	1.06	1.04
1.08	1.13	1.16				

Calculate the mean daily flow for March using the shift correction procedure

Solution : The steps to be followed are :

(i) Prepare the rating curve from this given rating table (Fig. 4.6). Extend the rating curve by eye judgement.

(ii) Calculate the shift in stage values available from reliable gauging. The calculation is shown ir the Table 4.3.

Table 4.3 : Computation of shift in reliable ganuge readings

Date	Observed discharge (m^3/s)	Observed stage (metre)	Stage from rating curve (metre)	Shift
(1)	(2)	(3)	(4)	(5) = (4) — (3)
1	8.0	0.85	0.7	—0.15
10	6.8	0.50	0.62	0.12
19	1.1	0.10	0.10	0
25	12.5	0.98	0.94	—0.04
31	17.9	1.16	1.16	0

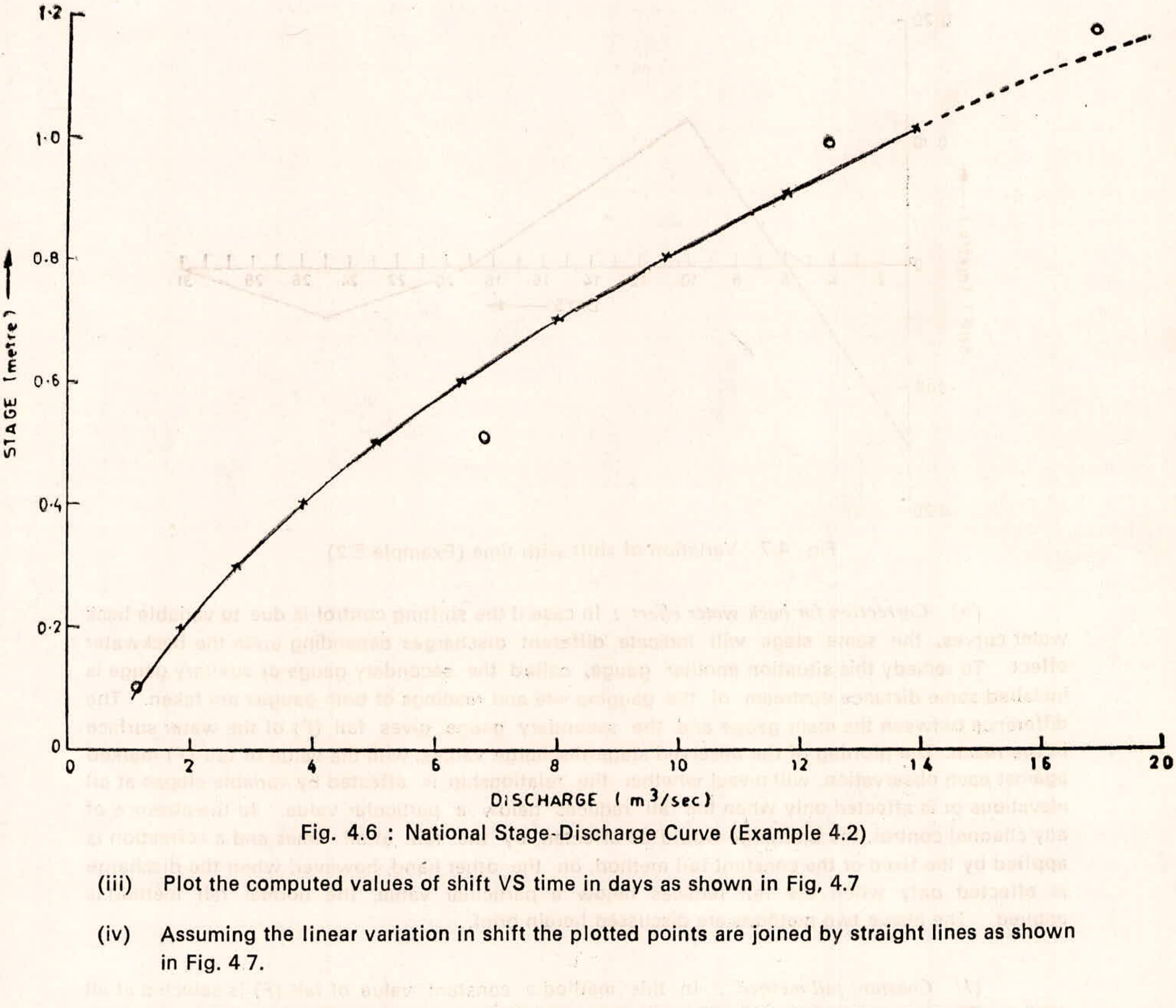

Fig. 4.6 : National Stage-Discharge Curve (Example 4.2)

(iii) Plot the computed values of shift VS time in days as shown in Fig, 4.7

(iv) Assuming the linear variation in shift the plotted points are joined by straight lines as shown in Fig. 4 7.

(v) Read the values of shift corrections for each day from Fig. 4.7. Enter these values in column (3) of Table 4.4.

(vi) Apply the shift corrections to the observed gauge values suitable for use in rating curve. Column (4) of Table 4.4 shows these values.

(viii) Read the discharge values corresponding to the corrected gauge values If provides the required estimates of mean daily flow for March. These discharge values are given in column (5) of Table 4.4.

