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Stage-discharge relationship for the Jamuna at Bahadurabad

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Stage–Discharge Relationship for The Jamuna at Bahadurabad

Jahir Uddin Chowdhury
Professor, IFCDR, BUET
and
Zahirul Haque Khan
River Survey Project FAP24

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River Survey Project (FAP24)

Institute of Flood Control and Drainage Research (IFCDR)
Bangladesh University of Engineering and Technology, Dhaka

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Acronyms and abbreviations

ADCP	:	Acoustic Doppler Current Profiler
BCL	:	Bangladesh Consultants Limited
BUET	:	Bangladesh University of Engineering and Technology
BWDB	:	Bangladesh Water Development Board
DHI	:	Danish Hydraulic Institute
EMF	:	Electromagnetic flow meter
EPC	:	Engineering Planning Consultants
FAP	:	Flood Action Plan
FPCO	:	Flood Plan Coordination Organization
GPS	:	Global Positioning System
IFCDR	:	Institute of Flood Control and Drainage Research
ISO	:	International Standard Organisation
JMBA	:	Jamuna Multipurpose Bridge Authority
NEDECO	:	Netherlands' Engineering Consultants
PWD	:	Public Works Department (datum level)
RPT	:	Rendel Palmer & Tritton
WMO	:	World Meteorological Organisation

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Summary

This report presents analyses of 103 pairs of stage–discharge data from the Jamuna River's left and right channels at Bahadurabad. The measurements for these 103 pairs of data were taken by the Hydrology Directorate of BWDB from 1 April to 15 November 1995; another 22 pairs of data were measured by a FAP24 project from April 1995 to March 1996. During 1995 there was much flooding. Daily water level data were collected for 1 April to 31 December 1995 from 6 staff gauges located at 5 to 9 km intervals along the two channels. This study is the continuation of an earlier study based on the data for the hydrologic year 1994-95 during which there was little flooding. A report was published in July 1995. The measured data have been used to study the relationships of local water surface fall, discharge, cross-sectional area, mean velocity, water surface width, hydraulic depth, conveyance factor, slope-roughness factor, and flow distribution with stages for the two channels. The study was done jointly by the IFCDR of BUET and the FAP24 River Survey Project.

Relationships among geometric and hydraulic parameters show that the flow regimes during the falling stage, flood season, and rising stage were different. The differences might have caused due to changes in the shape of cross-sectional geometry, bedform roughness and other factors caused by the morphological process. It was found that two segments for the rising stage, one segment for the flood season, and another two segments for the falling stage were appropriate for the stage-discharge relationships for 1995-96. Selection of segment limits was linked to the shape of the cross-section. Standard error analysis indicated that this approach can improve the accuracy of the fitted annual stage-discharge relationship. Recommendations were made on how to select the segments when the number of stage-discharge data are limited.

Channel–wise development of the stage-discharge relationship was a better approach since the hydraulic and morphological conditions in the right channel were different from those in the left channel. This approach reduced the uncertainty caused by the large measurement time required to complete the discharge measurements in two channels. However, standard error analysis indicated that the gain in accuracy achieved by this approach was not significant when compared with the approach of fitting a single relationship with the combined discharges of the left and right channels. This is because the small discharge of the right channel can not substantially influence the standard error based on total discharge.

Two methods for the extrapolation of discharges at stages beyond the range of measured discharges have been compared. Based on accuracy performances and practical considerations, these two methods were selected from five methods studied in the earlier report. Verification against measured discharges showed that the accuracy of the conveyance-slope method was better than the direct extrapolation of the fitted stage-discharge relation which is presently practised by the BWDB.

The highest discharges in the right channel at Bahadurabad during 1994 and 1995 were approximately 25% of the total flow, and its share decreased substantially with the fall in stage. The distribution of flow between the left and right channels was not proportional to their conveyance factors. The Froude number of flow in the right channel was much smaller than in the left channel. Analysis of local water surface fall data indicated that the right channel was aggrading. From 1994 to 1995, there was an upward shift in the stage–discharge curve in the right channel and a slight downward shift in the stage–discharge curve in the left channel.

It was recommended that frequent discharge measurements should be taken during the first half of the hydrological year. If there are cost considerations, the frequency can be reduced during the second half of the year. A consistency check of discharge measurement data for a hydrological year should be performed channel-wise. This can be done by plotting stage and discharge against cross-sectional area and cross-section averaged velocity for left and right channels.

1 Introduction

A study of the stage-discharge characteristics of the Jamuna River at Bahadurabad was done using the data collected by FAP24 during the hydrological year April 1994 to March 1995; the results were reported in July 1995. The report includes reviews of the theoretical aspects of the stage-discharge relation and of past studies on the stage-discharge characteristics of the Bahadurabad transit based on data from 1966 to 1992. The Jamuna River is a large multi-channel alluvial river. An inhabited high char divides the Bahadurabad reach into two distinct major channels, usually called the left and right channels. The report includes analysis of local water surface slope data, geometric data, and hydraulic elements extracted from the discharge measurement data from the two channels for 1994-95. Stage-discharge relationships based on total discharges of the two channels and on channel-specific discharges were compared. The accuracies of five methods for the extrapolation of discharges at stages beyond the range of measured discharges were also investigated. Whereever possible a limited morphological interpretaion was given to explain the observed hydrological relationships. The importance of such interpretations was stressed by the Project Adviser in his first and fourth mission reports (Peters, 1992; Peters, 1994): *In the wandering, braided area, if the gauged channel is not totally controlled by geology or geotechnics, then its water levels are not only related to discharges, but also to the overall resistance to the flow, which in turn depend on more factors than just roughness. This means that rating curves are not unique .... The meaning and use of the rating curves must be part of the studies. Discharge rating curves .... and their changes should be interpreted from morphological viewpoint.*

The flood flows in the Jamuna River in 1994 were unusually low and the maximum water level was well below the river bank level. A very high discharge occurred during the 1995 flood season. It was recommended that the study should be continued using 1995 data so that the analysis would include high flood discharge. This report presents the analysis of stage–discharge relationship for 1995. A preliminary analysis, based on 1994 data, was previously submitted as a draft version of the present report. This analysis is attached as Annex 1.

This is a joint study by FAP24 and IFCDR of BUET. The objective was to study the stage–discharge characteristics of the Jamuna River at Bahadurabad to determine methods for reliable estimation of unmeasured discharges. The report was written by Jahir Uddin Chowdhury and Zahirul Haque Khan. Contributions of Prof. J.J. Peters as a project advisor to FAP 24 are kindly acknowledged. Specially, his experience in the Zaire River helped us appreciate the importance of morphology in establishing the stage-discharge relationship.

2 Analysis of water level data

2.1 Staff gauge data

Water level data were collected from six staff gauges from 1 April to 31 December 1995. The gauge stations were along the left channel at Khatiamari, Bahadurabad, and Belgacha, and along the right channel at Kabilpur, Shankibhanga, and Bagirchaow (see Figure 2.1). The longitudinal distance between adjacent gauges in a channel range from 5 to 9 km. Analysis of water level data for 1994-95 was reported in the earlier report (IFCDR and FAP24, 1995).

Water levels at a station were recorded daily every 3 hours from 06.00 to 18.00 hours as per BWDB practice. The mean daily water level at a station was computed by averaging the five recorded values during the day.

The purpose of installing the gauges was to study the slope of the local water surface. The water level difference between two stations can not be converted into water surface slope because of the difficulty in determining the length of flow axis; therefore, the water level difference data can only be used as an approximate indicator of the local slope.

2.2 Data quality check

Several graphical checks were performed to detect errors in the water level data. The checks included inspection of stage hydrographs, correlation between upstream and downstream stations, time series of water level difference between two stations, and time series of differentiated water level at a station. Details of the methods for detecting the erroneous data and adjusting the inconsistent data were discussed in the previous report (IFCDR and FAP24, 1995).

Figures 2.2(a) and (b) show water level hydrographs after correcting the erroneous data. The figures show that there were four major flood waves from June to early October 1995.

2.3 Analysis of local water surface fall

The difference between the mean daily water level data in the left channel at Bahadurabad and Belgacha was plotted as a function of mean daily water level at Bahadurabad; the difference between the mean daily water level in the right channel at Kabilpur and Shankibhanga were plotted as a function of mean daily water level at Shankibhanga (see Figure 2.3). Some inconsistencies were observed in the data of Khatiamari and Bagirchaow due to some morphological developments in the reach. For further discussion on the issue, please consult RSP Main Report Annex 3 on Hydrology (RSP, 1996).

Figure 2.3(a) shows that the local water surface fall in the left channel at Bahadurabad increased with the rise in stage and then decreased with the fall in stage. The plot displays that the local water surface slope was higher during the rising stage than the falling stage for the same water level. This phenomenon was seen in many stable rivers (Khan, 1975; Peters, 1993, 1994; Khan and Barua, 1995).

Figure 2.3(b) shows different behaviour of local water surface fall in the right channel. This plot displays a clockwise loop unlike that observed for the left channel. A clockwise loop suggests that the local water surface fall during the falling stage was larger than during the rising stage for the same water level. This phenomenon can occur when the bed slope rises due to siltation upstream.

Figure 2.3(b) also shows that the water surface fall remained nearly constant during the low stage. With the increase in stage above 18 m+PWD when there was large discharge, the water surface fall decreased. This was probably due to the backwater effect caused by submerged char and/or confluence of branch channels. There was also the possibility of super elevation at Shankibhanga due to sharp curvature in the channel. A preliminary comparison of spot images taken on 24 March and October 1995 indicated that substantial morphological changes occurred in the right channel. The water surface fall can also be reduced when the flow path shortens because of the morphological process. An in-depth study of the morphology of the reach may provide information about the behaviour of water surface fall.

3 Analysis of discharge data

3.1 Discharge data of FAP24

3.1.1 Method of discharge measurement

A total of 22 discharge measurements were taken by FAP24 in Bahadurabad from April 1995 to January 1996. The following information is given in Tables 3.1 (a), (b) and (c) for the left channel, right channel, and combined section respectively: Date of measurement, stage at Bahadurabad gauge station, discharge, cross-sectional area, cross-section averaged velocity, and water surface width. The discharge was measured by the moving boat method using the combined Acoustic Doppler Current Profiler (ADCP), Electromagnetic flow meter (EMF), and Differential Global Positioning System (DGPS). The methodology was discussed in the second interim report of FAP24 (DELFT-DHI, 1995). Various approximations in the methodology and sources of uncertainties were briefly discussed in IFCDR and FAP24 (1995).

Table 3.1(c) shows that most of the measurements took 3 to 4 days; one measurement took 5 days. Since the discharge was recorded against the mean stage during the measurements period, there can be substantial error due to variation of discharge with time. The total number of data in Table 3.1 was inadequate for deriving a reliable annual stage-discharge relationship.

The stage-discharge data were plotted in Figures 3.1(a) and (b) for the left and right channels respectively. These plots show the usual stage-discharge relationship pattern.

3.1.2 Data consistency check

To check the consistency of data, stage and discharge data were plotted channel-wise against cross-sectional area data and against cross-section averaged velocity data (see Figures 3.2 and 3.1.3). These plots show that from the left channel, three pairs of cross-sectional area and mean velocity data, for 28 to 30 October, 9 to 12 November, and 18 November 1995, are not consistent. From the right channel, two pairs of cross-sectional area data, for 5 June and 18 December 1995, and one pair of mean velocity data, for 30 April 1995, are also not consistent. When similar plots were made for combined sections of the left and right channels using data from Table 3.1(c), some of the inconsistencies remained hidden .

3.2 Discharge data of BWDB

3.2.1 Method of discharge measurement

The BWDB discharge measurement data available for this report was as recent as 15 November 1995. A total of 103 discharge measurements were taken by the Surface Water Hydrology Directorate of BWDB during the study. The following information is given in Tables 3.2 (a), (b), and (c) for the left channel, right channel, and combined section respectively: Date of measurement, stage at Bahadurabad gauge station, discharge, cross-sectional area, cross-section averaged velocity, and water surface width. Figure 2.1 shows the transit line for discharge measurement. The measurements were taken using a non-directional Ott current meter suspended from a catamaran. Velocity was usually measured at about 80 verticals along the transit line; current meter readings were taken at 0.2 and 0.8 of the depth at each vertical. Details of the discharge measurement methodology were discussed by IFCDR and FAP24 (1995).

Table 3.2 shows that the discharge measurements were taken almost daily during April, May, October, and November, and at approximately one week intervals during the remaining four months from June to September. Daily measurements were taken by two teams, one for the left channel and another for the right channel. The weekly measurements were taken by one team. Each measurement took two days to complete, one day for the left channel and one day for the right channel.

Figure 3.4 shows the discharge and stage data plotted against time. The 26 June discharge data for the left channel were not consistent with the stage. The discharge data of the receding period in the right channel were not consistent with those in the left channel. Figures 3.5(a) and (b) show the stage data plotted against discharge data for the left and right channels respectively. Figure 3.5(b) also shows the inconsistency of the receding discharge data for the right channel. The increase in the conveying capacity of the right channel during the receding period could not be explained.

3.2.2 Comparison with FAP24 data

It was not possible to do an exact comparison between the BWDB and FAP24 discharge data in Tables 3.1 and 3.2 because the measurement periods did not match. The magnitude of the BWDB discharge data was consistently larger than that of the FAP24 data. Comparison between Figures 3.1(b) and 3.5(b) shows that the FAP24 discharge data for the receding period in the right channel do not display the inconsistency that was present in the BWDB data.

3.2.3 Data consistency check

Stage and discharge data were plotted channel-wise against cross-sectional area data and cross-section averaged velocity data in Figures 3.6 and 3.7 respectively. These plots also show the inconsistency of cross-sectional area and mean velocity data for the receding period in the right channel. There were abnormally large shifts in the right channel in the discharge, cross-sectional area, and mean velocity data during the rising stage from 20 to 21 May 1995. The cross-sectional area data for the left channel measured on 28 August 1995 was not consistent. The 4 September data also raised doubts. To detect the sources of these inconsistencies, it was necessary to scrutinize the field data sheets for discharge measurements in the left and right channels. Most of the inconsistencies were with the daily discharge measurement data for the right channel.

3.3 Geometrical characteristics and morphological effects

Figures 3.8 (a) and (b) show plots of stage versus water surface width (W) and hydraulic depth (D) for the left and right channels respectively. The hydraulic depth ($D=A/W$) and the hydraulic radius ($R=A/P$) were almost equal since the channels were very wide relative to depth. Here, A is the cross-sectional area and P is the wetted perimeter. BWDB's daily measurement data in 1995 on discharge, area, and water surface width make it possible to do an in-depth study of geometric and hydraulic characteristics [Tables 3.2(a) to (c)].

Figure 3.8(a) shows a plot of stage versus water surface width in which there were several abrupt changes in the width of the left channel. Such change in width can occur due to the presence of mega bar, char, or floodplain. Width changed abruptly during the following stage intervals: 15.03-15.21 m+PWD, 15.77-16.23 m+PWD, 16.69-17.23 m+PWD, 18.01-18.22 m+PWD, and 19.46-20.18

m+PWD during the rising stage; and 17.52–17.35 m+PWD, 17.03–16.94 m+PWD, and 15.73–15.63 m+PWD during the falling stage. Data during the falling stage were available as recently as 15 November 1995.

Figure 3.8(a) also shows the effect of abrupt change in width of the left channel in the plot of stage versus hydraulic depth. Abrupt decrease or increase in hydraulic depth was due to abrupt increase or decrease in width. Not all, but some of the abrupt width changes were caused by abrupt changes in hydraulic depth. Abrupt changes in hydraulic depth in the left channel occurred in the following stage intervals: 15.03–15.21 m+PWD, 16.69–17.23 m+PWD, and 19.46–20.18 m+PWD during the rising stage; and 17.52–17.35 m+PWD and 15.73–15.63 m+PWD during the falling stage.

Figure 3.8(b) shows that the results for the right channel had similar pattern. Abrupt changes in width and hydraulic depth occurred during the following stage intervals: 15.33–15.47 m+PWD and 16.69–17.23 m+PWD during the rising stage, and 16.70–16.66 m+PWD and 16.00–15.98 m+PWD during the falling stage. As discussed in section 3.2.3, the inconsistencies in the data affected the magnitudes of width and hydraulic depth [see Figure 3.8(b)]. The locations of change points in terms of stage, however, may not have been affected.

The comparison of hydraulic depths in Figures 3.8(a) and (b) shows that the right channel is much shallower than the left. Stage versus width plots for the left and right channels show that at the highest stage the width of the right channel did not change while the width of the left channel changed substantially (Figure 3.8). This finding is explained by the left channel having had a large floodplain on its left bank; the right channel had a floodplain on its right bank, however, it was restricted by the flood control embankment.

Plots in Figure 3.8 show that abrupt changes in water surface width and hydraulic depth occurred at different levels during the rising and falling stages. More importantly, the plots show a distinct clockwise loop for the width and stage relationship, and an anti-clockwise loop for the hydraulic depth and stage relationship. These results are explained by the width being substantially larger during the falling stage, and hydraulic depth being substantially smaller during the rising stage. This indicates that the shape of the cross-sectional geometry of the Jamuna River changes substantially due to the morphological process. A comparison of spot images taken on 24 March and 27 December 1995 showed that substantial changes occurred in the plan form of Bahadurabad reach.

3.4 Distribution of flow between channels

Based on the BWDB discharge measurement data in Tables 3.2(a) to (c), Figure 3.9 shows a plot of the ratio of the discharge in the left channel to the combined discharge in the left and right channels versus time. Figure 3.9 also shows a plot of the ratio of the left channel cross-sectional area versus the total cross-sectional area. This plot also shows the inconsistencies in the data for the right channel in an amplified manner. In particular, the plot shows that there was a very abrupt increase in the cross-sectional area of the right channel during the later part of the rising stage which was unlikely. Table 3.2(b) shows that this sudden change was from 20 to 21 May 1995. Before this time, the change in cross-sectional area data was relatively small. Section 3.2.3 also highlights this inconsistency in the data for the rising part of the hydrograph for the right channel. Figure 3.9 also shows inconsistencies in the data for the falling stage in the right channel after 1 October 1995. It was unlikely that the relative conveying capacity of the right channel would continue to increase for the falling stage during the recession part of the hydrograph. This inconsistency was also discussed earlier in sections 3.2.1 and 3.2.3.

Figure 3.9 shows that the data for the flood season are reasonable. The figure shows that the right channel carries only a relatively small portion of the total flow. The discharge shared by the left channel at the highest flood flow in 1995 was about 75% of the total discharge; the share increased to about 80% at the end of the flood season. While the hydrographs in Figure 3.4 show a decrease in the flood waves following the largest flood. Figure 3.9 shows an increase in the percentage discharge shared by the left channel during this period. A similar pattern was also present in the data for the hydrological year 1994-95 as shown by IFCDR and FAP24 (1995). FAP24 data in Tables 3.1 show that the share of the left channel increased to more than 90% in the early part of January 1996. A similar distribution was observed in the data for 1994-95.

3.5 Rate of change of discharge

The 1995 daily discharge data measured by BWDB in Table 3.2(c) show that there were very high rates of change of discharge in the Jamuna during the rising stage of the flood. For example, the discharge increased 6800 m^3/s from 20 to 21 May 1995, and 4400 m^3/s from 24 to 25 May 1995; the corresponding increases in stage were 0.47 and 0.20 m. From 3 to 11 July 1995 the discharge increased from 57800 to 84200 m^3/s, and the stage increased 0.74 m. Thus, the average rate of rise of discharge was 3300 m^3/s per day. The rate was much higher because the stage on 10 July was higher than on 11 July. The discharge decreased to 57100 m^3/s on 17 July ; thus, the average rate of fall of discharge was 4500 m^3/s per day. This rate was approximately 7% of the average discharge during this period. Due to such rapid change of discharge, there can be substantial error in the measured discharge when the measurement time is large.

3.6 Extreme flow

Both the present and previous (IFCDR and FAP24, 1995) reports include analysis of stage-discharge data from the Jamuna River for two successive hydrological years, 1994-95 and 1995-96. Examination of the annual maximum discharge and water level data for the last 40 years (1956 to 1996) show that 1994 had the lowest annual maximum discharge and very low flooding, and 1995 had the second largest annual maximum discharge and very high flooding. The annual maximum discharge in 1995 was more than double that in 1994. While the annual maximum stage in 1994 was about 0.5 m below the average floodplain level (19.1 m+PWD), the annual maximum stage in 1995 was more than 1 m above the floodplain.

3.7 Shift in stage-discharge curve

FAP24's stage-discharge data were plotted to determine whether or not there was a shift in the stage-discharge curve from 1994 to 1995. Figure 3.10 shows that there was an upward shift in the right channel, and a slight downward shift in the left channel. A significant shift in the right channel is consistent with the finding from the local water surface fall analysis (section 2.3) that aggradation was possibly occurring in the right channel.

3.8 Slope-roughness factor

Discharge divided by conveyance factor is sometimes called the slope-roughness factor. It is analogous to the Froude number. Its physical significance was discussed by IFCDR and FAP24 (1995). Figure 3.11 shows the plot of stage versus Chézy slope-roughness factor ($Q/AR^{0.5}$) computed from 1995 data for the left channel; Q is the discharge (m^3/s), A is the cross-sectional area (m^2), and R is the hydraulic radius (m). A similar plot for the right channel was not included because the data for the rising and receding periods were not consistent as discussed earlier.

Figure 3.11 shows that the slope-roughness factor increased with the increase in stage. The relationship between slope-roughness factor and stage includes a distinct counter-clockwise loop; the counter-clockwise direction is opposite from the generally observed clockwise direction due to unsteadiness of flow in a rigid bed channel. This loop feature in the Jamuna River, which is a large alluvial river, is due to the changes in the shape of channel geometry and bedform roughness. The changes in channel geometry were discussed in section 3.3. The loop covers the rising and the falling stages indicating that the hydraulic condition during the falling stage was different from that during the rising stage. Figures 3.11 and 3.4 show that the magnitude of the slope-roughness factor fluctuates at high stages with the passage of several flood waves during the flood season. The plot indicates that the hydraulic condition was quite different during the flood season.

The Chezy slope-roughness factor data for the right channel, from the consistent data period of 21 May to 1 October 1995, was plotted against corresponding data for the left channel (Figure 3.12). The slope-roughness factors for the right channel were much smaller than those for the left channel. Figure 3.12 shows that the distribution of flow between the two channels was not proportional to their conveyance factors. The right channel's discharge was much lower than the proportion of the conveyance factor. This is because the flow in the right channel faced substantially greater resistance than the flow in the left channel at the same stage.

3.9 Froude number

Analysis of 1995 data showed that while the stage varied between 17.3 to 20.3 m PWD, the Froude number in the left channel remained in the range of 0.17 to 0.27 during the flood season. The Froude number was reduced to 0.1 when the stage fell below 14 m+PWD. In the right channel, the Froude number varied between 0.09 to 0.16 during the 1995 flood season. It was reduced to 0.04 when there was low flow. During the 1994 flood season, during which there was very little flooding, the Froude number in the left channel varied from 0.13 to 0.19. and in the right channel from 0.09 to 0.13. During the 1995 flood season, during which there was much flooding, the Froude number in the right channel was even smaller than that in the left channel during the 1994 flood season. The dynamic conditions in the left and right channels were quite different.

4 Fitting of stage-discharge relationship

4.1 Physical considerations

The stage-discharge relationship for a river is usually divided into segments such that a particular segment is applicable to a particular hydraulic condition. A relevant question in this regard is the representativity of the water-level gauge which is used for establishing the relationship (Peters, 1996). Analysis of the slope-roughness factor in section 3.8 shows that the hydraulic conditions of the Jamuna River at Bahadurabad were different during the rising stage, flood season, and falling stage, as well as in the left and right channels. Changes in the bed topography and the shape of cross-sectional geometry caused by the morphological process were mainly responsible for the variation in the hydraulic condition. By accounting for variations in the hydraulic condition, three possibilities for achieving improved fitting of stage-discharge relationship were considered. They are as follows:

1 Different relationships for the rising stage, flood season, and falling stage;

2 Refinement of above by different relationships for lower and upper regions of the rising and falling stage; and

3 Different relationships for the left and right channels.

It is noted that the above approaches are not necessarily mutually exclusive; they can be applied in combination. Different stage-discharge relationships for rising and falling stage during flood season could not be investigated due to limited number of data, and data of rising and falling stages were not at the same level to derive the differences.

4.2 Segments based on cross-sectional shape

The elevation of bars, chars, and floodplain may produce kinks in the stage-discharge graph. Figure 4.1 shows these kinks in the plot of measured daily stage-discharge data for the left channel. These kinks correspond to the changes in width; see Figure 3.8(a) for verification. Stage-width data described the shape of a cross-section. The limit of one end of a segment corresponded to the stage near the elevation of a mega bar, char, or floodplain. The width of water surface sharply changed when the stage rose above or fell below such geometric features. The hydraulic depth changed sharply when the change in width was large enough. However, it should be noted that not only cross-sectional shape but also the river-planform should be studied to explain the variability. This was particularly stressed by Prof. Peters, during 'brain storming sessions' with the project based on his experience with the Zaire River.

The study of relationships among geometric and hydraulic parameters(discussed in sections 3.3 and 3.8) suggests that two segments for the rising stage, one segment for the flood season, and two segments for the falling stage would be appropriate for the stage-discharge relation at Bahadurabad for the 1995-96 hydrological year. Plots of water surface width versus stage and hydraulic depth versus stage (section 3.3) were helpful for identifying the ranges of stage which include 4 change points of 5 segments. In the left channel, the ranges were: 15.03-15.21 m+PWD and 16.69-17.23 m+PWD for the rising stage, and 17.52-17.35 m+PWD and 15.73-15.63 m+PWD for the falling stage. In the right channel, the ranges were: 15.33–15.47 m+PWD and 16.69–17.23 m+PWD for the rising stage, and 16.70–16.66 m+PWD and 16.00–15.98 m+PWD for the falling stage. Segment limits for the rising stage were different from those for the falling stage since the shape of cross-sectional geometry changes. A separate segment for the stage above 19.46 m+PWD seemed appropriate; however, it was not feasible because only one stage-discharge data set was available above this stage.

4.3 Investigation of accuracy

4.3.1 Fitted segments for left channel

As mentioned above, five segments were required for the stage-discharge relationship for the 1995-96 hydrological year to account for variations in hydraulic conditions during the rising stage, flood season, and falling stage. The accuracy of this approach can be investigated by fitting stage-discharge relationships to the daily measured data. Development of stage-discharge relationship is not required when daily measured discharge data are available. The purpose of fitting is to investigate whether the five-segment approach can improve discharge estimates. Data for the left channel is considered here.

The fifth segment could not be fitted since the available data did not cover the entire falling stage. The first to fourth segments were fitted. The method of fitting a stage-discharge equation to a set of data was discussed by IFCDR and FAP24 (1995). The fitted equations for the left channel for 1995 are as follows:

1st segment: $Q = 78.16(h-7.5)^{2.281}$ 1(a)
2nd segment: $Q = 196.33(h-8.0)^{1.967}$ 1(b)
3rd segment: $Q = 76.0(h-11.0)^{2.99}$ 1(c)
4th segment: $Q = 46.71(h-9.0)^{2.83}$ 1(d)
5th segment: can be fitted when data are available.

The coefficients and exponents in equations 1(a) to (d) change considerably. This indicates that the hydraulic conditions were different during the rising stage, flood season, and falling stage.

4.3.2 Accuracy of second and fourth segments

The second and fourth segments of the left channel were studied to determine whether accuracy was improved by using different relationships for the rising and falling stages. These two segments cover the upper regions of the rising and falling stages as explained in section 4.2. Discharges were generated from two fitted segments. The standard error of 2.81% was computed using the differences between generated and measured discharges. Discharges were also generated by fitting one segment to the combined data set for the rising and falling stages. This resulted in the standard error being increased to 4.62%. This experiment demonstrated that substantial improvement in accuracy was achieved when different relationships were used for the rising and falling stages.

4.3.3 Accuracy of first and second segments

Discharges were generated from the fitted first and second segments; the standard error was 3.21%. The combined data set covering the entire rising stage was fitted by one segment; the standard error was 3.44%. This experiment demonstrated that the accuracy of fitted stage-discharge relationship improved when two segments were used for the rising stage. The decrease in the standard error, however, was not much.

4.4 Choice of segments with limited data

The selection of 5 segments can improve the accuracy of fitted stage-discharge relationship. Using 5 segments is possible when there is an adequate number of stage-discharge data available for a hydrological year. The International Standard Organization (ISO, 1983) claimed that for a reliable assessment of uncertainty, it is preferable for the number of stage-discharge data to be greater than nineteen. In other words, at least nineteen data are required to obtain reliable fit for one segment. Hence, the number of available data may constrain the selection of segments in practical applications.

There should be a segment for the flood season. It is likely that number of stage-discharge data for the rising stage, which has a relatively short duration, will not be adequate for fitting two segments. One segment may have to be fitted to the data for the rising stage. This would not affect the accuracy significantly as shown by the experiment in section 4.3.3. Data from the later part of the previous hydrologic year are to be included in the data set for the rising stage if the stage has started rising. For example, the stage started rising in the second half of February 1995 (IFCDR and FAP24, 1995), therefore this data should be included in the data set for the rising stage. Two segments can be selected for the falling stage if the number of data permits, otherwise one segment can be selected for the falling stage.

4.5 Channel-wise relationships

Analyses in previous chapters show that hydraulic and morphological conditions were different in the left and right channels. Development of the channel-wise stage-discharge relationship was logical. Section 3.5 discusses how the discharge changes rapidly during flood flow. The channel-wise approach would reduce the uncertainty caused by the large amount of time required to complete the discharge measurement in two channels.

The third segment which covers the flood season was investigated. The fitted stage-discharge relationships for 1995 are given below.

Left channel: $Q = 76.0(h-11)^{2.99}$ (2a)
Right channel: $Q = 425.9(h-14)^{2.072}$ (2b)

Substantial differences in coefficients and exponents indicate that the hydraulic conditions were different in the left and right channels. The offset value was considerably higher in the right channel because its average bed level was higher than that of the left channel. The value of the offset for the left channel has remained unchanged since 1994. In 1994, the value of the offset for the right channel was 12 m. A substantially higher offset value indicates that the average bed level has risen. This is consistent with the results of the local water surface fall analysis in section 2.3.

BWDB's current practice is to derive a single stage-discharge relationship for the combined discharges from the left and right channels. The derived relationship for the third segment for the 1995 flood season is given below.

$$Q = 111.6(h-11\ 25)^{2.983} \qquad (3)$$

The standard error for the channel-wise method was 4.75%; the standard error for the single relationship for combined discharge was 4.87%. The channel-wise approach was much more accurate, however, the improvement was not significant. IFCDR and FAP24 (1995) obtained a similar result with their 1994 flood data analysis.

There was insignificant improvement in accuracy because the left channel's discharge was several times larger than the right channel's. The small discharge of the right channel did not influence the overall standard error significantly. The discharge shared by the right channel at the low stage was considerably smaller than at the high stage. Therefore, improvement in accuracy by the channel-wise approach is also likely to remain insignificant for the low flow condition.

4.6 Comparison of extrapolation methods

Extrapolation of a fitted stage-discharge relation is sometimes necessary to estimate the discharges at stages beyond the range of measured discharges. For example, the discharge at the highest stage during the 1995 flood season could not be measured. The following five methods of extrapolation were investigated by IFCDR and FAP24 (1995): (1) direct extrapolation of the fitted upper segment of stage-discharge relation, (2) the Stevens method, (3) the conveyance-slope method, (4) the slope-area method of peak discharge determination, and (5) the method based solely on the steady flow formula. The conveyance-slope method performed best. The slope-area method and the method based solely on the steady flow formula were ranked second and third respectively. These two methods, however, required determination of local water surface slope which, in turn, required measurement of stages from two staff gauges. They also required measurement of the cross-section at these two locations. Hence, the methods required extra man-power and additional cost. In addition, accurate determination of the local water surface slope in a morphologically active river reach is extremely difficult. For these reasons, these two methods are not pursued further. Although the direct extrapolation method and the Stevens method performed poorly, the direct extrapolation method is presently practised by the Hydrology Directorate of BWDB. Therefore, the direct extrapolation method and the conveyance-slope method are compared here.

The conveyance-slope method requires estimation of the Manning or Chèzy roughness coefficient. Using 1994 data, a methodology was developed in the previous report by IFCDR and FAP24 (1995). With this methodology, the Manning and Chèzy coefficients for the Jamuna River at Bahadurabad are expressed as a function of the stage for the left and right channels. For the present analysis, the roughness coefficient will be determined from that relationship. The range for the roughness coefficients for the stages is 16.75 to 18.5 m+PWD at Bahadurabad. The present comparative study also requires roughness coefficient for stages above 19 m+PWD. It was decided that roughness coefficients corresponding to 18.5 m+PWD at Bahadurabad would be used for the higher stages. The Chèzy roughness coefficients, C, are equal to 60 and 50 $m^{1/2}/s$ for the left and right channels respectively. The Chèzy coefficient is likely to be higher (which implies smaller roughness) at stages near 19 m+PWD at Bahadurabad. Plots of stage versus Chézy conveyance ($CAR^{0.5}$) and stage versus slope (Q^2/C^2A^2R) are required for the conveyance-slope method (see Figures 4.2 and 4.3 respectively).

Accuracy of extrapolation methods were assessed by pretending that some discharge data (from 19 June to 18 July, and from 21 July to 2 August) were not available. The remaining data were utilized in the fitting process. The discharge was extrapolated using the measured stage on the dates of discharge measurement. This gave an extrapolation range from approximately 52,000 to 84,000 m^3/s, and a range of stage from 19.08 to 20.18 m+PWD. Such a large range provided a rigorous test for the extrapolation methods.

Date	Stage (m+PWD)	Observed discharge (m3/s)	Extrapolated discharge (m3/s)		Percent deviation	
			Extrapolation of upper segment	Conveyance slope method	Extrapolation of upper segment	Conveyance slope method
19/6/96	19.45	57,900	56,824	59,882	-1.86	3.42
3/7/96	19.44	57,800	56,634	59,882	-2.02	3.60
11/7/96	20.18	84,200	71,584	72,424	-14.98	-13.99
17/7/96	19.26	57,100	53,292	54,916	-6.67	-3.82
21/8/96	19.27	57,300	53,383	54,915	-6.84	-4.16

Table 4.1: Comparison between observed discharges and extrapolated discharges obtained by two methods of extrapolation for stage-discharge relationship

Extrapolated discharges obtained by the two methods were compared with observed discharges in Table 4.1. This was a difficult test for the methods since almost equal discharges were observed at different stages. The observed discharge on 26 June 1995 was not included in the comparison because, as discussed earlier, its magnitude for the left channel was not consistent.

The comparison in Table 4.1 shows that the conveyance-slope method performed slightly better than the method of direct extrapolation of the fitted upper segment of the stage-discharge relationship. Both methods gave considerably smaller discharges at the highest stage. This suggests that further study is required to improve the reliability of the extrapolation method. As discussed earlier, estimates of the Chézy roughness coefficient required for the conveyance-slope method are available for the stage up to 18.5 m+PWD. Based on previous comparison with the 1994 flood data by IFCDR and FAP24 (1995) and present comparison with the 1995 flood data, the conveyance-slope method estimate is expected to improve when there are better estimates of the roughness coefficient.

4.7 Uncertainty in stage-discharge relationship

As defined in the *Annex-2 - Sustainable Survey Techniques (RSP, 1996)* 'Uncertainty implies that the collected data are doubtful or questionable as opposed to the data which can be confidently accepted'. It results from unknown or unidentified sources of errors (instrumental, measuring or human) and unexplained natural variability. The uncertainty in discharge data was high in the Jamuna River, a large multi-channel alluvial river with complex braiding characteristics due to shifting of mega-bars and chars and movement of channels. The uncertainty in the stage-discharge relationship was partly due to physical process and partly from measurement errors. This study was an attempt to develop a methodology for deriving the stage-discharge relationship based on physical considerations. The uncertainties in the fitted stage-discharge relationship were not quantified in this study. Analyses in chapters 2 and 3 indicate that the uncertainty can be high due to changes in the shape of channel geometry caused by the morphological process. Further studies should be undertaken for a quantitative assessment of uncertainty in the fitted stage-discharge relationship due to morphological factors and measurement errors.

Important sources of uncertainty in the fitted stage-discharge relationship from certain measurement errors at Bahadurabad are briefly mentioned below.

1 Random and systematic measurement errors in the water level data,

2 Random and systematic measurement errors in distance, water depth, point velocity, and direction,

3 Error in the measured flow area and water surface width due to imperfect alignment of the transit line and the deviation of the actual location of the boat from the transit line,

4 Error in the computed discharge due to the limited number of verticals selected along the transit line and the limited number of point measurements of velocity along the vertical,

5 Error due to the large amount of time required for the discharge measurement,

6 Error due to the long gap between successive measurements during which all flood waves are not appropriately covered,

7 Error due to variations in the location of discharge measurement section,

8 Error due to unmeasured flows in spill and cross channels and floodplain.

Other sources of uncertainty remain unidentified.

The reliability of the fitted stage-discharge relationship increases as the number of measured discharge data increase. There is a scope for optimizing the frequency of discharge measurements. The different relationships required for the rising stage, flood season, and falling stage need to be taken into consideration. Frequent discharge measurements should be taken during the first half of the hydrological year. If cost is a consideration, the frequency of discharge measurements should be reduced during the second half of the hydrological year.

5 Conclusions and recommendations

5.1 Conclusions

The conclusions of this study are based on the analysis of water level and discharge data collected from the Jamuna River at Bahadurabad during the 1994-95 and 1995-96 hydrological years. While there was very little flooding in 1994, there was a great amount of flooding in 1995. The highest discharge in 1995 was the second largest among the annual maximum discharge data for the last 40 years; the discharge in 1994 was the smallest.

Consideration of morphological factors in the process of developing an annual stage-discharge relationship for the Jamuna River at Bahadurabad improved the accuracy of the fitted relationship. Flow regimes during the falling stage, flood season, and rising stage were different due to changes in the shape of cross-sectional geometry and bedform roughness caused by the morphological process.

Analysis shows that different stage-discharge relations would be appropriate for the rising stage, flood season, and falling stage.

Study of daily discharge measurement data indicates that a total of five segments were appropriate for the stage-discharge relationship for the 1995-96 hydrological year; two segments for the rising stage, one segment for the flood season, and two segments for the falling stage. Study of the relationships of water surface width and hydraulic depth with stage provided the basis for determining the segment limits. Selection of five segments may not be possible, however, when the number of data is limited. Compromise is needed in the selection of segments as explained in section 4.4.

Extrapolated flood discharge based on the conveyance-slope method was more accurate than that based on direct extrapolation of the fitted stage-discharge relationship which is presently practised by the Hydrology Directorate of the BWDB. However, experience in the Zaire River shows that the best alternative is to measure them (Peters, 1996). Particularly, loop effects can also be important during peak river stages.

The discharge shared by the right channel at Bahadurabad was a small fraction of the total flow and its share decreased with the fall of the stage. The distribution of flow between the left and right channels was not proportional to their conveyance factors. The Froude number of flow in the left channel was substantially higher than that in the right channel. The average bed level in the right channel has risen.

Different stage-discharge relationships for the left and right channels was a better approach since hydraulic and morphological conditions were different in the two channels. This approach reduced the uncertainty due to the large amount of time required to complete the discharge measurement in the two channels. However, this approach did not significantly improve the accuracy because the right channel has much less discharge than the left channel.

Consistency of discharge measurement should be checked channel-wise. Plotting stage and discharge data against cross-sectional area data as well as against cross-section averaged velocity data will be helpful in detecting inconsistencies.

5.2 Recommendations

Frequent discharge measurements should be taken during the first half of the hydrological year. If cost is a consideration, the frequency of measurements should be reduced during the second half of the hydrological year.

The consistency of discharge measurement data obtained during a hydrological year should be checked using channel-wise data, otherwise some of the inconsistencies may remain undetected. The check can be performed by plotting stage and discharge data against cross-sectional area data, as well as against cross-section averaged velocity data.

Segments for fitting the stage-discharge data should be selected by satisfying the requirement of different stage-discharge relationships for the rising stage, flood season, and falling stage as explained in section 4.4. Segment limits can be selected by plotting stage against water surface width and hydraulic depth.

Use of the conveyance-slope method for the extrapolation of discharges to stages beyond the range of measured discharges should be given consideration.

Studies should be undertaken for a quantitative assessment of uncertainty in the fitted stage-discharge relationship due to morphological factors and measurement errors.

