# PROCESSING AND ANALYSIS OF STREAM FLOW DATA

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## INTRODUCTION

The stream flow data is important to determine the extent and pattern of available water supply and used in determining the reliable water supplies for various purposes, which include domestic water supply, commercial and industrial use; irrigation, hydropower and transport channels etc. These records are therefore very useful in planning and designing and later for operating and managing the surface water related projects. Apart from water resources projects the stream flow records are also utilized in designing the bridges, culverts, flood plain delineation and flood warming systems.

Stream flow records are primarily continuous records of flow passing through a particular section on the stream. These sections of interest where the flow is measured are called the stream gauging stations. A network of stream-gauging stations is established to get the information about the surface water resources of the region. However the measurement made at the gauging site may subject to various random, systemic and spurious errors. Therefore data processing is required to transform the raw data into their most usable forms through a variety of quality checks at appropriate stages to ensure data quality and reliability.

Processing of stream flow data is not a single step process. Several processing steps are required to produce reliable stream flow data. The first deals with flow measurements data, second incorporates the gauges flows into rating curves and third deals with the computation of flows from stage data and the final step outlines some standard analyses performed that use the flow estimates. This lecture describes some of the methods for stream flow data processing and analysis.

# PROCESSING OF STREAMFLOW DATA

## Preliminary Processing and Scrutiny

Preliminary Processing and scrutiny of the data are essential before the observed data is stored on computer. The preliminary processing is involved with comparisons within a single data series and is concerned with making comparisons between observations and pre-set limlis and/or statistical range of a variable or with the expected hydrological behaviour of a hydrological phenomenon. Preliminary data processing highlights those data, which are not within the expected range or are not hydrologically consistent. To sure data quality following information should also be furnished:

(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.

**Filling up of short Data gaps:** The following techniques can be used for data 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.

***Consistency of data:*** *The consistency of the data should also be checked to ensure*

***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.

***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. 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 or daily discharge at the control point with adjacent sites etc.

***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.
- 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.

**Secondary Processing**

Specific tasks in secondary data processing include :

- Calculation of mean velocity and discharge based on stream gauging.
- Analytical fitting of stage-discharge relations
- 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 elementary 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).

**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

## STAGE-DISCHARGE RELATIONSHIP

The stage-discharge (S-Q) relationship is determined by using the observed stage and discharge values over a wide range of flows to define a continuous curve also known as rating curve. These stages and discharges can be observed by using any suitable measuring technique. The measured value of discharges when plotted against the corresponding stages show a definite relationship between the two and it represents the integrated effect of a wide range of channel and flow parameters. The combined effect of these parameters is termed control. If the S-Q relationship for a gauging section is constant and does not change with time, the control is said to be permanent. If it changes with time, it is known as shifting control.

### Development of Rating Curve Under Permanent Control

A majority of streams and rivers, especially non-alluvial rivers exhibit permanent control. For such a case, the relationship between the stage and the discharge is a single-valued relation which is expressed as:

$$Q=a(H-H_0)^b \qquad (1)$$

in which Q = stream discharge, H = gauge height (stage), $H_o$ = a constant which represent the gauge reading corresponding to zero discharge, a and b are rating curve constants. This relationship can be expressed graphically by plotting the observed stage against the corresponding discharge values (in an arithmetic or logarithmic plot) (Fig. 1). Logarithmic plotting is advantageous as Eqn. (1) plots as a straight line in logarithmic coordinates. The advantage of using the double logarithmic plot is two fold. Firstly, the plot would produce a straight line since the general form of rating curve is parabolic. Secondly, different straight lines allow to further grouping of data. A part of the entire range of stage may form a straight line. It gives an indication about the stage at which the slope of the straight line changes if more than one lines are used to fit the data points.