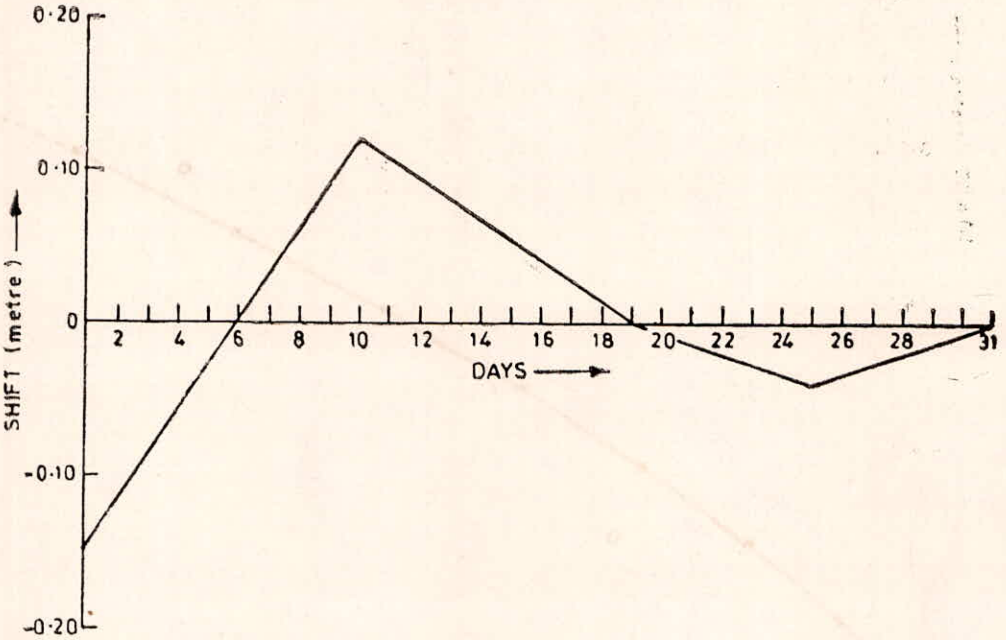

Fig. 4.7 Variation of shift with time (Example 5.2)

(b) Correction for back water effect : In case if the shifting control is due to variable back water curves, the same stage will indicate different discharges depending upon the backwater effect. To remedy this situation another gauge, called the secondary gauge or auxilary gauge is installed some distance upstream of the gauging site and readings of both gauges are taken. The difference between the main gauge and the secondary gauge gives fall (F) of the water surface in the reach. The plotting of the observed stage-discharge values, with the value of fall (F) marked against each observation, will reveal whether the relationship is affected by variable slopes at all elevations or is affected only when the fall reduces below a particular value. In the absence of any channel control, the discharge would be affected by the fall at all times and a correction is applied by the fixed or the constant fall method, on the other hand, however, when the discharge is affected only when the fall reduces below a particular value, the normal fall method is applied. The above two methods are discussed herein brief.

(I) Constant fall method : In this method a constant value of fall (F) is selected at all stages. The actual fall (F) at all observed gauge values are estimated. An approximate Q_o Vs H (Gauge height curve) for the constant fall F_o, called constant tall curve, is drawn (Fig. 4.8). For each observed data, Q/Q_o and F/F_o values are calculated and plotted as Q/Q_o VS F/F_o (Fig. 4.9). This curve is called the adjustment curve. Both the constant fall curve and adjustment curve are refined, by trial and error to get the best fit curves. Finally the two curves constant fall curve and adjustment curve, provide the stage-discharge information for gauging purpose. For example, if the observed stage is H_1 and fall F_1, first by using the adjustment curve the value of Q_1/Q_o is read for a known value af F_1/F_o. Using the constant fall rating curve, Q_o is read for the given stage H_1 and the actual discharge calculated as $(Q_1/Q_o)\ Q_o$.

Table 4.4 : Computation of mean daily discharge for March

Day	Observed gauge (metre)	Shift correction (metre)	Corrected gauge (metre)	Discharge from rating curve (m³/sec)
(1)	(2)	(3)	(4) = (2) + (3)	(5)
1	0.85	—0.15	0.70	8.0
2	0.84	—0.12	0,72	8.4
3	0.82	—0.09	0.73	8.5
4	0.75	—0.06	0.69	7.9
5	0.70	—0.03	0.67	7.6
6	0.66	0.00	0.66	7.4
7	0.61	0.03	0.64	7.1
8	0,57	0.06	0.63	7.0
9	0.54	0.09	0.63	7.0
10	0.50	0.12	0.62	6.8
11	0.45	0.105	0.555	5.0
12	0.41	0.09	0.50	5.0
13	0.36	0.08	0.44	4.3
14	0.29	0.07	0.36	3.4
15	0.24	0.05	0.29	2.7
16	0.20	0.04	0.24	2.2
17	0.16	0.03	0.19	1.8
18	0.13	0.01	0.14	1.4
19	0.10	0.0	0.10	1.1
20	0.09	—0.01	0.08	1.0
21	0.13	—0.012	0.118	1.2
22	0.30	—0.02	0.28	2.6
23	0.72	—0.03	0.69	7.9
24	0.88	—0.035	0.745	9.0
25	0.98	—0.04	0.94	12 5
26	1.00	—0.035	0.965	13,2
27	1.05	—0.028	1.022	14.2
28	1.04	—0.02	1.02	14.1
29	1.08	—0.015	1.065	15.6
30	1.13	—0.01	1.12	17.0
31	1.16	0	1.16	17.9

