FAP24

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RIVER SURVEY PROJECT

Special Report No.24

Morphological processes in the Jamuna River

October 1996

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Acronyms and abbreviations

ADCP	:	acoustic Doppler current-profiler
AWLR	:	automatic water-level recorder
BIWTA	:	Bangladesh Inland Water Transport Authority
BTM	:	Bangladesh Transverse Mercator (a geodetic grid)
BWDB	:	Bangladesh Water Development Board
DGPS	:	Differential Global Positioning System
DHA, DHB etc.	:	(names of FAP24 survey vessels)
EGIS	:	Environmental and GIS Support Project for Water Sector Planning
EMF	:	electromagnetic flow meter
FAP	:	Flood Action Plan
GIS	:	geographic information system
PSD24	:	(= Processed Survey Data of FAP24) (name of a data base)
PWD	:	Public Works Department (and name of a reference level)
RSP	:	River Survey Project (= FAP24)
SLW	:	Standard Low Water (a reference level)
UoN	:	University of Notingham
ISPAN	:	Irrigation Support Project for Asia and Near East

Notation

A	secondary flow coefficient	(-)
B	width	(m)
C	Chézy coefficient	($m^{1/2}s^{-1}$)
c	Concentration	(mg/l)
D_{50}	Median particle diameter	(mm)
D_*	particle diameter parameter	(-)
E	bank erosion rate	(m/year)
En,E	time averaged erosion coefficient	(-)
e_b	coefficient represent efficiencies for bed load	(-)
e_s	coefficient represent efficiencies for suspended load	(-)
Fr	Froude number	(-)
F_o	densimetric Froude number	(-)
g	Acceleration due to gravity	(ms^{-2})
H	height of bedform	(m)
h	Depth of flow	(m)
h	Mean depth of flow	(m)
h_b	dark height	(m)
h_{bs}	bend scour depth	(m)
h_{cs}	confluence scour depth	(m)
h_e	water depth in the middle of the river	(m)
h_p	protrusion scour depth	(m)
h_y'	water depth at the transverse location	(m)
i	Mean slope of water surface	(-)
k_s	Bed roughness	(m)
L	Length of bedform	(m)
L	adjustment length of suspended sediment concentration	(m)
P_T	total stream power	(w/m)
Q	Discharge	(m^3s^{-1})
R	Radius of curvature of meander	(m)
R_c	radius of curvature in the middle of the river	(m)
S	Sediment transport	(m^3s^{-1})
s_e	equilibrium suspended sediment transport per unit width	(m^2s^{-1})
s_s	Suspended load per unit width	(m^2s^{-1})or(kg s^{-1})
s_t	Total sediment load per unit width	(m^2s^{-1})or(kg s^{-1})
T	Period	(s)
T	Temperature	(°C)
T	bed-shear stress parameter	(-)
u,u	Time mean flow velocity component in x-direction; depth mean flow velocity in x-direction	(ms^{-1})
u_*	bed shear velocity	(ms^{-1})
w_s	fall velocity	
z_b	Bed level	(m)
α	Angle	

β	erodibility coefficient	(-)
Δ	Relative density $((\rho_s-\rho)/\rho)$; increment	(-)
δ	Angle	(-)
ϵ	Porosity	(-)
θ	Angle; dimensionless time (K_2t); weighting factor	(-)
κ	Von Karman's constant	(-)
ρ	Density of water	(kg m^{-3})
τ	Shear stress	(kg $m^{-1}s^{-2}$)
τ_b	Bottom shear stress	(kg $m^{-1}s^{-2}$)
τ_c	Critical shear stress	(kg $m^{-1}s^{-2}$)
ψ	Dimensionless shear stress $(\tau_b/(\rho_s-\rho)gD=u_*^2/\Delta gD)$;	(-)
λ	adaptation length of flow	(m)
λ	cutoff ratio	(-)
η	wash load factor	(-)

Abstract

This study deals with the morphological processes in the Jamuna River, the lower reach of the Brahmaputra River in Bangladesh. Over the flood season major changes take place in the planform and bed topography of this large, braided sand-bed river, and the cause and effects of these changes were studied in an attempt to better understand the behaviour of this type of rivers.

The basic data available for this study are seven bathymetric surveys of the left part of the river near Bahadurabad. The area had a total length of 20 km and the data were collected during the period June 1993 through November 1995. In the area many additional data were collected in the same period: on a routine basis water levels at four to six locations, discharges, sediment transport rates and bed samples, while also at some selected places detailed bathymetric soundings and main flow and secondary flow measurements were done in 1994 as part of other studies. Also some bathymetric soundings from other reaches were used, though to a lesser extent as the data collection there was less complete. In the analysis of the data GIS was used, which proved to be a powerful tool for interpretation of (spatial) morphological data. Moreover, a method to interpret ADCP backscatter intensity data for quantitative analysis was developed and applied. This enabled insight into sediment transport patterns, which are quite peculiar in these large untrained sand-bed rivers, due to the constant re-working of the bed.

During the period that was covered in these sounding maps, a major cutoff took place, which caused very substantial changes in flow pattern, bed topography and bank erosion locations and rate. In the report the results are analyzed to determine the interaction between bars, channels and flow and the constant re-working of the bed. This resulted in an improved understanding of cause and effects of the rapid changes taking place in this braided river system with fine sand as bed material. The results clearly demonstrate that small changes in flow and sediment distribution yield major changes in even the same flood season. It also shows that medium-term predictions can only be done with a limited accuracy, underlining the logic behind the probabilistic prediction technique proposed by Klaassen et al (1993).

Other analyses included (1) a detailed study of types, causes and dimensions of scour holes, (2) location and rate of bank erosion, including the testing of some predictors, and (3) the preparation of balances to study the exchange of sediments in these rivers. Based on the detailed analysis of the collected field data a prediction method for short-term development of the bed topography changes was developed and successfully tested.

All in all, the study showed that repeated soundings during the flood season, in combination with GIS for presentation and further study and interpretation, are a very promising method to increase the knowledge about these large, braided sand-bed rivers.

1 General

1.1 Framework of study

The Jamuna river, which is the lower reach of the Brahmaputra River in Bangladesh, down to the confluence with the Ganges river, is one of the largest braided rivers in the world with an overall width of some 10 to 15 km. The average flood discharge is about 65,000 m^3/s with discharge variation of about 15 times throughout the years. On a large scale, the morphology of a braided river is characterized by channels and bars. These are formed as a result of the interaction between the flow, riverbed and bank material. In response to the variation of discharge, continuous changes are taking place in the form of these channels and bars, as a result of ongoing bed and bank erosion. Insight into these interactions and the process of continuous changes, is essential for the development of a prediction method. Detailed investigations are needed to study the processes that cause these changes.

The first comprehensive study of the Brahmaputra River in Bangladesh was made by Coleman (1969). Since his benchmark study, various studies on different aspects of the morphological behaviour of the Jamuna river were published, in particular over the past decade: Bristow (1987), Klaassen and Vermeer (1988a, 1988b), Klaassen et al (1988), Klaassen and Masselink (1992), Klaassen et al (1993), Thorne et al (1993), and Mosselman et al (1994), etc. This list of recent publications is an indication of the increased interest in the behaviour of the Jamuna river, which stems from different projects: the design and construction of a bridge over the river and a number of flood protection and river training studies under the Flood Action Plan (FAP).

To improve the understanding of the behaviour of Bangladesh's main rivers, the River Survey Project (RSP) embarked on various special studies. This report is prepared as a "special" report of the River Survey Project. At the same time it served as an M.Sc. thesis of Mr. M. H. Sarker at IHE, the Netherlands. A major part of the data used in this study was collected and processed by RSP and EGIS respectively. Hence, the present study was carried out within the framework of the River Survey Project (RSP) and under the guidance of IHE, the Netherlands. The M. Sc. examination committee was formed with Prof. B. Petry as chairman, Ir. G. J. Klaassen as supervisor and Ir. M. vander Wal as member.

The study was carried out with cooperation of various team members of RSP, especially Msrs. Z. H. Khan, M. Z. Haque, M. S. Shikder, Azizul Haque, K.K. Jensen, Mrs. Parveen Akhter Annie, A.K.M. Monir Hossain, Badar Uddin and Enamul Haque. Special assistance was provided by EGIS team members, especially Mr. Ahmedul Hassan in processing the bathymetry, flow and sediment data with the help of GIS.

1.2 River Survey Project (RSP)

The Flood Action Plan (FAP) was initiated after the disastrous floods in Bangladesh in 1987 and 1988, and it was a coordinated action to study the flood problems of Bangladesh. The various studies were carried out under the Flood Action Plan since 1989. These studies were divided into two categories, i.e. regional and supporting studies. There were eleven supporting studies under FAP and the River Survey Project was one of those supporting components. The main objectives of the River Survey Project were to collect reliable all season data on the hydrology and morphology of the main rivers of Bangladesh, as well as to improve the knowledge about the processes in the main rivers of Bangladesh.

The River Survey Project began in June 1992 and until early 1996 the main rivers were surveyed regularly. The following surveys were carried out: (1) routine gaugings, (2) bathymetric soundings, and (3) surveys for special studies. The all-season routine gauging was carried out at eleven locations in the main rivers, one of the locations being Bahadurabad on the Jamuna River. Five areas were selected for bathymetric surveys. In addition, there were selected places where automatic water level gauges (AWLR) and staff gauges were installed for reliable water level data and for local slope information.

In the first phase of the Project the available data on the main river system were collected and subsequently assessed critically. From this assessment potential study topics were identified, and a number of these were taken up during phase 2 of the project, often leading to special surveys. The present study was one of these study topics. It is related to the data acquired by the routine gauging, special surveys, and bathymetric survey. More specifically, it dealt with the detailed analysis of bathymetric surveys performed by the project at the Bahadurabad location to identify and study the morphological processes in the Jamuna river. Also studies were carried out by the University of Nottingham and the University of Leeds within the framework of the RSP and these studies were mainly based on special surveys at the same location. Hereafter these studies will be referred to as "parallel studies".

1.3 EGIS Project

One of the important aspects of the present study is the use of GIS technology to better understand the morphological behaviour of the Jamuna River. Recent developments of computer performance in geographic information systems (GIS) provide a powerful tool for the capturing and manipulating of maps and other geo-referenced data (like bathymetric maps). A GIS is a computer-based form of technology for recording, manipulating, analyzing and displaying of data, such as digital maps or other information with a spatial reference. GIS and their associated mapbases and databases, can serve general or special purposes with large and diverse databases. One of the main features of GIS is that it can link separate data based with common spatial reference; for example, maps of land elevation and flood water level can be combined in a GIS to produce useful flood area/depth maps.

Currently, the Environment and GIS Support (EGIS) project is the combination of two previous FAP supporting projects: the Environment Impact Assessment Study (FAP16) and the Geographic Information Systems (FAP19). To continue the previous and further develop the GIS capability in Bangladesh, a new project was initiated by EGIS . This project is funded by the Dutch Government. The objective of this project is to assist the Ministry of Water Resources (MoWR) and the Water Resources Planning Organisation (WARPO) to preserve the environmental and GIS capabilities of earlier FAP projects. Including the further development of GIS in all water-related sectors, EGIS is aimed at establishing a computer database, and a mapping and information system for characterizing the morphology of the major rivers in Bangladesh. Accordingly, and at the request of the River Survey Project, EGIS has processed all the bathymetric surveys of the RSP by GIS. For a particular case, the velocity and backscatter data from the ADCP survey were also processed to demonstrate the capabilities of using GIS for the analysis of information collected with advanced survey techniques. The EGIS processed bathymatric surveys in the Jamuna River at the Bahadurabad location and the velocity and backscatter are used in the present study.

1.4 Objective and scope of the Study

The Jamuna River is a very dynamic braided river. The knowledge of its dynamics is still fairly limited. The changes in flow direction and channel topography and planform, the occurrence of new channels and abandonment of old ones, changes of the other morphological features like the changes of the bank erosion rates, scour holes with the changes of the discharge, all of them are quite pronounced. The inherent processes, which result in the observed behaviour of the river, are the continuous redistribution processes of sediment within the channel as a consequence of the constantly changing discharge conditions and other changes in boundary conditions.

Most of the previous studies were based on morphological data: satellite images, cross-sections etc. acquired during low-flow periods, because the data from flood periods is sparse. During low flow the sedimentary processes in a river slow down. However, most of the changes of the river morphology occur during flood due to the close interaction between flow and sedimentary processes. In the period 1992-1996 the River Survey Project has collected all season bathymetry, flow and sedimentary data. Bathymetric surveys done by the River Survey Project document the dynamics of the Jamuna River. The difference of two consecutive bathymetric surveys shows the erosion and deposition changes of width, depth and the changes of the curvature of bends, bank erosion and the changes and movement of the scour holes. The routine gauging surveys and the related study surveys provide the hydrological and morphological information, and facilitate the linking of this information to the dynamics of the river, i.e the continuous redistribution processes of the sediment in the river system.

The main objective of the present study is to improve the understanding of the river processes with the aid of high-tech collection of data and other parallel studies of the River Survey Project. The key features, to which this study limits itself, are as follows:

- to better understand the channel development and abandonment processes in the Jamuna River;
- to understand the processes of riverbed erosion and deposition i.e. sediment redistribution processes as a function of discharge and sediment load;
- to improve the knowledge of bank erosion processes and locations of bank erosion, as a function of sediment redistribution processes, depth, velocity and bend geometry;
- to identify the types and causes of scour holes and changes in dimensions and movement with changes of discharge and time, and their possible role in changing the planform of the river;
- to derive predictors for riverbed erosion and deposition, channel development or abandonment, bank erosion and scour holes.

1.5 Approach

This study is mainly based on the analysis of bathymetric surveys performed by RSP in the Jamuna River at Bahadurabad location. Flow and sedimentary data collected by RSP also used for analysis. Analysis of these data is performed to get a better insight into the morphological processes of the Jamuna River. Geographic Information System (GIS) is a powerful tool in analyzing spatial data. For processing, analyzing and presenting the spatial data GIS has been used in a number of occasions.

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The observation on the behaviour of the Jamuna River is made by the present analysis and compared with the previous theories. The previous prediction methods for predicting the various morphological features are assessed. In addition, on attempt is made to derive new methods for predicting the behaviour of the river.

This study was mainly performed in Bangladesh, more precisely, at the River Survey Project (RSP), Dhaka. Except for the first and last part of the study i.e. the preparation of the proposal of the study and finalizing the thesis which was written at IHE, the Netherlands, the rest of the work was done in Bangladesh. This part of the work in Bangladesh consists of data collection and processing, data analysis, integration of the results and drafting the thesis.

The major parts of the data used in this study, were from the surveys of the RSP. Other than the RSP-surveyed data, which were used in this study, such as Bangladesh Water Development Board (BWDB) discharge and sediment transport data and SPOT images, were also collected by the RSP. For this study the data collection was limited within the framework of the RSP. Generally, the survey data were processed in a standard format at the RSP. The collected data need further processing to meet the requirement of the study. In addition, the EGIS project processed bathymetric surveys, flow and backscatter data as requested to meet the requirement of this and the other studies of the RSP.

There was no sharp demarcation between the period of data collection and processing and the data analysis. Because the RSP surveys were performed inbetween, the period of the study was also used for analysis. Moreover, the collection of EGIS-processed data was delayed due to a late start of the processing of the RSP bathymetric surveys by the EGIS project. Therefore, the data collection, processing and analysis work occurred simultaneously during the study.

Integrating the results and deriving the predictors were performed after the analysis of the data for each of the sub-topics. The drafting of the thesis was done in the later phase of the work in Bangladesh.

1.6 Structure of Report

The framework, objectives and approach of the study are presented above. In Chapter 2, the description of the study area, along with the characteristics of the Jamuna River, are presented on the basis of the present knowledge about the river. Historic developments of the river are presented in the same chapter on the basis of the available literature and use of historic maps. Changes in the planform in the recent past (1989-1993) and the conditions during the study period are discussed in this chapter on the basis of the changes observed in satellite images.

In Chapter 3, a review of the literature on the formation, evaluation and characteristics of braided rivers is presented in addition to previous studies on similar types of large sand-bed rivers, such as the Zaire and Yellow rivers. A review of the literature and studies on the different morphological processes of the Jamuna River are also presented in this chapter. Furthermore, a review is presented on the UoN/RSP Joint study, the study area of which was same as the RSP study area.

In Chapter 4, Survey techniques of RSP, the measurements carried out in the Jamuna River at the Bahadurabad location and accuracy of the data are presented. In Chapter 5, the processing and analyzing of different types of data which are used in the study are presented. In addition, the use of Geographic Information System (GIS) for presentation and for analysis are presented.

Changes in planform during the study period, observed in the RSP bathymetric surveys at the Bahadurabad location, are presented in Chapter 6. In Chapter 7, erosion and deposition processes in the Jamuna River are presented on the basis of analysis of the bathymetric surveys, flow and sedimentary data measured by RSP. In Chapter 8, development of cutoff are presented by analyzing satellite images, RSP bathymetric surveys and flow and sedimentary data of the RSP. In Chapter 9, bank erosion processes in the river are presented by using Satellite images, RSP bathymtric surveys at Bahadurabad, FAP21/22 bathymetric surveys at Kamarjani and RSP measured flow data. In Chapter 10, the observed scour holes in the RSP bathymetric surveys at Bahadurabad location are analyzed and the result obtained from the analysis are also presented.

In Chapter 11, the predictability as well as methods for predicting the change of planform of the Jamuna River are presented. In Chapter 12, discussions about the RSP-surveyed data, current analysis and understanding developed through this study are presented. Finally, the conclusion and recommendations are given in Chapter 13.

2 Study Area

2.1 Introduction

Although the River Survey Project addressed the morphological processes of the Jamuna River, the area of this study was confined to the Bahadurabad location, see Figure 2.1. The reason behind this is explained in the following. The BWDB has been collecting discharge, water level, and sediment transport data on a regular basis since 1966. Bahadurabad is the only gauging station in the Jamuna River at which these data were regularly collected by the BWDB. Bahadurabad was also one of the main discharge, water-level and sediment gauging stations of the RSP where routine gauging had to be done. Bathymetric surveys were made at this location more frequently, than that at the other main gauging stations in the Jamuna river. Moreover, intensive study-related surveys were carried out at this location. Therefore, to use the opportunity of the availability of both abundant historical and RSP survey data, the Bahadurabad location was selected to study the morphological processes of the Jamuna River.

Bahadurabad is at the left bank of the Jamuna river, about 130 km upstream of the confluence with the Ganges River. Since the seventies two anabranches, known as Left Channel and Right Channel, flow at that location. The Left Channel is dominating as it carries 65-80% of the total discharge, slightly varying over the years and with the season. The RSP batymetric surveys were carried out at the Left Channel only, covering a 20 km stretch of the river. More precisely, the present study area is at the Left Channel and corresponds to the area covered by the bathymetric surveys of RSP.

Morphological processes in a natural untrained and braided river, like the Jamuna River, are very complex. Natural rivers are seldom stable and the processes of channel evaluation rarely occur at a steady rate. The morphological processes of the river by analysing short-term field measurements must be interpreted within the context of the overall characteristics of the river, its historic and recent development. These are described briefly in the following sections.

2.2 Characteristics of the Jamuna River

The Jamuna River is the lower part of the Brahmaputra River in Bangladesh. The Brahmaputra River originates in Tibet on the North slope of the Himalayas and drains an area of about 550,000 km^2, extending over China, Bhutan, India and Bangladesh, see Figure 2.2. Its length is about 2,740 km before meeting with the Ganges River at Aricha, of this 2740 km only 240 km is in Bangladesh. The reach downstream of the offtake of the Old Brahmaputra River is named the Jamuna River.

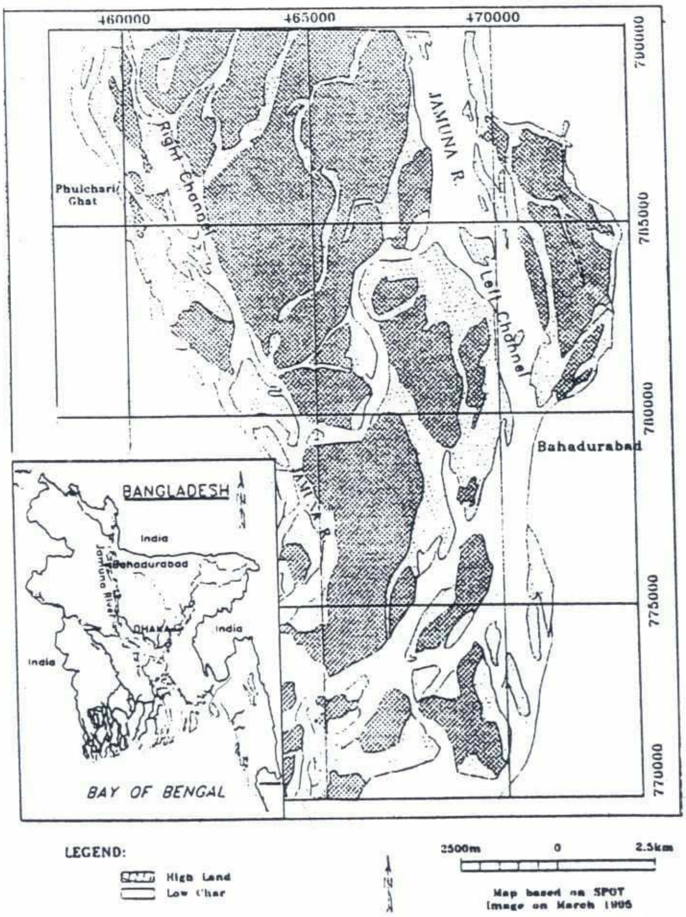

Figure 2.1 The location of the study area

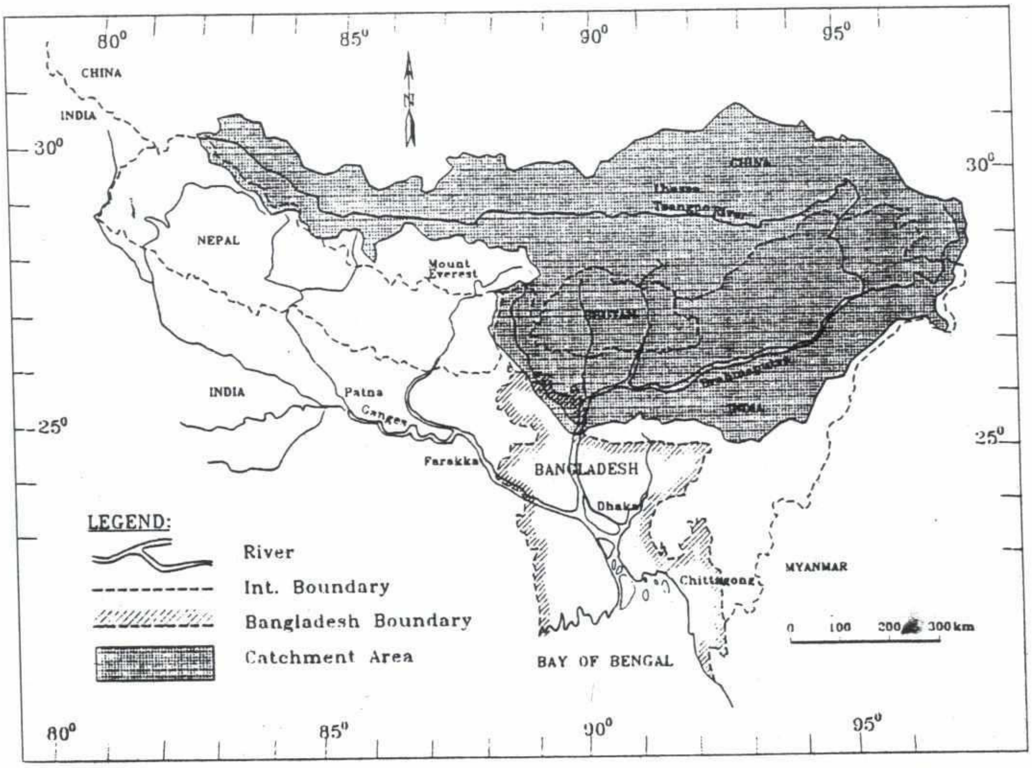

Figure 2.2 The catchment area of the Jamuna River

The Jamuna River is characterized by its highly variable discharges; its yearly variation ranges from 4,000 m^3/s to 68,000 m^3/s (Khan, 1995), whereas the yearly average discharge is about 20,000 m^3/s. The peak discharges occur during the period of July-August and the lowest flows in February-March of the year. The bankfull discharge of the river is about 48,000 m^3/s (RSP, Special Report 6, 1995). The slope of the river within Bangladesh decreases in downstream direction and is $8.5*10^{-5}$ where the river enters the country and $6.5*10^{-5}$ near the confluence with the Ganges River. The bed material sizes also decrease from the upstream towards the downstream and range from 0.22 mm to 0.16 mm.

The yearly sediment transport through the Jamuna river was estimated by various authors (Coleman, 1969; Holeman, 1968; Hossain, 1992) and in various studies in Bangladesh. The estimation of yearly average sediment transport varies from 400 to 800 Mt. The RSP finding was 590 Mt/year, almost in between the extremes. From this the estimated sand fraction is about 200 Mt/year (RSP, 1995a).

The Jamuna River is a braided river with a braiding index that varies spatially as well as with time. The range of variation is 2 to 5 (Klaassen and Vermeer, 1988). The overall width of the river also varies spatially and temporally, from 6 to 14 km. Generally, the braiding index and the overall width are larger at the upstream part than farther downstream, probably due to the effects of higher slope and grain sizes (Klaassen and Vermeer, 1988). The overall width of the river exhibits an increasing trend, and there is a tendency of shifting westwards, especially at the upstream part of the river within Bangladesh (Halcrow, 1993). The widening can be attributed to an advancing alluvial fan or to the not-yet completed adaptation process after the shift to its new course (Study Report 3, RSP, 1994).

There are different types of channel exits within the overall width of the river. The river often displays two major anabranches flowing down the right and left banks of the braided belt (Coleman, 1969; Thorne et al., 1993). The present study area is also located at one of the anabranches. In addition, Britow (1987) proposed a classification of river channels into different orders. The entire channel is the first-order channel comprising a number of second-order channels, which in turn have smaller channels classified as third-order channels, see Figure 2.3. The second-order channels have slightly different characteristics, like slightly different slopes, different water and sediment-carrying capacities and, as a result, they behave differently.

The shifting characteristics of the river can be divided according to the order of the channel i.e. the shifting of the first-order channel differs from the second-order channel. The shifting rate of the first-order channel of the Jamuna River is on the average 75 to 150 m per year over the past decades. The second-order channels change continuously, large channels are abandoned, and new ones are developing in a few years only. A bank-erosion rate of the second-order channels of 250 to 300 m per year is common and, in extreme cases, it can be more than 800 m/year (Klaassen and Masselink, 1992).

The bed configuration of the Jamuna River changes drastically under different flow regimes (Coleman, 1969). Deposition of sediment in one location causes deepening and scour in another location. This process is associated with the continuous wandering of the thalweg from one position to another. The process of erosion and deposition is pronounced during the high flow stages and slows down during the falling stages of discharge.

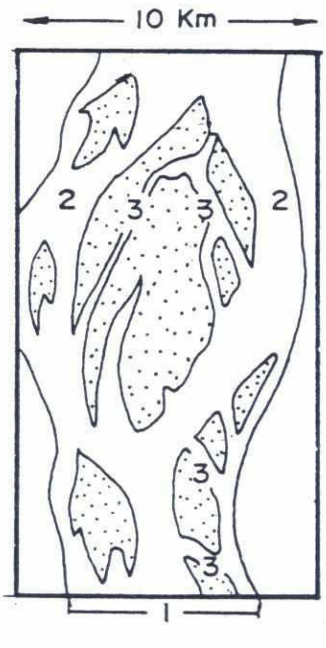

Figure 2.3 Channel classifications in the Jamuna River (Bristow, 1987)

2.3 Historic Development

About two hundred years ago the Brahmaputra river flowed through the present course of the Old Brahmaputra River. Although much of the Bengal basin is composed of recent sediment deposited by the Ganges, Brahmaputra, Meghna rivers and their large number of tributaries and distributaries, four Pleistocene alluvial terraces exist in the basin and the Madhupur tract is one of them. The Madhupur tract is in between the present and old course of the river. The likely cause of the avulsion around the Madhupur tract is a combination of tectonic movement and either a liquefaction flow (following a major seismic event) that partially blocked the old channel (Halcrow, 1993a), an increased flood discharge (Coleman, 1969), or a catastrophic flood in 1787 (La Touche, 1910). It is highly possible that the new course of the river occupied an older Teesta River channel and the Teesta River itself finally became a right bank tributary of the Brahmaputra River (Coleman, 1969).

To describe the historic development of the river, three maps are presented in Figure 2.4. The oldest one is known as the Rennels map, published in 1776, the second is the Wilcox map surveyed in 1821-1834 and published in 1840. The recent map is prepared by ISPAN, 1993, from satellite images (1991). To compare the bank line and migration of the river, old maps of 1914 and 1953 and maps derived from 1973 and 1992 satellite images were used as well, see Figure 2.5. The projection of satellite images, and the correction of the geo references of the old maps were done by ISPAN, 1993. They found the accuracy of the old maps to be good enough to estimate the migration of the river over time.

The Rennel's map clearly shows that in the second half of the 18th century the present Jamuna River was flowing at the Eastern side of the Madhupur tract and joined with the Upper Meghna River before meeting with the Bay of Bengal. The Wilcox map shows evidence that in the period between 1767 to 1830 a new channel evolved that was carrying the major part of the discharge. The Old Brahmaputra river was still important for draining off the water. The Dhaleshwari River, one of the left bank distributaries of the Jamuna River, was remarkably more prominent than in its present state. The planform of the river shown in 1830 was essentially a meandering river with very broad and low-curvature meander loops. With an increased discharge and a heavy silt load (resulting in part from the capture of the Teesta River as a tributary and the gradual loss of importance of the previous course), the stream gradually changed from meandering to a typical braided channel (Coleman, 1969). The change can be illustrated by the historic bank line position presented by ISPAN, 1993 (see Figure 2.5).

The position of the river banks were extracted from different old maps such as Wilcox's map, Survey of India (1914), Survey of East Pakistan (1953), and from the LANDSAT images of 1973 and 1992. The bank lines of these old maps and images are compared with the 1992 bank line position. In 1830 the river was farther East and the overall width was considerably less than the present state of the river. In between the period 1830-1914 the river width decreased slightly, it reduced its meander amplitude and migrated in westward direction. The increase of the width and migration westwards were very pronounced in between 1914 and 1953. Probably in this period the river evolved into its present fully grown braided form. From 1952 to 1973, although the overall river width reduced slightly, the westward migration continued. During the past two decades (1973-1992) the river had widened while continuing to migrate towards the west. The changes of average overall width and centre line migration in westward direction with respect to the 1830 centre line are summarized in Table 2.1.

Year	Average width (km)	Westward centre line migration (10^3m), compared to 1830 location
1830	6.2	
1914	5.5	1.9
1952	9.0	3.6
1973	8.1	4.5
1992	10.6	4.6

Table 2.1 Average width of the Jamuna River and centre line migration 1830 to 1992 (ISPAN, 1993)

Although the accuracy of the figures on the changes of average width and the migration as shown in Table 2.1 is limited, it can be said that the average overall width of the river had increased from 6.2 km in 1830 to 10.6 km in 1992 and the westward migration of the centre line of the river has been continuing since 1830 without showing any discontinuities. There are some discontinuities in the processes of widening in 1914 and 1973. The actual bank line movement towards the west might be different from the centre line migration, because the bank line movement is the result of both the migration of the centre line and the changes of the width.

From the above discussion it can be stated that the evolution of the river during the past two centuries can be attributed to four distinct processes, notably:

- There was a major avulsion of the river somewhere at the end of the 18th or the beginning of the 19th century, through which the river shifted from the eastern side of the Madhupur tract to the western side.
- The river has evolved from a meandering river to a braided river.
- The increases of the average overall width was probably the contribution of the changes of the planform.
- The river is continuously migrating in westward direction. The rate of migration might not be uniform but there is a sustained trend.

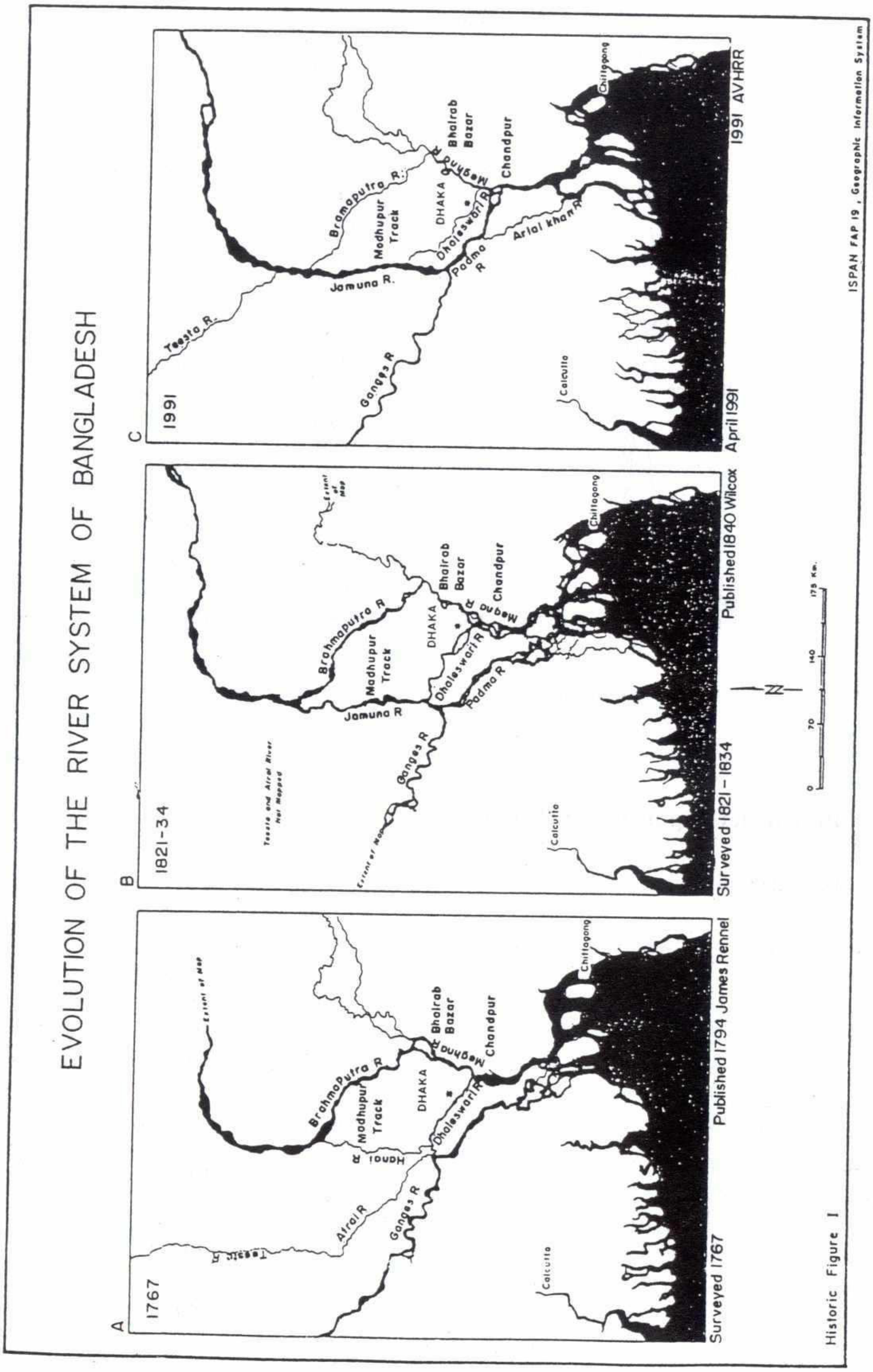

Figure 2.4 Historic maps of the river system of Bangladesh (ISPAN, 1993)

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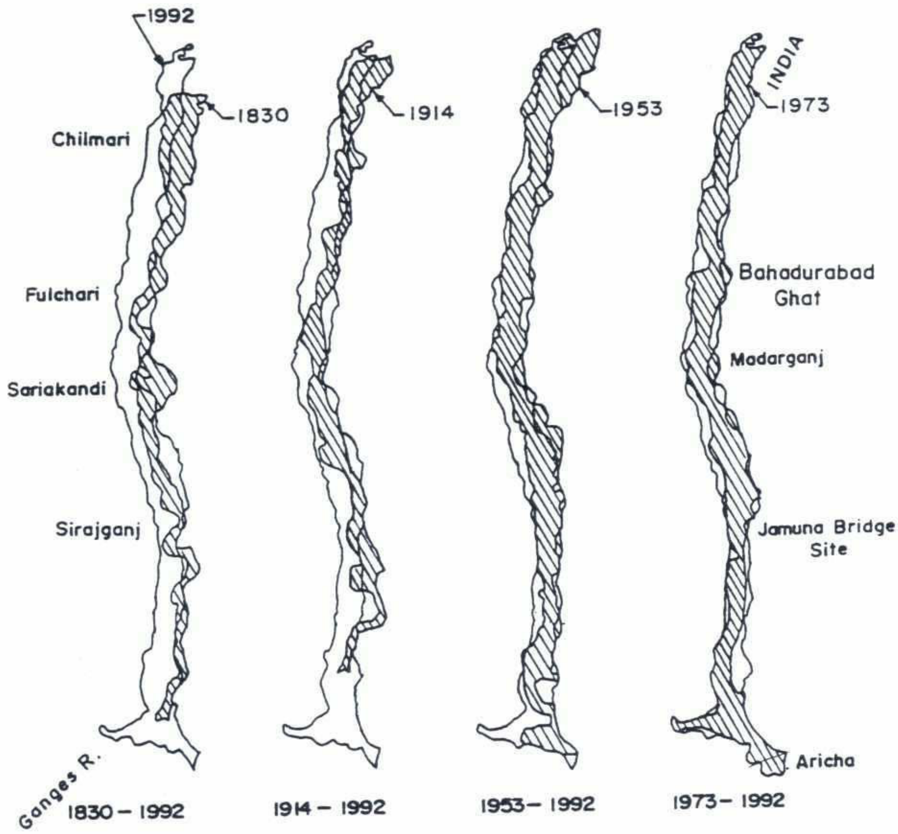

Figure 2.5 Historic bank line migration of the Jamuna River (ISPAN, 1993)

2.4 Recent developments (1990-1995)

2.4.1 Background

The previous section contains a brief description of the long-term development of the river. The long term trends of the river identified there, cannot be recognised during a short-term investigation of the river behaviour as done here. In a joint study of the RSP and the University of Nottingham, the past development of the Jamuna River at the Study Area in the period 1973-1994 was studied, see RSP, (1996b). In this Special Report a nicely presented analysis is given regarding the changes of planform of the anabranches together with the distribution of the discharge over them. The division of flow between the Left Channel and the Right Channel at Bahadurabad is variable. When the flow is predominant in one anabranch, then this channel braids and the smaller channel meanders. When it is equally divided, both channels have channels in the braided/meandering transition. In the seventies the Left Channel evolved from predominantly meandering to braided one and in the eighties the Left Channel flow diminished and the channel reverted to a meandering form with wide point bars and multiple chutes. However, at the beginning of the nineties a reversing process started again; the Left Channel is taking over in carrying a higher percentage of the total discharge. This is the background of our analysis of the recent development of the study area.

2.4.2 Development (1990-1993)

The recent development (1990-1993) of the study reach is done on the basis of a series of satellite images over subsequent years. The series is presented in Figure 2.6. In recent studies (Klaassen and Masselink, 1992 and Mosselman et al, 1994) similar satellite imagery was used to study morphological phenomena in the same river. In principle, the same image processing was used, consisting of selection of image, geocorrecting, resampling and classification. Four classes were identified depending on the reflection characteristics, notably water (blue), sand (yellow), vegetation (green) and an intermediate class, probably wet soil with some vegetation (gray). The images included in the analysis were taken during the low flow season, because these allow the identification of the deepest and most important channels.

The relevant characteristics of the images, such as date, origin of data, water level at Bahadurabad and discharge used here are presented in Table 2.2. For some images two dates are mentioned because Bahadurabad is at the edge of two images and sometimes images from two dates were combined. It can be noted here that the planform shown in the image of one year is the result of the flood of the preceding year; for example, the image of 1993 is related to the planform development by the flood of 1992.

Year	Date	Satellite	Hydrological condition	
			Water Level (m+PWD)	Discharge (10^3 m^3/s)
1990	6 Feb. & 30 Jan. 1990	MOS + Landsat	13.75/13.69	4.6/4.4
1991	24 Apr. & 21 Mar. 1991	MOS + Landsat	15.07/13.69	9.9/4.4
1992	8 Mar. 1992/missing	Landsat	13.76/-	5.4/-
1993	21 Jan. 1993 & 1 Dec 1992	MOS	14.10/14.55	5.8/7.5
1994	25 Jan. 1994	Landsat	13.61	5.0
1995	28 Jan. 1995	Landsat	13.04	3.6

Note: The first date, water level and discharge are related to the upper scene in the case of two images

Table 2.2 Characteristics of the imagery used

As discussed earlier, two anabranches can be seen in the images. There are some NE-SW cross-channel connecting the Left Channel to the Right Channel which are generally active during the higher stages. During the period, the Left Channel (study reach) is gradually beginning to dominate over the Right Channel. There were some major planform developments that occurred in this reach of the river. The following description of the recent development will be limited to the Left Channel.

In 1990 the Left Channel at the upstream of Bahadurabad appeared as braided in planform with a cluster of medial bars just upstream of Bahadurabad at location B and a northwest to southeast oriented medial bar further upstream near A. At the upstream end a confluence of two channels was present. The remnant of previous bends were present at the left bank just upstream of Bahadurabad. During the flood this abandoned channel conveys water as well.

In 1991, the confluence at the upstream end shifted in downstream direction, the medial bar near A became a left bank attached bar which forced the water to flow along the right side of the bar. Near

Bahadurabad the cluster of bars moved in downstream direction. The cluster of bars at the downstream (D) location remains as it was in 1990.

At the upstream end, the attached bar grew in lateral direction and forced the flow further westward which resulted in point bar development at the right bank in 1992. A short connecting channel developed upstream of A, and connected the right and left anabranches near the confluence. The cluster of medial bars near Bahadurabad merged with the left side attached bar through which in 1992 two smaller channels flowed in approximately southern direction. At the downstream end of Bahadurabad the cluster of medial bars shaped as point bar complexes inbetween C and D.

In 1993 the weak connection between the Left and Right channel developed (upper part of the scene), diverting a part of the flow from the Right Channel. The point bar at the right bank downstream of A moved in downstream direction, remarkably curving the angle of deviation from the upstream stretch more than 50° and making the main channel vulnerable for cutoff (see RRI et al, 1993). The small two channels near B over the attached bar complexes moved further eastward. At the location around C and D the point bar complexes remained unchanged.

2.4.3 Developments during the study period

In the monsoon of 1993 the RSP began their bathymetric surveys in this location. The phases of the channel development in the period of 1993-1994 can be seen from those bathymetric surveys (see Chapter 6). However, from the satellite image of 1994 it can be seen that the connecting channel of the two anabranches developed further, probably diverting more discharge from the Right Channel. A major cutoff occurred, diverting the main flow from the previously curved main channel to an almost straight channel; thus combining two previous and smaller channels. Further development of the old main channel and the new channel continued over the next years. The new main channel essentially formed a straight reach with a length of more than 15 kilometres reach of A to Bahadurabad. In the reach downstream of Bahadurabad the point bar complex C and D began to take the shape of a medial bar complex, as it was in 1990 and 1991. Hereafter, the old and new main channels will be refereed to as Old Main Channel and New Main Channel respectively.

The developments over 1993-1995 can be summarized as follows: in recent years the flow in the Left Channel increases. The medial bar near A has become a left bank attached bar, diverting the flow along the right bank. An attached bar had formed, developed and moved in downstream direction, which almost closed the offtake of the Old Main Channel. A new channel has developed directly linking A by a straight channel to Bahadurabad. As a result the point bar complex at C and D appeared as a medial bar complex. The meandering amplitude within braided belt reduced considerably resulting from the cutoff and developed as a long straight reach, which is not sustainable. In the 1995 image there is an indication of developing an opposite meandering curvature taking Bahadurabad and the point of cutoff as nodal points. More detailed discussions about the changes based on bathymetric surveys are presented in Chapter 6.