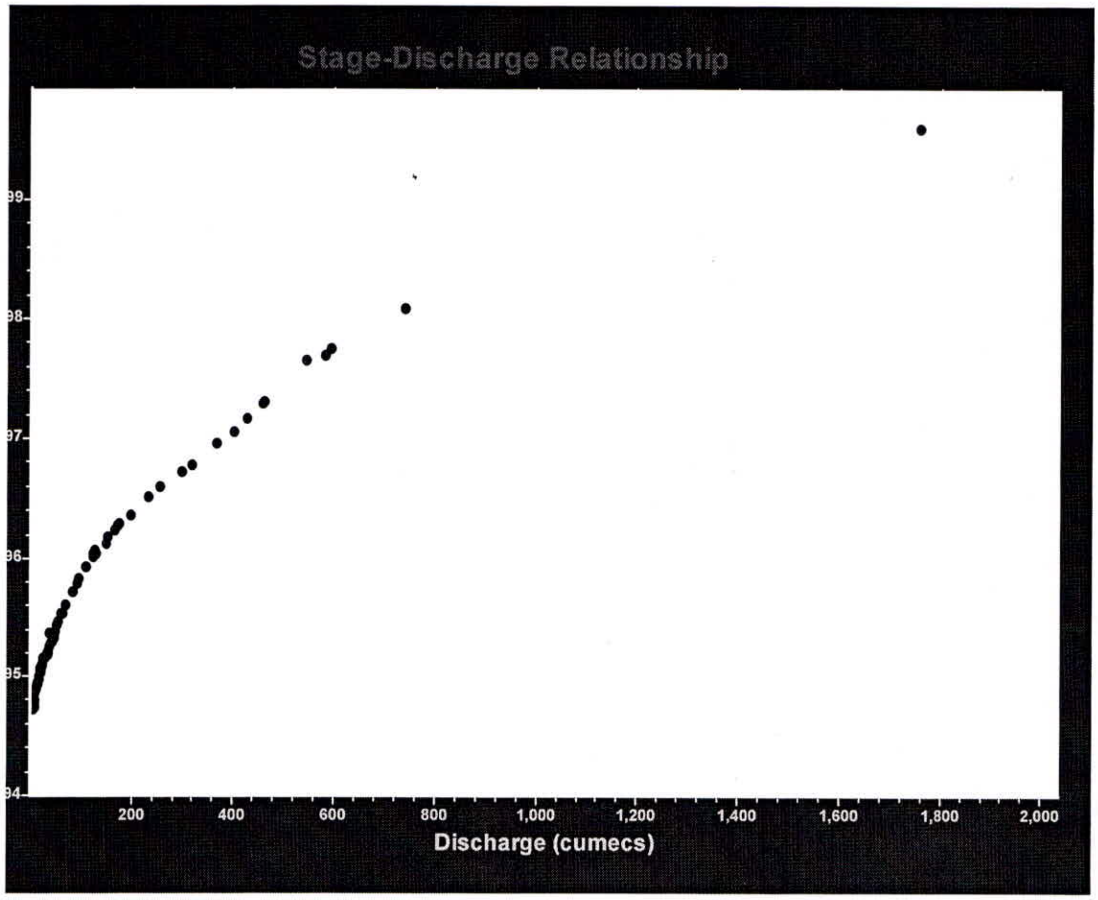


**Fig 1: Stage Discharge (S-D) Relationship**

While plotting the data on double log plot a prior knowledge about the value of $H_o$ 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 station. Marginal adjustment in the values of $H_o$ may be required in order to produce a straight line giving better fit to the plotted points. There is a possibility that more than one straight lines are fitted if so required to represent the changing conditions at different stages.

**Least square method**

The best values of a and b in Eqn. (1) for a given range of stage can be obtained by the least-square-error method. Thus by taking logarithms, Eqn.(1) may be represented as

$$\log Q = \log a + b \log (H - H_0)$$

or

$$Y = m X + c \qquad (2)$$

in which the dependent variable Y = log Q, independent variable X = log ($H$-$H_o$) and c = log a. The values of the coefficients for the best-fit straight line using data of N observations of X and Y are:

$$m = \frac{N\sum_{i=1}^{N}(X_i Y_i) - (\sum_{i=1}^{N} X_i)(\sum_{i=1}^{N} Y_i)}{N\sum_{i=1}^{N}(X_i)^2 - (\sum_{i=1}^{N} X_i)^2}$$

$$c = \frac{\sum_{i=1}^{N} Y_i - m\sum_{i=1}^{N} X_i}{N}$$

The Eqn. (2) is known as the rating equation of the stream and can be used for estimating the discharge Q of the stream for a given gauge reading H within the range of data used in its derivation.

The constant $H_o$ representing the stage (gauge height) for zero discharge in the stream is a hypothetical parameter and can not be measured in the field. As such, its determination poses some difficulties. Different alternative methods are available for its determination. However generally it is found by extrapolating the rating curve by eye judgement to find $H_0$ as the value of H corresponding to Q=0. Using the 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-$H_o$).

**Factors Responsible for Shifting Control**

The control that exists at a gauging section giving rise to a unique stage-discharge relationship can change due to: (i) changing characteristics caused by weed growth, dredging or changing encroachment, (ii) aggradation or degradation phenomenon in an alluvial channel, (iii) variable backwater effects affecting the gauging section and (iv) unsteady flow effects of a rapidly changing stage. There are no permanent corrective measures to tackle the shifting controls due to causes (i) and (ii) listed above. The only recourse in such cases is to have frequent current-meter gauging and to update the rating curves. Shifting controls due to causes (iii) and (iv) are described below.

**Development of Rating Curve under Shifting Control**

**Correction for backwater effect**

If the shifting control is due to variable backwater curves, the same stage will indicate different discharges depending upon the magnitude of the backwater effect. To overcome this situation another gauge, called the secondary gauge or auxiliary gauge is installed some distance downstream of the gauging section and readings of both gauges are taken. The difference between the main gauge and the secondary gauge gives the fall (F) of the water surface in the reach. 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. The discharge using manning equation can be expressed as:

$$Q = K_m R^{2/3} S^{1/2} A \qquad (3)$$

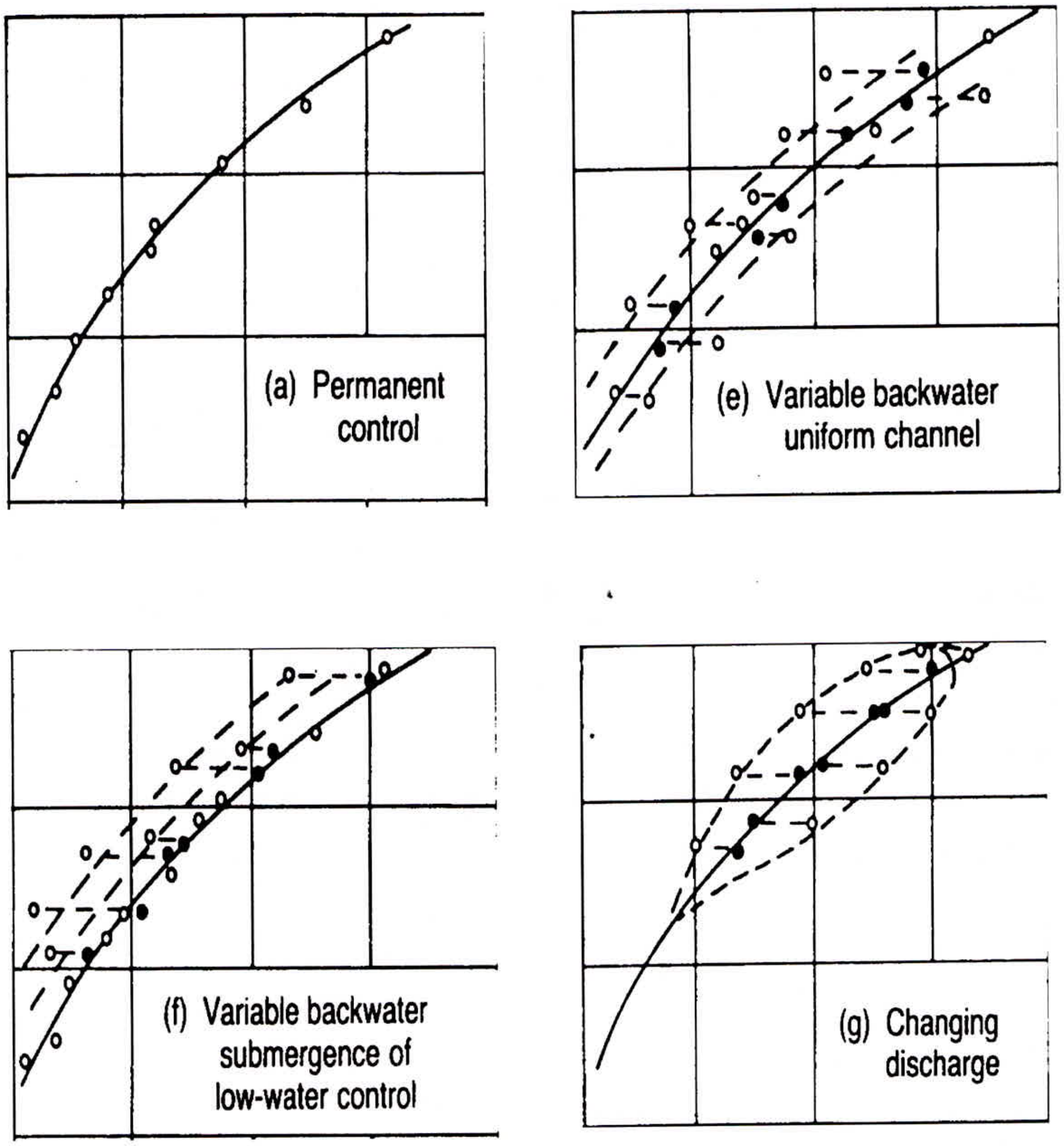


**Fig.2: Various factors which affects**

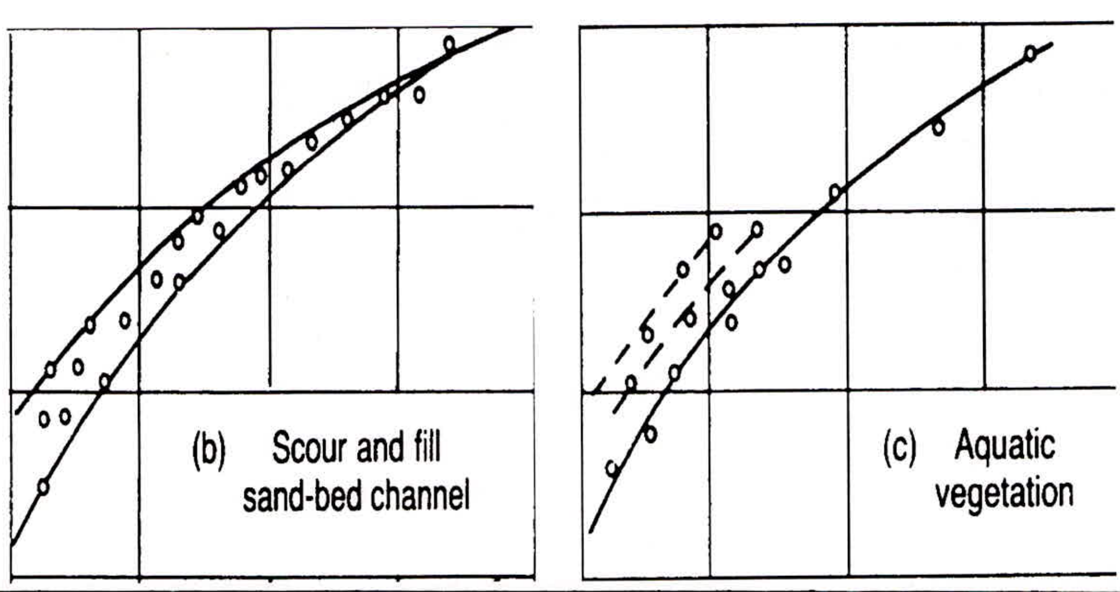

**Fig.2: Various factors which affects the Stage-Discharge relationship (Cont.)**

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:

$$\frac{Q_m}{Q_r} = \left(\frac{S_m}{S_r}\right)^p = \left(\frac{F_m}{F_r}\right)^p \qquad (4)$$

where $Q_m$ is the measure (backwater affected) discharge

$Q_r$ is the 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

Two methods are generally used for applying correction to discharges affected by backwater