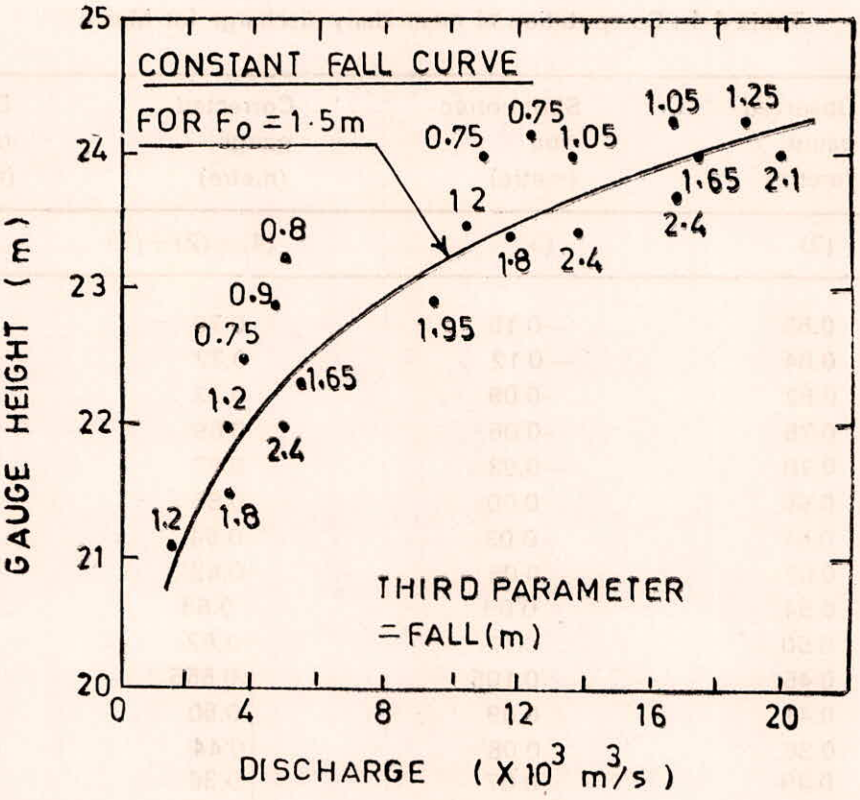

Fig. 4.8 Constant fall curve

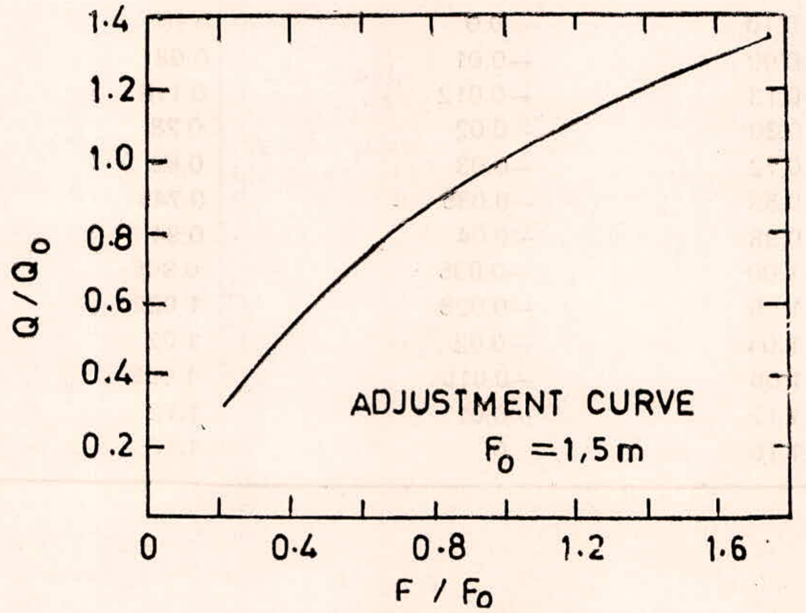

Fig. 4.9 Adjustment Curve

The following example illustrates the above method.

Example 4.3 The discharge measurements at a gauging station are given below together with the corresponding river levels at the primary gauge A and a subsidiary gauge B upstream. Draw a rating curve for a constant fall of 0.10 meters and hence obtain the best estimate for the discharge when the gauge reading at primary gauge A and subsidiary gauge B are 2.70 m and 2.86 m respectively.

A (m)	2.20	2.30	2.33	2.40	2.47	2.50	2 60	2 64	2.69	2,56
B (m)	2.35	2.50	2,38	2.52	2.60	2.54	2.67	2.79	2.77	2.67
Q (m^3/s)	15.0	26.8	9.2	24.5	37.5	19.1	34.5	65.0	54.0	42.0

Solution :-

The computation steps involved in the solution of the problem posed in the above example are given below :

(i) Compute the fall (F) corresponding to each observation by subtracting the observed stage values at B. These valuse are given in column (4) of the Table 4.5.

(ii) Mark the points on a sheet of graph paper corresponding to the values of stage & discharge for the primary gauge. (Fig. 4.10).

(iii) Write down the values of fall computed from step (i) closer to the marked points on the graph paper as shown in Fig. 4.10.

(iv) Draw a curve of constant fall of 0.10 meter through the plotted points as shown in Fig. 4.10. This curve is called constant fall curve.

(v) Read the values of Q_o, which is the normalized discharge at the given stage when the fall is equal to 0.10 metere, from the curve drawn at step (iv) corresponding to the stage values at the primary gauge A, These values are given in Column (6) of the Table 4.5.

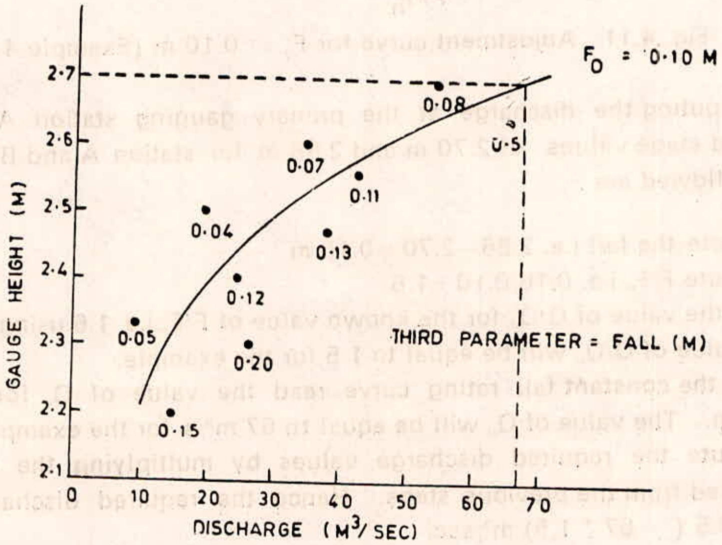

Fig. 4.10 Constant fall curve for F_o = 0.10m (Example 4.3)

(iv) Compute Q/Q_o for each observed data and enter these values in column (7) of the Table 4.5.

(vii) Compute F/F_o for each observed data and enter those values in column (8) of the Table 4.5. Here the values of F are computed from Step (i) and F_o is equal to 0.10 for the given example.

(viii) Draw a smooth curve through the plotted points on arithmatic graph paper taking Q/Q_o on Y-axis and F/F_o on X-axis as shown in Fig. 4.11. This curve is called the adjustment curve.

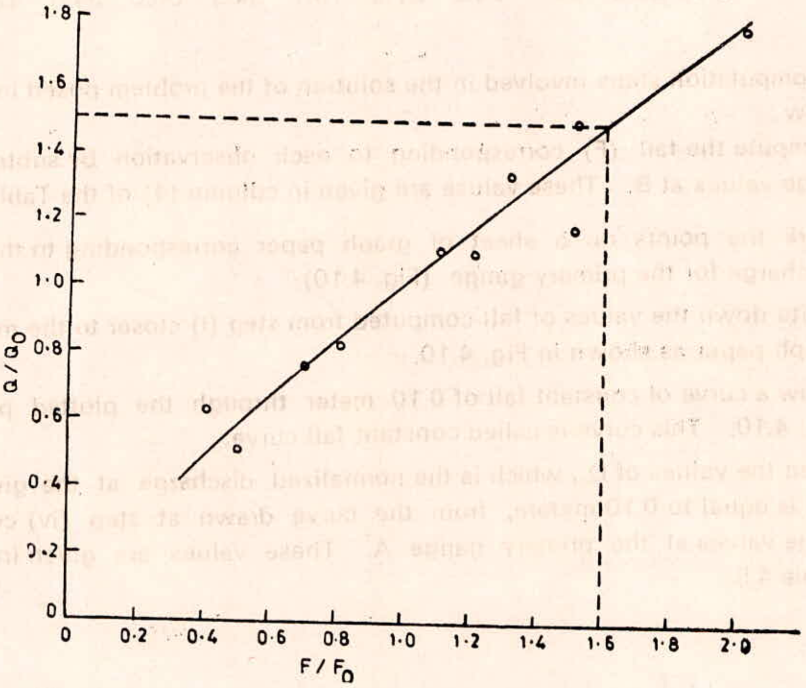

Fig. 4.11 Adjustment curve for F_o = 0.10 m (Example 4.3)