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sl no	Year	Month	Day	WL (m+PWD)	DIS (cumec)	C/Area (m²)	Mean-velocity (m/s)	Width (m)
1	1995	4	3	13.49	4090	5543	0.74	990
2	1995	4	29	14.48	6133	6180	0.99	1009
3	1995	4	30	14.73	6526	6425	1.02	1026
4	1995	6	2-4	17.62	19523	20605	0.95	3046
5	1995	6	20	19.46	39764	27816	1.43	13399
6	1995	6	21-22	19.43	40956	24442	1.68	3919
7	1995	7	7-10	20.12	56754	31973	1.78	4843
8	1995	7	11-12	20.22	59917	28692	2.09	4818
9	1995	7	21-25	19.14	39140	22772	1.72	4544
10	1995	8	25	18.72	30529	21873	1.40	2737
11	1995	8	28-29	18.51	26353	22916	1.15	3940
12	1995	9	17-21	17.79	21143	17771	1.19	3258
13	1995	10	9-10	17.78	20930	20901	1.00	3375
14	1995	10	28-30	16.47	14409	22455	0.64	3357
15	1995	11	9-12	15.53	10456	19805	0.53	3151
16	1995	11	18	15.46	9009	20267	0.44	3365
17	1995	12	7-10	14.59	6633	8689	0.76	1414
18	1995	12	17	14.26	5522	8059	0.69	1252
19	1996	1	8	13.82	4888	7412	0.66	1232
20	1996	1	22	13.64	4678	7149	0.65	1234
21	1996	2	16	13.25	3855	6339	0.61	1249
22	1996	2	29	13.25	3886	6361	0.61	1304

Table 3.1 (a): Discharge measurement data of River Survey Project FAP-24 for the left channel of the Jamuna River at Bahadurabad

sl no	Year	Month	Day	WL (m+PWD)	DIS (cumec)	C/Area (m²)	Mean-velocity (m/s)	Width (m)
1	1995	4	3	13.49	495	1569	0.32	280
2	1995	4	30	14.73	1293	1945	0.66	302
3	1995	4	30	14.73	1359	1945	0.70	302
4	1995	6	5	17.58	3803	7128	0.53	1815
5	1995	6	20	19.46	12948	13399	0.97	2331
6	1995	6	24	19.23	11415	12844	0.89	2328
7	1995	7	7	20.48	23641	15478	1.53	2729
8	1995	7	13	20.01	20211	14605	1.38	2333
9	1995	7	24	19.11	10038	11983	0.84	2552
10	1995	8	23	19.06	9905	10592	0.94	2654
11	1995	8	30	18.49	6808	7467	0.91	1840
12	1995	9	20	17.79	4363	5344	0.82	1616
13	1995	10	8	18.07	4974	4968	1.00	1094
14	1995	10	28	16.35	2259	3366	0.67	545
15	1995	11	11	15.55	1261	2689	0.47	520
16	1995	11	19	15.4	1197	2651	0.45	524
17	1995	12	9	14.51	581	2044	0.28	483
18	1995	12	18	14.24	339	841	0.40	350
19	1996	1	9	13.8	302	1599	0.19	435
20	1996	1	23	13.61	287	1191	0.24	358
21	1996	2	17	13.23	305	1105	0.28	452
22	1996	3	1	13.32	214	1149	0.19	491

Table 3.1 (b): Discharge measurement data of River Survey Project FAP-24 for the Right channel of the Jamuna River at Bahadurabad

Year	Month	Day	Sl. no	WL (m+PWD)	DIS (cumec)	C/Area (m^2)	Mean-velocity (m/sec)	Width (m)
1995	4	3	1	13.49	4585	7112	0.64	1270
1995	4	29-30	2	14.61	7426	8125	0.91	1311
1995	4	30	3	14.73	7885	8370	0.94	1328
1995	6	2-5	4	17.59	23326	27733	0.84	4861
1995	6	20	5	19.46	52712	41215	1.28	3502
1995	6	21-24	6	19.35	52331	37286	1.40	6247
1995	7	7-10	7	20.30	80395	47451	1.69	7572
1995	7	11-13	8	20.15	80128	43297	1.85	7151
*1995	7	15	9	19.61	65000	107268	0.61	15226
1995	7	21-25	10	19.08	49178	34755	1.41	7096
*1995	8	14	11	19.24	54318	129810	0.42	14711
*1995	8	17	12	19.67	62831	151930	0.41	16218
1995	8	23-25	13	18.89	40434	32465	1.25	5391
1995	8	28-30	14	18.52	33161	30383	1.09	5780
1995	9	17-21	15	17.74	25506	23115	1.10	4874
1995	10	8-10	16	17.88	25904	25869	1.00	4469
1995	10	28-30	17	16.36	16668	25821	0.65	3902
1995	11	9-12	18	15.54	11717	22494	0.52	3671
1995	11	18-19	19	15.43	10206	22918	0.45	3889
1995	12	7-10	20	14.55	7214	10733	0.67	1897
1995	12	17-19	21	14.25	5861	8900	0.66	1602
1996	1	8-9	22	13.82	5190	9011	0.58	1667
1996	1	22-23	23	13.62	4965	4965	1.00	1592
1996	2	16-17	24	13.25	4160	7444	0.56	1701
1996	2-3	29-1	25	13.25	4100	7510	0.55	1795

* measurements are not on the routine transect

Table 3.1 (c): Discharge measurement data of River Survey Project FAP-24 in the Bahadurabad transit (left + right channel) of the Jamuna River

Sl.NO	Year	Month	Day	WL (m+PWD)	Discharge (m^3/s)	Area (m^2)	Mean-Vel (m/s)	Width (m)
1	1995	4	1	13.47	4815	6590	0.73	1140
2	1995	4	2	13.48	4835	6611	0.73	1140
3	1995	4	3	13.49	4840	6625	0.73	1140
4	1995	4	4	13.54	4899	6673	0.73	1140
5	1995	4	5	13.67	4982	6717	0.74	1144
6	1995	4	6	13.78	5069	6779	0.75	1153
7	1995	4	8	13.94	5130	6817	0.75	1156
8	1995	4	9	14.01	5408	6902	0.78	1172
9	1995	4	10	14.04	5626	6964	0.81	1172
10	1995	4	11	13.99	5556	6944	0.80	1172
11	1995	4	12	13.91	5427	6941	0.78	1170
12	1995	4	13	13.48	5138	6881	0.75	1166
13	1995	4	15	13.77	5093	6860	0.74	1161
14	1995	4	16	13.77	5097	6841	0.75	1161
15	1995	4	17	13.77	5110	6856	0.75	1164
16	1995	4	18	13.75	5075	6825	0.74	1158
17	1995	4	19	13.78	5118	6851	0.75	1164
18	1995	4	20	13.91	5202	6889	0.76	1166
19	1995	4	22	14.34	6016	7175	0.84	1197
20	1995	4	23	14.38	6357	7239	0.88	1205
21	1995	4	24	14.34	6214	7214	0.86	1199
22	1995	4	25	14.27	6119	7166	0.85	1191
23	1995	4	26	14.20	6013	7137	0.84	1183
24	1995	4	27	14.18	5907	7117	0.83	1183
25	1995	4	29	14.50	6444	7333	0.88	1207
26	1995	4	30	14.75	7541	7621	0.99	1220
27	1995	5	2	15.03	8365	7953	1.05	1234
28	1995	5	3	15.21	9482	9289	1.02	1781
29	1995	5	4	15.33	9996	9567	1.04	1803
30	1995	5	6	15.47	10177	9677	1.05	1819
31	1995	5	7	15.77	11281	10062	1.12	1859
32	1995	5	8	16.23	12696	11516	1.10	2151
33	1995	5	9	16.52	13057	11876	1.10	2199
34	1995	5	13	16.69	13822	12740	1.08	2399
35	1995	5	15	16.37	13045	12021	1.09	2226
36	1995	5	16	16.29	12398	11950	1.04	2215
37	1995	5	17	16.26	12122	11833	1.02	2196
38	1995	5	18	16.21	11999	11779	1.02	2151
39	1995	5	20	16.68	14086	12800	1.10	2300
40	1995	5	21	17.23	18525	15799	1.17	3229
41	1995	5	22	17.63	20481	17036	1.20	3344
42	1995	5	23	17.81	22176	17696	1.25	3357
43	1995	5	24	18.01	23440	17997	1.30	3374
44	1995	5	25	18.22	27030	19994	1.35	3709
45	1995	5	28	18.21	26871	20169	1.33	3708
46	1995	5	29	18.07	26830	20755	1.29	3707
47	1995	5	30	17.93	26406	20641	1.28	3704
48	1995	5	31	17.79	24565	19645	1.25	3699
49	1995	6	5-6	17.51	20891	17328	1.21	3456
50	1995	6	12-13	17.63	21173	18094	1.17	3456
51	1995	6	19-20	19.46	42608	27378	1.56	4837
52	1995	6	26-27	19.26	42597	27214	1.57	4693
53	1995	7	3-4	19.45	42893	29002	1.48	4860
54	1995	7	11-12	20.18	64053	32829	1.95	6114
55	1995	7	17-18	19.27	42467	24945	1.70	5091

Sl.NO	Year	Month	Day	WL (m+PWD)	Discharge (m^3/s)	Area (m^2)	Mean-Vel (m/s)	Width (m)
56	1995	7	24-25	18.98	38563	24010	1.61	5191
57	1995	7-8	31-01	18.48	28681	22987	1.25	5138
58	1995	8	07-08	18.17	25781	22698	1.14	5059
59	1995	8	14-15	19.26	39221	28837	1.36	5439
60	1995	8	21-22	19.27	43485	30851	1.41	5418
61	1995	8	28-29	18.52	33562	27733	1.21	5255
62	1995	9	04-05	18.07	25621	23146	1.11	5058
63	1995	9	11-12	17.77	25163	20705	1.22	4747
64	1995	9	19-20	17.77	23168	18437	1.26	4554
65	1995	9	25-26	18.90	36686	24546	1.49	4745
66	1995	10	1	19.08	41053	26906	1.53	4954
67	1995	10	2	18.96	40222	25369	1.59	4911
68	1995	10	4	18.71	31999	22844	1.40	4849
69	1995	10	5	18.57	29916	22373	1.34	4846
70	1995	10	7	18.34	28054	21365	1.31	4841
71	1995	10	8	18.16	26550	20060	1.32	4833
72	1995	10	9	17.96	24565	18724	1.31	4826
73	1995	10	10	17.84	22968	18077	1.27	4823
74	1995	10	11	17.65	21447	17418	1.23	4817
75	1995	10	12	17.52	20248	16299	1.24	4356
76	1995	10	14	17.35	19757	15807	1.25	3708
77	1995	10	15	17.26	19036	15337	1.24	3683
78	1995	10	16	17.16	18353	15062	1.22	3665
79	1995	10	17	17.10	18175	14939	1.22	3651
80	1995	10	18	17.03	17210	14770	1.17	3636
81	1995	10	19	16.94	15958	13881	1.15	3367
82	1995	10	21	16.90	15635	13416	1.17	3359
83	1995	10	22	16.77	14633	12752	1.15	3353
84	1995	10	23	16.70	14193	12833	1.11	3353
85	1995	10	24	16.66	14249	12500	1.14	3343
86	1995	10	25	16.73	14450	12646	1.14	3343
87	1995	10	26	16.77	15579	13617	1.14	3350
88	1995	10	28	16.55	14326	12733	1.13	3329
89	1995	10	29	16.44	13975	12496	1.12	3329
90	1995	10	30	16.31	13193	12162	1.08	3218
91	1995	10	31	16.20	12543	11846	1.06	3208
92	1995	11	1	16.11	12110	11773	1.03	3202
93	1995	11	2	16.00	11601	11598	1.00	3184
94	1995	11	4	15.86	11073	10977	1.01	3126
95	1995	11	5	15.79	10630	10750	0.99	3099
96	1995	11	6	15.73	10441	10453	1.00	3033
97	1995	11	8	15.63	9460	10216	0.93	2472
98	1995	11	9	15.57	9272	9994	0.93	2463
99	1995	11	11	15.59	9210	9987	0.92	2471
100	1995	11	12	15.93	12365	12179	1.02	2836
101	1995	11	13	15.98	12548	12189	1.03	2869
102	1995	11	14	15.82	11255	11563	0.97	2822
103	1995	11	15	15.70	10293	10535	0.98	2532

Table 3.2 (a): Discharge measurement data of Bangladesh Water Development Board for the left channel of the Jamuna River at Bahadurabad

Sl.NO	Year	Month	Day	WL (m+PWD)	Discharge (m^3/s)	Area (m^2)	Mean-Vel (m/s)	Width (m)
1	1995	4	1	13.47	436	1796	0.24	408
2	1995	4	2	13.48	459	1805	0.25	408
3	1995	4	3	13.49	478	1808	0.26	408
4	1995	4	4	13.54	524	1837	0.29	411
5	1995	4	5	13.67	573	1881	0.30	416
6	1995	4	6	13.78	634	1940	0.33	419
7	1995	4	8	13.94	694	2005	0.35	423
8	1995	4	9	14.01	749	2040	0.37	425
9	1995	4	10	14.04	816	2061	0.40	426
10	1995	4	11	13.99	832	2062	0.40	426
11	1995	4	12	13.91	813	2030	0.40	424
12	1995	4	13	13.48	806	2015	0.40	424
13	1995	4	15	13.77	780	1978	0.39	421
14	1995	4	16	13.77	778	1972	0.39	421
15	1995	4	17	13.77	769	1961	0.39	421
16	1995	4	18	13.75	765	1956	0.39	420
17	1995	4	19	13.78	759	1948	0.39	420
18	1995	4	20	13.91	789	1994	0.40	423
19	1995	4	22	14.34	909	2167	0.42	435
20	1995	4	23	14.38	993	2200	0.45	437
21	1995	4	24	14.34	991	2197	0.45	436
22	1995	4	25	14.27	984	2165	0.45	434
23	1995	4	26	14.20	973	2146	0.45	434
24	1995	4	27	14.18	967	2139	0.45	433
25	1995	4	29	14.50	1115	2228	0.50	437
26	1995	4	30	14.75	1237	2333	0.53	447
27	1995	5	2	15.03	1424	2454	0.58	450
28	1995	5	3	15.21	1558	2533	0.62	454
29	1995	5	4	15.33	1682	2580	0.65	457
30	1995	5	6	15.47	1984	3202	0.62	931
31	1995	5	7	15.77	2195	3384	0.65	946
32	1995	5	8	16.23	2655	3814	0.70	1008
33	1995	5	9	16.52	3080	4354	0.71	1261
34	1995	5	13	16.69	3067	4311	0.71	1254
35	1995	5	15	16.37	2877	3964	0.73	1139
36	1995	5	16	16.29	2860	3913	0.73	1122
37	1995	5	17	16.26	2838	3814	0.74	1046
38	1995	5	18	16.21	2859	3780	0.76	1014
39	1995	5	20	16.68	3332	4388	0.76	1241
40	1995	5	21	17.23	5637	9210	0.61	2898
41	1995	5	22	17.63	6685	10273	0.65	2900
42	1995	5	23	17.81	7204	11002	0.65	2906
43	1995	5	24	18.01	7990	11934	0.67	3008
44	1995	5	25	18.22	8777	12562	0.70	3013
45	1995	5	28	18.21	8932	12932	0.69	3033
46	1995	5	29	18.07	8840	12599	0.70	3019
47	1995	5	30	17.93	8164	12071	0.68	3007
48	1995	5	31	17.79	7880	11809	0.67	3002
49	1995	6	5-6	17.51	5128	9796	0.52	2906
50	1995	6	12-13	17.63	5307	9810	0.54	2906
51	1995	6	19-20	19.46	15248	17165	0.89	3031
52	1995	6	26-27	19.26	12940	16383	0.79	3025
53	1995	7	3-4	19.45	14921	15774	0.95	3063
54	1995	7	11-12	20.18	20191	17213	1.17	3167
55	1995	7	17-18	19.27	14677	13997	1.05	3045

Sl.NO	Year	Month	Day	WL (m+PWD)	Discharge (m^3/s)	Area (m^2)	Mean-Vel (m/s)	Width (m)
56	1995	7	24-25	18.98	11880	14751	0.81	2914
57	1995	7-8	31-01	18.48	11507	13513	0.85	2907
58	1995	8	07-08	18.17	8899	13689	0.65	2885
59	1995	8	14-15	19.26	11568	15485	0.75	2898
60	1995	8	21-22	19.27	13822	15962	0.87	2902
61	1995	8	28-29	18.52	9832	12217	0.80	2938
62	1995	9	04-05	18.07	7206	9838	0.73	2939
63	1995	9	11-12	17.77	5540	9774	0.57	2937
64	1995	9	19-20	17.77	5946	10050	0.59	2934
65	1995	9	25-26	18.90	8413	12240	0.69	2937
66	1995	10	1	19.08	10420	13064	0.80	3133
67	1995	10	2	18.97	10083	13190	0.76	3129
68	1995	10	4	18.71	9787	12535	0.78	3114
69	1995	10	5	18.57	9526	12573	0.76	3115
70	1995	10	7	18.34	9428	12384	0.76	3119
71	1995	10	8	18.16	9339	12286	0.76	3130
72	1995	10	9	17.96	9243	12290	0.75	3128
73	1995	10	10	17.84	9063	12066	0.75	3125
74	1995	10	11	17.65	9003	11984	0.75	3124
75	1995	10	12	17.52	8830	11942	0.74	3125
76	1995	10	14	17.35	8605	11282	0.76	2983
77	1995	10	15	17.26	8559	11207	0.76	2983
78	1995	10	16	17.16	8479	10998	0.77	2986
79	1995	10	17	17.10	8413	10881	0.77	2988
80	1995	10	18	17.03	8358	10841	0.77	2988
81	1995	10	19	16.94	8324	10789	0.77	2988
82	1995	10	21	16.90	8178	10319	0.79	3002
83	1995	10	22	16.77	8141	10292	0.79	3002
84	1995	10	23	16.70	8049	10164	0.79	3020
85	1995	10	24	16.66	7476	9173	0.82	2583
86	1995	10	25	16.73	7689	9215	0.83	2593
87	1995	10	26	16.77	7812	9305	0.84	2597
88	1995	10	28	16.55	7677	9235	0.83	2587
89	1995	10	29	16.44	7586	8863	0.86	2562
90	1995	10	30	16.31	7431	8660	0.86	2544
91	1995	10	31	16.20	7403	8562	0.86	2541
92	1995	11	1	16.11	7283	8484	0.86	2516
93	1995	11	2	16.00	7071	8236	0.86	2404
94	1995	11	4	15.86	6580	7995	0.82	2113
95	1995	11	5	15.79	6321	7598	0.83	2108
96	1995	11	6	15.73	6108	7327	0.83	2092
97	1995	11	8	15.63	5571	6654	0.84	1987
98	1995	11	9	15.57	5344	6368	0.84	1965
99	1995	11	11	15.59	5351	6376	0.84	1981
100	1995	11	12	15.93	5496	6434	0.85	2000
101	1995	11	13	15.98	5678	6592	0.86	2025
102	1995	11	14	15.82	5538	6414	0.86	1993
103	1995	11	15	15.70	5359	6274	0.85	1992

Table 3.2 (b): Discharge measurement data of Bangladesh Water Development Board for the right channel of the Jamuna River at Bahadurabad

Sl.NO	Year	Month	Day	WL (m+PWD)	Discharge (m^3/s)	Area (m^2)	Mean-Vel (m/s)	Width (m)
1	1995	4	1	13.47	5251	8386	0.973	1548
2	1995	4	2	13.48	5294	8416	0.986	1548
3	1995	4	3	13.49	5318	8433	0.995	1548
4	1995	4	4	13.54	5423	8510	1.019	1551
5	1995	4	5	13.67	5555	8598	1.046	1560
6	1995	4	6	13.78	5703	8719	1.075	1572
7	1995	4	8	13.94	5824	8822	1.099	1579
8	1995	4	9	14.01	6157	8942	1.151	1597
9	1995	4	10	14.04	6442	9025	1.204	1598
10	1995	4	11	13.99	6388	9006	1.204	1598
11	1995	4	12	13.91	6240	8971	1.182	1594
12	1995	4	13	13.48	5944	8896	1.147	1590
13	1995	4	15	13.77	5873	8838	1.137	1582
14	1995	4	16	13.77	5875	8813	1.140	1582
15	1995	4	17	13.77	5879	8817	1.137	1585
16	1995	4	18	13.75	5840	8781	1.135	1578
17	1995	4	19	13.78	5877	8799	1.137	1584
18	1995	4	20	13.91	5991	8883	1.151	1589
19	1995	4	22	14.34	6925	9342	1.258	1632
20	1995	4	23	14.38	7350	9439	1.330	1642
21	1995	4	24	14.34	7205	9411	1.312	1635
22	1995	4	25	14.27	7103	9331	1.308	1625
23	1995	4	26	14.20	6986	9283	1.296	1617
24	1995	4	27	14.18	6874	9256	1.282	1616
25	1995	4	29	14.50	7559	9561	1.379	1644
26	1995	4	30	14.75	8778	9954	1.520	1667
27	1995	5	2	15.03	9789	10407	1.632	1684
28	1995	5	3	15.21	11040	11822	1.636	2235
29	1995	5	4	15.33	11678	12147	1.697	2260
30	1995	5	6	15.47	12161	12879	1.671	2750
31	1995	5	7	15.77	13476	13446	1.770	2805
32	1995	5	8	16.23	15351	15330	1.799	3159
33	1995	5	9	16.52	16137	16230	1.807	3460
34	1995	5	13	16.69	16889	17051	1.796	3653
35	1995	5	15	16.37	15922	15985	1.811	3365
36	1995	5	16	16.29	15258	15863	1.768	3337
37	1995	5	17	16.26	14960	15647	1.769	3242
38	1995	5	18	16.21	14858	15559	1.775	3165
39	1995	5	20	16.68	17418	17188	1.860	3541
40	1995	5	21	17.23	24162	25009	1.785	6127
41	1995	5	22	17.63	27166	27309	1.853	6244
42	1995	5	23	17.81	29380	28698	1.908	6263
43	1995	5	24	18.01	31430	29931	1.972	6382
44	1995	5	25	18.22	35807	32556	2.051	6722
45	1995	5	28	18.21	35803	33101	2.023	6741
46	1995	5	29	18.07	35670	33354	1.994	6726
47	1995	5	30	17.93	34570	32712	1.956	6711
48	1995	5	31	17.79	32445	31454	1.918	6701
49	1995	6	5-6	17.51	26019	27124	1.729	6362
50	1995	6	12-13	17.63	26480	27904	1.711	6362
51	1995	6	19-20	19.46	57856	44543	2.445	7868
52	1995	6	26-27	19.26	55537	43597	2.355	7718
53	1995	7	3-4	19.45	57814	44776	2.425	7923
54	1995	7	11-12	20.18	84244	50042	3.124	9281
55	1995	7	17-18	19.27	57144	38942	2.751	8136

Sl.NO	Year	Month	Day	WL (m+PWD)	Discharge (m^3/s)	Area (m^2)	Mean-Vel (m/s)	Width (m)
56	1995	7	24-25	18.98	50443	38761	2.411	8105
57	1995	7-8	31-01	18.48	40188	36500	2.099	8045
58	1995	8	07-08	18.17	34680	36387	1.786	7944
59	1995	8	14-15	19.26	50789	44322	2.107	8337
60	1995	8	21-22	19.27	57307	46813	2.275	8320
61	1995	8	28-29	18.52	43394	39950	2.015	8193
62	1995	9	04-05	18.07	32827	32984	1.839	7997
63	1995	9	11-12	17.77	30703	30479	1.782	7684
64	1995	9	19-20	17.77	29114	28487	1.848	7488
65	1995	9	25-26	18.90	45099	36786	2.182	7682
66	1995	10	1	19.08	51473	39970	2.323	8087
67	1995	10	2	18.96	50305	38559	2.350	8040
68	1995	10	4	18.71	41786	35379	2.182	7963
69	1995	10	5	18.57	39442	34946	2.095	7961
70	1995	10	7	18.34	37482	33749	2.074	7960
71	1995	10	8	18.16	35889	32346	2.084	7963
72	1995	10	9	17.96	33808	31014	2.064	7954
73	1995	10	10	17.84	32031	30143	2.022	7948
74	1995	10	11	17.65	30450	29402	1.983	7941
75	1995	10	12	17.52	29078	28241	1.982	7481
76	1995	10	14	17.35	28362	27089	2.013	6691
77	1995	10	15	17.26	27595	26544	2.005	6666
78	1995	10	16	17.16	26832	26060	1.989	6651
79	1995	10	17	17.10	26588	25820	1.990	6639
80	1995	10	18	17.03	25568	25611	1.936	6624
81	1995	10	19	16.94	24282	24670	1.921	6355
82	1995	10	21	16.90	23813	23735	1.958	6361
83	1995	10	22	16.77	22774	23044	1.939	6355
84	1995	10	23	16.70	22242	22997	1.898	6373
85	1995	10	24	16.66	21725	21673	1.955	5926
86	1995	10	25	16.73	22139	21861	1.977	5936
87	1995	10	26	16.77	23391	22922	1.984	5947
88	1995	10	28	16.55	22003	21968	1.956	5916
89	1995	10	29	16.44	21561	21359	1.974	5891
90	1995	10	30	16.31	20624	20822	1.943	5762
91	1995	10	31	16.20	19946	20408	1.923	5749
92	1995	11	1	16.11	19393	20257	1.887	5718
93	1995	11	2	16.00	18672	19834	1.859	5588
94	1995	11	4	15.86	17653	18972	1.832	5239
95	1995	11	5	15.79	16951	18348	1.821	5207
96	1995	11	6	15.73	16549	17780	1.832	5125
97	1995	11	8	15.63	15031	16870	1.763	4459
98	1995	11	9	15.57	14616	16362	1.767	4428
99	1995	11	11	15.59	14561	16363	1.761	4452
100	1995	11	12	15.93	17861	18613	1.869	4836
101	1995	11	13	15.98	18226	18781	1.891	4894
102	1995	11	14	15.82	16793	17977	1.837	4815
103	1995	11	15	15.70	15652	16809	1.831	4524

Table 3.2 (c): Discharge measurement data of Bangladesh Water Development Board in the Bahadurabad transit (Left + Right channel) of the Jamuna River

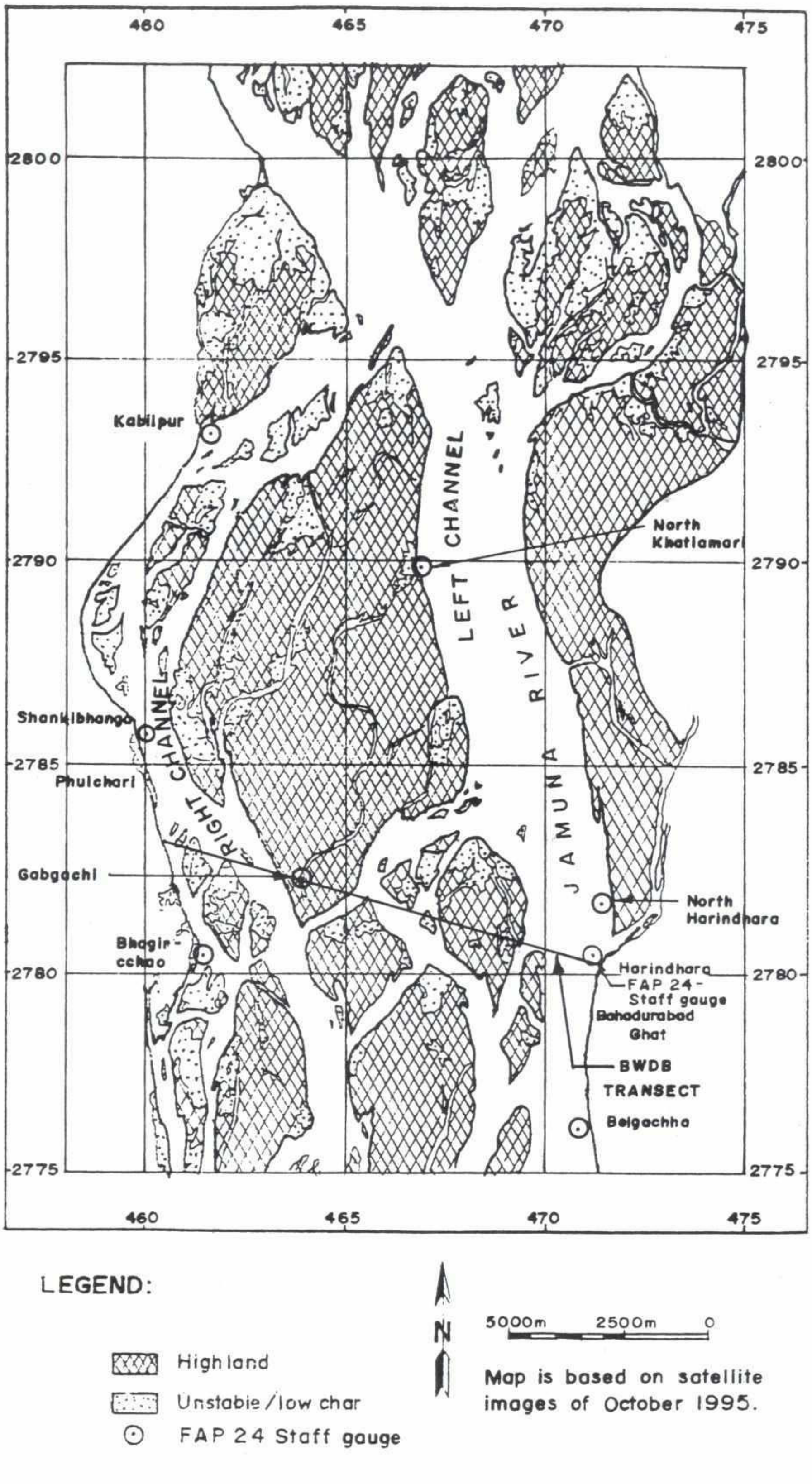
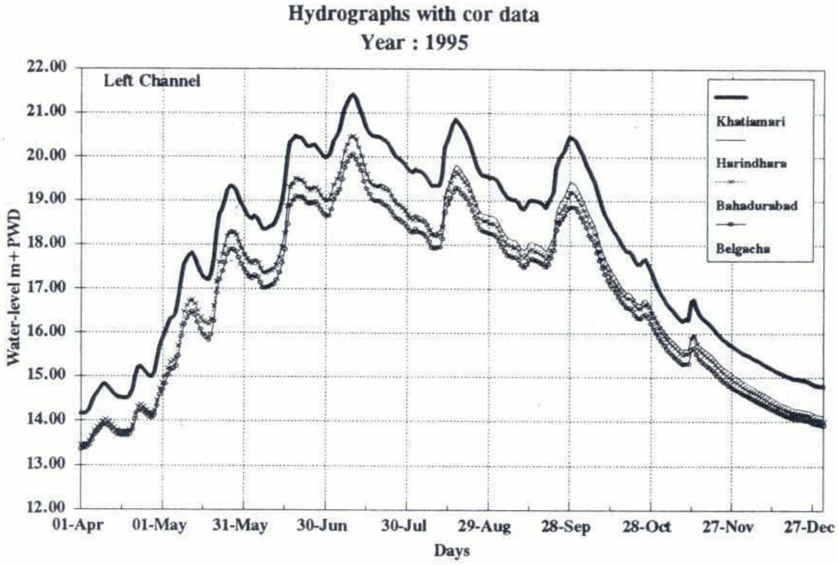


Figure 2.1: Staff gauge locations (map based on SPOT imagery December 27, 1995)



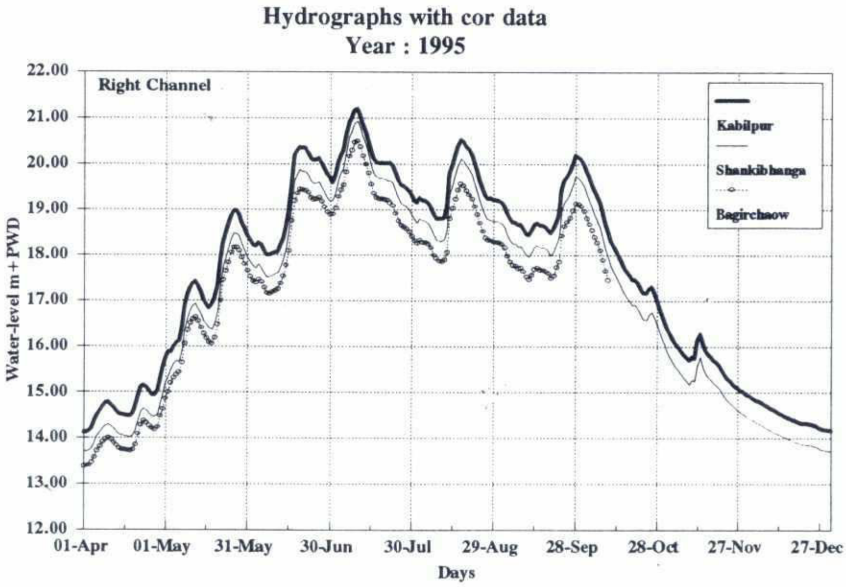
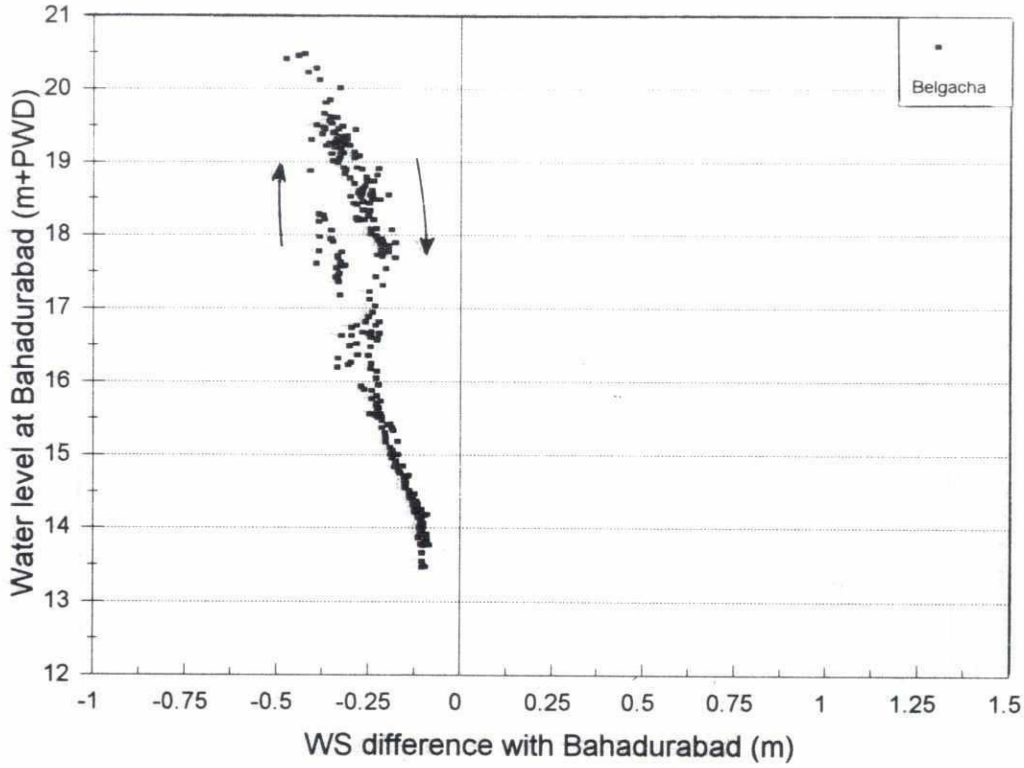


Figure 2.2: Water level hydrographs for the period of April to December 1995: (a) left channel, (b) right channel



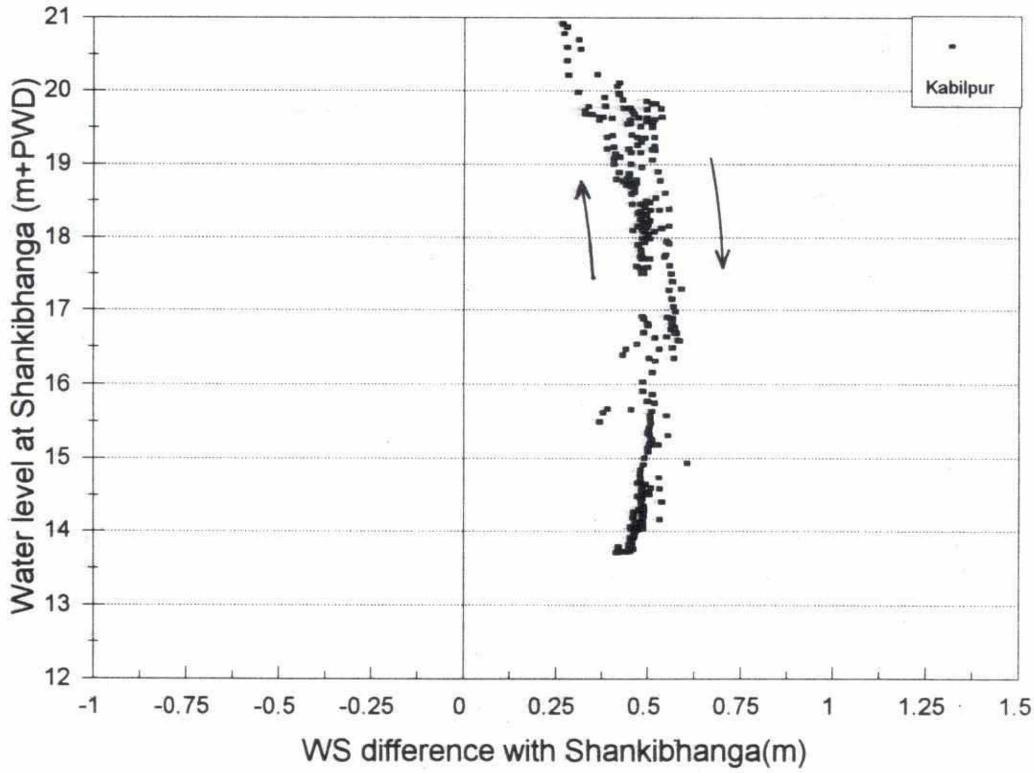
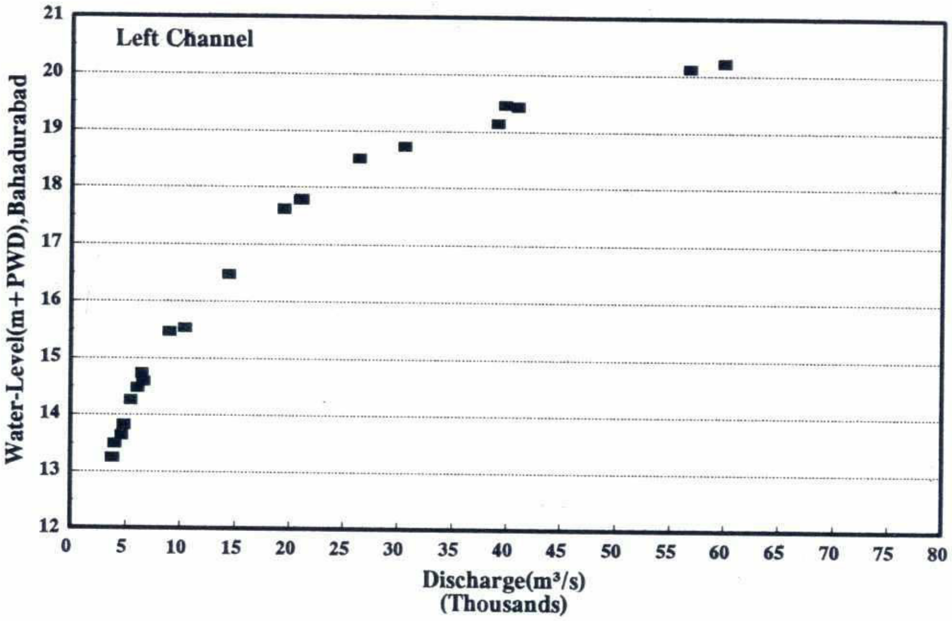


Figure 2.3: Plot of local water surface fall as a function of stage. (a) left channel. (b) right channel



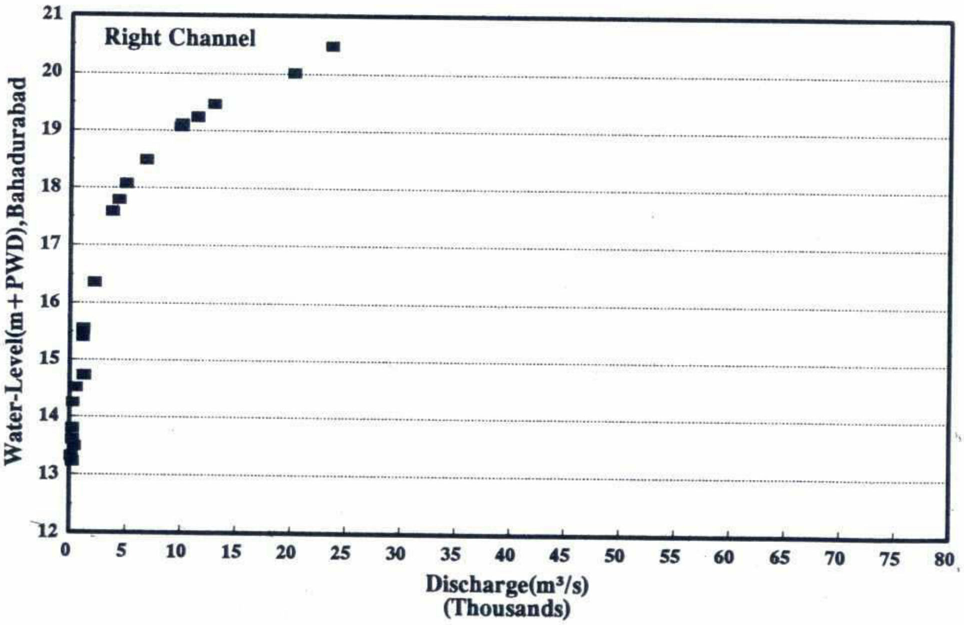
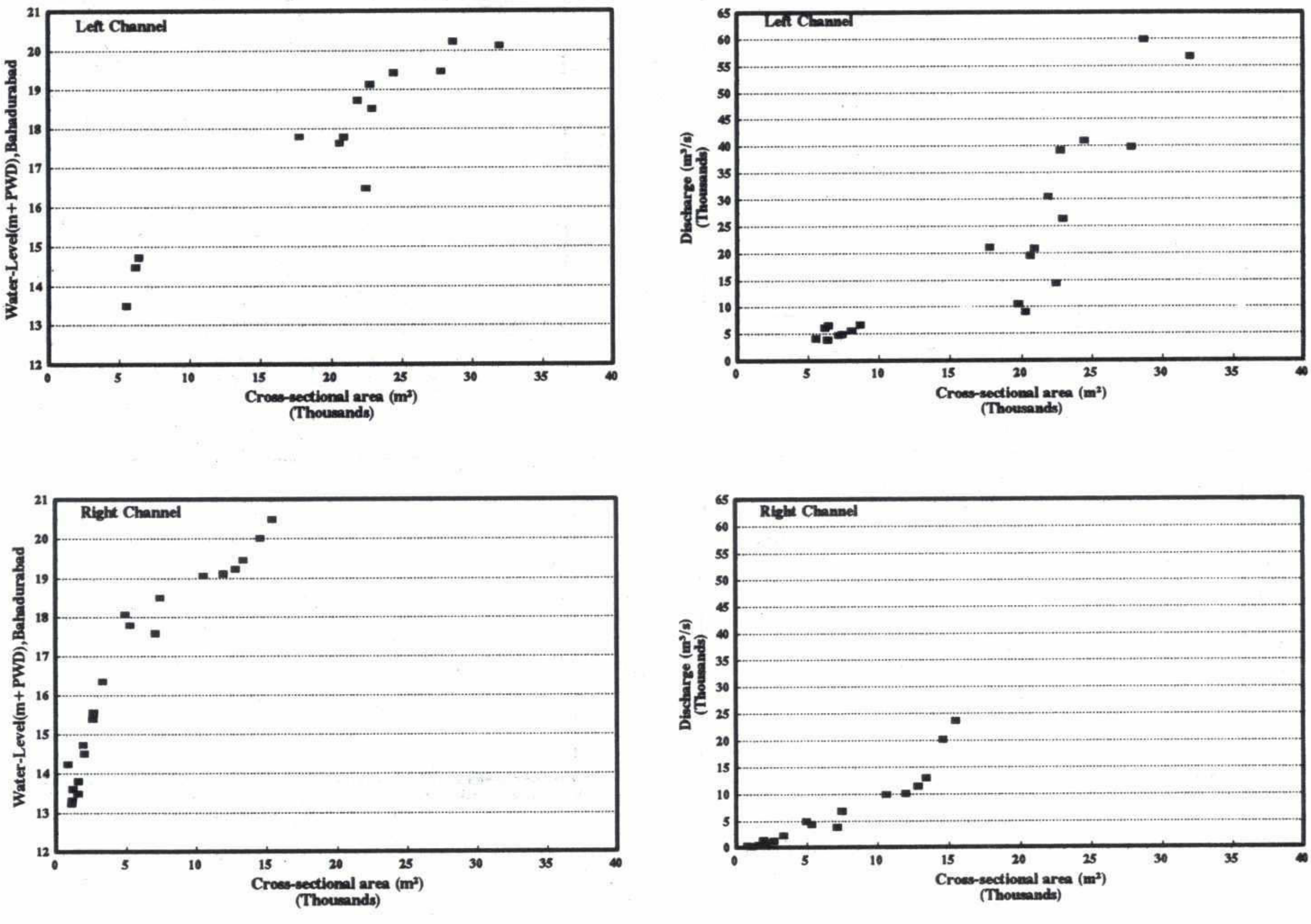


Figure 3.1: Plot of stage vs discharge using FAP-24 data for 1995. (a) left channel. (b) right channel