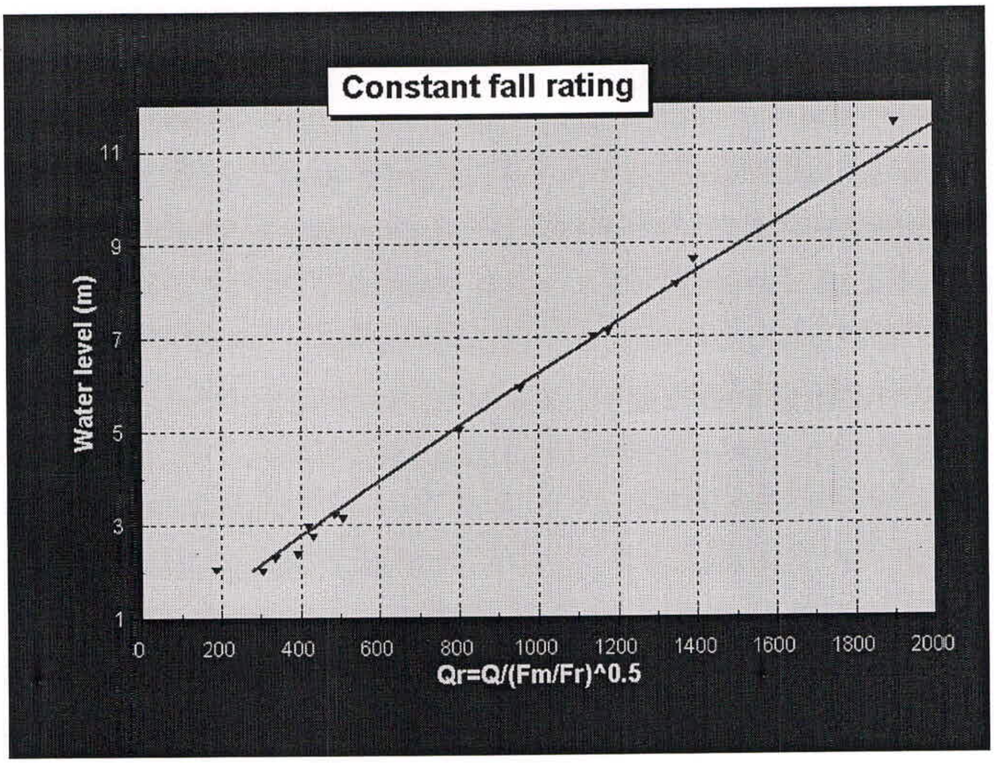


**Fig 3: $Q_r$=f(h) in constant fall rating**

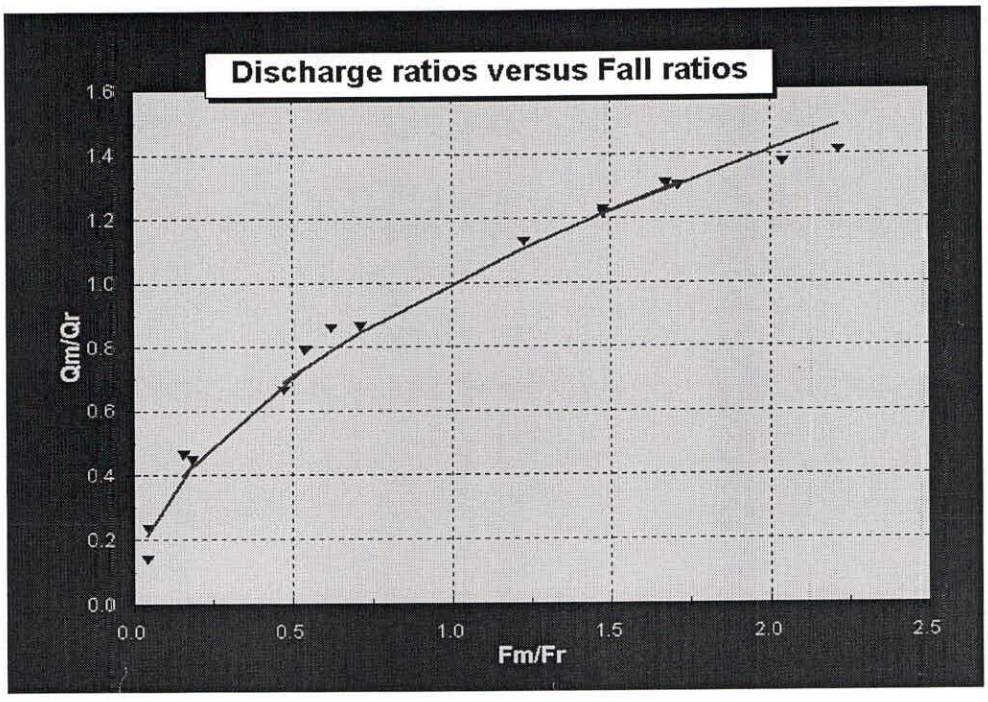


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**Fig 4: $Qm/Q_r=f(F_m/F_r)$**

The constant fall method is applied when the stage-discharge relation is affected by variable fall al 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. An iterative graphical procedure is used for computation wherin two curves as shown in Fig. 3 and 4 are used. The following steps are to be followed for computation.

- All measurements with fall of about $F_r$ are fitted with the curve as a simple stage discharge relation (Fig. 3). 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 ratio discharge ($Q_m/Q_r$) (Fig.4).
- 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.

The discharge at any time can 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 $Q_r$.

## Normal fall method

The normal fall method is used when there are times when backwater is not present at the gauging site. The following steps are to be followed for computation in this method.

- Plot stage against discharge noting the fall each point. The points with no backwater effect are identified. 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. Fig 5 shows such a rating curve.
- 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 fall $F_r$ (Fig 6). It can be observed from Fig.6 that the line separates the backwater affected and backwater free falls.
- 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.7)
- As for the constant fall method, the curves may be successively adjusted by holding two graphs constant and recomputing and plotting the third. Generally two or three iterations are required.

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

- From the plot between stage and the normal 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 $Q_r$

**Correction for unsteady flow effect**

When a flood wave passes a gauging station in the advancing portion of the wave the approach velocities are larger than in the steady flow at corresponding stage. Thus for the same stage, more discharge than in a steady uniform flow occurs. In the retreating phase of the flood wave the converse situation occurs with reduced approach velocities giving lower discharges than in a equivalent steady flow 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. It may be 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. If $Q_r$ is the normal discharge at a given stage under steady uniform flow and $Q_m$ is the measured (actual) unsteady flow the two are related as

$$\frac{Q_m}{Q_r} = \sqrt{[1 + \frac{1}{c S_0} * \frac{dh}{dt}]} \qquad (5)$$

where $Q_m$ is measured discharge
$Q_r$ is estimated steady stage discharge from the rating curve
c is wave velocity (celerity)
$S_o$ is energy slope for steady state flow
dh/dt rate of change of stage