(ix) For computing the discharge at the primary gauging station A corresponding to the observed stage values of 2.70 m and 2.86 m for station A and B respectively the steps to be followed are :

- Compute the fall i.e. 2.86—2.70=0.16 m.
- Compute F/F_o i.e. 0.16/0.10=1.6.
- Read the value of Q/Q_o for the known value of F/F_o i.e. 1.6 using the adjustment curve. The value of Q/Q_o will be equal to 1 5 for the example.
- Using the constant fall rating curve read the value of Q_o for the given stage value 2.70 m. The value of Q_o will be equal to 67 m³/s for the example.
- Compute the required discharge values by multiplying the values of Q/Q_o and Q_o obtained from the previous steps. Hence the required discharge value will equal to 100.5 (= 67 * 1.5) m³/sec.

Table 4.5 : Constant fall method computations

No. (1)	H_B (m) (2)	H_A (m) (3)	F (m) (4)=(2)—(3)	Q (m³/sec) (5)	Q_o (m³/sec) (6)	Q/Q_o (7)=(5)/(6)	F/F_o (8)=(4)/0.1
1.	2.35	2.20	0.15	15	10	1.5	1.5
2.	2.50	2.30	0.20	26.8	15	1.79	2.0
3.	2.38	2.33	0.05	9.2	18	0.51	0.5
4.	2.52	2.40	0.12	24.5	22	1.11	1.2
5.	2.60	2.47	0.13	37.5	28	1.34	1.3
6.	2.54	2.50	0.04	19.1	31	0.62	0.4
7.	2.67	2.60	0.07	34.5	45	0.77	0.7
8.	2.79	2.64	0.15	65.0	55	1.18	1.5
9.	2.77	2.69	0.08	54.0	65	0.83	0.8
10.	2.67	2.56	0.11	42.0	31	1.11	1.1

(II) Normal fall method :

This method is useful if the usual simple rating is applicable at sufficient falls when backwater effect is absent, while for low falls the discharge is affected by backwater. Critical values of the fall dividing these two regions are termed the "normal fall". The value of normal fall at any discharge can be determined by studying the plot of stage against discharge. The point at which back water has no effect will group at the extreme right. This is the simple rating curve as shown in Fig. 4.12. A plot of the normal fall values vs corresponding stages is made as shown in Fig. 4.13. Such plots enable the drawing of a curve for discharge ratios where normal fall is used in place of constant fall. Fig. 4.14 shows a typical curve where the ratio of measured fall to normal fall is plotted against the ratio of measured discharge to normal discharge. The rest of the procedure is similar to that of the constant fall method.

(c) Correction for unsteady flow effect :

The stage-discharge relationship for a single gauge station gives the value of the normal discharge i.e. the discharge under uniform steady flow conditions for a given stage. But in field it is very difficult to achieve the steady flow situations. When a flood wave passes a gauging site the approach velocities in the advancing portion of the wave are larger than in the steady flow at corresponding stages. Thus, for the same stage, more discharge than in a steady uniform flow occurs. In the receding phase of the flood wave the converse situation occurs with reduced approach velocities giving lower discharges than in an 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 Fig. 4.15. The looping in the stage discharge curve is called hysteresis in the stage-discharge relationship. From the curve, it can be easily noted that at the same stage, more discharge passes through the river during rising stages than in falling ones. Since the conditions for each flood may be different; different floods may give different loops.