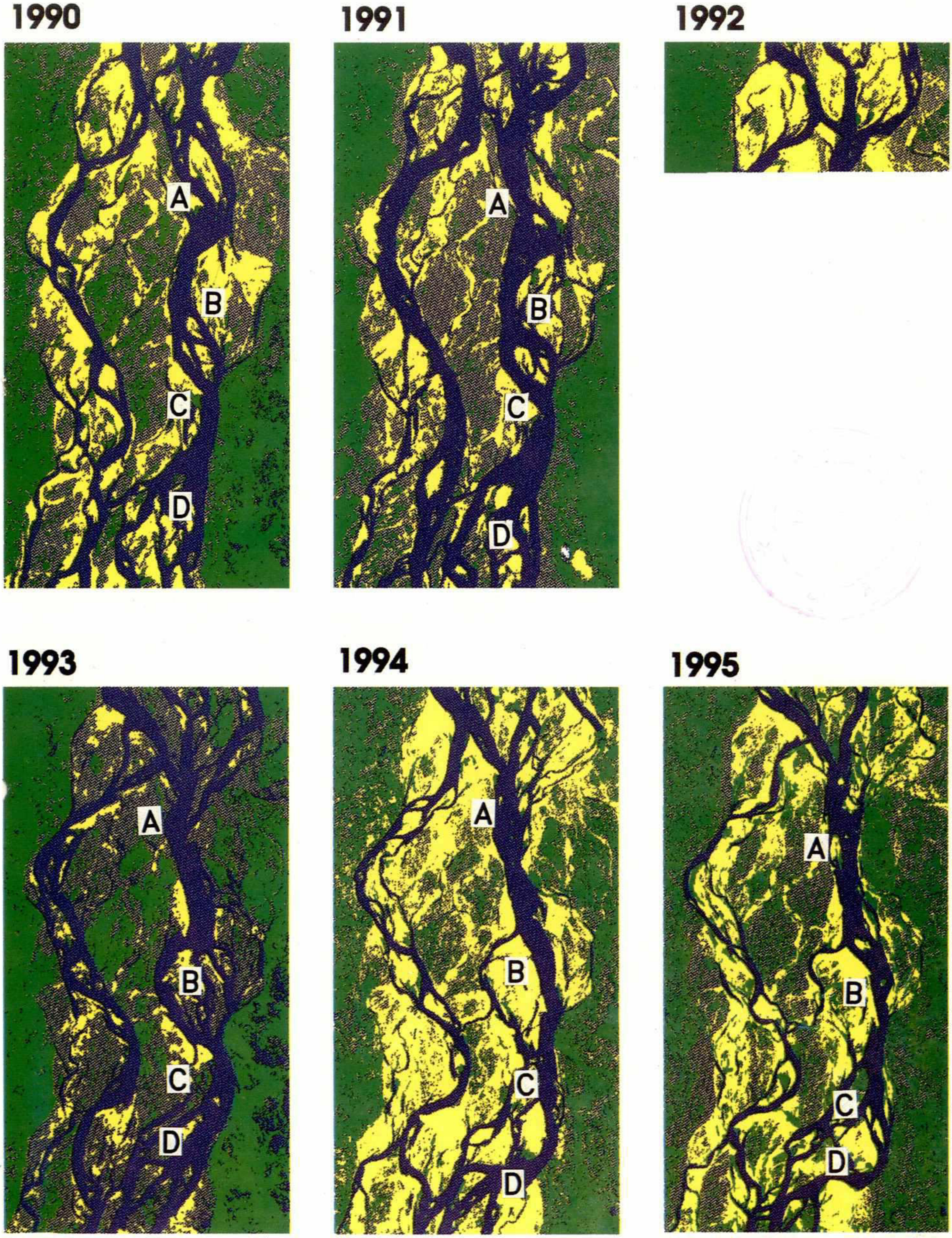

Figure 2.6 Satellite images of the Jamuna River (1990-1995), around the study area

3 Review of literature: previous and parallel studies

3.1 General

Rivers are the channels through which drain water flows from their catchment area to the sea. Draining of water is generally associated with the draining of landmasses i.e. rivers carry a mixture of water and sediments. A river is shaped by the flow, quantity and character of the sediment and the character or composition of the bed and bank materials (Leopold et al., 1964). Natural controls such as rock crops, human interference i.e. bridges, revetments and the dikes also influence the shape of a river. The effect of natural controls are limited to an alluvial river. An alluvial river can be defined as a river which has formed its channel in the sediments that is transported or has been transported by the river (Schumm and Winkley, 1994). An alluvial river can be classified on the basis of appearance of a reach in a plan view, such as braided, straight or meandering. A braided river differs from the other types of river as it consists of more than one channel. The straight and meandering river is generally identified by the sinuosity i.e. the ratio of valley length and river reach length. These types are shown diagrammatically in Figure 3.1. Although these three types represent the major divisions, it is common in any single river to find more than one type of pattern occurring along its length.

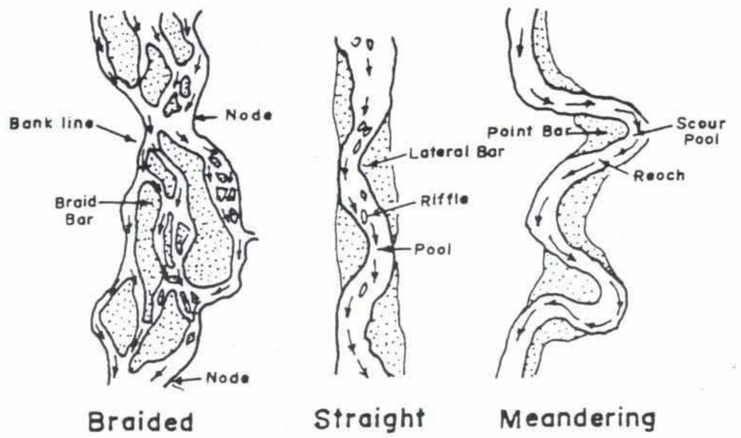

Figure 3.1 Definition diagram of the channel pattern

For the present study the braided rivers are of main interest. Why a river braids as well as the formation and characteristics of a braided river, are discussed in the first part of this chapter in Sections 3.2 and 3.3. The literature review of the previous studies of sand-bed braided rivers including the Jamuna River are presented in Sections 3.4 and 3.5, and later a review of a parallel study is presented in Section 3.6. Finally, the summary of the literature review is presented in Section 3.7. The parallel study is the 'Secondary Currents and Morphological Evolution in a Bifurcated Channel' studied by the University of Nottingham, U.K.

3.2 Why a river braids

The reasons of why a river braids is not clearly known. Various opinions about the definition and causes of braiding are present in the literature. Leopold and Wolman (1957) defined a braided river as one which flows in two or more anastomosing channels around alluvial islands, whereas Lane (1957) stated, 'a braided stream is characterized by having a number of alluvial channels with bars and islands between meeting and dividing again, and presenting from the air the intertwining effect of a braid'. The general conditions required for the development of a braided planform described by Knighton

(1984) are as the necessity of a large amount of sediment to provide an abundant bed load. Coarse fractions, which the stream is locally unable to transport, can provide the initial deposits for bars, which then divert the flow towards the river bank. Erodible banks are therefore another requirement as these are not only a readily available source of sediment but also allow the widening of the channel. There is good agreement regarding the requirement of easily erodible banks for braiding (Friedkin, 1945; Leopold and Wolman, 1964; Thorne, 1988). Generally, rivers with erosion-resistant banks meander rather than braid. The highly variable discharge is not a prerequisite for braiding. The fact that braided streams can be produced in flumes under steady flow conditions undermines the importance of the high variation of discharge. But the rapid variation of discharge often accelerates the bank erosion and thus contribute to braiding process.

In the literature a number of methods of classification of channel patterns are available, which provided the threshold between the braiding and the other channel patterns. A review of channel pattern classification is presented in Annex 1. This can also provide a fair understanding of the causes of braiding. Leopold and Wolman (1957) provided a threshold value on the basis of bankfull discharge and channel slope. In addition, recent studies on the channel classification based on stability analysis, indicate that braiding initiates from the instabilities in the riverbed (Struiksma and Klaassen, 1988). There is a common threshold parameter in most of the channel pattern classification based on stability analysis, is the form ratio (see Annex-1). For braiding the width-depth ratio should be higher.

It appeared that braiding is likely for the river with highly erodible bank, higher slope, discharge and width-depth ratio. However, the width-depth ratio is the function of sediment size, slope, sediment transport and the characteristics of the bank material.

3.3 Formation and characteristics of a braided river

The detailed processes giving rise to the formation of a braided river are still poorly understood. Many researchers studied the process of braiding but little agreement can be found, and the hydraulic parameters of a braided streams are extremely complex (Coleman, 1969). Most of these works were based on small mountain rivers and flume studies and which are difficult to extrapolate to the large natural rivers, like the Jamuna. Nevertheless, these works are significant for a general understanding of the processes in braided rivers. However, the stages of development of a braided bar in a laboratory flume, as presented by Leopold and Wolman (1964), is shown in Figure 3.2. The flume channel was in uncemented sand and initially straight. Firstly, a small deposit of grains of somewhat coarser sediment was introduced by lag deposit of the coarser fraction, which could not be carried by the flow. The probable reason for this given by Leopold and Wolman for initial deposition was that the turbulent flow creates the fluctuation of instantaneous velocity, which causes a brief decrease in intensity allowing some particles to rest. Velocities required to keep them moving, are less than those required for reinitiating movement after they have come to rest, Once concentrated, the particles form a locus for continued deposition. Once initiation of the bar has occurred it accretes vertically and also in downstream direction. The presence of a bar reduces the flow area and diverts the flow towards the bank, initiating bank erosion thus increasing the flow area. The velocity distribution over a mid-channel growing bar reduces after accreting the bar to a certain level (Ashworth, 1995). This forces the flow further towards the bank attributing the further widening of the channel. Widening of the channel increases the flow area and drops the water level, which results in the bar emerging for constant discharge. These are the mechanisms of the mid-channel bar initiation as based on Leopold and Wolman (1957).

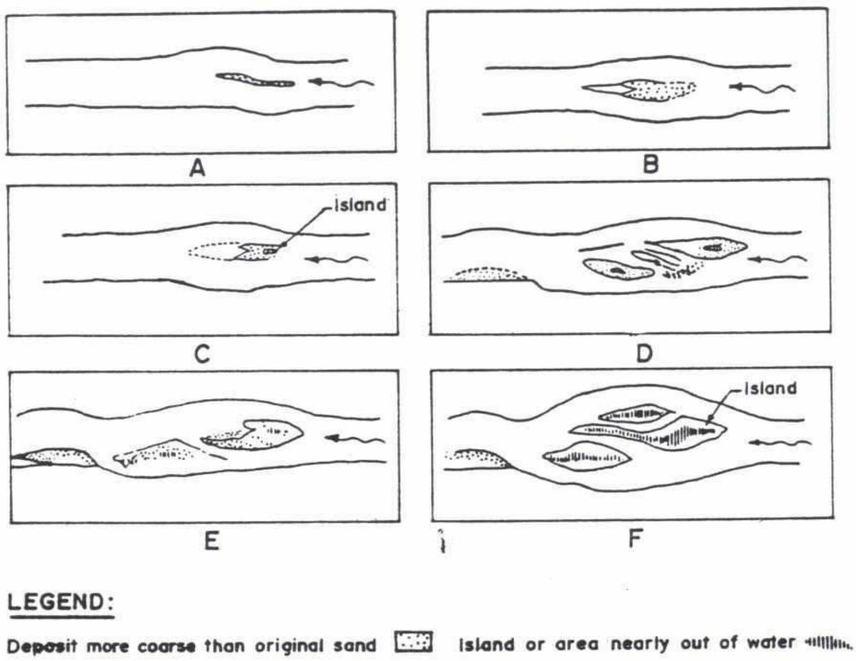

Figure 3.2 Steps in the development of a braided river (Leopold and Wolman, 1957)

The large braided river is characterized by a wide channel, rapid shifting of bed material and continuous shifting of the channel course. Bed material shifting associated with the sorting of the grains is one of the requirements for the braided form (Leopold and Wolman, 1964). Peters (1978) observed significant grain-sorting processes among the braided channels and the various features of the braided stretches of the Zaire River. The channel shifting process is quite pronounced and rapid at the higher stages of flow and less during low flow (Chien, 1961; Coleman, 1969). Chien pointed out that the amount of shifting i.e. the lateral movement is controlled by the spacing of the controlling points along the river. The controlling points are the bed rocks, and resistant strata on the banks. The continuous shifting of the channel is attributed to the rapid movement of the bed material associated with the erosion and deposition in the riverbed sediment.

According to Leopold and Wolman (1964) 'there is a close relation between braiding and meandering: braided channels may exhibit curves that have a characteristic relation of radius to channel width, and the river has at least some reaches that would be called meandering'. This can be explained by the division flow of a bar resulting in the reduction of discharge in an individual channel and consequent reduction of the flow power, which causes the meandering. This sort of meandering characteristics are often used for analysing certain features of the braided river (Bridge, 1993). Due to lack of studies on large braided rivers, Bridge argued that the essential features of flow in braided rivers are curved channel segments joined by a zone of flow convergence (confluence) or divergence (bifurcation). Considering the flow dynamically, similar to a sinuous single thread channel, it possible to piece together a picture of the 3D geometry, flow and sediment transport of a braided river. On the basis of the above a number of studies were carried out on braided rivers, especially on the Jamuna River (Klaassen and Vermeer, 1988a; Klaassen and Masslink, 1992; Thorne and Russel, 1993 etc.). But extrapolating the characteristics of a single thread channel in studying the braided river shows higher uncertainties in the result.

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The initial deposition of relatively coarser particles in mid-channel, associated with instantaneous decrease of competence as indicated by Leopold and Wolman, may be valid for flume and small-scale gravel bed river, but it can hardly be applied to the large-scale braided river. Summarising the above it appears that the bed of a braided river is extremely unstable. The channel pattern classification based on stability analysis also shows that braiding is initiated by the instability of the riverbed i.e. instability is inherent in the braiding process. This does not imply that the river itself is unstable. Rather, it may be as close to equilibrium as are rivers showing meandering or other patterns (Leopold and Wolman, 1964).

3.4 Previous studies on large sand-bed braided rivers

3.4.1 Introduction

In the previous sections the reasons for braiding as well as the general characteristics of braided rivers were discussed. Earlier it was noted that studies on large sand-bed braided rivers are sparse. But to understand the characteristics of the Jamuna River, rivers like Jamuna in consideration to their size, and other hydraulic and morphological parameters are essential. The comparable hydraulic parameters used here the discharge, water surface slope, discharge variation and comparable morphological parameters are: bed material size, sediment transport, planform etc. A few of such parameters of the Zaire, Yellow and Jamuna rivers are presented in Table 3.

River	Discharge (min-max) (m^3/s)	Average Discharge (m^3/s)	Water surface slope (cm/km)	Bed material size (mm)	Av. sediment concentration (mg/l)	Planform
Zaire	23,000-8,0000	42,000	10-1	1-0.3	40	braided
Yellow		1,500		0.03-0.018	$3.5*10^4$	braided
Jamuna	4,000-100,000	20,000	10-5	0.35-0.1	300-500 (sand fraction)	braided

Table 3.1 Characteristics of the Zaire, Yellow and Jamuna rivers

In this section the characteristics of the Zaire and Yellow rivers are discussed on the basis of the available literature.

3.4.2 Zaire River

Introduction

To improve and maintain the maritime access of the Zairian ports Matadi and Boma, the Belgian State Hydraulic Laboratory had been involved in association with the Zairian Maritime service. Physical model studies and field investigation were performed for this purpose. A number of literature based on the above field investigation are available, such as Peters (1977); Peters (1981), Peters (1988), Peters and Goldberg (1989), Peters (1990), Peters and Wens (1990), Lukanda et al. (1992) etc. The characteristics of the Zaire River relevant to our study, are described in this section on the basis of the literature mentioned above.

Characteristics of the Zaire River

The length of the Zaire River is about 4700 km from its origin near Lubumbashi to the river mouth on the Atlantic Ocean. The length of the braided reach of the river is only 60 km upstream from Boma to downstream Malela, see Figure 3.3. The characteristics of these stretches of the river are relevant to our study. The river drains the water from a $3.7*10^6$ km^2 large basin. The minimum and maximum observed discharge variation is from 23,000 to 80,000 m^3/s. The mean annual discharge is about $1.4*10^{12}$ m^3 year making it the second largest river in the world on the basis of annual flow. The tidal amplitude at the mouth of the river amounts to 1 m and gradually decreases in upstream direction. Near Boma tidal variations are small and flow conditions may be considered as stationary (Peters, 1977). The mean water surface slope gradually decreases from 10^{-4} near Boma to 10^{-5} near Malela at the downstream limit of the braided area. The shear velocities vary from 0.01 to 0.15 m/s, but generally less than 0.1 m/s.

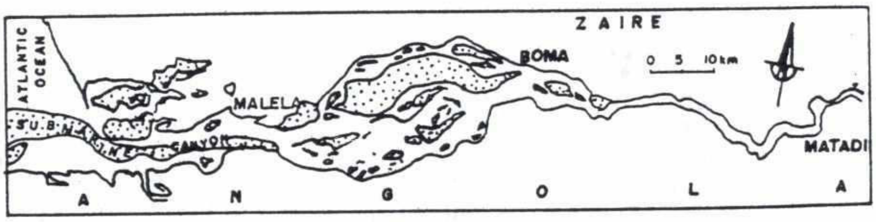


Figure 3.3 Braided part of the Zaire River

The bed-material sizes of the braided reach of the river ranges from 1 to 0.30 mm. The grain sorting in longitudinal direction is quite significant and 1 to 0.33 mm over 40 km (Peters, 1977). The sediment concentration of the river is exceptionally low in comparison with other large rivers such as the Amazon, the Mississippi and the Yang Tse Kiang, which have a suspended concentration in the order of 100 to 1400 mg/l, whereas the average concentration in the Zaire River is about 40 mg/l (Peters and Wens, 1990).

Planform

At the upstream end of Boma the river has to cut through the Crystal mountain and essentially consists of a single thread deep channel. At the downstream end at Malela the river is connected with a submarine canyon, before debouching into the Atlantic ocean. The braided part of the river is about 19 km wide, where shoals and islands divide numerous channels. A few of the channels are deeper and the formation of the new channel silted up of the older one is a regular feature in the braided reach of the Zaire River. The width of the braided channels range from a few hundred to a few thousand metres. The average bank erosion rate is about 100 m/year. The development of a braided part of the Zaire River from 1900 to 1976 is shown in Figure 3.4. This figure indicates that the channel shifting processes in the braided part of the river are probably slower than in the Jamuna River.

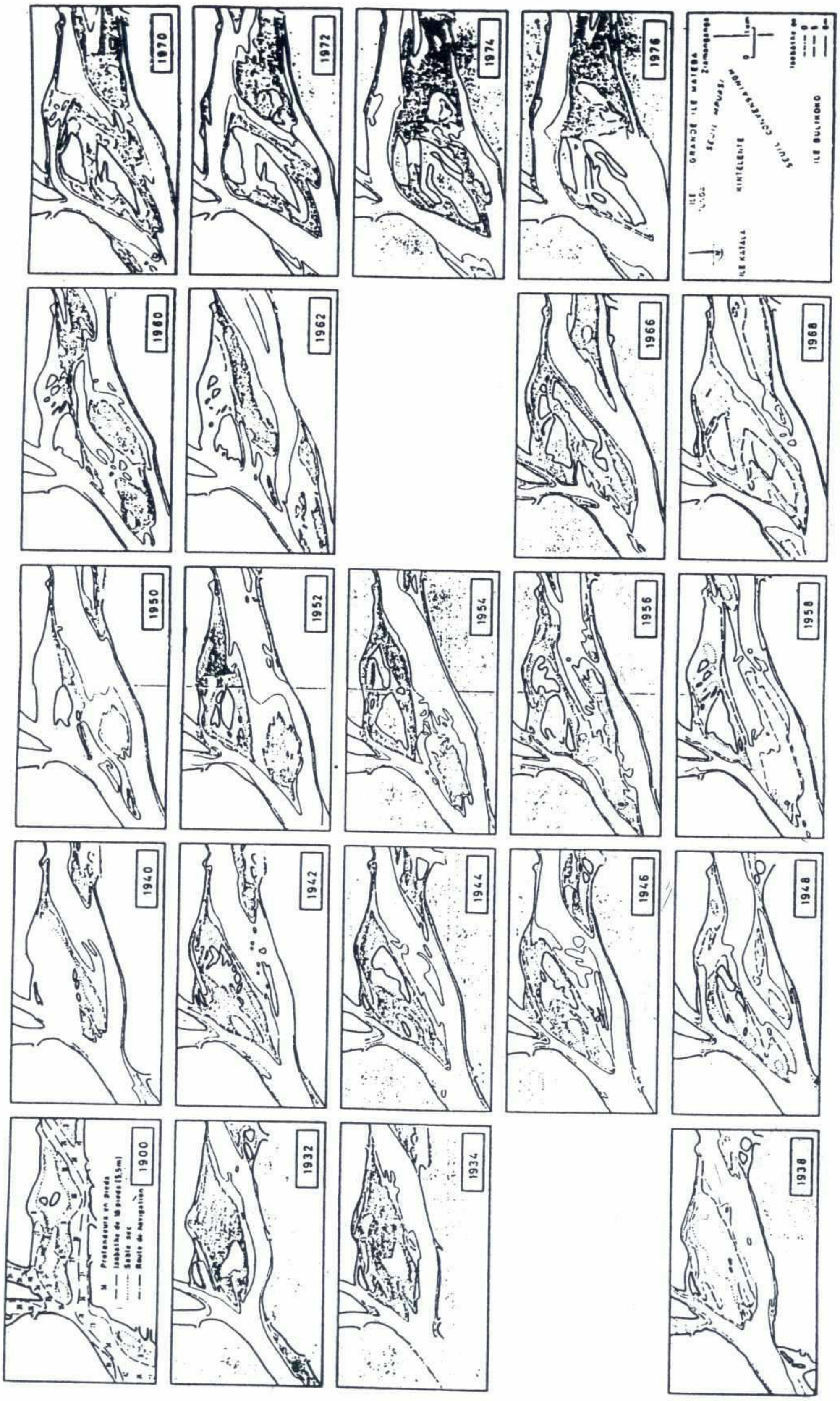


Figure 3.4 Development of a braided reach of the Zaire River with time

Bed forms

Bed forms are generally large-scale dunes, their average length and height average respectively 100 m and 2 m. Their shapes and sizes depend upon many parameters mainly the local power of the flow and the bottom sediment size (Peters and Goldberg, 1989). The power of the flow here are expressed as: ($u*\tau$), the product of depth averaged velocity (u) and the bottom shear stress (τ). At lower stages of flow, the bed forms are generally the large-scale dunes and they flatten out at flood stages corresponding to the mean annual discharge. Peters (1977) observed the development of bedform of length and height of 20 m and 1 m respectively in upper flow regime, classified by Simons and Richardson (1966).

Peters (1993) suggests, based on the experience from the Zaire river, that the traditional concept of predicting flow resistance is not applicable in straight forward manner for the large alluvial rivers. It also appeared that the bed form has little influence on roughness and bed-material transport (Lukanda et al, 1992).

Sediment transport

The contribution of wash load in total sediment transport is much less in comparison with the Jamuna River. The sediment transport in the Zaire is dominated by the bed-load transport mode, which contributes almost half of the total transport (Milliman and Meade, 1983). Bed-load transport is here defined as the transport through a layer of several decimeters above the bed where sediment concentration is comparatively very high (Petters and Goldberg, 1989). Lukanda and Peters, 1992 found that the sediment transport in the Zaire River is in good agreement with the modified Bagnold (1966) power-related relation, which says:

$$s_t = P\left[\frac{e_b}{\tan\alpha} + \frac{e_s u_s}{W_s}(1-e_b)\right] \tag{3.1}$$

where s_t = the total bed material transport, P = the available power per unit length and width, u_s = the mean velocity of the transported solids, W_s = the settling velocity and e_b, e_s = the efficiencies for bed load and suspended load. The available power can be estimated as $P = \rho * u * u_*^2$ instead of $P = u\tau$, where ρ = the density of water and u_* = the shear velocity and can be measured from vertical velocity profiles, assuming a two-dimensional shear flow (Prandtl-von Karman velocity-law, logarithmic velocity profile):

$$u_y = \frac{u_*}{\kappa}\ln y + C \tag{3.2}$$

in which, u_y = the velocity in vertical direction, y = elevation of the bed, and κ = von Karman coefficient. Using this relation to determine the power of flow and subsequently to estimate the sediment transport by Equation 10, was named as modified Bagnold approach by Lukanda et al. (1992) and this method is in good agreement with the sediment transport in the Zaire River thus conforming the validity of the power-related approaches. Comparatively, the bed load transport has the better agreement with the first part of the Bagnold Equation and the suspended sediment concentration often governed by the morphological features. They found that the power estimated from local water surface slope and water depth and using those for sediment transport is inappropriate for large alluvial rivers.

The gradient of sediment transport at a layer of thickness several decimeters above the riverbed (bed-load transport + saltation) is liable for the bed-level changes (Peters and Goldberg, 1989). The sediment transport at this layer depends on the shear velocity determined from the logarithmic velocity profile.

Prediction of the morphological changes

On the basis of the analysis of gauging, sounding maps and the dredging report, an empirical relationship was established between surface velocity, depth, sediment grain size and the tendency to scour and aggradation (Peters, 1981). Accordingly, a simple empirical relation with water depth and surface velocity showing the area having a tendency to riverbed aggradation and scour, was presented by Peters (1988), see Figure 3.5. The figure did not show the influence of the grain sizes on aggradation and degradation processes. Peters (1991) mentioned that the above prediction method works quite well when sediment transport rates are close to the transport capacities. If these exist some geological or other types of controls, the method may not be applicable.

Peters (1988) mentioned another prediction method, in which local slope variation from the average slope of a reach is an indicator of the siltation or scouring of a channel. Comparatively higher slope increases the sediment transport capacity and enhance the erosion of the bed of a channel. These processes are reversed in the opposite case.

The above two prediction methods were successfully applied to maintain navigation channel by dredging and shifting of navigation route from one to another possible eroding channel. Peters (1991) suggested that these methods could be tried out in similar river environments as in the Zaire River.

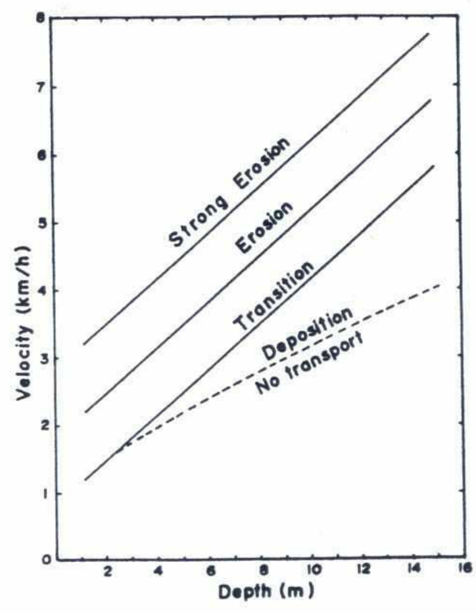


Figure 3.5 Relation between the depth-averaged velocity and water depth with the erosion and deposition of riverbed for the Zaire River (Peters, 1988)

The above discussion about the characteristics of the Zaire River based on the available literature, can be summarized as follows:
The yearly discharge variation in the Zaire River is 3-4, which is much smaller than the Jamuna River. The average water surface slope in the river is nearly the same and the grain sizes are coarser than those of the Jamuna. The planform changes are comparatively slower than in the Jamuna River.

The established roughness and bed form predictors are not applicable for the Zaire River.

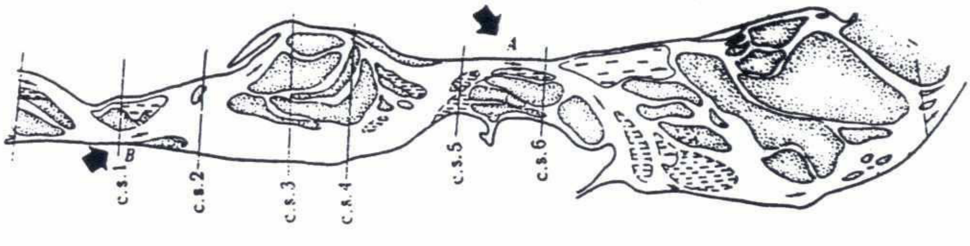
There is comparatively less fine sediment transport in the Zaire River and the average sediment concentration is considerably less than the other comparable rivers in size. Almost half the sediment transport occurs at the near bed zone and the transport at this zone depends on the shear velocity u^* i.e. depends on the velocity profile gradient near the riverbed.

The near bed sediment transport is mainly responsible for the bed-level changes and thus the changes of planform of the river.

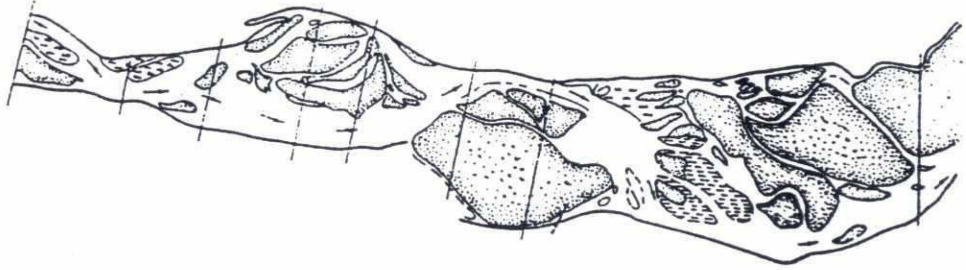
3.4.3 Yellow River

The Lower Yellow River is about 790 km long. A part of it, which is about 280 km long, has a width between the dikes of 5-23 km. This 280 km reach of the river is braided in planform. The characteristics of this braided part of the Yellow River are here presented on the basis of Chien (1961). The river is highly choked with sediment. The suspended sediments are fine in nature with sizes ranging from 0.018 to 0.03 mm. The average annual runoff is $4.82*10^9$ m^3, where the average annual sediment transport is about $1.72*10^8$ tons, which results in average sediment concentration of about $3.5*10^4$ mg/l, although for same discharges the range of concentration may vary 10 to 20 times. It is observed from the Chien (1961) data that the braided part of the river is shallow and the width depth ratio is within a range of 2500 to 4000.

In the Yellow River the surface width of the flow varies widely, and there exists successive zones of convergence and divergence. The River expands and contracts intermittently in alteration, which is illustrated by Figure 3.6. The flow pattern differs considerably in these two zones. In the zone of divergence the channel is wide and shallow and subdivided into a number of channels and bars. In the zone of convergence the channel is comparatively deeper and narrower. This convergent zone acts as a control point. The control points are identified as two types in the Yellow River. The first type of controls fixed on both sides by bank protection work, high cliff, erosion resistant shore lines. The second type of control point is restricted to one side only, with low sand-bank forming along the opposite side. Former type of control keep the river as a zone of convergence for a long time. But the latter type of control can keep the river as a zone of convergence for the time being as it is determined by the upstream flow direction.



(a) March 21, 1959.



(b) March 26, 1959.

Figure 3.6 A plan view of a typical reach of the Lower Yellow River and showing the changes in planform occurred in a short period of time

In the zone of divergence the location of the main current is extremely unstable, which can also be observed from Figure 3.6. The thalweg of the river shifts rapidly in association with enormous erosion and deposition on the riverbed. The water course can completely reverse its position from one bank to the other after the passage of a larger flood. During floods the rate shifting of thalweg varied about 50 to 130 m/day. The rate of thalweg shifting is higher in the flood season than in the low-flow season. During the passage of flood the thalweg shifting is faster than at the rising stage. Chien found that the amplitude of the channel shifting in a divergence is directly proportional to the length of the divergence reach. The moving rate of sand bar, is also very high; their observed rate is about 90-120 m/day.

Two types of channel shifting processes are present in the Yellow River. For the first, the main channel often captures a branch smaller channel and fills the old channel with sediment. For the other, the channel is shifted either by the movement or by the bank erosion. According to Chein, the planform of the river is the result of a number of interactive processes, such as the interaction between the input sediment and the sediment carrying capacity of the flow, and the interaction between the erosion resistance of the bank material and the bank erosion capacity of the flow. The location where the bank material is highly erosion resistant, the river is meandering in planform. Where the case is reverse, the river is braided in planform and due to the higher input of sediment than the transport capacity of the flow, an aggradation of the riverbed is an ongoing process. Chien suspected that if the aggradation process continued, it may also alter the planform of the meandering reach of the river.

3.5 Previous studies on the Jamuna River

3.5.1 Introduction

The general characteristics of the Jamuna River are described in Section 2.2. To know the present understanding of the morphological processes in the Jamuna River, the available literature and the various studies on the Jamuna River can be of greater help than anything else. Among the available literatures the pioneering work on the Jamuna River is Coleman (1969) on the scientific investigation of river morphology in Bangladesh. Later a different number of publications (Bari and Alam, 1979; Bristow, 1987; Klaassen and Vermeer, 1988a, 1988b; Klaassen et al, 1988; Klaassen and Masselink, 1992; Thorne and Russel, 1993 etc.) were made and those are mainly related to the different studies on the Jamuna River related to the river engineering works (bridge, floodplain management, bank protection) or flood protection. In this section the various morphological aspects of the Jamuna River on the available literature and studies, are discussed. These aspects are certainly relevant to our study.

3.5.2 Channel characteristics

In a braided river exist a number of channels within the braided belt. As noted earlier, Bristow (1988) classified various types of channels for the Jamuna River (see Figure 2.3). Klaassen and Vermeer (1988) studied the geometry of the second order channels of the Jamuna River considering those channels as individual channels. Leopold and Wolman (1960) derived empirical relations for meandering rivers, which are as follows:

$$\lambda = 10.9 B^{1.01} \quad (3.3)$$

$$A = 2.7 B^{1.1} \quad (3.4)$$

$$\lambda = 4.7 R^{0.98} \quad (3.5)$$

in which λ = meander length, A = amplitude and R = radius of curvature. The definition diagram of these parameters is shown in Figure 3.7. Combining Equation 3 and 5, yields:

$$R = 2.35 B^{0.99} \quad (3.6)$$

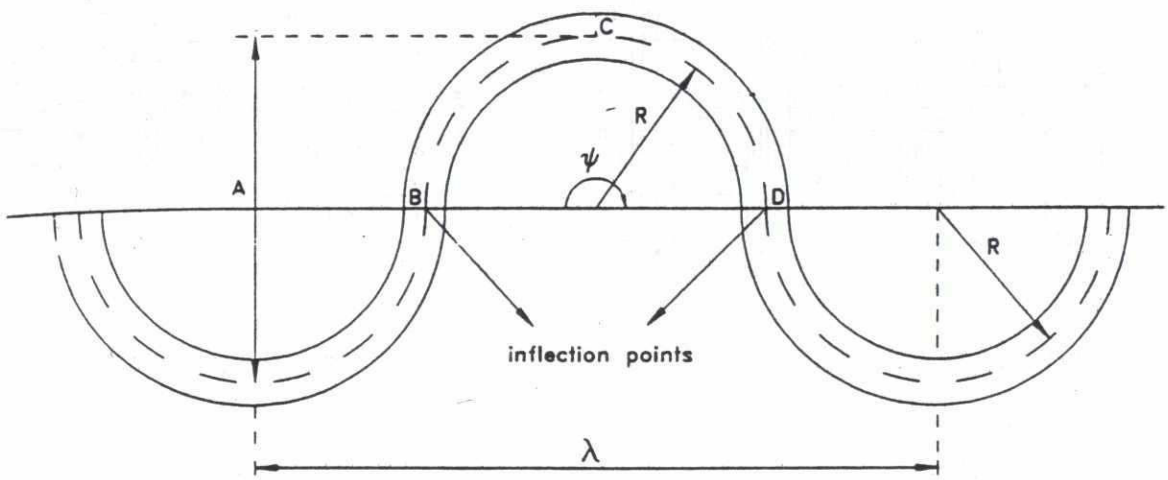


Figure 3.7 Definition diagram of meandering wave length, amplitude and radius of curvature

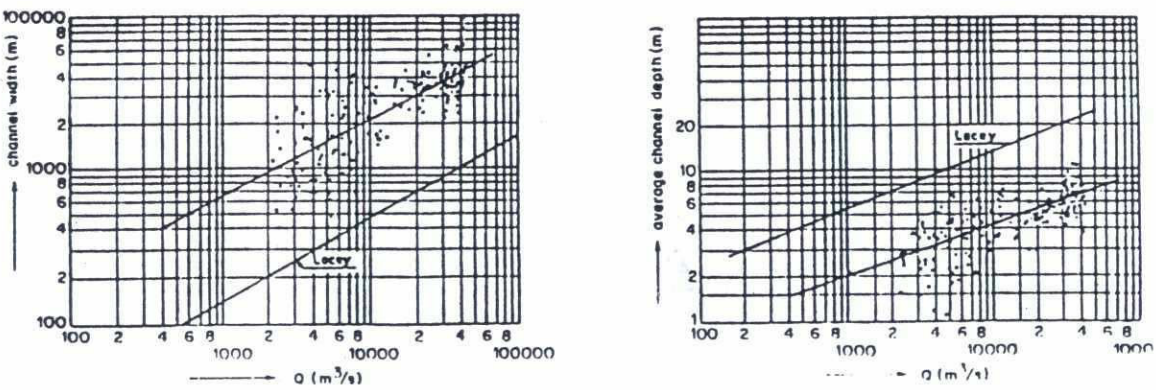
Based on Equation 3.6, Klaassen and Vermeer (1988) related the radius of curvature to the width of second order channels in the Jamuna River. They estimated the width and radius of curvature of the channels from lean season satellite images and found a high scatter of data while plotted lean season width vs. radius of curvature of curved channels. For a particular width (lean season) of a curved channel the radius of curvature is higher than the meandering river. On the other hand, if bankfull width is considered and assuming no change of radius, then it appears that the radius of curvature is less than that of Equation 3.5. Klaassen and Vermeer also related R to the arc length and channel direction with the conveyance. They found an inverse relation between radius of curvature and arc length and a similar inverse relation was observed for the case of channel direction deviated from valley slope and channel conveyance.

Based on Lacey's (1930) regime relation on channel dimensions Klaassen and Vermeer (1988) found the following relations for second order channels in the Jamuna River (see also Figure 3.8):

$$h = 0.23\, Q^{0.32} \qquad (3.7)$$

$$B = 16.1\, Q^{0.53} \qquad (3.8)$$

where Q = bankfull discharge (m^3/s), B = bankfull width and h = the average depth at bankfull condition. The estimation of width and depth were made by using the BWDB standard cross-section, generally surveyed in the lean season. The bankfull discharge was distributed among the channels in a section according to the relative conveyance factor ($Bh^{3/2}$) assuming Chézy's C and slope were constant for a section of the river. In this case, data in the plot (Figure 3.8) are also scattered; yet, it was observed that the channels in the Jamuna River were about 4 times wider and almost 3 times shallower than Lacey's channel. It is obvious that the aspect ratio of the braided river is quite higher than the single thread rivers.



(a) width versus discharge (b) average depth versus dischar

Figure 3.8 Regime relations for the Jamuna River (Klaassen and Vermeer, 1988)

Klaassen and Vermeer (1988), derived at-a-station relations for the Jamuna River, considering that different levels in the cross-sections for different discharges and corresponding water surface width and average depth were estimated from the BWDB measured cross-section. The discharge in an individual channel was estimated as indicated for regime relations. The at-a-station relations are as follows:

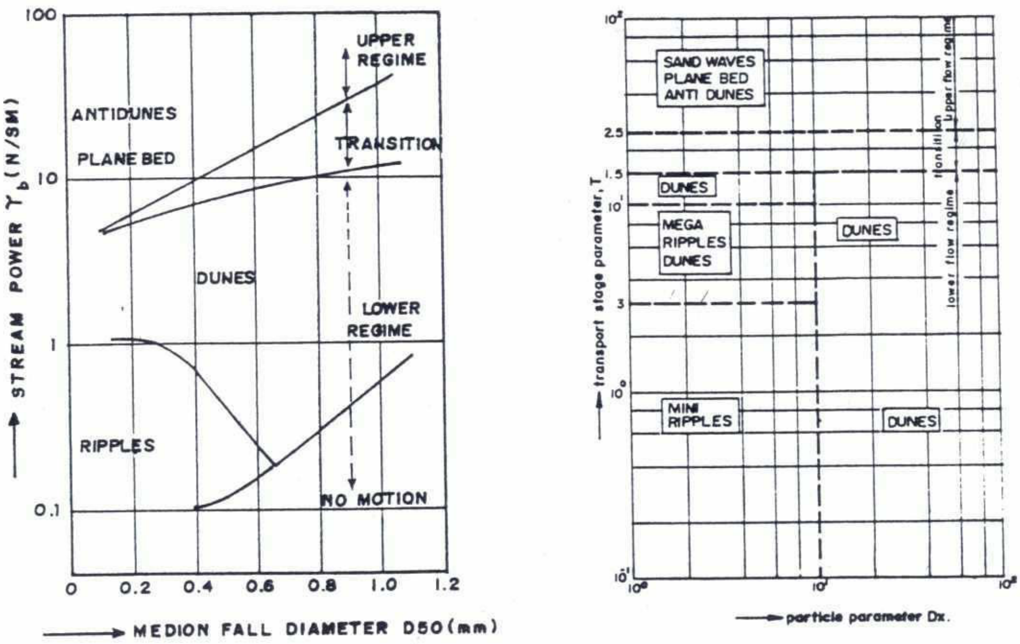
$$h = 0.56\,Q^{0.23} \tag{3.9}$$

$$B = 18.9\,Q^{0.51} \tag{3.10}$$

These at-a-station relations are quite similar to the regime relation, indicating that the channels of the Jamuna River are quickly responding to adjust their depth and width with the variation of discharges, although the data were, as usualing, highly scattered. Klaassen and Vermeer indicated that the probable reason behind the scatterness of the data was due to the fact that the alignment of the BWDB standard cross-sections are often oblique to the flow. They suggested that perpendicularity correction of the cross-section would help in reducing the scatterness. The RSP did a similar type of study with perpendicular corrections of the BWDB cross-sections and found a slight reduction of scatterness of the data but it was still considerable, see RSP (1995b). It was observed that a channel having the same discharge at a certain reach may have width variation of 200% at a certain moment. Moreover, no channel in the Jamuna River is in regime condition, continuous change of channel development and abandonment process is a rather common phenomena, which is absent in a meandering river. Another issue of using BWDB standard cross-sections is that whether these cross-sections measured in low flow condition are representative for the channel section at high flow condition. This question has yet to be answered.

3.5.3 Bed form and roughness

The bed forms are the result of the channel bed modification to achieve the most efficient balance between sediment and water discharge (Coleman, 1969) i.e. the bed form is the action of a riverbed to discharge water and sediment mixture of a given situp of a river (the valley slope, bed material, planform) with the variation of water and sediment input. The different types of bed modification occur depending on the flow regime. Accordingly, the flow regime is classified as lower, transition, and higher flow regime. The different types of bed forms in different flow regimes according to Simons and Richardson (1961) are shown in Figure 3.9. This classification is based on the form of bed configuration, mode of sediment transport, process of energy dissipation and phase relation between the bed and water surface. Generally, the bed roughness i.e. resistance to flow depends on the types and shapes of the bed form.



(a) Simons and Richardson (1966) (b) Van Rijn (1984)

Figure 3.9 Bed forms classification diagrams

Most of the information on occurrence of bed form are based on flume studies, among those Simons and Richardson (1966) and Van Rijn (1984) are presented in Figure 3.9, although the classification of Van-Rijn is based on flume data as well as field data. For classification the following parameters are used:

Simons and Richardson (1966): τ_b, u and D_{50}

Van Rijn (1984): T and D_x

in which τ_b = bed shear stress, u = depth-averaged velocity, D_{50} = median grain size, T = bed-shear stress parameter and D_x = particle diameter parameter. According to Van Rijn bed-shear stress parameter defined as $T = (\tau_b - \tau_c)/\tau_c$, where τ_c = critical shear stress and particle diameter parameter defined as, $D_x = D_{50}\,(\Delta g/\nu)^{1/3}$, where Δ = specific relative density, g = acceleration due to gravity, ν = kinematic viscosity coefficient.

Van Rijn also provided the method of roughness estimation from the bed form size and shape dividing the effective roughness height of Nikuradse (k_s) into two parts. One is the grain related part (k_s') and the other is the form-related part k_s", which are as follows:

$$k_s = k_s' + k_s'' \qquad (3.11)$$

Then Chézy's roughness coefficient (C) can be estimated as:

$$C = 18 \log \frac{12h}{k_s} \qquad (3.12)$$

where h = water depth. Van Rijn proposes for grain related roughness:

$$k_s' = 3D_{90} \quad For\ \theta < 1\ (lower\ regime\ flow) \tag{3.13}$$

$$k_s' = 3\theta D_{90} \quad For\ \theta > 1\ (upper\ regime\ flow) \tag{3.14}$$

where θ = Shield parameter. In lower flow regime, the bed form that contributes significantly to roughness is dune. Dunes are defined by Van Rijn as asymmetrical bed forms with a length of about 7 times the water depth for which roughness is proposed as (Van Rijn, 1984b, 1989):

$$K_s'' = 1.1\ \gamma_d\ H(1 - e^{-25HL}) \tag{3.15}$$

where H = dune height, L = dune length and γ_d = form factor, generally 0.7 for field condition. The dune height estimated by Van Rijn (1982,1984), based on flume and field data are as follows:

$$H = 0.11\ h^{0.7} D_{50}^{0.3}\ (1 - e^{-0.5T})(25 - T) \tag{3.16}$$

There are a number of prediction methods for occurrence and types of bed form, their size and shape, and their contribution to resistance to flow. Van Rijn is one who analysed flume and field data and provided all the prediction methods mentioned above. According to Simons and Richardson (1966) and Van Rijn (1984), as the shear stress (τ_b) increases, the flow regime steps up from lower to high flow regime and subsequently the bed form changes from ripple to sand wave and anti-dune. The bed form dimensions depend on the flow depth, grain size and also bed-shear stress (Equation 3.16) and finally the roughness is the function of the size, shape of the bed form.

Due to the higher variability of flow condition in a natural river, the bed forms generally differ from the classification diagram shown above. Coleman (1969) is the first who provided the data on the bed forms in the Jamuna River which are distinguished as follows:

Ripples	:	Typical height is 0.2 to 0.5 m.
Mega ripples	:	Typical height is 1 m and celerity is 120 m/day.
Dunes	:	Typical height is 5 m and celerity is 60 m/day.
Sand Waves	:	Typical height is 10 m and celerity is 200 m/day.

A recent study on bed form and bed roughness in the Jamuna River was conducted by Klaassen et al. (1988a). The study was based on field data on bed form and historical discharge and cross-sectional data measured by the BWDB. The occurrence and dimensions of bed forms were found directly from field investigation and the resistance to flow was estimated in two methods. One was based on the BWDB discharge measurement and C was computed as follows:

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$$C = \frac{Q}{B(h)^{\frac{3}{2}} i^{\frac{1}{2}}} \tag{3.17}$$

where Q = discharge (m³/s), B = width (m), h = water depth (m) and i = water surface slope. Q, B and h are measured during the discharge measurement and i is estimated. The other method was based on the at-a-station relations for width and depth as a function of discharge derived by Klaassen and Vermeer (1988a) (Equation 3.9 and 3.10), for the Jamuna River and using the BWDB standard cross-section measurement. Using the coefficient and exponents of B and h, the Chézy's C was expressed as follows:

$$C = 0.126 \frac{Q^{0.14}}{i^{\frac{1}{2}}} \tag{3.18}$$

From the field measurement, they found the ratio of the length of bed form to the water depth (L/h) within the range 5 to 10 and which is nearer to Van Rijn's ratio. The ratio of height of bed form to water depth (H/h) varies from 0.05 to 0.30 and on average is higher than the Van Rijn's. Their observation contradicts with Coleman (1966) and they concluded that Coleman probably erroneously found the gigantic sizes of bed forms. Interestingly, they found the bed forms of comparable sizes of 200 m length and 3 m height during high flood, in which the condition plain bed is likely according to the theory. Even these types of bed forms do not reduce their form ratio H/L (which generally reduces the resistance to flow) during the high flood discharge. These appears a contradiction between the bed roughness predicted by literature for bed form and the roughness estimated from field observation. The estimated roughness coefficient C is within the range of 70 to 100 $m^{1/2}/s$ during high discharge, whereas the roughness predicted only from grain contribution (Equation 3.13 and 3.14) can yield this value. Klaassen et al (1988) concluded that during high discharge the contribution of the form to resistance to flow is insignificant. Although at the lower stages of flow, the bed roughness due to the presence bed form is similar to the theory.