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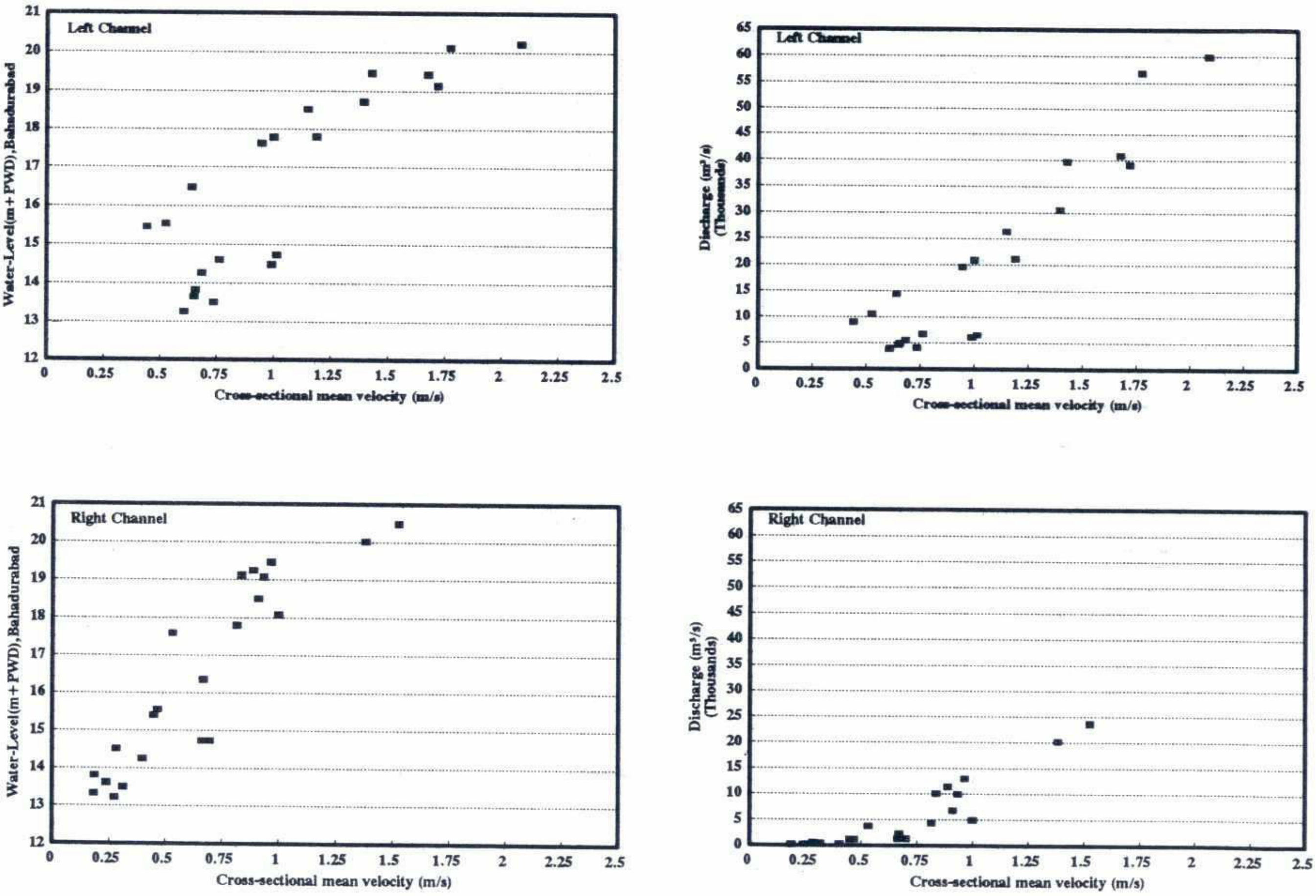

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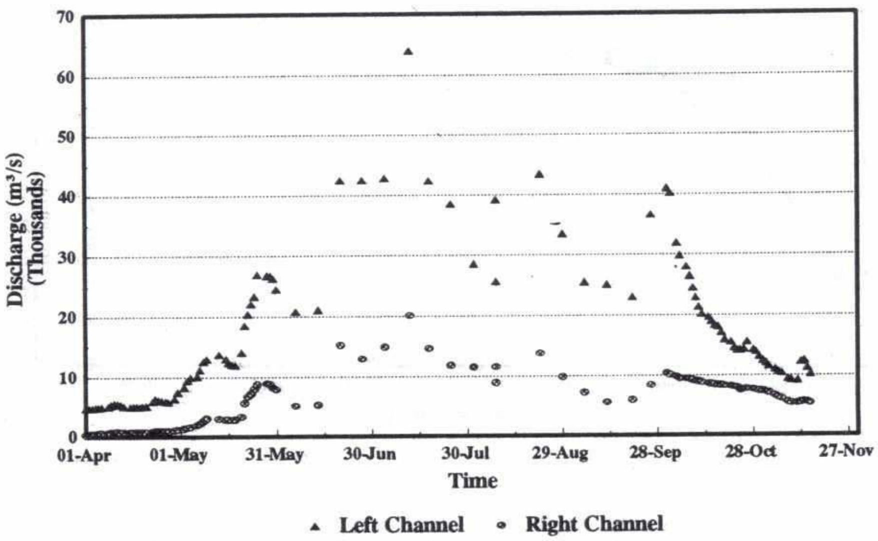

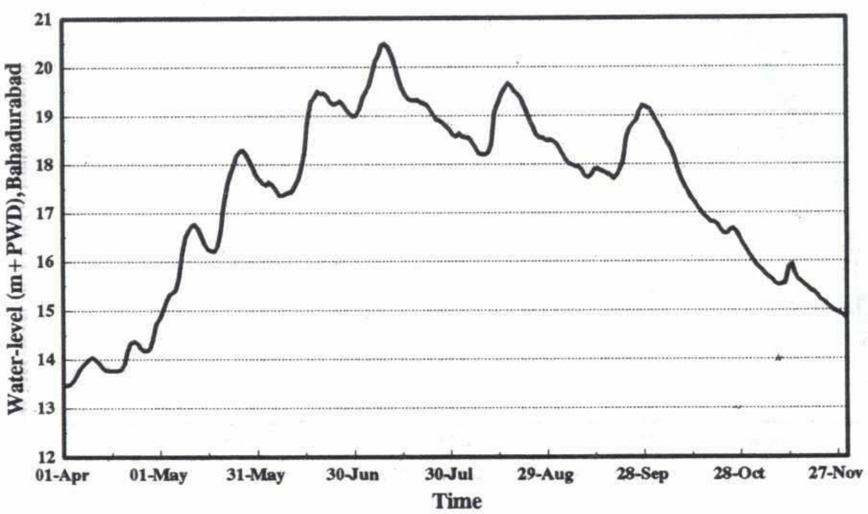

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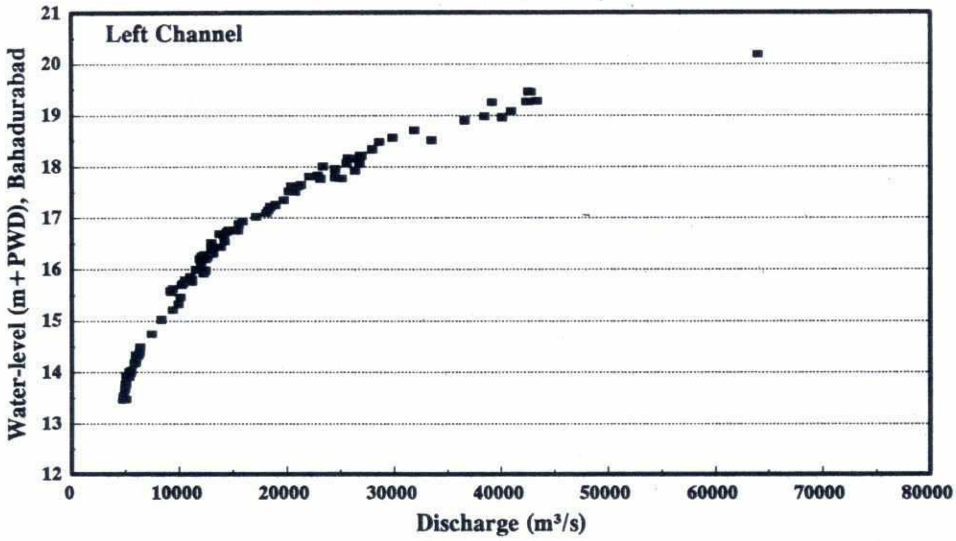

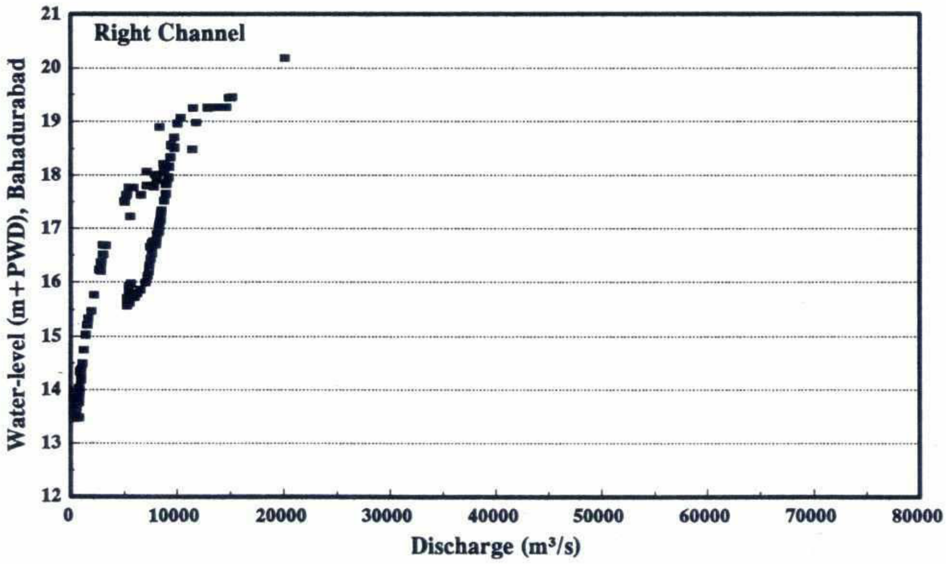

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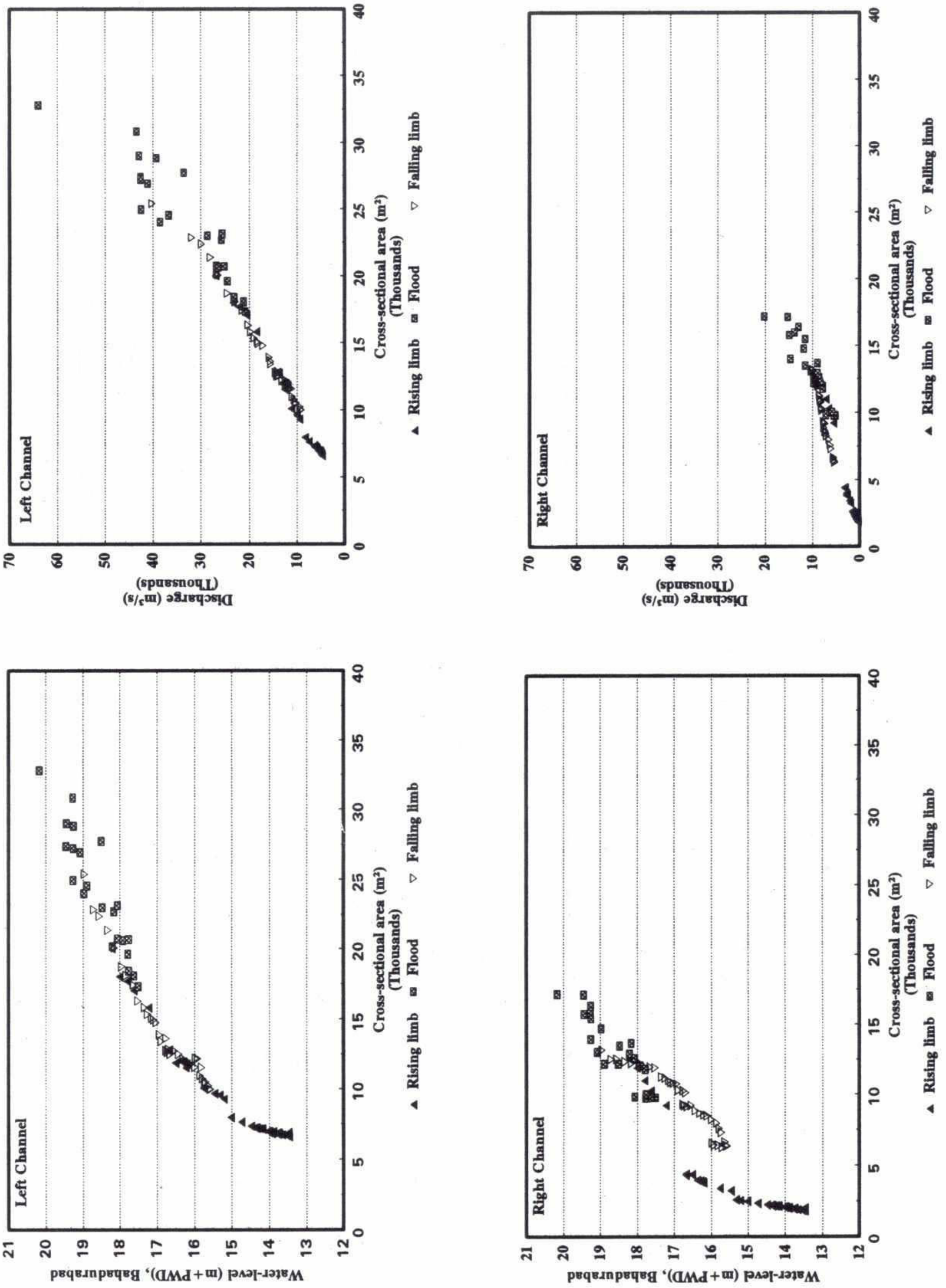

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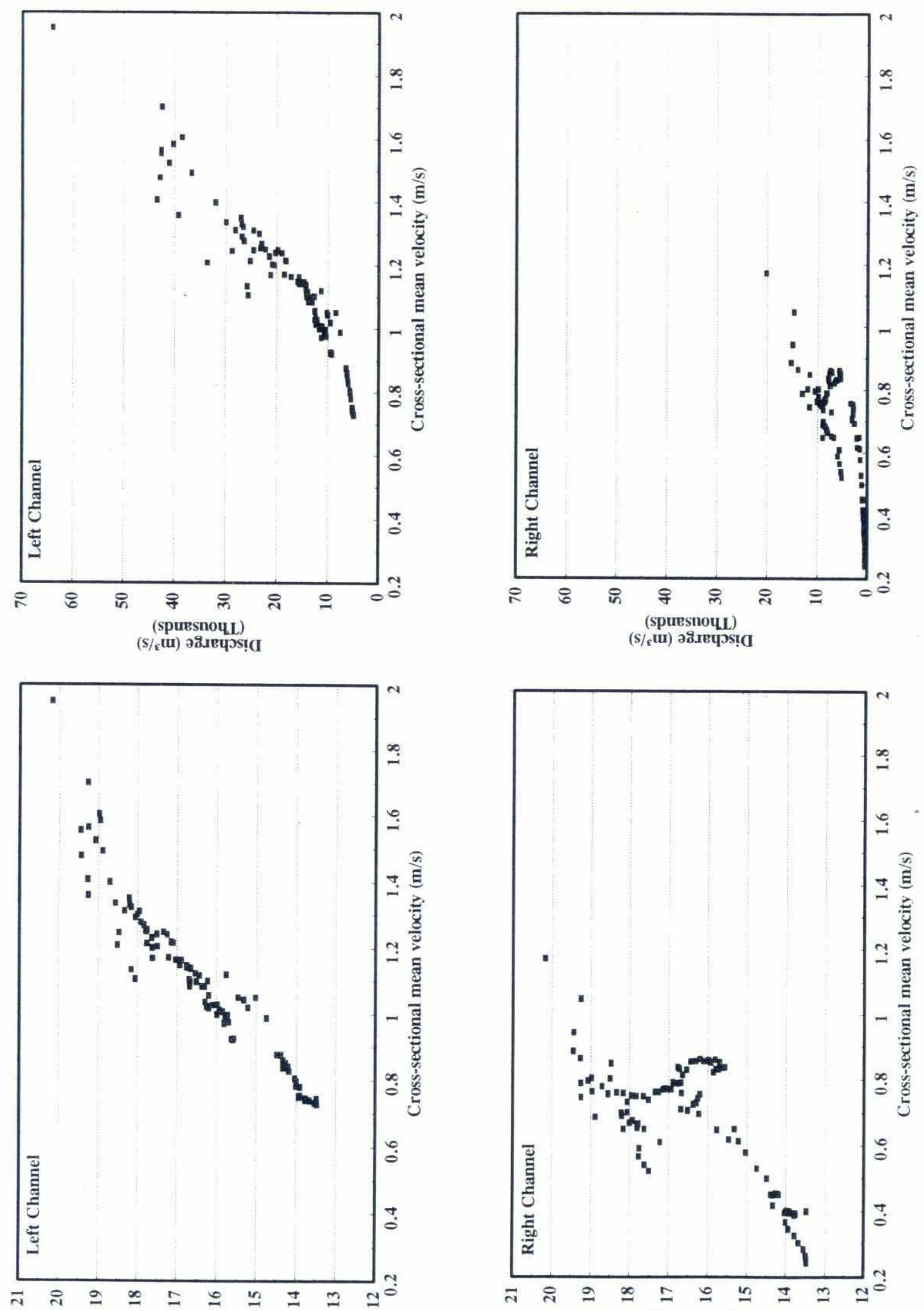

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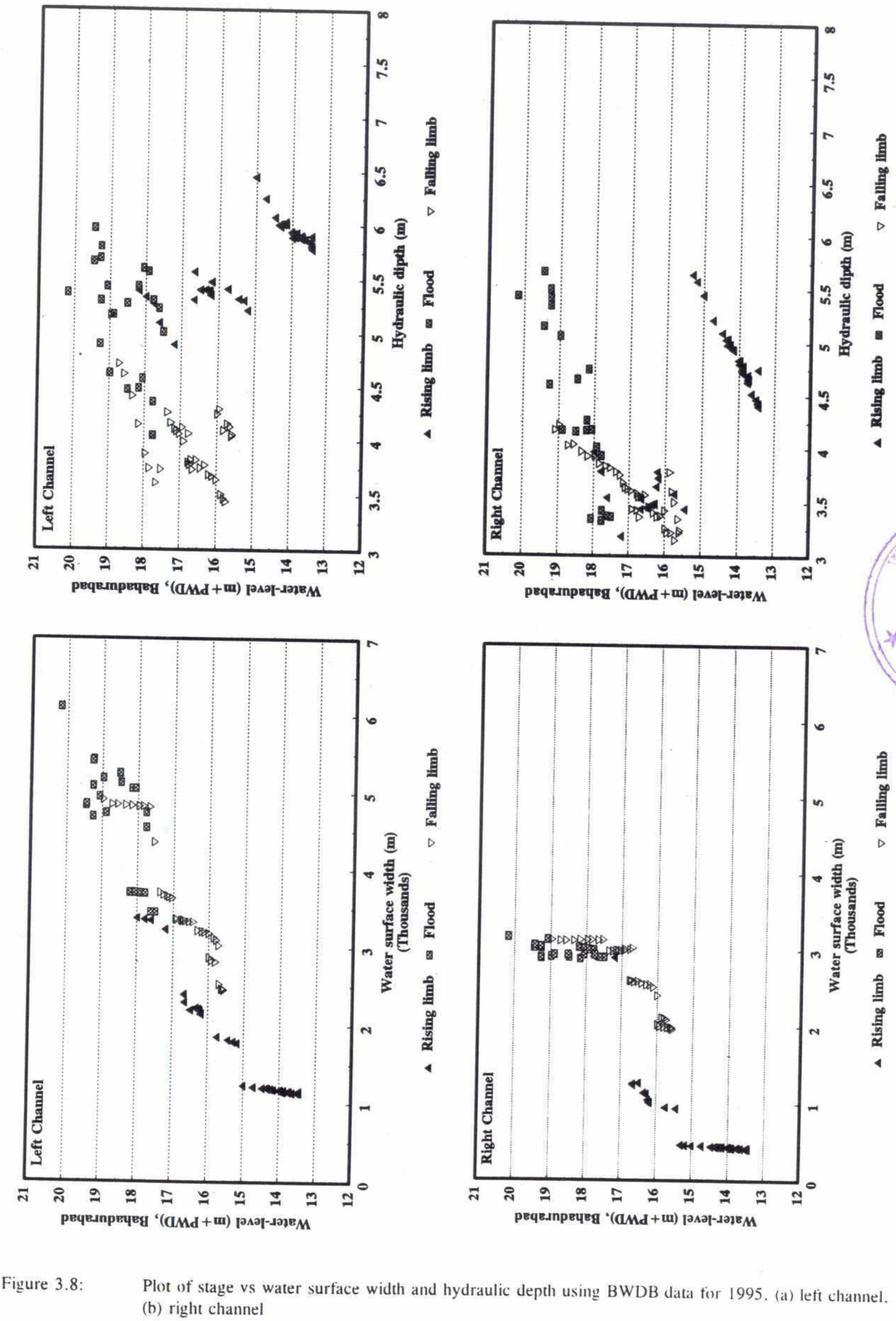

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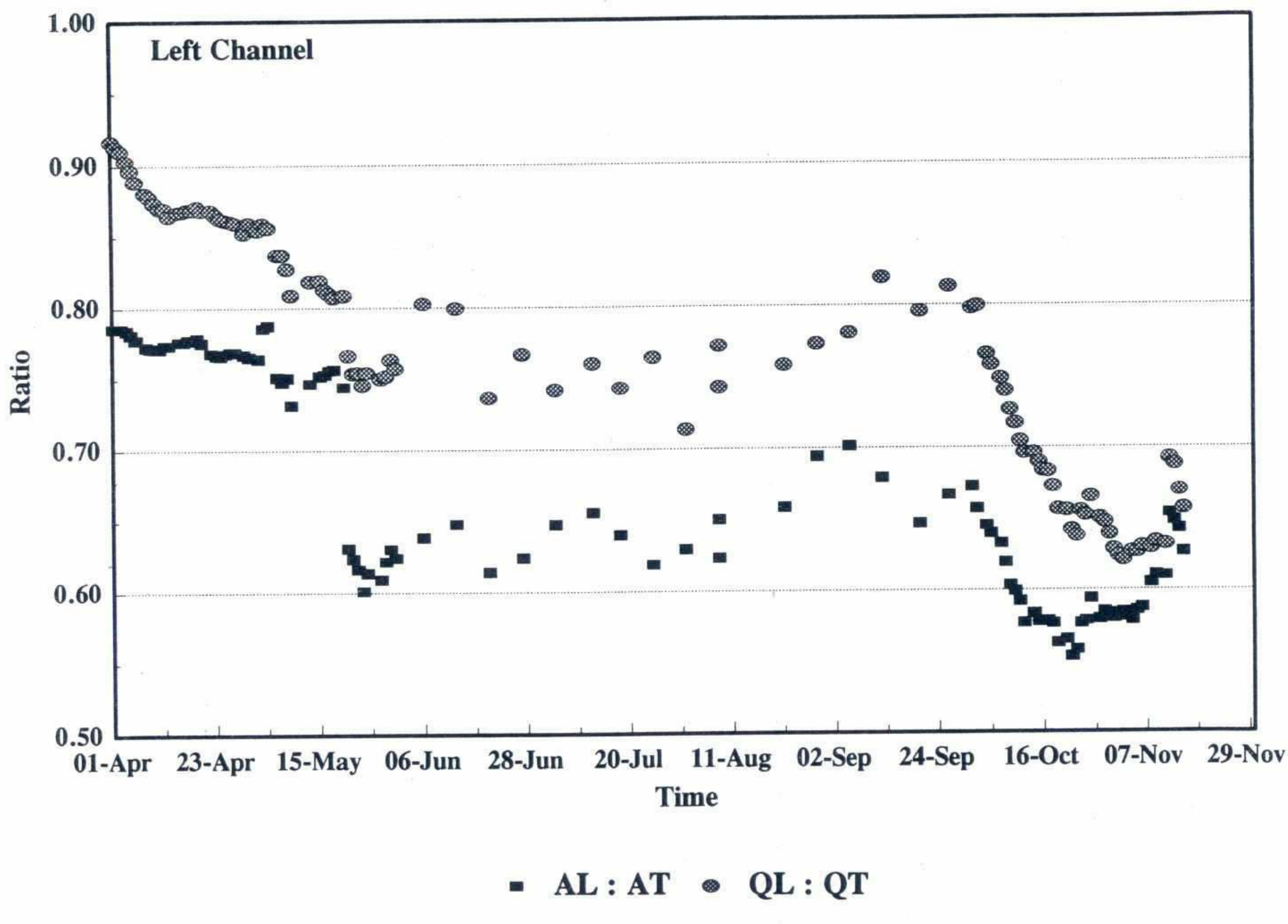

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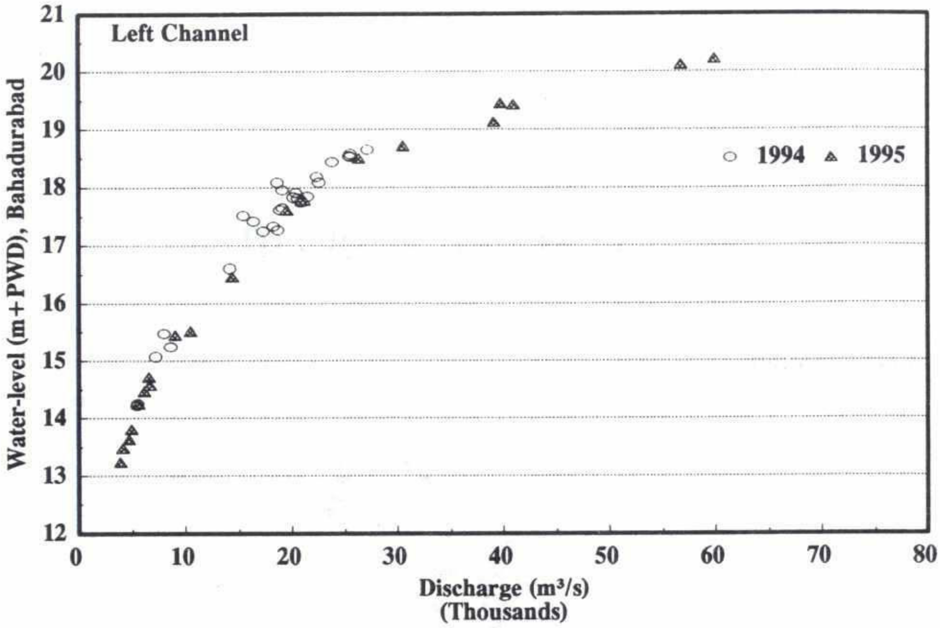

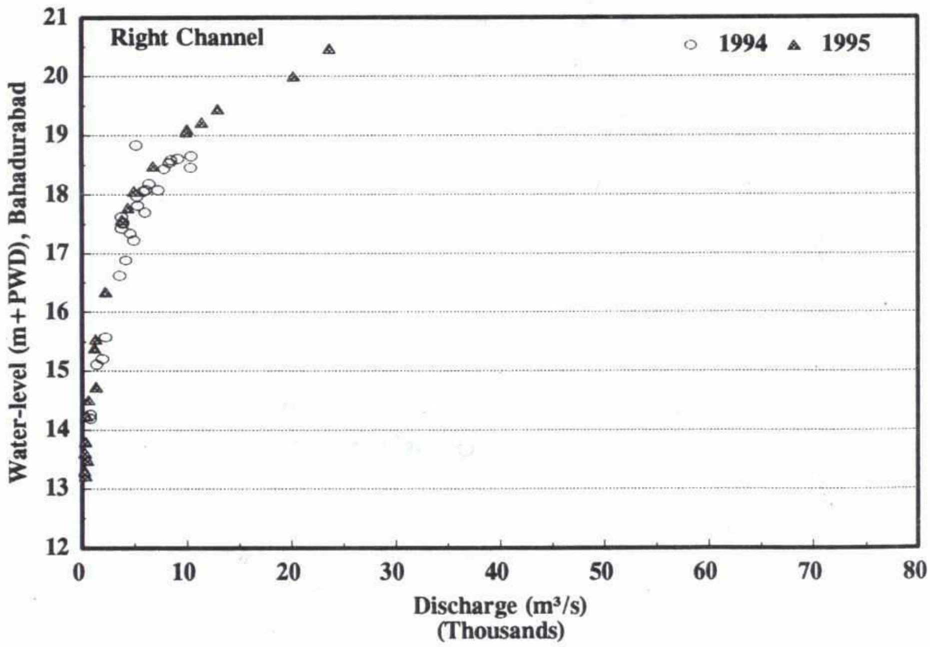

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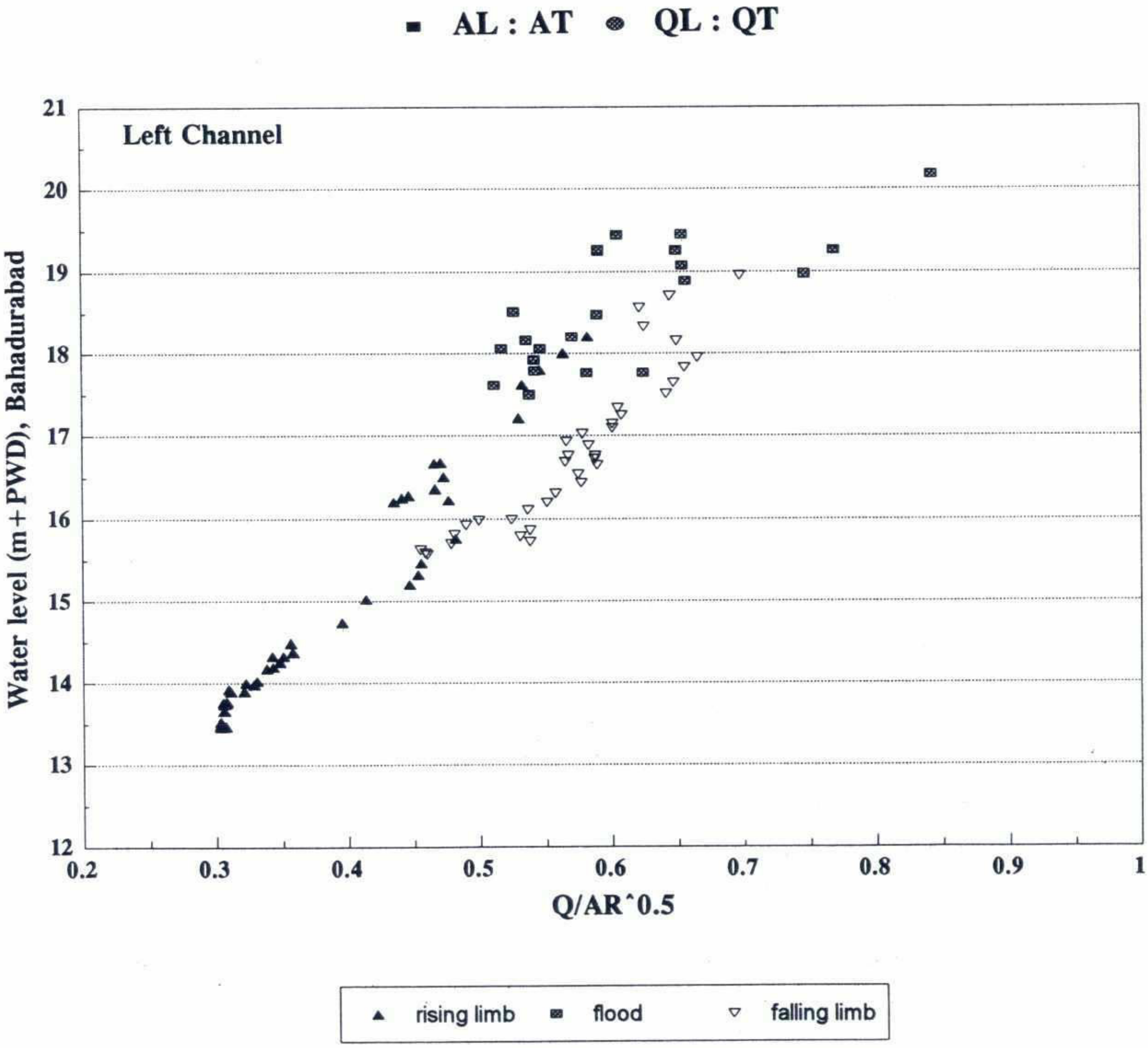

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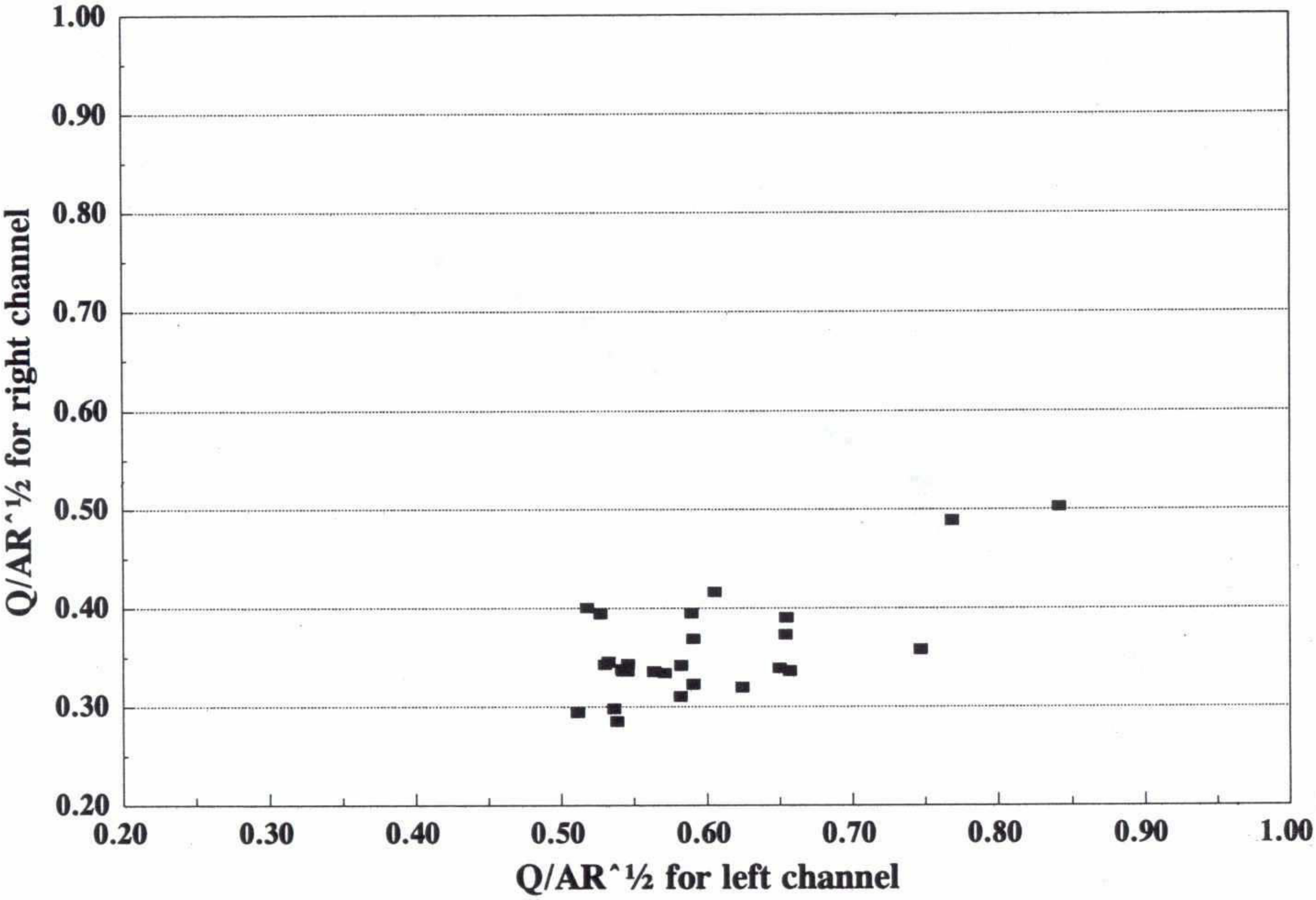

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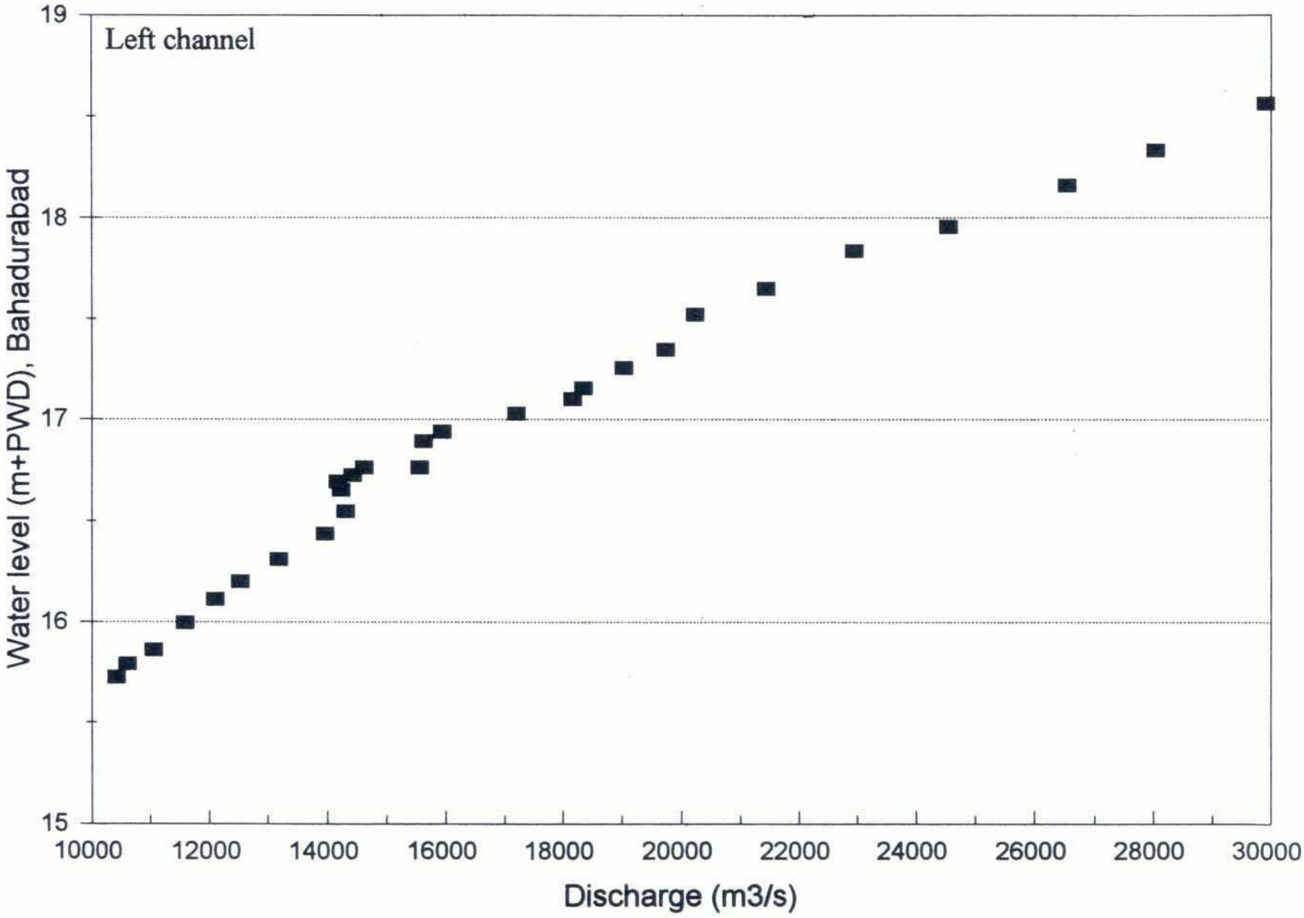

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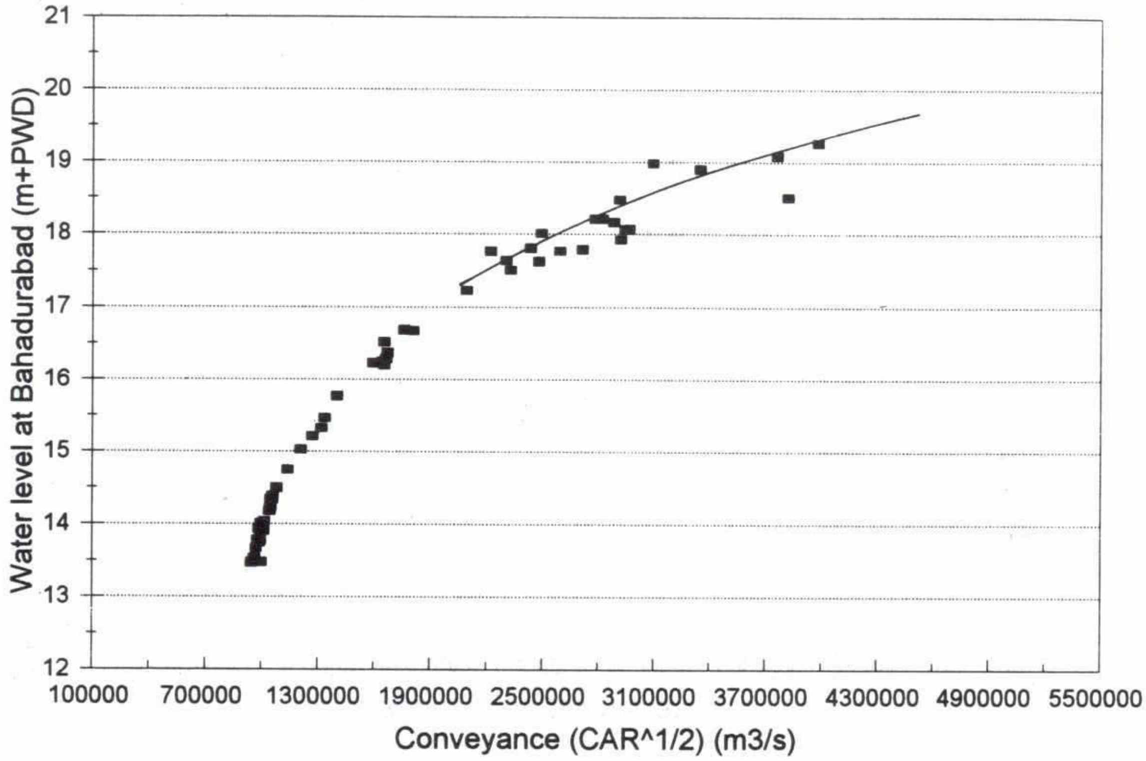