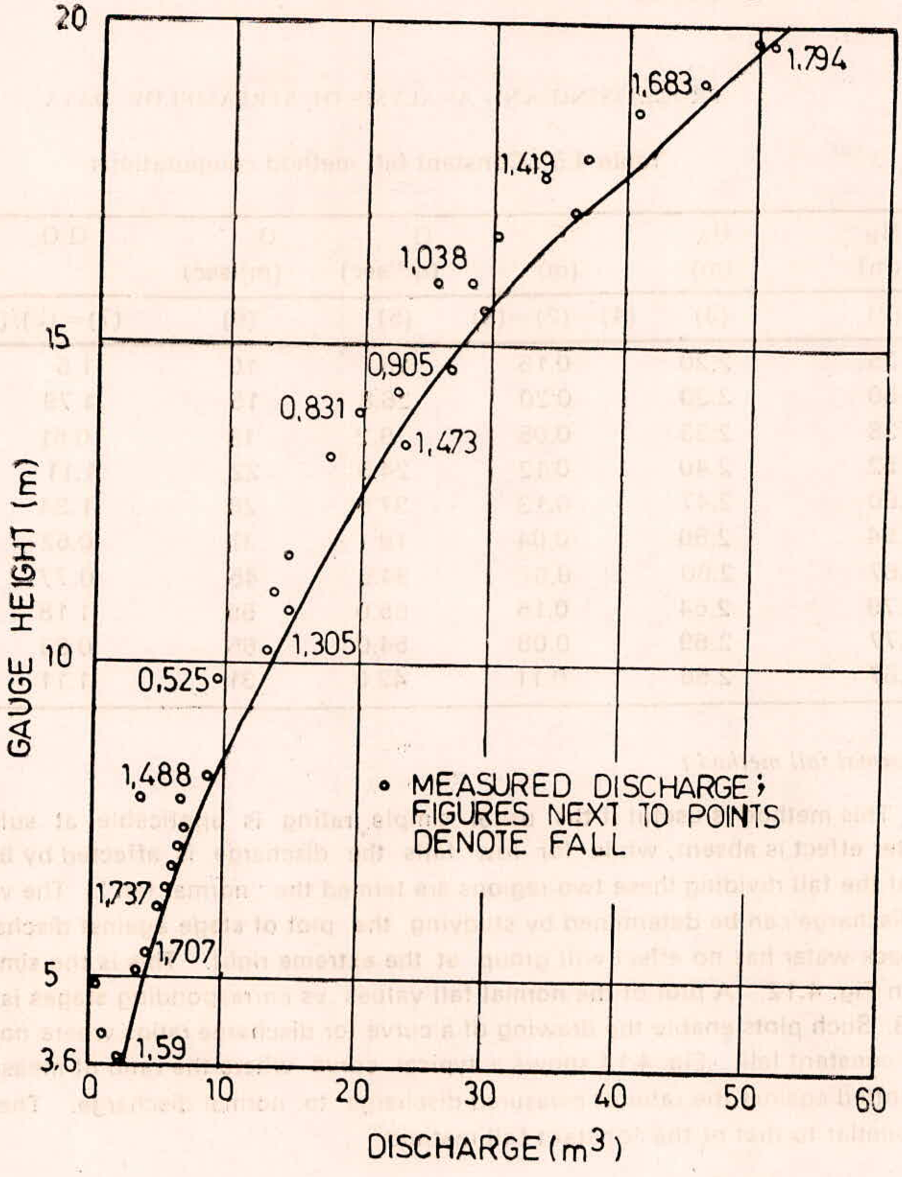

Fig. 4.12 Normal-Fall Method-Sample Rating-Curve

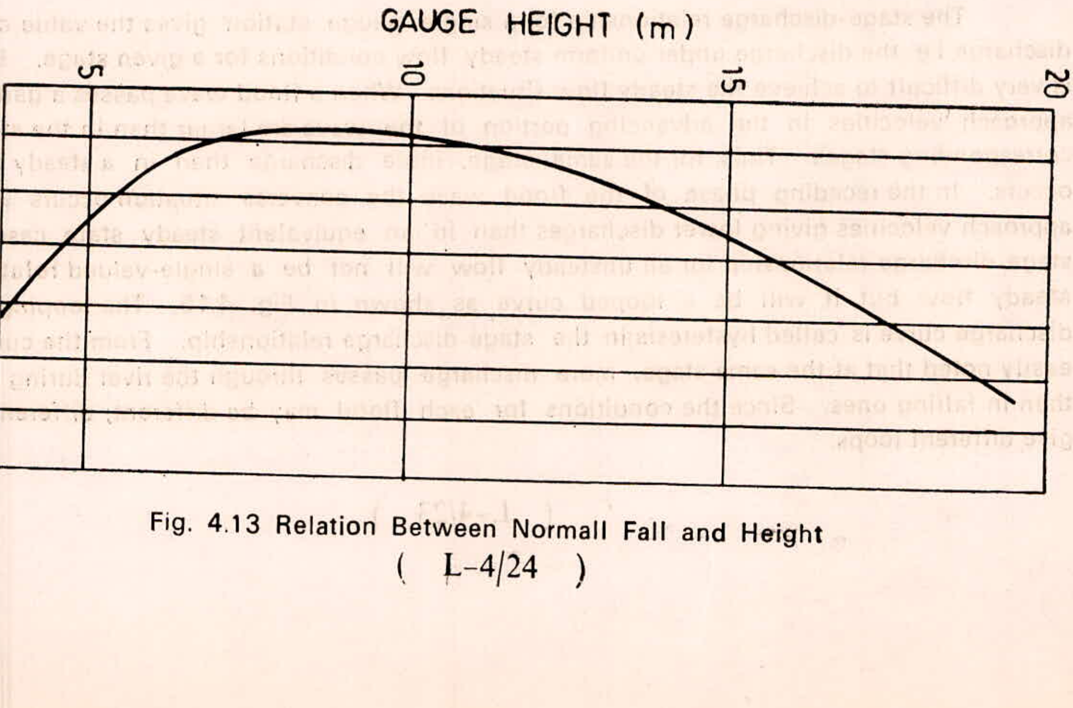

Fig. 4.13 Relation Between Normall Fall and Height

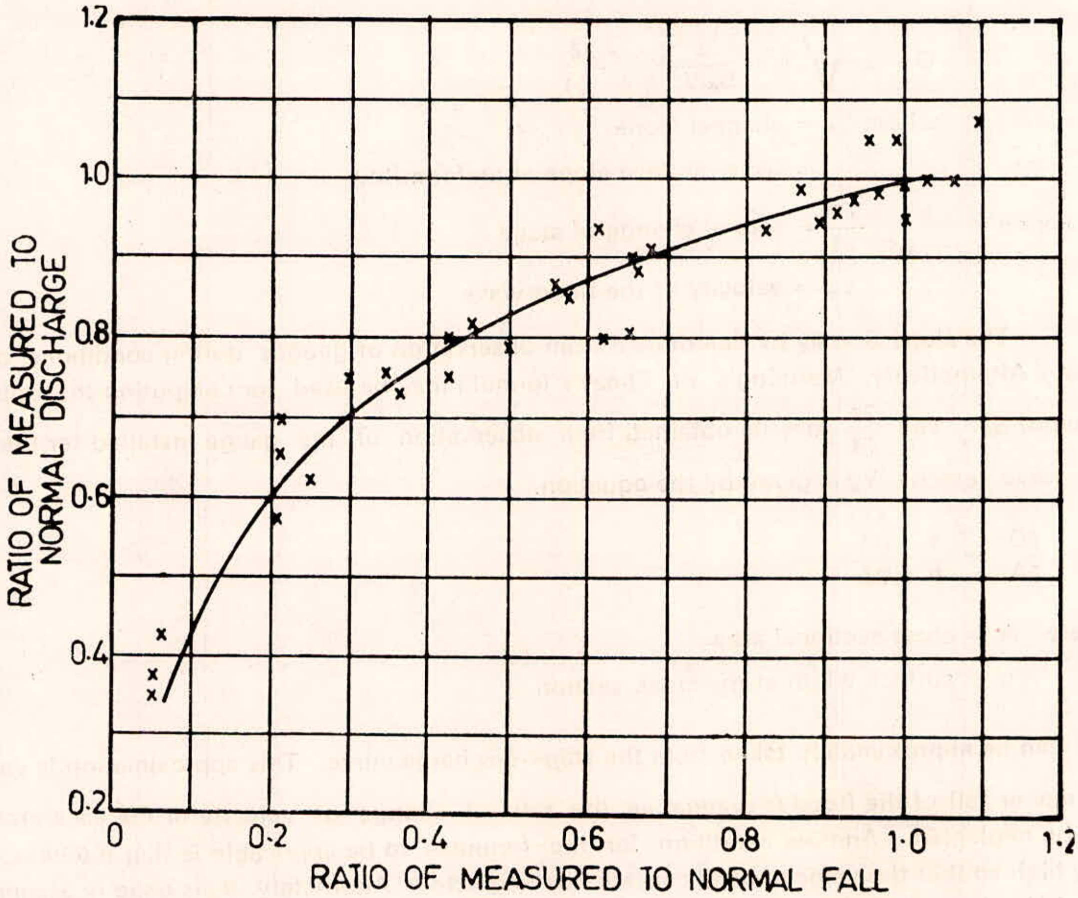

Fig. 4.14 Measured Discharge-Fall Relation

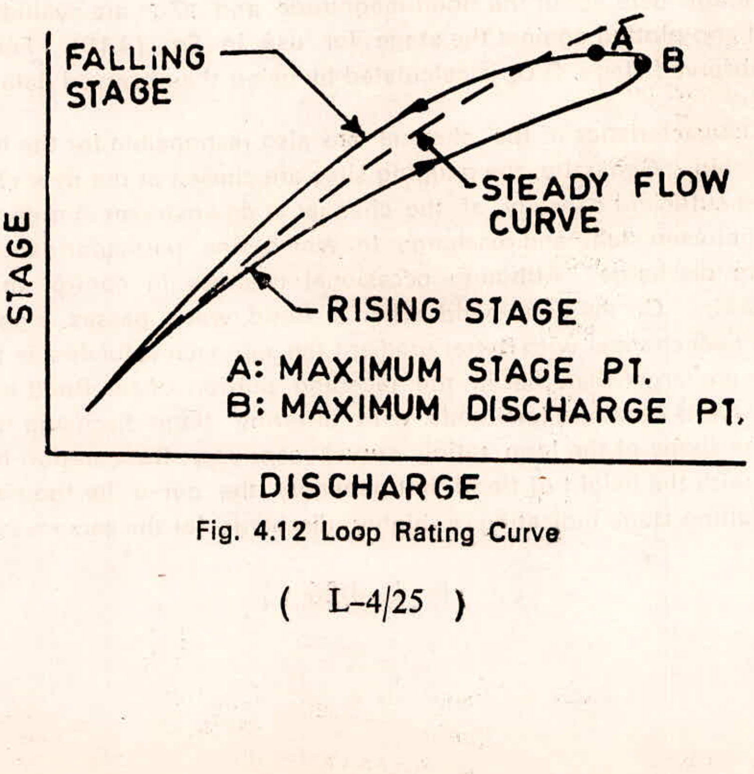

Fig. 4.12 Loop Rating Curve

Under certain conditions the normal discharge (Q_o) obtained from the stage-discharge curve and the actual discharge (Q) of an unsteady flow condition are related as ;

$$Q = Q_0 \sqrt{1 + \frac{1}{S_0 V_w} \quad \frac{\partial Z}{\partial t}} \qquad \ldots\ldots (4.10)$$

where S_0 = channel slope

= water surface slope at uniform flow

$\frac{\partial z}{\partial t}$ = rate of change of stage

V_w = velocity of the flood wave

The slope S_o may by determined from observation of gauges during conditions of steady flow. Alternatively, Manning's or Chezy's formula may be used for computing the approximate value of S_0. The $\frac{\partial z}{\partial t}$ may be obtained from observation of the gauge installed for the purpose. The wave velocity, V_w is given by the equation.

$$V_w = \frac{\partial Q}{\partial A} = \frac{1}{b} \frac{\partial Q}{\partial Z} \qquad (4.11)$$

where A = cross sectional area

b = surface width at the cross section

$\frac{\partial Q}{\partial Z}$ can be approximately taken from the stage-discharge curve. This approximation is valid when the rise or fall of the flood is gradual i.e. the rate of change of velocity or the acceleration head can be neglected. Another condition for the formulae to be applicable is that the velocity is not very high so that the velocity head can also be neglected. Alternately, V_w is usually assumed equal to 1.4 V, where V = average velocity for a given stage estimated by applying Manning's formula and the energy slope S_f. Also the energy slope is used in place of S_o in the denomiator of Eq (4.10). If enough data about the flood magnitude and $\partial Z/\partial t$ are available, the term $(1/V_w S_0)$ can be calculated and plotted against the stage for use in Eq. (4.10). For estimating the actual discharge at an observed stage, Q/Q_0 is calculated by using the observed data of $\partial Z/\partial t$.