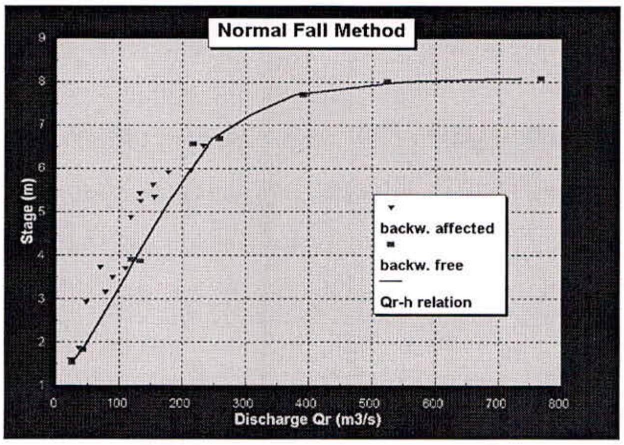


**Fig 5: $Q_r$-h relationship for Normal fall method**

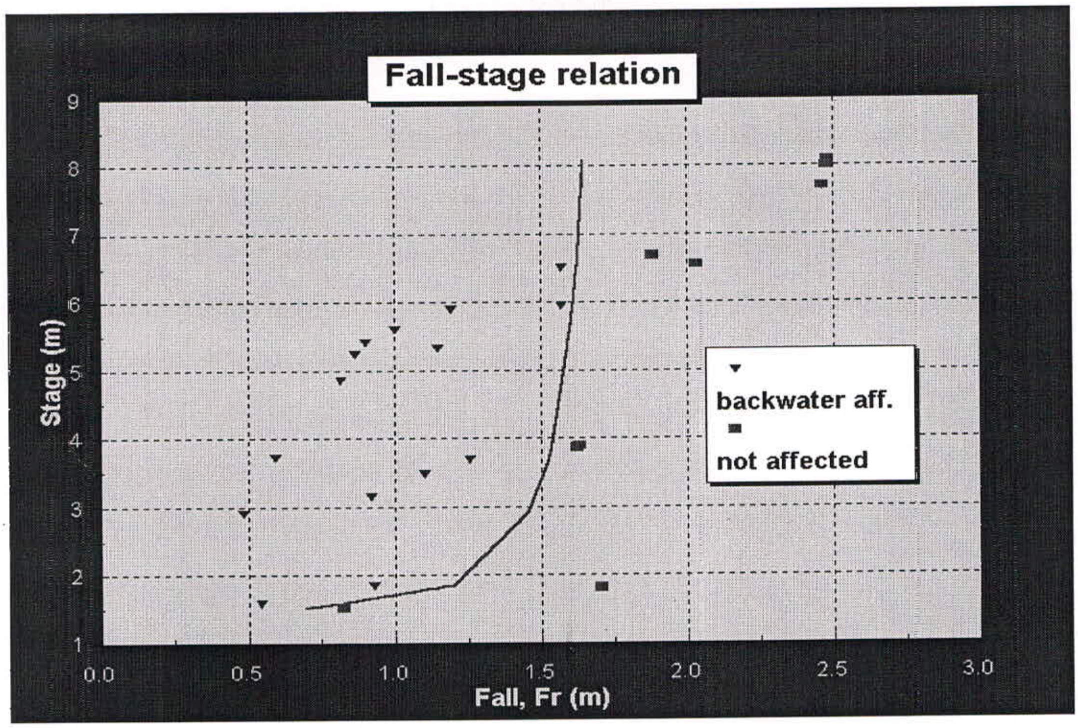


**Fig 6: $Q_r$-h relationship for Normal fall method**

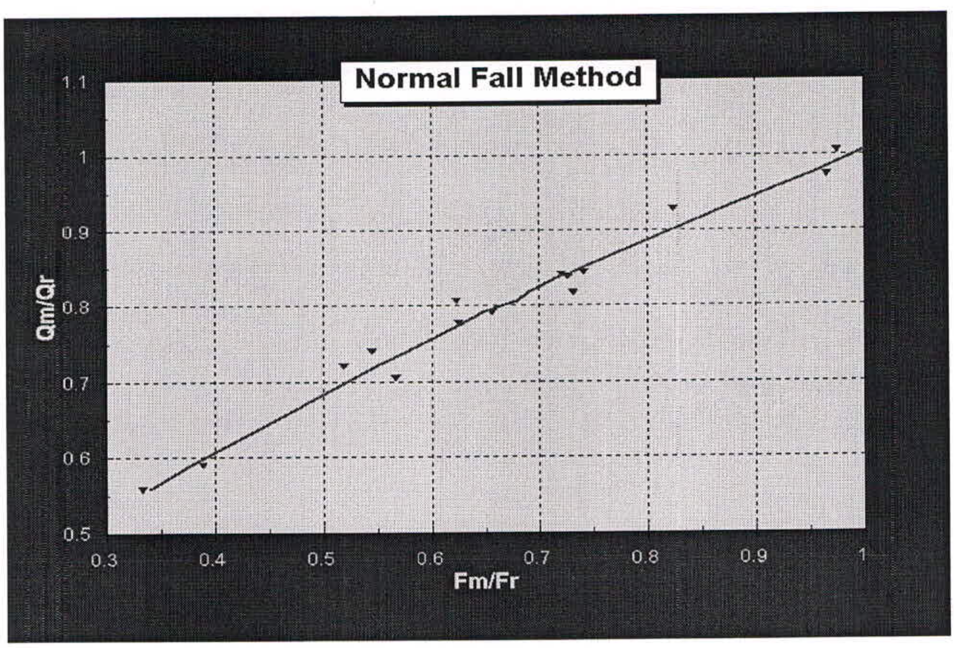


**Fig 7: $Q_m/Qr=F_m/Fr$ relashionship**

## Correction for stations affected by shifting control

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. Some of these bed and surface configurations in sand bed channels are shown in Fig 8. 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 as shown in Fig.9. 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 referred to the same cross section. These plots (Fig 10) will identify the bed-form regime associated with each individual discharge measurement. 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 rating