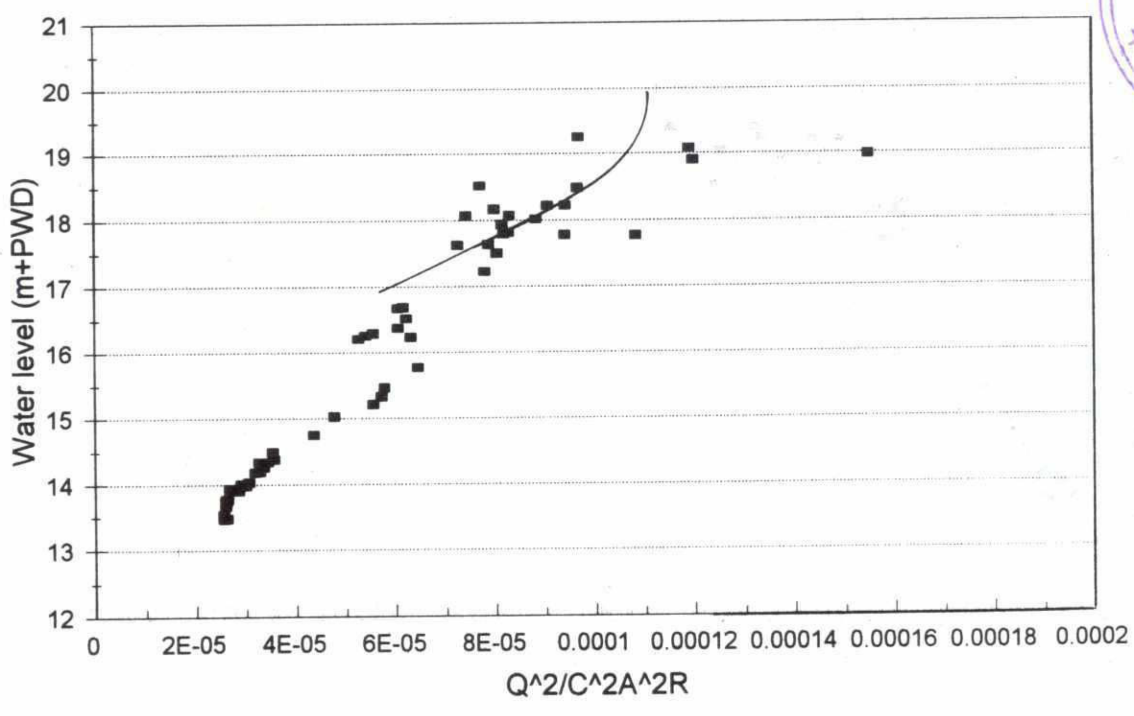

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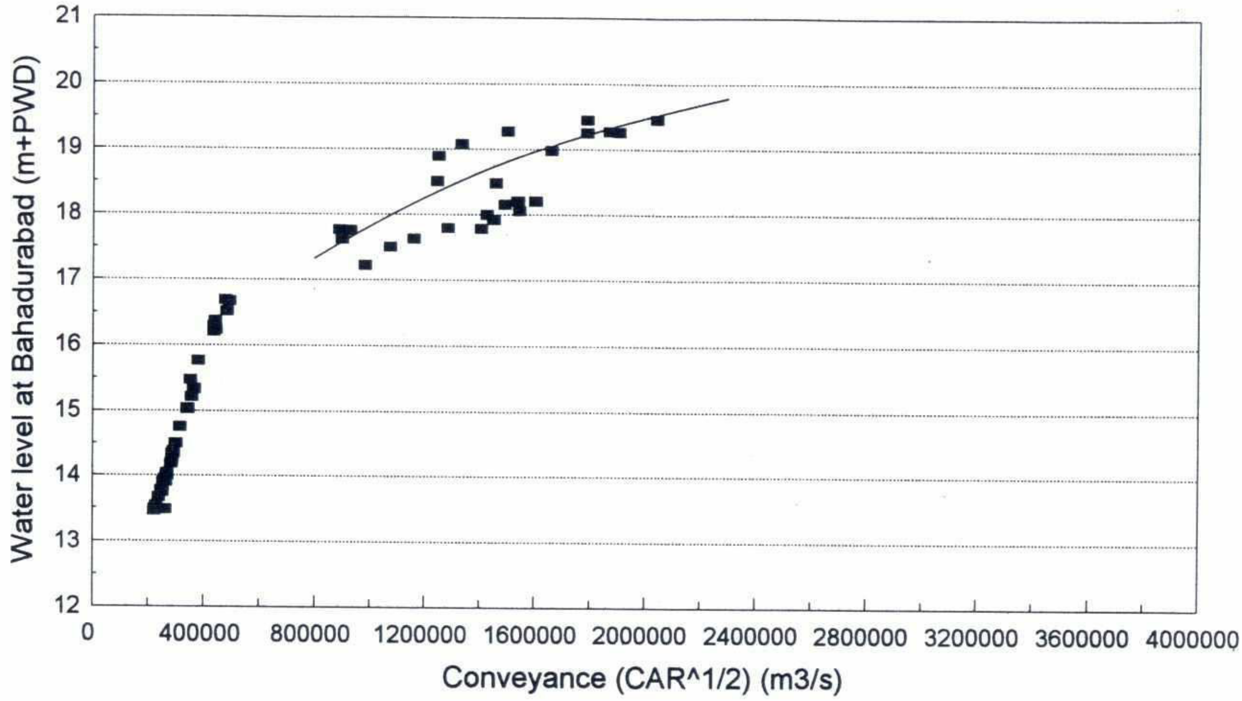

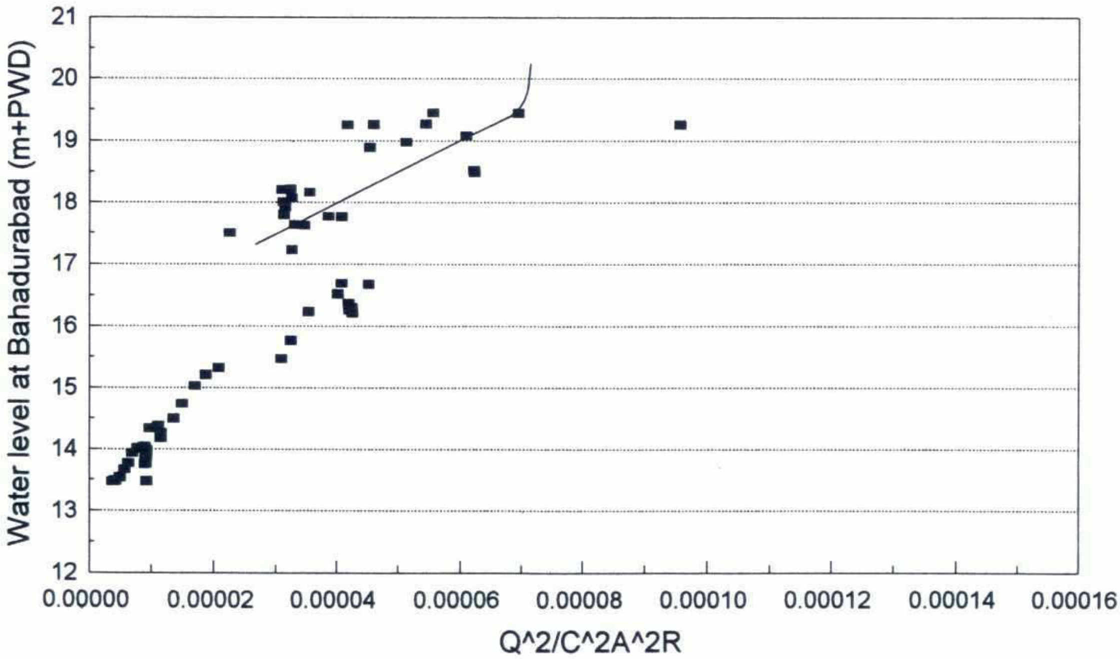

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Special Report 4, Annex 1

Stage–Discharge Relationship for the Jamuna at Bahadurabad, 1994 Data

July 1995

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1 Introduction

1.1 Background

The discharge of the Jamuna River is measured routinely at Bahadurabad by the Surface Water Hydrology Directorate of the Bangladesh Water Development Board (BWDB). The measurement is carried out by the conventional two-point velocity method by using a current meter suspended from a catamaran. Sometimes discharge measurement in this mighty river is not possible during high currents at high flood stages due to practical difficulties. Discharges at stages beyond the range of measured discharges are estimated by direct extrapolation of the fitted stage-discharge relationship (rating curve). In the River Survey Project, which is component number 24 of the Flood Action Plan (FAP24), the discharge is measured by the moving-boat method along with integrated current measurement by using modern equipments and vessel. It has the capability to measure discharge during high currents at high flood stages. In the early part of 1994, the Institute of Flood Control and Drainage Research (IFCDR) of the Bangladesh University of Engineering and Technology (BUET) proposed a study of the methods of estimating the discharges at stages beyond the range of measured discharges at Bahadurabad by utilizing FAP24 data. This has resulted in a collaboration between FAP24 and IFCDR on the study of the stage-discharge relationship for the Jamuna at Bahadurabad.

An alternative to the direct extrapolation of the fitted stage-discharge equation at a river section is the extrapolation based on the hydraulic elements of the flow section. The hydraulic elements can be derived from the geometric and hydraulic data collected during a discharge measurement. There are several variations in this approach. Two of them are the Stevens method and the Conveyance-slope method. These methods involve a process of extrapolation guided by hydraulic principles. It may be possible to avoid the process of extrapolation if data on local water surface slope is available, so that the unmeasured peak discharge can be estimated by the slope-area method. The data on water surface slope is also useful in the investigation of the hydraulic behaviour of a flood flow.

It was decided to install three staff gauges along the left channel and another three along the right channel in the Bahadurabad reach to measure the local water surface slopes. Sites for the gauges were selected during a field visit in May 1994 by the investigators of FAP24 project and IFCDR. Measurements of water levels were started in the first week of June 1994. This report presents the analysis of data collected till March 1995. A draft report was submitted in May 1995. The report has been finalized in July 1995 after receiving the comments. This report is written by J. U. Chowdhury and Zahirul Haque Khan.

1.2 Objectives

The main objective of this study is to compare methods for the estimation of discharges at flood stages beyond the range of measured discharges at the Bahadurabad reach of the Jamuna river by utilizing the data from stage-discharge measurements by FAP24.

1.3 Contents of the Report

The analysis presented in this report is based on the data collected by FAP24 during the period April 1994 to March 1995. The hydraulic and computational aspects of stage-discharge relationships have been discussed briefly in Chapter 2. A description of the Bahadurabad transit is given in Chapter 3. Some recent analyses of BWDB stage-discharge data reported elsewhere are reviewed in Chapter 4.

Chapter 5 includes an analysis of water level data from six staff gauges and local water surface slopes in the left and right channels during the period June 1994 to March 1995. Chapter 6 includes an analysis of the discharge data collected during the period April 1994 to March 1995. It includes also an analysis of hydraulic elements and section factors extracted from discharge measurement data. Chapter 7 includes comparison of the accuracy of a single stage-discharge relationship for combined discharges of two channels with that of separate relationships for discharges in the left and right channels. It also presents results of a comparison of five methods of estimating discharges at flood stages beyond the range of measured discharges. Conclusions and recommendations of this report are presented in Chapter 8.

2 Hydraulic and computational aspects of stage-discharge relation

2.1 Theoretical aspects

The theoretical aspects of stage-discharge relations have been discussed in detail in an operational hydrology report of WMO (1980b). Other discussions can be seen in text books by Henderson (1966), Jansen et al. (1979) and also in Mosley and McKerchar (1993) in the Handbook of Hydrology. A brief summary will be given here to understand the principles that underlie the stage-discharge relation.

For converting the continuous records of stage data to discharges at gauging stations, stage-discharge relations are usually expressed by a power function that plots as a straight line on logarithmic paper. The equation is given by

$$Q = \gamma(h+\alpha)^{\beta} \tag{2.1}$$

where Q is the discharge, h is the stage α is the stage at which discharge is zero, γ and β are constants.

There cannot be a unique relationship between stage and discharge as in Eq. (2.1) unless the flow is uniform where bed slope (S_o), water surface slope (S_w) and energy line slope (S_f) are equal. The three slope terms are illustrated in Figure 2.1. For steady flow condition, the discharge can be computed by using the familiar Chèzy equation or Manning equation. The discharge is given by

$$Q = CA\sqrt{RS} \tag{2.2a}$$

or

$$Q = \frac{\varnothing}{n} A R^{2/3} S^{1/2} \tag{2.2b}$$

where C is the Chèzy coefficient, n is the Mannings roughness coefficient, ϕ is 1.0 in SI units and 1.49 in FPS units, A is the cross-sectional area of flow, R is the hydraulic radius and S is the slope. In Eq.(2.2), $S=S_o$ for uniform flow conditions and $S=S_f$ for non-uniform flow conditions. Eqs. (2.2a, b) show that the discharge is not a function of depth only in non-uniform flow, even if the flow is steady.

In unsteady flow conditions, the friction slope S_f is also dependent on convective and temporal accelerations (inertia). To see the terms that make up the friction slope, the dynamic equation of gradually varied unsteady flow can be written in the following form (Henderson, 1966):

$$S_f = S_o - \frac{\partial y}{\partial x} - \frac{v}{g} \cdot \frac{\partial v}{\partial x} - \frac{1}{g} \cdot \frac{\partial v}{\partial t} \tag{2.3}$$

Steady uniform flow
Steady non-uniform flow
Unsteady non-uniform flow

where y is the depth of flow (see Figure 2.1), V is the mean flow velocity and g is the acceleration due to gravity. The alone equation shows clearly how non-uniformity and unsteadiness introduce extra terms into the dynamic equation.

Substituting S_f from Eq. (2.3) into Eq. (2.2a)

$$Q = CA\sqrt{R(S_o - \frac{\partial y}{\partial x} - \frac{v}{g}\frac{\partial v}{\partial x} - \frac{1}{g}\frac{\partial v}{\partial t})} \tag{2.4}$$

where the Chèzy equation has been used for convenience. The last three slope terms in Eq. (2.4) cause a closed loop in the rating curve for a single flood during which Q is larger on the rising stage than on the falling stage for a given stage as shown in Figure 2.2. The change in resistance due to a change in bed-form during flood flow in an alluvial river also has a role in the formation of a loop. If the last three slope terms in Eq. (2.4) are small compared to S_o, the discharge can be computed as for uniform flow, where discharge depends on the depth only.

When the bed slope is very flat, the $\delta y/\delta x$ term may well be of the same order as S_o but the third and fourth terms in Eq. (2.4) are still negligible since the Froude number will be very low (Henderson, 1966). Data on discharge measurements at Bahadurabad during 1994 indicate that the Froude numbers were below 0.2. In such condition, Eq. (2.4) can be approximated as

$$Q = CA\sqrt{R(S_o - \frac{\partial y}{\partial x})} \tag{2.5a}$$

or

$$Q = CA\sqrt{RS_w} \tag{2.5b}$$

Figure 2.1 explains S_o and S_w. When the effects of unsteadiness and non-uniformity cause significant variation in the water surface slope (S_w) at a location, Eq. (2.1) does not provide a satisfactory estimate of discharge. Eqs. (2.5) explain the significance of S_w in the computation of discharge in rivers with a flat bed slope S_o. Variable water level slopes that effect flow in open channels are caused by variable backwater, by changing discharge, or by variable backwater in conjunction with changing discharge (WMO, 1980).

Where a variable S_w is caused by variable backwater, the discharge is expressed as a function of stage and local water surface fall (a measure of S_w). An auxiliary gauge is installed at a downstream location to measure the water surface fall with respect to the base gauge and there can be constant fall rating or normal fall rating. Such approach has been investigated for the stage-discharge relationship for the Meghna river at Bhairab Bazar, which is under the influence of tide from the Bay of Bengal (see DELFT-DHI, 1995).

Where a variable S_w is caused by changing discharge, adjustments are made to the measured discharges such that the adjusted discharge can be expressed as a function of stage. At Bahadurabad in the Jamuna river, the changing discharge causes the variation in S_w.

Where a variable S_w is caused by a combination of variable backwater and variable discharge, the fall-rating methods can handle the combined effect of the two factors.

Eq. (2.5) can be modified so that the required adjustments in a rating curve for varying discharge at the same stages can be made from the flood record itself, if taken at a single river section. Applying a kinematic wave approximation and considering a wide rectangular cross-section, the term $\delta y/\delta x$ can be replaced in Eq. (2.5a) and the following approximate relation can be obtained (Henderson, 1966)

$$Q = Q_o \sqrt{1 + \frac{1}{S_o V_w} \frac{\partial h}{\partial t}} \tag{2.6}$$

where Q_o is the discharge in uniform flow condition [$S = S_o$ in Eq. (2.2a)] at same depth and V_w is the wave velocity (also called celerity).

Eq.(2.6) is well known as the " Jones formula" and it forms the basis of most of the methods to adjust a rating curve based on the observed stage-hydrograph. The methods have been discussed in WMO (1980). It is seen from Eq. (2.6) that Q is greater during rising stage ($\delta h/\delta t$ is positive) than during falling stage ($\delta h/\delta t$ is negative) for the same stages. If the difference is substantial, a loop forms in the rating curve for a flood. Eq.(2.6) explains that the effect of changing discharge is greater in a channel with a smaller bed slope.

2.2 Stage-discharge controls

The physical element or combination of elements that controls the stage-discharge relation is known as a control. Knowledge of channel features that control stage-discharge relationships is important for studying stage-discharge relations. Details of stage-discharge controls can be found in WMO (1980 a). The controls are mainly classified as section control and channel control. There are other classifications such as natural and artificial controls or complete, partial and compound controls.

Section control exists when the geometry of a single cross-section is such that a fairly stable relation between stage and discharge is maintained; it may be natural (e.g. a ledge of rock across the channel) or man-made (e.g., a constructed weir). Channel control exists when the geometry and resistance of a channel reach downstream of the gauging station are the elements that control the stage-discharge relation. The channel reach that acts as the control may lengthen as the discharge increases. Generally, the flatter the channel slope, the longer the reach of channel control. The presence of a loop in the rating curve for the Jamuna as observed by Tejada-Guibert (1993) suggests that the channel control is effective in the Bahadurabad reach. There can be other sources of influence on the stage-discharge relation such as backwater effect from the confluence with another river or road bridges. Usually, a gauge site is selected such that it is free from such effects.

Generally no single control is effective for the entire range of stage. Section controls are often effective only at low discharges, and are completely submerged by channel control at medium and high discharges. The compound control sometimes includes two section controls, as well as channel control. In that situation the section control at the gauging station is effective for the very low stages, the downstream section control is effective for intermediate stages, and the channel control is effective at the high stages (see Figure 2.3).

Shifts in the discharge rating reflect that stage-discharge relations vary from time to time because of changes in the physical features that form the control for the gauge station. In braided alluvial rivers such as the Jamuna, stage-discharge controls may change because of morphological processes such as erosion and deposition, shifting of bars and chars (islands), and changes in the configuration of channels and floodplains.

2.3 Fitting of stage-discharge equation

An equation can be fitted analytically to a series of stage-discharge measurements by transforming the Eq. (2.1) into the following form.

$$\log Q = \log\gamma + \beta\log(h+\alpha) \qquad (2.7)$$

A stage-discharge equation may consist of several segments; a particular segment is applicable to a particular control as discussed in the previous section. Study of changes in hydraulic conditions at the gauging section due to changes in control is essential to select an appropriate number of segments and their limits, while fitting an equation to stage-discharge data. After selecting the segments, the three parameters α, β and γ are to be estimated for every segment. The fitting procedure has been discussed in detail in WMO (1980) and Mosley and McKerchar (1992). By some trials, a value of the parameter α is determined for a segment such that the plot of measured points for that segment lie close to the straight line given of Eq. (2.7). With α determined for a segment, the parameters β and γ are estimated by fitting the straight line Eq.(2.7) to the points for that segment by the least square method. By varying α and refitting the regression, the value of α can be obtained which minimizes the deviation of the data from the fitted equation.

The accuracy of the fit of a segment is generally assessed by the standard deviation which is determined from the differences between the measured discharges and the computed discharges obtained from the fitted stage-discharge equation for the corresponding stage. The uncertainty in the computed discharge is usually expressed by confidence limits by assuming independence of the observations and a Gaussian distribution of the deviations from the fitted stage-discharge equation. The uncertainty due to measurement errors is not fully included in this confidence interval, though those errors are of course embedded in the actual set of stage–discharge data.

2.4 Methods for extrapolation of stage-discharge relation

The extrapolation of stage-discharge relations is often required to determine discharges at stages beyond the range of measured discharges. Such extrapolations are always subject to error, but the error may be minimized when the principles that govern the stage-discharge relation (discussed in sections 2.1 and 2.2) are utilized for guidance. In the BWDB procedure, the unmeasured discharges are estimated by a direct extrapolation of the uppermost segment of the fitted stage-discharge equation. Alternative methods based on hydraulic elements have been proposed and they are: (1) velocity-area method; (2) modified velocity-area method; (3) Stevens method; and (4) conveyance-slope method. The hydraulic elements are derived using data obtained during discharge measurements. Sometimes the indirect method of determining the peak discharge of a flood can be helpful.

The velocity-area method involves a plot of V and A against h and the computation of Q using the product of extrapolated values of V and A. As a modification of this method, log R is plotted against log V which should give a straight line relation as Eq.(2.2) suggests. However, these two methods are not used now-a-days. The Stevens method largely supplanted the velocity-area method. The Stevens method involves the extrapolation of Q as a function of the Chèzy conveyance factor $AR^{1/2}$ based on Eq.(2.2a). A variant of this method is to plot Q against Manning's conveyance factor $AR^{2/3}$

based on Eq.(2.2b). It is assumed that the slope S and the hydraulic roughness are constant for varying stages in these methods.

The conveyance-slope method is based on equations of steady flow given by Eqs.(2.2). This method is now-a-days widely practised. Eqs. (2.2) can be rewritten as

$$Q = KS^{1/2} \tag{2.8}$$

where K is the conveyance of the flow section and K equals $CAR^{1/2}$ in the Chèzy equation and equals $AR^{2/3}/n$ in the Manning equation, when SI unit is used. The conveyance slope method involves plotting of K and S against stage h. The discharge Q for a given h can then be obtained from the product of K and $S^{1/2}$ as given by the Eq.(2.8). For the K-h plot, values of K can be obtained from the data of cross-sectional geometry and values of C or n are estimated in the field. Values of S are usually not available. However, $S^{1/2}$ can be computed from Eq.(2.8) by dividing each measured Q by its corresponding K value. Using computed values of $S^{1/2}$, a plot of S against h can be obtained. The extrapolation of S-h relation is guided by the knowledge that S tends to become constant at the higher stages. Plot of K and S against h requires estimation of the coefficient C or n. The errors in estimating C or n will have a minor effect, because they cancel each other when the product of K and $S^{1/2}$ is performed. However, if the upper end of the S-h plot has not reached the stage where S has a near constant value, the extrapolation of S-h plot will be subject to uncertainty.

If data on local water surface slope are available, the unmeasured peak discharge of a flood can be determined by the use of indirect methods. The slope-area method is a commonly used indirect method. This method provides a good estimate of the peak flow rate in stable river reaches where the channel section varies uniformly. The ISO (1983) mentions that the use of the slope-area method is sometimes necessary to define the extreme high-stage end of rating curves in situations when discharge can not be measured. Discussion of this method can be seen in text books on open channel hydraulics e.g. French (1986) and also in WMO (1980a). In this method, the peak discharge is estimated by a combined use of the steady flow Eq.(2.2) and the energy equation. Installation of an auxiliary gage is required for obtaining data on local water surface slope S_w (see Figure 2.1) or it can be estimated from flood marks. Application of Eq.(2.2a) or (2.2b) requires estimation of roughness coefficients C or n and also friction slope S_f. Using the energy equation, the value of S_f (see Figure 2.1) can be determined as given below

$$S_f = S_w + \frac{k(V_u^2 - V_d^2)/2g}{L} \tag{2.9}$$

where V_u and V_d are cross-section averaged velocities at upstream and downstream sections respectively, L is the length of the reach and k is the contraction/expansion correction factor. If the reach is expanding, that is, $V_u > V_d$, then k = 0.5, otherwise k = 1.0 (French, 1986). The above Eq.(2.9) can also be deduced from Eq.(2.3) by neglecting the unsteady term i.e. the temporal acceleration $\delta v/\delta t$. The peak flow of the flood is computed from

$$Q = \sqrt{K_u K_d S_f} \tag{2.10}$$

where K_u and K_d are the conveyances of upstream and downstream sections respectively for the stages at which the peak discharge occurred. The value of S_f is determined from Eq.(2.9) by an iterative procedure where improved estimates are obtained by a successive substitution method till two consecutive values of Q are close within a tolerance limit.

A less accurate approach is to ignore the kinetic energy loss in Eq. (2.9). Then the method becomes equivalent to using Eq.(2.5b). Computation of Q does not require an iterative process. The method still requires the estimation of the roughness coefficient and the installation of the auxiliary gauge to measure the local water surface slope S_w. The discharge is computed by using the cross-sectional data at the base gauge, the measured water surface slope and the estimated roughness coefficient.

3 Description of the Bahadurabad transect

The Jamuna river in Bangladesh is a large multi-channel alluvial braided river. The pioneering study on the morphology of the Jamuna was done by Coleman (1969). There are also some recent studies on the hydraulic and morphological processes in the Jamuna. Notable of them are RPT-NEDECO-BCL (1989) for the Jamuna Bridge project, China-Bangladesh Joint Expert Team (1991) for the Flood Action Plan and Halcrow and others (1993) for the Master Plan of Brahmaputra River Training. The last study observes that the river has chaotic tendencies. This means that it is inherently unstable and that relative small changes in the boundary conditions can probably result in major changes in the geometry over one or two seasons. The international standards for discharge measurement procedures and methods of deriving stage-discharge relationships do not cover such a large river. One of the objectives of the River Survey project (FAP24) is the better understanding of the hydraulic and morphological behaviours of the major rivers in Bangladesh, so that improvement in the reliability of hydrologic measurements and computations can be achieved.

The Bahadurabad transect for discharge measurement in the Jamuna is located in a highly active braided river section of approximately 15 km width (Figure 3.1). The river reach where discharge measurements are taken is about 20 km long. The ferry route of the Bangladesh Railway connecting Bahadurabad and Fulchari is in this reach. Bahadurabad is located a few kilometres downstream of the off-take of the Old Brahmaputra. There are several main and secondary channels along with offshoots, spill channels and cross channels in the reach containing the transit line. The number, the shape, and the relative magnitude of channels are transient. An inhabited high char (island) divides the section into two distinct parts (see Figure 3.1), which are usually named as left and right channels. At present the discharge of the left channel is about 3 to 4 times that of the right channel.

Cross-sections measured on two dates in the Bahadurabad reach are shown in Figure 3.2. The complex geometry of the Bahadurabad reach and its highly transient nature make the discharge measurement a difficult task. Measurement of flows in spill channels and cross channels are also required in order to make corrections for the transfer of flows from one main channel to the other. The shape and position of the stage-discharge relation can vary from time to time, and from flood to flood, because of scour and deposition, shifting of bars and chars (islands) and because of changes in the configuration of the channels and flood plains. The complexity of the gauging procedure at Bahadurabad was felt during a test gauging under FAP24. The report on test gauging (DELFT-DHI, 1993) mentioned that detection of a so-called ideal cross-section according to international recommendations and standards may be nearly impossible.

BWDB operates two staff gauges in the reach where discharge measurements are made. One gauge is at Bahadurabad on the left bank of the left channel and the other at Fulchari on the right bank of the right channel (see Figure 3.1). The north-south distance between Fulchari and Bahadurabad is approximately 3.75 km. The water level is observed daily every 3 hours from 0600 to 1800 hrs. The gauges are required to be shifted several times in a year. The FAP24 project has installed one automatic water level recorder at Bahadurabad and another one at Gabgachi.

4 Stage-discharge data collected by hydrology directorate of BWDB

4.1 Measurement of stage-discharge data

The discharge of the Jamuna river at Bahadurabad is measured routinely by the Surface Water Hydrology Directorate of BWDB. The measurements are carried out using a non-directional Ott current meter suspended from a catamaran. Velocity is measured usually at about 100 verticals along the transit line. The number of verticals is determined by a rule that one vertical should not represent more than 10% of the total flow in a channel. Required positions along the transit line are fixed using sextants and land markers. Because of the very wide transit line crossing a number of channels, the measurement is done in two consecutive days; one day for the eastern channels and the other day for the western channels. One measurement per week is usually made during the flood season and one every two weeks during the low flow season. Sometimes discharge measurement is not possible during high currents.

The flow velocity is measured at 0.2 and 0.8 of the depth at each vertical. The mean flow velocity in the vertical is approximated as the average of the flow velocities at these two points. At each vertical, a correction factor, accounting for the deviation of the direction of the current with respect to the normal to the transit line is introduced based on the direction of a surface float.

The discharge through the entire transit is calculated using the conventional velocity-area method. In a flood hydrology study report (Kruger Consult, 1992), all stage-discharge data of the BWDB Hydrology Directorate for the period 1966 to 1990 were plotted, which is reproduced here in Figure 4.1.

Tejada-Guibert (1993) points out two shortcomings of the measurement technique of the Hydrology Directorate and they are:

(1) the effects of the departure of flow velocity distributions and directions from the assumed conditions cannot be judged, and

(2) the duration of the measurement itself is so long that hydrological conditions might have changed meanwhile, especially during the flood season.

Besides there is a possibility of an over estimation of depths during high currents since depths are measured by a tape running with the string which suspends the current meter during velocity measurements. Based on results from consecutive discharge measurement over a week, the potential sources of error in discharge measurements in the Jamuna were elaborately discussed in the Brahmaputra River Training Study (Halcrow and Other, 1991a). The micro changes in river morphology during the measurement period is one of the variety of potential sources of errors.

4.2 Derivation of the stage-discharge relationship

A new rating curve is usually developed for a hydrological year (1st April to 31st March) by using all measured discharges during that hydrological year and also including some discharge data from the previous and the following year. The discharge is related to the average stage at Bahadurabad on the left channel. This stage is the average of water levels recorded from the staff gauge at Bahadurabad during the two days of discharge measurement. Shift corrections are applied to the stage, so that the new discharge corresponding to a stage is equal to the discharge from the mean rating curve that corresponds to the adjusted stage. The procedure inherently assumes that the measured discharge is a true value without error. If this is not the case, application of shift correction may introduce new errors (DELFT-DHI, 1993).

In most years, the rating curve consists of two or three segments. The equation for the upper most segment is used for extrapolation. In developing the rating curve, a fixed value for the offset [parameter α in Eq.(2.1)] is used for all segments. This has implications on the reliability of the derived stage-discharge relation as discussed below.

In the Flood Hydrology Study report (Kruger Consult, 1992) of FAP25, annual rating curves were fitted to the stage-discharge data of the BWDB Hydrology Directorate for the period 1966 to 1989. Two or three segments were used, but the offset value is constant for all segments and for all years and is equal to -9 m. Estimated values of the remaining two parameters of the rating curve equation have been reported for all years in Kruger Consult (1992). These data were used in the General Model simulations in the Flood Action Plan studies.

In the report on Phase 1 of the Hydrological Study by FAP24 (DELFT-DHI, 1993) it is observed that the fixed offset procedure may result in wrong estimates of the extrapolated high flood discharges. It is emphasized that the offset value should be derived separately for each segment as per ISO standard (1982). Employing this procedure, they have fitted annual rating curves to the stage-discharge data of the Hydrology Directorate for the period 1966 to 1988. The fitted curve has three segments except for the year 1985. Estimated values of the three parameters of the rating curve Eq.(2.1) have been reported for all years in DELFT-DHI (1993).

Comparison of parameter values estimated in the FAP24 Study (DELFT-DHI, 1993) with those reported by Kruger Consult (1992) shows that the coefficients and exponents for the second and third segments in the FAP25 study are smaller and larger respectively than those in the FAP24 Study. A comparison between FAP25 and FAP24 estimates of the parameters of the annual rating curves has been presented in Table 4.1.

Parameter	Segment of rating curve	Range of FAP25 estimates	Range of FAP24 estimates
α (offset)	Lower Middle Upper	-9.0 m -9.0 m -9.0 m	-8.0 to -10.0 m -10.0 to -15.0 m -13.0 to -15.0 m
γ (coefficient)	Lower Middle Upper	33.6 to 230.3 0.1 to 65.1 0.01 to 8.2	37.8 to 650.3 69.3 to 3560.2 264.7 to 6155.1
β (exponent)	Lower Middle Upper	2.1 to 3.1 2.8 to 5.6 3.7 to 6.5	1.3 to 3.0 1.4 to 3.0 1.6 to 3.0

Table 4.1: Comparison between FAP25 and FAP24 estimates of parameters of the annual rating curves at Bahadurabad fitted to the stage-discharge data of the BWDB Hydrology Directorate for the period 1966 to 1988

The value of the exponent β commonly varies between 1.3 and 1.8 in natural channels and seldom reaches a value as high as 2.0 (WMO, 1980). The main reason for very small coefficients and unrealistic large exponents for second and third segments in the FAP25 study is that all segments of the fitted rating curve were forced to pass through a fixed offset value of -9 m.

4.3 Analysis the of stage–discharge relation

The FAP24 Phase 1 report (DELFT-DHI, 1993) assessed the uncertainty of the individual values of mean daily discharges generated from the rating curves for the period 1966 to 1992. It was based on the observed scatter of the stage-discharge data, the number of measurements available and the basis for and degree of necessary extrapolations of the rating curves. Results for Bahadurabad show uncertainty of less than 15 to 20% in the measurement range and less than 25% in the extrapolated high discharges.

In the Brahmaputra River Training Study (Halcrow and others, 1993) and the Hydrological Study by FAP24 (DELFT-DHI, 1993), the shift of the annual rating curves has been investigated by performing specific gauge analyses. The time series of water levels derived from the annual rating curves are plotted for fixed discharges. The results show that there are no real significant long term trends in the stage-discharge relationship at Bahadurabad. The changes from year to year are however considerable, up to a maximum of about 0.5 meters. The passage of macro-scale bed forms such as sand waves, and the shifting of braid bars and chars can radically alter the resistance characteristics and water surface topography, so altering the stage-discharge relationship (Halcrow and others, 1991b).

4.4 Analysis of hydraulic elements

An analysis of hydraulic elements at Bahadurabad was done by Tejada-Guibert (1993) based on data drawn from stage-discharge measurements by the BWDB Hydrology Directorate for 11 hydrological years from 1982 to 1992. The hydraulic elements considered in the analysis are water discharge (Q), water level (h), cross-sectional hydraulic area (A), sectional hydraulic width(w), mean velocity (V), hydraulic radius (R), mean river bed level (B), Manning conveyance factor ($AR^{2/3}$) and Manning slope-roughness factor ($Q/AR^{2/3}$). The hydraulic variables take on only lumped values, that is one value has been taken for the entire transit section for each measurement. No distinction is made for individual channels.

This study of hydraulic elements observes that the regime in the time series of hydraulic variables was relatively stable in the years before 1987, that it underwent sudden changes during the period 1987 to 1989, and that it is apparently settling into another stable phase after 1990. The relative stability has not been judged on the basis that unique relationships over time are established, but that annual cycles (hysteretic loops) recur more regularly. This study suspected that a systematic distortion has been introduced in the discharge determination procedures at Bahadurabad for the four years 1989 to 1992. Based on time series analysis of monsoon flow volumes, the hydrological study by FAP24 (DELFT-DHI, 1993) also concludes that there are systematic overestimates rather than random errors in the discharge measurements at Bahadurabad during the period 1989 to 1992.

Tejada-Guibert (1993) observes that the stage-discharge relationship is remarkably consistent given the unstable nature of the river. A hysteretic loop is quite evident in the relationships of some variables with the water level. Some distinct loops in the relationship of mean velocity, discharge, conveyance factor and slope- roughness factor with water level are shown in Figures 4.2. and 4.3. Loops in the stage-discharge plots are distinct in the lower part of the plots. The range of stage that covers the loop, suggests that the stage-discharge relationships for the rising limb of the annual hydrograph and the receding limb are not same.

Very few discharge measurements were made above 19 m PWD and above 60,000 m^3/s. The daily and annual peak flows computed from the rating curve reach many times reach above 60,000 m^3/s. The peak discharge for the 1988 flood was estimated in 98,600 m^3/s. This underscores the need of reliable extrapolating methods.

4.5 Concluding remarks

The procedure of keeping a constant offset value for all segments of an annual rating curve should be discontinued. All three parameters should be estimated separately for each segment as emphasized in the Phase 1 Hydrological Study Report by DELFT-DHI (1993). The loop feature can be prominent in the lower part of the annual rating curve that covers the rising and receding limbs of the annual hydrograph.

5 Analysis of water level data of FAP24

5.1 Analysis of 1993 data

An analysis of water level data from two automatic recording water level gauges and three staff gauges collected by FAP24 during the period April 1993 to March 1994 has been done by J. J. Peters, the FAP24 Project Advisor (1994). The auto-gauges were at Gabgachi in the right channel and at Bahadurabad in the left channel and the staff gauges were at Khatiamari, Charparul and Thantaniapara in the left channel (see Figure 3.1). The basic idea of placement of these gauges was to identify the possible influence of morphological changes on the local water surface slopes. The differences in water level readings of each gauge with those of a reference gauge have been plotted as a function of the water levels of that reference gauge. The analyses show that the local water surface slope is almost constant in the lean season for water levels lower than 15 m+PWD at Bahadurabad, followed by a steady increase till a water level of approximately 17 m PWD is reached, whereafter the slope becomes again quite constant. It is mentioned that a single water level measurement would not be a good indicator of the flow in a channel when there is intense reworking of the morphology.

The second interim report of FAP24 Project (DELFT-DHI, 1995) shows the variation in local water surface slope along the 20.4 km reach at Bahadurabad. The water surface slope upstream of Bahadurabad decreases from 8.4 to 5.4 cm/km from August to December 1993 and varies downstream of Bahadurabad from 9.1 to 5.5 cm/km from July to December 1993.

5.2 Measurement of water level during 1994-95

Six staff gauges were installed whose operations started in the first week of June 1994. The sites were selected during a field visit on 15-16 May 1994. Three gauges are at North Khatiamari, North-Harindhara and Belgacha along the left channel and the remaining three are at Kabilpur, Shankibhanga and Bagirchaow along the right channel. Locations of gauges are shown in Figure 3.1. FAP24 has a staff gauge at Bahadurabad which is in between North Khatiamari and Belgacha and another one at Gabgachi in between Kabilpur and Bagirchaow. Because of short distances between Bahadurabad and Belgacha, and between Gabgachi and Bagirchaow, gauges were installed at North Harindhara and Shankibhanga so that the water surface fall is substantial. The longitudinal distance between adjacent gauge sections in a channel are in the range of 5 to 9 km. The gauges have been linked to the PWD datum.

Water levels at a station have been recorded daily every 3 hours from 06:00 to 18:00 hrs as per BWDB practice. The mean daily water levels at a station have been computed by averaging the five measured water levels during the day. The averaging process removes part of random measurement errors. Plots of mean daily water levels against time during the period June 1994 to March 1995 have been shown in Figures 5.1(a) and (b) the for left and right channel reaches respectively. The figures show that there were five distinct " flood waves " between mid-June and end of October. The figures display that the variation in water level with time is similar in the left and right channel reaches.

5.3 Detection of data errors

The detection of errors followed the approach outlined by J. J. Peter the FAP24 Project Advisor (1994). The errors in the water level data were checked by inspecting the plots of water level hydrography and making graphical correlations between water level data from upstream and downstream stations. Plots of water level differences between two stations against time were also utilized to detect data errors. Correction of some erroneous data can be made by the combined study of water level hydrography, graphical correlations and water level difference plots. The suspected data have been adjusted such that consistency with the general trends in the plots is preserved. A summary of the corrections made to the data have been given in Table 5.1.

Name of station	Period	Water level correction (m)	
		increase	decrease
Khatiamari	3 Feb to 31 Mar.	-	0.03 to 0.05
N-Harindhara	6 Nov to 10 Dec.	0.09 to 0.12	-
Bahadurabad	-	-	-
Belgacha	10 Oct to 31 Oct	0.19 to 0.28	-
Kabilpur	5 Nov to 8 Dec 9 Dec to 31 Mar	- -	0.05 to 0.10 0.41
Shankibhanga	-	-	-
Bagirchaow	1 Nov 24 Nov 9 Dec to 31 Mar	- 0.10	- 0.05 to 0.07

Table 5.1: Water level corrections in the data of various stations

The mean daily water level data for North Khatiamari, North Harindhara and Belgacha have been correlated with the data for Bahadurabad as shown in Figure 5.2(a). These correlations are along the reach in the left channel. For the reach in the right channel, data for Kabilpur and Bagirchaow have been correlated with the data from Shankibhanga as shown in Figure 5.2(b).

Shifts of a segment of the plot from the general trend in the correlations indicate an error in the transfer of water levels during the shifting of a staff gauge. Such systematic errors are present in the data for the gauges at Belgacha, Kabilpur and Bagirchaow.

Figures 5.2(a) and (b) show that the correlation between mean daily water levels along a channel is almost linear. It is seen that the upper plot has greater slope than that of the middle plot and the lower plot has a smaller slope. This indicates that the water surface fall between two gauges increases with the increase in stage. Scatter of data can be seen at flood stages above the recession limb of the hydrograph. This scatter is likely due to the difference in the local water surface slopes during rising and falling stages of the flood flow. The scatter may also be due to greater uncertainty in the measurements during high flood stages. The waves at the water surface is one of the sources of uncertainty. However some portion of this random error is filtered out when the measured water levels in a day are averaged to obtain the mean daily water level.

The local water surface fall as measured by the difference in mean daily water levels between two staff gauges, has been plotted against time in Figures 5.3(a) and (b) for the left and the right channel reaches respectively. There are random fluctuations in the plots which indicate that random measurement errors are still present in the data. Sudden displacement of a segment of the plotted line in these figures indicate error in the transfer of water level during gauge shifts. Comparison with other plots in the figure helped to identify the staff gauge which was affected by such systematic error. The graphs display such error in the data from Belgacha, Kabilpur, Shankibhanga and Bagirchaow.

There are sudden fluctuations (spikes) in the plots in Figures 5.3(a) and (b). The staff gauge at which the sudden fluctuation in water level data is present can be identified by comparing the plot for one pair of staff gauges with that for another pair. These sudden fluctuations in the plots may be due to erroneous data or to morphological process. Fluctuation up to 6 cm has been observed. A study by Halcrow and others (1991 b) indicates that the water surface slope may be affected by the changes in resistance characteristics due to passage of macro-scale bed forms such as sand waves, and the shifting of braid bars and chars.

Figures 5.3(a) and (b) display that water level data from the left channel has a better quality than those from the right channel. The gauge shifts due to bank erosion may cause greater uncertainty in the data. Such uncertainty is present in the water level data from staff gauges at Belgacha and Bagirchaow, which are areas of intense erosion and deposition.

5.4 Analysis of local water surface fall

Figures 5.3(a) and (b) indicate that the plots of local water surface falls as obtained from various pairs of staff gauges follow a fairly similar trend. The fall remains more or less constant during June to mid-October with slightly higher value during larger floods. It gradually decreases during the receding phase of flood flow. This phase starts in October.

The differences between daily water level data for the staff gauge at North Harindhara and those for upstream and downstream staff gauges at North Khatiamari and Belgacha have been plotted as a function of the stage at North Harindhara as shown in Figure 5.4(a) for the reach in the left channel. A similar graph has been obtained for the reach in the right channel as shown in Figure 5.4(b). These analyses have been done with corrected data. Although the water level difference between two stations can not be converted to water surface slope because of difficulty in determining the length of flow axis, this data can be used as an approximate indicator of the variation in the slope.