Physical characteristics of the channel are also responsible for the hysteresis in the stage discharge relationship. Generally, the gauging sites are chosen at the river channel with sufficient steep gradient and sufficient capacity of the channel at downstream in order to ensure the consistent relationship between stage and discharge in which one particular gauge height will indicate one corresponding discharge. Although occasional changes in control may effect the stage-discharge relationship. On the other hand, when a flood wave passes a gauging station located at the constricted river channel with flatter gradient the approach velocities in the advancing portion of the flood wave are larger than that in the receding portion of the flood wave Thus, a looped stage discharge curve is obtained for floods with differing stage-discharge relations for rising and falling levels. The shape of the loop rating curves can vary from station to station, and also at the same station, with the height of flood, but generally the curve for the rising stage will plot to the right for the falling stage indicating a higher discharge for the same water level. The reason for this is that the flood wave front is significantly steeper than the steady state hydraulic gradient of the river during a rising flood while the reverse is true during the recession. There can be significant difference in discharge caused by this effect.

If discharge measurements are made equally on rising and falling states, an average rating curve falling between the two is obtained, which in most cases is usually of sufficient accuracy. In practice. however, there is a tendency for flood gauging to be made on falling stage only, especially on rivers which rise quickly and carry quantities of debris on the rising flood. On stations, therefore, where channel conditions are favourable for hysterisis, precaution should be taken to check the extent of the effect before a decision is made on whether to use an average rating curve or a series of looped curves.

4.5.3 Extrapolation of Stage-discharge relation

Most hydrological designs consider extreme flood flows. As an example in the design of hydraulic structures, such as barrages, dams and bridges one needs maximum flood discharges as well as maximum flood levels. While the methods are available for the estimation of design flood magnitude, the stage-discharge relationship at the project site will have to be used to predict the stage corresponding to design flood discharges. Rarely will the available stage-discharge data include the design flood range and hence the need for extrapolation of the rating curve in the higher range. On the other hand low flows and corresponding stages are also required during the planning and design of water resources projects. The range of stage and discharge values observed in the field may not include the design low flow values. Therefore, it becomes necessary to extrapolate the stage-discharge curve in the lower end also.