Klaassen et al (1988), estimated that cross-sectional average bed roughness by indirect methods and slope is considered for long stretches of the river instead of local slope. The roughness estimated from particular flow, bed form environment and local slope, can better estimate the contribution of the bed form to bed roughness. However, this indirect followed method is convincing regarding the insignificant contribution of bed form to bed roughness at higher discharge, which is in line with the observation of Lukanda et al (1992) in the Zaire River.

3.5.4 Sediment Transport

A particle movement occurs when the instantaneous fluid force on that particle is just larger than the instantaneous resisting force related to the submersed particle weight and the friction coefficient (neglecting the cohesive forces). These fluid forces are strongly related to the near bed velocities. Although in natural rivers the velocities are fluctuating in space and time due to turbulence, the particles in a riverbed also vary in size, shape and density and hence result in a variation of resisting forces. Generally, for estimating sediment transport a number of predictors are available, in which an averaging of the above a parameters were considered. Here, it is not intended to present or discuss on sediment predictors. To show the parameters related to the sediment transport, only one simple but widely used sediment predictor (Engelund-Hansen, 1967), based on the energy balance idea, is presented as follows:

$$s_t = \frac{0.05\,u^5}{\Delta^2 g^{0.5} D_{50} C^3} \tag{3.19}$$

where s_t = sediment transport in m^2/s, u = depth average velocity. The other parameters are in S.I. unit, described earlier. It is noted here that the parameters in Equation 3.19 may differ for the different sediment predictors. However, the parameters involved in the sediment transport as Equation 3.19, are velocity, bed roughness, particle size and relative density. In one way or another these are the basic parameters in most of the sediment predictors.

It has been mentioned earlier that in the Jamuna River fine fractions of sediment are dominating, i.e. approximately 66% of the total volume of transport. Most of the previous studies (Alam and Hossain, 1988; Hossain, 1992 etc.) estimated the total sediment transport (fine + coarse fraction) in the Jamuna River based on BWDB-measured data and related to the discharge of the river in a form, which is as follows:

$$S_t = a\,Q^b \tag{3.20}$$

where S_t is the total sediment (bed material) transport, Q is discharge and a, b are the coefficient and exponent of the discharge respectively. However, a few studies (BWDB, 1972; Klaassen and Vermeer, 1988c) related the suspended coarse fraction or total bed material load transport to the discharges. This type of relation is most suitable for sediment balance, but as regards the morphological point of view, it says little.

Alam and Hossain (1988) compared the total suspended sediment transport in the Jamuna River using different sediment transport predictors and found better agreement with the Colby (1964) and Hossain (1985) predictors. They considered the water surface width as the width of the river, and depth as flow area/width and velocity as the discharge/flow area.

Using BWDB 1968-70 sediment transport data in the Jamuna River, Klaassen and Vermeer (1988c) found a relation for total bed material transport as:

$$S_t = 4.5\ 10^{-6}\ Q^{1.38} \tag{3.21}$$

where S_t = total bed material transport (m^3/s). Bed load transport is included here estimating from dune tracking as 10% of suspended bed material transport. Using at-a-station relations (Equation 3.9 and 3.10), they convert Engelund-Hansen for total bed material transport into:

$$S_T = \frac{0.01}{D_{50}} i^{3/2} \frac{Q^2}{Bh^{1/2}} \tag{3.22}$$

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The total bed material transport S_T in m^3/s is estimated. Taking into account D_{50} is 0.18 mm and $i = 7 * 10^{-5}$. It was observed that the total bed material transport from Equation 3.21 is almost double that from Equation 3.22 for different discharge condition. They suggested to use Engelund-Hansen with multiplying factor 2 for the Jamuna River. This approach of Klaassen et al (1988) can better be used in a 1-D model.

Recently, the RSP (1995c) attempted to derive sediment transport predictors from the BWDB data as:

$$\psi = 80\ \theta^{1.8} \tag{3.23}$$

where

$$\psi = \frac{s_s}{\sqrt{g \Delta D_{50}^{\ 3}}} \tag{3.24}$$

in which Δ is the relative specific density, θ is the shield parameter and is expressed as:

$$\theta = \frac{hi}{\Delta D_{50}} \tag{3.25}$$

Here, the local depth (h) is the measured depth and by the estimating local slope for different stages of discharge C is estimated from:

$$C = \frac{u}{\sqrt{hi}} \tag{3.26}$$

in which u is measured depth-averaged velocity.

The RSP (1995c) also found that Bagnold and Engelund-Hansen has better agreement with the sediment measured data. This type of calibrated sediment predictors can be used in the 2-D model and plausibly be used for 2-D approaches of morphological analysis.

The previous sediment data in the Jamuna River measured by the BWDB excluded the bed load transport measurement, Klaassen et al. (1988) estimation shows that the suspended bed material transport is dominating over the bed load transport. The RSP (1996a) estimated from their survey that the near bed (20 cm from bed) sediment transport vary from 15 to 20% an average of which can be considered as 20% of suspended bed material transport, which supports the estimation of bed load by Klaassen et al. (1988).

Most of the previous studies on sediment transport in the Jamuna River are suitable for sediment balance. Klaassen et al (1988) can be applied to the 1-D approach. In the previous studies no 2-D approach was made to sediment transport predictors, except the sediment transport predicted by the RSP, (1995c).

3.5.5 Erosion and deposition processes in the riverbed

The riverbed erosion and deposition in the Jamuna river was first studied by Coleman (1969). He found that due to high sediment load the erosion deposition in the riverbed is extremely high and the processes are very complicated. His study was mainly based on the shifting of the thalweg, which is always associated with erosion and deposition in the riverbed, by comparing cross-sectional profiles measured several times in a year at a certain section of the river, and by comparing each cross-sections measured in two successive lean seasons at different locations in the Jamuna River.

Coleman (1969) found that the thalweg shifting during the flood discharge is very high (500 to 1000 m) and erratic. The scouring of bed is about 15 to 20 percent of the flood flow area during the rising limb of the flood. Although the erosion and deposition in a cross-section is quite high (5 to 8 m) within a year, no significant changes of the overall balance between erosion and deposition were observed.

The observation of Bristow (1987) from satellite images also suggest that the yearly volume of erosion and deposition in the Jamuna River is the function of the high discharge and the duration of discharge. Bristow subdivided identified depositional areas from satellite images into four categories: addition to bars, lateral accretion to the bank, new mid channel bars and channel abandonment. Each types of deposition results into the other types of erosion, say for example abandonment of an old channel is the subsequent result of the formation of a new channel. Formation of a new medial bar results in the widening of a channel by bank or bar erosion.

Furthermore, different studies (Klaassen and Masselink, 1992; Klaassen and Vermeer, 1988) on the Jamuna River shows that the channel processes in the Jamuna river are quite rapid and generally associated with erosion and deposition in the riverbed. In such a quickly responding river with comparatively low bed load transport, whose processes of sediment transport i.e. the bed, near-bed or suspended load transport activate the changes of riverbed left a question to model morphological processes of the river.

3.5.6 Channel shifting processes

The channel shifting processes in the Jamuna River are quite rapid. The abandonment of large channels and the developing of new channels in a few years only are common features in the Jamuna River. Klaassen and Masselink (1992) found that three types of processes are related to the channel shifting processes, viz. bar-induced shifting, development of cutoff and outer bend channels in bends. Among these, the development of the cutoff in the channel shifting process happens quit often in the Jamuna River. For our study the channel shifting processes related to the development of cutoff is relevant. Therefore the discussion in this section about the development of cutoff will be limited.

Klaassen and Van Zanten (1989), analytically studied the cutoff processes in meandering channels. Their study was based on the ratio of the sediment supply from the offtake into the cutoff channel and the sediment transport capacity of the channel. They found that the most important parameter is the cutoff ratio (λ), which they defined as the ratio of the length of the channel and the length of the cutoff channel. Later study by Klaassen and Masselink (1992) based on the analysis of satellite images in the Jamuna River, found that for cutoff the ratio λ varies from 1 to 1.7 and the average value of cutoff ratio as they suggested is 1.25. The cutoff ratio in the Jamuna River is very low in comparison to the

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meandering river, where the cutoff ratio of 5 to 30 is common, suggesting that cutoff occurs very quickly in the Jamuna River.

Recently carried out studies on the bifurcation analysis by RRI et al (1993), showed that the deviation angle of a channel from the upstream channel direction is more important than the cutoff ratio. The study of RRI et al, (1993) is also based on the analysis of Satellite images. To derive a predictive model on the planform changes they made extensive analysis on the channel abandonment in the bifurcation. The summary of the result obtained from their analysis is presented below:

- The angle of deviation from upstream channel direction is a more important factor in channel abandonment than sinuosity or cutoff ratio, whereas abandonment generally takes place when the deviation angle is greater than 40°.
- The geometry of the bifurcation point can be expressed as deviation angle and which greatly influenced the sediment distribution. The relation between deviation angle and the channel abandonment supports the view of Klaassen and Zanten (1989) that sediment distribution activate the channel cutoff or abandonment process.
- There are more chances of abandonment for a channel located in an inner bend whereas an outer bend channel has fair chances of developing cutoff.
- The rapid changes of channel configuration affect bifurcation geometry, and upstream changes lead to a change in downstream channel direction. This makes the analysis very complicated and sensitive to importing uncertainties into the analysis.

It appeared from the above discussion that the deviation angle of a channel from upstream channel direction is an important parameter for channel cutoff processes although this parameter may change with the changes upstream, often making the prediction obscure.

3.5.7 Bank erosion

Coleman (1969), first studied the bank erosion rate of the Jamuna River by analysing old maps and he identified the type of bank failure. Two types of bank failure generally occur in the Jamuna River: liquefaction and flowage of material, and shearing away of bank materials. The former type of bank failure can occur below the low water level or in the zone of low and high water level. Generally they occur during the receding of flood discharge. Receding rates of water level directly influence the rate of failure. The most common processes of bank failure in the Jamuna River is due to shearing, caused by flow attacking the bank or over steepening the bank by a thalweg approaching the bank. However, the bank erosion and accretion rate provided by Coleman (1969) at an interval of 5 to 8 km apart for two different periods, 1944-1952 and 1952-1963, based on the analysis of three maps, showed that the bank erosion rate was erratic and varied from 0 to 800 m/year. Taking the bank accretion as zero, the average bank erosion rates of the Jamuna River based on Coleman (1969) are presented in Table 3.2.

Bank	Bank erosion rate (m/year)	
	Period	
	1952-1963	1944-1952
Left	43	118
Right	67	177

Table 3.2 The average bank erosion rate of the Jamuna River

The average bank erosion rate at the right bank is higher for the two periods, consistent with the Westward migration of the Jamuna River. The period 1944-1952 showed an average bank erosion rate of more than two times the later period, illustrating the variability with time of bank erosion rate. This variation of average bank erosion rate may be due to the number of higher flood events during these periods and selection of time scale. This can be illustrated from the analysis of bank erosion rate of the Jamuna River by Thorne et al (1993). By analysing satellite images Thorne et al. estimated the bank erosion rate of the right bank of the Jamuna River for the period of 1973-1992. They estimated bank erosion at an interval of 500 m apart and averaged the erosion rate for 10 km. The average bank erosion rate for the period 1973-1992 varies from 0 to 160 m/year and the average erosion rate is about 80 m/year. They found that for a shorter time scale the bank erosion rate increases, and the average bank erosion rate is higher for a higher number of flood discharges. They also found that catastrophic events of bank erosion (> 350 m/year) generally occur for short duration: 2 to 4 years and this erosion took place at the outer bank of the curved channels. Thorne and Russel (1988) attempted to predict the bank erosion rate for the right bank of the Jamuna River for different time scales and different locations, extrapolating the previous results.

Klaassen and Masselink (1992), studied the bank erosion rate of the curved channels in the Jamuna River by analysing the Satellite images from 1976 to 1987. As the Jamuna River is a braided river, the various braided channels having different discharges, width and radius of curvature are usually active in eroding the bank at different places. They found that in the Jamuna River the bank erosion is generally associated with the rotation and extension of bend rather than translation. This can be illustrated in Figure 3.10 in which bank erosion rate with relative direction of the valley slope is plotted. Klaassen and Masselink, based on the analysis of Hickin and Nanson (1985) tried to relate the bank erosion rate of the curved channel of the Jamuna River, as follows:

$$E = f\,(B,\ R/B) \tag{3.27}$$

where, E = bank erosion rate/year, B = channel width and R = radius of curvature. Findings of their study are summarised as:

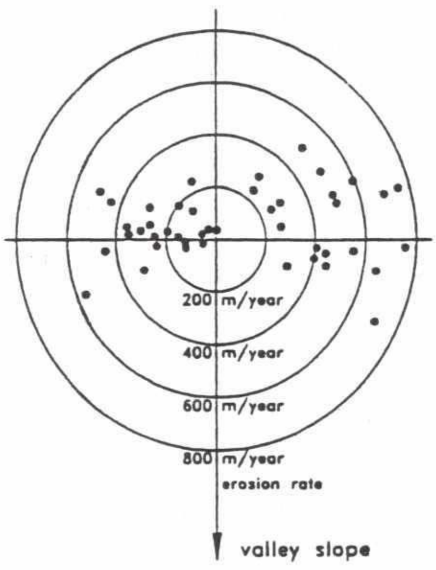

Figure 3.10 Direction of bank erosion along curved channels of the Jamuna River (Klaassen and Masselink, 1992)

- The bank erosion rate varies generally from 0 to 500 m/year and under exceptional conditions it may be up to 1000 m/year.
- The erosion rate is higher for large channels in general. While relative radius of curvature (R/B) was plotted with relative erosion rate (E/B) it showed a negative correlation, like Hickin and Nanson (1985). Pick relative erosion rate although not distinct but appeared to be at R/B = 3 nearer to 2.5. Unlike Hickin and Nanson, no reduction of relative bank erosion rate was observed for R/B > 2.5.
- Estimated bank erosion rate based on Hickin and Nanson is much smaller than the observed erosion rate in the Jamuna River.
- The bank erosion data of the Jamuna River showed substantial scatter while plotted E vs. R/B or E/B vs. R/B and possible reasons for that were measuring inaccuracy, variation radius of curvature and inclusion of less active bends.

From satellite images it is difficult to estimate the discharges causing bank erosion, the flow curvature, width at high flow and the rapid shifting of flow direction within a channel. This probably increases the uncertainties in estimating the bank erosion of the curved channel of the Jamuna River.

From the literature discussed above, the bank erosion process in the Jamuna River can be summarised as follows:

- Bank erosion may occur for liquefaction and flowage of material, and shearing away of bank material.
- Like a meandering river bank erosion occur at the outer bend of a curved channel but unlike, it may occur at other places also in the Jamuna River. The bank erosion rate is higher for the former case.
- The average bank erosion rate depends on the time scale depending on a number of factors: duration of erosion rate, number of higher flood events, erosion and accretion cycle.
- Two types of prediction methods for bank erosion rate of the Jamuna River were derived: one of them can be described as a macro-scale prediction method (Thorne et al, 1993) and the other as micro-scale prediction methods (Klaassen and Masselink, 1992) and can be related only to the outer bank erosion rate of curved channels, after their emergence into the system. The time scale and purposes of usage of these two prediction methods are different.

3.5.8 Scour holes (confluence scour)

The confluence scour that occurs at the downstream of confluences of two channels, such channels may either be two separate rivers or two braided channels of a braided river. The confluence scour is characterised as an elongated reach of relatively high depth in the middle of the combined downstream channel.

Klaassen and Vermeer (1988c), studied the confluence scour of the Jamuna River. Their study is mainly based on the study of Ashmore and Parker (1983) on the confluence scour in the gravel bed river by using the previous hydrographic surveys of Bangladesh Inland Water Transport Authority (BIWTA) and special surveys in relation to the feasibility study for the Jamuna bridge. They estimated the discharge of the different confluencing anabranches with the help of at-a-station relation (Equation

3.10). They also obtained a relation between relative scour depth and θ for the Jamuna River as follows:

$$\frac{h_{cs}}{\bar{h}} = 1.292 + 0.037\,\theta \tag{3.28}$$

It was observed that the maximum scour depth in the Jamuna River is slightly smaller than the Ashmore and Parker (1983).

3.5.9 Planform changes

The changes of the Jamuna River are often very rapid and the process is quite chaotic in nature. Based on the recent understanding of the processes of the Jamuna river, Klaassen et al (1993) attempted to develop a model for planform changes of the Jamuna River. Their study was performed by using a continuous series of satellite imagery from 1973 to 1993. They observed that there are a number of limitations in making a deterministic model for the planform changes of the Jamuna River. The main problems they encountered are in determining the initial conditions, boundary conditions and also in the formulation of the predictive model. The reasons behind these, as they indicated, can briefly be described as follows:

(i) The initial conditions are generally determined from the previous observations, but the accuracy of the satellite images and the representativeness of these dry season images of the river is questionable. Moreover, the large changes generally occur during the monsoon, whereas the satellite images only exhibit the final result of the changes. The river morphology is the result of a three-dimensional effect, whereas the satellite images can provide two-dimensional information.

(ii) Boundary conditions, such as upstream input of water and sediment fully depend on the meteorological processes. A long-term meteorological prediction is not possible.

(iii) The limitations of the present predictive methods of the different morphological processes of the Jamuna River. Often the river behaviour seems to be a chaotic in nature.

Therefore, instead of a deterministic approach Klaassen et al. suggested a stochastic approach for modelling the planform changes of the river. The components to their models are: channel migration, mid-channel bar formation, behaviour of bifurcated channels and migration of confluences and bifurcations. They observed that for a shorter time scale the model can predict the planform with a fair accuracy providing the indication of a few possible developments of planform. But as the prediction time increases, the number of possible developments increases (see Figure 3.11) as well, whereas the accuracy of the prediction reduces.

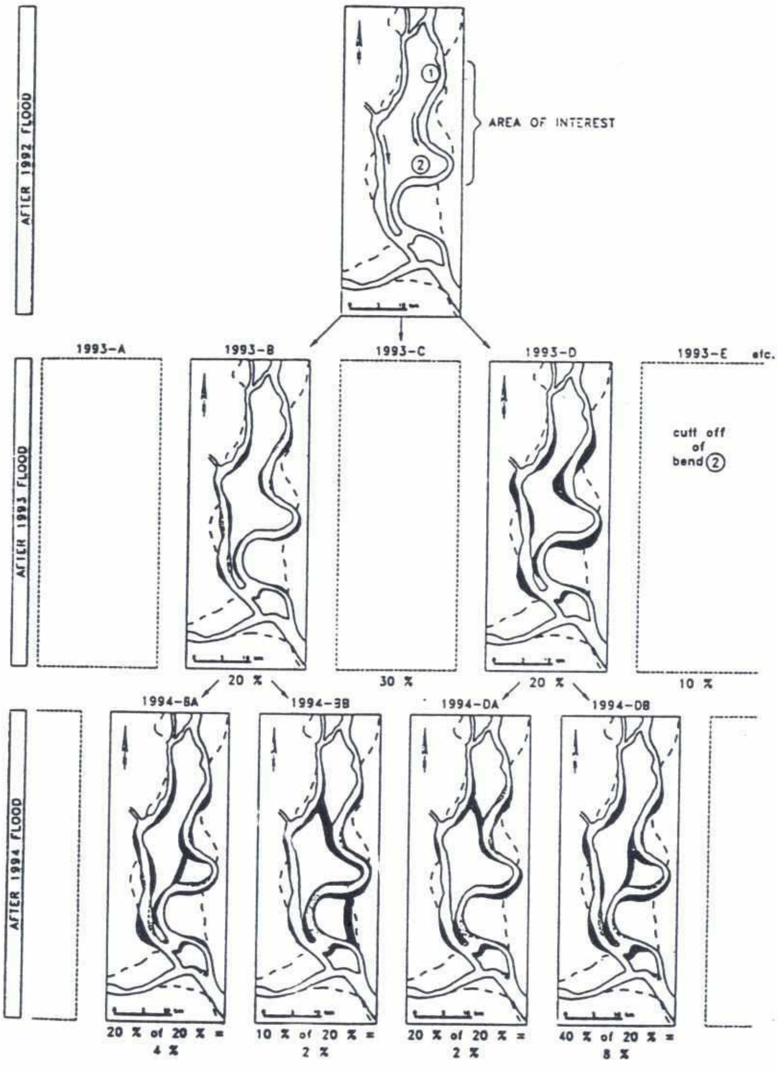

Figure 3.11 Methodology of predicting future planform changes by a stochastic model (Klaassen et al, 1993)

3.6 Parallel study

3.6.1 Introduction

As mentioned earlier, two joint studies of FAP 24 with the Universities of Nottingham and Leeds were performed. Their study area is the same as that of the present study. Among these studies, UoN/FAP24 joint study is completed. The study topic is: 'Secondary Currents and Morphological Evolution in a Bifurcated Channel'. The measurement location was around a bar downstream of Bahadurabad, see Figure 3.12. This study is mainly performed by using the data from special surveys. In the next section this study is reviewed.

3.6.2 Secondary Currents and Morphological Evolution in a Bifurcated Channel

Secondary currents are defined as currents which occur in the plane perpendicular to the axis to the primary flow (Prandtl, 1952). This type of flow generally occurs by skewing of cross-stream vorticity into longstream direction when the flow is curved. Skew-induced flow cell carrying fast surface water towards the outer bank and slow near bed water towards the inner bank (England, 1974). Thus the flow of water and sediment in different direction results in: point bar formation, bank erosion at the outer bend and meander migration that leads to the planform evolution of a typical meandering river. Decades of research into meandering rivers had established the secondary flow models, which consist of a single skew-induced cell. Later, direct measurements of secondary currents using electromagnetic current-meters indicated that close to the eroding bank there was often a smaller cell of reverse rotation (Thorne and Hey, 1979). Furthermore, it was identified that beyond the secondary cell, the flow over the upper point bar is directed radially outwards through the whole water column, see Figure 3.13.

Recently Ashworth and Ferguson (1992) extended the secondary current concept for the braided river. They suggested that a bifurcated channel could be viewed as consisting of back-to-back meander bends, one channel being a mirror image of the other. Their concept was based on the single skew-induced flow cell in each bend. On this basis, the secondary flow pattern would consist of twin skew induced cells, diverging at the surface and the converging at the bed. Extending Ashworth and Ferguson, the University of Nottingham (UoN) made a hypothesis, introducing the secondary-current model shown in Figure 3.14. Based on this hypothesis, UoN conducted their study surveys around a braid bar downstream of Bahadurabad in different periods of 1994, and they attempted to relate their hypothesis to the development of the bar through the passage of flood of that year.

In addition to the special surveyed data, UoN analysed satellite images to study the recent development of their study area. UoN nicely presented the pattern of bank of bankline retreat of the study area and the bank line retreat was estimated by superimposing the subsequent satellite images. They linked the dimension of the embayment with the dimension of the braid and point bars in the Jamuna River and also the meander wave length of the braided channels. UoN named the bowl-shaped bankline formation by curved channel which is very common at both banks of the Jamuna River, an "embayment". They found that the spacing of left bank embayment near Bahadurabad was about 6 to 8 km, which coincides with the length of braid/point bars of the Jamuna River as indicated by Thorne et al (1993) and it is also approximately half of the meander wavelength of the left bank anabranch. UoN concluded that, geometrically, the bank embayment and other planform features are scaled on the channel parameters.

UoN's surveys around the Roy's bar consist of about 750 m spaced ADCP transects, which covered the front, lee, left and right side of the bar. Three surveys were carried out in May, August and September 1994. The survey vessel used in the measurement was unable to measure by ADCP the water column about 0.50 m from the riverbed and about 2.70 m from the water surface. The ADCP measures flow velocity and its three components in three directions and backscatter intensity at an interval of 0.50 m. Backscatter intensity is a measure of suspended sediment concentration. In the RSP survey vessel an Electro-magnetic Flowmeter (EMF) was mounted to measure the flow velocity at a depth of 0.50 m from the water surface. During the analysis it was observed that the direction of EMF flow velocity was not consistent with the ADCP measurement. Therefore, UoN did not use the EMF velocity measurement during their analysis. For each transect measurement they tried to analyses the perpendicular components of flow to the long flow direction at different depths to identify the secondary currents direction. These perpendicular flow components will from now on be called "cross-stream flow direction".

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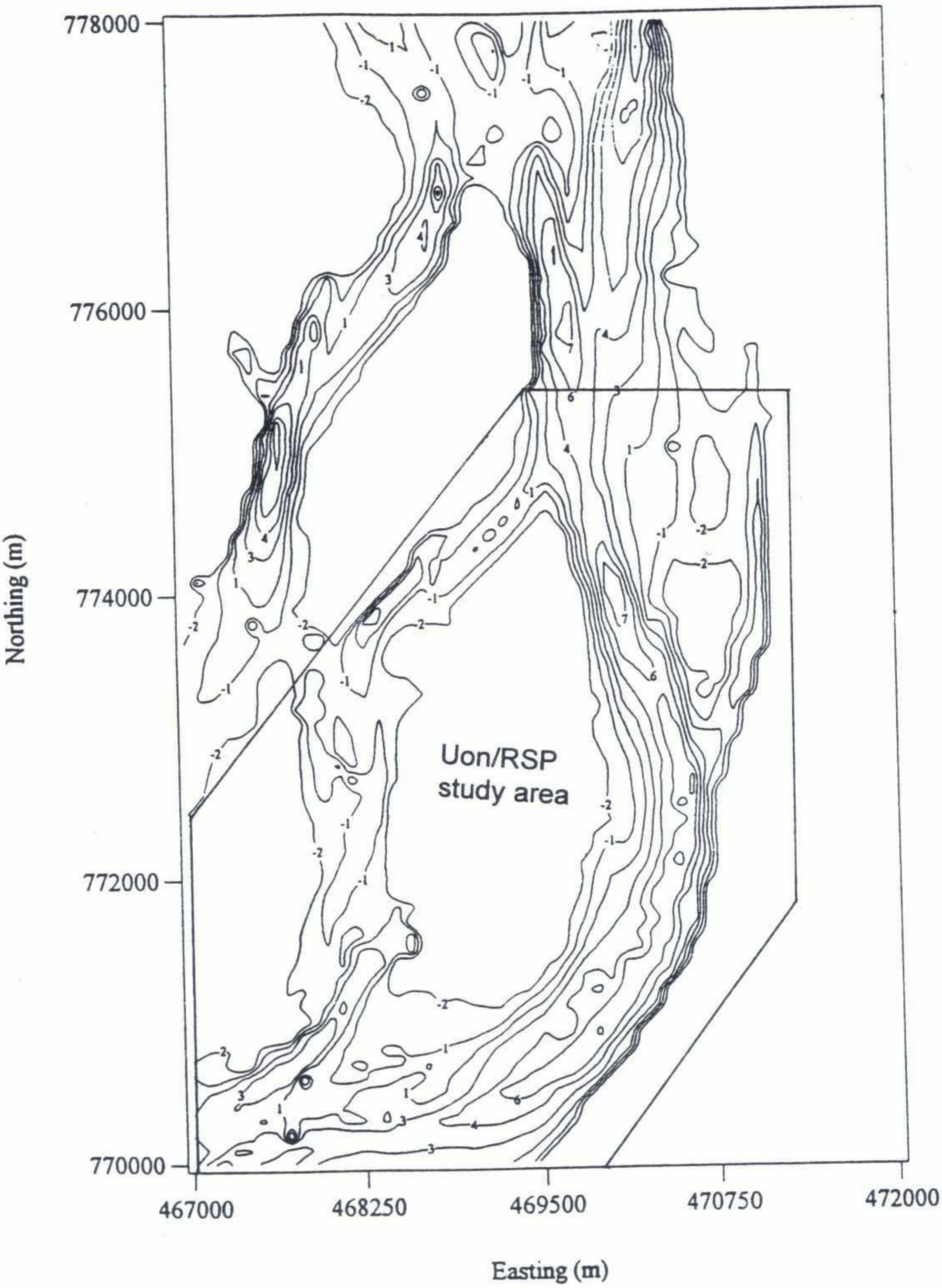

Figure 3.12 The study area of UoN/RSP Joint Study shown on November 1993 bathymetric survey

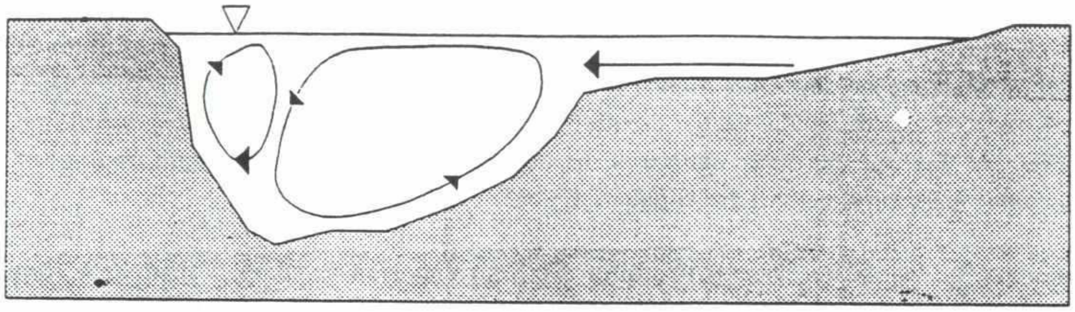

Figure 3.13 Secondary currents in a river bend (Thorne and Hey, 1979)

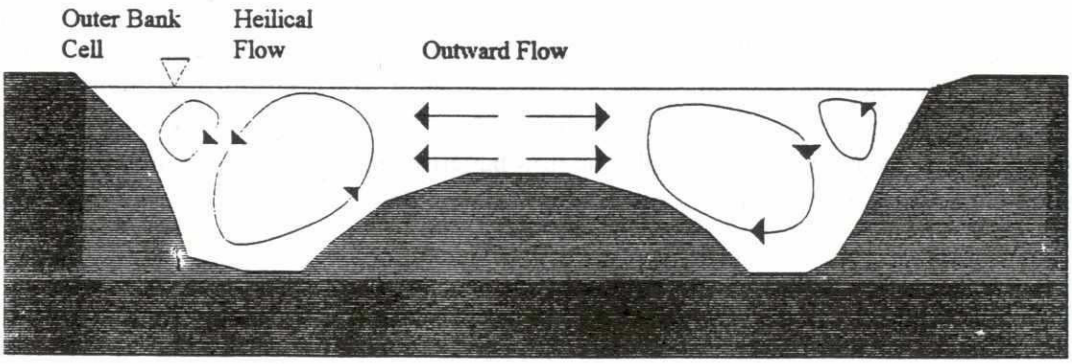

Figure 3.14 UoN hypothesis for the pattern of secondary currents in a bifurcated channel

In general, the cross-stream flow direction resulting from ADCP measurement, did not show distinct secondary flow currents. It is probably due to the survey by moving boat method, in which the turbulence of flow contribute to spreading of the flow direction instead of averaging it. Although in a few transect measurements there were some indications of secondary currents direction.
Instead of cross-stream flow direction obtained from ADCP, UoN used indirect methods to identify the secondary currents. This indirect method was based on the iso-velocity and iso-backscatter profile of a transect and the basis of the method was that upwelling should be associated with upward bulging of iso-vels and downwelling causes the compression of isohels (Figure 3.15). Similar to the velocity, upwelling is associated with high sediment concentration

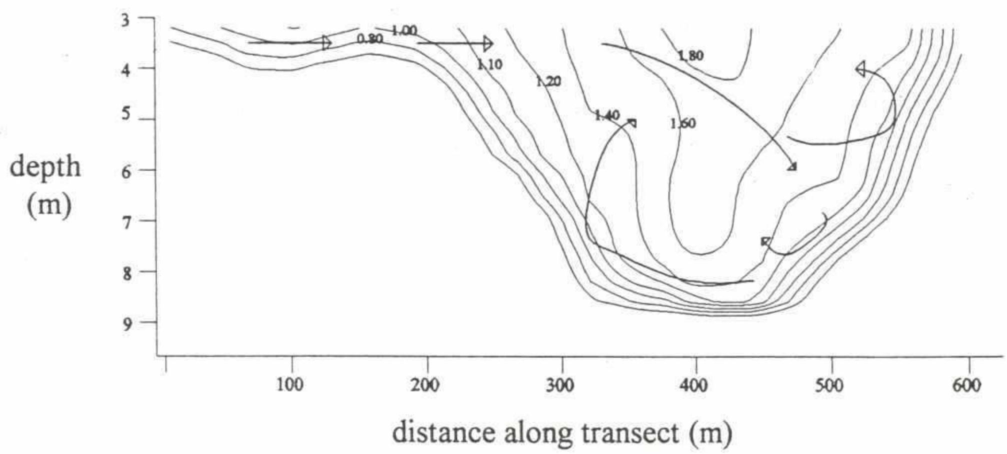

Figure 3.15 Iso-vels and iso-backscatter and estimated secondary currents in a section

In the body of flow, whereas the downwelling brings sediment-free water down closer to the channel perimeter. Following the above mentioned method, UoN attempted to draw secondary currents for all the transects measured around the bar in different periods and also attempted to explain the development of the bar with the aid of the pattern of the flow (see Figure 3.16). The main findings of UoN from the analysis of flow pattern are summarised below:

The pattern of the secondary currents in a bifurcating currents is more complex than their hypothesis mentioned earlier. It appeared that in contrast to Figure 3.14, at the point of hydraulic division of the two streams of water, the helical flow is clockwise in the left channel and counter clockwise in the right channel. This pattern of the flow attacks the tip of the bar and leads to migrating the bar nose in downstream direction.

The crossing of the flow in both branches occurred about one third of the bifurcated reach and nearly at the middle of the reach; strong helical flow exists associated with outward flow in the inner bend, which leads to lateral growth of the bar. The helical flow at this reach is counter clockwise in the left channel and clock wise in the right channel. The flow patterns and bed topography in the middle reach is corresponding to the hypothesised shown in the Figure 3.14.

The next crossing of the flow was at about two thirds of the way along the bifurcated reach. Downstream of the crossing the direction of the helical flow reverses again in both branches of the channel, where both parallel channels came closer again. The overall flow pattern around the bar was such that it moved the bar into downstream direction.

In this study the bar length that was found, was much higher than the space between the crossing of the flow, which indicate late-stage processes in a divided reach.

In addition to the UoN conclusions, a few more interesting morphological features were observed from their analysis and presented figures, which are as follows:

Most of the channel sections were lagging in response to adjust to the primary velocity distribution in a section. The UoN identified that secondary currents often change direction and location in a section within the measured period.The characteristic wavelength of the thalweg differs from the wave length of the flow. The characteristic wavelength of the flow changes with time i.e. changes with discharge of the channels and the wavelength of the flow in two divided branches were different due to having different discharge carrying capacity. On the other hand, in a section the distribution of the discharge rapidly changes due to the formation and diminishes medial bars within a short period. Moreover, the rapid changes of cross-sectional profiles and changes of the locations of medial bars in a section with time makes the channel processes very complicated. Therefore, it is very difficult to relate the flow wave length or wave length of the thalweg to the discharge, especially in the monsoon. Similarly uncertainty in scaling the bar dimensions with the channels parameters is also high.

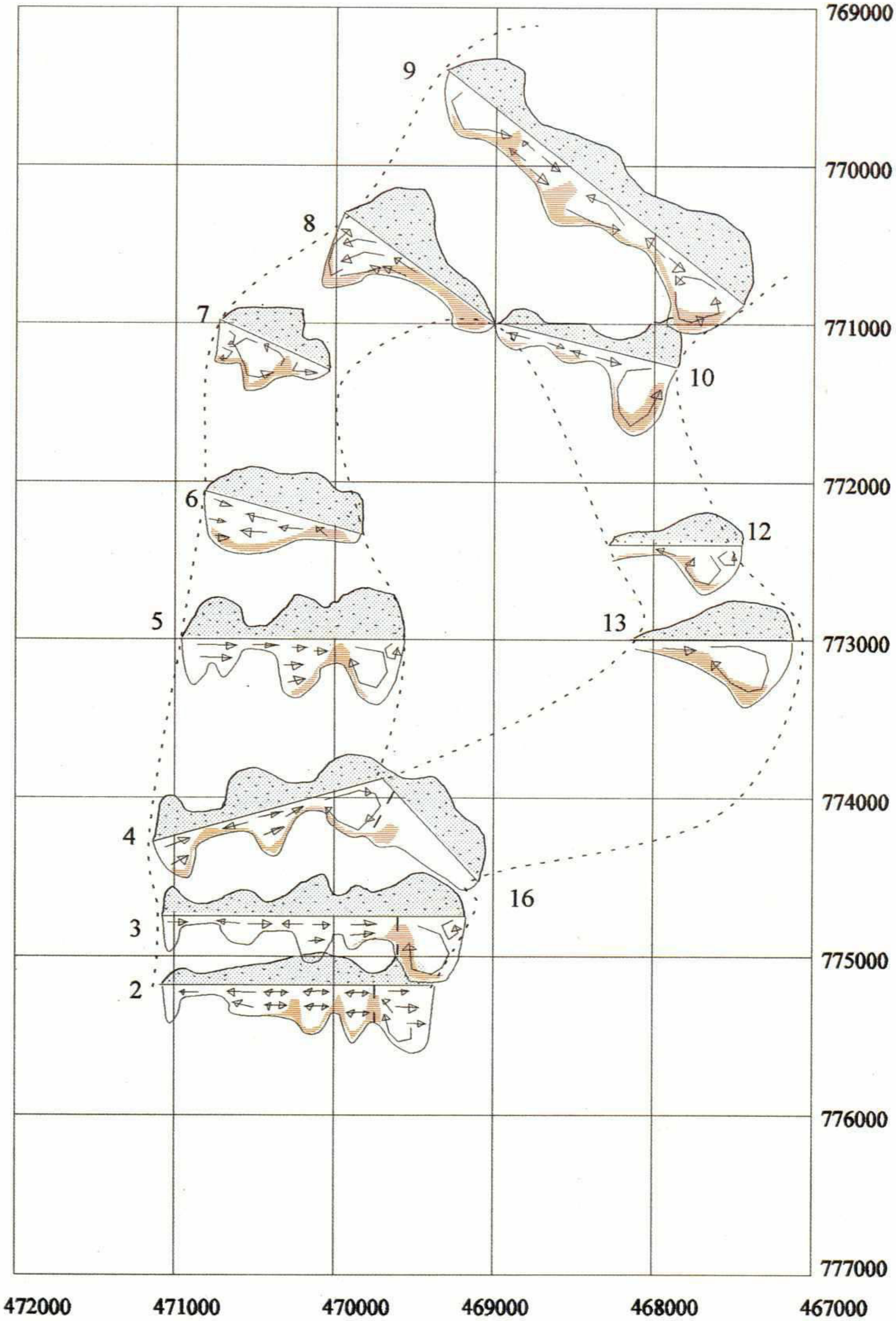

Figure 3.16 Near surface velocities and inferred secondary currents around a bar in August 1994

3.7 Summary

The literature review presented above can be summarized as follows:

- The braided rivers are unstable in nature and braiding is initiated from the instability from the riverbed. Generally erodible banks are prerequisite for braiding including the higher discharge, slope and form ratio.
- Knowledge of the processes in the large braided rivers is still limited. In addition, literature on large braided river is sparse. Moreover, reliable and relevant data on large braided rivers is also limited. Most of the studies of braided rivers are based on studies in a flume or in small-scale braided rivers.
- The prediction methods presently available in literature for predicting bedforms and roughness, are not sufficient for predicting a fair range of accuracy for the large braided rivers.
- A number of studies (Klaassen and Vermeer, 1988a; UoN/FAP 24 Joint study reviewed here as a parallel study) on the braided river mainly based on the extrapolation of the characteristics of a single thread channel. It appeared that the range of uncertainties is quite high, if such extrapolation is applied to the braided river, like the Jamuna.
- In recent years the use of satellite imagery in studying the morphological process in the Jamuna River contributed a lot to the knowledge of the complicated processes of the river. Although there are a number of limitations to these images as for representing the river processes, as they have been taken during the dry season.
- A number of prediction for formulas for the Jamuna river are now available for its main parameters such as the channel dimensions, sediment transport, cut-off processes, bank erosion rates, scour hole depths etc. These prediction formulas were mainly derived by using dry season satellite imagery, historical data (old maps and BWDB data) and also by collecting data more data from the river. Uncertainties of these perdition methods are considerable. Therefore only a stochastic type of model for the planform changes are feasible.

4 Data collection

4.1 Introduction

The River Survey Project began to regularly surveying the main rivers in Bangladesh in 1992. The surveys comprised (1) routine gauging, (2) detailed bathymetric soundings, and (3) surveys for special studies. The all-season routine gauging was carried out in eleven transects of the main rivers over a period of four years. Five areas were selected for detailed bathymetric surveys and twelve automatic water level gauges (AWLR) were installed. In addition, quite a number of staff gauges were placed at selected locations and they were read by local gauge readers. For an overview of the measuring locations, see Figure 2.1.

The bathymetric soundings were carried out on a 100 m grid. In this report, in particular the detailed bathymetric soundings carried out near Bahadurabad in the Jamuna River are used. In addition, use is made of data collected during routine surveys and the results of gauge readings of some specially installed staff gauges, all near Bahadurabad as well. Furthermore, satellite imagery of the Jamuna River is used to study the development before 1993 (Chapter 2) and additional evidence, notably a series of LANDSAT/MOS images taken during low-flow conditions over the period 1990-1995, was used for checking purposes.

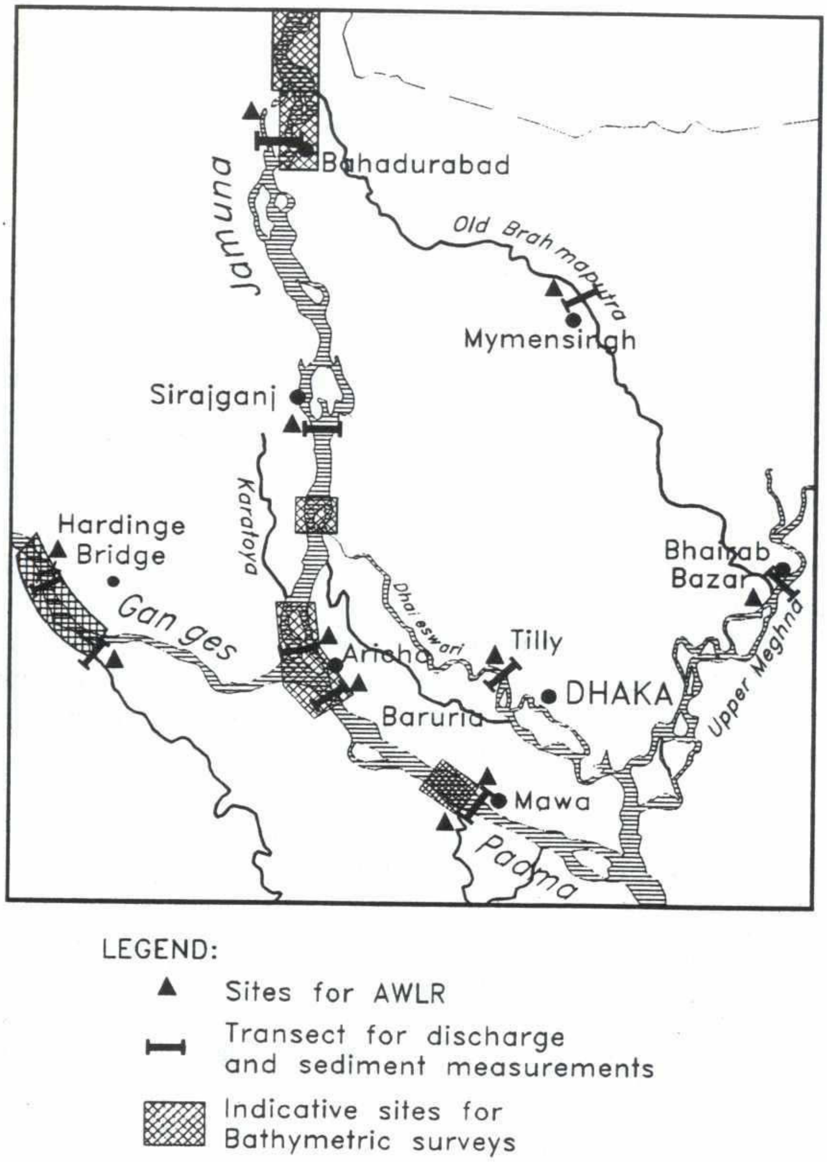

Figure 4.1 Location of transects for routine measurements and areas for bathymetric soundings

The data from the special surveys for the Joint Study of UoN/RSP, mentioned in Chapter 3 as parallel study, were used in this study to see the velocity pattern in the river bend. In addition, RSP rating curves based on BWDB discharge data are used for the study period. FAP21/22 bathymetric surveys August to October 1995 and FAP24 ADCP data of August 1995 at Kamarjani location are used to study the bank erosion processes at a place other than, but near, Bahadurabad.

4.2 RSP survey techniques

For the various surveys a fleet of five boats was available. All these boats had (slightly) different characteristics and also the instruments with which they were equipped were slightly different. The data used in this study were mostly obtained with a large vessel (named DHA) and two vessels (DHD and DHE) that were "specialized in" (especially equipped for) bathymetric soundings.

All vessels were equipped with up-to-date positioning and surveying instruments. The positioning of a vessel was determined with an estimated accuracy of 5 to 10 m by a Differential Global Positioning System (DGPS), for which system a few reference stations along the river were installed. The flow velocities were measured in the three directions (u,v,w) by an Acoustic Doppler Current Profiler (ADCP) in verticals with 0.5 m interval, except for the upper layer with a height of approximately the draught of the vessel and a bottom layer. The upper layer was sampled in two directions (u,v) by an EMF electromagnetic flow meter. During the surveys the discharge in the larger rivers was measured with an ADCP, using the moving boat method while sailing from one bank to the other. In these large rivers the bank-to-bank distance for one channel is often 1 to 3 kilometre. While sailing across the channel, ADCP measurements in subsequent verticals were done every 5 s. If required, the special vessels for bathymetric surveys (DHD and DHE) could measure the flow patterns with float tracking.

During the routine surveys the suspended sediment transport was measured by depth-integrated sediment samplers in a number of verticals, during special (study) surveys often pump-bottle sampling was used. The back-scatter of the ADCP provides qualitative and as well as quantitative insight into sediment concentrations. The bed-load transport was estimated with a Helley-Smith sampler and the near bed transport with a Delft bottle sampler on a frame. Due to the mesh size of 0.2 mm the Helley Smith only measures the coarser fraction of the bedload. The Delft bottle performs better in this respect, but also here the wash load of fine silt and clay passes this instrument. Bed sampling is carried out with an USBM-54 sampler in view of the large depths and high velocities.