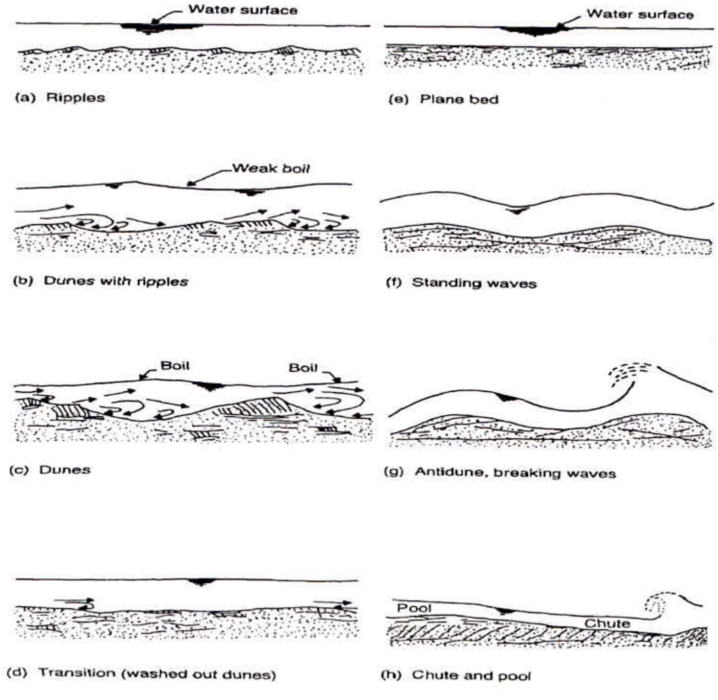

**Fig.8: Bed and surface configurations in sand-bed channels**

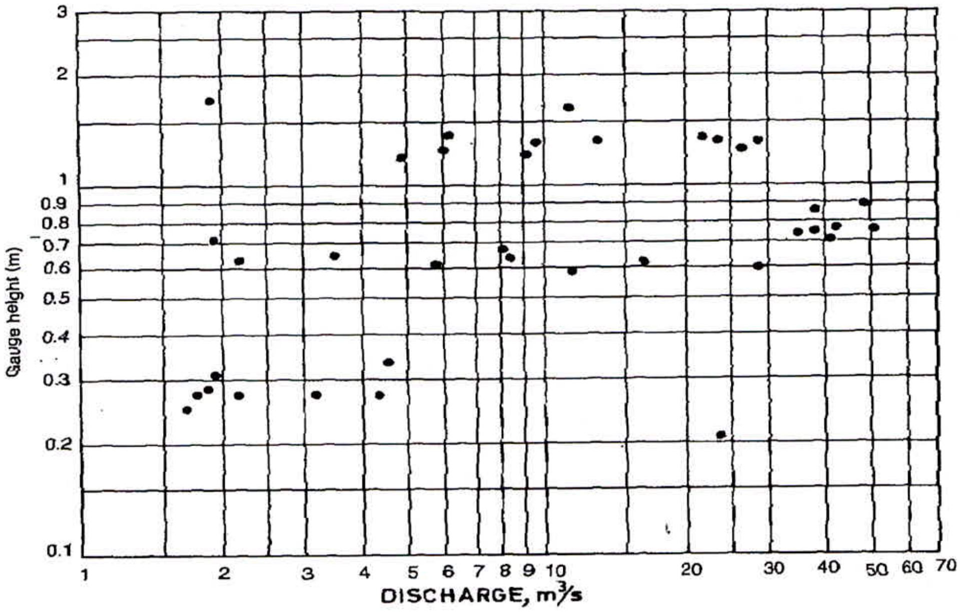


*Fig. 9: Plot of discharge against stage for a sand bed channel with indeterminate stage-discharge relation*

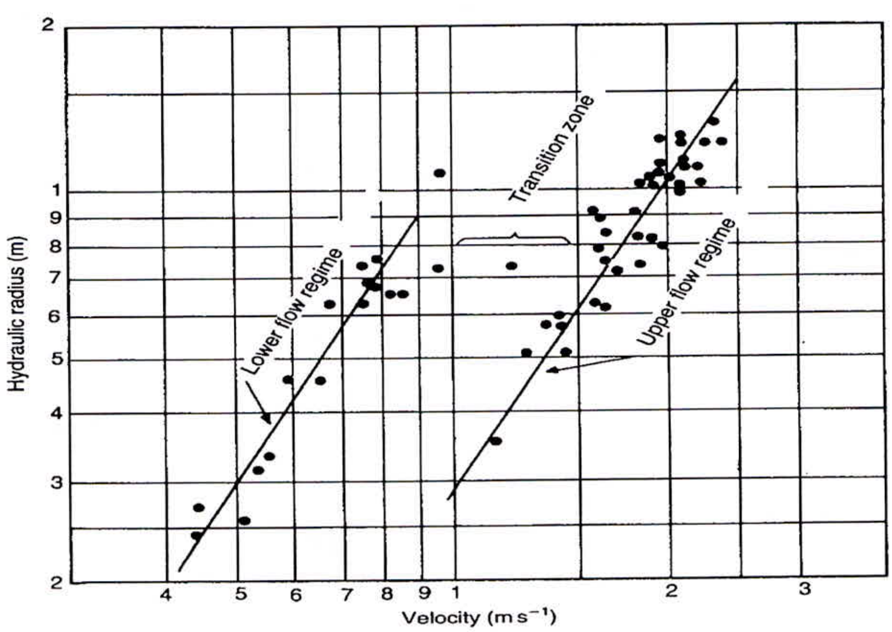


*Fig. 10: Relation of mean velocity to hydraulic radius of channel in fig.8.*

**Extrapolation of Rating Curve**

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 design flood discharge magnitude can be estimated from other considerations, the stage-discharge relationship at the project site will have to be used to predict the stage corresponding to design-flood discharges. Since, the discharge measurement at very high flows involves risk for personnel and equipment the observation of stage-discharge data in such very high ranges of stage/discharge is not available. Hence the behaviour of stage-discharge relationship is not known in the higher ranges and need to be established by extrapolating the available rating curve.

Before attempting extrapolation, it is necessary to examine the site and collect relevant data on changes in the river cross-section due to flood plains, roughness and backwater effects. The reliability of the extrapolated value depends on the stability of the gauging section control. A stable control at all stages leads to reliable results. Extrapolation of the rating curve in an alluvial river subjected to aggradation and degradation is unreliable and the results should always be confirmed by alternate methods. There are many techniques of extending the rating curve and two well-known methods are described here.

**Double-log plot method**

In this technique the stage is plotted against the discharge on a log-log paper as shown in Fig11.