Figures 5.4(a) and (b) indicate similarity in the behaviours of water level variations in the left and right channel reaches. The local water surface slope fluctuates during the flood season (June to September). Thereafter the slope gradually decreases with the fall of water level during the receding phase of flood flow.

The local water surface slope data are not available for the period April, May and first week of June 1994 during which water level rose. Thus comparison between the rising stage slopes during the beginning of flood season and the receding stage slopes during the post monsoon could not be made. Analysis of annual rating curves by Tejada-Guibert (1993) for the period 1982 to 1992 reveals distinct loops (see Figure 4.2), which occur during rising and receding phases of the annual hydrograph. This indicates that the local water surface slopes during rising and receding limbs of an annual hydrograph may not be the same.

5.5 Analysis of at-site water level variations

The rate of change of water level in m per day at a staff gauge has been determined by subtracting the daily water level for a day from that for the previous day. This rate of change of water level at four gauges along the left channel reach has been plotted as a function of time in Figure 5.5(a). The Figure 5.5(b) shows the plot for four gauges along the right channel reach. These figures display remarkable similarity in the behaviour of flood stages in the left and right channel reaches. The maximum rate of rise in Figures 5.5(a) and (b) is approximately 0.26 m in one day while the maximum rate of fall is approximately 0.15 m in one day, which is low compared to the data of previous years, see Table 5.2 (a) and 5.2 (b).

The similarity in the behaviour of flood stages in the left and right channels can also be seen from correlations between the water levels along the left channel and those in the right channel. The correlations have been made between North Khatiamari and Kabilpur gauges, Bahadurabad and Shankibhanga gauges, The correlations for the two pairs have been shown in Figure 5.6.

Year	Name of Stations						
1994	Khatiamari	North-Horindhara	Bahadurabad	Belgacha	Kabilpur	Shankibhanga	Bagirchaow
Maximum rise (m)	0.27	0.27	0.26	0.29	0.28	0.27	0.29
Maximum fall (m)	0.17	0.17	0.19	0.19	0.17	0.18	0.19

Table 5.2 (a) Maximum rise and maximum fall of water level at different stations in Bahadurabad reach, Jamuna River (June 7,1994 to March 1995)

Year	Maximum		Year	Maximum		Year	Maximum	
	Rise (m)	Fall (m)		Rise (m)	Fall (m)		Rise (m)	Fall (m)
1965	0.57	0.34	1975	0.42	0.22	1985	0.74	0.26
1966	0.55	0.29	1976	0.48	0.28	1986	0.52	0.23
1967	0.53	0.22	1977	0.52	0.36	1987	0.46	0.23
1968	0.66	0.35	1978	0.48	0.29	1988	0.67	0.31
1969	0.47	0.17	1979	0.55	0.48	1989	0.79	0.27
1970	0.66	0.31	1980	0.71	0.22	1990	0.47	0.30
1971	-	-	1981	0.49	0.45	1991	0.64	0.25
1972	0.57	0.30	1982	0.69	0.29	1992	0.65	0.31
1973	0.78	0.43	1983	0.59	0.28	1993	0.67	0.30
1974	0.86	0.31	1984	0.57	0.21			

Table 5.2 (b) Maximum rise and fall of water level at Bahadurabad, Jamuna River

6 Analysis of geometric and discharge data of FAP24

6.1 Method of discharge measurement

FAP24 measures the discharge by the moving boat method. It uses the combined Acoustic Doppler Current Profiler (ADCP), Electro-Magnetic Flow Meter (EMF) and differential Global Positioning System (GPS) to get a detailed measurement of the cross-section velocity field. The methodology has been discussed in the second Interim Report of FAP24 (DELFT-DHI, 1995).The channel is crossed four times during one discharge measurement. The measurements generate computer data which are processed using an off-line software package specifically developed for the River Survey Project. The off-line software reads the raw ASCII formatted data which come from the survey vessel and then performs the integration to obtain cross-sectional area and total discharge.

An example of a measured cross-section velocity field is shown in Figure 6.1. There are four gaps in the measured velocity field due to limitations of the instruments. They are: a surface gap, a bottom gap and two side gaps. The height of surface gap where the ADCP can not measure is 1.7 m or 2.7 m depending upon the vessel used. An EMF is installed mostly at 0.5 m below the free surface to measure the velocity. The off-line software uses a constant flow velocity for the surface gap obtained from the EMF value. The bottom gap is equal to 5% of the depth. The off-line software fits a power function to compute the flow velocity in the bottom gap.

The two side gaps are adjacent to the two banks of the channel. The side gap starts when the depth becomes too shallow for the vessel to travel or for the ADCP to measure. The off-line software uses the bank distance to make a triangular depth averaged approximation in the side gap section. In the triangular area, the flow velocity is approximated using the adjacent EMF and top adjacent ADCP data, a zero velocity at the bank, and then depth averaging over the area.

6.2 Discharge and geometric data of 1994

A total of 34 discharge measurements were carried out in the Bahadurabad reach during April 1994 to March 1995. The date of measurement, stage, discharge, cross-sectional area, cross-section averaged flow velocity and water surface width have been presented in Tables 6.1 (a), (b) and (c) for the left channel, right channel and combined channel respectively. The locations of discharge measurement sections have been shown in Figure 6.2 where the numbers refer to the serial number in Tables 6.1. The measured discharges in the cross-channel were added to the measured discharges in the left channel. It is seen that the location of the measurement section is not the same for all measurements. Variation in the locations is greater in case of the right channel, especially during the low flow season they are located far upstream.

Orientations of the transect were not always perpendicular to the flow direction. Corrections for the angle are made by the processing software while computing the discharge. Such correction is not made to the cross-sectional area (A), width (W) and wetted perimeter (P) data in Tables 6.1(a) to (c). In the absence of angle correction, the cross-sectional geometric data (A, W, P) are larger in magnitude than the corrected ones. Thus the magnitudes of geometric and hydraulic parameters in Tables 6.1(a) to (c) are to be treated as approximate as they are not corrected for angle. Since the channel reach is not prismatic, angle correction does not ensure that it will lead to the correct values of the geometric parameters. The hydraulic depth ($D = A/W$) and the hydraulic radius ($R = A/P$) would not be affected much by the angle correction. But the mean flow velocity (V) data are likely to be smaller than the corrected data. The errors in the uncorrected geometric and hydraulic parameters would not be substantial since the angle was small and in many measurements transects were perpendicular to flow.

The discharge data have been plotted against time along with the water level hydrograph at the reference gauge as shown in Figures 6.3 and 6.4 for the left and right channels respectively. The time interval between discharge measurement is quite uneven, sometimes consecutive or very short and sometimes very long. The measured discharge data do not cover fully all features of the water level hydrograph as can be seen from Figures 6.3 and 6.4. Especially the number of discharge measurements during the rising stage of the flood waves is relatively small.

The data in Table 6.1 (c) show that the maximum value of the measured total discharge at Bahadurabad did not exceed 37,700 m^3/s in the year 1994. The maximum water level remained below the floodplain level. During the previous 12 years period (1982 to 1993), the measured maximum discharge was always above 40,000 m^3/s. Only in one year it was below 50,000 m^3/s. The maximum discharge exceeded 60,000 m^3/s in eight years. These data suggest that the flood flows of the Jamuna at Bahadurabad in the year 1994 were far below average.

Sl. no	Year	Month	Day	WL (Bahadurabad) (m + PWD)	DIS (m³/s)	C/Area (m²)	Mean-velocity (m/sec)	Width (m)	Wetted perimeter (m)
1	1994	4	3	15.25	8598	9786	0.88	1688	1701.60
2	1994	4	26	15.48	7975	9154	0.87	1618	1764.40
3	1994	6	2-3	17.65	19108	12365	1.55	1786	1820.5
4	1994	6	23	18.53	25527	18241	1.40	3336	3362
5	1994	6	24-26	18.54	25500	18302	1.39	3292	3314.1
6	1994	6	27	18.65	27219	17300	1.57	2775	2808.4
7	1994	6	28	18.58	25587	19313	1.32	3295	3321.2
8	1994	7	13	18.19	22380	17974	1.25	3333	3348.7
9	1994	7	15-16	17.91	20380	18652	1.09	3518	3549.7
10	1994	7	16	17.85	21524	17512	1.23	3501	3540
11	1994	8	2	18.09	22596	20091	1.12	3474	3499.3
12	1994	8	6-8	17.83	20160	19235	1.05	3612	3687.8
13	1994	8	18	18.44	23848	21043	1.13	3773	3799.2
14	1994	8	30	18.09	18686	19716	0.95	3685	3717.6
15	1994	8-9	31-1	17.96	19128	18576	1.03	2821	2854.2
16	1994	9	01-04	17.81	20574	18552	1.11	2849	2859.9
17	1994	9	6	17.42	16412	16360	1.00	2711	2767.5
18	1994	9	17	17.52	15431	15179	1.02	3175	3194.8
19	1994	9	21-25	17.75	20904	20320	1.03	3587	3625
20	1994	9	28	17.62	18895	19747	0.96	3590	3631.1
21	1994	9	30	17.33	18318	18765	0.98	3200	3263.4
22	1994	10	17	17.24	17324	19261	0.90	3680	3690.9
23	1994	10	18-21	17.26	18721	19365	0.97	3600	3587.6
24	1994	10	23	16.61	14194	17037	0.83	3503	3560.6
25	1994	11	7-8	15.08	7195	7330	0.98	1147	1155.6
26	1994	11	26	14.25	5519	5932	0.93	759	765.1
27	1994	11	27	14.22	5459	5944	0.92	756	760.30
28	1994	12	13	13.77	4844	5543	0.87	954	959.60
29	1995	2	8	12.95	3336	4877	0.68	677	684.31
30	1995	2	9	12.94	3315	4863	0.68	677	685.01
31	1995	3	11	13.10	3487	5124	0.68	856	860.45
32	1995	3	12	13.10	3481	5113	0.68	864	872.12
33	1995	3	27	13.30	3740	5259	0.71	910	914.86
34	1995	3	28	13.32	3906	5336	0.73	907	911.20

Table 6.1(a): Observed discharge data and hydraulic parameters in the left channel of the Jamuna River at Bahadurabad

Sl. no	Year	Month	Day	WL (Bahadurabad) (m+PWD)	DIS (m^3/s)	C/Area (m^2)	Mean-velocity (m/sec)	Width (m)	Wetted perimeter (m)
1	1994	4	4	15.21	1946	2256	0.86	582	588.50
2	1994	4	28	15.58	2265	2284	0.99	611	626.70
3	1994	6	4	18.46	10418	10533	0.99	2144	2155.0
4	1994	6	23	18.54	8402	10359	0.81	2143	2155.9
5	1994	6	24	18.61	9150	10622	0.86	2121	2137.6
6	1994	6	27	18.66	10460	12253	0.85	2661	2678.6
7	1994	6	28	18.59	8544	10648	0.80	2113	2074.9
8	1994	7	13	18.19	6419	9917	0.65	2249	2260.0
9	1994	7	15	18.08	6106	9602	0.64	2281	2288.0
10	1994	7	16	18.84	5213	8883	0.59	2270	2283.3
11	1994	8	2	18.08	7288	9435	0.77	2060	2317.8
12	1994	8	7	17.82	5335	7580	0.70	1583	1577.0
13	1994	8	18	18.44	7862	14125	0.56	2711	2736.7
14	1994	8	30	18.06	5889	12823	0.46	2685	2703.5
15	1994	9	1	17.97	5252	7370	0.71	1922	1936.6
16	1994	9	2	17.53	3952	7097	0.56	1958	1983.9
17	1994	9	6	17.43	3792	6783	0.56	1396	1495.6
18	1994	9	17	17.52	3868	5433	0.71	1325	1335.9
19	1994	9	21	17.70	6020	7507	0.80	1694	1714.5
20	1994	9	28	17.63	3793	5547	0.68	1332	1335.9
21	1994	9	30	17.34	4597	10972	0.42	1934	1961.7
22	1994	10	17	17.23	4941	7024	0.70	1680	1698.0
23	1994	10	18	16.89	4183	6315	0.66	1690	1712.6
24	1994	10	23	16.62	3613	5958	0.61	1641	1641.7
25	1994	11	7	15.11	1406	2202	0.64	333	335.7
26	1994	11	26	14.25	816	1858	0.44	269	273.9
27	1994	11	27	14.19	789	1875	0.42	263	272.5
28	1994	12	13	13.77	572	1658	0.34	246	252.5
29	1995	2	8	13.01	247	1358	0.18	220	226.65
30	1995	3	11	13.10	331	1425	0.23	260	262.30
31	1995	3	27	13.29	413	1503	0.27	259	260.61
32	1995	3	29	13.37	438	1548	0.28	274	276.48

Table 6.1(b): Observed discharge data and hydraulic parameters in the right channel at Bahadurabad

Sl. no.	Year	Month	Day	WL (Bahadurabad) (m + PWD)	DIS (m³/s)	C/Area (m²)	Mean-velocity (m/sec)	Width (m)	Wetted perimeter (m)
1	1994	4	3-4	15.25	10544	12042	0.88	2270	2290.1
2	1994	4	26-28	15.48	10240	11438	0.90	2229	2391.1
3	1994	6	2-4	18.24	29526	22898	1.29	3930	3975.5
4	1994	6	23	18.53	33929	28600	1.19	5479	5517.9
5	1994	6	24-26	18.57	34650	28924	1.20	5413	5451.7
6	1994	6	27	18.65	37679	29553	1.27	5436	5487
7	1994	6	28	18.58	34131	29961	1.14	5408	5396.1
8	1994	7	13	18.19	28799	27891	1.03	5582	5608.7
9	1994	7	14-16	17.96	26486	28254	0.94	5799	5837.7
10	1994	7	16	17.86	26737	26395	1.01	5771	5823
11	1994	8	2	18.09	29884	29526	1.01	5534	5817.1
12	1994	8	6-9	17.82	25495	26815	0.95	5195	5264.8
13	1994	8	18	18.44	31710	35168	0.90	6484	6535.9
14	1994	8	30	18.09	24575	32539	0.76	6370	6421.1
15	1994	9	1	17.96	24380	25946	0.94	4182	4790.8
16	1994	9	01-06	17.81	24526	25649	0.96	4807	4843.8
17	1994	9	6	17.42	20204	23143	0.87	4107	4263.1
18	1994	9	17	17.52	19305	20612	0.94	4500	4530.7
19	1994	9	21-28	17.75	26924	27827	0.97	5281	5339.5
20	1994	9	28	17.62	22688	25194	0.90	4922	4967
21	1994	9	30	17.33	18318	18765	0.98	3200	3263.4
22	1994	10	17	17.24	22265	26285	0.85	5360	5375.9
23	1994	10	18-21	17.26	22904	27827	0.82	5281	5300.2
24	1994	10	23	16.61	17807	20280	0.88	5144	5201
25	1994	11	7-8	15.09	8601	9532	0.90	1480	1491.3
26	1994	11	26	14.25	6335	7790	0.81	1028	1039
27	1994	11	27-28	14.22	6248	7819	0.80	1019	1032.8
28	1994	12	13	13.77	5416	7201	0.75	1200	1212.1
29	1995	2	8	12.95	3583	6235	0.57	897	910.96
30	1995	2	9	12.94	3562	6221	0.57	897	911.66
31	1995	3	11	13.10	3818	6549	0.58	1116	1122.75
32	1995	3	12	13.10	3812	6538	0.58	1124	1124
33	1995	3	27-28	13.30	4153	6762	0.61	1169	1175.47
34	1995	3	28-29	13.32	4344	6884	0.63	1181	1187.68

Table 6.1(c) : Observed discharge data and hydraulic parameters in the Bahadurabad transit (left + right channel)

6.3 Data consistency and uncertainty

To check the consistency of discharge measurement data, measured water levels at the reference gauge have been plotted as a function of the cross-sectional area and cross-section averaged flow velocity separately for left and right channels as shown in Figure 6.5. It is seen that one cross-sectional area data and two velocity data for the left channel and one cross-sectional area data and four velocity data for the right channel are not consistent with the other data in the plots.

Figure 6.5 shows that there is considerable scatter in the plots. Various sources of uncertainty in these data are discussed below.

(1) Uncertainty due to random measurement errors in the water level data. Presence of such error has been indicated by Figure 5.3. Small errors in the water level can cause large errors in the cross-sectional area since the channel section is very wide.

(2) Uncertainty in the measured flow area of the discharge measurement section (which is away from the reference water level gauge) due to variation in the local water surface slope with the change in stage as indicated by Figure 5.4. This error will be of a systematic nature when the discharge measurement sections remain always on one side of the reference gauge and since the variation of local water surface fall with the change in stage has a quite distinct pattern as can be seen from Figure 5.4. There will be a bias towards smaller flow areas in both channels with the increase in stage since the discharge measurement sections are downstream of the selected reference water level gauges. However, this error is likely to be very small since the distance between the discharge measurement section and the reference water level gauge is small. The error varies with time as the distance between the discharge measurement section and the staff gauge varies among the measurements.

(3) Uncertainty due to random measurement errors in the cross-sectional area and the flow velocity.

(4) Uncertainty due to variations in the locations of the discharge measurement section as can be seen from Figure 6.2. The shape of the cross-section varies with the change in location.

(5) Uncertainty due to the long measurement time. There are nine data from the left channel for which the measurement time was more than one day as can be seen from Table 6.1(a).

(6) Uncertainty due to the natural variability in area and flow velocity caused by changes in the hydraulic and morphological conditions of the braided alluvial river during the passage of a flood wave.

Uncertainties in items (2) and (4) can be avoided if the discharge measurement section can be kept fixed at the location of the reference water level gauge. This is difficult to fulfil in a multi-channel braided alluvial river like the Jamuna.

To check the consistency of discharge measurement data by avoiding uncertainties in items (1) and (2), plots of discharge versus cross-sectional area and discharge versus cross-section averaged flow velocity have also been examined. The plots are shown in Figure 6.6. These plots clearly show two inconsistent velocity-area data for the left channel and another four data for the right channel. It has been found that the inconsistent data for the left channel belong to 2nd and 27th June of 1994 and those for the right channel belong to 4th June, 18th and 30th August and 30th September of 1994.

After excluding the two inconsistent data from the data of the left channel and the four inconsistent data from the data of the right channel, the remaining stage-discharge data have been plotted in Figure 6.7 (a) and (b) for the left and right channels respectively.

The period of rising stage from April to the first week of June 1994 does not contain discharge data, as shown by Figures 6.3 and 6.4. In the annual rating curves for the Jamuna river at Bahadurabad, the presence of loops in the range of rising and receding limbs of the annual hydrography has been shown by Tejada-Guibert (1993) for the period of 1982 to 1993 (see Figure 4.2). Due to the absence of adequate data, it can not be studied whether the loop is present in the stage-discharge plots in Figure 6.7.

6.4 Analysis of hydraulic elements

6.4.1 Geometric variables

Plots of the water surface width (W) of the flow section, hydraulic depth (D=A/W) and hydraulic radius (R=A/P) versus stage are shown in Figures 6.8 (a) and (b) for the left and right channels respectively. It is seen from Tables 6.1 and Figures 6.8 that P is almost equal to W while R is almost equal to D for all stages. This is because the channels are very wide. This suggests that the hydraulic analysis can be performed by approximating the flow section as a wide rectangular section. Almost equal values of water surface width and wetted perimeter suggest that the wetted perimeter is not increased substantially by the low chars submerged at the flood stage. Figure 6.8 shows that the values of D and R at low stages (below 16 m PWD) are larger than the values at flood stages. This is because at high stages the channel cross-section has a very large width with shallow regions due to submerged low chars, while at low stages it has only deep channels with a small width. Change in the location of the discharge measurement section is also one of the reasons.

Geometric element	Left channel	Right channel
Water surface width	2.7 to 3.8 km	1.4 to 2.7 km
Hydraulic depth	4.8 to 6.6 m	3.6 to 5.2 m
Area of flow section	15,500 to 21,000 m^2	3,700 to 10,500 m^2
Mannings conveyance factor	50,000 to 65,000 $m^{8/3}$	13,000 to 32,000 $m^{8/3}$

Table 6.2: Approximate ranges of variations in geometric elements in the left and right channels of the Jamuna at Bahadurabad during the flood season in 1994

The plots in Figure 6.8 show clusters of points for the flood season. A comparison of ranges of water surface widths, hydraulic depths and areas of flow section between the left and the right channels has been given in Table 6.2 for the flood season in 1994. The width-depth ratio is greater in the right channel compared to that in the left channel. The right channel is shallower than the left channel. The Figures 6.5 and 6.8 show wide variations in the magnitudes of geometric elements for a given stage during the flood season. This is perhaps because the cross-sectional geometry changes in the course of time due to morphological processes. Erosion and deposition on the river bed and the movement of bars during flood flows induces changes in the depth and the area of the flow section. Of course, the variation in the location of discharge measurement sections as shown in Figure 6.2 and the measurement errors also contribute the variations in the magnitudes of geometric elements.

The relationship of the Manning conveyance factor ($AR^{2/3}$) with the water level and the discharge have been presented in Figures 6.9 (a) and (b) for the left and the right channels respectively.

Similarly, relationships of the Chèzy conveyance factor ($AR^{1/2}$) have been shown in Figures 6.10 (a) and (b). These figures do not show differences in the patterns in the plots for the Manning and the Chèzy conveyance factors. The tendency in the plots is to show larger values of the conveyance factors with the increase in flood stage and discharge. The large scatter in the conveyance factor suggests that there can be considerable uncertainty in the extrapolation of stage-discharge relationships based on conveyance factors only, such as Stevens method.

The presence of loops in the yearly stage-conveyance factor plots has been shown by Tejada-Guibert (1993) using the data from the Jamuna river at Bahadurabad for the period of 1982 to 1992 (see Figure 4.3). Due to the absence of FAP24 data in the period of rising limb of the annual hydrograph, it can not be investigated whether the loop feature is present in the plots in Figures 6.9 and 6.10 for the year 1994 to 1995.

6.4.2 Hydraulic factors

The relationships of the Manning slope-roughness factor [$Q/AR^{2/3}$] and the Froude number [$V/(gD)^{1/2}$] with the water level have been shown in Figure 6.11 (a) and (b) for the left and the right channels respectively. From Eq. (2.2b) in Section 2.1, the term involving roughness and slope [$S^{1/2}/n$] in the Manning steady flow formula can be shown to be equal to $Q/AR^{2/3}$. This is why the term $Q/AR^{2/3}$ is called the Manning slope-roughness factor. Plots in Figure 6.11 display that they have similar patterns for both the slope-roughness factor and the Froude number. This can be explained by the similarity of the Froude number [$V/(gD)^{1/2}$ i.e. $Q/A(gD)^{1/2}$] with the Chèzy slope-roughness factor [$Q/AR^{1/2}$] in a wide rectangular channel where R is almost equal to D, which is the case for the Jamuna river.

Figure 6.11 shows that the plots of slope-roughness factors and Froude numbers for the left channel is better defined than those for the right channel. The Froude number in the left channel varies from approximately 0.10 to 0.19, while in the right channel it varies from 0.04 to 0.14. The magnitudes of the Manning slope-roughness factors for the left channel varies from 0.23 to 0.45 while those for the right channel very from 0.10 to 0.35. The values for the left channel are within the range of values obtained for the total flow section (left and right channels combined) by Tejada-Guibert (1993) for the period of 1982 to 1992. However, the presence of the loop as observed by Tejada-Guibert can not be studied in Figure 6.11 due to inadequate data.

Figure 6.11 displays that the slope-roughness factor and the Froude number generally increase with the increase in the flood stage. It appears that there is a break at a stage close to 17 m PWD. This break is close to the upper break point in the plot of local water surface slope versus stage in Figure 5.4. This break corresponds to the start of the receding limb of the annual stage hydrograph as can be seen from Figure 6.3. This feature can be utilized as an indicator in the selection of segments for the stage-discharge relationship.

Figure 6.12 shows plots of the log of the cross-section averaged flow velocity (V) versus the log of the hydraulic radius (R) for the left and right channels. As per the Manning or Chézy steady flow formula, the log R should plot as a straight line against log V if the term involving the roughness coefficient and the energy gradient remains constant. The clusters in the log V versus log R plots in Figure 6.12 do not display a distinct relationship. The ill defined relationships in these plots indicates a poor prospect for the extrapolation of the stage-discharge relationship based on the log V versus log R plot. A similar observation was made by Tejada-Guibert (1993) based on the data for the period 1982 to 1992.

6.5 Distribution of flow between channels

A study of the flow distribution between the two channels has been made. Table 6.3 shows the ratios between the two flow areas, the two discharges and the two cross-section averaged flow velocities using the measured data from the two channels during April 1994 to March 1995. Flow areas, discharges and flow velocities in the right channel always remain substantially smaller than those in the left channel. But the distribution of flow between the two channel does not remain constant. It is seen from Table 6.3 that flow area and discharge of the right channel are about one-fourth and one-fifth respectively of the combined flow area and discharges of the two channels at the low stages, and the share increases to about one-third and one-fourth at the high stages. The flow velocity in the right channel varies from two-fifths to three-fourths of the flow velocity in the left channel. The observation that the discharge shared by the right channel increases with the increase in the stage is important in the study of the stage-discharge relationship especially at high flood stages.

Serial no.	Stage at Bahadurabad (m, PWD)	$A_R: A_L$	$Q_R: Q_L$	$V_R: V_L$
1	15.25	--	--	--
2	15.48	0.249	0.284	1.138
3	18.24	--	--	--
4	18.53	0.568	0.329	0.579
5	18.57	0.580	0.359	0.619
6	18.65	--	--	--
7	18.58	0.551	0.334	0.606
8	18.19	0.552	0.287	0.520
9	17.96	0.515	0.300	0.587
10	17.86	0.507	0.242	0.480
11	18.09	0.470	0.323	0.688
12	17.82	0.394	0.265	0.667
13	18.44	--	--	--
14	18.09	--	--	--
15	17.96	0.397	0.275	0.689
16	17.81	0.383	0.192	0.505
17	17.42	0.415	0.231	0.560
18	17.52	0.358	0.251	0.697
19	17.75	0.369	0.288	0.777
20	17.62	0.281	0.201	0.708
21	17.33	--	--	--
22	17.24	0.365	0.285	0.778
23	17.26	0.326	0.223	0.680
24	16.61	0.212	0.255	0.735
25	15.09	0.300	0.195	0.653
26	14.25	0.313	0.148	0.473
27	14.22	0.315	0.145	0.457
28	13.77	0.299	0.118	0.391
29	12.95	0.278	0.074	0.265
30	12.95	--	--	--
31	13.10	0.278	0.095	0.338
32	13.10	--	--	--
33	13.30	0.286	0.110	0.380
34	13.32	--	--	--

(Note: Doubtful data have not been included)

Table 6.3: Ratios of flow areas, discharges and cross section averaged flow velocities between the right and the left channels during April 1994 to March 1995

6.6 Estimation of roughness coefficient

An attempt has been made to estimate the Manning and the Chèzy roughness coefficients by utilizing the stage-discharge and local water surface slope data. Eq. (2.2a) in Section 2.1 shows that the Chèzy roughness coefficient is given by $(Q/S^{1/2})/(AR^{1/2})$. The Chèzy conveyance factors $AR^{1/2}$ have been plotted against $Q/S^{1/2}$ in Figure 6.13 for the left and right channels. From a fitted curve, the magnitude of $(Q/S^{1/2})/(AR^{1/2})$ corresponding to a given stage gives the Chèzy roughness coefficient for that stage. The Chèzy conveyance factor corresponding to a stage can be obtained from a curve fitted to the plot in Figure 6.10. Similarly the Manning coefficient can be obtained from the plot of $AR^{2/3}$ against $Q/S^{1/2}$ in Figure 6.14.

It appears from the Figures 6.13 and 6.14 that there are loops in the plots. The number of data for a flood wave is not adequate to establish the loop. A curve has been fitted to the upper points while another one to the lower points. Roughness coefficients have been estimated from each curve corresponding to a set of water levels. Then the water levels have been plotted against the values of the roughness coefficient as shown in Figure 6.15. The general tendency is that the roughness decreases as the water level approaches the bank level.

Figure 6.15 shows that the roughness generally decreased with the increase in water level in 1994. The Chèzy roughness coefficient in the left channel varies from approximately 35 to 47 $m^{1/2}/s$ at a stage of 17.0 m PWD and from 45 to 60 $m^{1/2}/s$ at 18.5 m PWD. The Manning roughness coefficient in the left channel varies from approximately 0.035 to 0.027 at 17.0 m PWD and from 0.029 to 0.023 at 18.5 m PWD. In the right channel, the Chèzy coefficient is 36 $m^{1/2}/s$ at 17 m+PWD and varies from 37 to 45 $m^{1/2}/s$ at 18.5 m PWD, while the Manning coefficient varies from 0.042 to 0.032 and 0.035 to 0.029 respectively. These values are within the range of the roughness coefficients $N(=1/n)$ used for the Jamuna river in the simulation of the 1988 flood with a hydrodynamic model by Halcrow and others (1993). The calibrated values of N in that study varied within the range 31 to 50 at bankfull conditions and 20 to 40 at low flows; the corresponding Manning roughness coefficients (n) are 0.032 to 0.020 at bankfull conditions and 0.050 to 0.025 at low flows.

7 Extrapolation of the stage-discharge relationship

7.1 Selection of segments

The stage-discharge relationship for the Jamuna at Bahadurabad usually consists of two or three segments as discussed in Section 4.2. Selection of segments should be such that a particular segment is applicable to particular hydraulic conditions or control. Analysis of the local water surface slope in Figure 5.4 indicates a change in the hydraulic conditions at a stage near to 17 m PWD at Bahadurabad. Analysis of the slope-roughness factor and Froude number in Figure 6.11 also show a change in the relationship close to this stage. This change point corresponds to the beginning of the receding limb of the annual stage hydrograph as can be seen from Figure 6.3.

Based on above hydraulic considerations, a segment limit at 17 m PWD at Bahadurabad has been selected for the stage-discharge relationship. All stage-discharge data above this stage are in the flood season. There are 19 data for the left channel and 17 data for the right channel. One segment has been fitted to the data above 17 m PWD stage. There are only twelve stage-discharge data below 17 m PWD. These data are inadequate for a reliable fit of a segment. This study concentrated on the upper segment of the stage-discharge relationship.

7.2 Approaches for segment fitting

7.2.1 Single relationship for combined discharges

The current practice of BWDB is to derive a single stage-discharge relationship for the combined discharges of the two channels at Bahadurabad. The discharge is expressed as a function of stage at Bahadurabad in the left channel. The method of fitting a stage-discharge equation to a set of data has been discussed in Section 2.3. The derived stage-discharge relationship for the upper segment using the measured stage-discharge data above 17 m+PWD in 1994 is given below.

$$Q = 382.4\ (h-11.0)^{2.193},\quad h > 17.0 \text{ m PWD} \qquad (7.1)$$

7.2.2 Channel specific relationship

Study of separate rating curves for the left and right channels at Bahadurabad for improvement of the accuracy of the discharge time series has been proposed under the hydrological study topics for Phase 2 of FAP24 (DELFT-DHI, 1993a). This is an alternative to the present procedure with a single rating curve based on the total observed discharges. A comparison between the time series of total discharge based on a single rating curve and based on channel specific rating curves has been made for the year 1987 in the second Interim Report of FAP24 (DELFT-DHI, 1995). The monthly mean, annual mean and maximum discharges obtained by the two approaches do not show significant differences.

Analysis of hydraulic elements, discharge and roughness coefficient in Section 6.4, 6.5 and 6.6 show that there are differences in the hydraulic characteristics of the left and right channels. Therefore, it is reasonable to apply separate rating curves for the left and the right channels. But the variations in water levels in the left and right channels were remarkably similar during June 1994 to March 1995 as the analysis in Chapter 5 shows. Based on this observation, the stage-discharge relationships of the two channels have been expressed as a function of the stage at the Bahadurabad gauge station, which has the most accurate water level data.

The derived stage-discharge relationships for the upper segment using the measured stage-discharge data above 17.0 m PWD in 1994 are given below.

Left channel : $Q = 447.8\ (h-11)^{1.981},\ h > 17.0$ m PWD (7.2a)

Right channel : $Q = 36.7\ (h-12)^{2.859},\ h > 17.0$ m PWD (7.2b)

It is seen that the offset value is substantially higher in the case of right channel. This is because the right channel is shallower. The substantially larger value of the exponent in case of the right channel suggests that a relatively greater part of the flow is shared by the right channel with the increase in stage. This observation is consistent with the analysis of the flow distribution in Section 6.5.

It is emphasized that the rating curves for the two channels can not be related to the stages in one channel if the variations in water levels in the two channels are different.

7.2.3 Standard error

ISO (1983) remarks that the number of stage-discharge data should preferably be greater than 19 for a reliable assessment of uncertainty. In this study, the equations for the upper segment have been obtained by fitting of 19 data for the left channel, 17 data for the right channel and 16 combined discharges for the two channels. The discharge for a day through the entire transect is obtained by adding the two discharges determined from two relationships corresponding to observed stages on that day in the two channels. Then the standard error has been computed by using the differences between observed and rated discharges through the entire transect. The standard errors for the single stage-discharge relationship approach and for the channel specific relationship approach are 7.8 and 7.6% respectively, which are not substantially different. The uncertainty due to errors in discharge measurements has not been considered in this analysis.

The standard error in the fit of Eqs. (7.2a) and (7.2b) are 7.5 and 16.2% respectively. Despite the large standard error in Eq. (7.2b) for the right channel, the standard errors for the total discharge in the two approaches are not large. This is because the discharge of the left channel is several times those of the right channel. The small discharges of the right channel can not influence significantly the overall standard error. This may not be the case at higher flood stages since the percentage of total discharge shared by the right channel increases with the increase in stage.

The standard error of 7.5% in the fitted Eq. (7.2a) for the left channel is slightly on the high side. But the standard error of 16.2% in the fitted Eq. (7.2b) for the right channel is very high. This may be due to quite large scatter in the stage-discharge plot in Figure 6.7(b). The possibility of the existence of a loop can not be ruled out. When the loop feature is present in a rating curve, an improved fitting of the stage-discharge equation can be obtained by using adjusted discharges to account for the variable water surface slope caused by changing discharge. Perhaps further segmentation of the range of the stage-discharge relation above 17.0 m PWD could improve the fit. These can not be investigated due to an inadequate number of data. The highly uneven distribution of measurements with respect to time as seen in Table 6.1 (b) can also be one of the reasons for the poor fit.

7.3 Comparison of extrapolation methods

Various methods of extrapolation of stage-discharge relations have been discussed in Section 2.4 and five of them are investigated. The methods are:

(1) direct extrapolation of the upper segment the fitted rating curve,

(2) Stevens method,

(3) conveyance-slope method,

(4) slope-area method of peak discharge determination and

(5) the method solely based on the steady flow formula.

The existing BWDB procedure is the direct extrapolation of the upper segment of the fitted rating curve. Hydraulic elements required for the Stevens and conveyance-slope methods have been taken from the analysis presented in Section 6.4. The conveyance-slope and slope-area methods require an estimation of the Manning or Chèzy roughness coefficient. It has been taken from the analysis presented in Section 6.6.

The slope-area method and the steady flow formula method give the peak discharge for the observed highest stage of a flood. Then the discharges in the range between the estimated peak discharge and the end of the upper segment of the fitted stage-discharge relation are determined simply by linear interpolation in the log-space.

The accuracy of the above five methods have been assessed by pretending that the discharges for stages above the stage recorded on August 13, 1994 are not available. This gives an extrapolation range of approximately 30,000 to 38,000 m^3/s. This does not provide a rigorous test since the range and the magnitude of extrapolation is small. The roughness coefficient is assumed constant in the extrapolation range and is taken equal to the value from the plot in Figure 6.15, that gives smaller roughness for the stage on August 13, 1994. Plots of stage against the Chèzy conveyance ($CAR^{0.5}$) and stage against slope (Q^2/C^2A^2R) required for the conveyance-slope method are shown in Figure 6.16.

A comparison of estimated discharges by the five methods with the measured discharges has been presented in the Table 7.1 using the Chèzy roughness coefficient where required. The table shows that all methods give smaller values compared to the observed discharges. The conveyance slope method has the best performance followed by the slope area method and the steady flow formula method. Performances of the direct extrapolation of the upper segment of the fitted rating curve and of the Stevens method are poor.

Date	Water level (m PWD)	Observed discharge (m^3/s)	Estimated discharge (m^3/s)				
			Extrapolation of upper segment	Stevens method	Conveyance slope method	Slope area method	Steady flow formula
23/06/94	18.53	33929	30349	29780	32287	31459	31237
24-26/06/94	18.54	34650	30492	30000	32468	31762	31524
28/06/94	18.58	34131	30661	31220	32843	31815	31555
	Average relative deviation		10.9%	11.4%	5.0%	7.5%	8.2%

Table 7.1 : Comparison between observed discharges and estimated discharges by five extrapolation methods for stage - discharge relationship

7.4 Accuracy of slope-area method

In the previous section, the highest peak discharge determined by the slope-area method has been used to interpolate the intermediate discharges. Then the accuracy of interpolated discharges has been assessed. In this section, the accuracy of the slope-area method in determining the peak discharge has been assessed by using data on measured peak discharges during the flood season of 1994. Table 7.2 shows input data, observed and computed peak discharges. The data on width and cross-sectional area at upstream and downstream sections are not available for the peak stage. They have been estimated from the available data for a lower stage based on the observation in Section 6.4.1 that the flow section can be approximated as a rectangle.

Channel	Date	Khatiamari		Belgacha		S_w cm/km	Upper C $m^{1/2}/s$	Q_c m^3/s	Q_o m^3/s
		Width (m)	Area (m^2)	Width (m)	Area (m)				
Left channel	27/6/94	2481	16062	2775	18594	9.34	57	25656	>25587
	2/8/94	2505	16008	3474	20091	10.0	56	24761	22596
	18/8/94	2481	15268	3773	21043	9.80	60	26030	23848
Channel	**Date**	**Shankibhanga**		**Bagirchaow**		**S_W cm/km**	**Upper C $m^{1/2}/s$**	**Q_c m^3/s**	**Q_o m^3/s**
		Width (m)	Area (m)	Width (m)	Area (m)				
Right channel	27/6/94	1687	9589	2661	13104	9.01	41	10441	10460
	2/8/94	1677	7161	2060	9435	7.31	44	6688	7288

Table 7.2 : Input data for the slope-area method along with computed and observed peak discharges

The Chèzy roughness coefficient for the observed peak stage has been used in the computation. It has been taken from the upper limit in Figure 6.15 which gives higher values of the Chèzy coefficient. A lower Chèzy coefficient implies roughness. Table 7.2 shows that the estimated largest peak discharge is reasonable and the relative deviations in the remaining estimates are less than 10%. Such error is not unexpected considering the uncertainties in roughness coefficient, local water surface slope and cross-sectional area.

The main source of uncertainty in the slope-area method are the errors involved in the selection of the value of the roughness coefficient. It can be questioned that the comparison in Table 7.2 is biased because the above method uses data on local water surface slope and conveyance factor, which also have been used along with the discharge in the development of the stage-roughness relationship in Figure 6.15. But while applying the slope-area method in the estimation of an unmeasured peak discharge at the highest stage at a gauge station, discharge measurement data at lower stages can be used to develop stage-roughness relationship like in Figure 6.15. Hence, the comparison can be considered near to the real situation. It may be mentioned that the slope-area method is used when estimation of discharge by more accurate methods is not possible.

8 Conclusions and recommendations

8.1 Conclusions

The conclusions of this study are based on the analysis of water level and discharge data collected by FAP24 for the period April 1994 to March 1995.

Analysis of the local water surface slopes and the rates of change of water levels show remarkable similarity in the water level variations in the left and the right channels of the Jamuna river at Bahadurabad. But the analysis of the relationships of conveyance factors, slope-roughness factors, Froude numbers, distribution of flow and roughness coefficients with the water level indicate differences in the dynamical behaviours of the flows in these two channels.

The discharge of the left channel is three to five times the discharge of the right channel. The fraction of the total discharge shared by the right channel in 1994 is about one-fourth at high flood stage and reduces to about one-fifth at the end of the flood season. It is seen that the percentage of total discharge shared by the right channel at high stages is greater than at lower stages.

The local water surface slope decreases gradually during the receding phase of the annual hydrograph. Due to the absence of measured data, the variation of the water surface slope during the rising phase of the hydrograph could not be studied.

A dividing point for segmenting the stage-discharge relationship seems appropriate at a stage close to the beginning of receding limb of the annual water level hydrograph. This break point has been established by studying the variations of local water surface slopes, slope-roughness factors and Froude numbers with the change in water level. The number and the time interval of discharge data for the period of 1994 to 1995 were not adequate for investigating the loop feature.

The standard errors in the fitted upper segment of the rating curves for the left and the right channels are 7.5 and 16.2% respectively which are on the high side. But there is no significant difference in the standard errors of the computed discharges of the Jamuna river at Bahadurabad when the single stage-discharge relationship is used or when the channel specific stage-discharge relationship is used. This may not be the case at very high flood stages since the percentage of the total discharge shared by the right channel increases with the increase in stage. The channel specific stage-discharge relation approach is consistent with the BWDB practice of discharge measurement in two days : one day in the left channel and the other day in the right channel. Uncertainty due to errors in discharge measurement has not been addressed in this study.

Among the five methods for the extrapolation of a stage-discharge relationship, the conveyance-slope method performs best followed by the slope-area method and the steady flow formula. The average relative deviation of the estimated discharges from measured discharges is 5% for the conveyance-slope method. Performances of the direct extrapolation of the upper segment of the rating curve and of the Stevens method are poor.

Relationships of the Chèzy and the Manning roughness coefficients with the water level have been developed for the Jamuna at Bahadurabad by using data on local water surface slopes, discharges and conveyance factors. The estimated roughness coefficients are found within the range of the calibrated values in a hydrodynamic model study by Halcrow and others (1993). The right channel has substantially greater roughness than that of the left channel.

8.2 Recommendations

The flood flows in the Jamuna in the year 1994 were unusually low. The maximum water level at the Bahadurabad transect was substantially below the river bank level. The comparison of the methods of extrapolation of stage-discharge relationships in this study is based on an extrapolation range of approximately 30,000 to 38,000 m^3/s. This is not representative for the situations when extrapolations are usually required for discharges exceeding 60,000 m^3/s, which crosses the bank level. It is recommended to continue this study so that the stage-discharge data for the year 1995 can be included in the analysis. The highest stage in July 1995 was 20.36 m PWD at Bahadurabad on the 10th July of 1995. The discharge measured by the BWDB Hydrology Directorate was approximately 84,000 m^3/s at 20.18 m PWD during 11 to 12 July 1995. It is an opportunity to study the behaviour of the Jamuna at Bahadurabad at high flood stages, which is essential for a better understanding of the stage-discharge relationship.

The time interval and the number of discharge measurement at the Bahadurabad transect should be such that important hydraulic features of the annual hydrograph are covered by the observed data. The discharge data collected by the BWDB Hydrology Directorate should be utilized in the future study.