The bathymetry was usually determined measuring cross-sectional profiles at a mutual distance of 100 m. The instrument used is a echo-sounder, which were available on all five survey vessels (see Table 2.1). The bedforms on the riverbed could be measured by echosounding in longitudinal sailing lines. In addition, a side-looking sonar was available, which however provided only useful information in the lean season when the velocities and sediment transport rates were relatively low.

The survey data were checked online, whereas the final processing of the data was done offline in the project office. A selection of these data were stored in a user-friendly database, called PSD 24, using Paradox and Quattro Pro software (Borland). A series of data books was being prepared with a summary of the data and these books could be used as a guide to the use of this database.

Parameter	Instruments and/or methodology	Survey Vessel				
		DHA	DHB	DHC	DHD	DHE
Positioning	■ Differential Global Positioning System (DGPS)					
	- Trimble 4000, 9 channel	x	x	x		
	- Trimble Navtrac, 6 channel				x	x
Discharge	■ Moving boat with ADCP	x	x	x		
	■ Area-velocity method	x		x	x	
Flow velocity and flow direction	■ 300/600 kHz Acoustic-Doppler-Current-	x	x			
	Profiler (ADCP)	x	x	x	x	
	■ EMF electromagnetic flow meter	x		x	x	
	■ S4 Inter Ocean electromagnetic flow meter	x	x	x	x	x
	■ Braystroke propeller velocity meter float tracking					
Cross-sectional area	■ Echo-sounder	x	x	x	x	x
	■ ADCP	x	x			
Suspended sediment transport	■ Pump sampler	x		x	x	
	■ Depth integrated suspended sediment sampler	x				
	■ MEX-3 turbidity meter	x	x			
Bed load transport	■ Helley-Smith basket-type sampler	x		x	x	
	■ Delft Bottle sampler	x				
Bed material samples	■ USBM-54 sampler	x				
	■ Van Veen grab sampler	x		x		
Bathymetry	■ Echosounder	x	x	x	x	x
Bedforms	■ Echosounder and	x	x	x	x	x
	■ Side Scan Sonar EG & G Model 260	x				

Table 4.1 Instruments aboard the vessels

4.3 Measurements carried out

The present study is based on a detailed analysis of a variety of measurements in a reach of the Jamuna River near Bahadurabad. The basis are seven bathymetric soundings, which have been made at relatively short intervals. In addition, other measurements of parameters like discharges, sediment transport measurements, water-level slopes, etc. are used. In this chapter a brief overview of the data collected in the period June 1993 - December 1995 is given. In subsequent chapters these data will be used for the interpretation of the changes that have taken place in this period.

The measurements carried out by RSP can be divided into the following categories:

- routine measurements of flow and sediment, and water-level measurements;
- bathymetric surveys;
- special surveys for study purposes.

Moreover, data collected on a routine basis by the Bangladesh Water Development Board (BWDB) were used as well. Finally, results from gauge readings are used. These are partly BWDB routine gauging and partly AWLRs placed by the RSP. An overview of the various measurements carried out and used in this study is given in Table 4.1.

No.	Measurements	Type of data	Times of surveys	Frequency	Period
1	Routine gauging	ADCP transect	41	Once/month	Jan.93-Dec. 95
		Sediment transport	41	Once/month	Jan.93-Dec. 95
		Bed material samples	103		Jan.93-Mar.94
2	Bathymetric surveys	Bathymetry	7	Twice/year	Jun.93-Dec.93
3	Special surveys		4		
	a. Test gauging	ADCP transects	1		Aug.93
		ADCP long profiles			
		Dune tracking			
	b. Weekly discharge	ADCP transects	19	Once/week	Jun.94-Apr.95
	c. Local slope	ADCP transects	3	Irregular	Jun.94-Nov.94
	d. Secondary currents around a bar	ADCP transects	3	Irregular	May-Sept.94
	e. Dune dynamics	ADCP long profiles	26	Irregular	Aug.94-Dec.95
		Dune tracking			
	f. Bar dynamics	ADCP transects	5	Irregular	Aug.94-Sept.95
		ADCP long profiles			

Table 4.2 Overview of measurements carried out in the study reach at Bahadurabad in the period June 1993 to December 1995

4.4 Accuracy of the data

Accuracy of the data mainly depends on the instrument used and the methodology followed during the data collecting. Inaccuracies are generally introduced due to: (1) instrumental errors, indicating the limitation of the instruments and (2) errors in the applied methodology of surveying. Here both types of errors are discussed in the following:

Instrumental errors

The instruments mainly used were ADCP, EMF, Echosounder, AWLR and different bed and suspended sediment samplers. ADCP cannot measure the lower 6% of the depth due to its configuration and it is also unable to measure a certain distance from the water surface due its position in the vessel and its required vertical clearance of 1.7 m (see Figure 1 in Annex 2). During FAP24 measurement a combination of EMF and ADCP was able to measure from the surface to a depth about 6% of the water depth above the bottom. For estimating the discharge, velocity profiles are needed to extrapolate down to the bottom. The accuracy of the double frequency Echosounder has a range of about two centimetres and the AWLR has also have same range of accuracy. The standard errors of the different instruments used in measuring velocity and direction of velocity, sediment concentrations are presented in Table 4.3.

Instruments	Standard deviation (%)			
	Velocity	Direction	Silt fraction	Sand fraction
ADCP	±4.6	±1		
EMF	±2.5			
S4	±5.1	±1.3		
Pump bottle			±3.9	±18.6
Delft bottle				±10

Table 4.3 Observed standard errors of the different instruments used in FAP 24 surveys (based on RSP 1996a)

In addition to the standard errors, inter-comparison of the instruments shows that the depth integrated-bottle as applied in the DHA vessel, underestimates the sand concentration by about 23 to 33%. The Delft bottle sampler on the other hand, does not represent particles less than 0.125 mm correctly. From the standard error of the instrument observed from the RSP analysis it is observed that accuracy of the instruments are quite fair. A few instruments have limitation in measuring the sediments, especially the Helly-Smith bed load samplers, the reason of which is indicated earlier.

Errors due to applied methodology

An error may be introduced by the methodology followed during the survey. This type of error can only be compared between the results obtained by following different methods. This type of comparisons beyond the scope of this study. Here the possibilities of error introduction can be indicated. As stated earlier, in estimating the discharge from ADCP measurements extrapolation of velocity was needed, which may introduce uncertainties. During the sediment gauging, the point-integrated or depth-integrated suspended sediment, the movement of the vessel introduced errors as measuring is not possible at a fixed point.

The BWDB measures discharge using Ott-propeller, the standard deviation of which is ±6.5%. The methodology followed by them is the velocity-area method. The comparison of the ADCP-EMF moving boat method followed by RSP with the BWDB, results in the ranges of variation of almost ±8.5% (estimated during two BWDB/RSP joint surveys). But often higher ranges of variation are observed if the results of discharges are compared for same period.

The accuracies in the bathymetric surveys are very important in comparing the riverbed erosion and deposition. In addition to the instrumental errors, the accuracy of the bathymetric surveys depends on the line spacing of the surveys and the variation of the local slopes at the river reach. The bathymetric surveys are presented in respect to m +SLW level of one water-level gauging station only, thus the different local slopes during different surveys can result in a different level for a point without any changes. For example, at a point 10 km from Bahadurabad, a change of 3 cm/km local slope may result in 30 cm error.

In a braided reach of the river, a number of channels are present and the channel's number is also the function of the stages of the discharges. Surveys in the monsoon can cover almost all the channels, but during the dry season, some of shallow channels were not surveyed due to the lack of availability of required draft for the surveys vessels, while comparing the two surveys under different levels, can results in uncertainties in estimating the overall erosion and deposition on the riverbed. The bathymetric surveys required a number of days to cover a certain reach of the river. Due to comparatively rapid changes of the riverbed in the monsoon, bathymetric surveys are unable to represent the riverbed for a particular moment.

To survey in the river there will remain some uncertainties, especially while surveying in a braided river like the Jamuna river, where the riverbed, flow direction and the channels are continuously changing. Although there are number of possibilities of error introduction in the bathymetric surveys, the instruments used and applied methods of survey followed by RSP can produce a better bathymetry than ever had performed in such large rivers in Bangladesh.

5 Data processing and analysis

5.1 Introduction

The data used in this study are discussed in the previous chapter. Processing and analysis of the different types of data used are also discussed in this chapter. For this purpose the data are identified as follows: hydrological and sedimentological data, overall and local slopes data, ADCP data, bathymetric surveys etc. The processing and analysis of these data are presented with examples. The type of the river processes which can be observed from these data are also given. In addition to the data processing within RSP, a further elaboration of the data was done by using a Geographic Information System (GIS). GIS was also used for presentation of the data, and for subsequent studies.

The different data processing at the RSP are discussed in Section 5.2. The uses of GIS for presenting the data and further elaboration of the data are described in Sections 5.3 and 5.4.

5.2 Data processing

5.2.1 Discharges

Here mainly the processing and the analysis of the discharges measured during FAP24 surveys and of BWDB data are presented. Routine measurements by FAP24 began in January 1993. As an example of the results obtained, some results from the routine survey carried out from 31 October to 3 November 1993 along transect Cr 2 (see Figure 5.1) are presented in Figure 5.2.

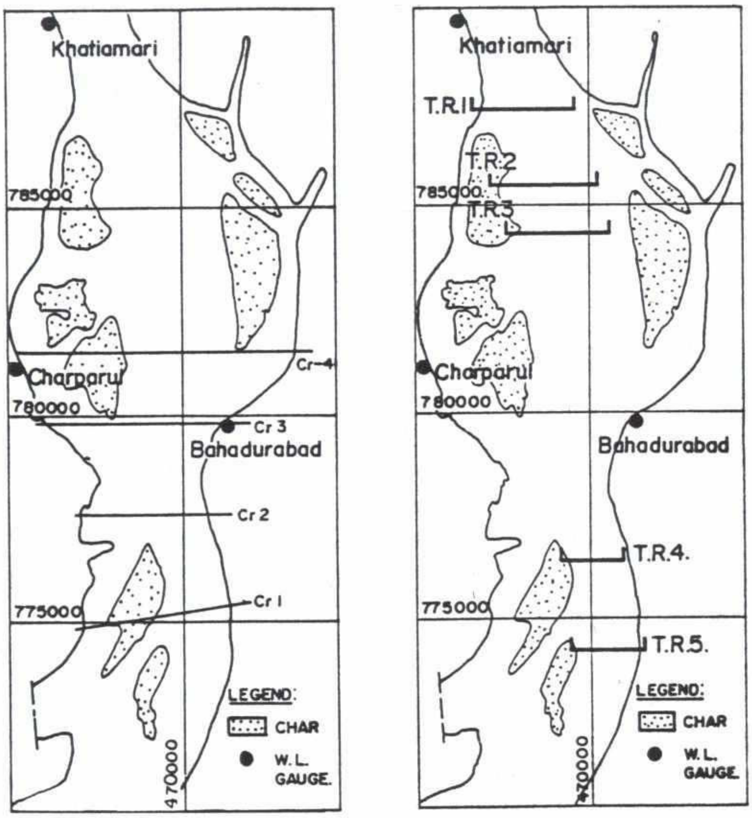

Figure 5.1 Locations of RSP routine measurements (Cr 2), cross-sections and water level gauges for local slopes (a) and ADCP transects (b) (see Section 5.3)

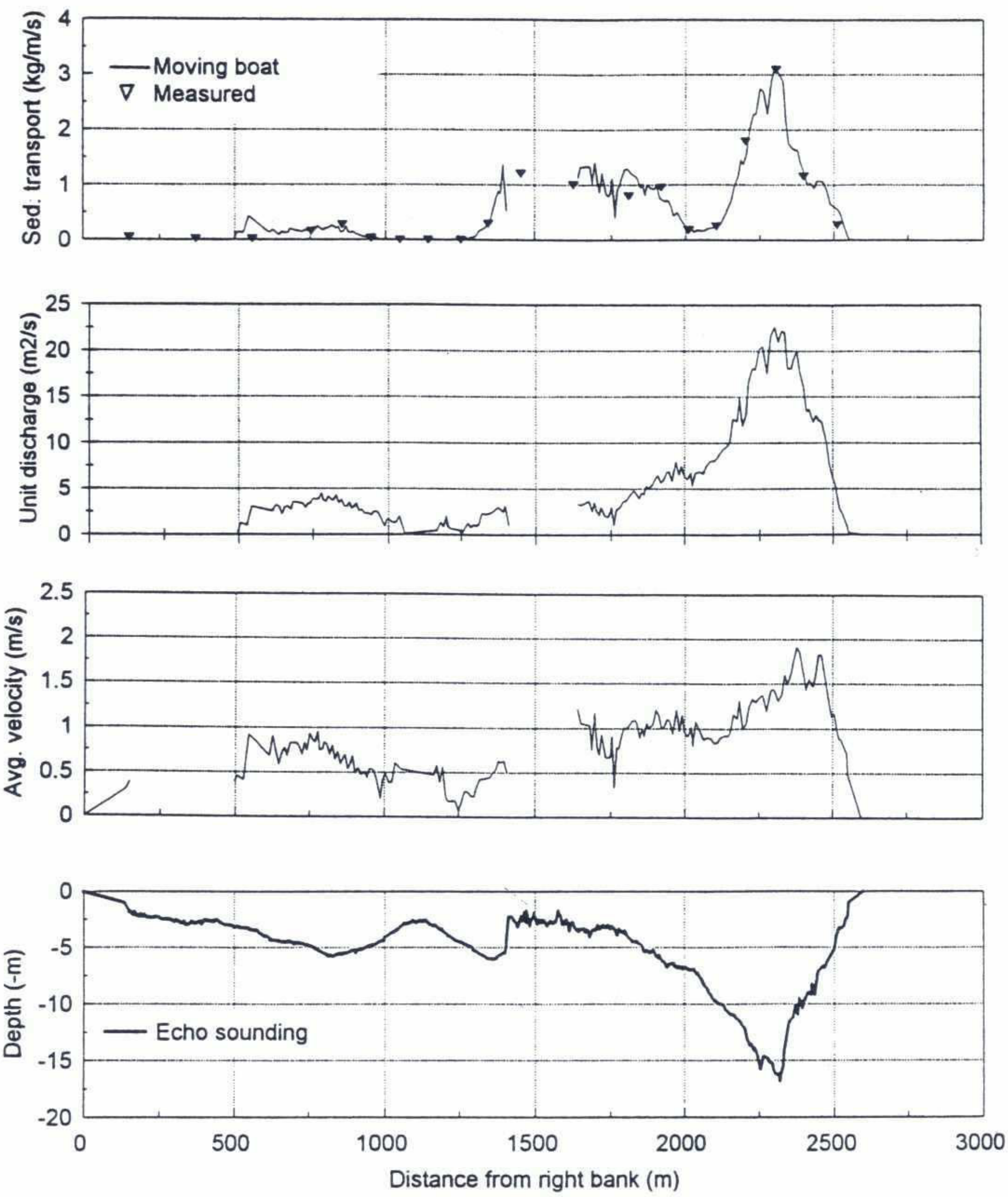

Figure 5.2 Results of RSP routine measurement carried out between 31 October and 3 November 1993

The cross-section is characterized by a main channel with a depth of up to 15 m below the water level and two smaller channels with a depth of 5 m. The depth-averaged flow velocities were measured with the ADCP. The maximum flow velocity in the main channel, which carries also the major part of the discharge, is almost 2.0 m/s. Where the water depth was less than about 2.5 m, the ADCP could not measure. For those more shallow parts the flow velocities had to be estimated. For this particular routine measurement the discharge in the left channel (measured several times) varied between 10,000 and 10,500 m^3/s.

BWDB also carries out routine measurements and determines rating curves valid for particular years on the basis of these measurements. These rating curves are used to calculate the daily discharge in the Jamuna river by combining them with the stages observed daily. The thus obtained (calculated) daily discharges in 1993 to 1995 are shown in Figure 5.3. Based on BWDB measurements the RSP also separately derived rating curves for the year 1995 for the Left Channel. This rating curve is used to estimate daily discharges in the left channel for the study period. Although the stage discharge relation varies yearly, this rating curve is used here to derive the discharge in the left channel in comparison to the whole Jamuna River. It can be concluded that the left channel is the main one, as it carries 65 to 75% of the total discharge during the monsoon 1993. In the lean season this percentage increases up to 75 to 85% of the total discharge.

Moreover, based on the RSP weekly discharge and routine gauging, a rating curve was derived for the year 1994 and this rating curve was used to estimate the discharge in the Left Channel, see Figure 5.3. It was found that the RSP discharge at Bahadurabad is about 15 to 20% less than the BWDB discharge. For this study RSP measured discharges are more relevant as the RSP measured velocity and sediment transport which are used for different analysis. Furthermore it is observed that the flood discharge and overall discharges in 1994 were comparatively small compared to the years 1993 and 1995.

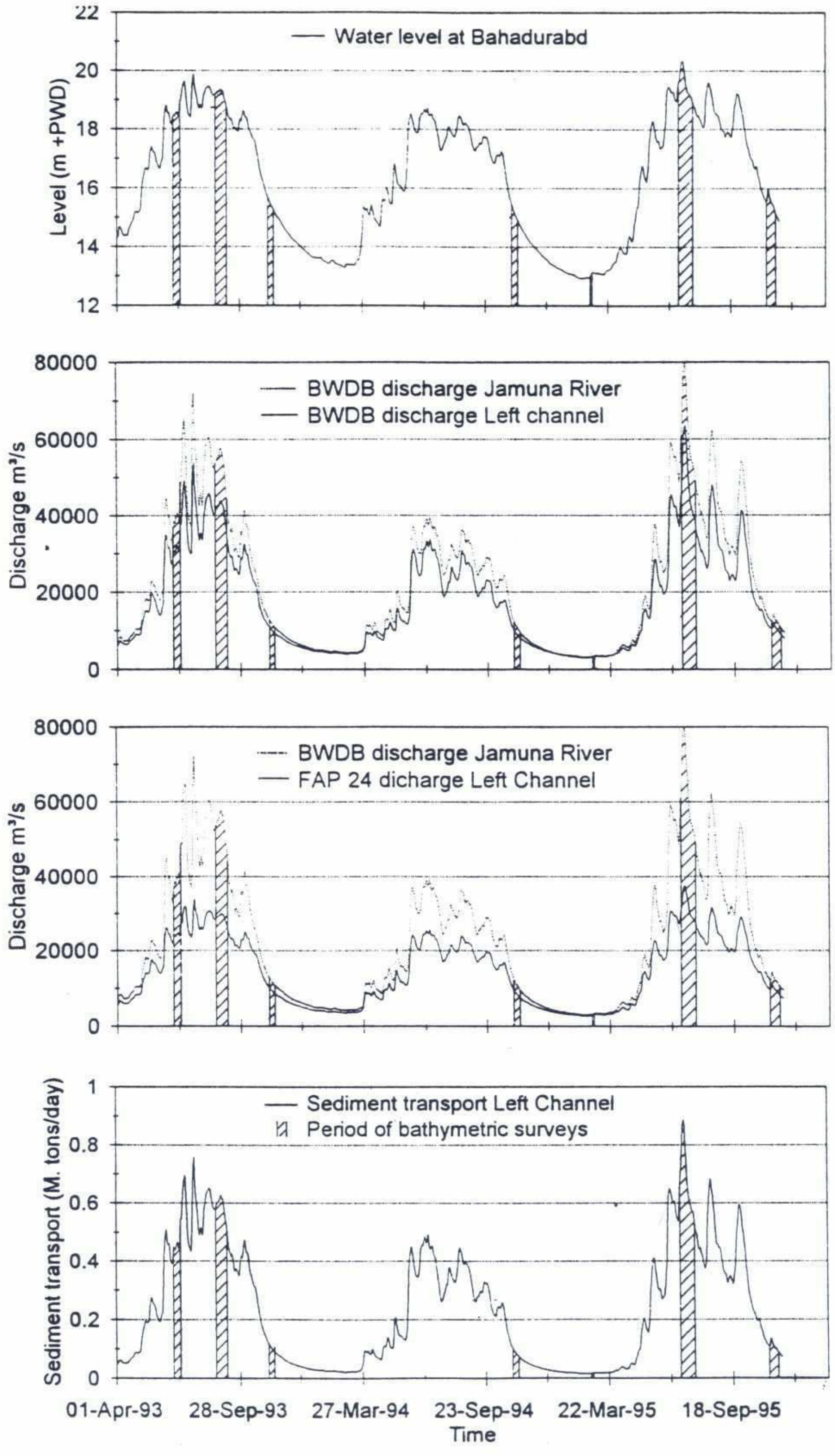

Figure 5.3 Daily water level at Bahadurabad, daily discharges (obtained from BWDB rating curves), daily discharges in the left channel based on BWDB data (obtained from rating curves 1995), daily discharges in the left channel (obtained from rating curves 1994) and sediment transport in left channel based on FAP 24 surveys near Bahadurabad in period April 1993 - November 1995 (Note: Period of bathymetric soundings also indicated)

5.2.2 Sediment transport

During the routine measurements average sediment concentrations were measured in about 20 verticals and these were multiplied with the ADCP flow velocities to calculate the sediment transport. For the particular example of 31 October to 3 November the thus obtained unit sediment transport (hence in kg/m/s) are presented in Figure 5.2 as well. The maximum sediment transport rate occurs again in the main channel, but also in the shallow area between the main channel and the other two smaller channels the sediment transport intensity is relatively high. This is observed often and it is explained by the three-dimensional phenomena, notably the effect of morphological features (Peters, 1993) and locations with high velocity gradients.

By integrating over the width the total sediment transport (expressed in kg/s) can be determined. By relating the total sediment to the total discharge, a sediment rating curve can be obtained. Such a curve can be used for generating daily sediment transport rates. The results obtained via this sediment rating curve are also presented in Figure 5.3. In this figure only the suspended bed-material transport is considered. In the Jamuna River the average fraction of total sediment transport (bed material) less (about 30% of the wash load) than the wash load (RSP 1995a). The total bed-material transport in the Left Channel in-between the period of successive bathymetric surveys can be estimated using these data (using Figure 5.3), see Table 5.1

Period	**Sediment transport in the Left Channel**	
	M. tons	**Bulk volume (Mm^3)**
27/6/93 to 31/8/93	39	24
01/9/93 to 14/11/93	25	15
15/11/93 to 5/11/94	64	39
06/11/94 to 25/2/95	4	2
26/2/95 to 15/7/95	35	21
16/7/95 to 18/11/95	50	30

Table 5.1 Total bed material sediment transport in between the consecutive bathymetric surveys

It can be observed that the yearly bed-material transport volume (bulk) in the Left Channel varied between 39 to 52 Mm^3. These transported sediments are instrumental in causing erosion and deposition of the riverbed.

The bed load and near-bed load up to a few centimetres above the riverbed was measured by the Helley-Smith sampler. The D_{50} values of these samples varied from 0.20 mm in the monsoon with high sediment transport to 0.27 mm in the lean season with low sediment transport. The D_{50} of the bed samples is 0.02 mm to 0.10 mm less than the D_{50} of the Helley-Smith samples, because the Helley-Smith samples do not catch the fine fraction whereas the bed sampler does.

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5.2.3 Overall and local slopes

Water levels are routinely measured by BWDB on a daily basis in among others Chilmari (at the right bank about 47 km upstream of Bahadurabad), Bahadurabad and Sirajganj (also at the right bank and about 78 km downstream of Bahadurabad). For the period considered the observed stages are presented in Figure 5.4. In general, the hydrograph has a very regular receding limb towards the lean season, but the monsoon discharge shows much more variability. The water-level variation through the flood season of 1993 at Bahadurabad was about 6.5 m. In the figure also Standard Low Water Level (SLW) is indicated. SLW is the water level that is on the average exceeded during 95% of the hydrological year. The relation between PWD and SLW was determined by the Bangladesh Inland Water Transport Authority (BIWTA), and in Bahadurabad the SLW corresponds to 12.03 m +PWD. It can be concluded that the 1993-1994 lean season was not very dry.

From the observed stages the overall water-level slope between these stations can be calculated. The results for the two reaches Chilmari-Bahadurabad and Bahadurabad-Sirajganj are presented in Figure 5.4 as well. Apparently the overall water-level slope between Bahadurabad and Sirajganj varies between 0.07 to 0.08 m/km with the lower value being representative for the end of the flood whereas during the lean season the overall slope slowly increases again. There is evidence that the water-level gauge data from Chilmari are less reliable than from the other gauges, therefore the relatively high values of the overall slope between Chilmari and Bahadurabad may be less doubtful.

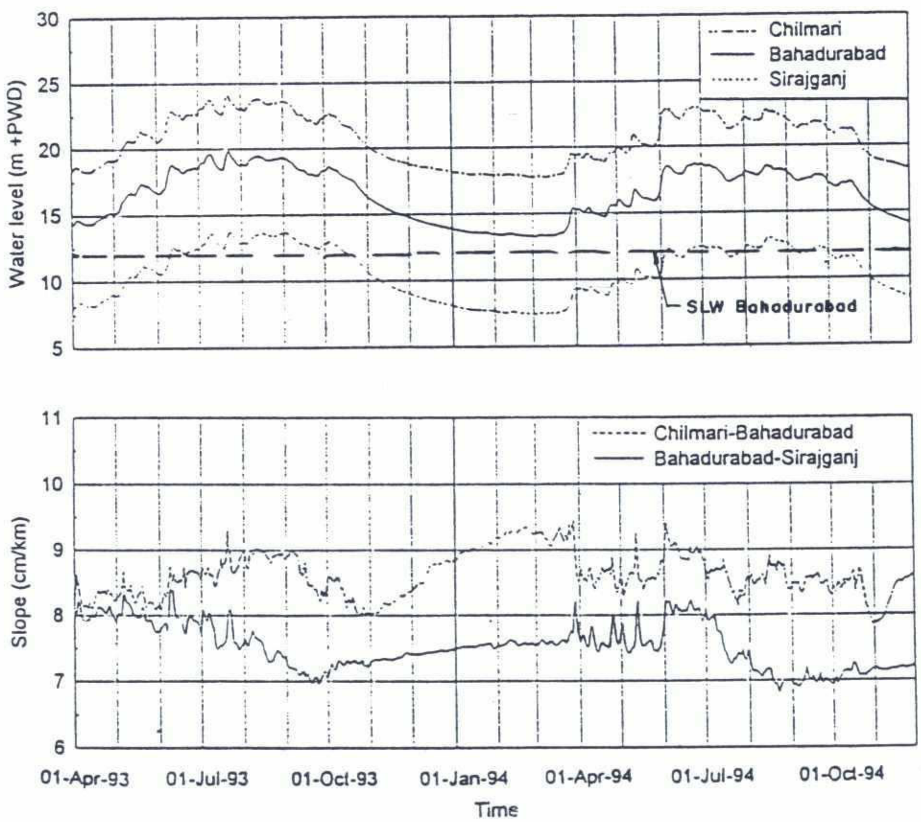

Figure 5.4 Observed water level and overall slopes: Chilmari-Bahadurabad and Bahadurabad-Sirajganj

As part of the hydrological study component of the project, the local water-level slopes were measured at a number of stations in the Bahadurabad area. These can be compared with the overall water level slope in this river reach. For this purpose the temporary staff gauges of the water level were placed in Charparul and Khatiamari (see Figure 5.1). The measured water levels are presented in Figure 5.5. In the same figure also the local slopes, determined by dividing the measured water-level differences by the distance along the channel, are presented. The local slopes seem to reduce from 0.08 to 0.11 m/km in the monsoon period to 0.04 to 0.07 m/km in the lean season. Due to local effects (large-scale morphological features like islands and bars) the local slopes can reach higher values than the overall water level slopes. It is also observed from Figure 5.5 that the local slope of Khatiamari-Bahadurabad is higher than that of Khatiamari-Charparul. This difference is probably due to the curved lengths of the parallel channels. The difference in the local slopes of two anabranches may be an indicator of planform changes (Peters, 1988).

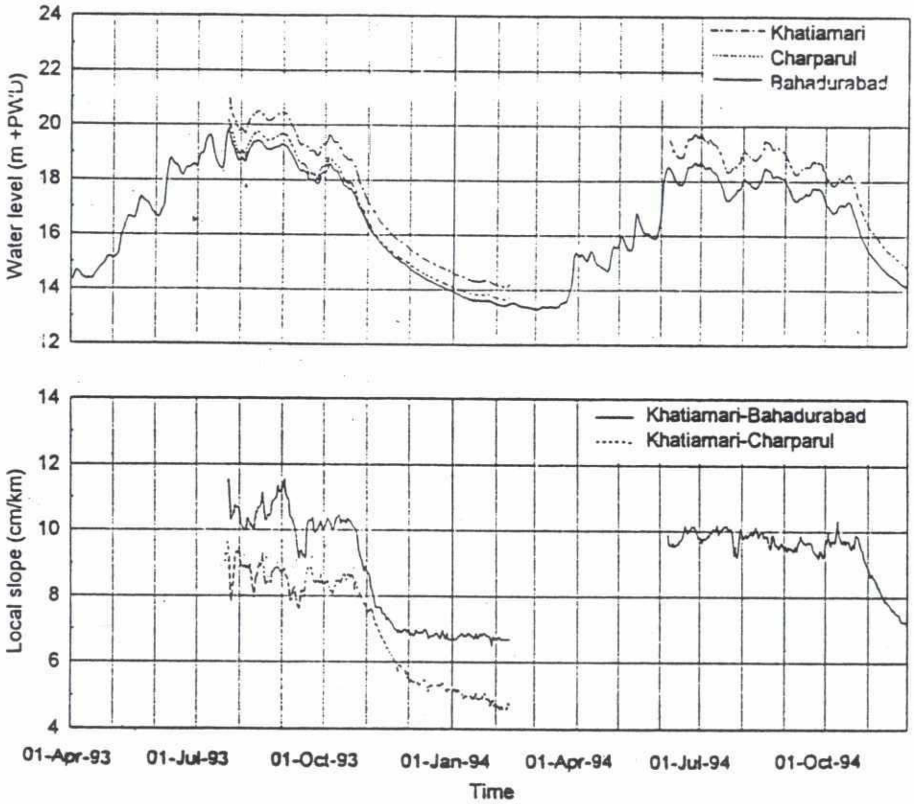

Figure 5.5 Observed water levels near Bahadurabad and local water-level slopes

5.2.4 ADCP velocity and backscatter intensity

During a part of the bathymetry survey in August 1993, which was done by the DHA vessel, the ADCP was recording the flow velocities and the backscatter. The latter is a measure for the sediment concentration. The backscatter intensity as measured by the ADCP can be combined with the bathymetry. See for example the cross-sections in Figure 5.6, the location of which is indicated in Figure 5.1 as well. The cross-sections are shown when looking in upstream direction and the transects are approximately perpendicular to the main flow. The transects Tr-1 through Tr-3 are upstream of Bahadurabad, whereas the other two are slightly downstream of Bahadurabad (see Figure 5.1). Maximum velocities (u > 2 m/s) and maximum ADCP backscatter (> 90 dB) are indicated by hatching.

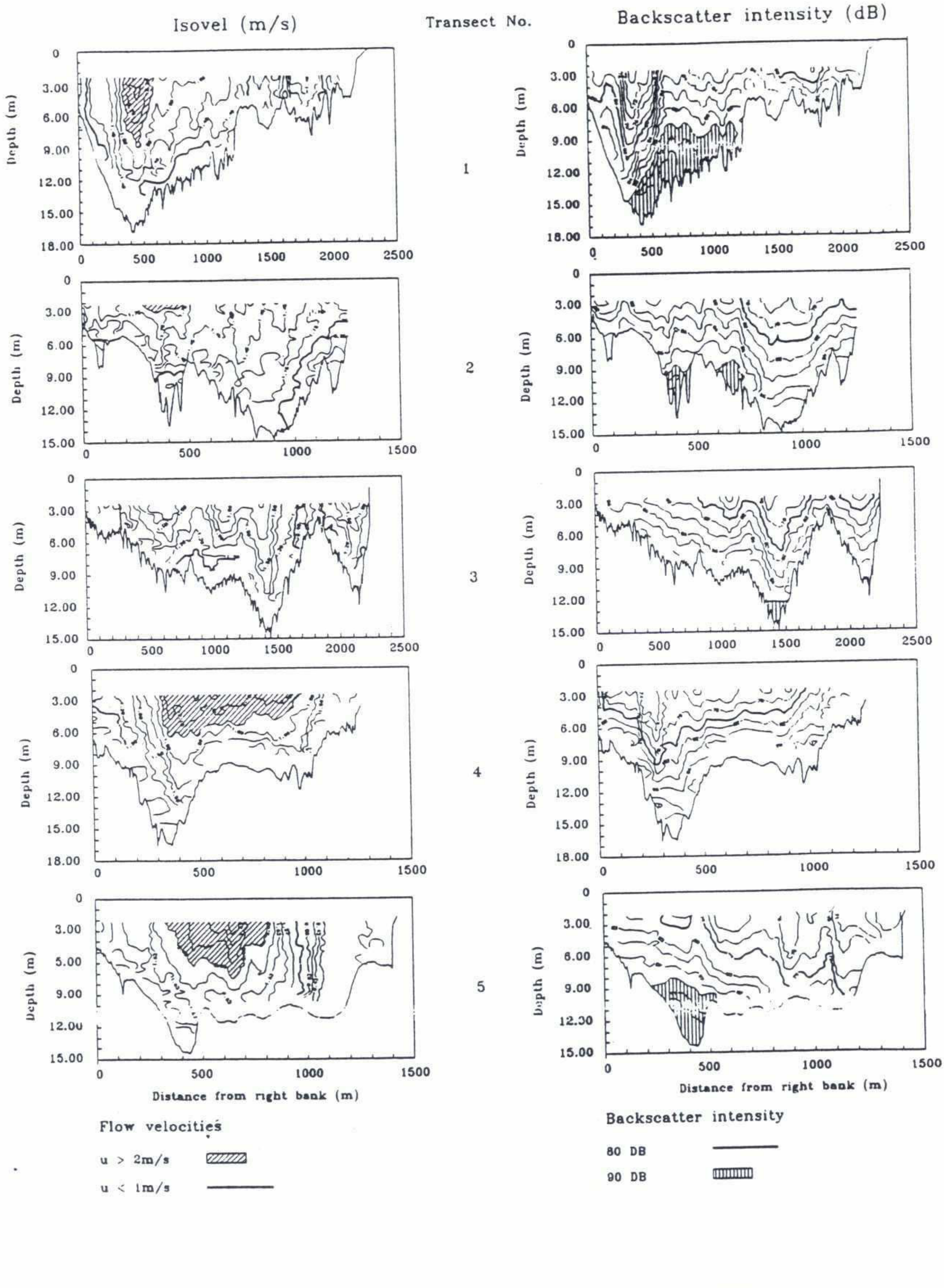

Figure 5.6 Iso-vels and iso-backscatter of a number of transects surveyed in August 1993

Following the flow from cross-section Tr-1 to Tr-3 the following tendencies can be identified:

- The maximum flow velocity is near the surface in the deepest channel and it shifts from the right bank to the middle and it decelerates from about 2.4 m/s to about 1.8 m/s.
- The backscatter indicates the maximum sediment concentration on a side slope of the deep channel 400 to 1200 m from the right bank. Backscatter intensity is decreasing in the downstream cross-sections. This tendency is similar to the deceleration of the flow velocity.

It is clear, however, that the largest sediment concentration do not coincide with the largest depths.

Following the flow from Tr-4 to Tr-5 (hence downstream of Bahadurabad) also some tendencies can be seen:

- The maximum flow velocity is not in equilibrium with the cross-section and is probably influenced by the upstream conditions. The maximum flow velocities concentrate in the middle of the channel, because the left bank in Tr-5 is just downstream of a sedimentation area (see Chapter 7).
- The backscatter shows not much sediment transport activity in Tr-4, but in the scour hole of Tr-5 quite some sediment transport activity can be expected.

During this study a relation was derived between the ADCP backscatter intensity (dB) and the suspended sediment (bed material) concentration (see Annex 2). The relation (Figure 5.7) was found very encouraging and it is now possible to estimate the suspended bed-material concentration at Bahadurabad with ADCP, provided the frequency of ADCP signal should be around 300 kHz, see Figure 5.8. This is probably the first time that the bed-material concentration in a river is estimated by the ADCP backscatter intensity (dB). The result obtained from the ADCP measurements is shown later.

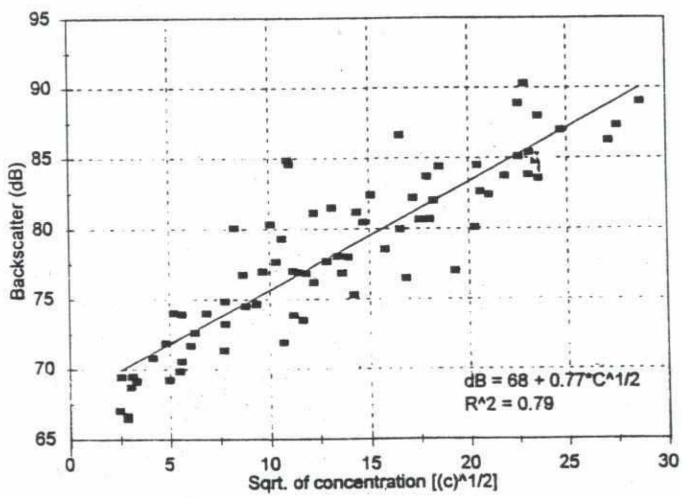

Figure 5.7 Relation between suspended sediment (bed material) concentration and backscatter intensity (dB)

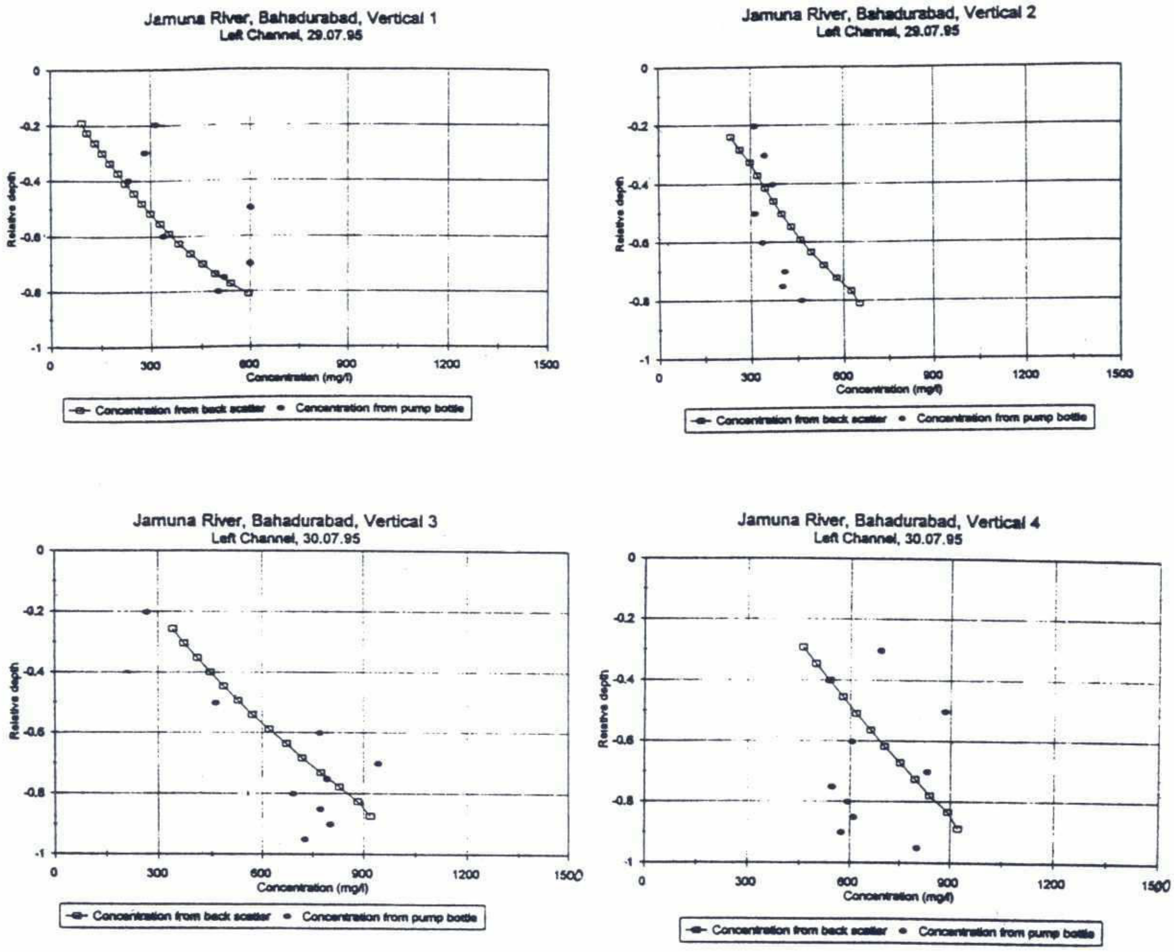

Figure 5.8 Comparison of estimated suspended sediment (bed material) concentration from ADCP backscatter intensity (dB) and the measured concentration by pump bottle sampler

5.2.5 Float measurements

During the Jul.95 and Nov.95 bathymetric surveys, the surface velocity and direction of the flow lines were measured for a number of lines using floats. These floats consist of two parts: the float proper and a cross frame, onto which, in general, thick cloth is attached. The width of the cross-frame is 0.50 m and the height is about 1 m. This frame along with a weight is hung onto the float by a thread. The length of the thread is in principle variable, but for the surveys in the Jamuna river the length was fixed at 1 m. A part of the float tracking lines measured during November 95 bathymetric survey is shown in Figure 5.9. The travelling length for which the time is measured to estimate the average surface velocity is also shown in the figure with the observed average velocity in m/s. The higher velocity is observed in the deeper part of the channel and consequently less velocity in the shallower part of the channel. The flow distribution here is almost in line with bed topography.

During the November 95 bathymetric surveys, a number of ADCP transects were measured. The flow lines derived from the ADCP discharge measurements are presented in the figure as well. It is observed that float tracking and flow lines derived from ADCP discharge are almost parallel, indicating the consistency of both measurements. From the surface velocity observed from float tacking, an estimation of the overall surface velocity is made by interpolating the subsequent velocities from float tracking. During the interpolation of the velocities, continuity of discharges were maintained in between two consecutive float tracks. This process was performed by EGIS and the result is shown later.

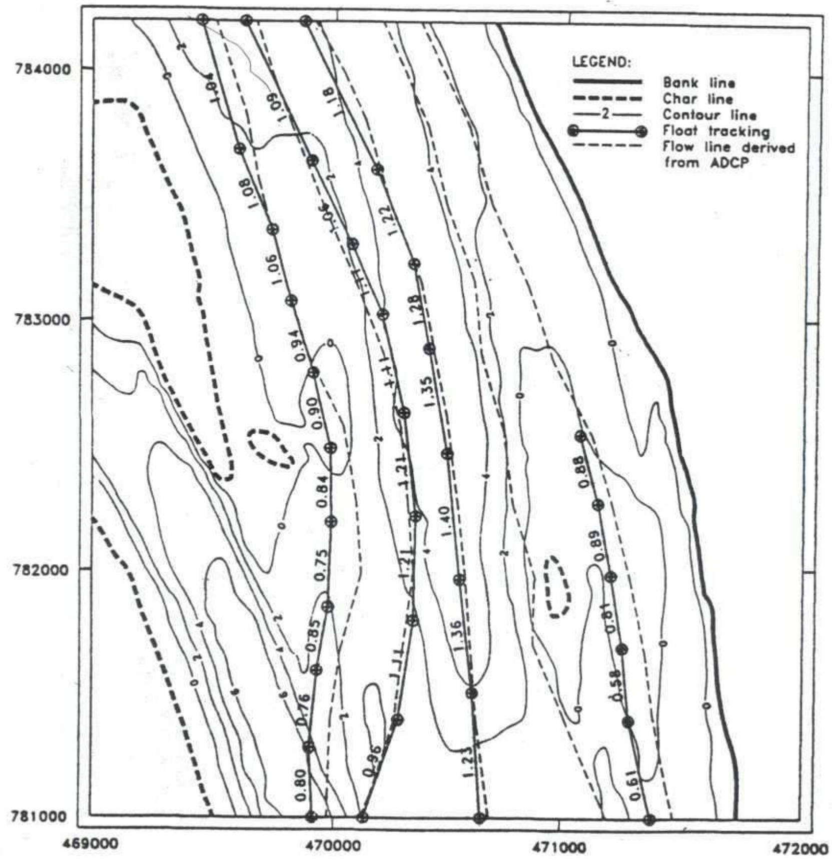

Figure 5.9 Float tracking lines and surface velocities, and the flow lines derived from ADCP measurements on the Nov. 95 bathymetric survey

5.3 Bathymetric charts

In the period June 1993 to November 1995 seven bathymetry surveys were carried out in the left channel over a length of 20 km, from Northing 770.000 to Northing 790.000. The results of these surveys are presented in seven bathymetric charts (Figure 6.1). Some information on the conditions during the periods when the surveys were carried out, are presented in Table 5.2. The periods during which the bathymetric surveys were done, are also indicated in the Figures 5.3 and 5.4.

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The survey lines were spaced on average 100 m apart in these surveys. No topographic measurements of the chars or sand banks were carried out in conjunction with these surveys, hence only the bed topography of the submerged parts were measured.

All the depth data were reduced to Standard Low Water (SLW) at Bahadurabad, where an AWLR was present. SLW represents a sloping reference level. The standard horizontal reference level in Bangladesh is Public Works Datum (PWD). The relation between PWD and SLW has been determined by the Bangladesh Inland Water Transport Authority (BIWTA). The SLW-datum is not accurately defined at places other than where long-term water-level measurements are available. In this area this is Bahadurabad, where SLW = 12.03 m + PWD. It was assumed during the elaboration that the instantaneous water surface is parallel to SLW during the surveys, though local water-level slopes may vary from 0.05 to 0.10 m/km depending on the river stage.