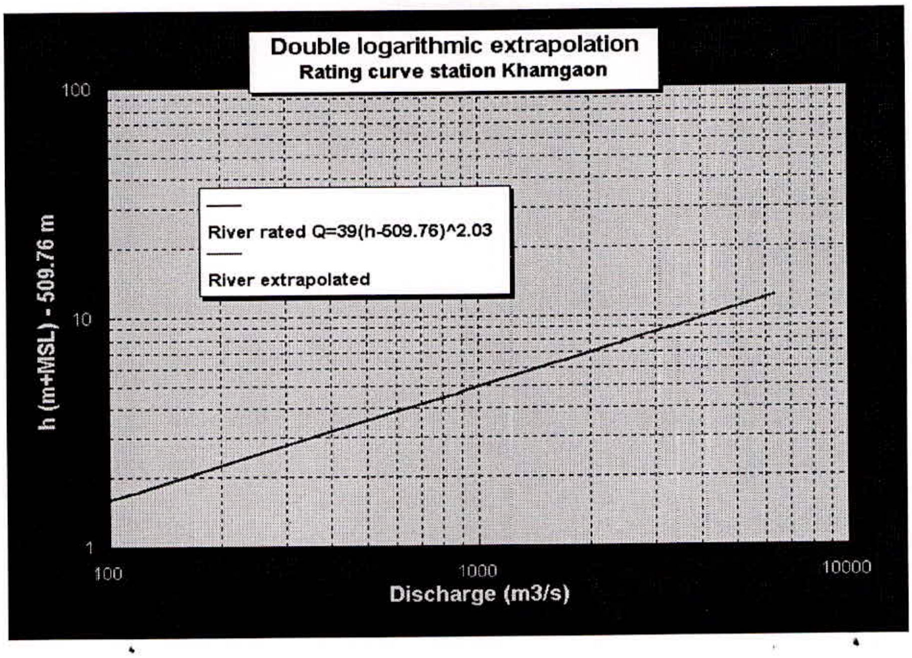


**Fig 11: Example of double logarithmic extrapolation of rating curve**

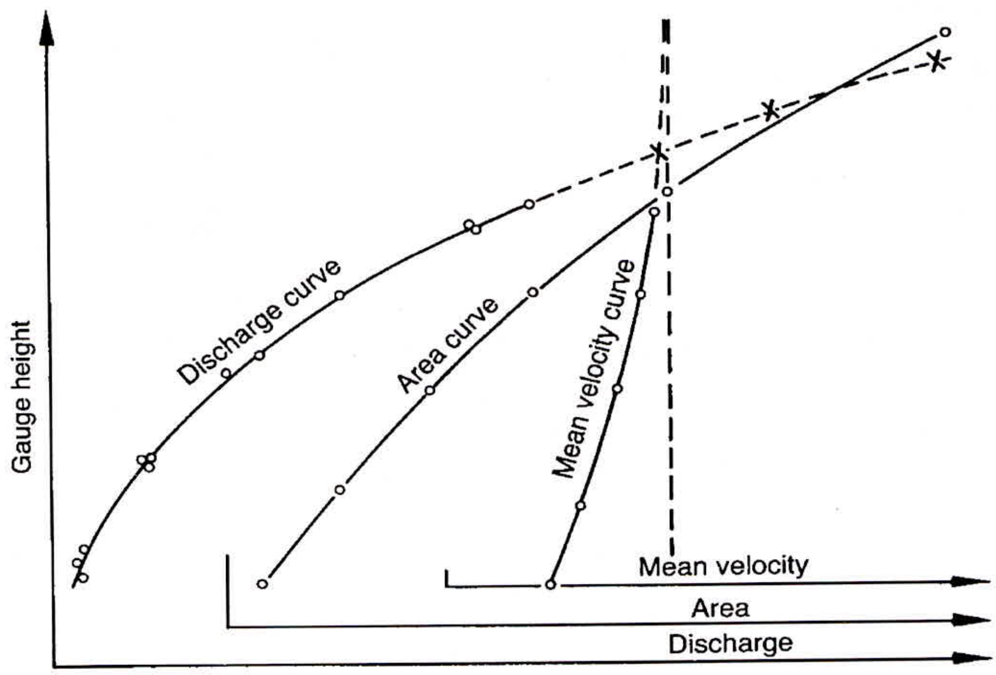


**Fig 12: Extrapolation based on stage-area/stage-velocity technique**

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. Alternatively, the rating equation developed (Eqn. 2) may also be used to determine stages corresponding to given discharges.

**Stage-area / Stage-velocity method**

Where extrapolation is needed either well beyond the measured range, or there are known changes in the hydraulic characteristics of the control section, then a combination of stage-area and stage-velocity curves may be used. Stage-area and stage-mean velocity curves are extended separately. For stable channels the stage-area relationship is fixed and is determined by survey up to the highest required stage. The stage-velocity curve is based on current meter gaugings within the measured range and, since the rate of increase in velocity at higher stages diminishes rapidly this curve can be extended without much error for in-bank flows. Discharge for a given (extended) stage is then obtained by the product of area and mean velocity read using extrapolated stage-area and stage-mean velocity curves (Fig. 12). This method may be used for extrapolation at both the upper and lower end of the rating.

**Conveyance slope method**

In the conveyance slope method, the conveyance and the energy slope are extrapolated separately. It has greater versatility than the methods described above and can be applied in sections with overbank flow. It is therefore recommended for use. It is normally, again, based on the Manning equation:

$$Q = K_m R^{2/3} S^{1/2} A$$

Or $$Q = K S^{1/2}$$

Where the conveyance is

$$K = K_m R^{2/3} S^{1/2} \qquad (6)$$

For the assessment of *K* for given stage, *A* and *R* are obtained from field survey of the discharge measurement section and values of n are estimated in the field. Values of *K* are then plotted against stage up to the maximum required level (usually on natural graph paper) as shown in Fig. 13.

Values of S, which is the energy gradient are usually not available but, for measured discharges, $S_{1/2}$ can be computed by dividing the measured discharge by its corresponding *K* value. *S* is then calculated and plotted against stage on natural graph paper and extrapolated to the required peak gauge height, in the knowledge that *S* tends to become constant at higher stages at the limiting slope of the stream-bed as shown in Fig. 14.

The discharge for given gauge height is obtained by multiplying the corresponding value of *K* from the *K* curve by the corresponding value of $S_{1/2}$ from the *S* curve. It should be noted that in this method, errors in estimating $K_m$ have a minor effect, because the resulting percentage error in computing *K* is compensated by a similar percentage error in the opposite direction in computing $S_{½}$.