The rating curve fitting procedure by keeping a constant value of the offset for all segments of an annual rating curve should not be followed as emphasized in the Phase I Hydrology Study Report by DELFT-DHI (1993). All three parameters should be estimated separately for every segment of the rating curve. One of the dividing points for segments can be the stage close to the start of the receding limb of the annual water level hydrograph.

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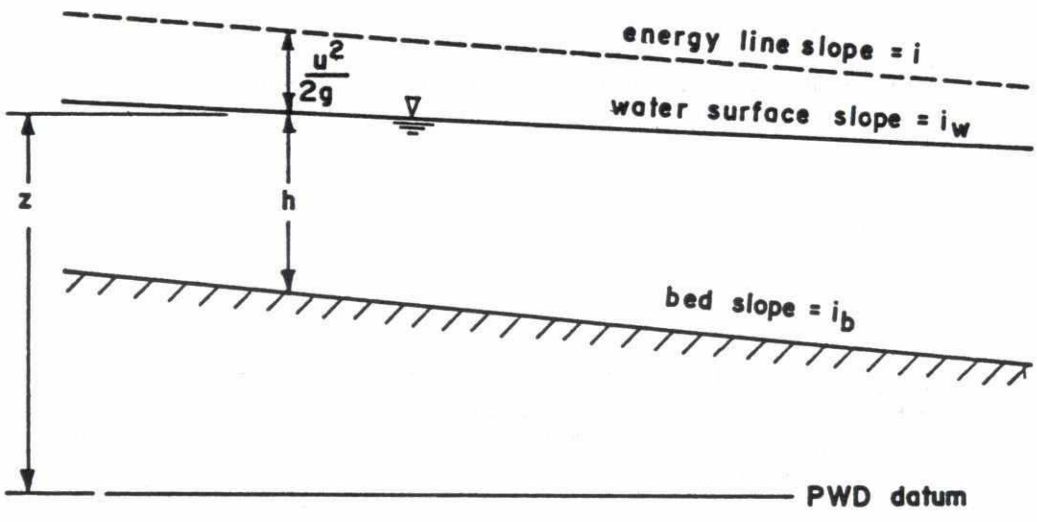


Figure 2.1: Definition sketch

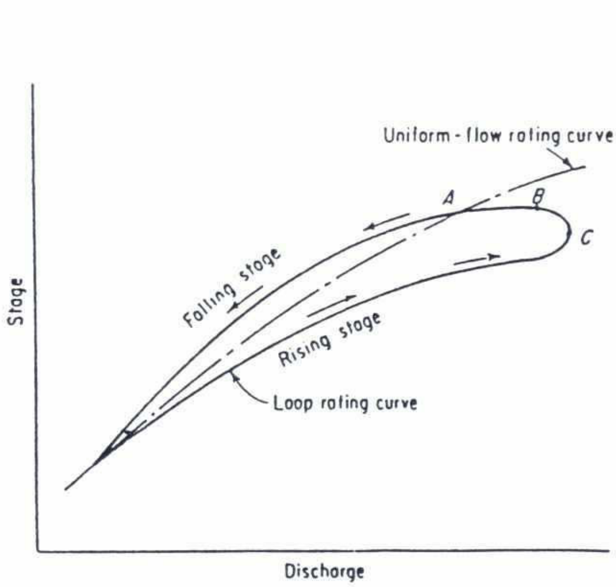


Figure 2.2 The loop-rating curve, showing the progress of a typical flood wave

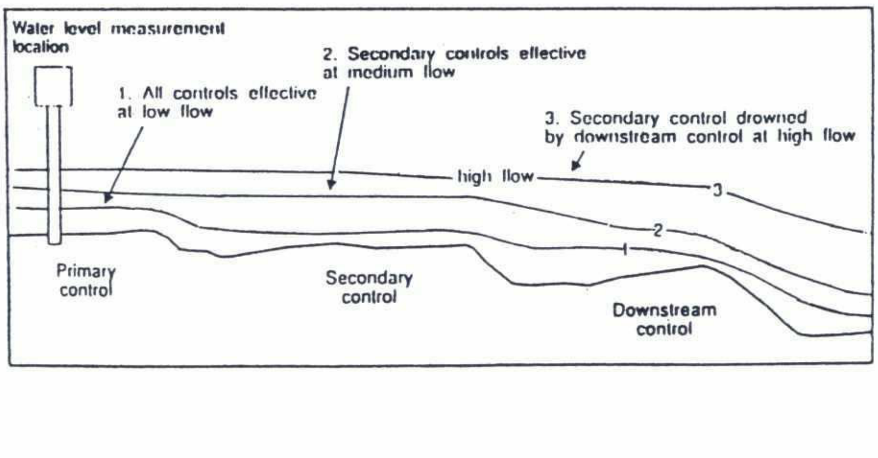


Figure 2.3: The influence of downstream controls on water levels (after Mosley and McKerchar, 1993)

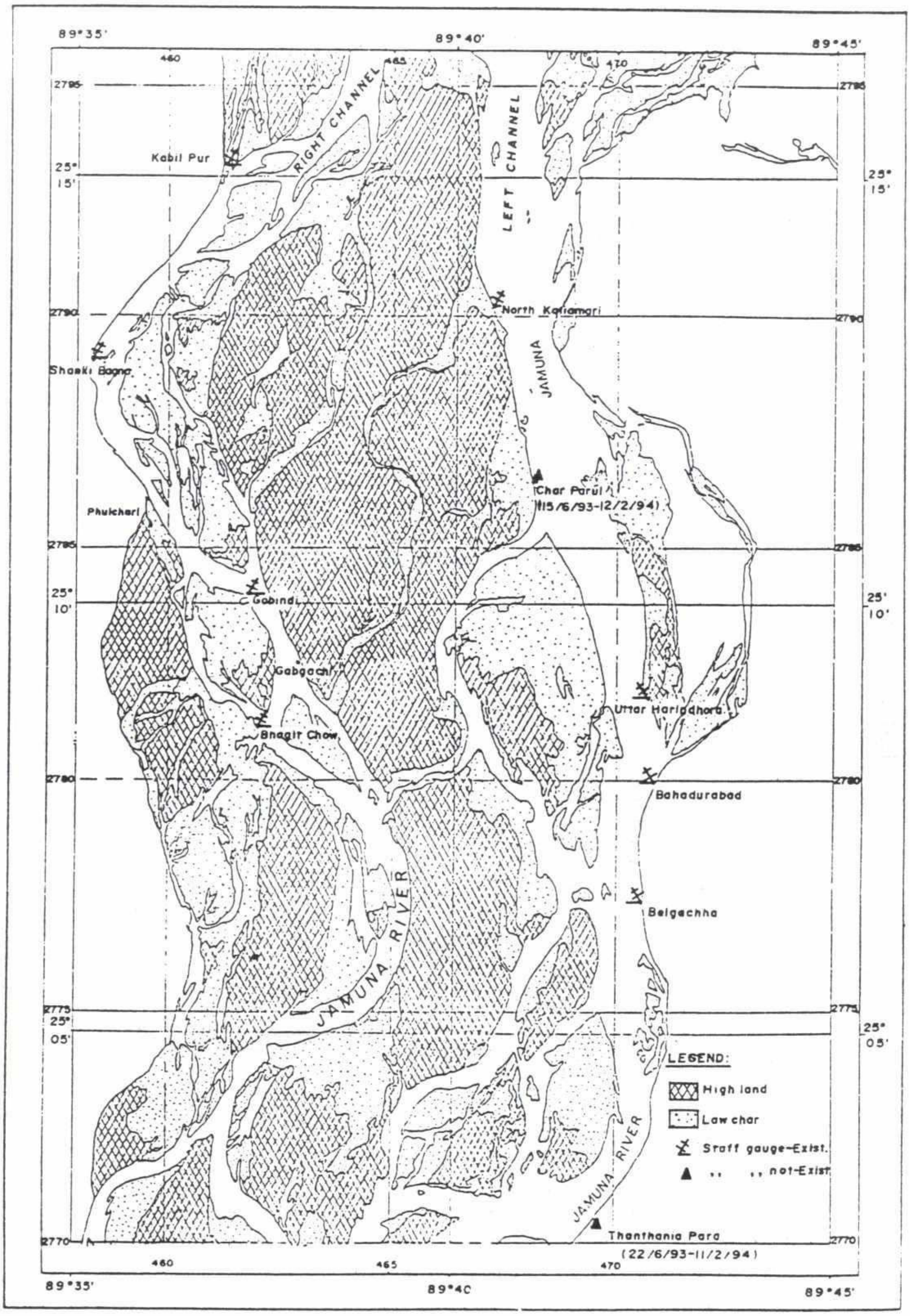


Figure 3.1: Bahadurabad transit, Jamuna River

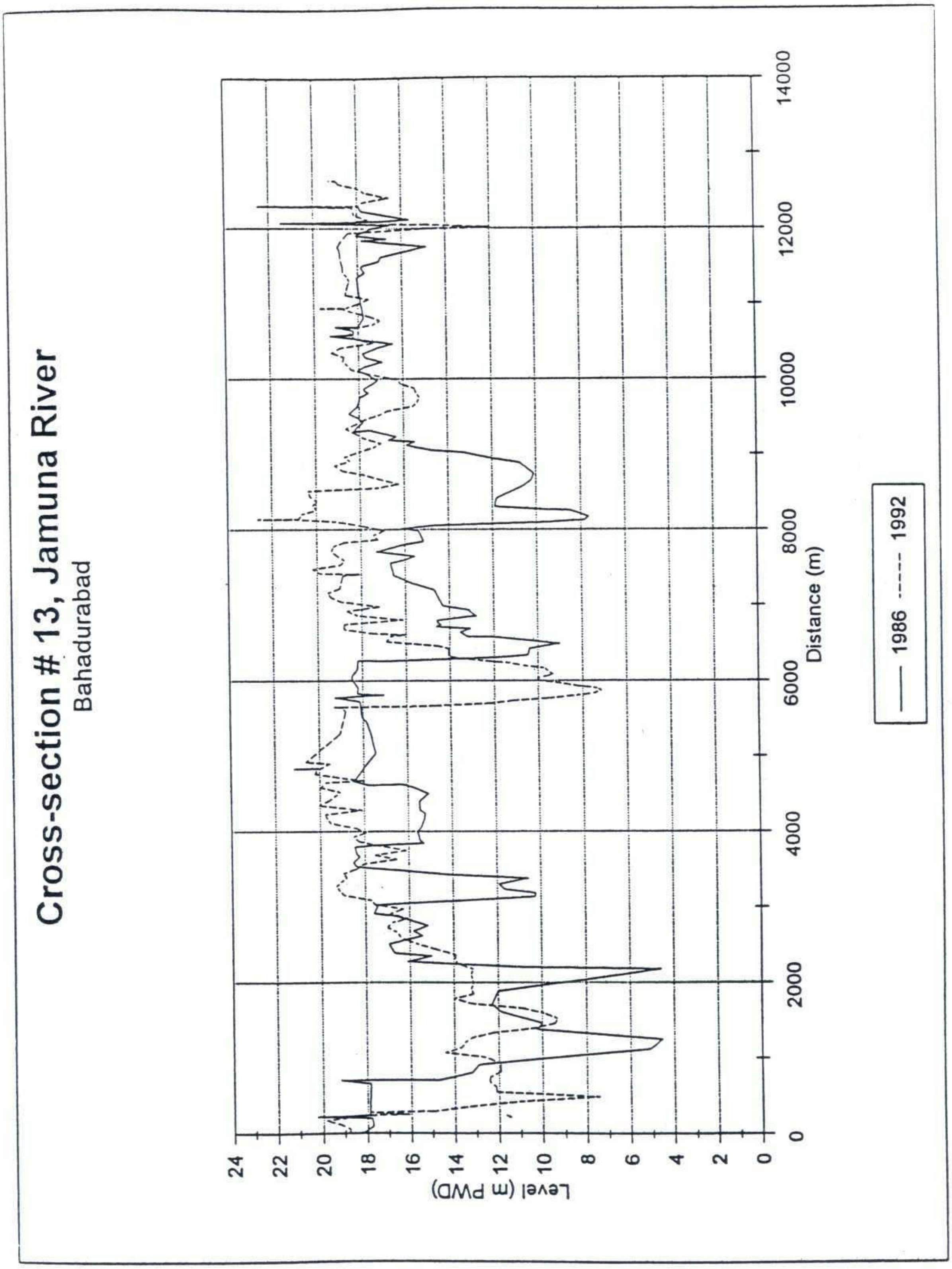


Figure 3.2 Location map for the measured cross sections

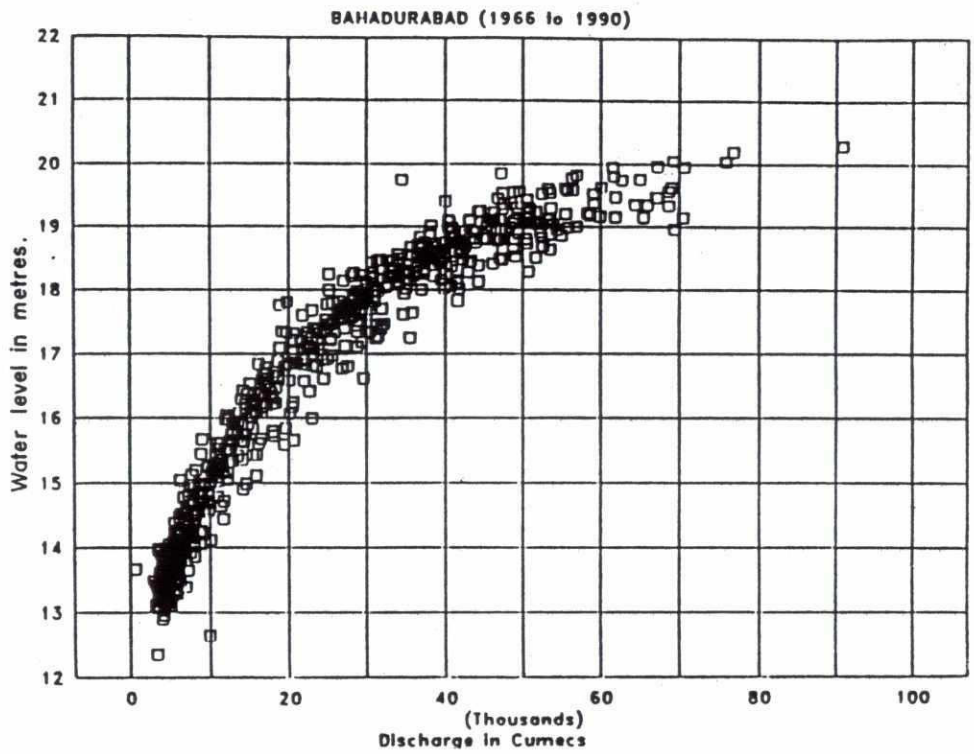


Figure 4.1: Plot of 25 years gauged data at Bahadurabad (from Kruger Consult, 1992)

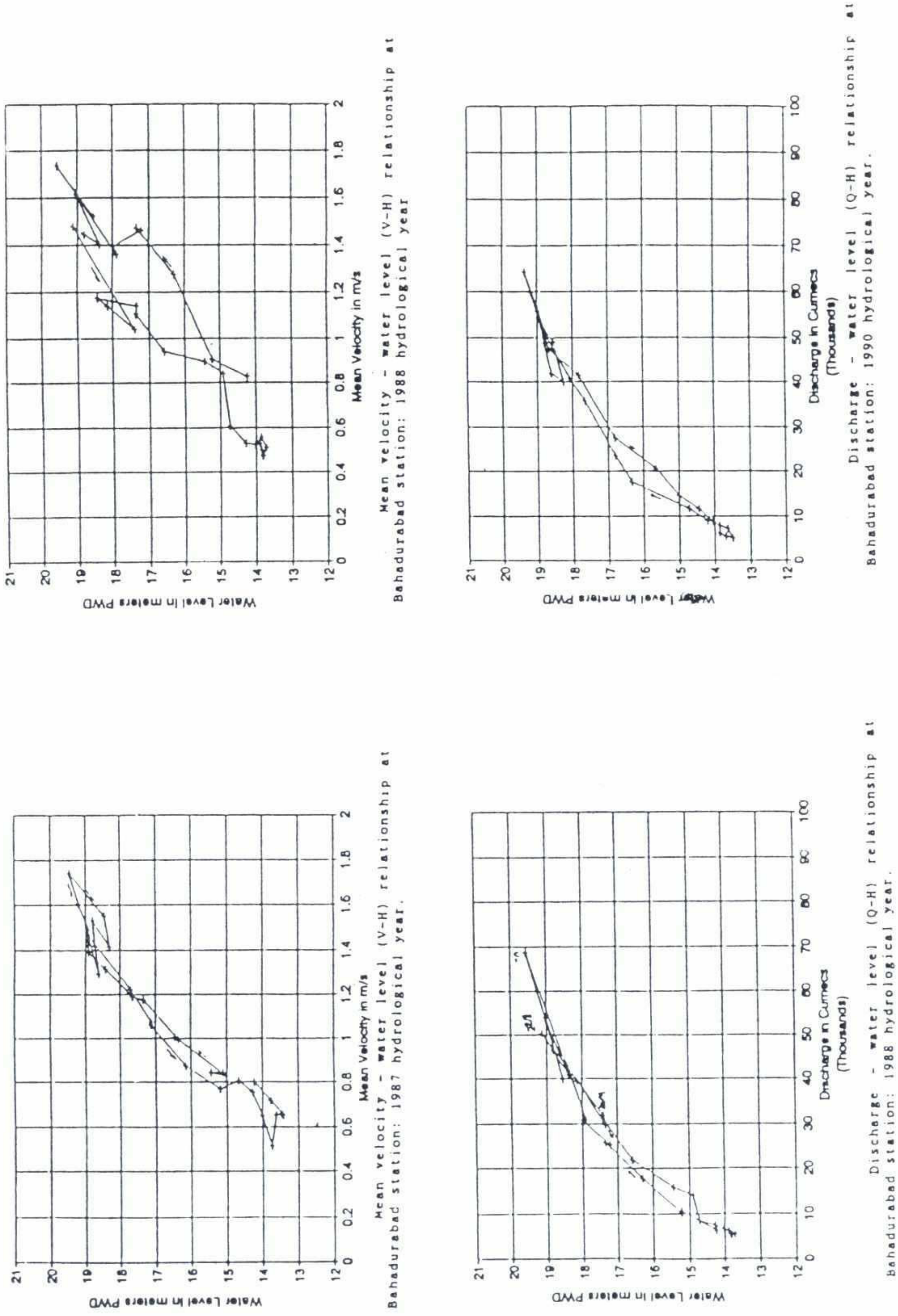


Figure 4.2: Loops in the relationships of flow velocity and discharge with stage at Bahadurabad (extracted from Tejada-Guibert, 1993)

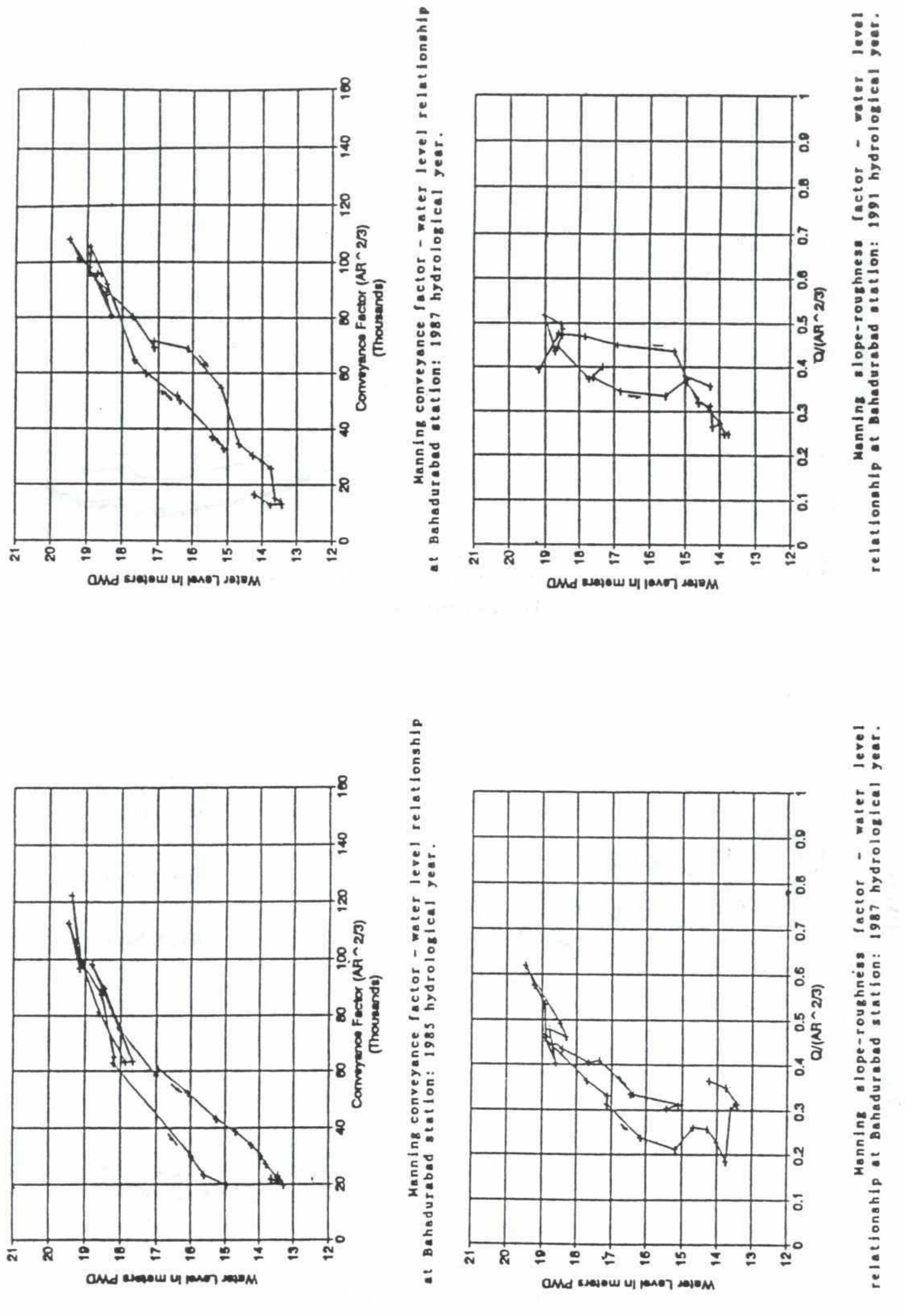
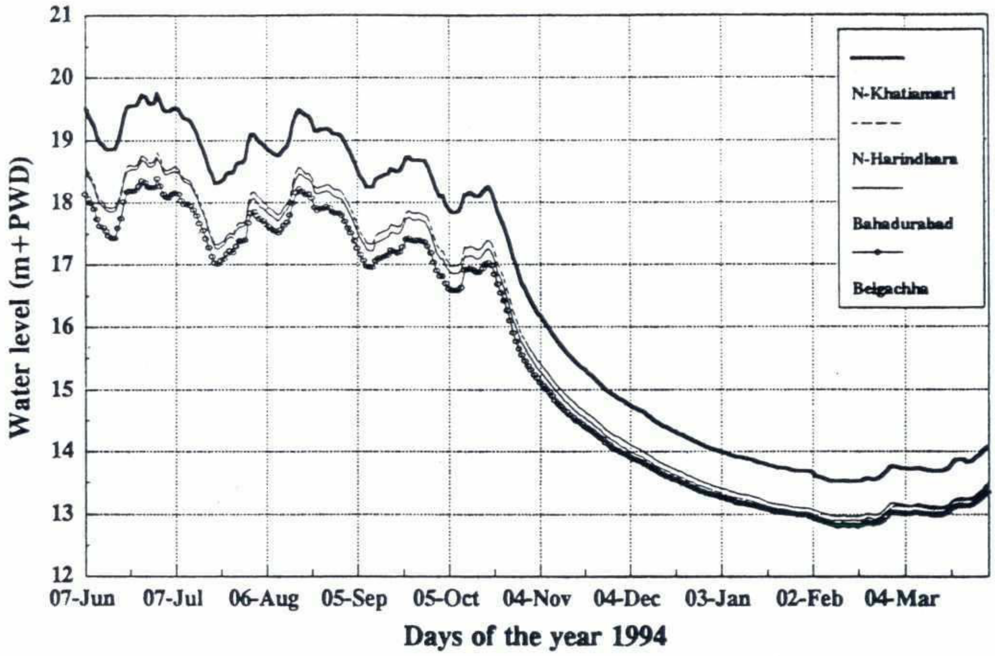


Figure 4.3: Loops in the relationship of hydraulic elements with stage at Bahadurabad (extracted from Tejada-Guibert, 1993)



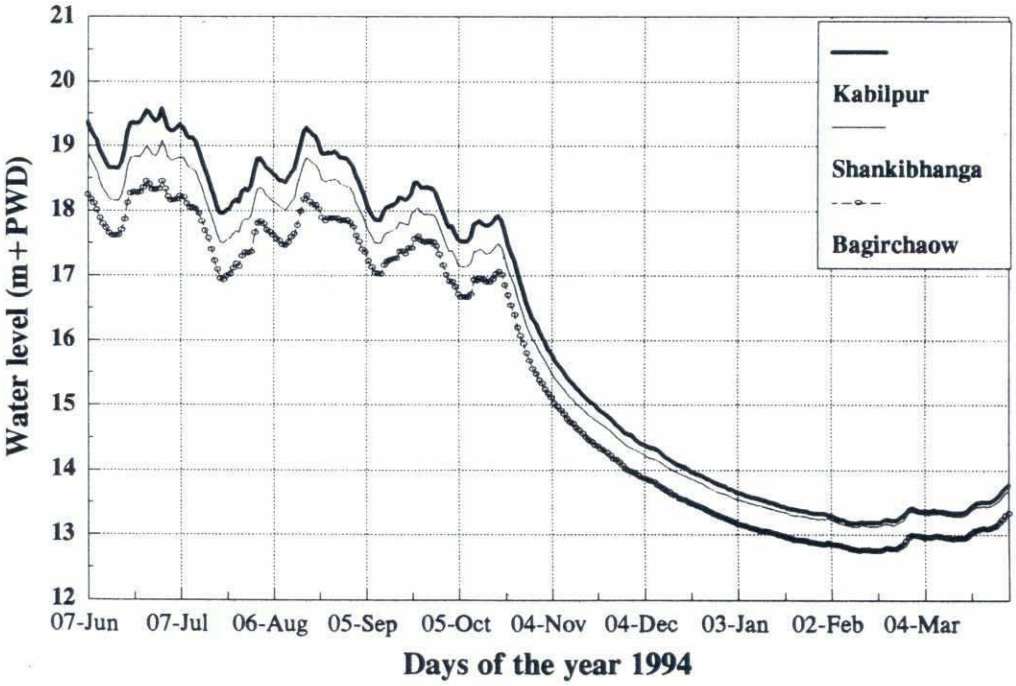
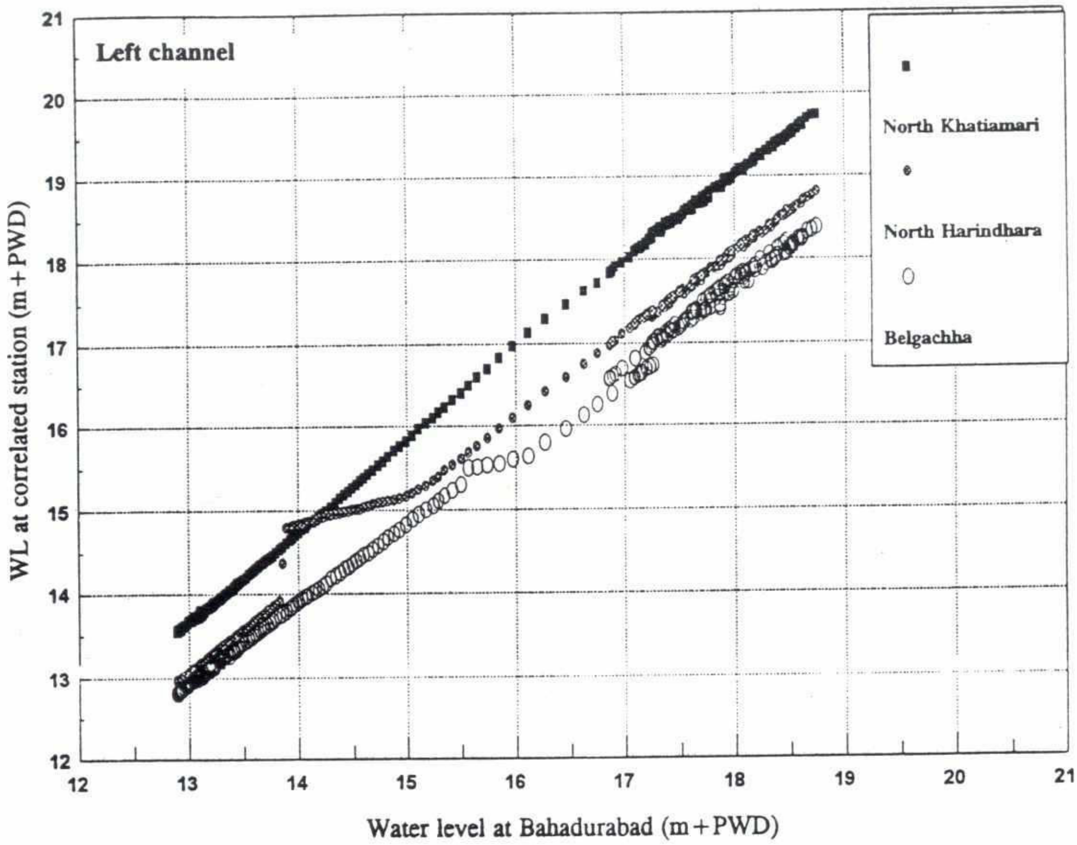


Figure 5.1: Water level hydrographs: (a) left channel (b) right channel



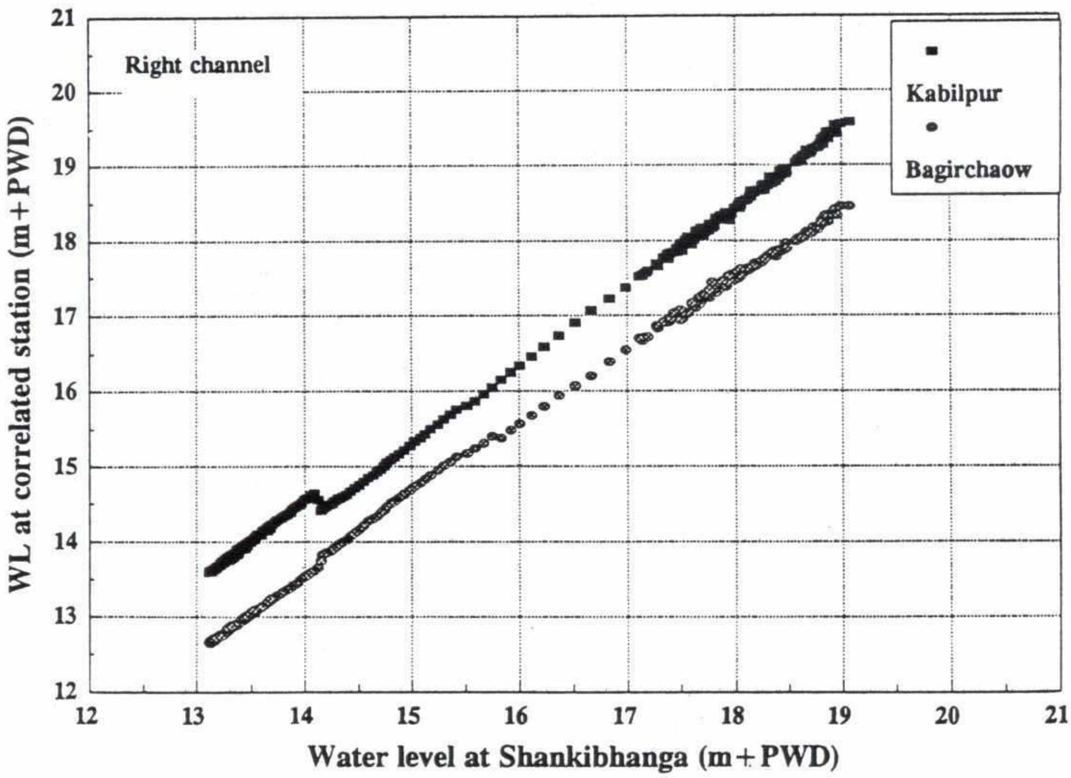
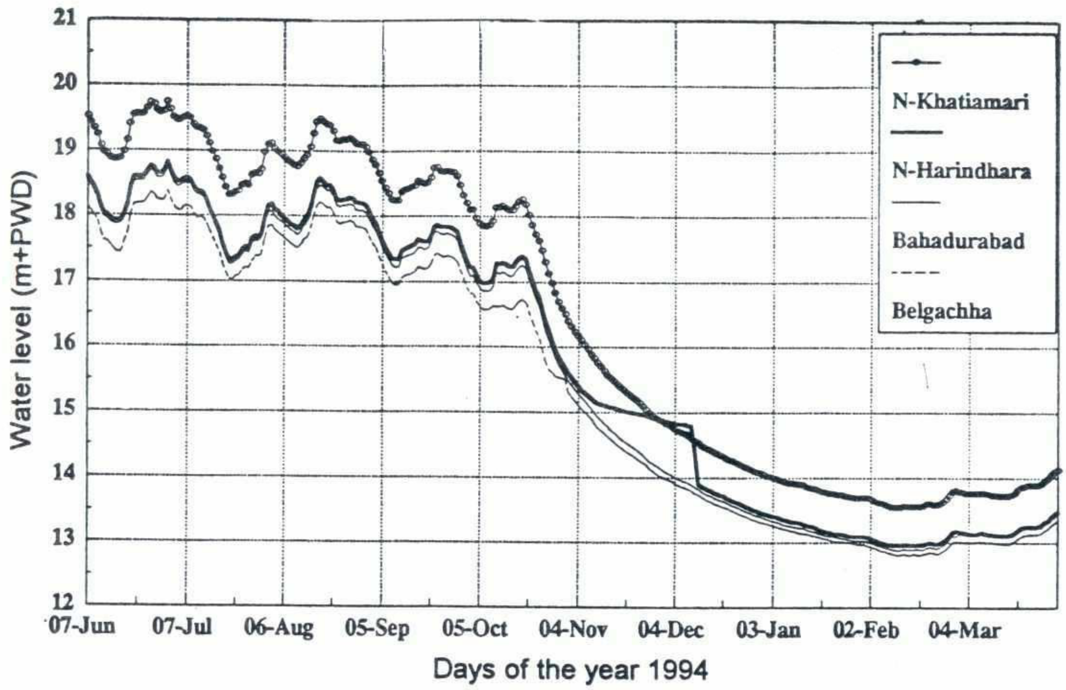


Figure 5.2: Correlation between water levels along a channel (a) left channel (b) right channel



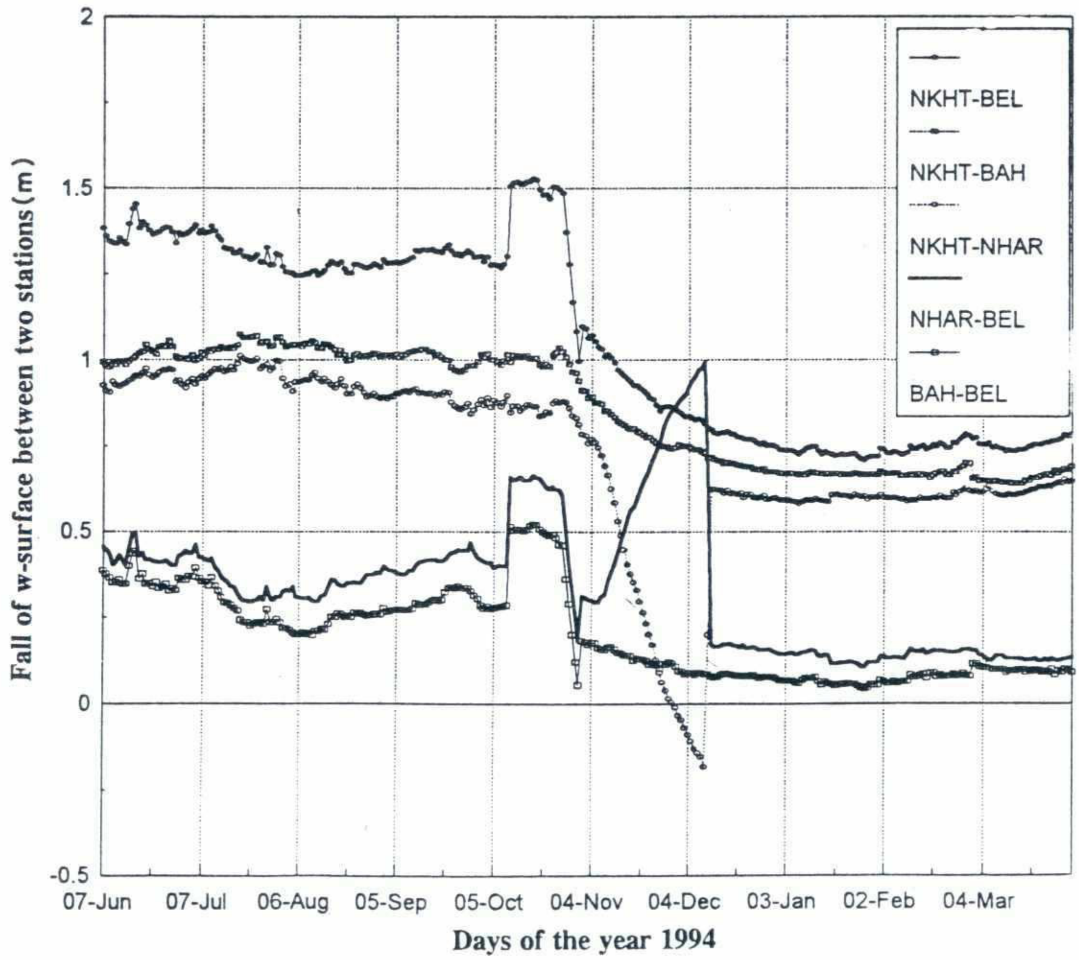
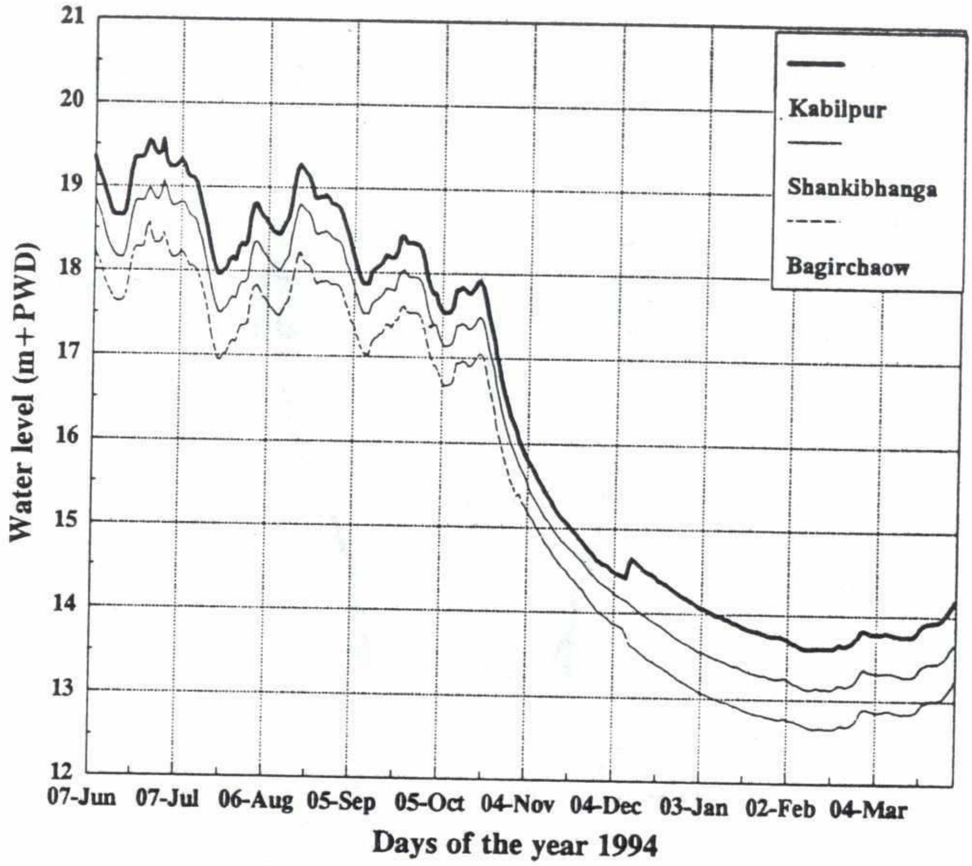


Figure 5.3 (a): Plot of water surface fall along a channel against time, left channel



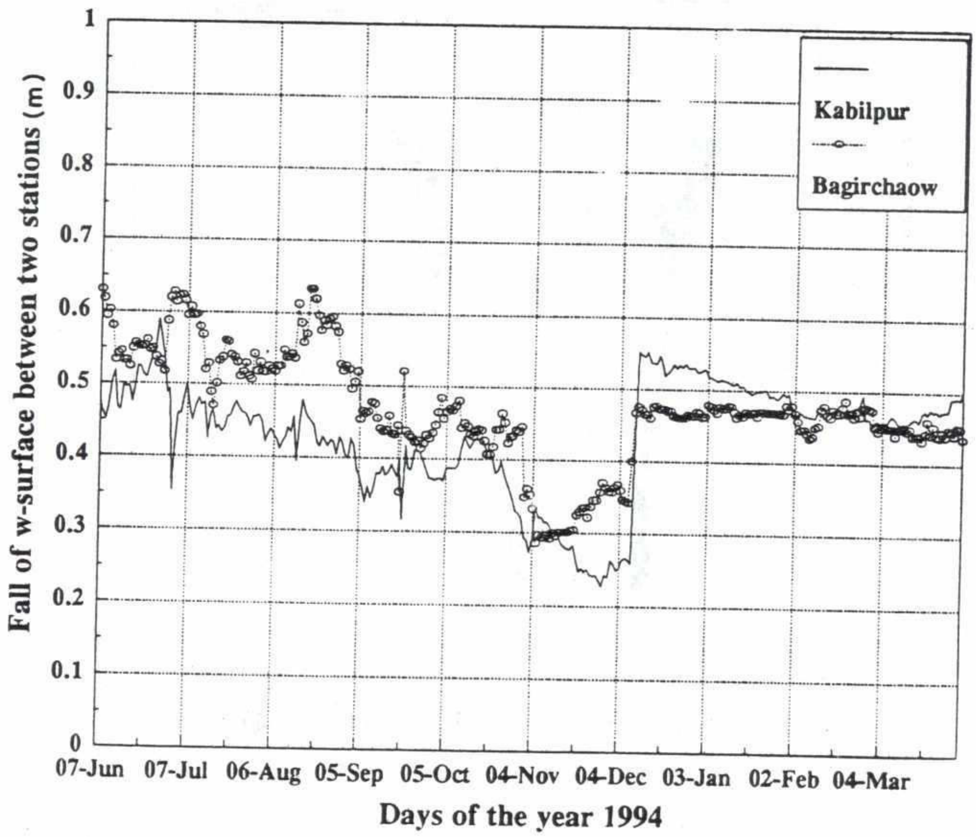


Figure 5.3 (b): Plot of water surface fall along a channel against time, right channel