No	Reference	Period		Average water level Bahadurabad		Discharge left channel	Local water level slope (cm/km)
		Start	End	(m+PWD)	(m+SLW)	(10^3 m^3/s)	
1	Jun 93	20 Jun 93	03 Jul 93	18.51	-6.48	26.34	8.4
2	Aug 93	23 Aug 93	09 Sep 93	19.15	-7.12	28.86	8.5
3	Nov 93	10 Nov 93	18 Nov 93	15.48	-3.45	7.90	7.0
4	Nov 94	01 Nov 94	10 Nov 94	15.18	-3.15	8.24	6.5
5	Feb 95	24 Feb 95	27 Feb 95	13.03	-1.0	3.04	5.0
6	Jul 95	4 Jul 95	25 Jul 95	19.65	-7.62	31.97	9.0
7	Nov 95	11 Nov 95	24 Nov 95	15.52	-3.49	9.61	6.9

Table 5.2 Overview of the bathymetric maps of the left channel at Bahadurabad included in this study

By comparing the same sections of two consecutive bathymetric surveys, it is possible to identify the erosion and deposition on the riverbed, see Figure 5.10. The August 93 and November 93 surveys are compared in this figure. The sections 1 and 2 are downstream of Bahadurabad and the sections 3 and 4 are covering the Old Main Channel and the New Main Channel. In the former sections, it is observed that the largest erosion and deposition is about 8 m. One part of the section was eroded and the other part of the same section deposition took place; the magnitudes of erosion and deposition are almost the same. In the cross-sections Cr 3 and Cr 4 the development of the New Main channel and the abandonment of the Old Main Channel can be observed. The depth in the Old Main Channels was decreasing by deposition on the riverbed and at the same time the depth as well as the width in the New Main Channel was increased by erosion. From the figure two types of erosion and deposition processes can be recognized. One is lateral erosion and deposition in a section with or without any changes of flow area, and the other process is the net erosion and deposition in downstream direction.

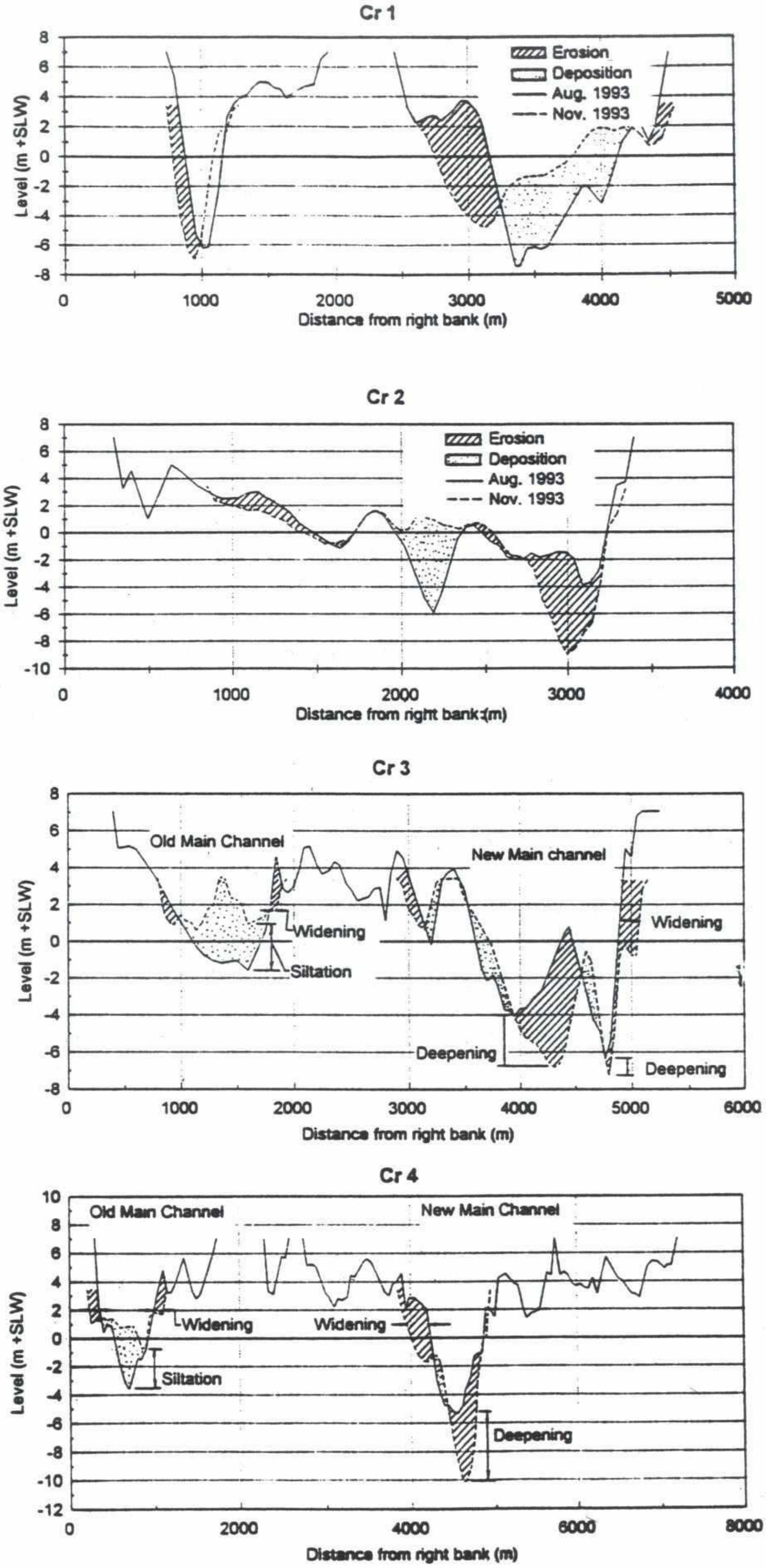

Figure 5.10 The erosion and deposition in the different cross-sections (see Figure 5.1) derived from August 93 - November 93 bathymetric surveys

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5.4 Use of GIS for Presentation

Use was made of a GIS (Geographic Information System) for the presentation of the bathymetric surveys, velocity, sediment concentration data using GIS (Geographic Information System). GIS was selected for three reasons, notably:

(1) GIS can visualize spatial information more effectively than any other means of presentating data.

(2) GIS enables additional manipulation of the data.

(3) Different sets of data but with the same georeferencing can be combined for analysis in a GIS.

In a first step the bathymetric data were assembled and processed off-line in the project office. After data checking and, if required some editing, they are reduced to SLW. Next, using MIKE 21 software, data are generated on a 50 x 50 m^2 grid. In the EGIS office the grid data are interpolated onto a continuous surface using GIS techniques. Additional GIS software is used to generate bathymetric colour contour slices at 1 m interval and produce maps like the ones shown in Figure 6.1. With the thus obtained GIS also other manipulations are possible, like spatial and temporal analyses to detect changes in planform and bed topography, to produce mass balance tables, statistics and maps.

The depth-averaged velocity from the ADCP are entered into the GIS to arrive at a better understanding of the interaction between flow, on the one hand, and channels and bars, on the other hand. The depth-averaged velocity field estimated from ADCP transects in August 1993 and manipulated by GIS is presented in Figure 5.11. By comparing the bathymetric survey of Aug. 93 it can be observed that the deeper channel and maximum velocities are not always coinciding. Often the maximum velocities are not at the deeper part of the channel. Similar types of the velocity distribution can also be observed from the flow manipulation by GIS from float tracking in July 1995 (see Figure 5.12). Here it is observed that very high surface velocity about 3.5 m/s occurs near the bank at Bahadurabad. In later chapters the occurrence of these high velocities in relation to planform development are analysed.

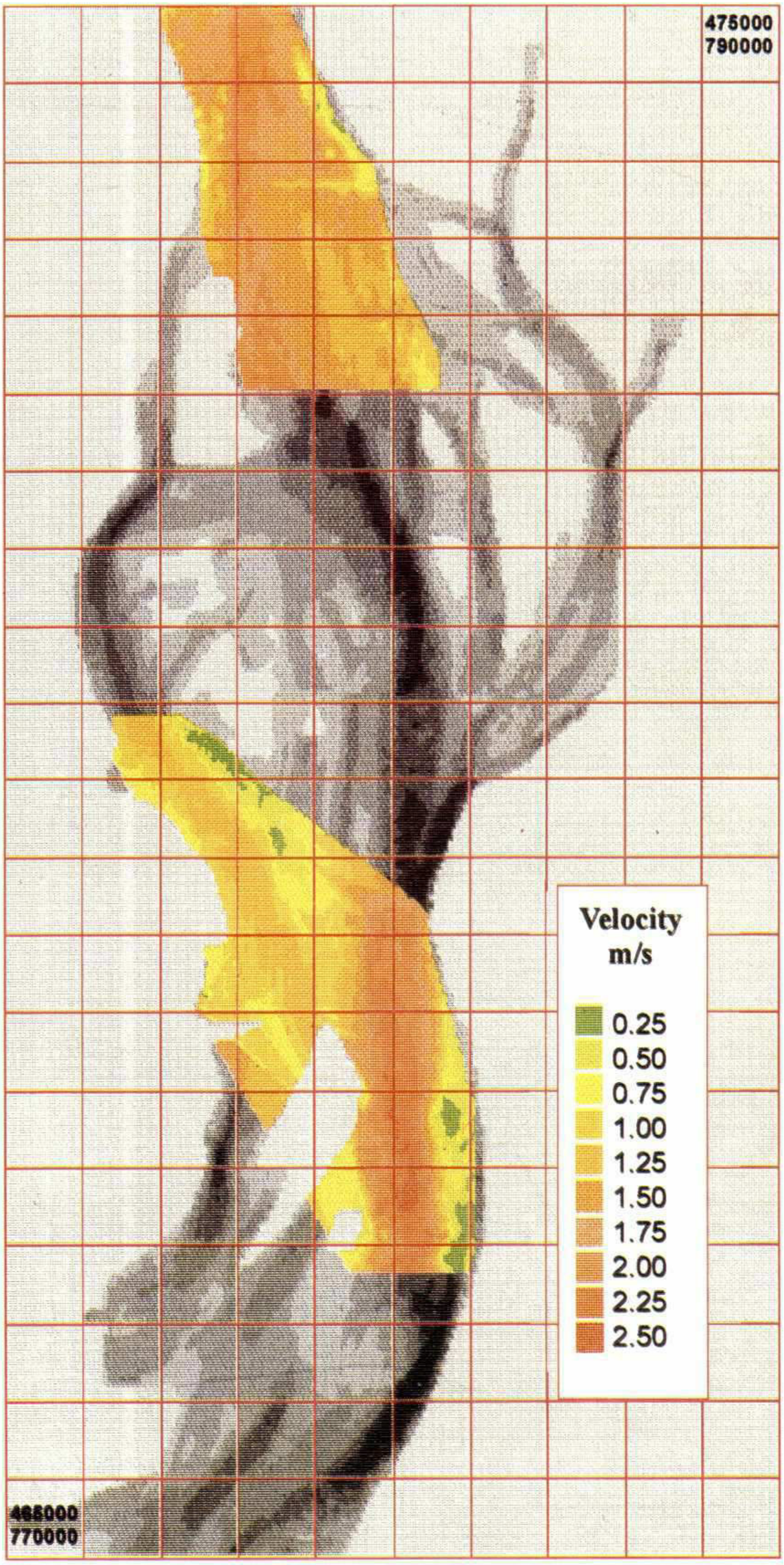

Figure 5.11 Manipulated depth-averaged velocity measured by ADCP during the August 93 bathymetric survey

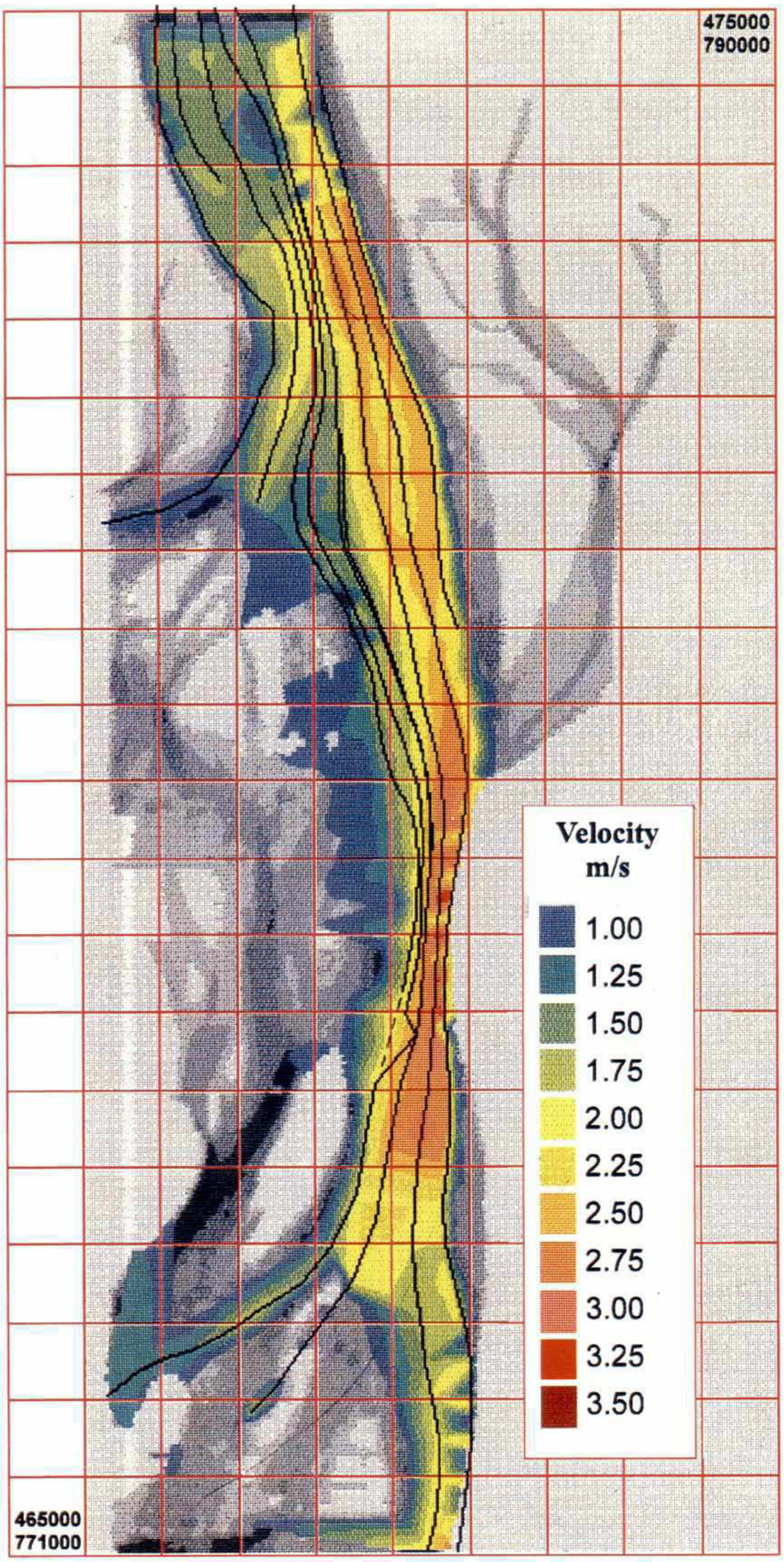

Figure 5.12 Manipulated surface velocity measured by float tracking during July 95 bathymetric survey

As mentioned before the suspended bed-material concentration can be obtained from the ADCP backscatter intensity (dB). The relation developed to correlate the backscatter and the suspended bed material concentration reads as (see Annex 2):

$$dB = 68 + 0.77\sqrt{c} \tag{5.1}$$

where c = suspended bed material concentration in mg/l. The ADCP measures the backscatter intensities at 0.50 m intervals in vertical direction. The required clearance from the water surface and from the bottom of the river for ADCP measurement is indicated earlier. Using Equation 5.1, the backscatter intensity (dB) is converted into concentration. By simple averaging the sediment concentration in a water column, depth-averaged sediment concentration is obtained. Although this method deviates from the real condition, but for the time being to get depth-averaged sediment concentration this method has been applied. The average concentration obtained from the ADCP measurement in August 93 is also presented using the GIS, see Figure 5.13. Here it can be observed that the concentration of sediment varies in a wide range, from 50 mg/l to more than 700 mg/l. In the downstream part of the Old Main channel, the concentration is small. At the upstream part of the surveyed reach the variation range is considerably higher. The concentration suddenly increased and gradually decreased in downstream direction. The depth-averaged velocity at that river reach does not vary to the extent as the concentration does. By comparing with the depth-averaged velocities of Figure 5.10, it is observed that the highest concentration of sediment often does not follow the location maximum velocities. In Chapter 7 this concentration is used to better understand the erosion and depositional processes in the river.

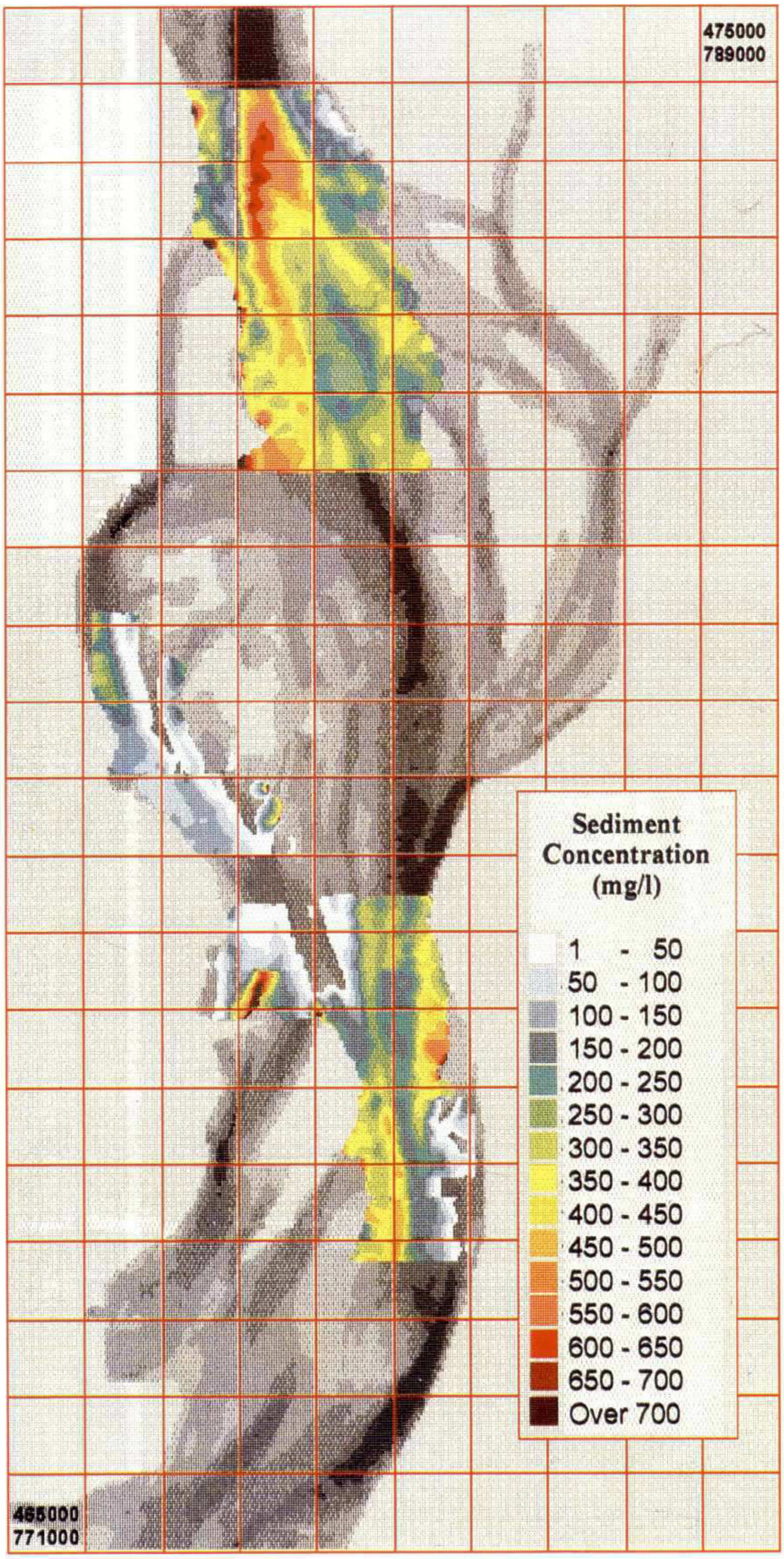

Figure 5.13 Suspended sediment concentration estimated from ADCP backscatter, measured during August 93 bathymetric surveys

5.5 Use of GIS for study

By using the ability of GIS in analysing two different sets of data with the same georeference, the erosion and deposition on the riverbed can be obtained from two subsequent bathymetric surveys, see Figure 5.14. In this figure the bathymetric surveys of Aug. 93 and Nov. 93 were compared and the location and magnitude of erosion and deposition are presented. It is observed that the maximum range of erosion and deposition is more than 10 m. The maximum deposition, related to the shifting of the scour holes, such as the outward shifting of the bend scour downstream of Bahadurabad, results in more than 10 m of deposition on the riverbed. The maximum erosion that occurred in shallow areas is associated with the shifting of the channel thalweg. The riverbed erosion related to the bank erosion is not shown in this figure as the area survey in both surveys is shown only. Therefore, the figure does not give a complete picture of the changes of the riverbed. It can also be observed from this figure that in the New Main Channel the erosional process is dominating, while in the Old Main channel deposition is dominating in the period Aug.93 to Nov.93. This was already shown in Figure 5.9, but there only for some cross-sections.

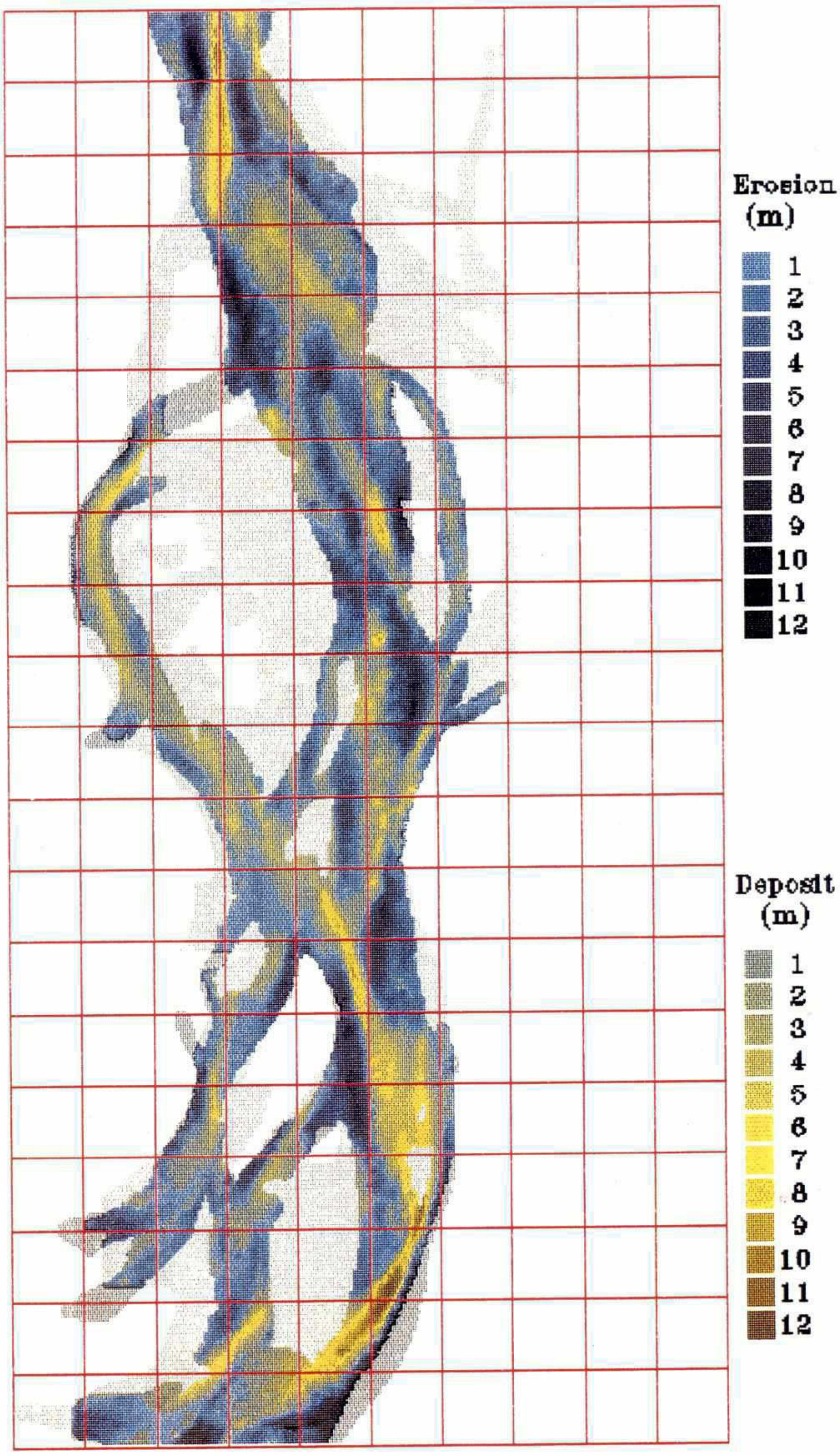

Figure 5.14 Observed erosion and deposition on the riverbed in the period of August - November 1993

The volume of erosion and deposition within the common survey area of the consecutive bathymetric surveys at Bahadurabad location is shown in Figure 5.15. It should be mentioned that only bank or char erosion below the lowest water level prevailing among the compared consecutive surveys are shown here. For example, when the Aug.93 and Nov.93 bathymetric surveys are compared, the eroded volume of either char or bank is estimated below the level -3.45 m +SLW only (see Table 5.2). Therefore erosion within the common survey area is underestimated here. However, accretion of chars above the lowest prevailing water level among the compared surveys are not included in the estimation either. In spite of the underestimation of both the eroded and the deposited volumes, it can be observed that the volume of erosion and deposition within 20 km stretches of the left channel near Bahadurabad can be about 100 Mm^3 within a period of only two months.

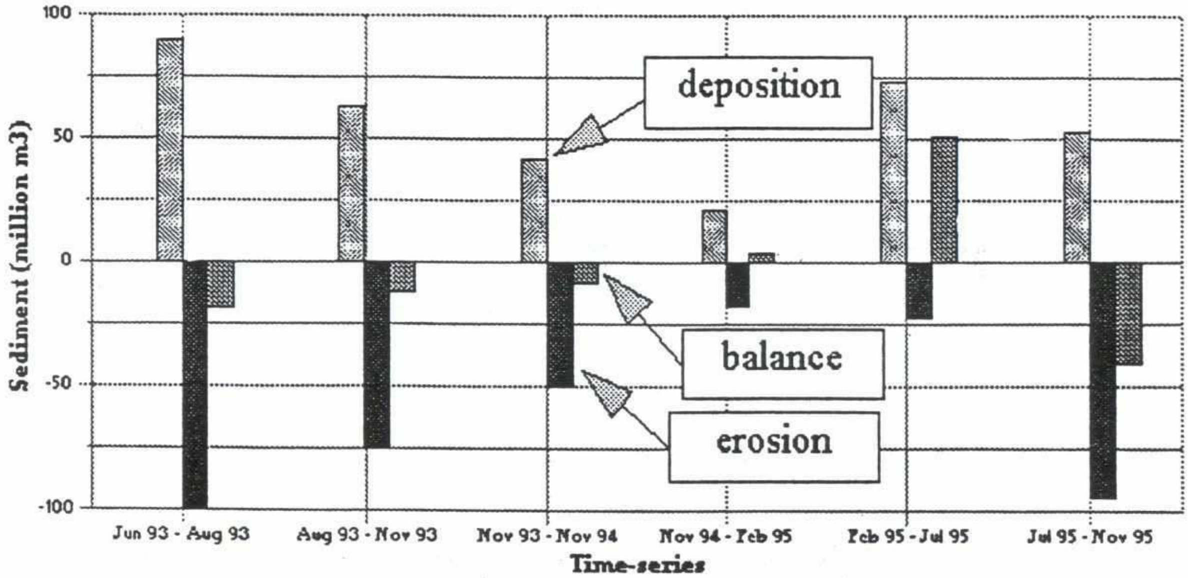

Figure 5.15 Volume of erosion and deposition on the riverbed estimated by comparing consecutive bathymetric surveys (RSP/EGIS, 1996)

The above-mentioned method of estimating the erosion and deposition has some limitation for the estimation of the overall balances within the channel. GIS can provide the depth-area data from which it is possible to estimate the wet volume of different bathymetric surveys under different levels, see Figure 5.16. The overall net erosion and deposition under different rivers can be estimated in this way. The discussion about the overall balance is presented later. This type of depth-area data can also be extracted for any areas within the bathymetric surveys and it is possible to compare the changes of any location by comparing with another bathymetric survey.

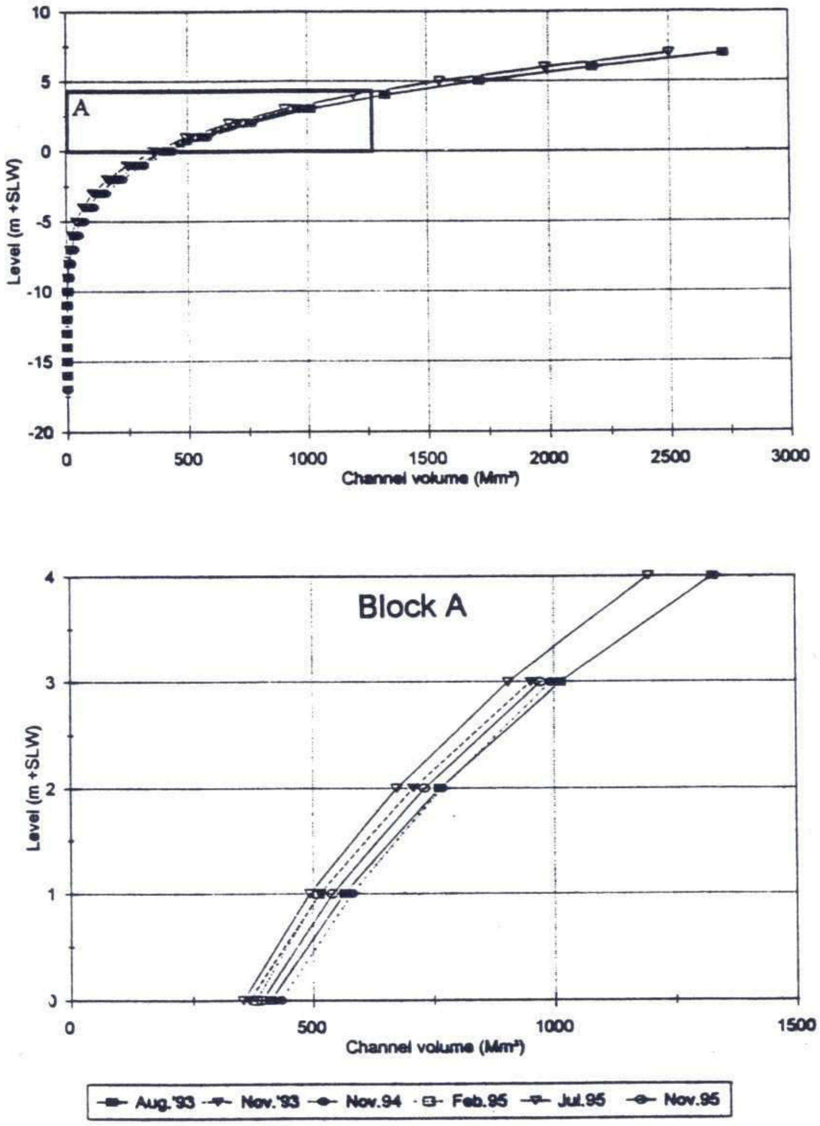

Figure 5.16 Wet volume of different bathymetric surveys under different levels

A few examples are presented here about the uses of GIS for analysing the bathymetric surveys data. In addition, a few more analyses are also performed by using GIS, including the comparison between the predicted and observed data, which are presented in the corresponding chapters. GIS has a number of options to process and analyses a huge number of spatial data like the bathymetric surveys and also to present and visualize the processes of velocity distribution, sediment concentration, erosion/deposition on the riverbed etc.

6 Changes in the planform during the study period

6.1 Introduction

The recent planform development in the study area is already discussed briefly in Chapter 2 by using Satellite images. In this chapter the planform development of the study area is described in more detail with the aid of seven bathymetric surveys performed by the River Survey Project (RSP) during the period June 1993 to November 1995. These bathymetric surveys are the basis of the present study. The main difference between the satellite images and the bathymetric surveys is the following: the satellite images provide two-dimensional information (banklines) and only for the non-submerged parts and images are mainly available for the dry season, whereas the bathymetric surveys provide a three-dimensional picture of the riverbed though only of the submerged part and bathymetric surveys, during monsoons are available as well.

The methods applied during, as well as accuracies of the RSP bathymetric surveys, are discussed in Chapters 4 and 5. The bathymetric survey charts presented here as the Figures 6.1a-6.1g are processed via a GIS under the EGIS project. The surveys are presented in a Modified BTM grid system. The grid values are shown in two corners of the survey charts; the upper one represents the Easting and the lower one represents the Northing. The grid spacing shown on the chart is 1 km. The depths with respect to SLW (see Section 5.2) are shown in 1 m intervals by colours. It should be noted here that SLW level increases in downward direction. For easy reference during the subsequent discussion, the different locations within the survey area, (especially the location of bars) are marked with a letter. For instance, A represents a point bar at the upstream end, while B represents the medial bar complexes upstream of Bahadurabad. The planform changes are discussed mainly by visual comparison of two consecutive bathymetric surveys. For comparison of the bathymetric surveys the average water level during the survey is essential, which is shown in Table 5.3.

Here a qualitative description of the different changes is given. In the Chapters 7 through 11 the different changes are analysed quantitatively in more detail.

6.2 Detailed description of changes

Jun.93-Aug.93

The Jun.93 survey is the first bathymetric survey performed by the RSP. A channel through the medial bar complexes B was not included in the survey. The accuracy of this survey, especially in defining the bank lines is not optimal. These should be considered when making a comparison with the Aug.93 survey.

A shallow channel along the left bank can be observed immediately upstream of Bahadurabad. This is a remnant of a previous channel; in the monsoon season these abandoned channels contribute to the conveyance of the discharge. During the lean season these channels are completely dry. It is observed from the Jun.93 survey that the channel upstream of A flowed in NW-SE direction and the main channel was at the right of the medial bar complexes B. In the subsequent months these features of the Jun.93 survey changed.

The bank erosion upstream of point bar A and the changing of the direction of the deeper channel from NW-SE to almost N-S direction, probably contributed to a growing of the point bar in downstream direction. This extension of the bar increased the diversion angle of the curved channel from the upstream channel to about 90° and almost closed off the offtake of the channel. A cutoff channel developed by widening and deepening a previously shallow and narrow channel through the medial bar complexes (a dramatic event in the study period). As a result the Old Main Channel lost its importance in carrying discharges and the previous confluence scour upstream of C rotated and moved downstream while reducing its depth. The outer bend as well as the location of the bank erosion shifted more than 2 km in downstream direction. A new bar at location D became apparent. This was the bar around which special surveys were performed for the UoN/RSP joint study for, in total, three times in 1994 (see Section 3.6).

Aug.93-Nov.93

The average water level reduced about 3.7 m in the period between Aug-Nov. 1993, resulting in a less wet area shown in the bathymetric chart of Nov. 1993. The changes in this period are mainly the adjustment of the downstream channels after the development of the cutoff. The offtake of the Old Main Channel moved with an upstream reduction of the deviation angle from the upstream channel direction. The Old Main channel reduced in depth and width. The New Main Channel became wider and deeper and showed a more regular shape of the thalweg in Nov. 1993. The scour hole near Bahadurabad moved in downstream direction. The confluence of the Old and New Main channel upstream of bar C existed no longer, although the remnant of the confluence scour hole remained visible. The size and shape of the bar C hardly changed during the period Aug.-Nov. 1993. Bar D appeared as a full grown point bar with a chute channel on the right side of the bar. Bank erosion occurred at the downstream part of the bar. The depth of the bend scour hole reduced considerably in this period, which is characterized by the recession of the flood.

Nov.93-Nov.94

The time interval between these two surveys is about one year. The difference of the average water level between the surveys is only about 0.3 m. The upstream end had moved eastward direction. A new medial bar had formed just right upstream of the offtake, which forced the offtake in downstream direction thus increasing the deviation angle. The major part of the Old Main Channel had diverted and a very shallow and narrow link remains at the downstream part of this channel. The importance of the confluence with the New Main Channel has diminished. Complex B is now shaped as a single unit bar elongated in downstream direction. The New Main Channel appeared as a braided channel with medial bar and a division of the thalweg. The upstream flow hits the Bahadurabad area directly with an incident angle of more than 25° and as a result a deep scour hole is observed in front of Bahadurabad. It appears from the shape of the upstream channel that the channel is trying to create a river bend here, but probably due to the retarded bank erosion and possibly more resistant bank material the flow had to follow the river bank.

The upstream tip of bar C did not change too much, but the bar has elongated in downstream direction. A considerable change had occurred around Bar D. The upstream tip of the bar moved in downstream direction and a new small bar appeared at the location of the previous tip of the bar. The upstream sides of the bar have been eroded, but the bar has widened and accreted in the downstream part associated with the bank erosion in the outer bend channel. The offtake of the outer bend channel at the right side of the Bar D became shallower with formation of a number of smaller bars. The sizes of the channel reduced considerably, although bank erosion by the channel had been considerable during the monsoon of 1994.

Nov.94-Feb.95
The average water-level reduction in this period was about 2.1 m, resulting in a narrower river. Not many changes are observed from a comparison of the bathymetric surveys. A slight reduction of the depth of the scour hole near Bahadurabad is observed. About 4 m retarded scour is observed at the crossing of the outer bend channel upstream of bar D. No further development of the channel in between bars C and D had occurred during the period; as a result these two bars have joined together to form one complex (during the low-flow period).

Feb.95-Jul.95
The averaged water level increased by about 6.6 m. The channel in July 1995 can not be recognized even as a following channel of February 1995. The deep channel at the upstream end shifted in eastward direction, but a considerable bank erosion is observed at the right bank upstream of A. The thalweg profiles are not so regular as the lean season channels; this behaviour can also be observed in the Aug. 93 survey. The left bank shallow channel upstream of Bahadurabad has become more narrow and shallow in comparison to Aug.93. Bar B had changed in size and shape, but the bar C did not change so much in comparison to Aug.93.

The scour hole depth near Bahadurabad has reduced, but widening of the hole is observed. Bank erosion had occurred near Bahadurabad, the concave shape of the river bank at Bahadurabad became more straight. A discontinuity in the survey is observed at the main channel left side of the bar C and on the left side of bar B. These discontinuities are due to an interruption of the survey at this location for seven days. It can be observed that the thalweg laterally shifted over more than 300 m within seven days, showing how active the river is during the monsoon period. A number of shallow channels has appeared at the right side of bar D. Instead of a curved channel in a river bend, these shallow and divided small channels approach the bank under an angle and, consequently, they are significantly eroding the bank.

Jul.95-Nov.95
The deeper channel at the upstream end became deeper and, in contrast to Feb.95-Jul.95, the thalweg moved in westward direction over a distance of about 800 m. More bank erosion occurred upstream of point bar A and resulted in the lateral growth of the bar at the downstream end. The medial bar upstream of bar B has reduced in size and moved in downstream direction. The main channel flows along the right side of this bar. Point bar A and the medial bar have pushed the offtake of the Old Main Channel further downstream. The sinuosity of the Old Main Channel increased considerably in one year. The thalweg is approaching Bahadurabad in a curved shape and the bank at Bahadurabad appears as an outer bank of a river bend.

A pronounced change had occurred downstream of Bahadurabad around bar D. This bar has moved in downstream direction, almost blocking the outer bend channel. It is no longer a single bar but has developed into a bar complex. Instead of the following outer bend channel left of bar D the main channel developed in between bars C and D, thus probably ending the life of an eroding outer bend channel.

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6.3 Summary

The various features of the planform development during the study period are analysed in more detail in the following chapters. The development of the planform near Bahadurabad as observed from the bathymetric surveys can be summarized as follows:

- In 1993 a cutoff developed through a narrower and shallower channel in medial bar complexes, resulting in the development of a new planform in the downstream reach within a short period. The Old Main Channel lost its importance. Also the confluence at the upstream of Bar C gradually vanished, the location of the bank erosion downstream of Bahadurabad shifted, and a new point bar developed associated with the shifting of the river bend.

- A comparatively deep channel upstream of the Offtake of the Old Main Channel was sustained for the whole study period, although the thalweg shifted laterally in a to-and-fro manner. The location of the offtake also moved its position in time as a result of the cutoff process, the formation of a bar upstream of the offtake, and erosion of the upstream right bank.

- The new main channel first appeared (Nov.93) as a straight channel directly approached toward the inward concave bank at Bahadurabad, where a huge scour hole was present. As a straight wide channel is unstable, in the following years the channel developed into a braided channel by forming a medial bar and dividing the thalweg. During the study period, the shape of the bank line at Bahadurabad changed completely due to continuing bank erosion.

- After the development of the cutoff, the outer bend channel downstream of Bahadurabad shifted over a distance about 2 km at the downstream end. Also the bend scour and the bank erosion shifted accordingly. In the following years this channel was changed gradually and almost abandoned at the end of study period.