Before going to discuss about the various methods for extrapolation, let us know the factors which effect the rating corve in the both of the extremes. Those factors include :

(i) Overbank spills at high stages
(ii) shift in controls at very low and very high stages
(iii) changes in rugosity co-efficients at different stages.

The above factors affect the nature of the relationship at the extreme ends and must be taken into account. As far as possible, extrapolation should be avoided, but where this is necessary the results obtained should be checked by more than one method. The physical condition of the channel, that is whether the channel has defined banks over the entire range or only upto a certain stage and over bank spill above that stage as well as whether the channel has fixed or shifting controls, should govern the methods to be used in the extrapolation. Consideration should also be given to the phenomenon of the kinemetic effect of open channel flow when there may be a reduction in the mean velocity in the channel during inundation of the flood plain. There are many techniques available for the extrapolation of stage-discharge relationship for a gauging site of a river channel with defined banks and fixed controls as well as a channel with spills. Some of those techniques are described below :

(a) Double log plot method

If the control does not change beyond a particular stage, it may be possible to develop the rating curve relationship in the form given by the Eq. 4.1. In this technique the range is plotted against the discharge on double log paper. A best fit linear relationship is obtained for data points lying in the high stage range and the line is extended to cover the range of extrapolation Similarly a best fit linear relationship may be obtained for data points lying in the low stage range and the relationship thus developed may be used for the extrapolation in the lower range. Alternatively, least square method can be used to derive the equation for best fit line as discussed in section 4.5.2.1 (d).

(b) Conveyance Method

The conveyance of a channel in non-uniform flow is defined by the relationship

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

where, Q = Discharge in the channel

S_f = Slope of the energy line, and

K = Conveyance of the channel

If Manning's formula is used for the discharge computation, then discharge Q is given as.

$$Q = \frac{AR^{2/3}}{n} S_f^{1/2} \qquad \text{......(4.13)}$$

where R = Hydraulic Radius

A = Cross section area of the channel.

n = Manning's roughness co-officient

From Eq. (4.12) and (4.13) the conveyance K is given by the relatian

$$K = \frac{1}{n} AR^{2/3} \qquad \text{......(4.14)}$$

The steps involved in extrapolating the stage values for corresponding discharge values using conveyance method are :

(i) Calculate A and R values corresponding to different stage values (A and R are the function of stage values).

(ii) Calculate conveyance K for various stage values by using Eq. (4.14).

(iii) Plot the values of K against their corresponding stage values.

(iv) Fit a smooth curve to the plotted points as shown in Fig. 4.16.

(v) Compute the values of S_f from the available discharge and stage data by using Eq. (4.18).

(vi) Plot the values of $\sqrt{S_f/_n}$ against the stage values.

(vii) Fit a smooth curve through the plotted points as shown in Fig. 4.17.

(viii) Extrapolate the fitted curve (Fig. 4.16) keeping in mind that S_f approaches a constant value at high stages.

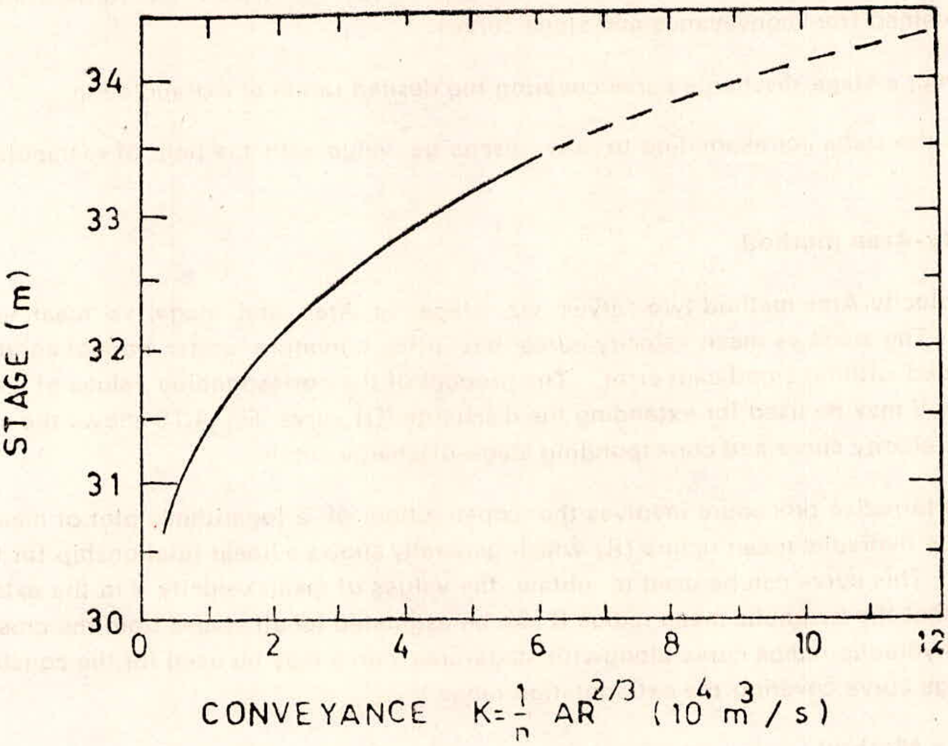

Fig. 4.16 Conveyance Method of Rating Curve Extension; K vs Stage

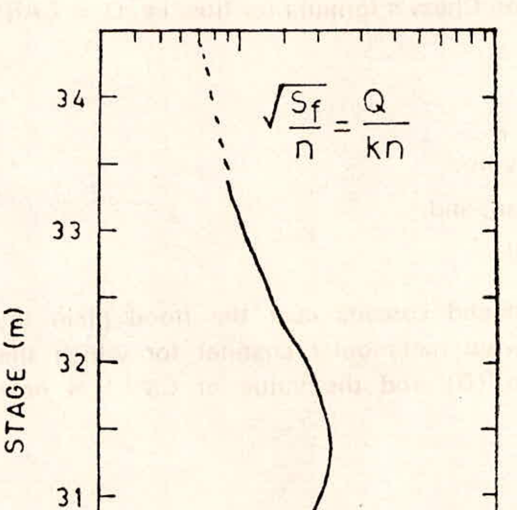

Fig. 4.17 Conveyance Method Rating Curve Extension; S_f Vs Stage

(ix) Calculate the discharge at any stage using Eq. (4.12) for which the value K and slope S_f are obtained from conveyance and slope curves.