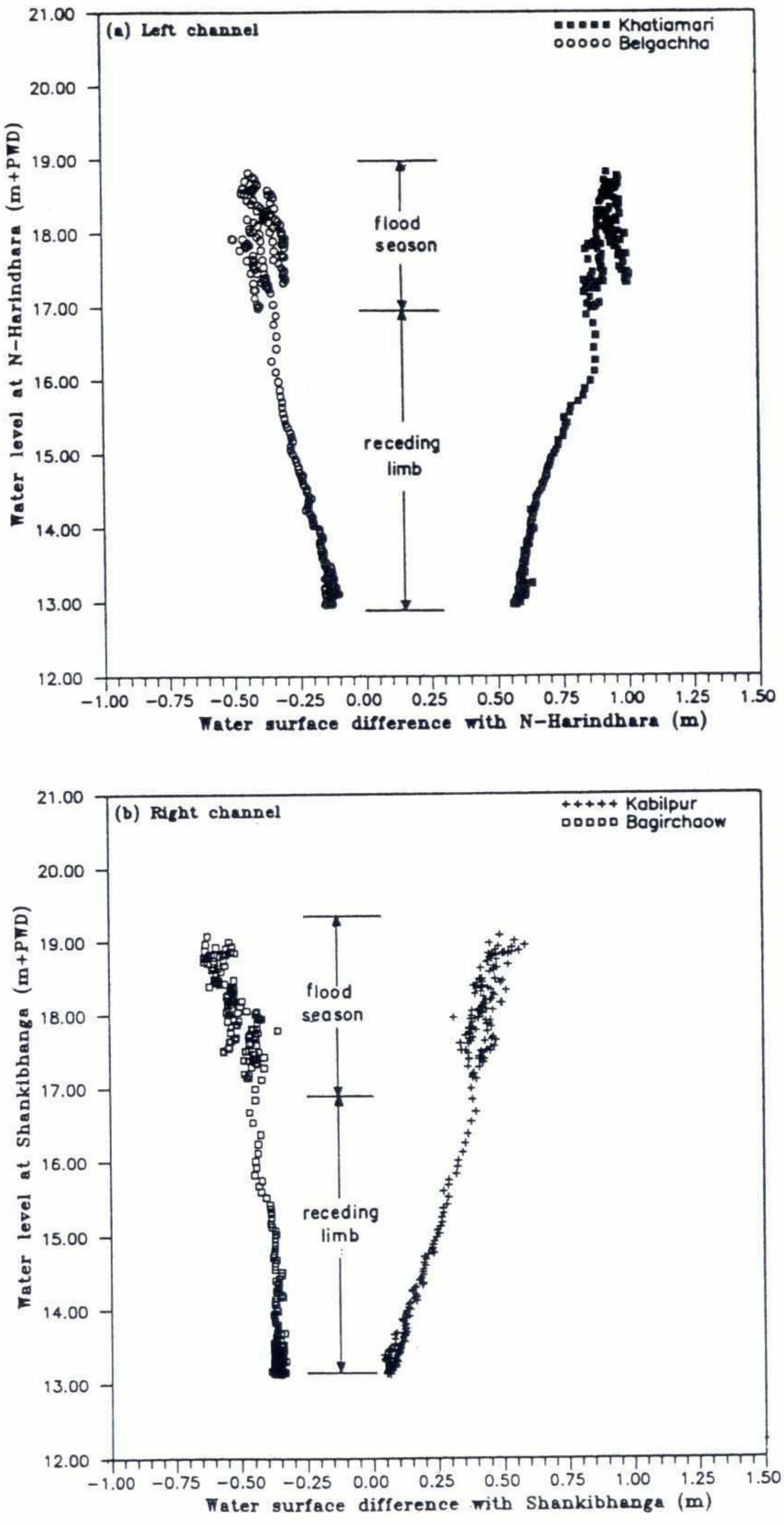


Figure 5.4: Plots of local water surface fall as a function of stage: (a) left channel (b) right channel

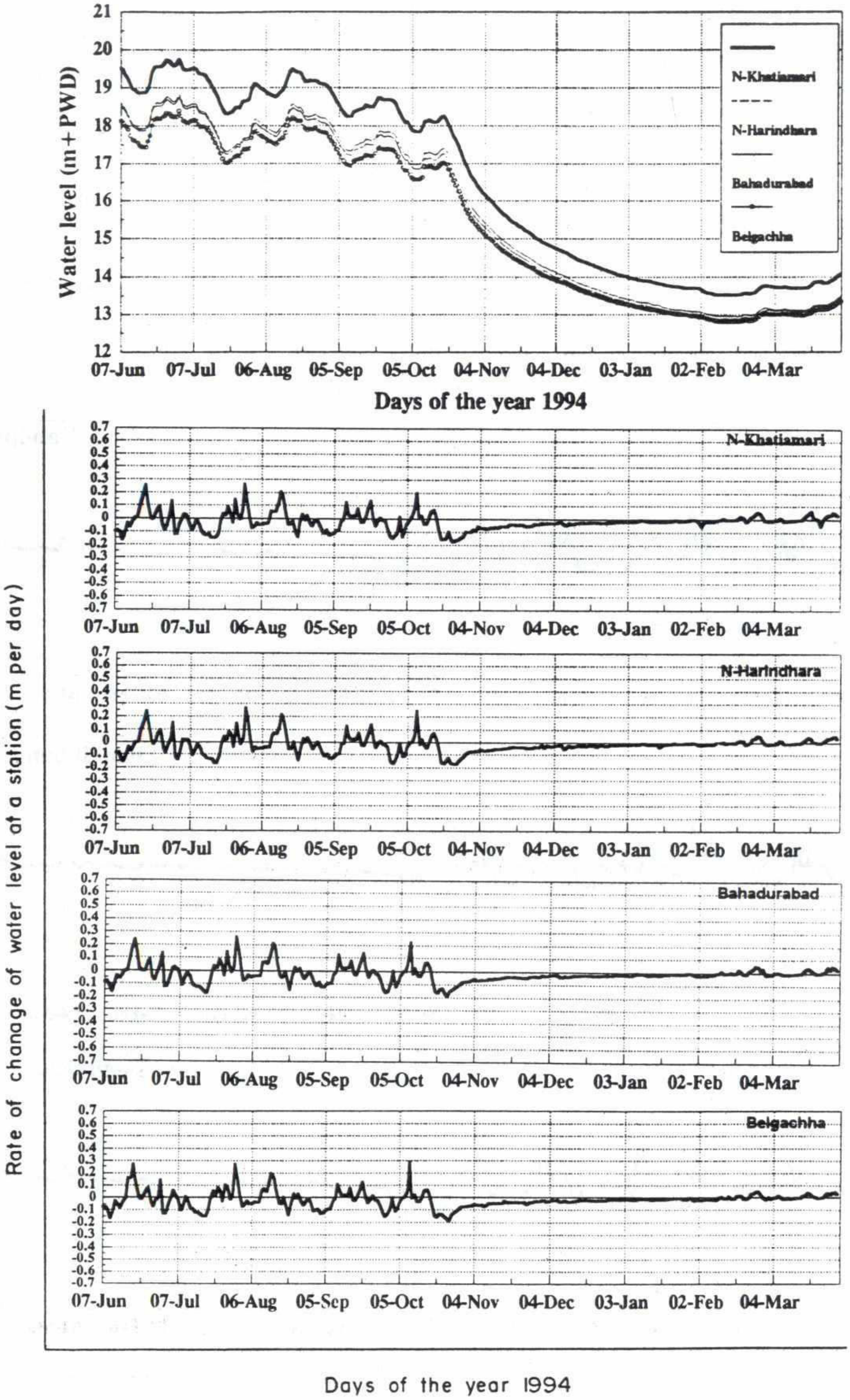
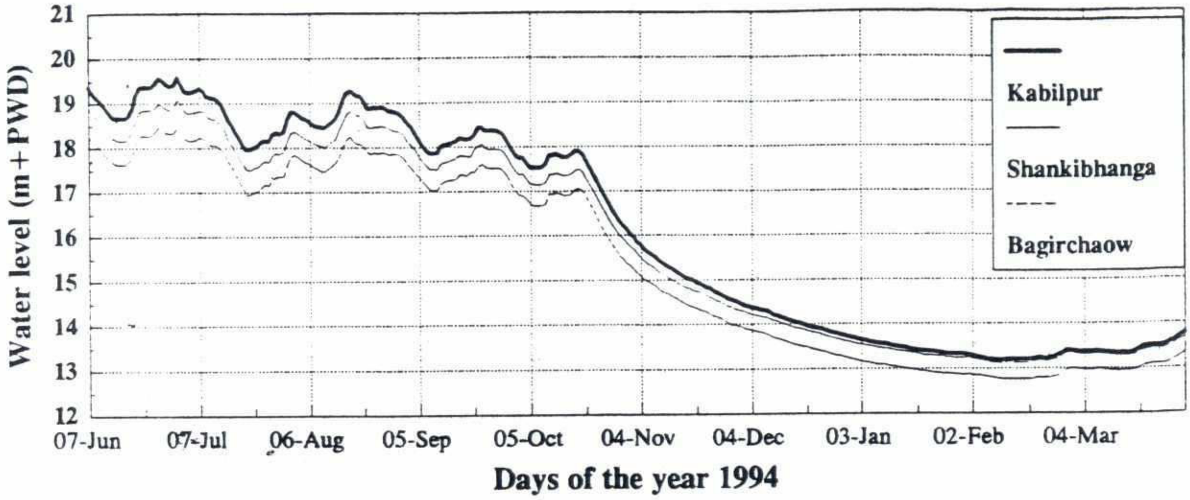


Figure 5.5 (a): Plots of rate of water level change at a location against time, left channel



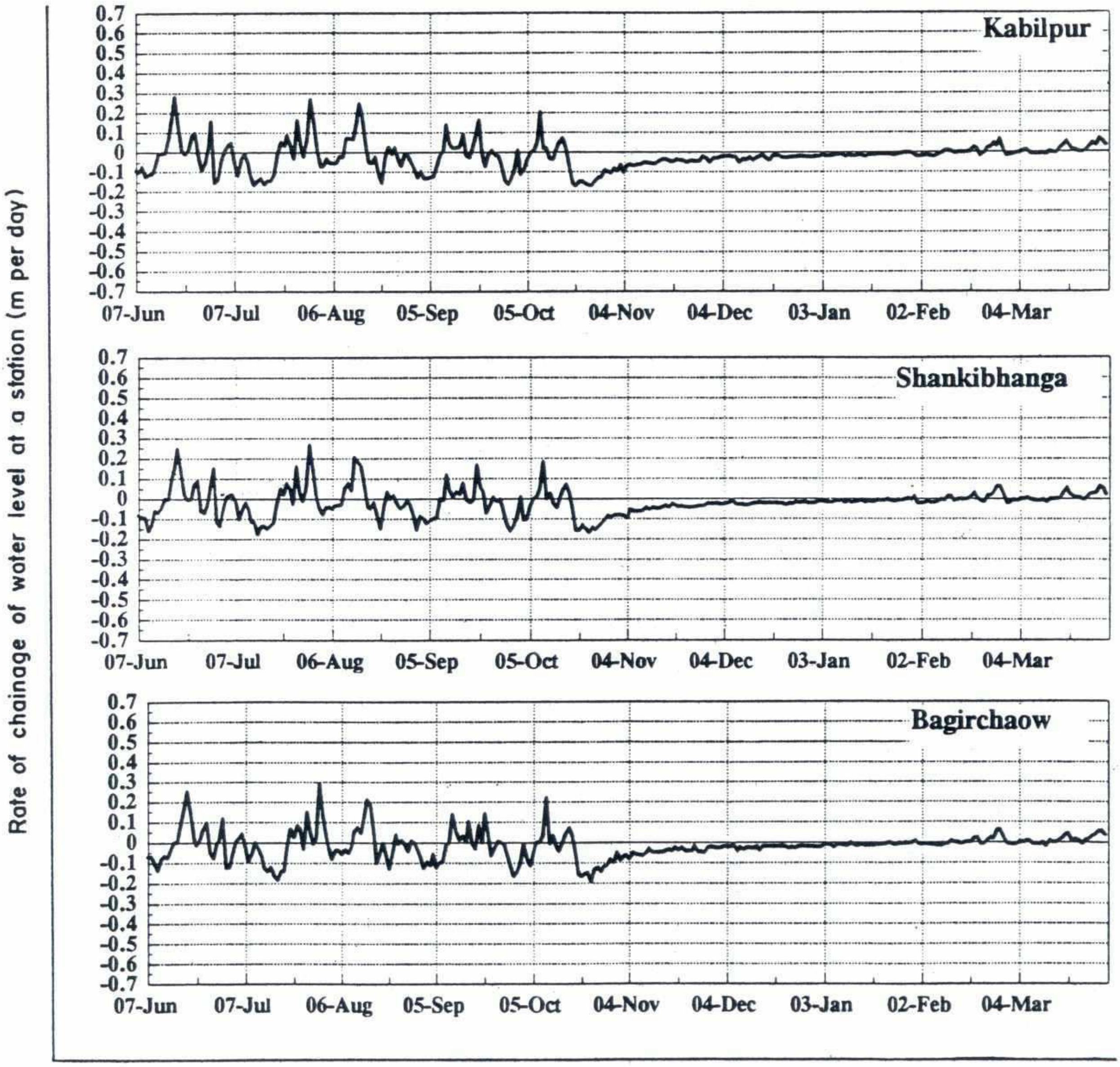


Figure 5.5 (b): Plots of rate of water level change at a location against time, right channel

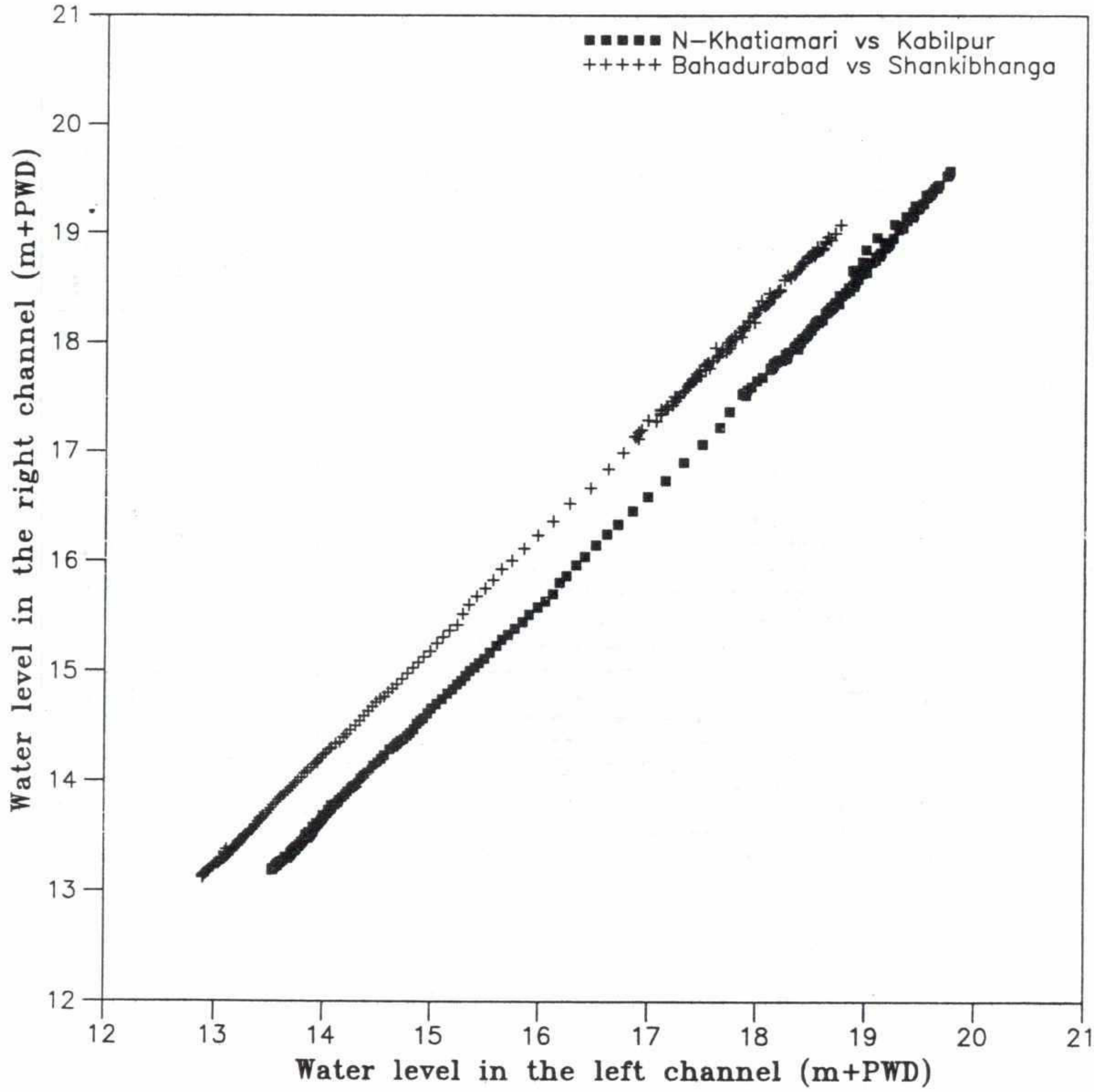


Figure 5.6: Correlations between left channel and right channel stations

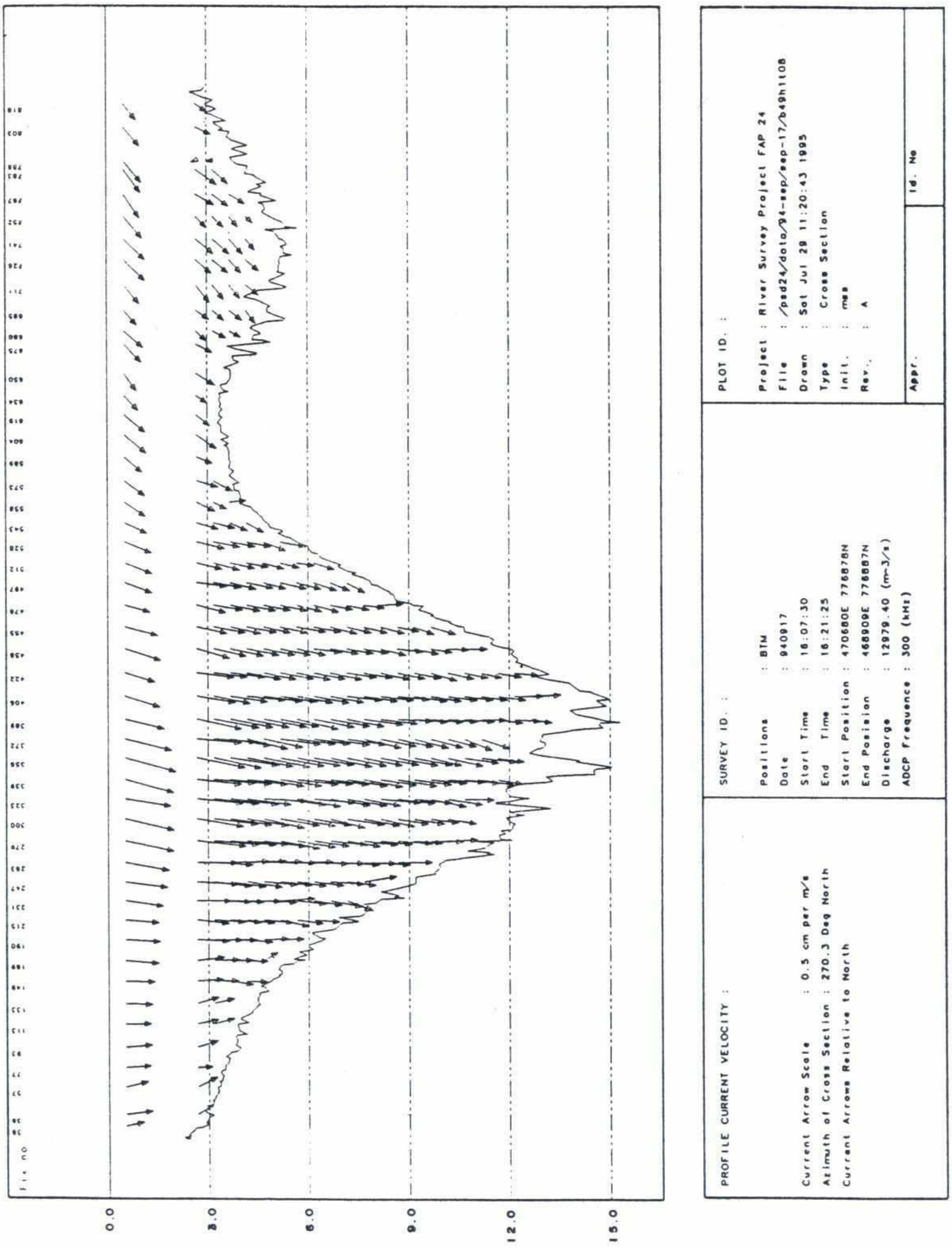


Figure 6.1: Velocity vector field in a measured cross-section in left channel at Bahadurabad

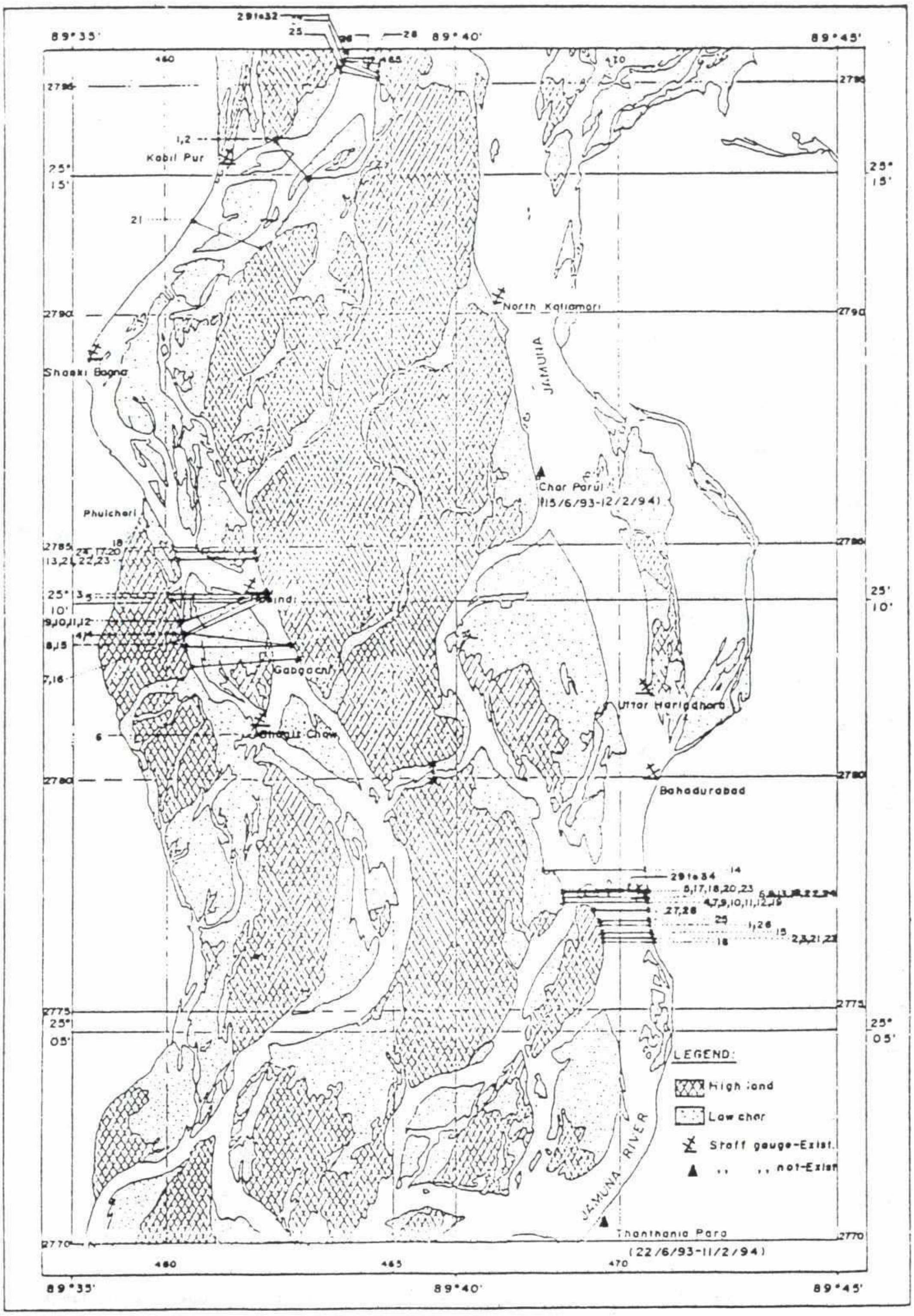
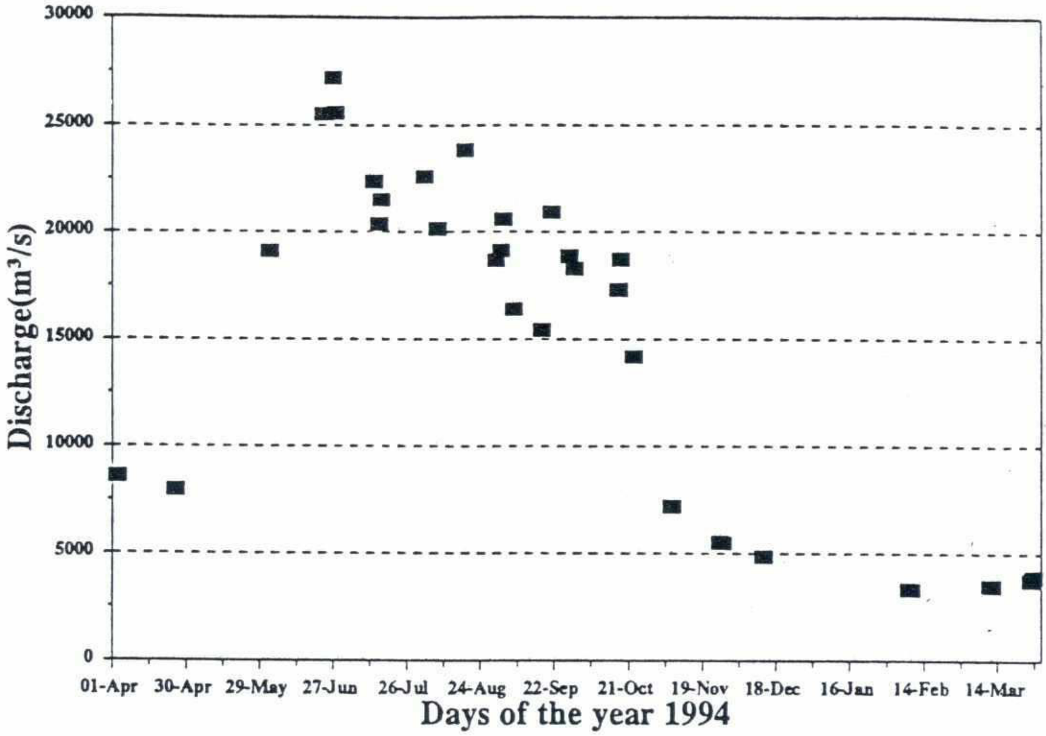


Figure 6.2: Locations of discharge measurement sections



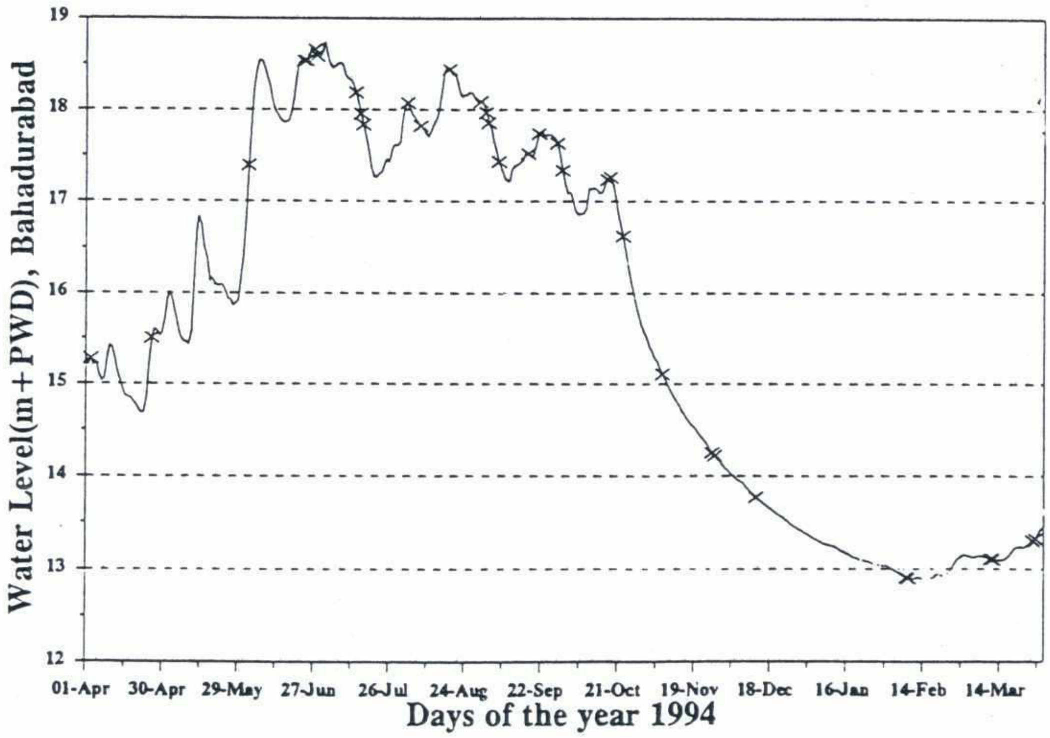
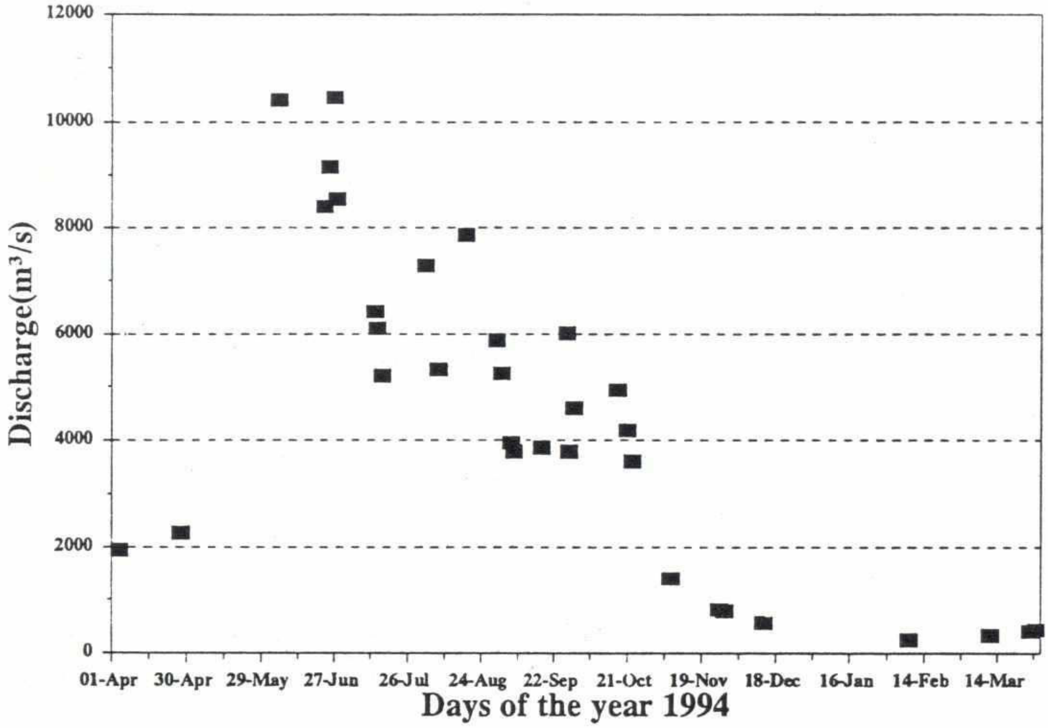


Figure 6.3: Plot of discharge data against time along with water level hydrograph, left channel



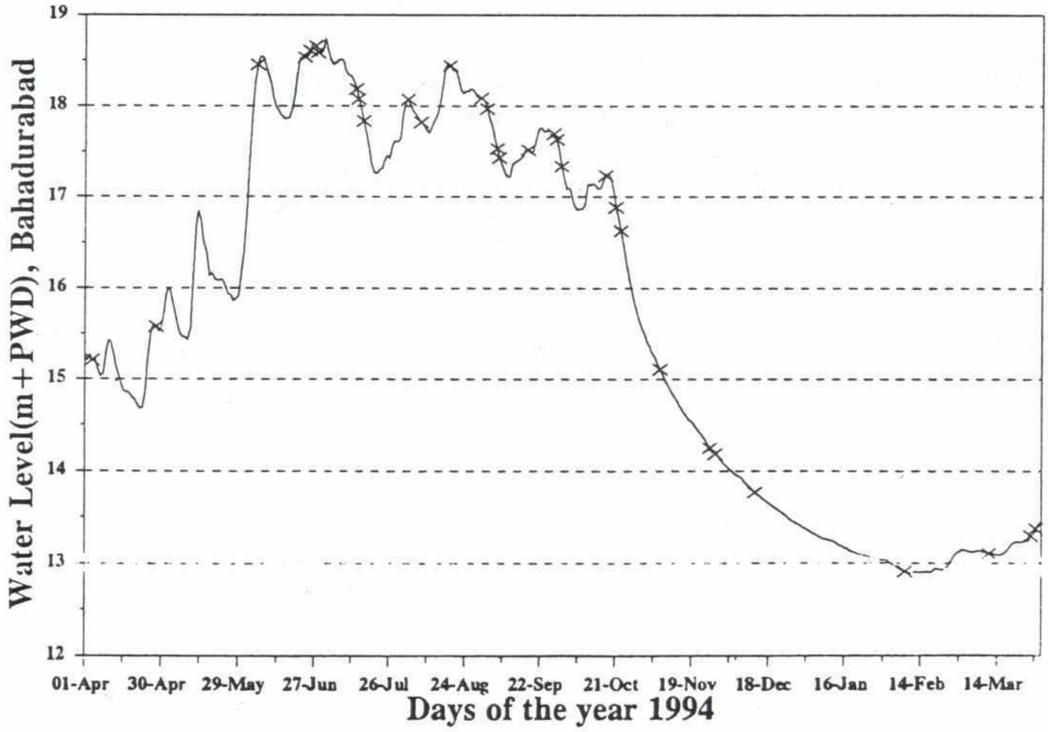


Figure 6.4: Plot of discharge data against time along with water level hydrograph, right channel

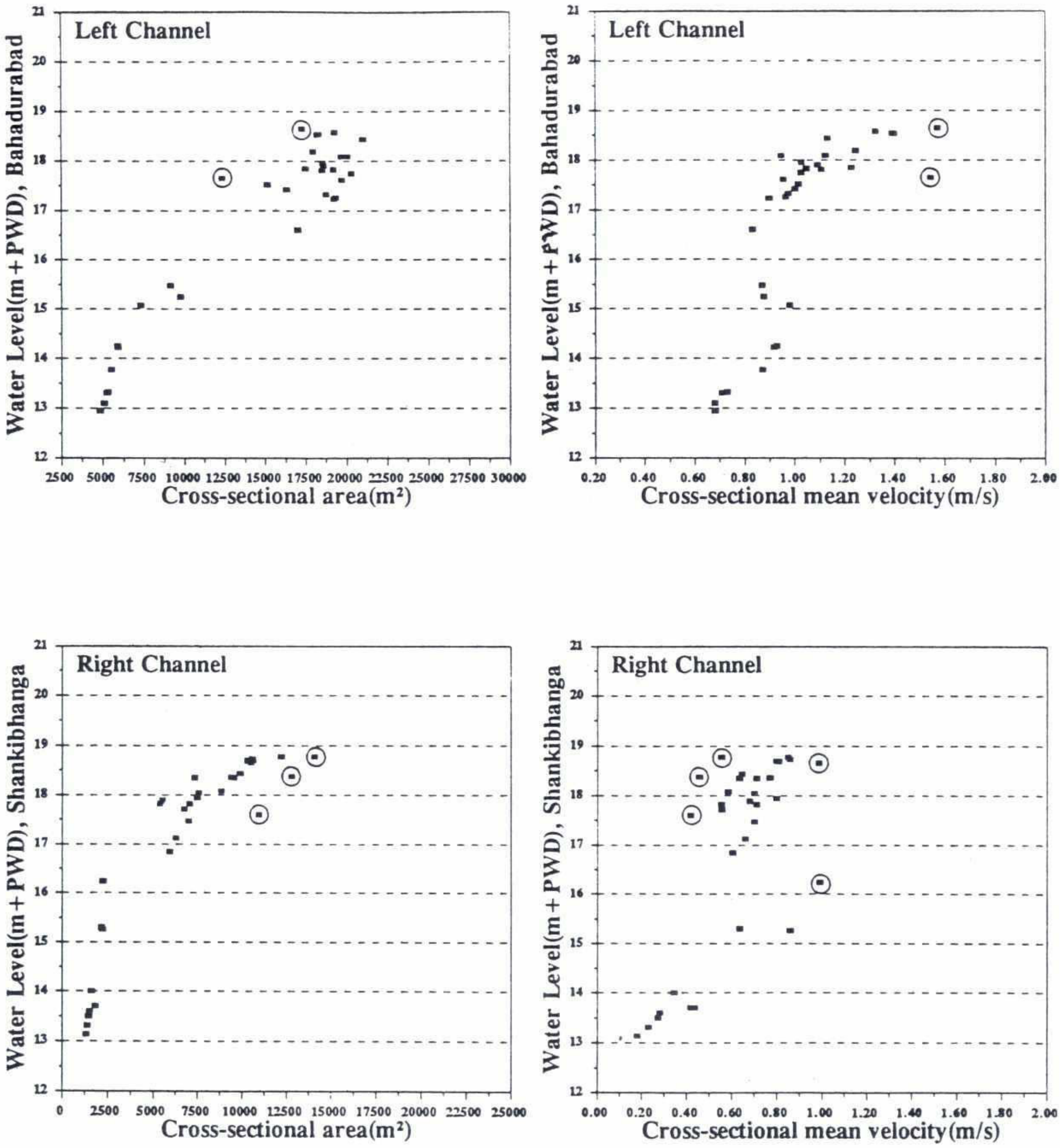


Figure 6.5: Plot of stage vs. cross-sectional area and cross-sectional averaged velocity: (a) left channel (b) right channel

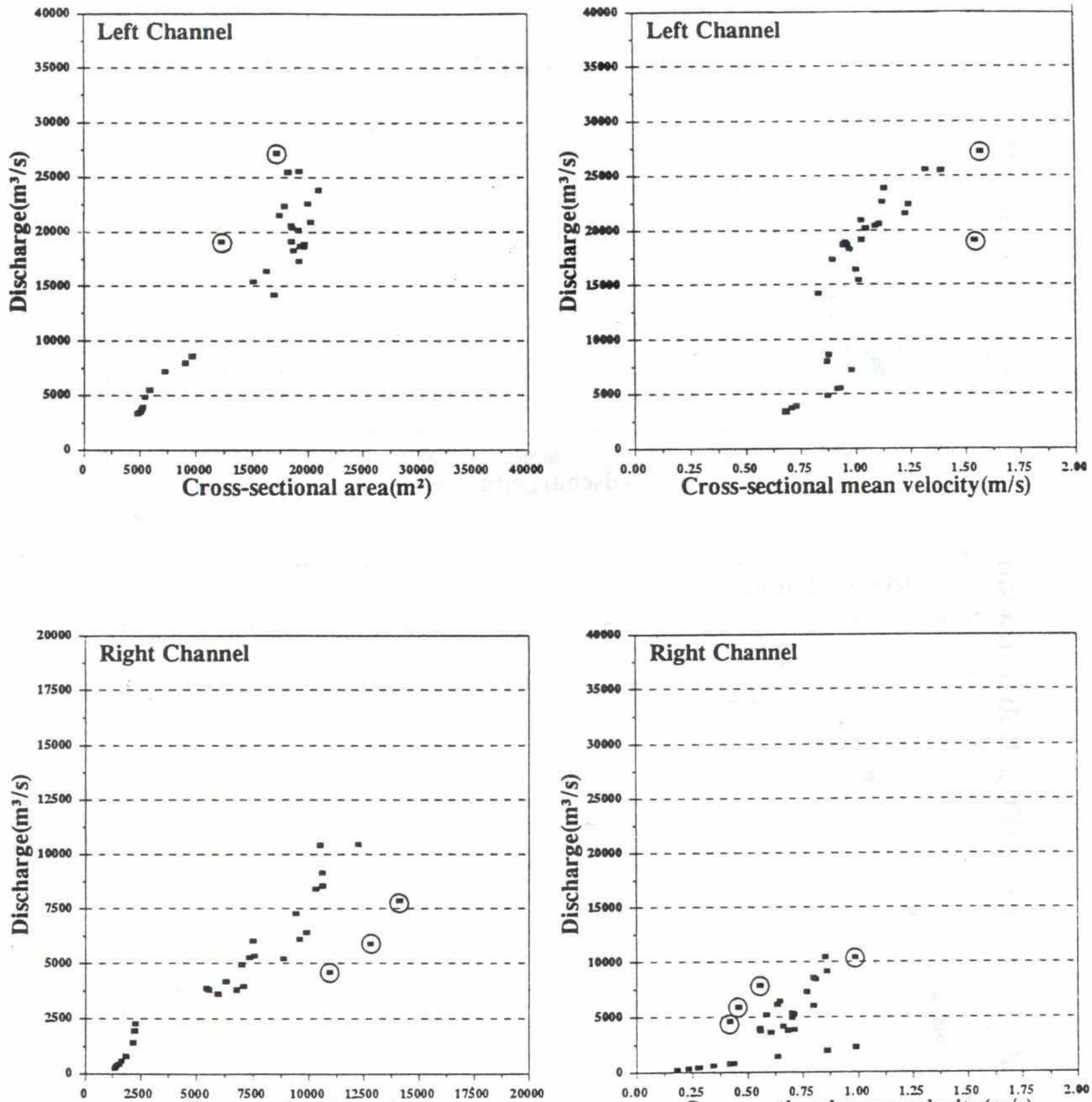
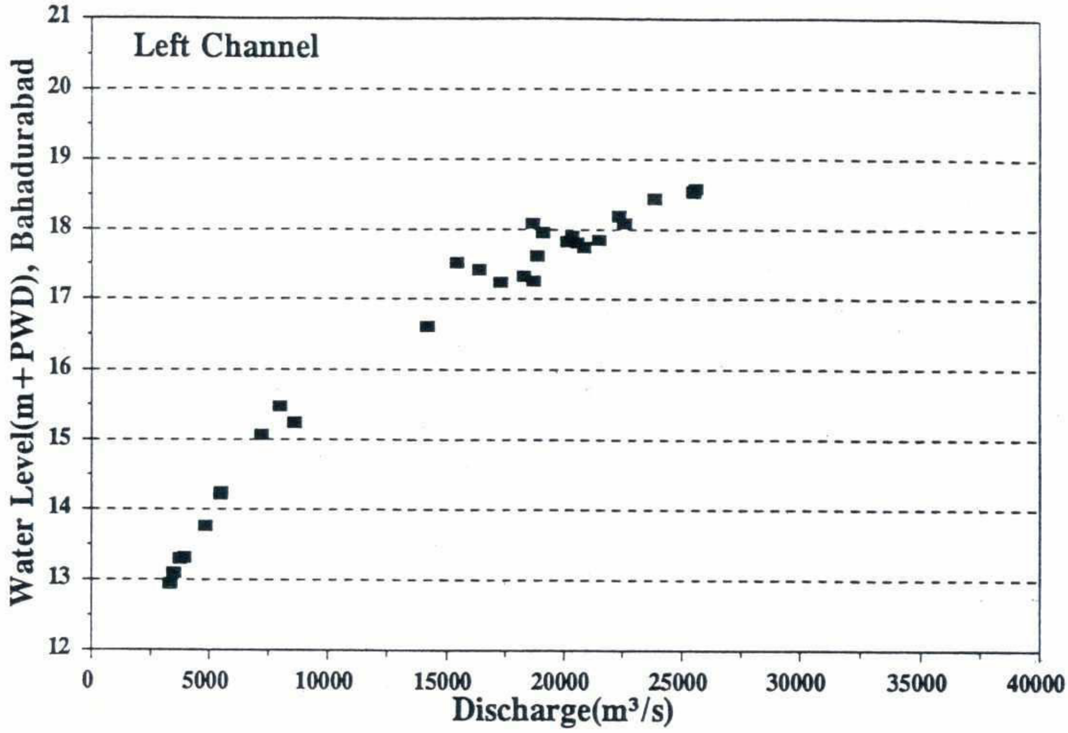