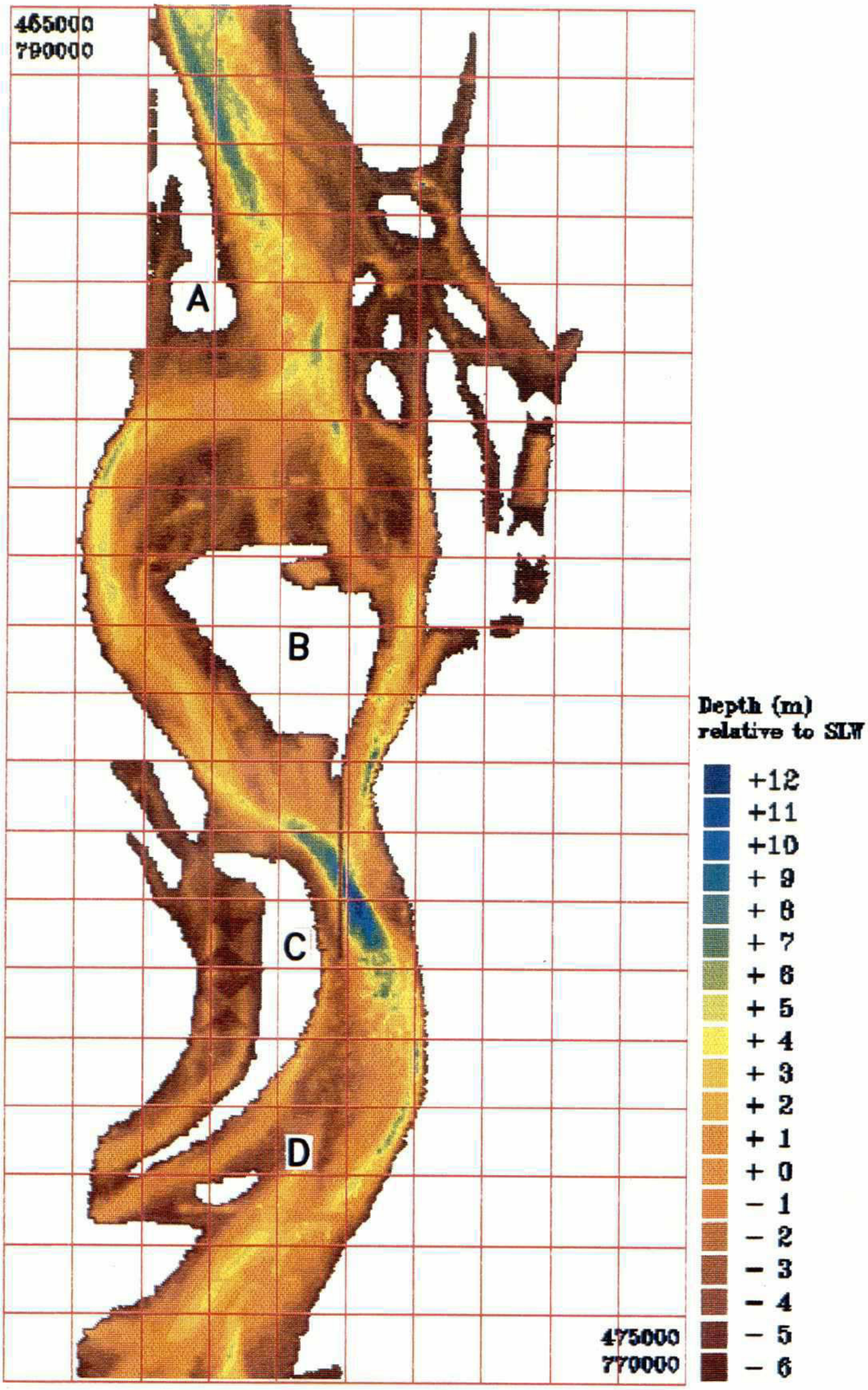

Figure 6.1a Bathymetric survey of RSP in the left channel of the Jamuna River near Bahadurabad (Jun.93)

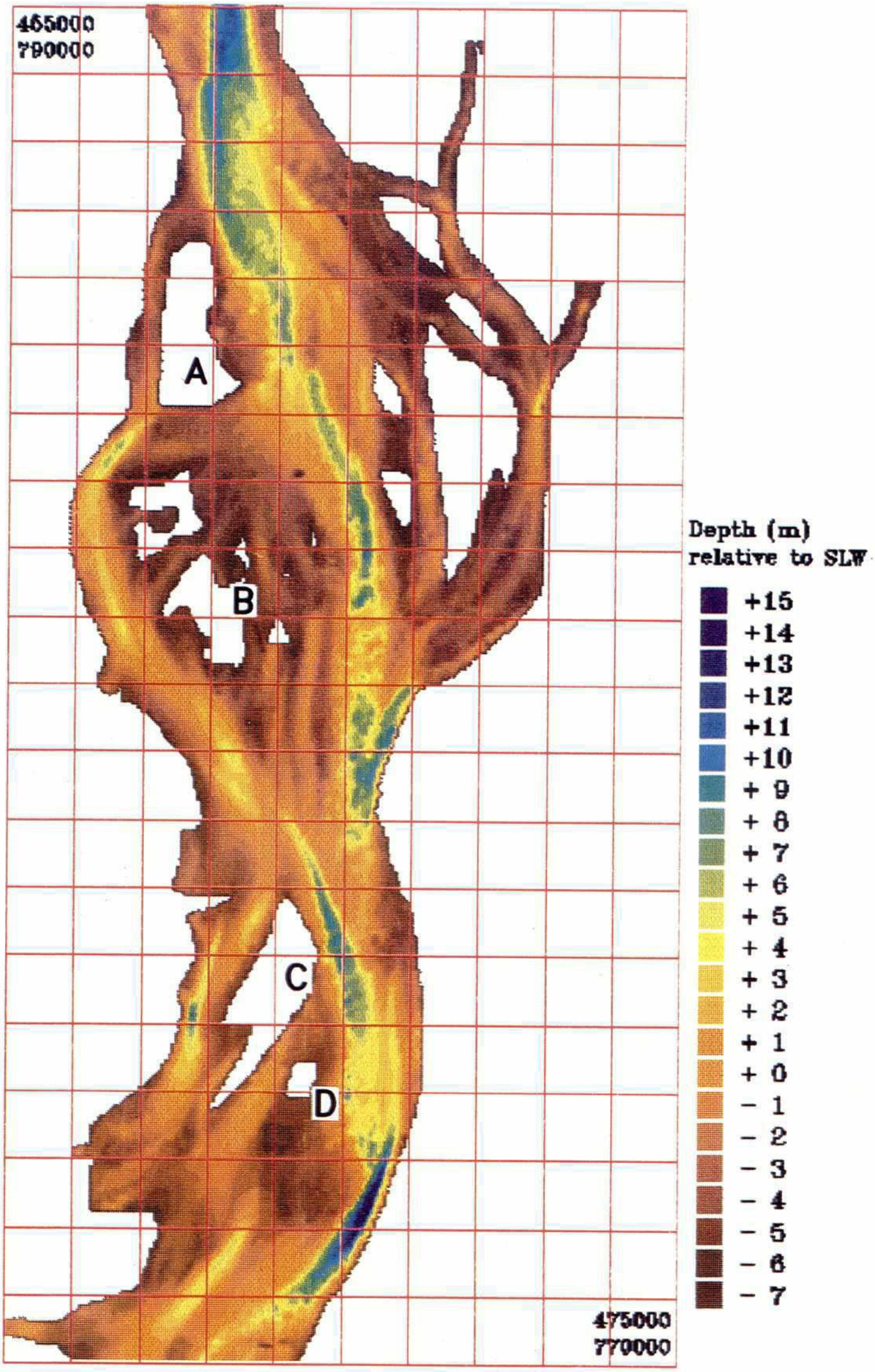

Figure 6.1b Bathymetric survey of RSP in the left channel of the Jamuna River near Bahadurabad (Aug.93)

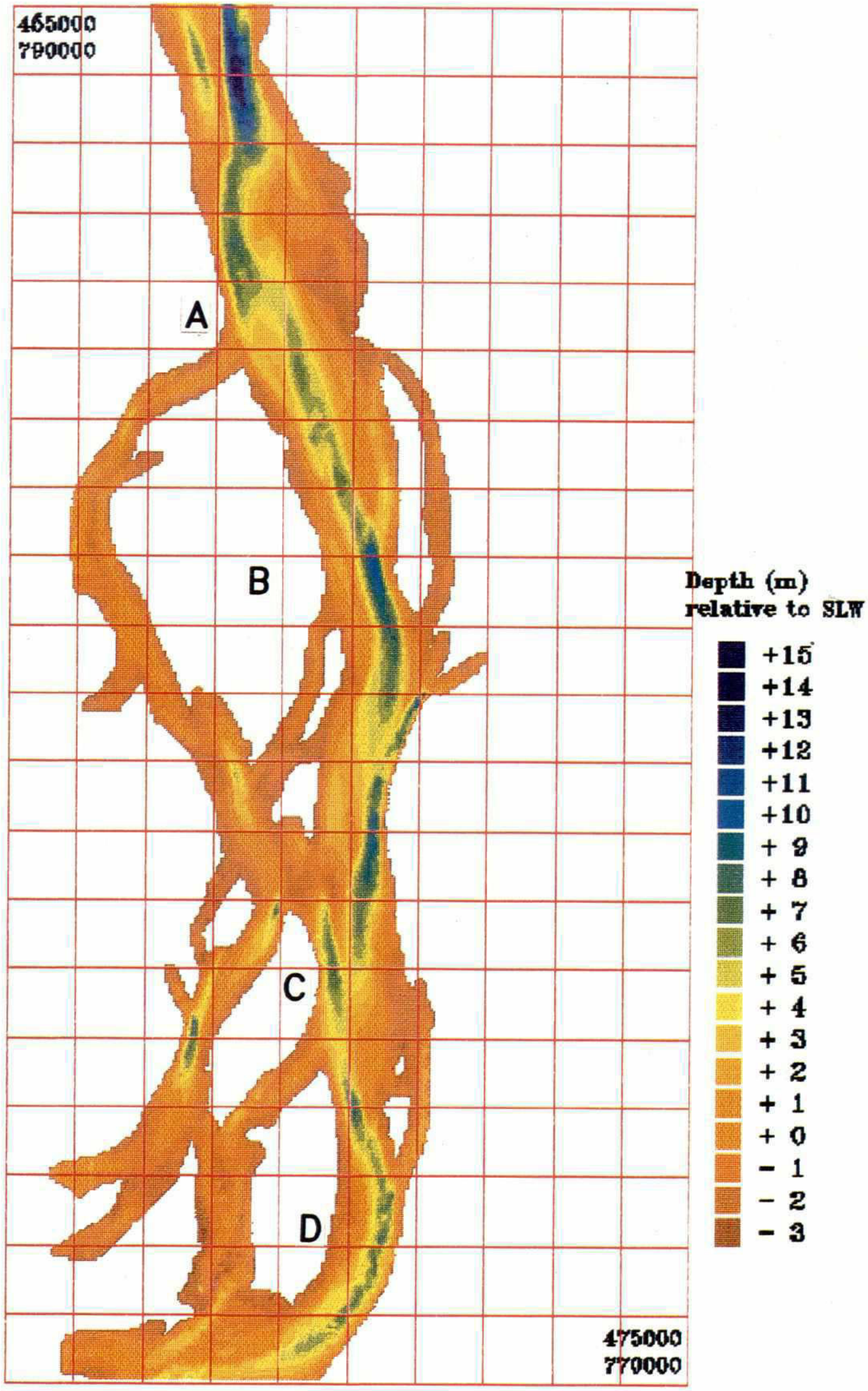

Figure 6.1c Bathymetric survey of RSP in the left channel of the Jamuna River near Bahadurabad (Nov.93)

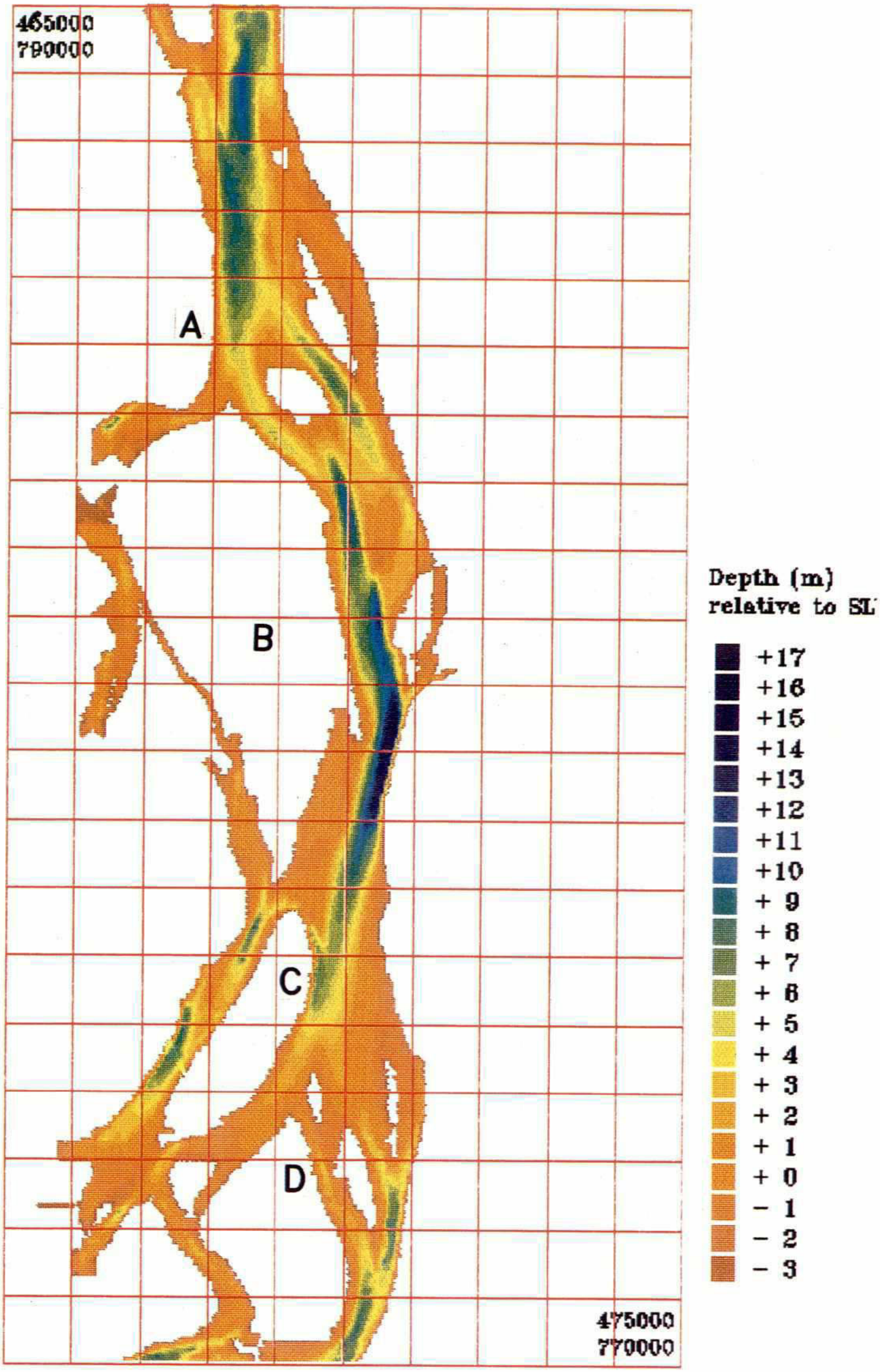

Figure 6.1d Bathymetric survey of RSP in the left channel of the Jamuna River near Bahadurabad (Nov.94)

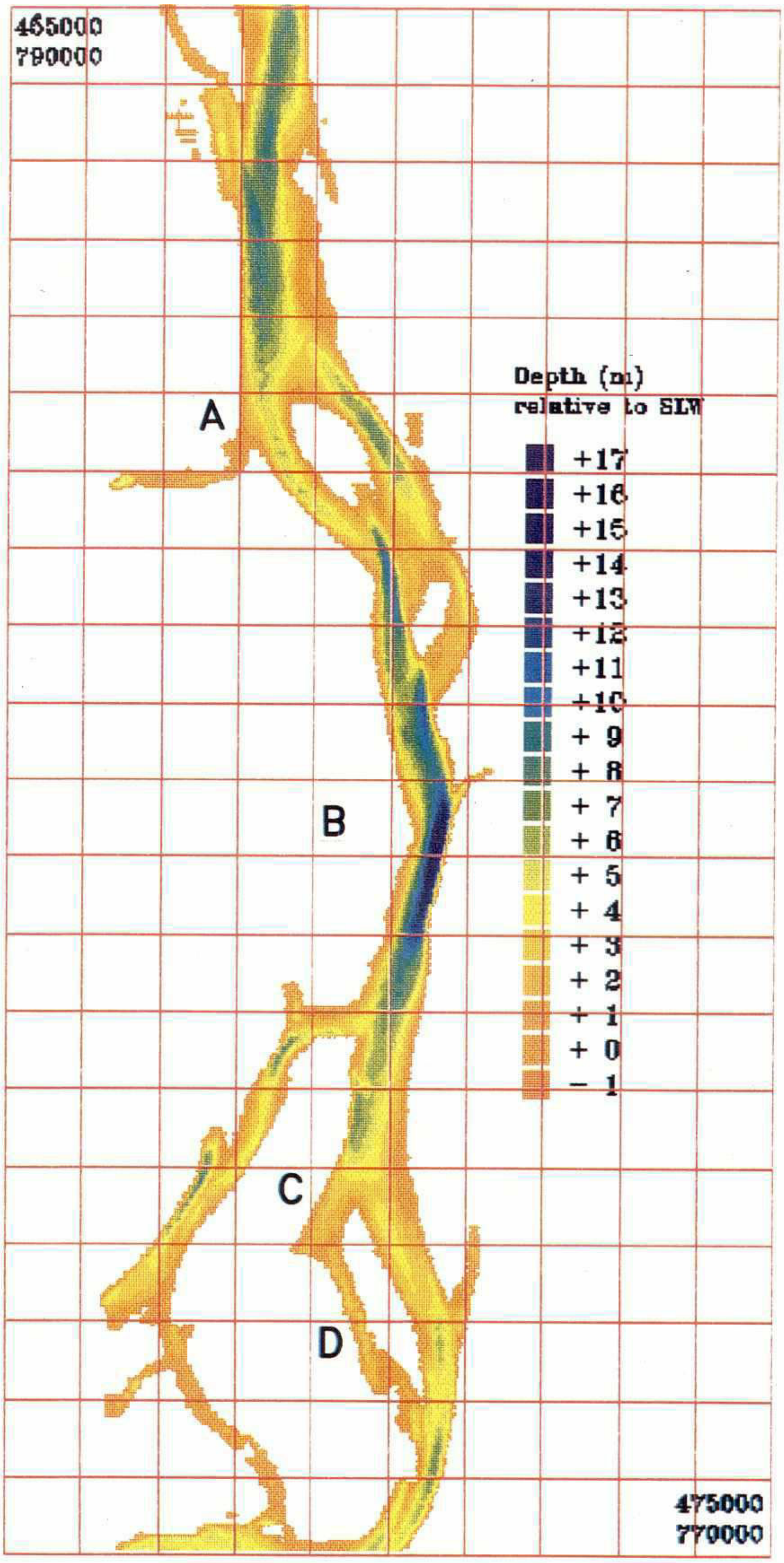

Figure 6.1e Bathymetric survey of RSP in the left channel of the Jamuna River near Bahadurabad (Feb.95)

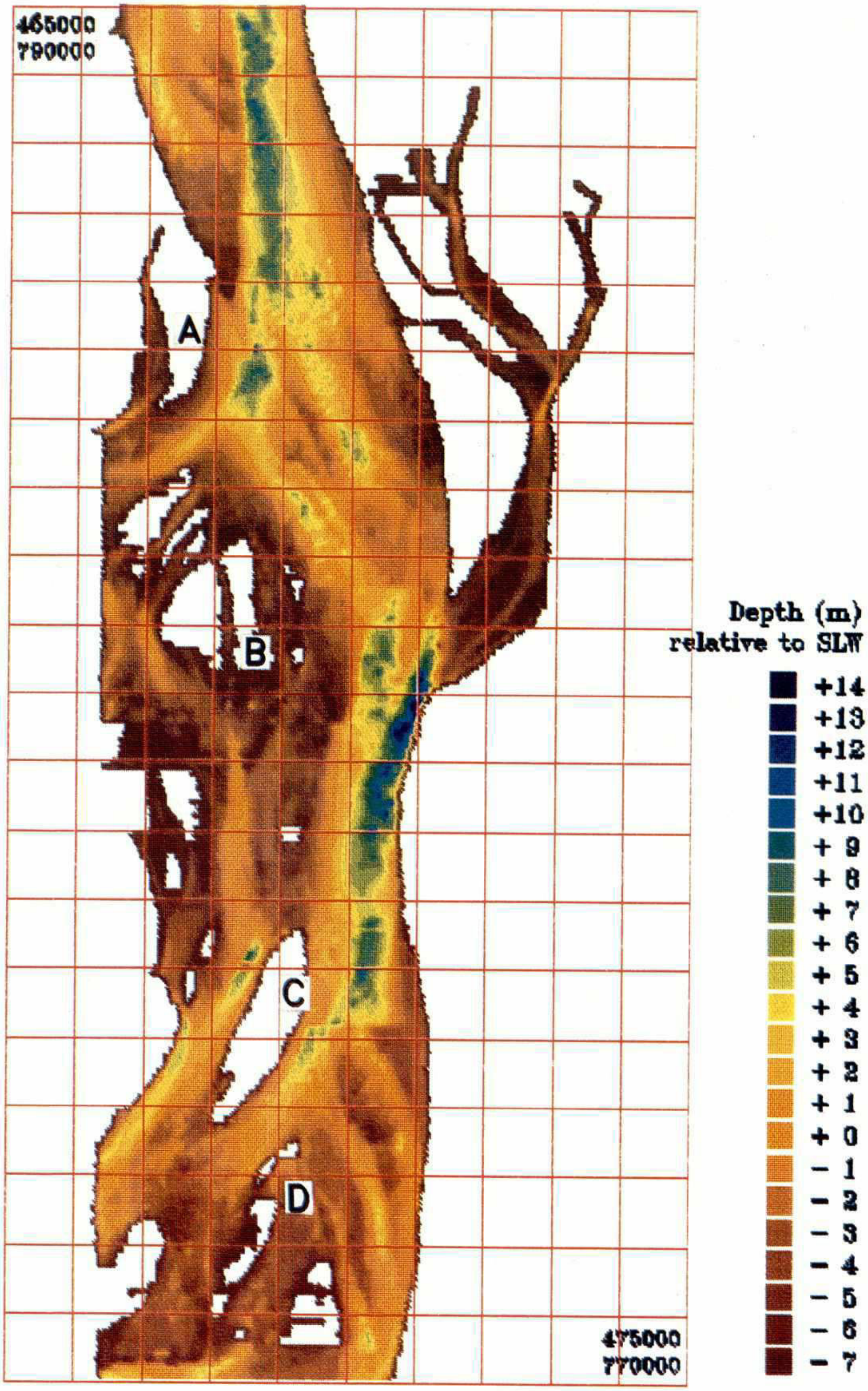

Figure 6.1f Bathymetric survey of RSP in the left channel of the Jamuna River near Bahadurabad (Jul.95)

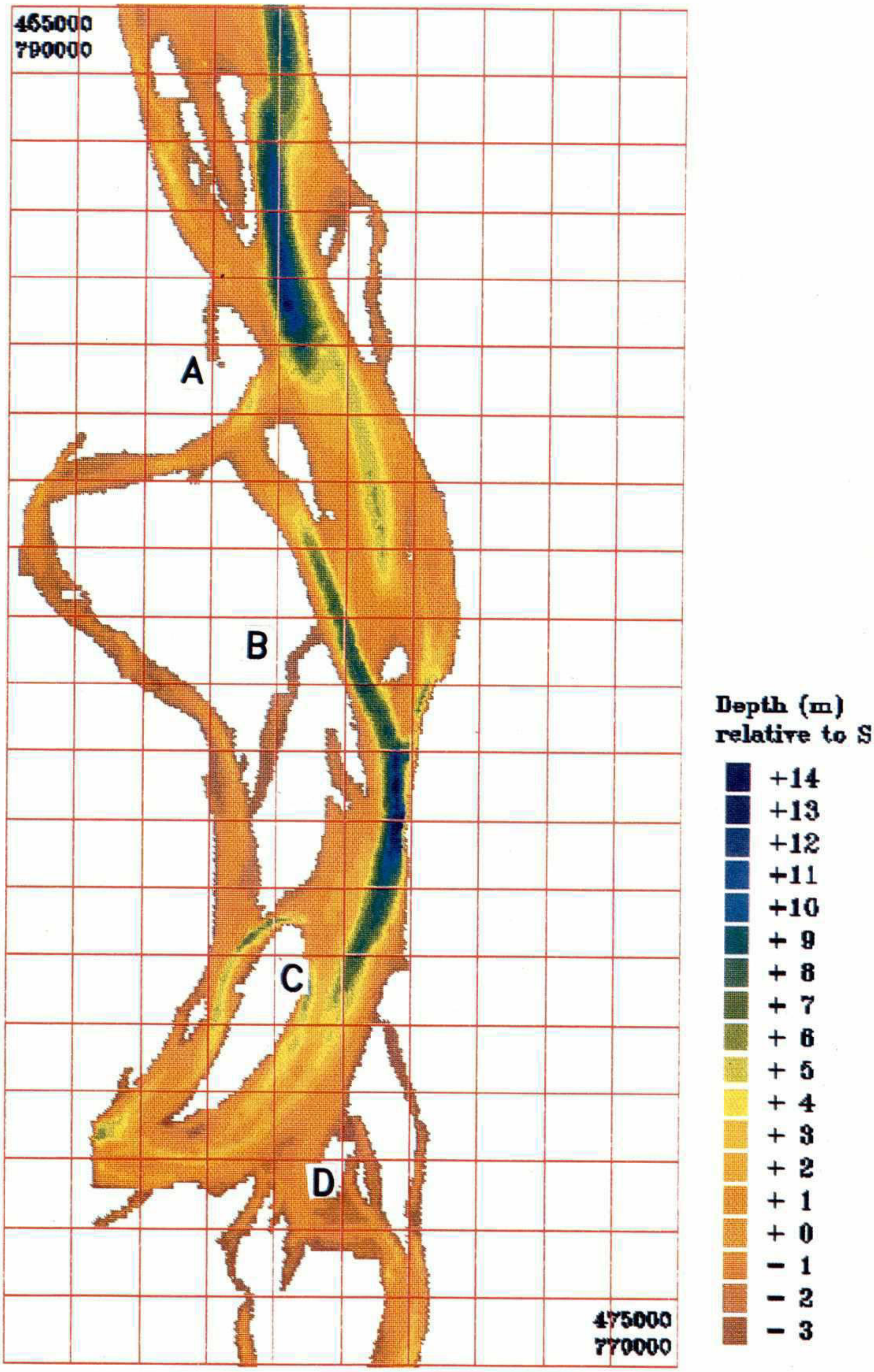

Figure 6.1g Bathymetric survey of RSP in the left channel of the Jamuna River near Bahadurabad (Nov.95)

7 Erosion and deposition processes

7.1 Introduction

In sand-bed rivers there is a continuous process of erosion and deposition. Changes of the planform of the river are generally determined by this process of aggradation and degradation of the bed. Coleman (1969) observed from the analysis of a number of cross-sections that magnitude of this type of erosion and deposition within a short period is immense in the Jamuna River. A better estimation of the magnitude of the volume of erosion and deposition has become possible using the RSP bathymetric surveys. Especially the use of GIS to analyses the bathymetric surveys is advantageous in this respect. Methods were developed during the study to estimate the reach averaged width, flow area, total volume of flow and local and overall volume of erosion and deposition on the riverbed by using GIS processed bathymetric survey data. A GIS is also able to present all this information in a better way than any other method. In this chapter the erosion and deposition processes in the river are studied considering flow and sediment transport in the Jamuna River.

7.2 Causes of erosion and deposition (on the riverbed)

The erosion and deposition in a river is linked to the flow and to sedimentary processes in a river. The interaction between the flow and the riverbed results in three types of opposing forces. One is the shear force exerted by the flow on the riverbed, which is determined by the flow itself, and the resistance to flow generated by the riverbed. The other two forces are gravity and resistance of the particle in the riverbed to move, depending on the characteristics and composition of the bed material. These forces determine the sediment transport capacity of the flow. However, this does not determine the net erosion or deposition on the riverbed. This process is governed by gradients in sediment transport capacity of the flow and the sediment is carried by the flow at a certain time and location. Erosion or deposition in a channel bed can be described from the sediment continuity equation which reads, in an elementary form, as:

$$\frac{dz_b}{dt} + \frac{ds_x}{dx} + \frac{ds_y}{dy} = 0 \qquad (7.1)$$

where z_b = bed level above horizontal datum, s_x and s_y = sediment transport in x and y direction respectively. The changes of bed level at a certain point in a riverbed depend on the changes of sediment transport capacity at the upstream and downstream boundary. In the field where suspended sediment transport is dominant, adjustment of the sediment transport verticals plays an important role in erosion and deposition processes on a riverbed. The adjustment of the bed load transport is instantaneous, because transport takes place close to the bed. In a river mainly dominated by the bed load transport, Equation 1 will be valid for changes of riverbed. The adjustment of the suspended load transport proceeds relatively slow, because it takes time and hence distance for the particles to settle out from suspension according to Van Rijn (1987), depending on the ratio of the bed-shear velocity and fall velocity. The adjustment of the suspended load transport was studied by Jansen (1979) initially, later by Van Rijn (1987) using a two-dimensional mathematical model. In dimensionless form the adjustment length is given as:

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$$\frac{L}{h} = f\left[\frac{s}{s_e}, \frac{w_s}{u_*}, \frac{k_s}{h}\right] \tag{7.2}$$

where L = adjustment length, h = water depth, s = actual suspended load transport, s_e = equilibrium suspended load transport, w_s = fall velocity, u_* = bed-shear velocity, k_s = effective bed roughness height. The result is presented in graphical form in Figure 7.1, where k_s/h is kept constant at a value of 0.01. The parameter s/s_e represent the ratio of incoming suspended sediment transport and the transport capacity and this parameter, have significant influence on the riverbed erosion and deposition. According to Figure 1, the adaptation length of suspended sediment for different grain sizes and densities of particles assuming water depth 10 and 5 m, overloading factor (s/s_e) is 3 and shape factor 0.7 are presented in Figure 7.2. Suspended bed material particle varied in the Jamuna River from 0.10 mm to 0.03 mm, and the shape factor and density can be considered as 0.7 and 2650 km/m^3. The adaptation length of suspended sediment for overload is factor 3 would be 3000 m to 600 m for 15 m water depth.

In a natural river, depth and distribution grain sizes are quite variable, making a large range of variation in adaptation length of sediment in a river.

Thus Equation 7.1 can be modified for taking into account the contribution of suspended sediment transport in erosion and deposition processes as (Van Rijn) :

$$\frac{dz_b}{dt} + \frac{d(hc)}{dt} + \frac{ds_x}{dx} + \frac{ds_y}{dy} = 0 \tag{7.3}$$

where c is depth-averaged suspended sediment concentration. For the cases of overloading/underloading of sediment, the concentration of suspended sediment is mainly determined by the adaptation processes of the suspended sediments.

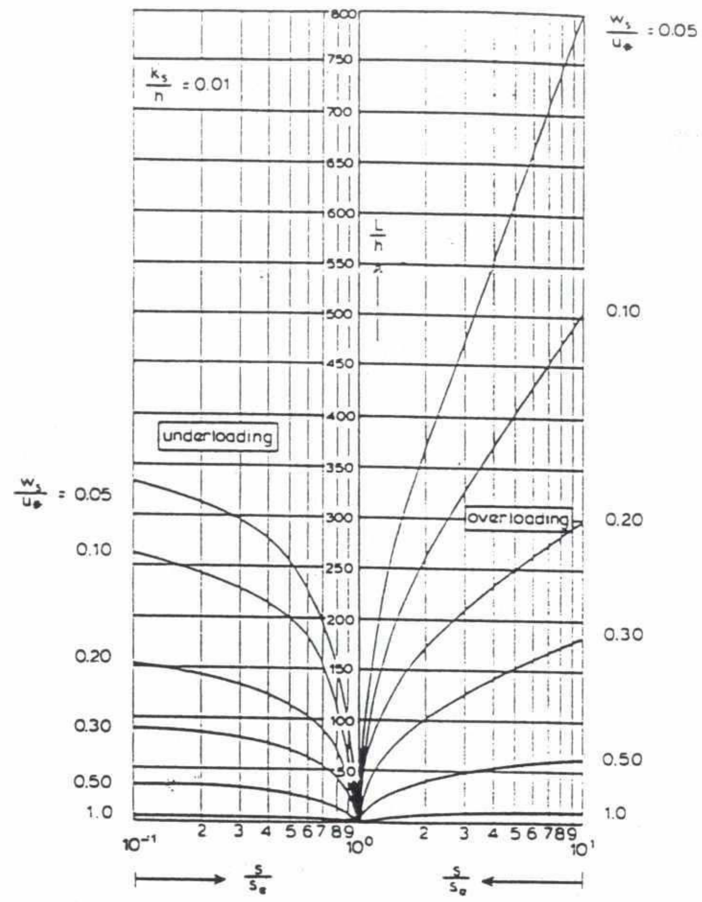

Figure 7.1 Adjustment length of suspended sediment transport (Van Rijn, 1987)

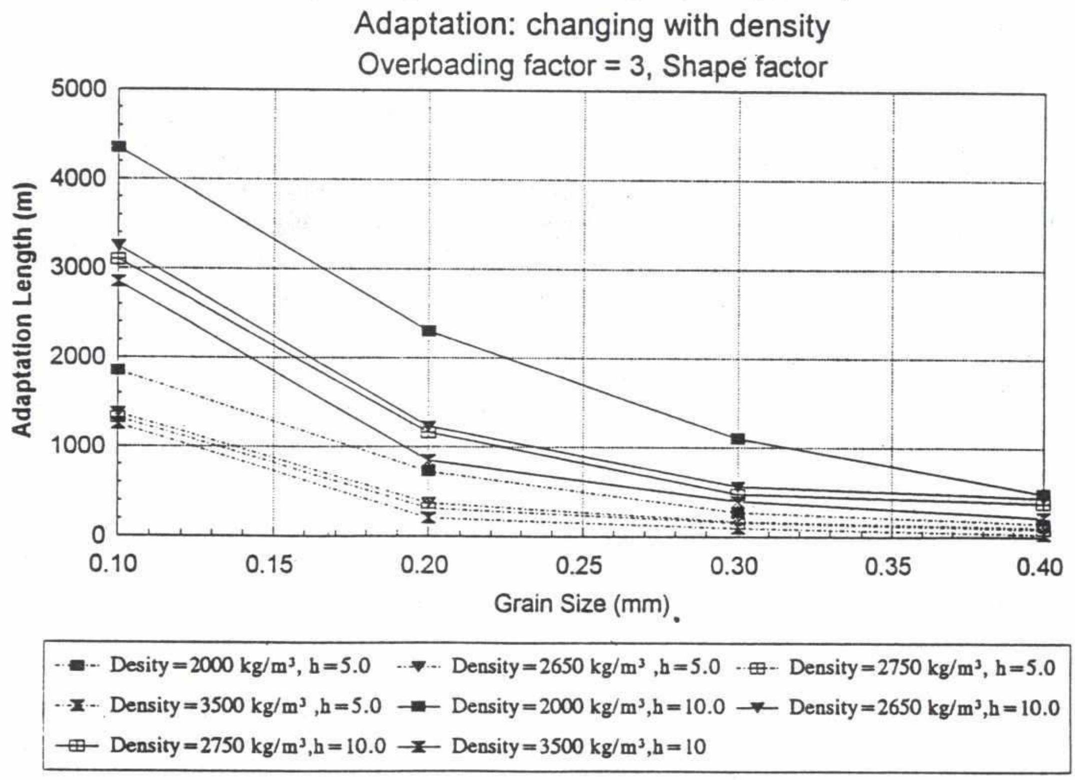

Figure 7.2 Estimated adjustment length of suspended sediment based on Van Rijn (1987) as a function of grain sizes and depth

7.3 Estimation of the erosion and deposition on the riverbed

Erosion and deposition of the riverbed can be estimated by comparing two consecutive bathymetric surveys. This estimated volume of erosion and deposition on the riverbed may not be the result of one cycle of the erosion and deposition process. Rather, it is likely that the estimated volume may be the result of a number of cycles of erosion and deposition processes in the river depending on the time interval between the consecutive surveys and the duration and intensity of the flood flow during the period.

As indicated in Chapter 5, two types of erosion and deposition can be identified, such as: erosion/deposition in lateral direction, and net erosion/deposition in downstream direction. The comparison of August 1993 and November 1993 bathymetric surveys, processed by GIS, can provide a fair impression on the magnitude of erosion and deposition in the riverbed within a time interval of less than two and a half months (see Figure 5.13). In one section of the river the simultaneous occurrence of erosion and deposition may often be in the range of 10 m or more. The two categories of erosion and deposition mentioned above are present in this difference map.

The changes in the riverbed are often compared in the following sections and chapters, with the sediment transport volume so as to get an idea about the participation of sediment transport in different processes. For the time being here only suspended sediment transport is considered. This will give an over estimation of the participation of the sediment transport in various processes due to not taking into account the bed load transport. Klaassen et al. (1988) estimated the bed load in the Jamuna River in about 10% of the suspended load. Later, in Chapter 12, this matter is further discussed.

Overall balances

In a difference map the local erosion and deposition of the riverbed can be very high. It is interesting to study whether any net aggradation or degradation had occurred during the period of study or any changes of average width, area of the channel had occurred by using the overall balances. This can provide an idea about the overall processes in the Jamuna River. The bathymetric surveys at Bahadurabad were performed during different water levels prevailing at Bahadurabad, see Table 5.2. Therefore, the reach averaged width and flow area and total flow volume of the channel estimated for the different bathymetric surveys, can be compared in relation to the respective levels.

The main problem identified here to estimate the overall balances, can be described as follows: (1) the balance between the char and the channel cannot be estimated from the present surveys, (2) during the monsoon it is possible to include all types of deep, shallow and narrow channels within the prefixed survey area, but in the dry season surveys. The shallow channels in which survey vessels were unable to sail was not included and (3) in the June 93-survey a shallow channel over the medial bar complexes, and in July 95-survey a part of the Old Main Channel were not surveyed, see Figures 6.1a and 6.1f. Therefore, during the comparison of the flow volume of the various surveys the mentioned points should be considered.

Using the GIS processed depth frequency data, the reach averaged sectional width and area of the river are estimated, see Figure 7.3. The wet volume of the total survey area in respect to various levels during the different surveys are presented in Figure 5.15. The June 93 survey is excluded for comparing the overall balances, the reason of which was indicated earlier. The volume below certain levels, relative to SLW, are also shown in Table 7.1. In the figures and the table the levels are sounded off to full metres although the prevailing average water levels are in fractions of metres. This adds some uncertainties in estimating the balances.

Level(m +SLW)	Volume Mm³					
	Aug.93	Nov.93	Nov.94	Feb.95	Jul.95	Nov.95
-7	2720				2500	
-6	2180				1990	
-5	1720				1550	
-4	1230				1200	
-3	1010	950	990		910	970
-2	760	710	770		670	730
-1	560	510	580	510	490	540
0	410	370	430	380	350	390

Table 7.1 The volume of the channels under different levels

It is understood from Figure 7.3 that the changes of the reach averaged width of the different surveys are very little under different levels. However, the levels represent the different discharges. The figure indicating that on average the river maintains a width in relation to discharges, although the spatial variation of width of a channel is often two-fold. This implies the applicability of the at-a-station relations derived by Klaassen and Vermeer (1988a) for the Jamuna River.

Figure 5.15 also shows a little variation of the overall volume among the different surveys, but in comparison to the total sediment transport volumes in between the consecutive surveys (see Table 5.1), Table 7.3 shows often a higher change in flow volumes. This seems to be unrealistic, the reason of which is mentioned earlier. Therefore, it can be noted here that from the RSP bathymetric surveys the estimation of overall balance is not possible.

Local balance

It appeared that for overall balances the range of uncertainties is very high. For the local balances uncertainties due to the exchange of sediment in between bars and channels remain applicable, but the other reasons of introducing uncertainties mentioned in previous sections such as: the missing of surveys at different shallow channels can be omitted by comparing only the common channels surveyed in two consecutive periods.

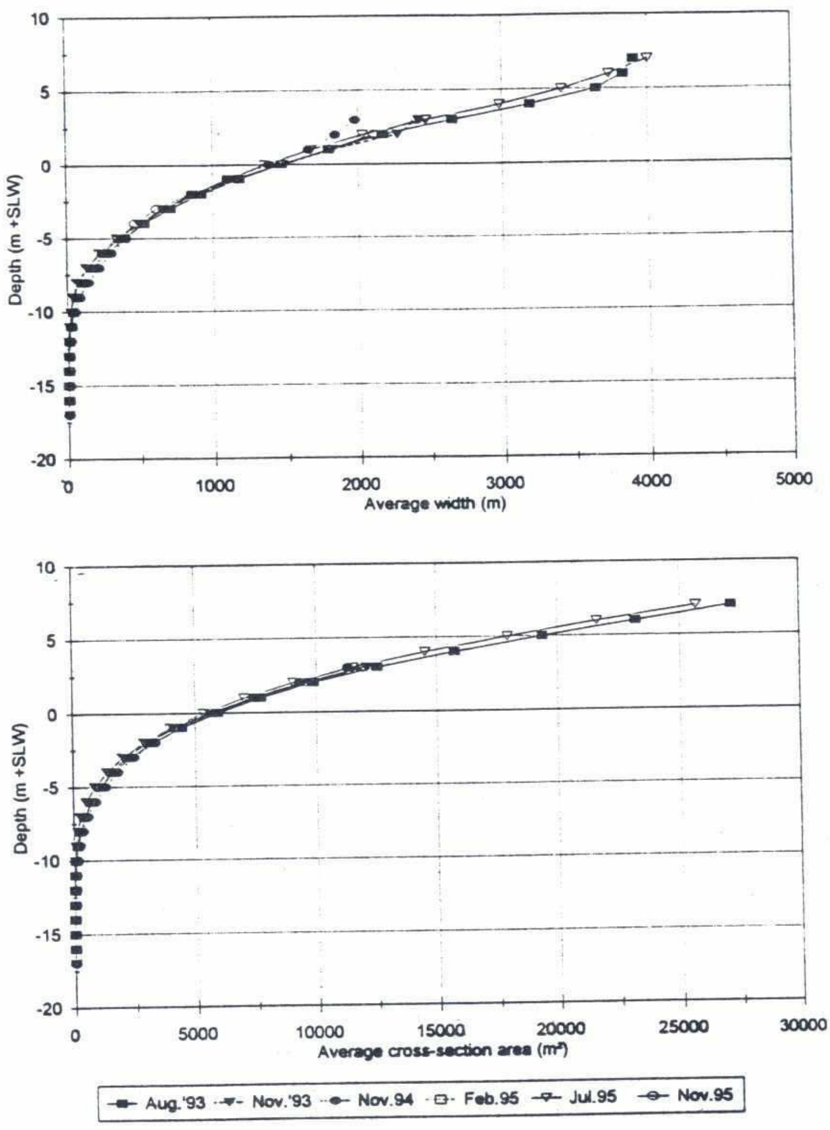

Figure 7.3 The changes of reach averaged flow width and area under different level in different bathymetric surveys at Bahadurabad

To study the local erosion and deposition of a flood cycle, the bathymetric surveys of June 1993, August 1993 and November 1993 were selected. It should be mentioned that local balances using June 1993 surveys is subject to some uncertainties, especially in branch 2 (Figure 7.4), for reasons indicated earlier. The local erosion and deposition also compared with the bed material transport during the period of June-August 1993 and August-November 1993 (see Table 5.1). It is assumed that the estimated sediment transport volume is the total sediment input into the system during the mentioned period. As the system is fairly in balance, the input is the same as the output sediment volume. Furthermore, it is assumed that only the bed material (and not the silt and clay fraction) participated in the erosion and deposition processes. The local erosion and deposition is estimated from two consecutive surveys telative to the lowest prevailing water level of the two considered (see Table 5.2).

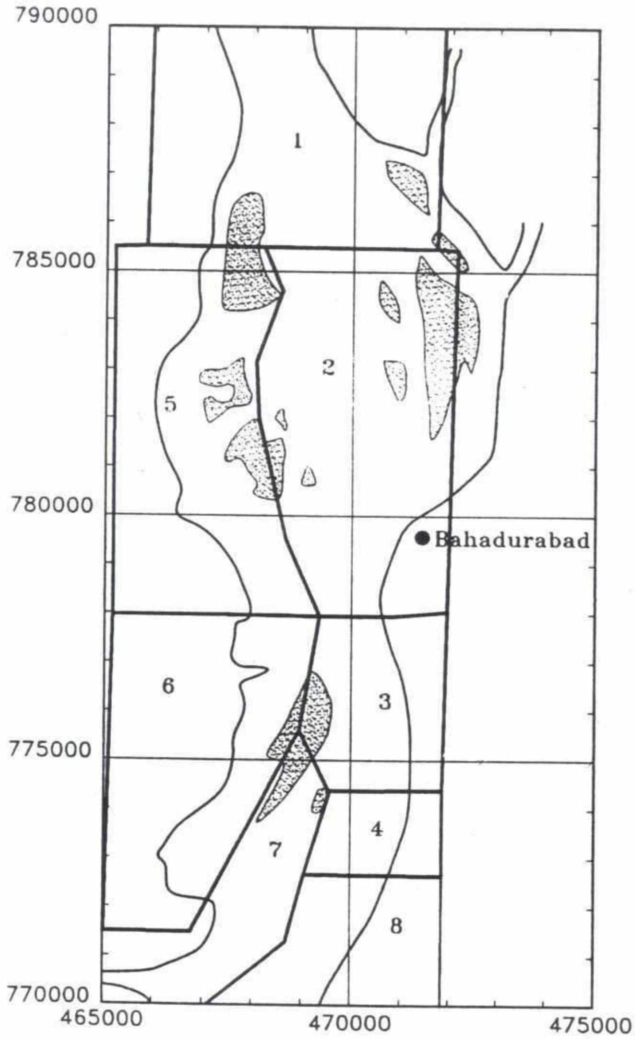

Figure 7.4 The division of different branches of the left channel for comparing local balances based on August 1993 survey

Branch	Volume of erosion (-) and deposition (+) (Mm³)	
	Jun-Aug. 1993	Aug-Nov. 1993
1	-15	4
2	-41	-8
3	1	-1
4	-4	3
5	17	4
6	-11	-3
7	2	1
8	-14	-1
Total	-65	-2

Table 7.2 Local erosion and deposition in the period of August-November 1993 in the different branches

The net erosion and deposition volumes in the different branches are shown in Table 7.2. In the period of June-August 1993 the maximum deposition in branch 5 (the Old Main Channel) is about 17 Mm^3, equalling more than 60% of the sediment transport in the left channel during this period. The maximum erosion shown in the table for the same period in branch 2, representing the New Main channel is 41 Mm^3. This value shows a higher erosion than occurred in reality for reasons indicated earlier. It can be expected though that substantial erosion did occur in this branch due to the cutoff development of the channel. In the period of August-November, the maximum deposition (4 Mm^3) occurred in the upstream part (branch 1) and in the Old Main channel (branch 2). The maximum erosion is 8 Mm^3 in the New Main channel; compared to the total bed material transport in the left channel this is more than 50%. The overall balance by adding the local balances in the left channels in the August-November 1993 period are very close to zero. It indicates that due to some inconsistencies in the survey the overall balance can be estimated by addition of the local balances.

Figure 7.7 presents the net erosion and deposition of the river from the upstream end of the bathymetric survey along branches 1 and 2 in the period of August-November 1993 as function of the chainage. It is observed that in branch 1 the net cumulative deposition increases and with chainage in branch 2 downstream of the bifurcation the net erosion processes compensate the previous deposition. The overall sediment transported volume (see Table 5.1) during the period of August-November survey can be compared with the net erosion and deposition along the chainage from the upstream, see Figure 7.6. This figure gives an impression of the relative importance of erosion and deposition processes in the total sediment transport in the river. It is interesting to observe that up to 40 to 60% of the average sediment transport participated in erosion and deposition processes, indicating that the sediment transport in the Jamuna river is not uniform in downstream direction; but it is an intermittent process. This implies that in the Jamuna River two simultaneous sediment measurement campaigns in two different locations for a period can result in a varying factor of 2.

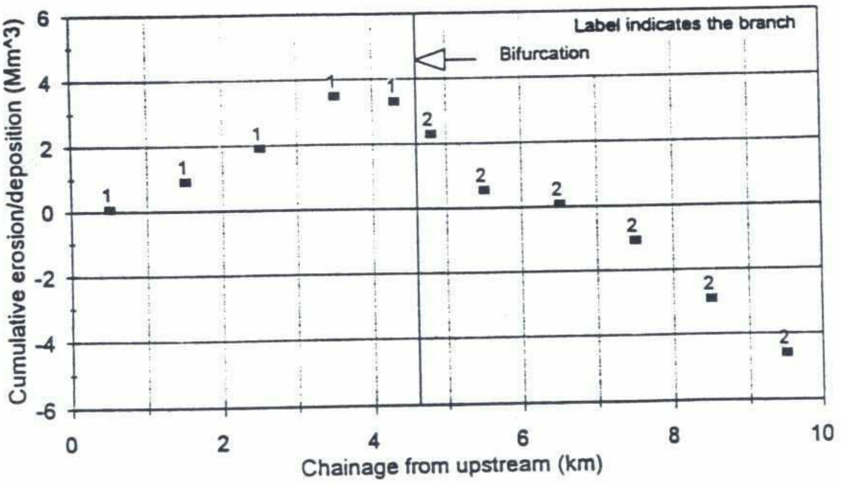

Figure 7.5 The variation of erosion and deposition in downstream direction

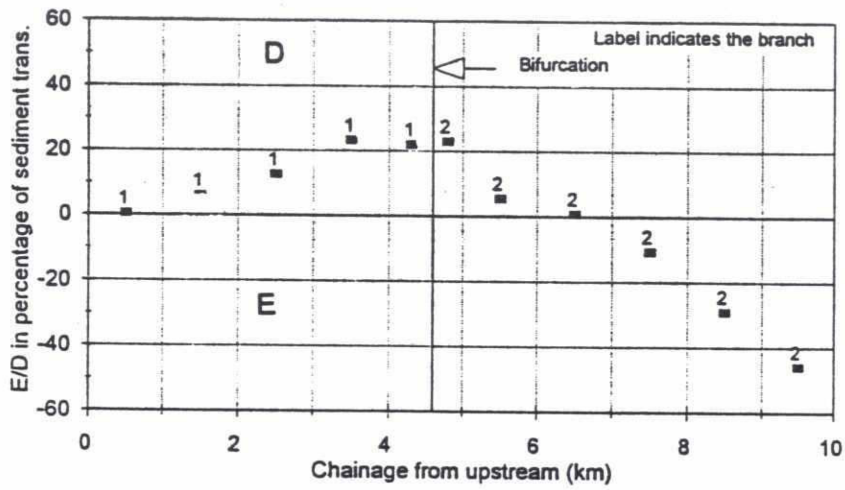

Figure 7.6 The erosion and deposition in percentage of sediment transport in downstream direction

7.4 Processes of the erosion and deposition on the riverbed

Evidently the observed riverbed erosion and deposition are the result of the flow and sediment transport processes in the river. Here an attempt is made to understand the processes of the flow and sediment transport in relation the erosion and deposition on the riverbed. This is done by using the ADCP transect measurements during the August 1993 bathymetric survey and the erosion and deposition is estimated by comparing the August-November 1993 surveys. Therefore this analysis is limited to these two surveys only.