(x) Construct a stage-discharge curve covering the desired range of extrapolation.

(xi) Obtain the stage corresponding to any discharge value with the help of extrapolated rating curve.

(c) Velocity-Area method :

In velocity-Area method two curves viz. stage vs Area and stage vs mean velocity are constructed. The stage vs mean velocity curve has little curvature under normal conditions and can be extended without significant error. The product of the corresponding values of area A and mean velocity V may be used for extending the discharge (Q) curve. Fig. 4.18 shows the stage-Area curve, stage-velocity curve and corresponding stage-discharge curve.

An alternative procedure involves the construction of a logarithmic plot of mean velocity (V) against the hydraulic mean radius (R) which generally shows a linear relationship for the higher stage values. This curve can be used to obtain the values of mean velocity V in the extrapolation range. Note that the hydraulic mean radius R can be estimated for all stages from the cross section. The velocity-hydraulic radius curve alongwith stage-area curve may be used for the construction of stage discharge curve covering the extrapolation range.

(d) Steven's Method :

This method is based on Chezy's formula for flow i.e. $Q = CAR^{1/2} S_f^{1/2}$ (4.15)

where Q = Discharge.

R = Hydraulic radius

S_f = Slope of the energy line

A = Area of cross section, and

C = Chezy's co-efficient

When flood water spills and spreads over the flood plain the cross-section of the river may be approximated as a wide rectangular channel for which the hydraulic mean radius is equal to hydraulic mean depth (D) and the value of $CS_f^{1/2}$ is nearly constant for the higher stage values. Hence

$$Q = KAD^{1/2} \tag{4.16}$$

If the values of discharge are plotted against the corresponding values of $AD^{1/2}$ on arithmetic graph paper, one may be able to fit a best line through those points. This straight line can be further extended to extrapolate the discharge values. As far as possible the extrapolation using this method should be avoided in the long range of stage and discharge value.

(e) Station correlation method : The station correlation methods are used only when another gauging site exists on the same stream, upstream or downstream. In this method

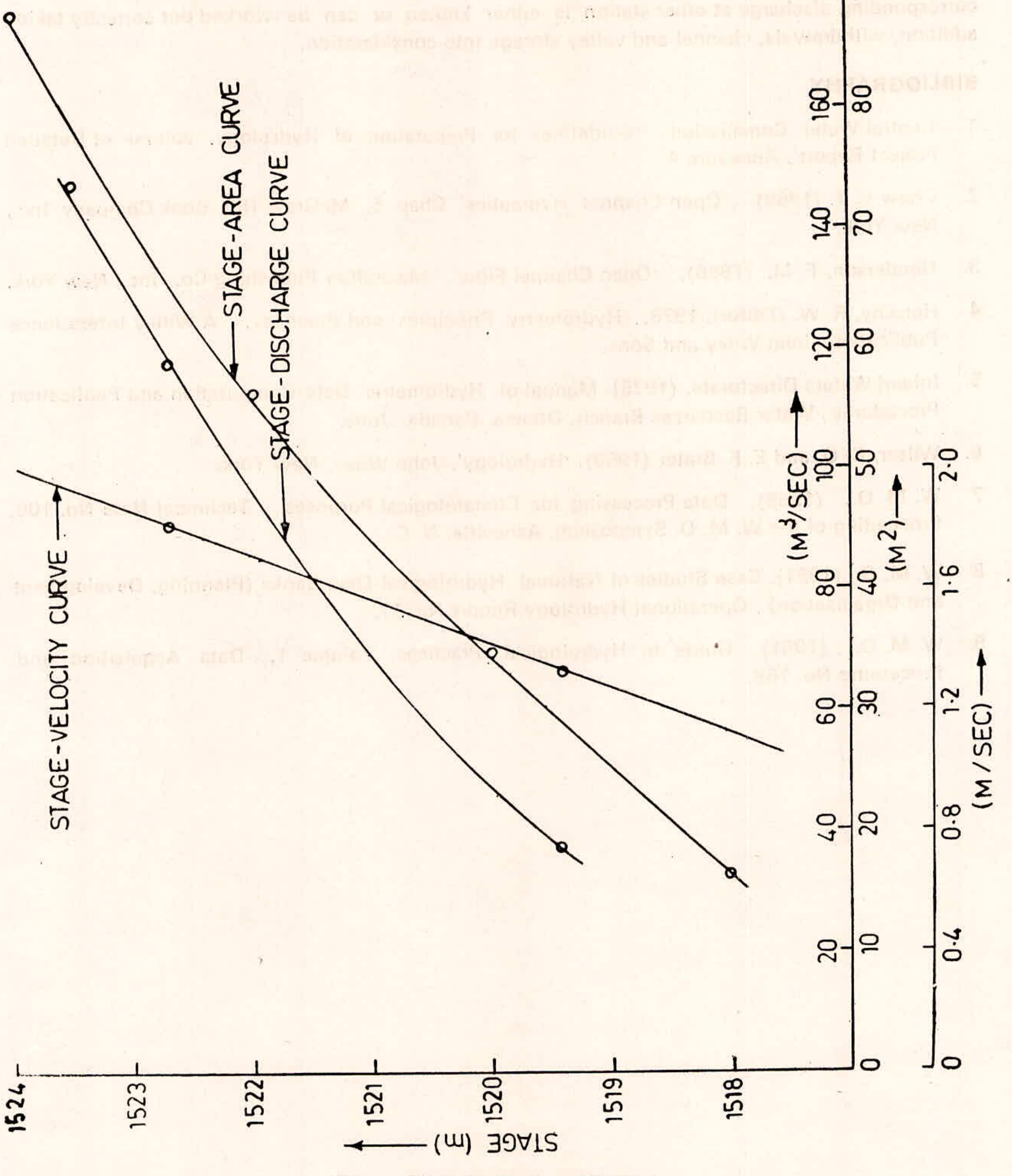

Fig. 4.18-Velocity-Area Method

the rating curves of the two gauging stations are correlated and discharge at the required stations are computed knowing the corresponding discharge at other station. This method presumes that corresponding discharge at other station is either known or can be worked out correctly taking addition, withdrawals, channel and valley storage into consideration.

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