Figure 6.6: Plot of discharge vs. cross-sectional area and cross-sectional averaged velocity: (a) left channel (b) right channel



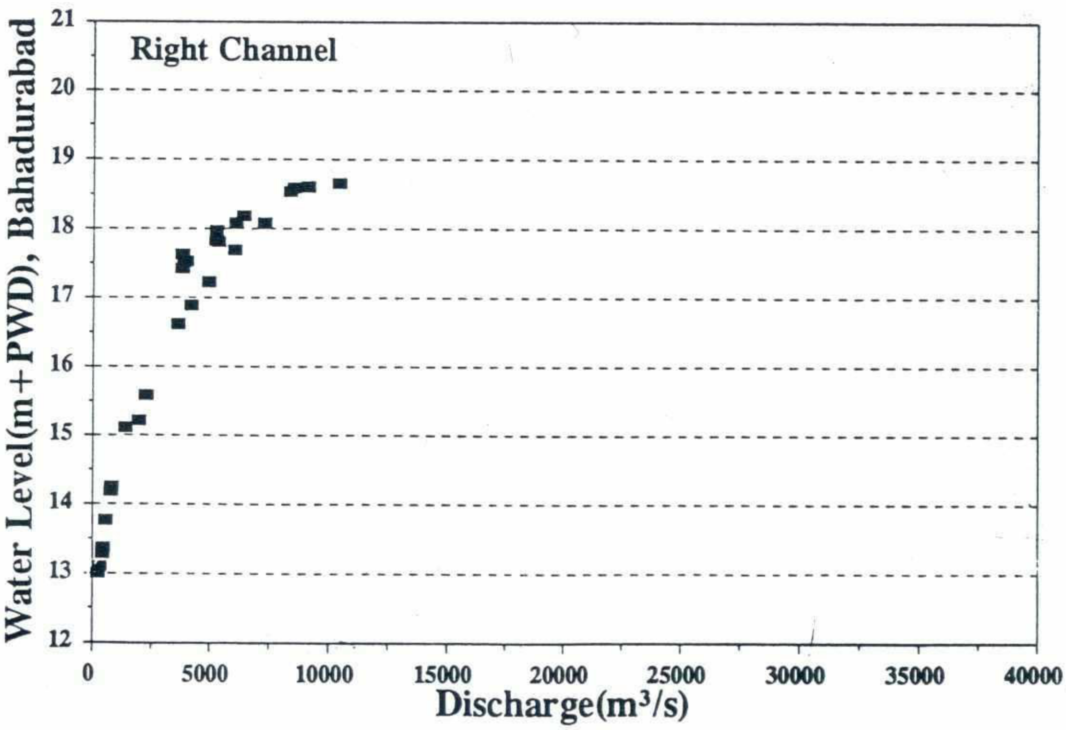


Figure 6.7: Plot of stage vs. discharge: (a) left channel (b) right channel

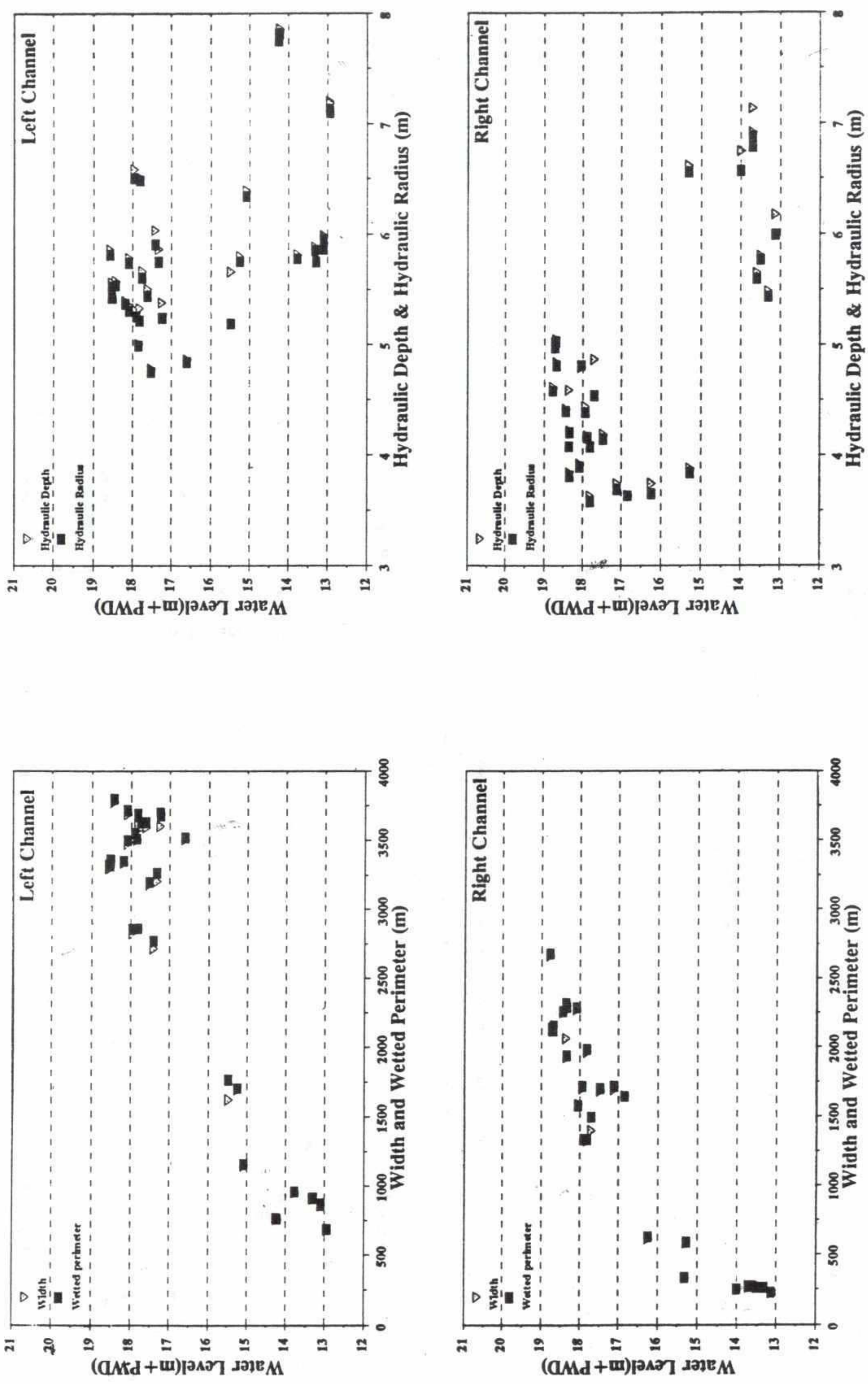


Figure 6.8: Stage vs. wetted perimeter, width hydraulic depth and hydraulic radius: (a) left channel (b) right channel

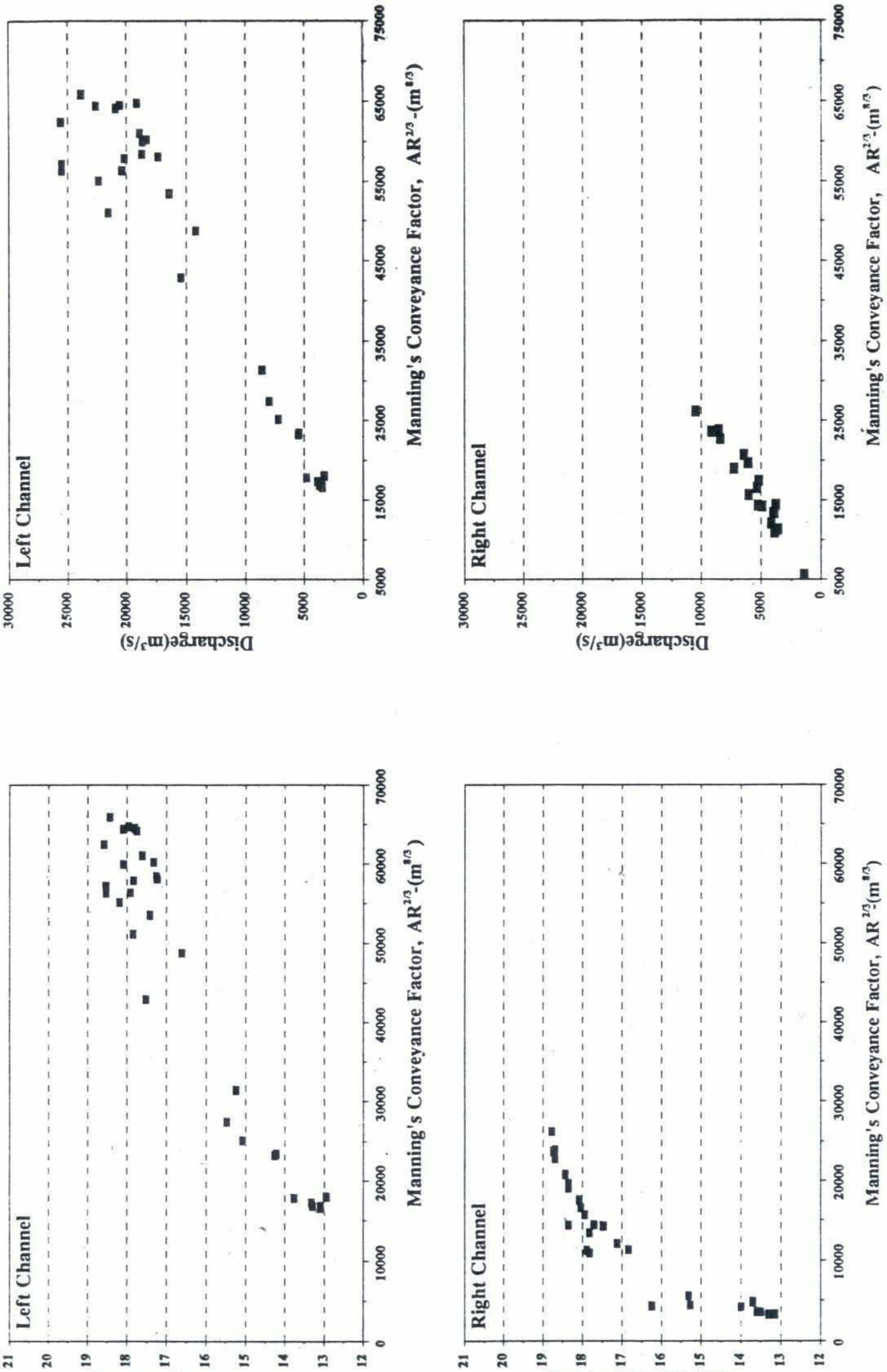


Figure 6.9: Stage and discharge vs. Manning conveyance factor: (a) left channel (b) right channel

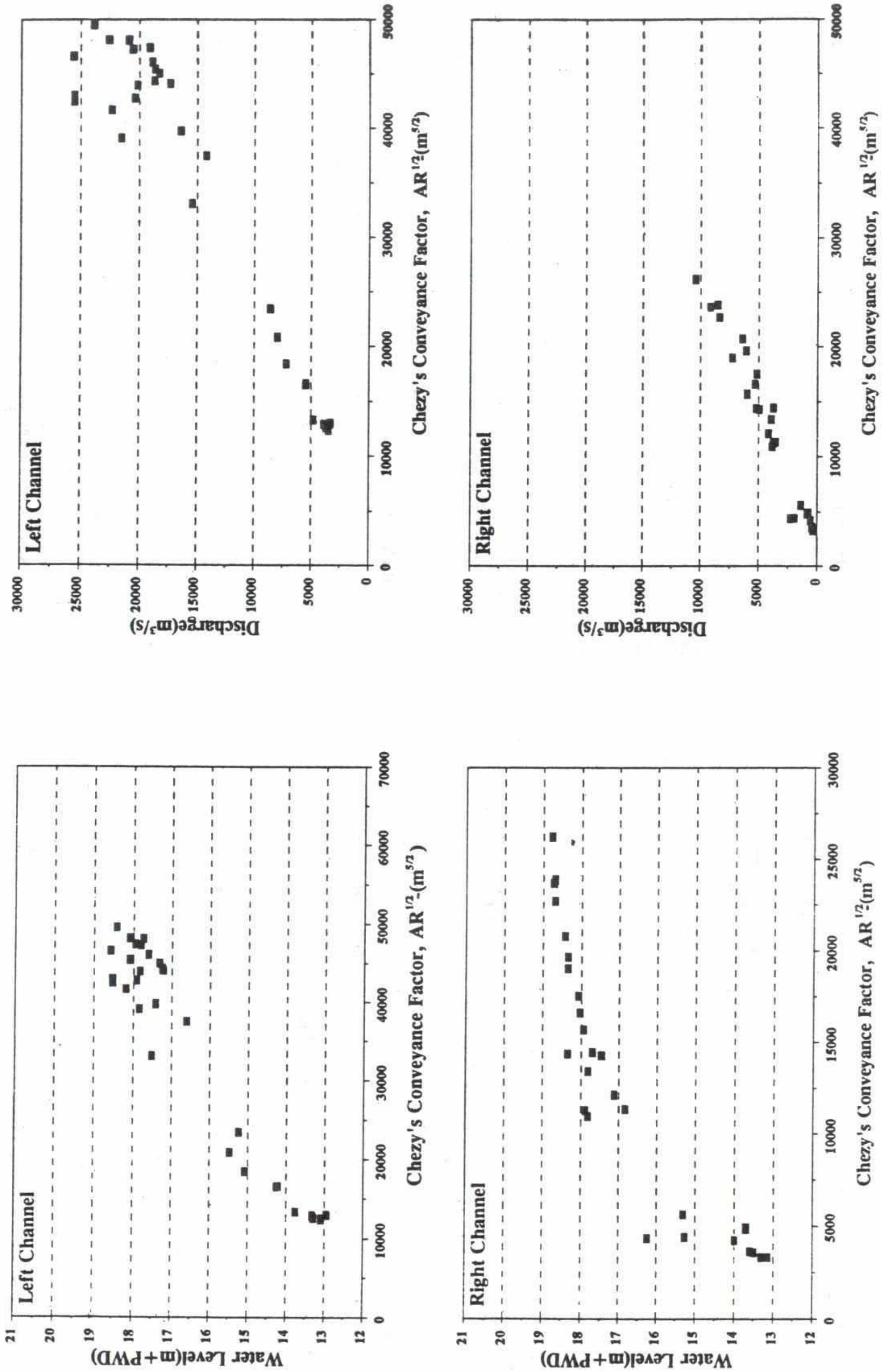


Figure 6.10: Stage and discharge vs. Chézy conveyance factor: (a) left channel (b) right channel

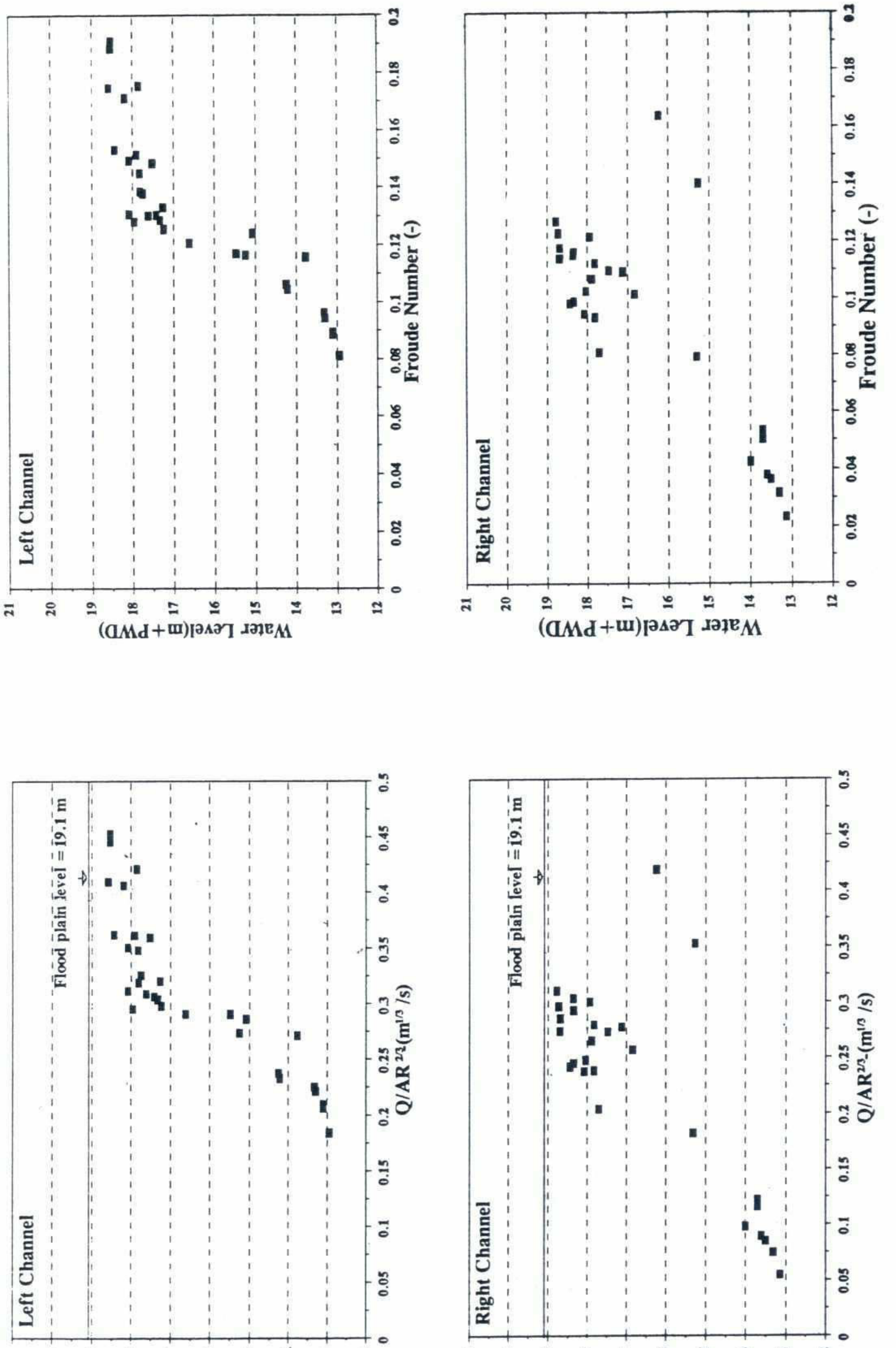


Figure 6.11: Stage vs. Manning slope-roughness factor and Froude number (a) left channel (b) right channel

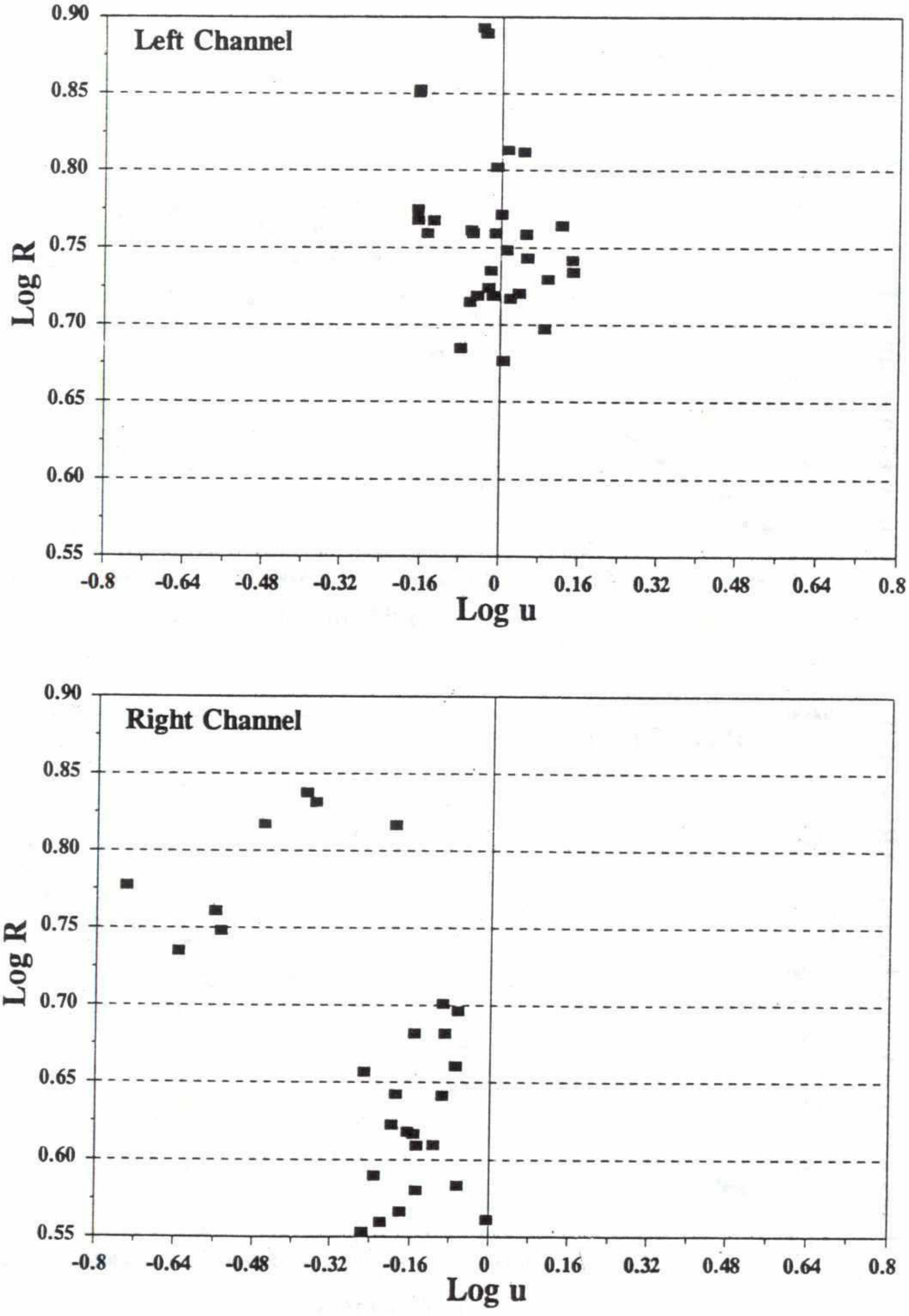
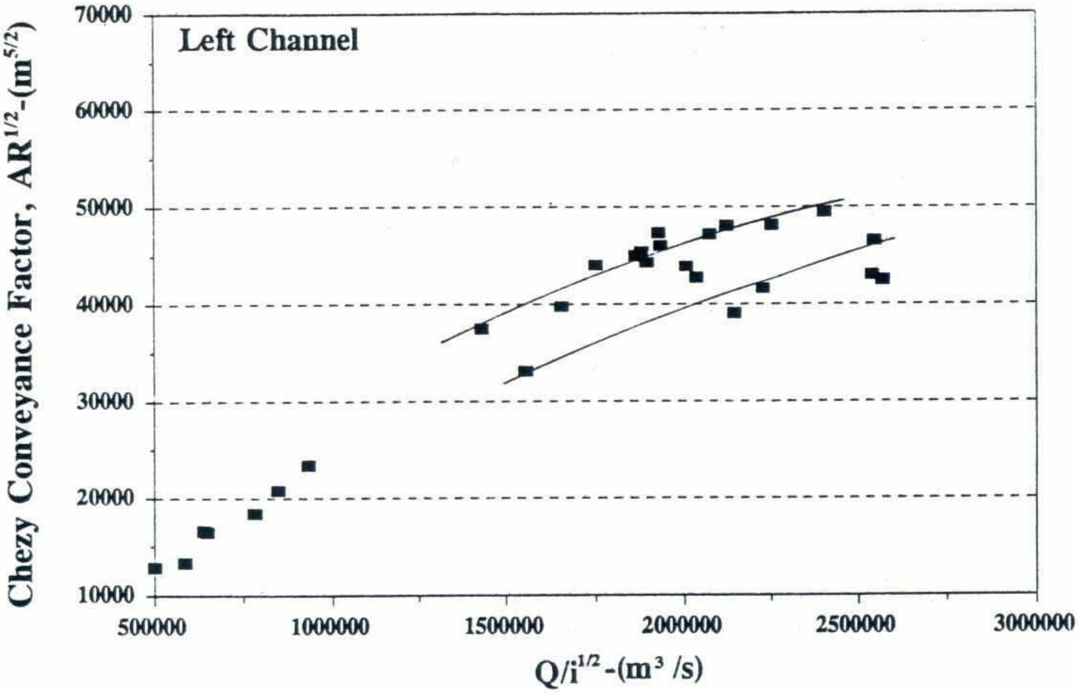


Figure 6.12: Log of hydraulic radius vs. log of cross-section averaged flow velocity : (a) left channel (b) right channel



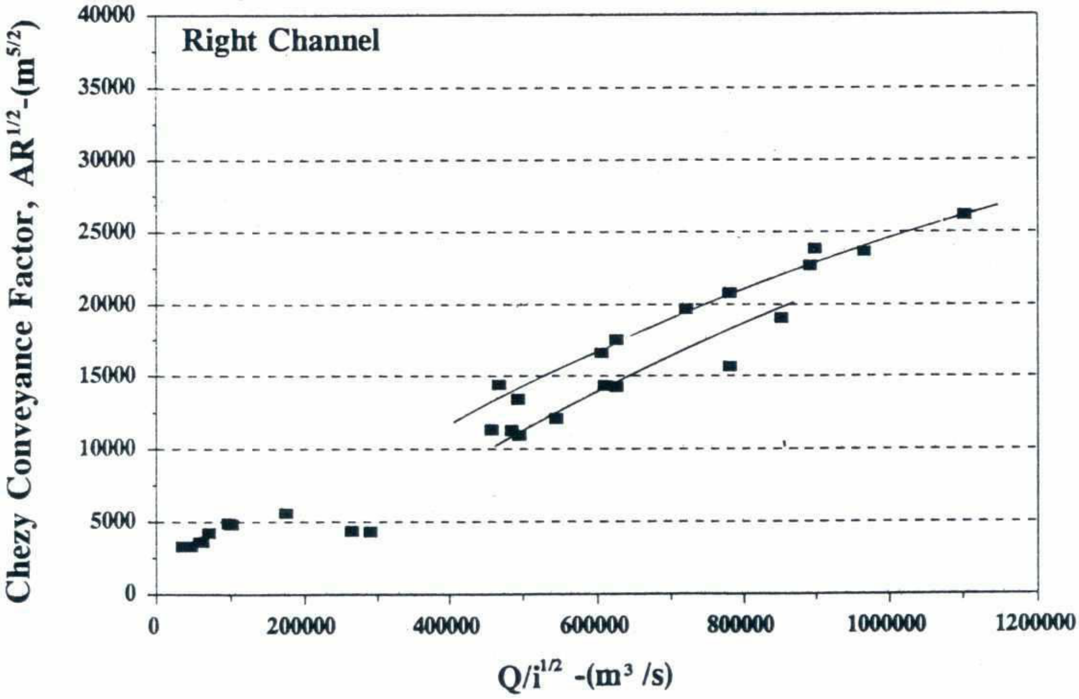
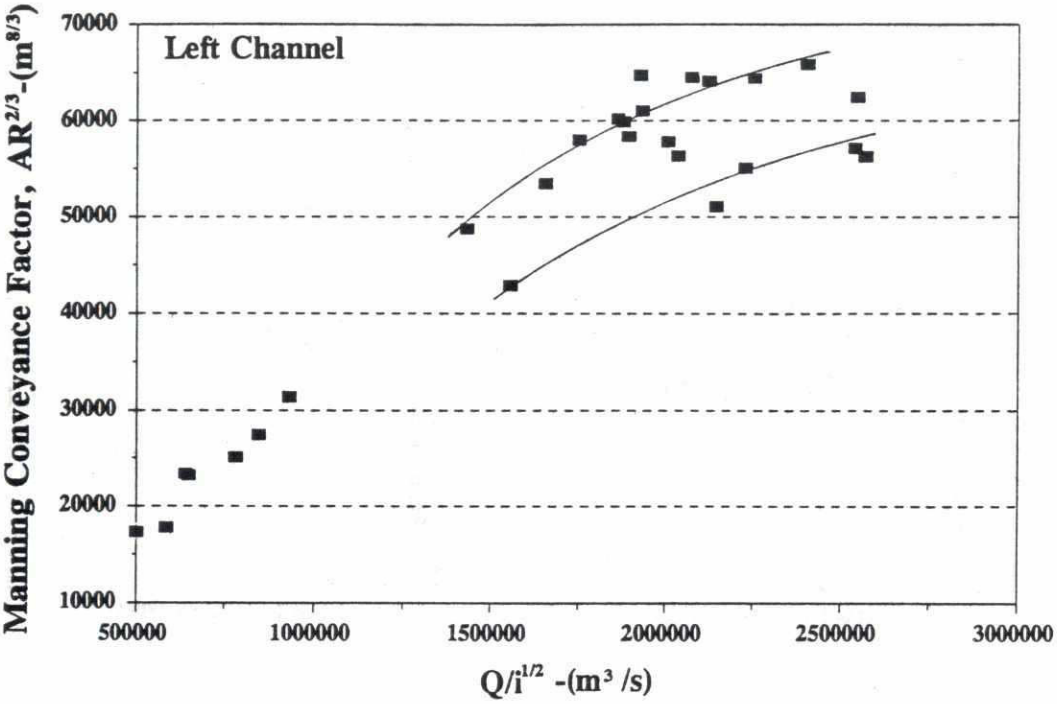


Figure 6.13: Plot of Chèzy conveyance factor against discharge divided by square root of water surface slope: (a) left channel (b) right channel



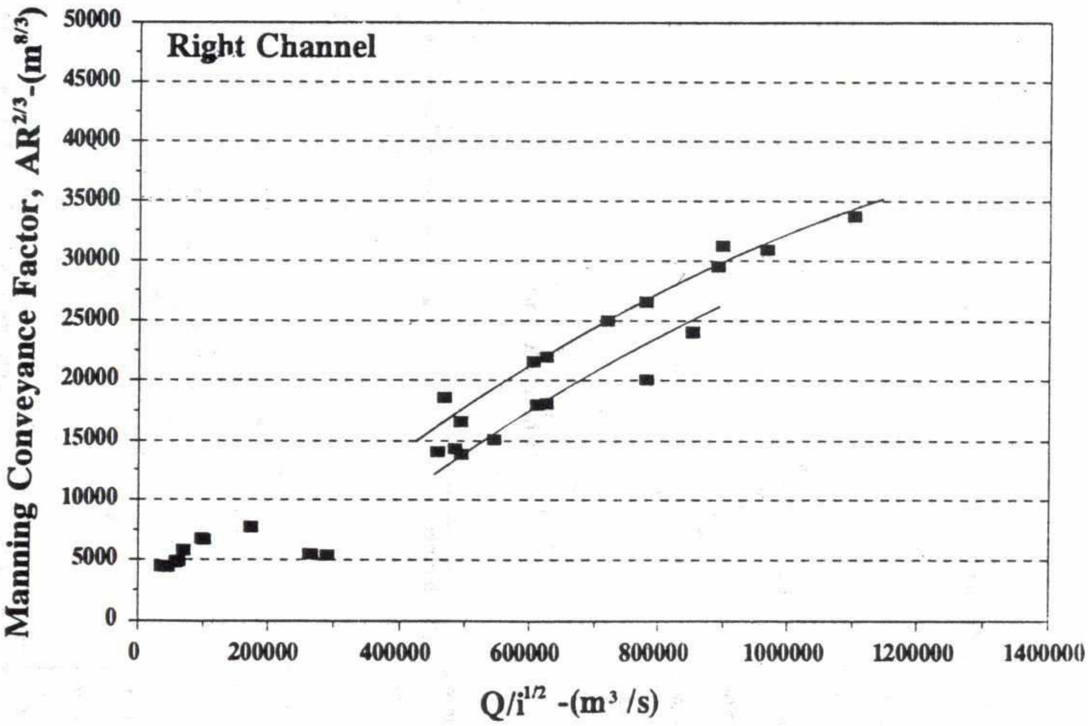


Figure 6.14: Plot of Manning conveyance factor against discharge divided by square root of water surface slope: (a) left channel (b) right channel

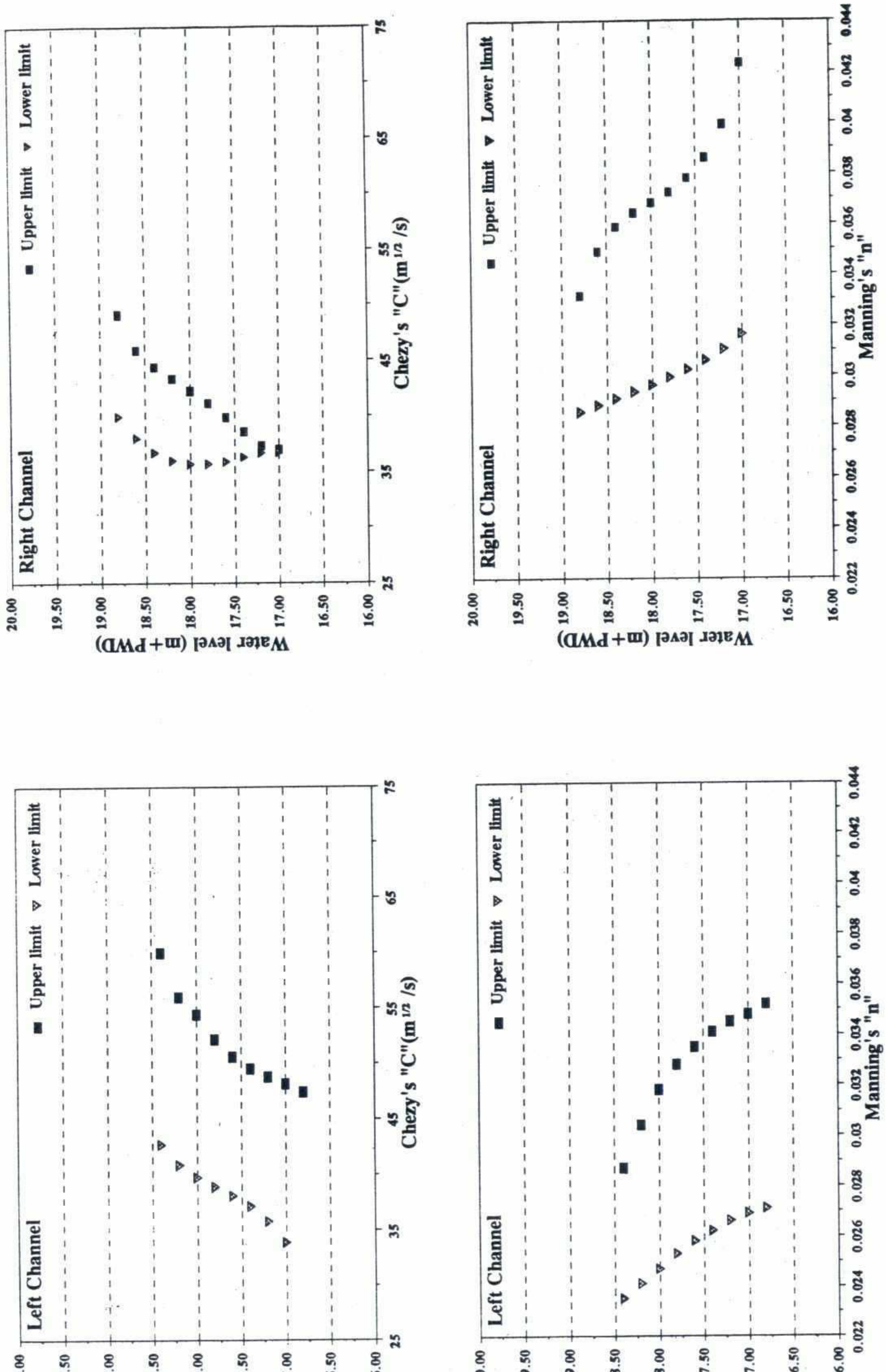
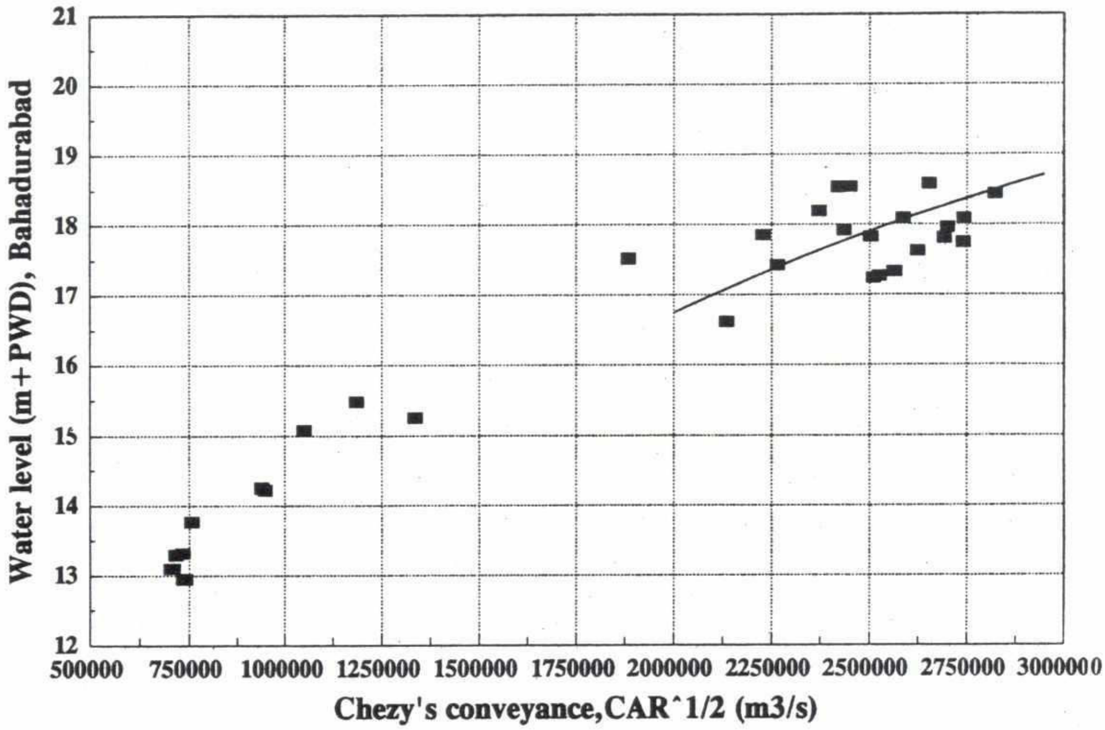


Figure 6.15: Variation in roughness coefficient with stage : (a) Chézy coefficient (b) Manning coefficient. [Plot shows the limits of the range]



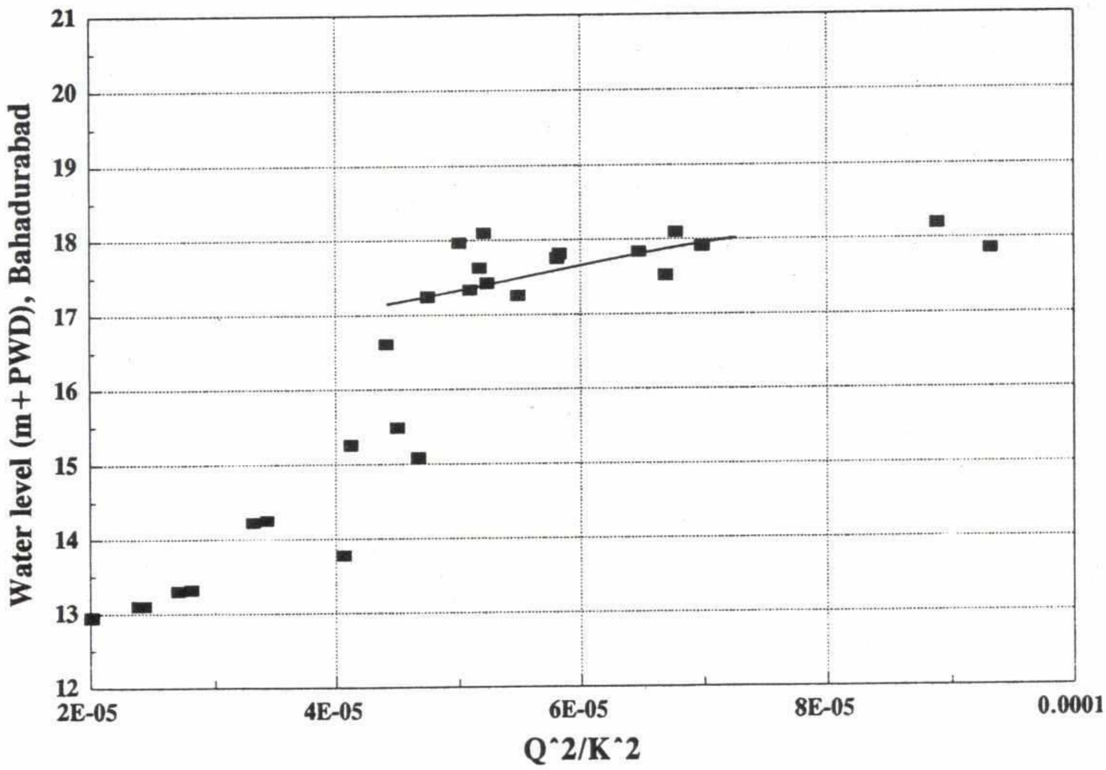


Figure 6.16: Plot of stage vs. Chézy conveyance ($CAR^{0.5}$) and stage vs. Q/K (discharge/conveyance), left channel