Flow processes in the river

The case of uniform flow can be described by the Chézy's equation ($u = C\sqrt{(hi)}$, where for the same bed roughness (C) and the same energy slope (i), the depth-averaged velocity is proportional to the square root of water depth (hydraulic radius). In a natural river, especially in rivers like the Jamuna substantial deviations from this can be observed, due to the spatial variation of these parameters. Figure 7.7 shows the erosion and deposition on the riverbed during the period August-November 1993 together with cross-sectional profiles, interspaced at 400 m with an indication of the depth-averaged velocities measured during the August 1993 bathymetric survey. The depth-averaged velocities are derived from the ADCP transects measurements. It can be seen from the figure that at location (A), the depth-averaged velocity is small compared to the water depth and deposition occurred at this location. On the contrary, at another location (B) where the water depth is comparatively small, erosion did occur. This can be better illustrated by Figure 7.9, in which erosion and deposition on the riverbed in relation with water depth and depth-averaged velocity is shown.
It is observed that the flow distributions are not in line with the riverbed topography. Due to cutoff development upstream the flow direction changes, which is probably the main reason of this type or especially valid for this location.

If observed distribution of depth-averaged velocity is compared with predicted velocity using Chézy's relation, assuming C is on 70 $m^{1/2}/s$ and $7.5*10^{-5}$ respectively (see Figure 7.9), a range of variation of spatial distribution of velocity 50 to 100% can often be observed. The reason of this type of variation can be explained as follows: (1) The changes in the upstream reach, (2) adaptation process of flow, (3) local variation of roughness and slope. The adaptation of flow can be expressed as (Struiksma, 1983):

$$\lambda w = \frac{c2}{2g} h \tag{7.5}$$

where λw = adaptation length of flow; h = water depth for the Jamuna River, assuming c = 70 $m^{1/2}/s$ and average depth = 7 m, the adaptation length of flow is about 2 km. During these adaptation processes of flow for one disturbance, other disturbances are very likely during the monsoon which makes the system a continuous process of flow adaptation.

Due to the changes upstream, the continuous process of adaptation of flow, changes of flow momentum with the variation of discharges, variation of local slopes and roughness the two-dimensional distribution of flow in the river appeared a complicated one, especially in the monsoon.

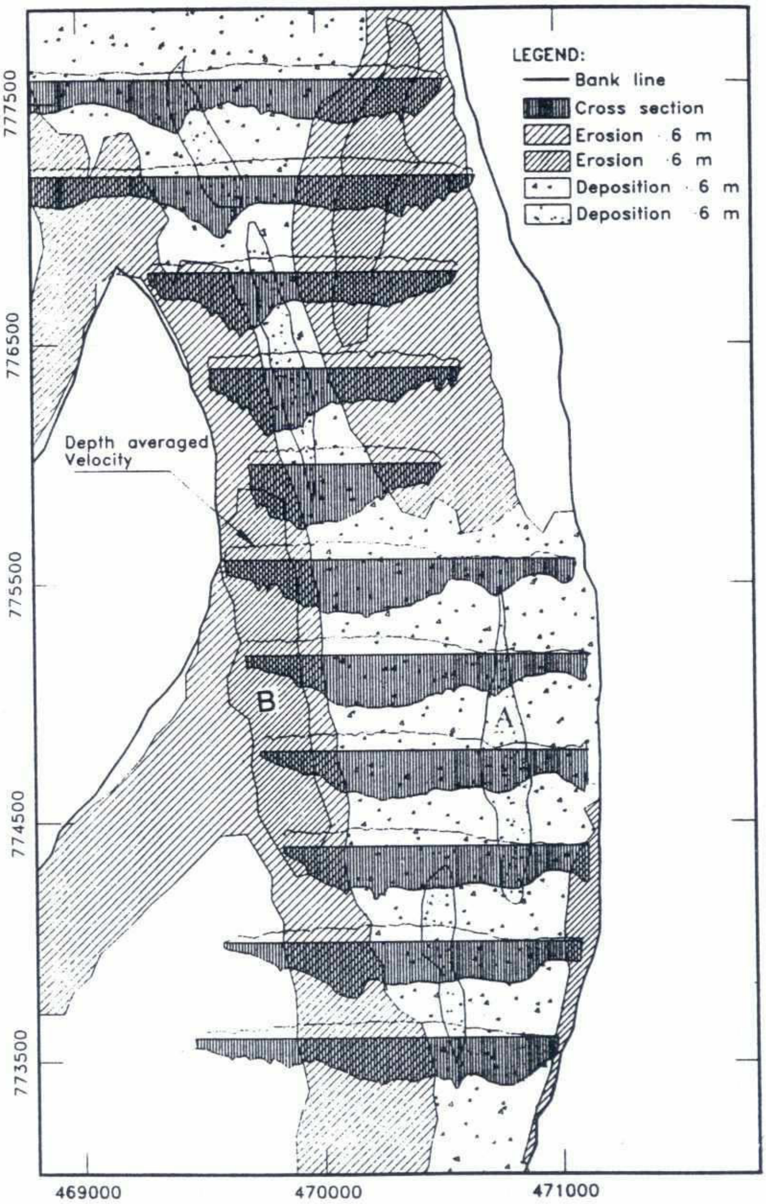

Figure 7.7 The depth-averaged velocity over cross-sectional profiles measured in August 1993 and erosion and deposition on the riverbed (August-November 1993)

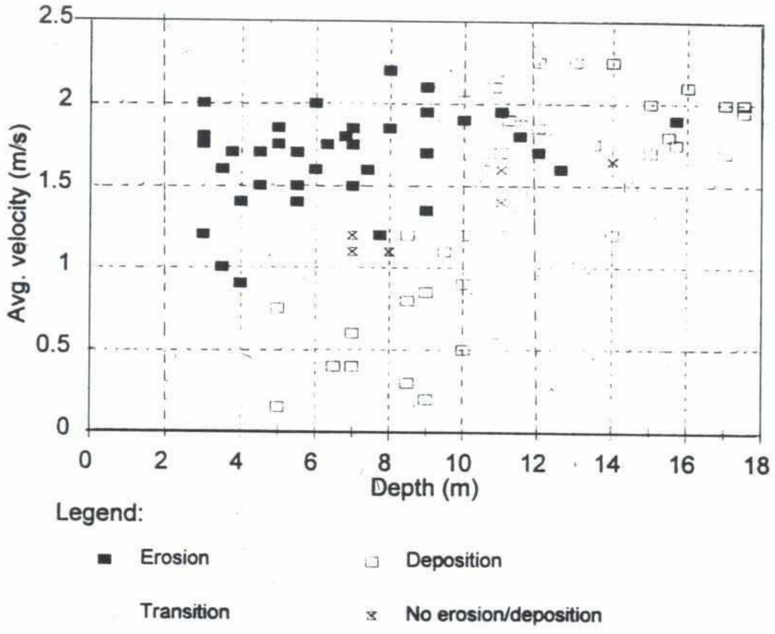

Figure 7.8 Erosion and deposition on the riverbed in relation with depth-averaged velocity and water depth

Sediment transport processes in the river

To better understand the sediment transport processes in the river, the upstream part of the bathymetric survey of August 1993 was selected. The reasons for this selection were that the ADCP measurement covered a comparatively large area and that the large variation of sediment concentration can provide a better idea about the underloading and overloading processes of the suspended sediment. The flow lines derived from the ADCP transect measurements can be seen in Figure 7.10. The discharge between two subsequent flow lines is 3,000 m^3/s. Along the flow lines the water depth, the sediment concentration derived from ADCP backscatter, and predicted sediment concentration are shown in Figure 7.11. The predicted concentration corresponds to the sediment transport capacity using a sediment transport predictor specially developed for the Jamuna River (Equation 3.23). In estimating the sediment concentration instead of using the parameter θ, the depth-averaged velocity is replaced by using Chézy's relation, and the modified relation reads as:

$$c = \frac{80}{1-\varepsilon} * \sqrt{\Delta g D_{50}^{\;3}} * \left(\frac{1}{C^2 \Delta D_{50}}\right)^{1.8} * \frac{u^{2.6}}{h} \qquad (7.6)$$

where c = depth-averaged concentration. Assuming Δ = 1.65, C = 70 $m^{1/2}/s$ and D_{50} = 0.2 mm, Equation (7.5) can be expressed as:

$$c = 1024 * \frac{u^{2.6}}{h} \qquad (7.7)$$

in which c is expressed in mg/l.

In the flow lines 1 and 2 of Figure 7.11 the sediment concentration is in fair agreement with the predicted transport capacity. In a few cases where the predicted concentration shows a sudden jump, the actual sediment concentration does not show such sudden changes. The concentration along the flow line 2 shows a clear lagging behind compared to the predicted concentration. In the flow line

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1, downstream of chainage 4000 m, the predicted concentration is much higher than the actual sediment concentration, clearly showing a zone of underloading. Erosion is likely for that location, see Figure 7.10 and 7.11.

From the flow lines 4, 5, 6 and 7 it is observed in Figure 7.11 that if the sediment transport capacity increases, a certain distance is needed for adaptation to the new transport capacity. These overloading of sediments are prone deposition. It can be observed that most of the overloading area is deposited in the period of August-November 1993. The magnitude of over concentration and the gradual diminishing of over-concentration in downstream direction can be better illustrated in Figure 7.12. In this figure are only shown the observed suspended sediment concentration which is higher than the predicted concentrations. The estimated relative adaptation length and the overloading are presented in Table 7.3. The overloading is estimated by the ratio of sediment concentration and the predicted concentration. The estimation is done for a length where predicted concentration shows almost no variation in downstream direction, and average depth along the flow line is considered (see Figure 7.11). In natural rivers there are always some uncertainties in estimating the relevant parameters due to their variation in space. It can be seen though that the adaptation lengths derived from the field which are given in the table, is close to the predicted length estimated for the Jamuna River using average grain size based on Van Rijn (1987), see Figure 7.13.

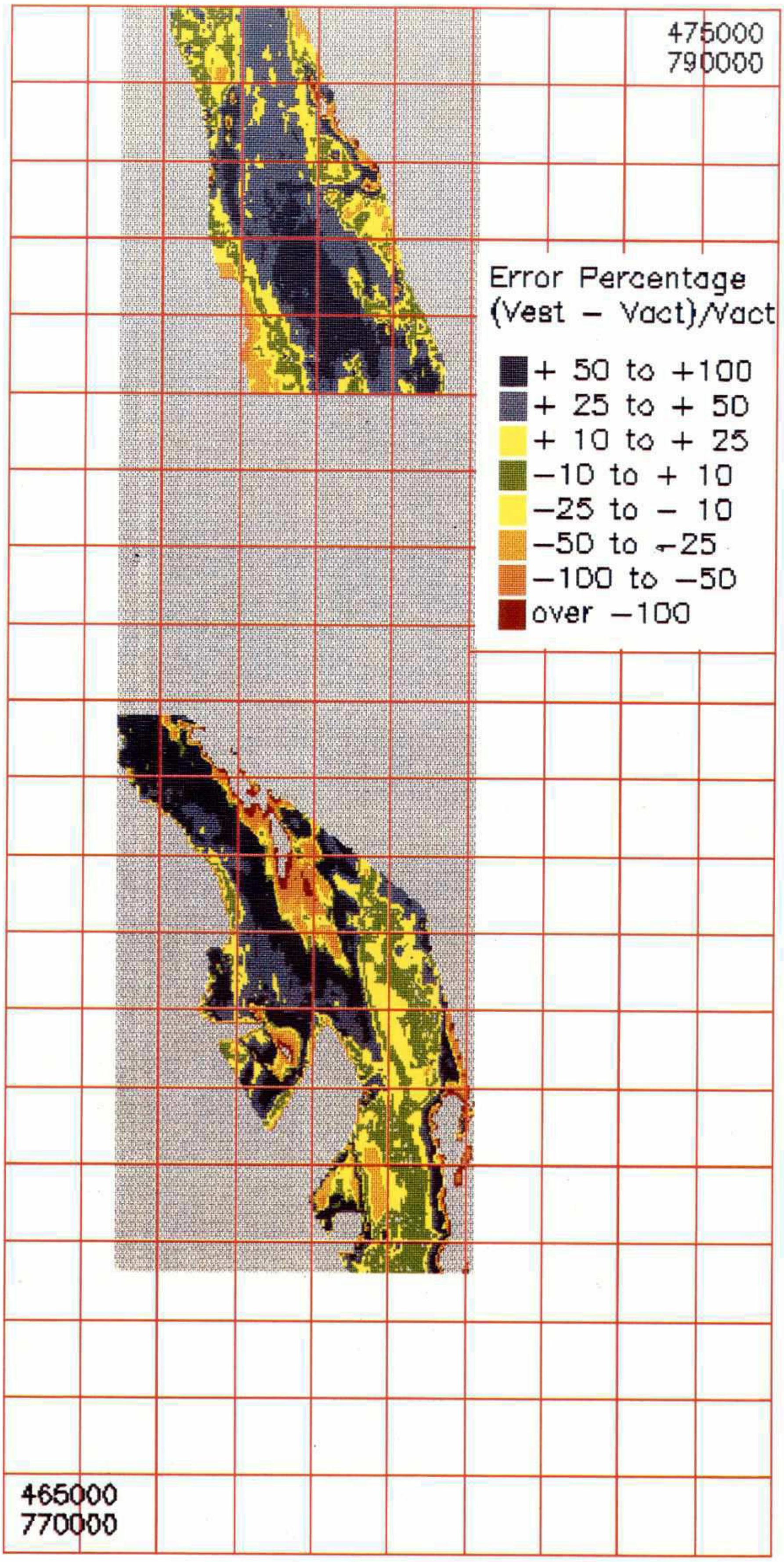

Figure 7.9 The difference between measured depth-averaged velocity and predicted velocity assuming uniform flow ($C = 70\ m^{1/2}/s$, $i = 7.5*10^{-5}$)

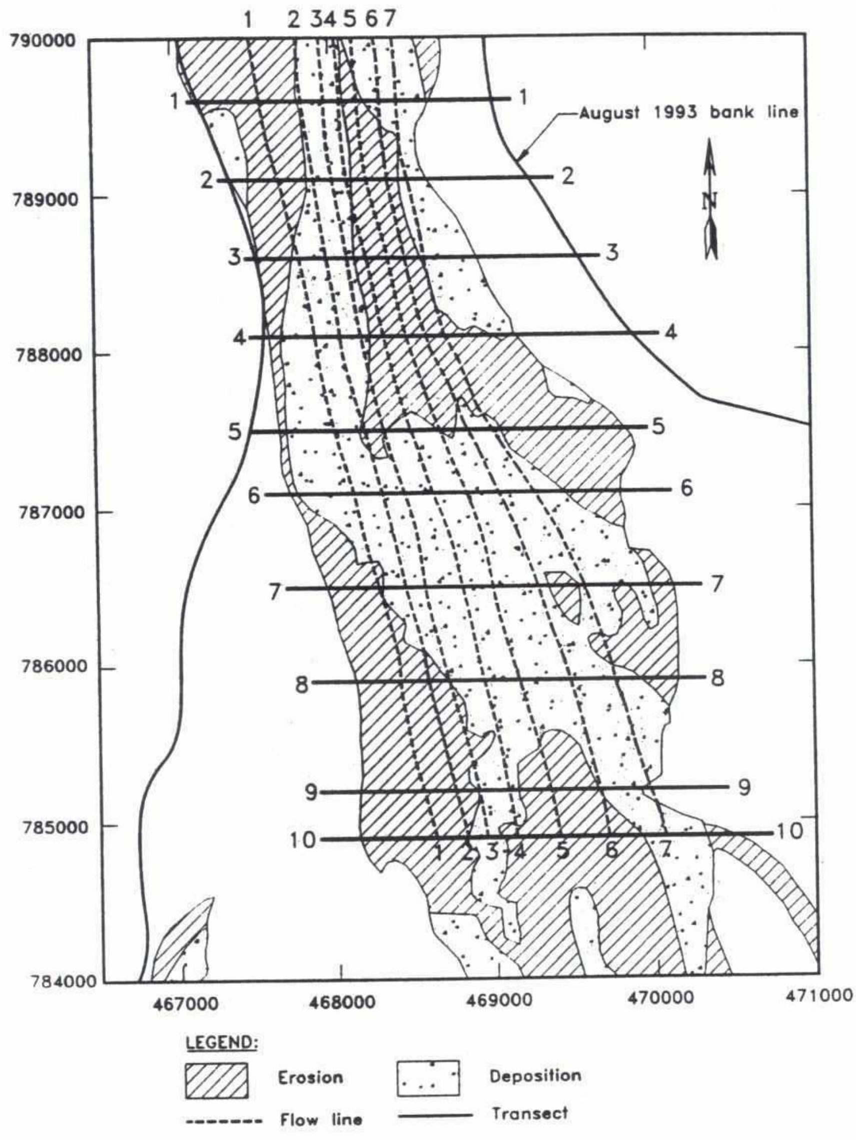

Figure 7.10 Erosion and deposition (August-November 1993) and flow lines based on August 1993 measurement

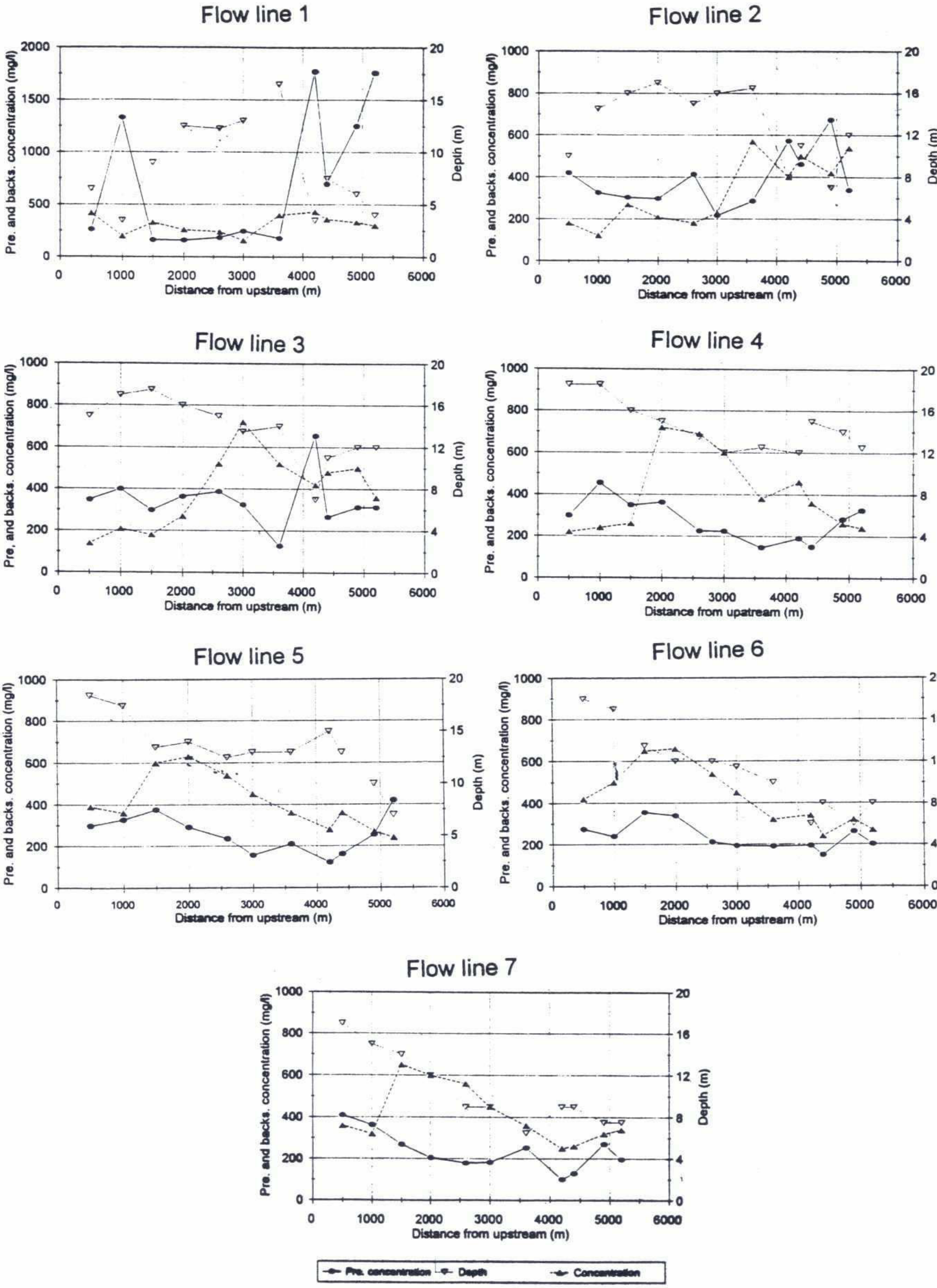

Figure 7.11 Depth, predicted concentration and actual sediment concentration along two flow lines

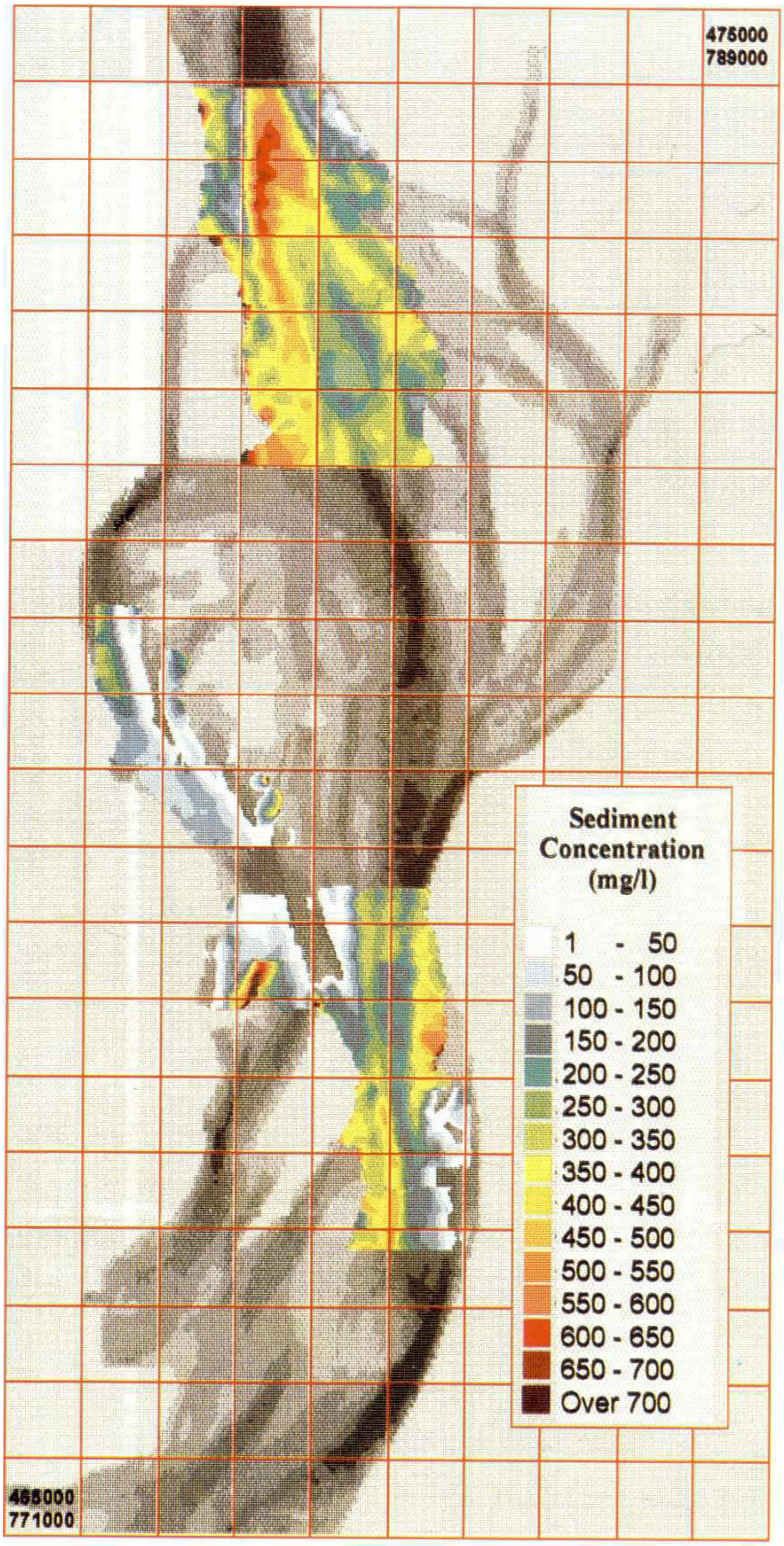

Figure 7.12 The magnitude of observed over concentration (Aug. 93)

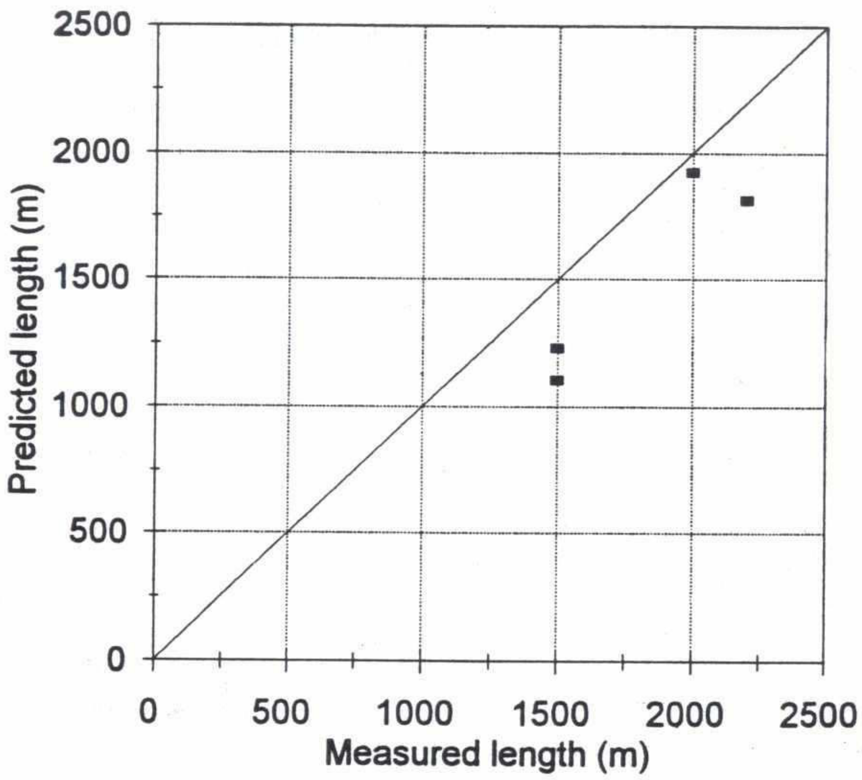

Figure 7.13 The observed and predicted (Van Rijn, 1987) suspended sediment adaptation length

Flow lines	Overloading	Depth (h) (m)	Adaptation length (L) (m)	L/h
4	3.5	12	2000	167
5	2.5	12	2200	169
6	2.5	10	1500	150
7	3	10	1500	150

Table 7.3 Measured and predicted adaptation length along the flow lines

The reason for sudden increase of sediment of about 200 to 400% is not clear. But from Figure 7.14 it can be observed that where the sediment concentration in a section is very high, the bedforms on the riverbed at that location are prominent. It is probable that bedforms had contributed to increase the bed roughness and hence the sediment transport. By using Chezy's roughness predictor (Equation 3.12) and the Equation 3.23, it can be shown that increasing of roughness of 1 m, then for 12 m depth, sediment transport increased by 300% from an area where Chezy's roughness is 70 $m^{1/2}/s$, considering other condition remain same. It is interesting to see that the bed form height at the high sediment concentrated area appears to be about 2 m. It is mentioned here that the roughness height for bed form not only depends on the bedform height, but also very much depends on the shape of the bedform. This observation contradict with the observation of Lukanda et al (1992) and Klaassen et al (1988) as mentioned in Chapter 3. To estimate the average roughness and sediment transport, the effect of the bedform during the high flow may not be relevant, but for particular locations it might have some influence in contributing the local roughness as well as to the sediment transport. Here it should be

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mentioned that apart from the high sediment concentration, there are some location where the bedforms are also prominent. More detailed information on the shape, height and length of the dune, and also about the flow may enable to elucidate the influence of bedforms on the sediment transport.

It is observed that the flow in the Jamuna River, especially during the high flow, is not in equilibrium with the riverbed topography, but rather is governed by upstream conditions and the momentum of the flow. Also variation of the roughness and the local slope variations around the average value might be significant. However, it is observed that to model the changes of a riverbed, it is required to have sufficient insight into the adaptation processes of sediment concentration in the Jamuna river while also prediction methods for bedforms and corresponding roughness are needed.

7.5 Summary

The processes of riverbed erosion and deposition in the Jamuna river have been studied here for the first time with detailed estimate of the quantities of bed material involved and by linking it to the flow and sediment transport processes of the river. The following interesting findings were obtained:

- Two types of riverbed erosion and deposition can be identified, one is the riverbed erosion/deposition in a channel section and the other is the net erosion and deposition in downstream direction. Both processes occur simultaneously in an active river.
- Locally, quantities of erosion and deposition are quite high and depend on the flow stage in the river and may be up to 20 Mm^3 (Old main channel in June-August, 1993) in a 5 to 6 km long channel.
- The magnitude of the erosion and deposition on the riverbed can be linked to the average sediment transport capacity of the river. It is observed that more than 50% of the average sediment transport is participating in the erosion and deposition processes over a distance of some 5 to 10 km. This implies that the sediment transport in the Jamuna River is rather an intermittent processes and thus the measurement in a channel at different cross-sections can result in a high variation in measured values of up to 100% or more.
- The direction of flow often changes, mainly determined by the upstream reach and also probably the changes of momentum of flow due to discharge variation. It appeared that spatial distribution velocity in the Jamuna river is very complicated as a result of interaction processes of above two causes, continuous adaptation processes of flow and local variation of slope and roughness.
- The processes of erosion and deposition is determined by the sediment continuity relations and overloading and underloading of suspended sediment govern the processes. A sudden increase of sediment transport was observed, which may be related to the bed roughness generated by the bedform.
- It appeared that the adaptation length for the suspended sediment, especially for the overloading, is in good agreement with the predicted adaptation length based on Van Rijn (1987).
- It appeared that to betten interpret the observation made on the flow and sedimentary distribution, a two-dimensional mathematical model would be helpful a tool.

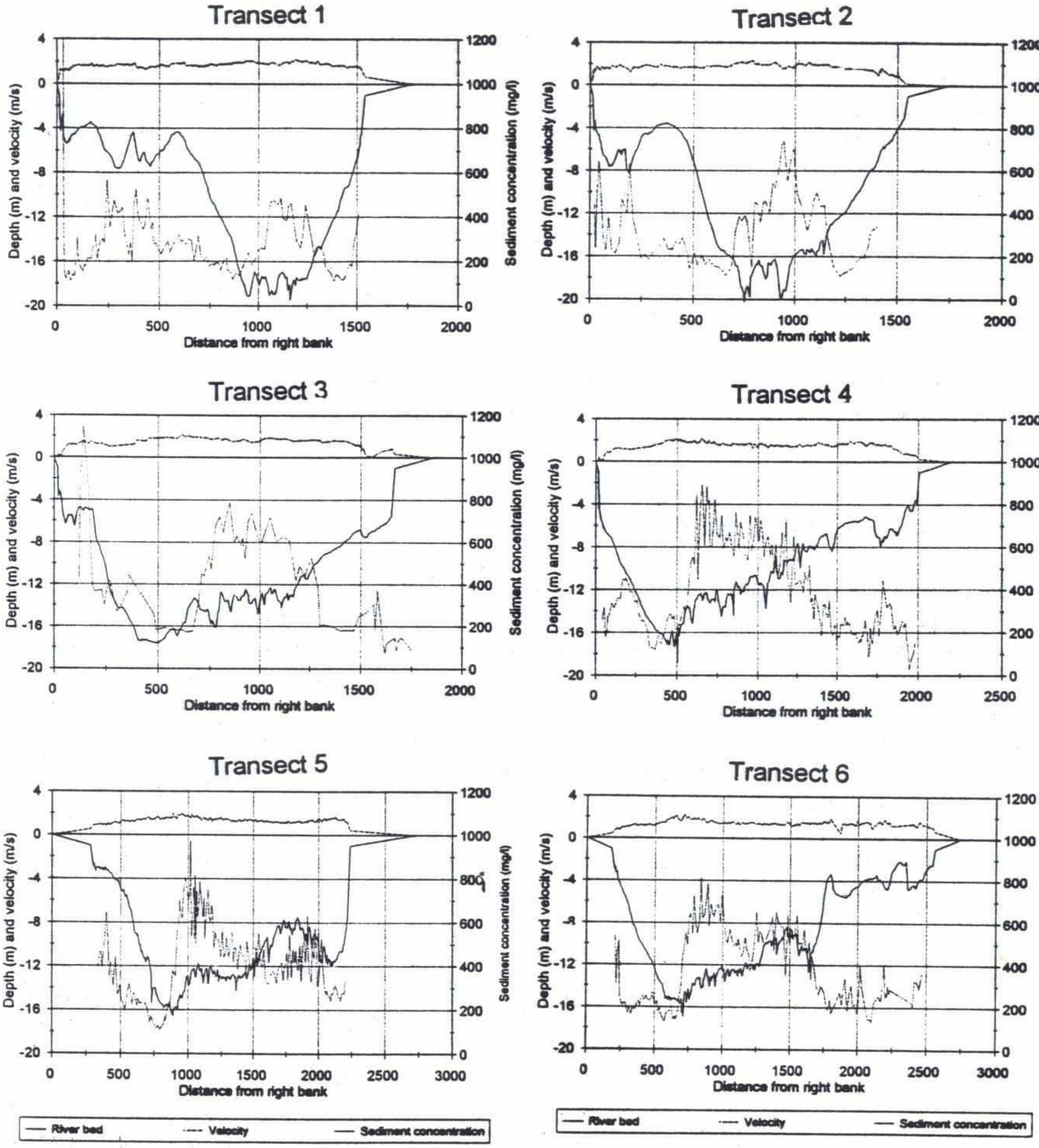


Figure 7.14 Depth-averaged velocity over cross-sectional profile and sediment concentration

8 Development of cutoff

8.1 Introduction

Cutoffs of curved channels are often observed in meandering rivers and cutoff processes play an important role in planform development. Although being a braided river, in the Jamuna similar cutoff processes are often observed in river bends (Klaassen & Masselink, 1992). Here the river bend is mostly formed by an outflanking anabranch and after a few years the anabranch is abandoned, often by a cutoff process. This type of cutoff process markedly changes the downstream planform of the river. Therefore, a better understanding of the cutoff process is quite relevant to better predict the morphological development of the river. During the RSP bathymetric surveys at Bahadurabad, a cutoff took place and later surveys show the channel and planform development in that reach. Here the development of the cutoff and the later development of the channel is discussed using the RSP bathymetric surveys.

Causes and previous studies on cutoff processes are presented in Section 8.2. The cutoff process at Bahadurabad and the subsequent channel development is described in Sections 8.3 and 8.4 respectively, and finally, the findings of the study on cutoff near Bahadurabad are summarized in Section 8.5

8.2 Previous and recent studies of causes of cutoffs

In a meandering river, usually bank erosion along the outer bank increases the length of the river. This type of increment in the length of a river is generally counteracted by occasional cutoffs during a flood. The cutoff is caused by the development (scouring and widening) of a cutoff channel that develops in the floodplain at the neck of the meander bend. Gradually, the cutoff channel increases its dimensions and the old channel develops into an oxbow lake. To better understand these cutoff processes and to predict when a cutoff will occur is obviously an essential element in meander-modelling. It is also relevant for the planform development of a braided river, although in literature mainly information on cutoffs in meandering rivers is available.

Joglekar (1971) introduced a parameter (called the 'cutoff ratio') which characterizes to what extent a curved channel may develop before a cutoff occurs. The cutoff ratio is defined as the ratio of the length of the bend to that of the cord, see Figure 8.1. According to Joglekar, this ratio depends on the characteristics of the river like the magnitude of the discharge, height of the flood rise, surface fall, the floodplain material and its suitability for the growth of protective grass and bushes. He also observed that cutoff ratios vary between 1.7 for Punjabi rivers in India and Pakistan, and 8 to 10 for the Mississippi River. Klaassen & Van Zanten (1989) observed even much higher values for a river in Indonesia.

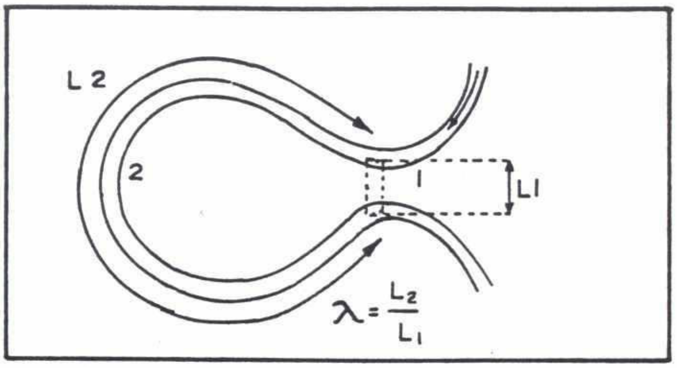


Figure 8.1 Definition sketch of cutoff ratio

Recently, Klaassen and Van Zanten (1989) studied analytically the cutoff processes in curved channels as part of a braided river system. There appears to be an essential difference between cutoffs in meandering rivers and cutoffs in braided ones. For the development of a cutoff channel in a meandering river it is sufficient that in the floodplain the critical shear stress of the floodplain soil is exceeded. Often it is required to correct for floodplain vegetation that is responsible for a part of the resistance. In braided sand-bed rivers the critical shear stress is always exceeded, and whether a potential cutoff channels develops depends on the ratio of sediment supply from the offtake into the cutoff channel (1) and the sediment transport capacity of the channel, moreover the ratio of the roughness of channel (1) and the curved channel (2), see Figure 8.1.

$$C_1 = \gamma C_2 \tag{8.1}$$

They assumed that the sediment entering the potential cutoff channel is given by:

$$\frac{S_{1\,incoming}}{S_{2\,incoming}} = \frac{1}{\sigma}\frac{Q_1}{Q_2} \tag{8.2}$$

where C_1 and C_2 = Chezy's roughness coefficients for the channel (1) and (2) γ = ratio of the Chezy's roughness respectively, Q_1 and Q_2 = discharge in channel (1) and (2), $S_{1\ incoming}$ and $S_{2\ incoming}$ = sediment supply from the offtake into the channels, and σ = ratio of sediment distribution, depends on the geometry of the bifurcation. For the case of a smaller ratio of the width of channels 1 and 2, Klaassen and Van Zanten developed a criterion for a cutoff, which reads as follows:

$$\frac{h_1}{h_2}\sigma\gamma(\lambda)^2 > 1 \tag{8.3}$$

where h_1 and h_2 = depth of channel (1) and (2) respectively. According to this criterion graphs were presented by Klaassen and Van Zanten, one of them shown in Figure 9.2. Although a number of simplifications were made (see Klaassen and Van Zanten, 1989) to derive this criterion, it provides a clear idea about the contribution of the parameters involved in a cutoff processes in a braided river.

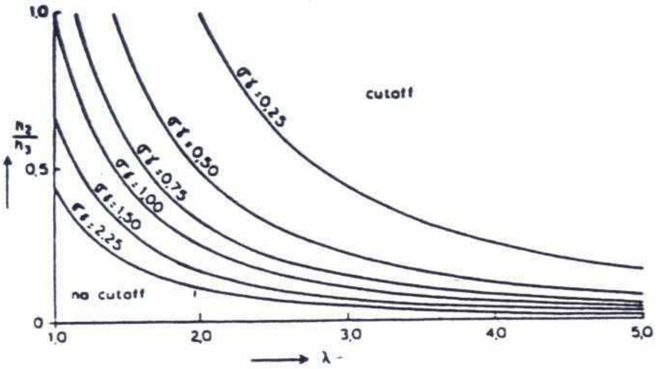


Figure 8.2 Influence of sediment distribution (σ) and relative roughness (γ) on cutoff criterion

Previous studies on cutoff processes in the Jamuna River were summarized in Chapter 3. It was mentioned that Klaassen and Masselink (1992) observed that the cutoff ratio is an important parameter for cutoff processes and their observed average cutoff ratio is 1.25 for the Jamuna River, which is very small compared to critical values for meandering rivers.

Recently, Mosselman et al (1994) showed that the deviation angle of a channel from the upstream channel is more important in the Jamuna River and based on their observation the probability of channel abandonment as a function of deviation angle is shown in Figure 8.3. They suggested to consider the deviation angle of the curved channel as 40° as a threshold value for the development of cutoff. In the Zaire River, Peters (1986) found that cutoff process can be derived from local slope variation among two anabranches and a predictive method was developed for the river on the basis of local slope variation.

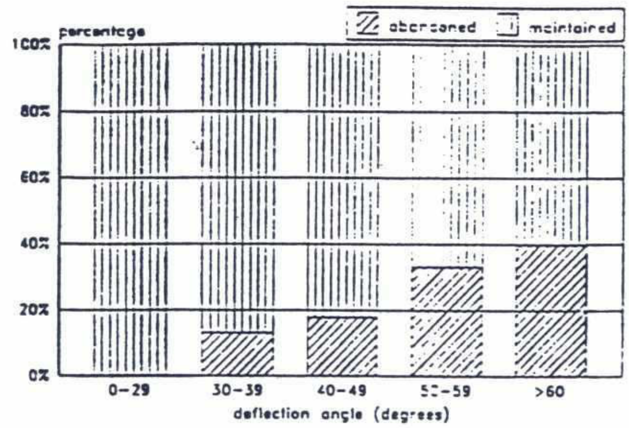


Figure 8.3 Probability of cutoff development as a function of deviation angle (Mosselman et al, 1994)

8.3 Cutoff processes at Bahadurabad

The planform development and the occurrence of a cutoff upstream of Bahadurabad in 1993 was described in Chapters 2 and 6. The development of the planform before and after the cutoff is shown in Figure 8.4 from SPOT images. The development of the planform during the cutoff process is presented in Figure 8.5 on the basis of RSP bathymetric surveys. Peters (1994) indicated likely causes of the cutoff that occurred at Bahadurabad in 1993. According to Peters, due to bank erosion along the right bank upstream of the bifurcation in the period of 1992-1993, the point bar 'A' moved in downstream direction (see 1993 imagery of Figure 8.4) and almost closes the offtake of the old main

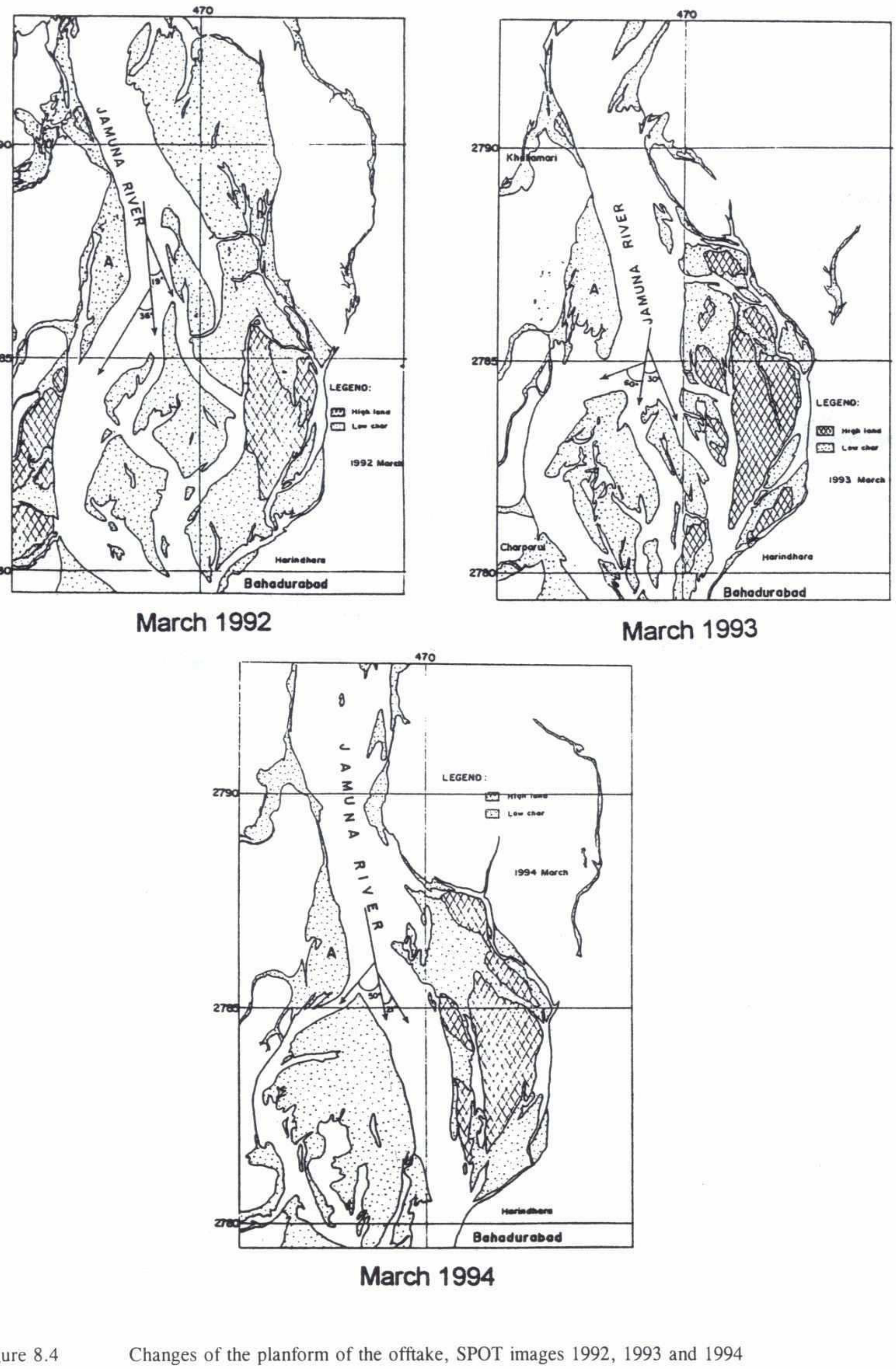


Figure 8.4 Changes of the planform of the offtake, SPOT images 1992, 1993 and 1994

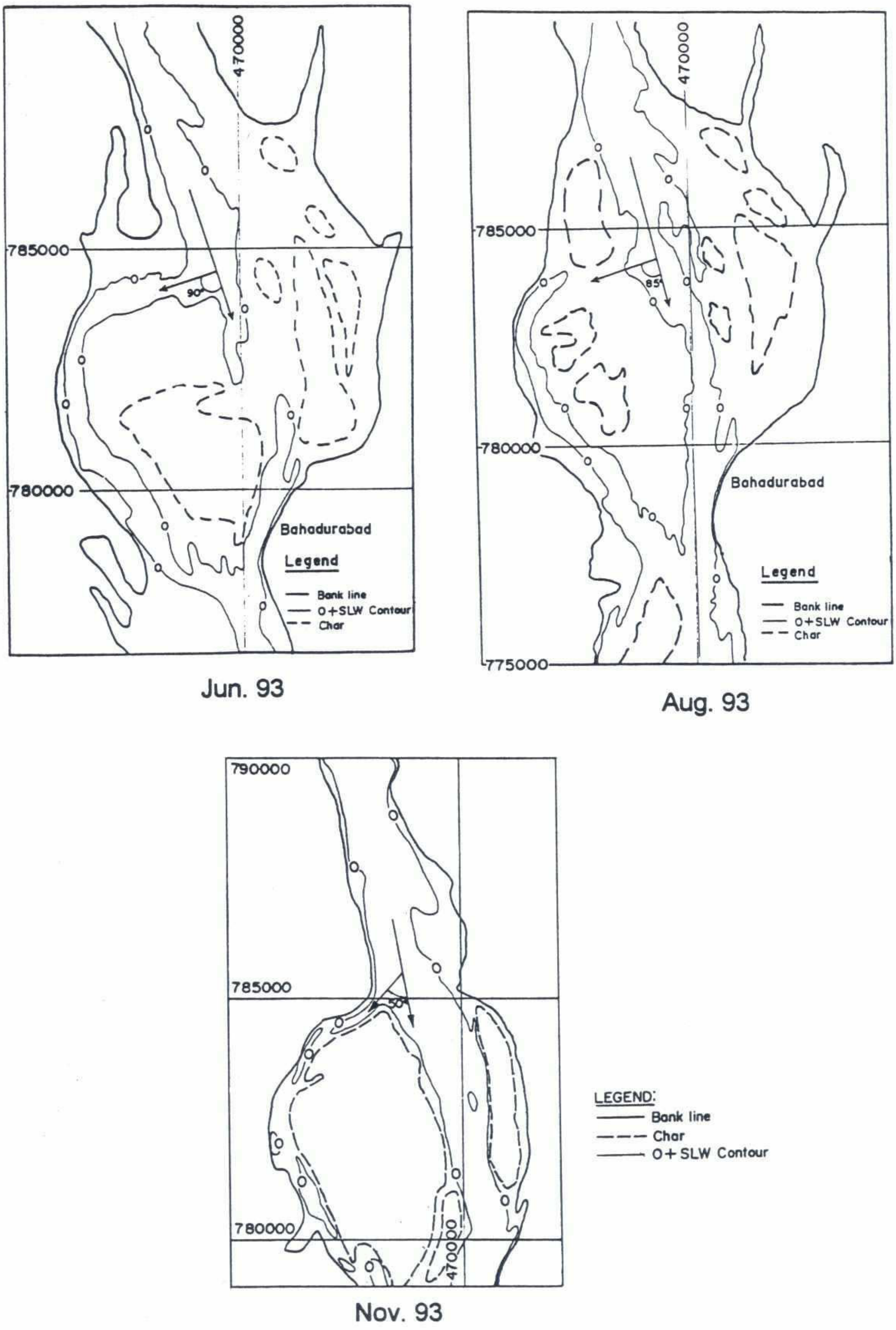


Figure 8.5 Changes of the planform of the offtake in 1993, bathymetric surveys

channel. As a consequence, the flow from the upstream end had no alternative than to cut through the smaller channels in the medial bar complexes. With the development of the point bar and the opposite bank erosion, the bifurcation also moved in downstream direction over a distance of about 2 km during 1992 to 1993. Three channels flowed in downstream direction from the bifurcation including the main channel in 1992 and 1993 although the bifurcation points was not at same location. The offtake angle (α) and the cutoff ratio (λ) varied throughout time as shown in Table 8.1. The offtake angle from the upstream main channel was 36° in 1992 and it increases up to 60° in 1993. The latter value is greater than the average cutoff angle estimated by Mosselman et al, (1994). The cutoff processes virtually began during the monsoon of 1992: as can be seen in Figure 8.4 the curved channel was decaying in size and the smaller channel through the bar complex grew in size in 1993. The further development of the point bar in the monsoon 1993 almost blocked the offtake of the main channel and the flow from the upstream end chose the path along the smaller channels directed toward Bahadurabad (see Figure 8.4). In June 1993 the offtake moved further downstream and at one stage the deviation angle reached almost 90°. Instead of a gradual further development of the cutoff, it suddenly accelerated as can be seen in the August 1993 bathymetric survey. After the development of the new cutoff channel the deviation angle of the old main channel reduced to 50°. In subsequent years this angle varied from year to year and the location of the bifurcation had shifted within a range of a few kilometres.