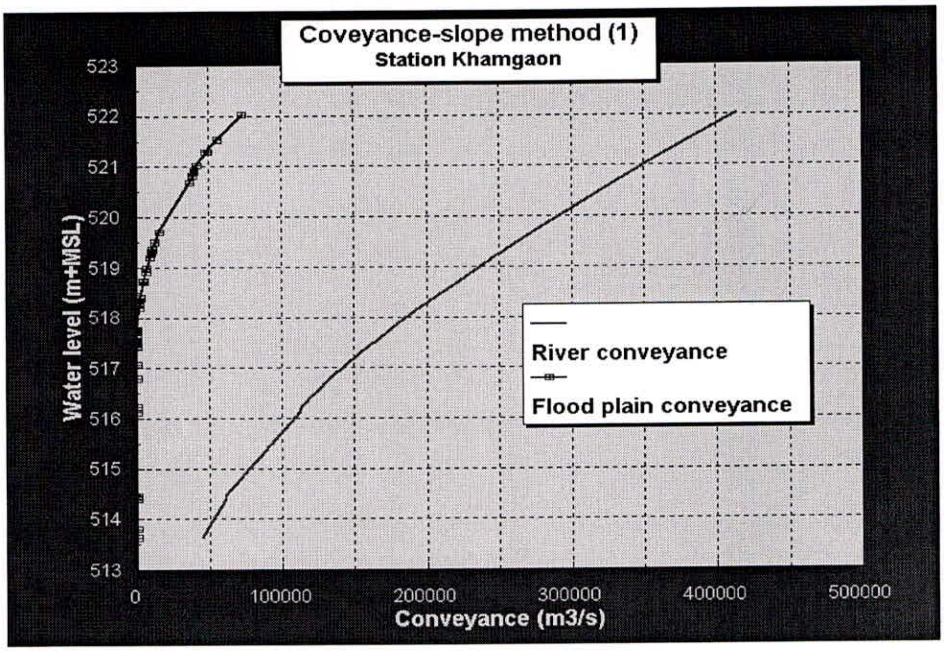


**Fig 13: Conveyance as F(h)**

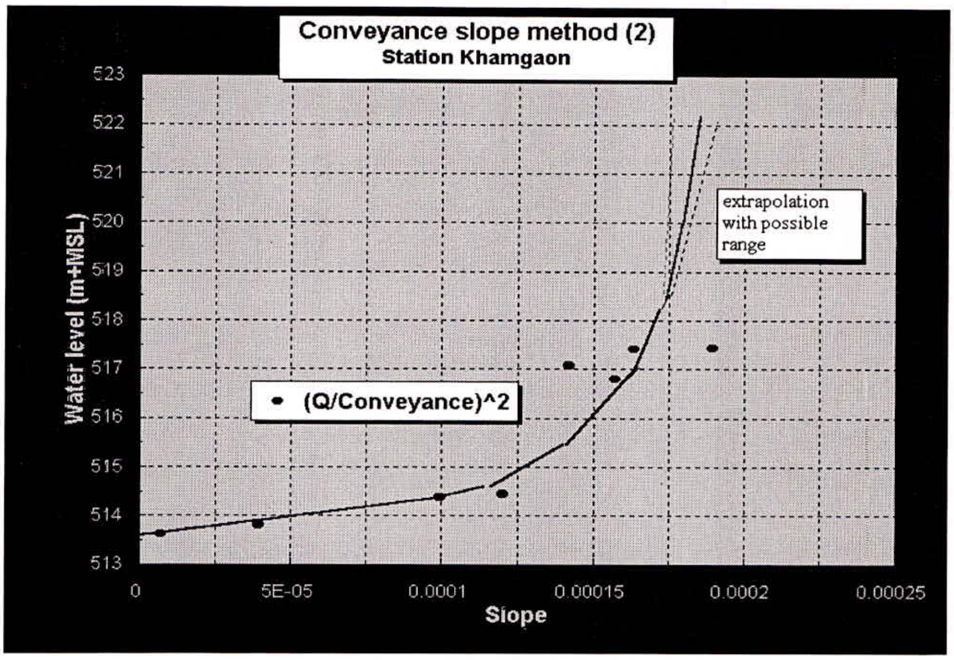


**Fig 14: Slope extrapolation**

**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 the rating curve 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.

## REMARK

This introductory lecture outlines some of the procedures for stream flow data processing and analysis. These procedures are important to ensure stream flow data quality and its reliability for use in various planning and development activities. It is important for raw data to go through various checks before their storage in any hydrological data base. Processing of stream flow data is carried out in a series of stages, starting with the preliminary checking in the field and successively higher levels of validation before it is accepted as fully validated data. It is also important to know that processing and validation of hydrological data requires an understanding of field practices. This includes the principles and methods of observation in the field and the hydrological variable measured. Typical flow data errors can be identified with the knowledge of measurement techniques.

## BIBLIOGRAPHY

Chow V.T., 1959. *Open Channel Hydraulics.* Chap 5, McGraw-Hill Book Company. Inc, New York.

Gupta, R. S.,1989. *Hydrology & Hydraulic Systems.* Prentice Hall, Englewood cliffs, NJ.

Henderson, F. M., 1966. *Open Channel Flow.* Macmillan Publishing Co., Inc., New York.

Herschey, R. W. (Editor), 1978. *Hydometry Principles and practices.* A Willey Interscience Publication, John Wiley and Sons.

Herschey, R. W. (Editor), 1995. *Streamflow Measurment.* II Edition, An Imprint of Chapman & Hall, E & F N SPON.

W. M. O., 1968. *Data processing for Climatological Purposes.* Technical Note No. 100, Proceeding of the W. M. O. Symposium, Ashevillr, N.C.

W. M. O., 1980. *Manual on Stream Gauging.* Vol. II, Computation of Discharge, No. 519, Secretariat of the W . M. O., Geneva, Switzerland.

W. M. O., 1981. *Guide to Hydrological Practices.* Volume 1, Data Acquisition and Processing No. 168.

W. M. O., 1981. *Case Studies of National Hydrlogical Data Banks ( Planning, Development and Organisation).* Operational Hydrology Report No. 17.