Period	Source	α	λ
March 1992	SPOT image	36°	1.20
March 1993	SPOT image	60°	1.39
June 1993	Bathymetry	90°	1.43
August 1993	Bathymetry	85°	1.38
November 1993	Bathymetry	50°	1.41
March 1994	SPOT image	50°	1.40

Table 8.1 Variation of deviation angle α and cutoff ratio λ with time

It is observed in Figures 8.4 and 8.5 and Table 8.1 that the deviation angle, which determines the sediment distribution among the channels from the offtake changes considerably during the process of cut-off. Although the cutoff process started during the monsoon of 1992, the fulfilment of the criterion by Klaassen and Masselink (1992) and Mosselman (1994) for cutoff was only observed in the March 1993 SPOT images and later. This is probably due to the fact that both predictive methods were based on satellite imagery. Due to the very rapid morphological processes in the river and the lagging behind of the planform with respect to the changes of flow distribution, satellite images are unable to reveal these processes.

To better understand the cutoff process, the variation of local slopes of the channels were studied as well. In Figure 5.5 the local slopes of the reaches Khatiamari-Bahadurabad and Khatiamari-Charparul (see Figure 5.1) from the month of July 1993 onwards, are shown. It is observed that the local slope of the Khatiamari to Bahadurabad reach varied within a range from 9 to 11 cm/km, whereas the slope of the Khatiamari-Charparul varied from 8 to 9 cm/km in the period of July to October 1993. The local slopes here presented are not completely representative for the slope of the Old Main Channel and of the New Main Channel respectively, as Khatiamari is located about 4 km upstream of the bifurcation. However, this figure indicates that while the cutoff was taking place, the local slope of the cutoff channel was considerably higher than that of the old main channel and also higher than in the following years.

Unfortunately, due to the missing of a channel in the June survey the volume of net erosion in the cutoff channel in the period June-August cannot be estimated. The estimated net erosion in the period August-November 1993 is about 7 Mm^3 in the new channel; this can provide an idea about the quantities involved in the erosion of the New Main Channel bed during the period June-August 1993. It can be assumed that the total eroded volumes over the whole period would be more than 2 to 3 times 7 Mm^3, which is about 70 % of the average sediment transport through the left channel. To transport such large quantities of sediment it is evident that the local slope of the new channel has to be higher. An increase in slope from 6.5 to 10 cm/km, increases the sediment transport (that scales with $s :: i^{1.8}$) with 100%.

Similar to the observations by Mosselman et al (1994), it is also observed here that the planform at the bifurcation depends on the changes upstream. The changes of deviation angle are also quite rapid and larger, making the prediction vulnerable. The processes that accompany a cutoff are very complicated; for instance, the changes of the deviation angle during the monsoon are very rapid (from 60° to 90° within two months) and the same holds for the location of the bifurcation. During the rapid development of the cutoff (June to August 1993), the planform of the bifurcation appears to become very unstable and goes through a process of rapid changes. This makes it difficult to exactly predict whether a cutoff will occur during a specific year.

The sediment distribution at the offtake delivered into the curved and the cutoff channels plays an important role (Equation 8.3). The distribution of sediment depends on the deviation angle from the upstream channel. It is observed that the deviation angle was very high during the development of the cutoff upstream of Bahadurabad. Here an attempt is made to estimate the sediment distribution during the development of the cutoff.

In the period of June-November 1993, the estimated discharges from RSP routine gauging survey are shown in Table 8.2. During the survey, RSP did not separately measure the discharge of the Old Main Channel and the New Main Channel, rather they measured slightly upstream of the confluence of both channels, from where the discharge of both channels separated and presented in Table 8.2. Now it can reasonably be considered that the average percentages of total discharge in the Old Main Channel are 34% and 20%, during the period of June-August and August-November in the Old Main Channel (by simple averaging).

Date of survey	**Discharge (10^3 m^3/s)**			**% of discharge in the old main channel**
	Total	**Old main channel**	**New channel**	
10/7/1993	37	17	20	46
20/8/1993	27	6	21	22
1/11/1993	11	2	9	18

Table 8.2 Discharge distribution in 1993 among the Old Main Channel and the New Main Channel

In the period June-August and August-November 1993 about 15 Mm^3 and 4 Mm^3 of sediment deposited in the old main channel respectively, see Table 7.4. In comparison to the sediment transport volume in the entire left channel during the mentioned period these are about 60% and 27% respectively. It is not possible to determine the sediment distribution ratio σ among the channels from the offtake by using RSP sediment transport measurement. If it is assumed that all the sediment input into the old main channel from the offtake is deposited (though input volume must be higher than the deposited volume) then the estimated σ value becomes about 2.9 and 1.5 for the period June-August 1993 and August-November 1993 respectively. It is interesting to see that the estimated value of σ is higher when the deviation angle is also higher (Jun-Aug.93), see Table 8.1 and is less when the deviation angle is reduced in the following period. This supports the concept of the sediment distribution being dependent on the deviation angle from the upstream channel. Also it is possible to check the criterion proposed by Klaassen and Van Zanten (1989). As $h_1 \cong h_2$, and $\gamma = (h_1/h_2)^{0.5}$ it follows that a cutoff will occur if

$$\sigma > (\frac{1}{\lambda})^2$$

This was definitely fulfilled during the monsoon of 1993, as λ is always larger than 1.

8.4 Channel development after cutoff

A number of significant changes occurred during and after the cutoff in the affected channels. Here only the adjustment of width, depth and flow area of the old main channel and the new channel, and the volumes of erosion and deposition are discussed on the basis of the bathymetric surveys of June, August and November 1993. It is often stated that the depth of a channel reacts first with an increase or decrease of the flow. This is probably caused by the bed material being comparatively more erodible than the bank material and the shear stresses on the bed are comparatively higher than the shear stresses exerted by the flow on the bank. A similar response of the depth occurs in the case of the reduction of the flow in a channel. The analysis of the changes of the cross-section of the Old Main Channel and the New Main Channel can provide the response of the channels of the Jamuna River affected by the cutoff processes. In addition, the volume of erosion and deposition in both channels can provide an estimate about the sediment distribution processes at the bifurcation.

As mentioned earlier, the river sections in the new cutoff channel cannot be compared for the period of June-August 1993 during which the major changes occurred. However, it appeared that in the cross-sections (Figure 8.6) of the Old Main Channel marked changes had occurred during the period of June-August 1993 (Figure 8.7). The depth as well as width of these sections reduced considerably. The process of reduction of width and depth continued in the August-November period. However, the cross-sections of the cutoff channel show that depth as well as width increased in the period June-November 1993, although the different sections showed different rates of change. It is interesting to observe that during the adjustment of depth and width, the sections also shows a frequent shifting of the thalweg and changing of the shape of the cross-sections. The thalweg profiles along the Old Main Channel and along the New Main Channel indicated in the thalweg depth in the next channel increased with almost 3 m during June-August, whereas the reduction of the thalweg depth in the Old Main Channel was about one metre only in the same period (Figure 8.8). The processes continued in the period of August-November.

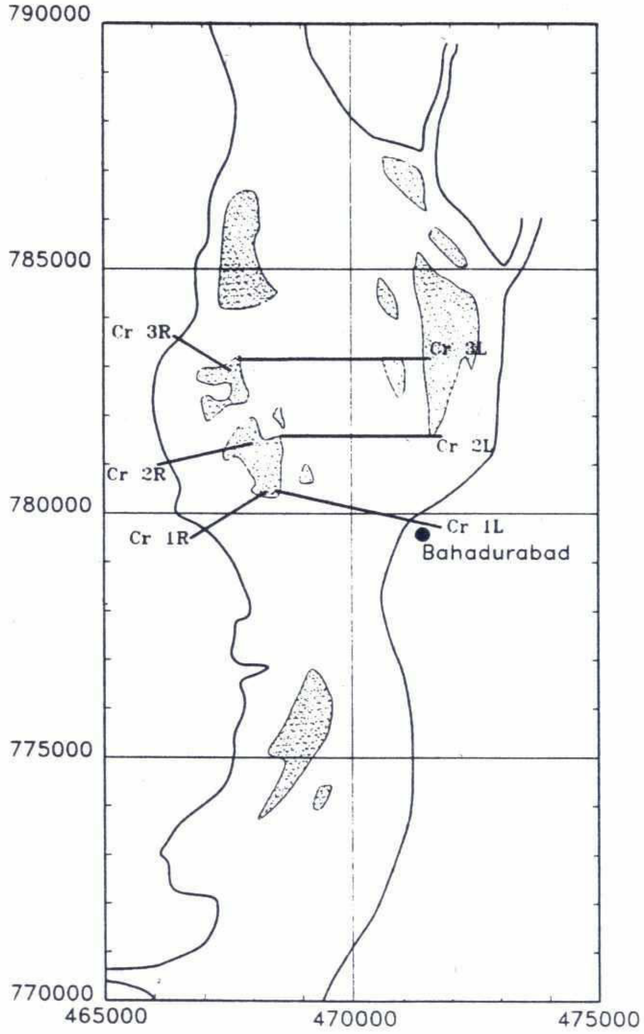


Figure 8.6 Location of the cross-sections (see Figure 8.7)

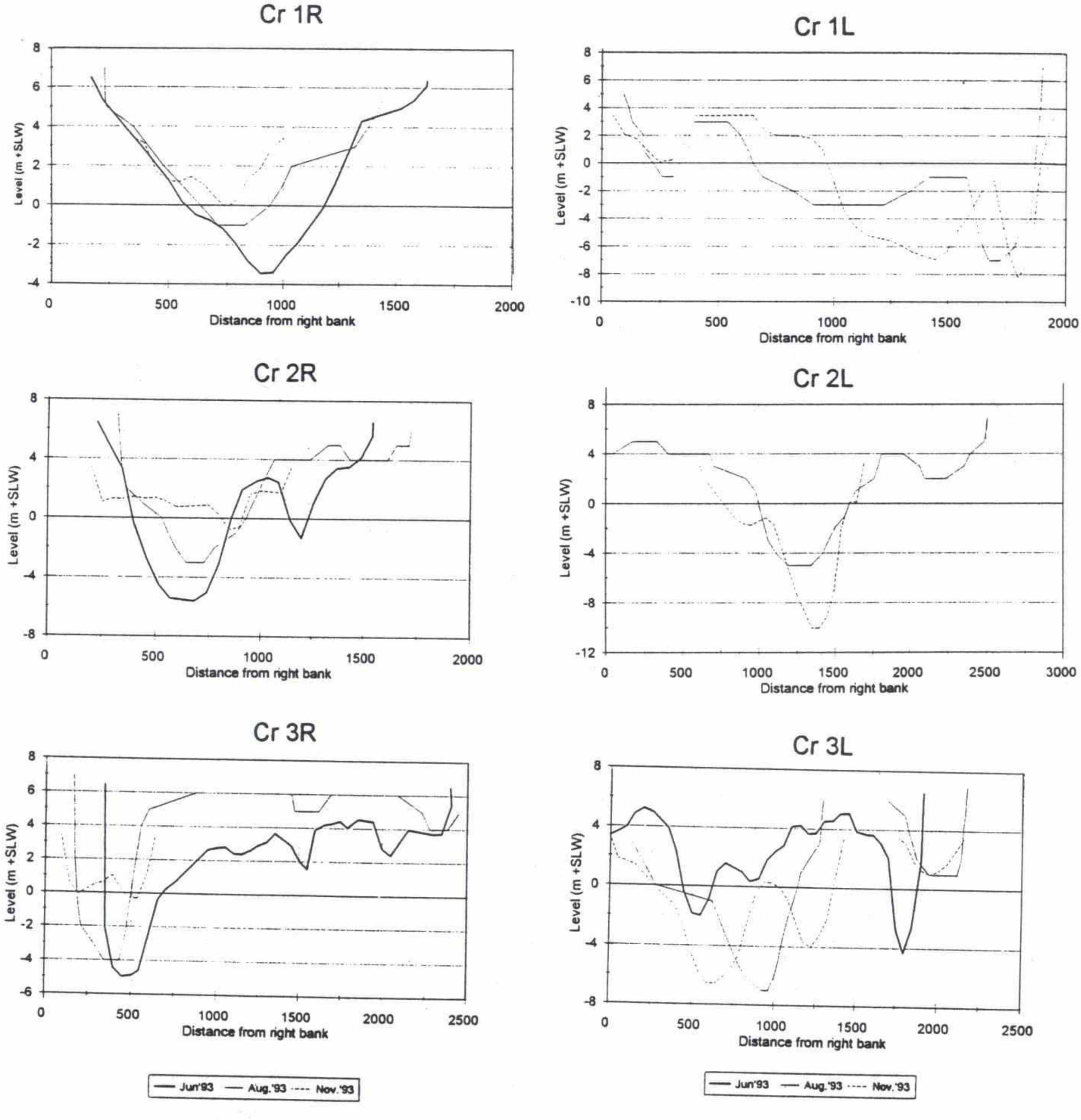


Figure 8.7 Changes of the cross-sections of the old main channel and new channel in 1993

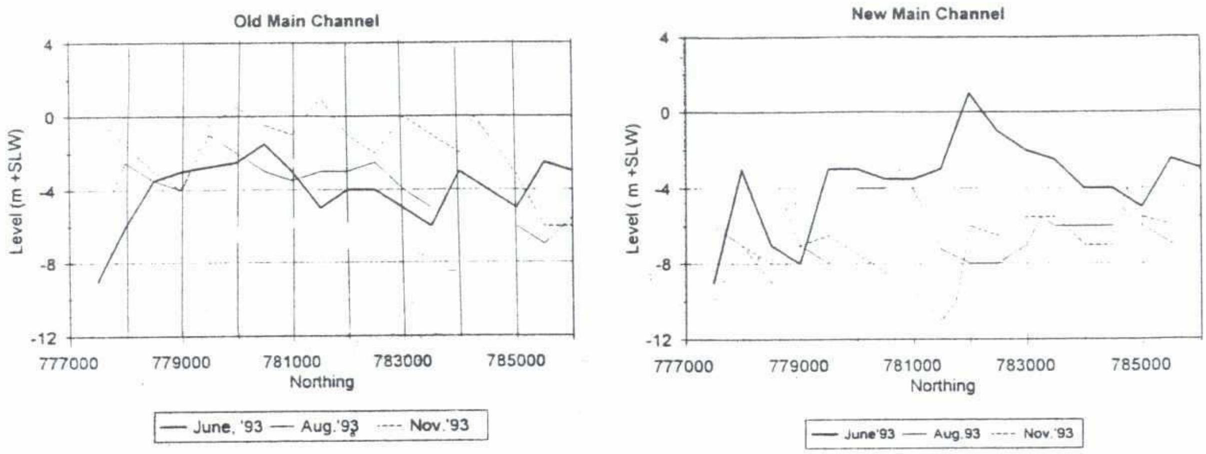


Figure 8.8 Changes of the thalwegs depth of the old main channel and new channel

Due to the lack of data from the June 1993 survey, and the varying responses from different sections, it is difficult to draw firm conclusions about the response of the depth and width of the channels. It seems, however, that the changes in depth and width are almost simultaneous in both cases. The changing of the average width and cross-sectional area can be illustrated using the EGIS processed data for the Old Main Channel, see Figure 8.9. The figures showing the reach averaged width and flow area variation with level. This figure also supports the above statement that in the old main channel the adjustment of depth and width are almost simultaneous. This can probably be explained by the erodibility of the bed and bank (char) material being of the same magnitude and also by the rapid shifting of the channel in lateral direction.

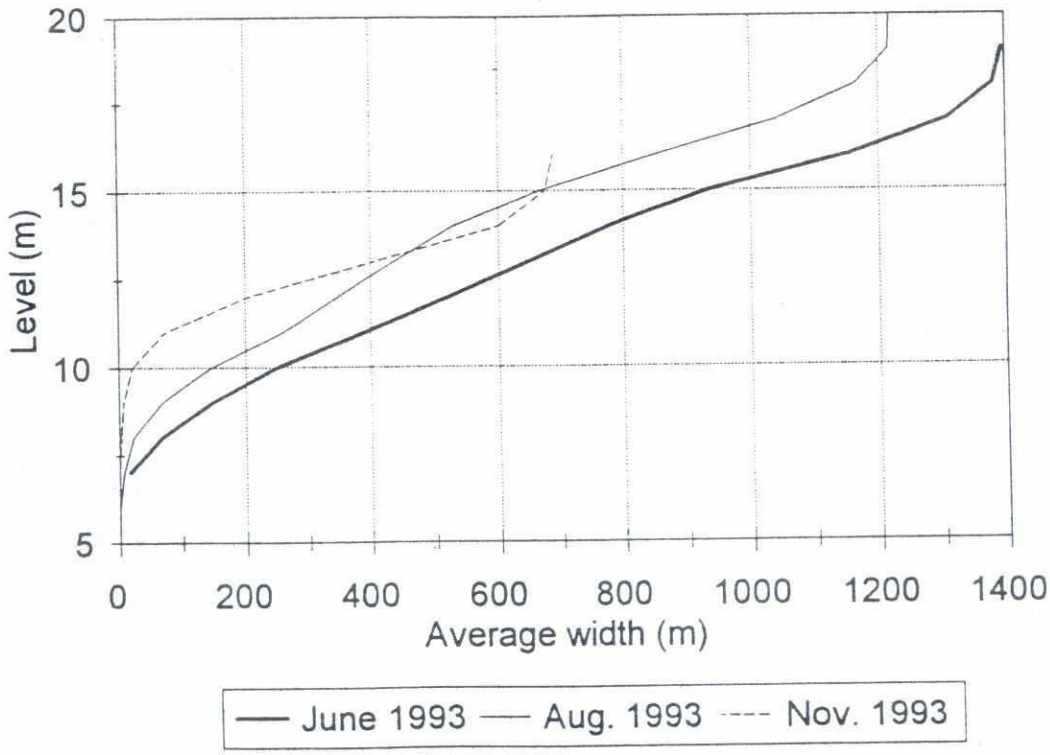


Figure 8.9 Variation of average width and flow area with level of the old main channel and the new channel

8.5 Summary

The study on the cutoff processes that occurred in 1993 near Bahadurabad can be summarized as follows:

- Upstream changes can trigger processes more downstream. In this case, bank erosion upstream triggered the processes of cutoff at the offtake and, subsequently, planform changes in the downstream reach from the cutoff.

- Similar to Mosselman et al, (1994) observation it appeared that the planform of an offtake is unstable and shifting in quite an irregular manner.

- During the cutoff processes, the planform becomes more unstable causing rapid changes of the deviation angle of the curved channel (α may reach up to values 90^o) and a quick shifting of the location of the offtake. It appeared that sediment distribution at the offtake deliver into the curved channel mainly determined by the deviation angle α.

- The prediction method of Klaassen and Masselink (1992) and Mosselman et al, (1994) may predict well on the basis of the cutoff ratio (λ) and deviation angle (α). The deviation angle is more sensitive to the cutoff processes and probably can better be used for predictive purposes.

- Although not fully verified, it appears that the local slope of the anabranches can also be used for predicting the occurrence of a cutoff.

9 Bank erosion

9.1 Introduction

A good understanding of bank erosion processes and bank erosion rates is important for the prediction of future planform changes and, hence, implicitly for the protection of levees, of flood protection structures or of other hydraulic structures in the river. Bank erosion is one of the most complicated processes in river morphology and even more complexity arises as we are dealing with a braided river like the Jamuna, where the location of bank erosion may vary quickly in time and space. Previous studies on bank erosion along the Jamuna River were discussed in Chapter 3. Those studies are mainly based on the analysis of historic maps and satellite imagery. Within the present study more detailed data on channel bathymetry and often the flow intensity in a river bend became available from the RSP surveys. The present study of bank erosion in the Jamuna River is based on (i) RSP bathymetric surveys performed at Bahadurabad location and (ii) FAP 21/22 bathymetric surveys in 1995 at Kamarjani, slightly north of Bahadurabad. In addition RSP special surveys for the RSP/UoN joint study are used to study the flow structure in a bend. As mentioned earlier (see Section 3.6) the latter study was meant to investigate the secondary flow structures in a channel bifurcation and around a bar, for which an area downstream of Bahadurabad was selected.

In this chapter, the present insight into bank erosion processes and prediction methods is summarized in Section 9.2. The flow field near the eroding bank at Bahadurabad and changes in the curvature and thalweg position of the eroding channel bend are presented in Sections 9.3 and 9.4 respectively. Bank erosion rates, comparison with different predictors and, finally, a summary of the main findings of this study in bank erosion are presented in Sections 9.5, 9.6 and 9.7, respectively.

9.2 Bank erosion processes and prediction methods

River bank erosion is a complex process in which many factors play a role. Important factors are flow, sediment transport, channel geometry and bed topography, vegetation and ground water level and their variation in time and space and bank material properties. The flow exerts shear stresses that can remove particles from the bank either via 'peeling off' or via mass movement. The near bank flow pattern is determined by the flow and the channel geometry. Bank material properties determine the cohesiveness of the bank, an important parameter for the type of bank erosion (Osman & Thorne, 1985), and is also important for how quick erosion products are transported by the river and thus determine the time needed for the typical cycle toe-erosion-failure-transport important for mass failures. Vegetation does not play an important role in bank erosion processes along the Jamuna River. Groundwater flow may have an important effect on the bank erosion, especially during the recession of flood.

The flow in a river bend attacks the toe of the river bank, removing the sediment from the toe, resulting in an over-steepening of the river bank and causing the bank failure by slumping (Figure 9.1). Although bank erosion is quite a complicated process, over the recent years a number of methods were developed to predict the bank erosion rates along a river. These methods can be distinguished into two types: the first one is related to a 2-D mathematical model and developed to compute bank erosion on the basis of local channel geometry, flow and/or sedimentary processes (Mosselman, 1992 and DHI 1996). The other type of prediction method estimates the yearly bank erosion rate on the basis

(1) overall channel parameters such as discharge and characteristics of bank materials, and (2) local channel geometry (Hickin and Nanson, 1984).

Mosselman (1992) developed a simple expression as:

$$\frac{\delta n}{\delta t} = E_u(u_b - \bar{u}) + E_h(h_b - \bar{h}) \qquad (9.1)$$

where $\delta n/\delta t$ = bank erosion rate, u_b = velocity near-bank, u = average velocity, h_b = near-bank depth, h = average depth and E_u and E_h = time-averaged erosion coefficients. In this equation the erosion rate is proportional to the increment of the flow velocity and of the water depth near the bank over the average velocity and depth, whereas the erosion coefficients represent the characteristics of the bank material.

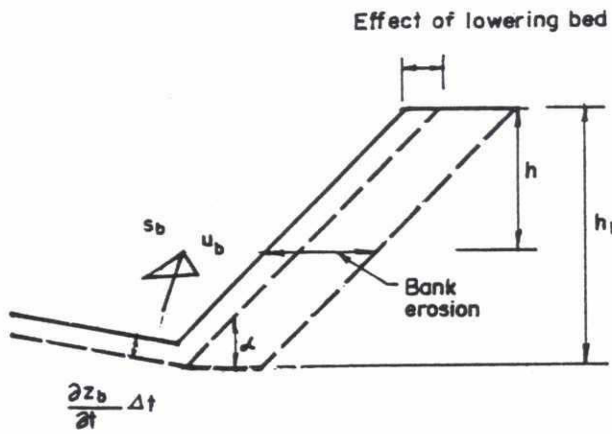


Figure 9.1 A definition diagram of the parameters involved in bank erosion processes

In the Mathematical Morphological Model study of the Jamuna River at the Jamuna Bridge Site (DHI, 1996), the bank erosion rate was linked to the near-bank depth, near-bank riverbed slope and near-bank sediment transport. It was assumed that the erodibility of the bank and bed material of the Jamuna River are the same and the erosion rate is higher for comparatively lower near-bank bed level. The assumed expression for bank erosion includes bank erosion due to channel lowering and bank erosion due to sediment transport near the toe. The assumed expression reads:

$$\frac{\delta n}{\delta t} = \alpha * \frac{\delta z}{\delta t} + \beta * \frac{s_b}{h_b} \qquad (9.2)$$

where s_b = sediment transport capacity parallel to the bank (m^2/s), $\delta z/\delta t$ = bed erosion rate, α = slope, and β = erodibility coefficient. Using the parameter β for calibration purpose, DHI attempted to simulate the bank erosion in the Jamuna River near Sirajganj.

To develop a prediction method for yearly averaged bank erosion Hickin and Nanson (1984) argued that the rate of bank erosion is determined by two opposing forces, on the one hand, the erosion resisting force of the bank material and, on the other hand, the fluid forces. They expressed the bank erosion rate for a meandering river as a function of the following parameters:

$$E = f\,(P,\ Y_b,\ h_b,\ R,\ B) \tag{9.3}$$

where E = bank erosion rate, P = stream power per unit bed area, Y_b = erosion resisting force per unit boundary area, h_b = bank height, in first approximation equivalent to the near bank depth, R = bend radius and B = river width. Hickin and Nanson performed an extensive study on a number of meandering rivers in Western Canada with clay, sand and gravel as bank material. They found that the erosion rate is a function of R/B and that the maximum erosion rate occurs at values of R/B of about 2.5. The empirical relation found between E and B/R reads:

$$E = 2.5\ E_{2.5}\ \frac{B}{R} \qquad for\ \ \frac{R}{B} > 2.5 \tag{9.4}$$

$$E = \frac{2}{3}\ E_{2.5}\left(\frac{R}{B} - 1\right) \qquad for\ \ \frac{R}{B} < 2.5 \tag{9.5}$$

where $E_{2.5}$ is defined as the erosion rate (m/year) for R/B = 2.5. This $E_{2.5}$ is linked to the hydraulic forces and resisting forces via:

$$E_{2.5} = \frac{P_T}{h_b Y_b} \tag{9.6}$$

in which Y_b = resistance expressed as shear forces (N/m^2) (used a calibration coefficient and given in the form of a graph), and P_T = total stream power (W/m) defined as:

$$P_T = \rho\ g\ Q_5\ i \tag{9.7}$$

in which Q_5 = discharge exceeded on the average once every 5 years (m^3/s). Klaassen and Masselink (1992), during their study of bank erosion rates in the Jamuna River, attempted to apply the Hickin and Nanson (1984) method for curved channels. They found a considerably smaller yearly bank erosion rate, when using Y_b as estimated by Hickin and Nanson for different grain sizes, than actually were observed from a comparison of satellite images. It appeared that, though like Hickin and Nanson, in the Jamuna River the maximum bank erosion rates were observed, when B/R is about 2.5.

9.3 Flow field near the eroding bank

In a meandering river, bank erosion generally occurs along outer bends due to the presence of secondary flow currents, which makes surface layer and bottom layer flow in a different direction, see Figure 9.2. As the maximum sediment concentration is in the bottom layer, in a river bend the direction of the average flow follows the bend axis, while the average sediment transport directed towards the inner bend, thus liable for the formation of point bar. In a meandering river the river bend is generally well defined. In a braided river, however, the bend is formed as a part of one of the anabranches. In such a river there is a continuous change in distribution of the water and sediment in between the different anabranches, which makes a river bend more unstable and less defined than in the case of a meandering river. Also the flow structure in such a bend is more complicated. Here data from the RSP/UoN special study are analysed to demonstrate the complexity of the flow pattern.

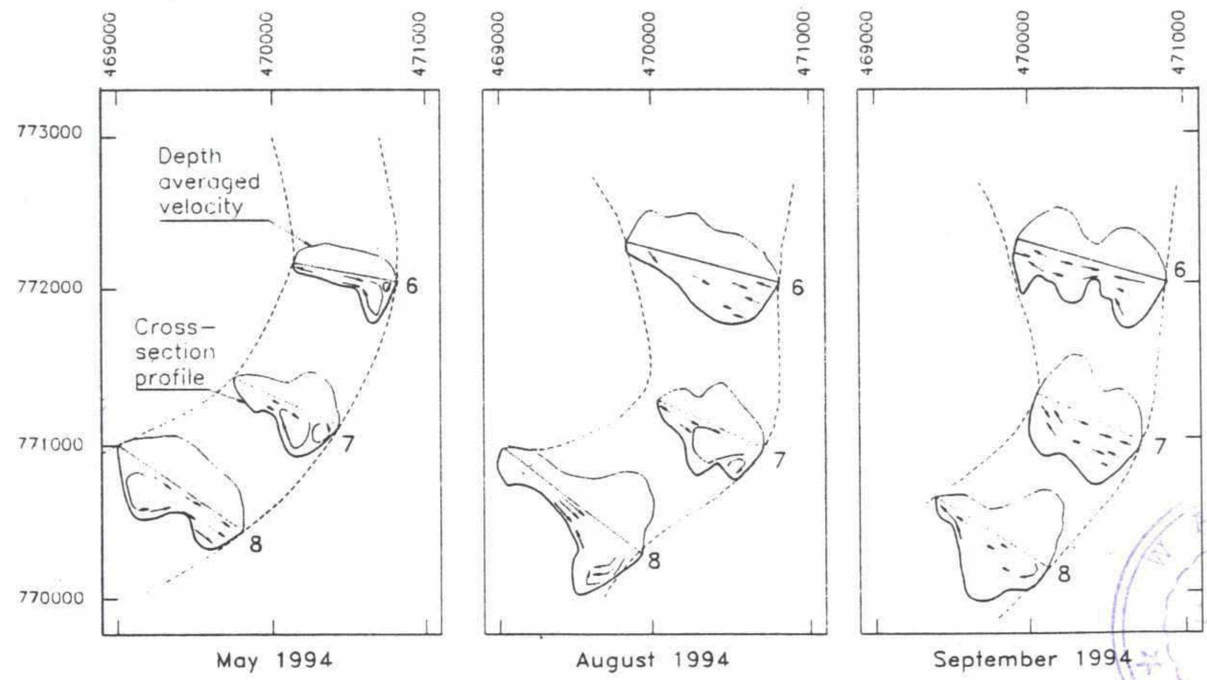


Figure 9.2 Secondary flow and the direction of surface layer and bottom layer flow

To study the flow structure near an eroding bank of a river bend in the Jamuna River, data from three surveys carried out 1994 are used (see Figures 9.3 and.9.4). From the surveys three cross-sections were selected (notably the sections 6, 7 and 8) where bank erosion was taking place. For easy reference the cross-section numbers are kept the same as in RSP SPR-16, (see also Figure 3.16). At the other sections the left bank shifted due to the overtopping of a low level bar by rising of the water level in the river (Figure 9.3), say for instance in the sections 5 and 9, and not due to bank erosion. The secondary flow structure presented in Figure 9.3 is also based on RSP SPR-16. The flow structure and the river response in connection to bank erosion are discussed below as an example of the complexity of these processes in these braided rivers.

The shape of Section 6 in May 1994 was a typical river bend profile, with a long flat point bar (about 400 m wide) at the inner bend and a deeper channel at the outer bend. The convergence of iso-vels and iso-backscatter (which is the indicator of secondary flow structure) are not at the outer part but rather at the inner part of the deeper channel. Instead of high depth-averaged velocities near the outer bank, the largest velocities were present over the point bar, resulting in erosion of that area (compared with the section in August). In this section the flow gradually shifted towards the right bank and riverbed erosion also followed the flow. In May Section 6 was lagging behind the changing of the flow direction. As a result negligible bank erosion occurred in the subsequent period.

The shape of Section 7 in May is not showing a perfect bend section as Section 6. The convergence of iso-vels and iso-backscatter, however, indicate the presence of secondary currents near the bank and the depth-averaged velocities are also higher near the outer bend. This caused bank erosion of about 340 m in the May-August period. After this marked large bank erosion rate, conditions changed and the flow structure in the August survey was already different: the high flow shifted toward the inner bank, resulting in almost no bank erosion in the August-September period.

The shape of Section 8 in May 1994 was a typical cross-section in a river crossing. Minor bank erosion occurred in the May-August period. In the August survey the section appeared as a typical river bend section with respect to its shape, the convergence of iso-vels and iso-backscatter at the outer bend and the maximum velocity near the outer bend. As a result a rapid bank erosion occurred at this section in the period of August-September. The survey of September also indicates that the bank erosion was probably continuing.

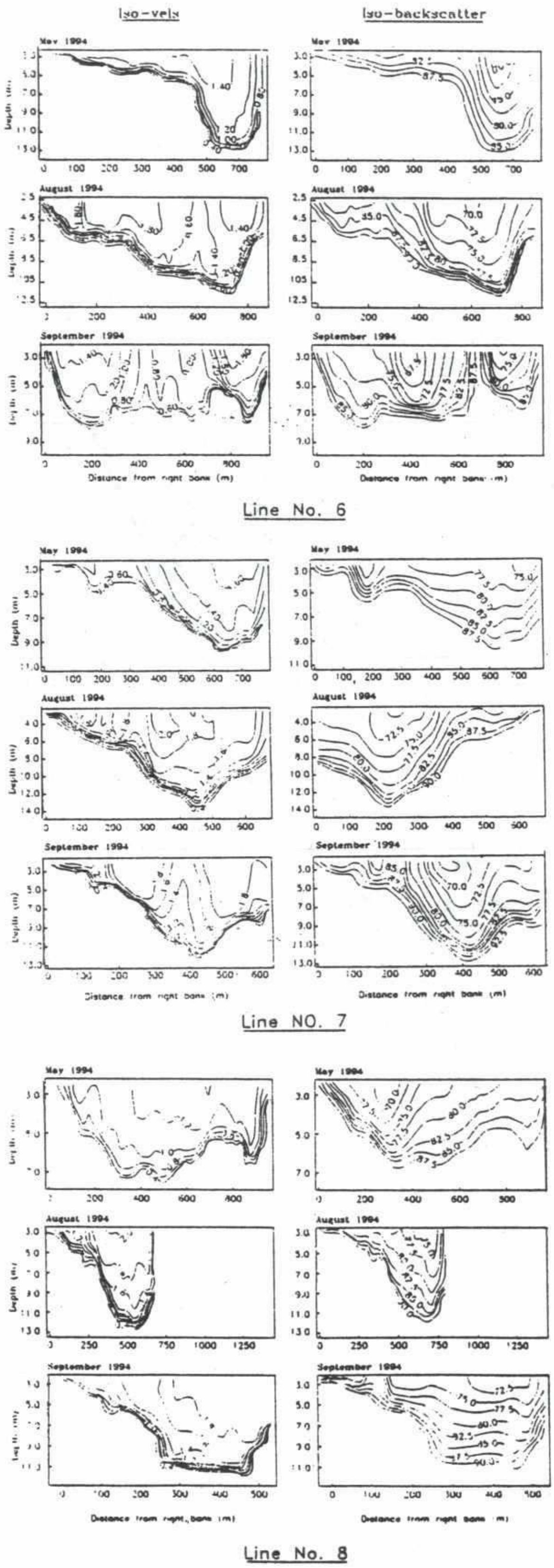


Figure 9.3 Flow structures in the different sections of the eroding river bend downstream of Bahadurabad in 1994

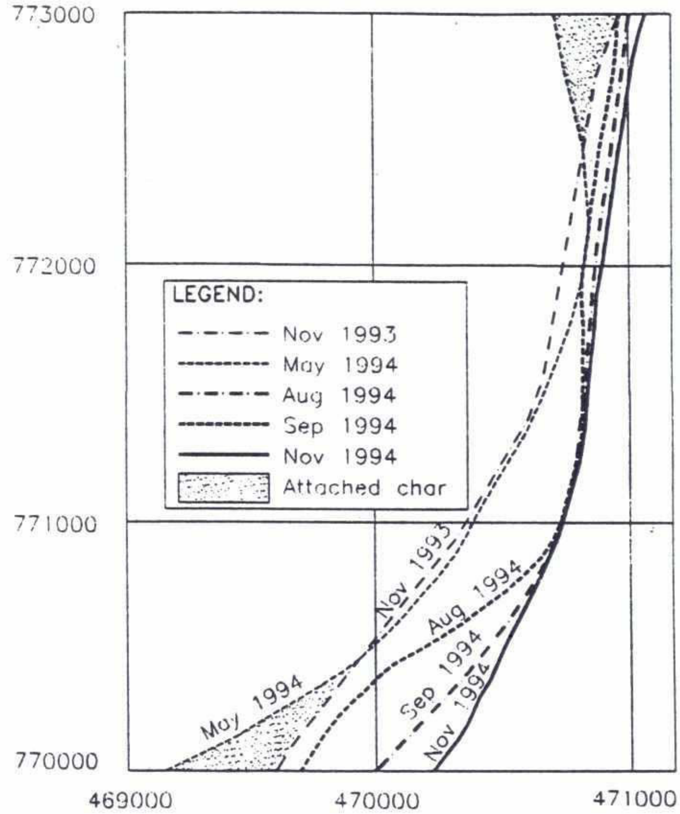


Figure 9.4 The bank erosion at the river bend downstream of Bahadurabad in 1994

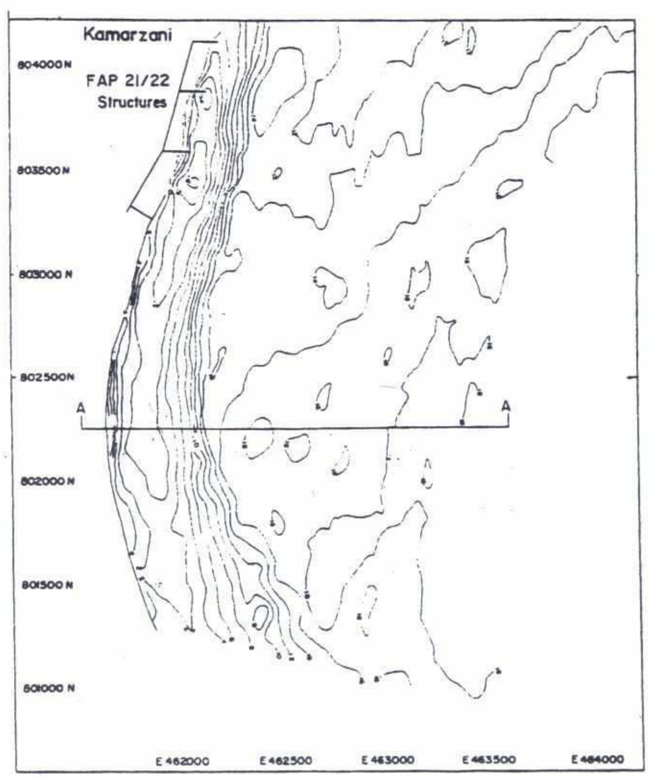


Figure 9.5 Bathymetry of river bend near Kamarjani in August 1995

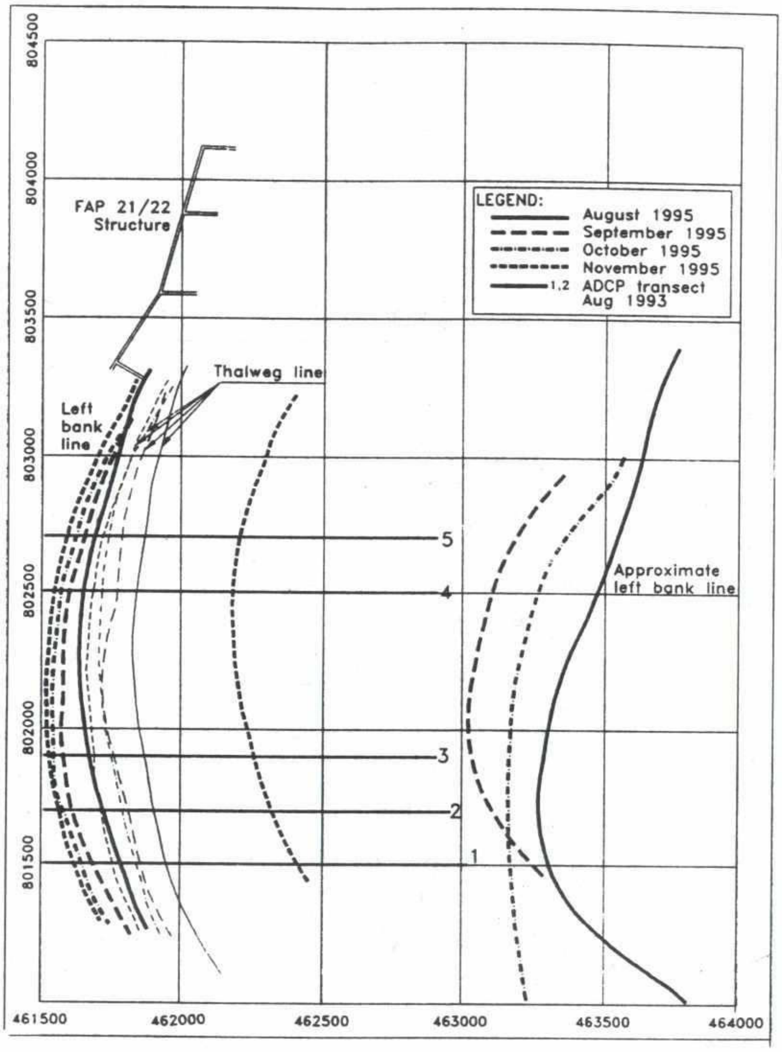


Figure 9.6 Bank erosion in the river bend at Kamarjani (FAP 21/22 bathymetric survey 1995)

In this example of a river bend downstream of Bahadurabad, the bank erosion rapidly shifted in downstream direction associated with the changing of the cross-sectional profiles and probably also with the changing of the planform of the river bend. The type of bank erosion often encountered in meandering rivers is also present in the Jamuna River. As an example, here the bend at Kamarjani is shown in Figure 9.5. In this bend bank erosion was quite uniform along the whole length of river bend downstream of the FAP 21/22 test structures in the period from August to November 1995, as can be observed from the bank line locations for August, September, October and November 1995 (see Figure 9.6).

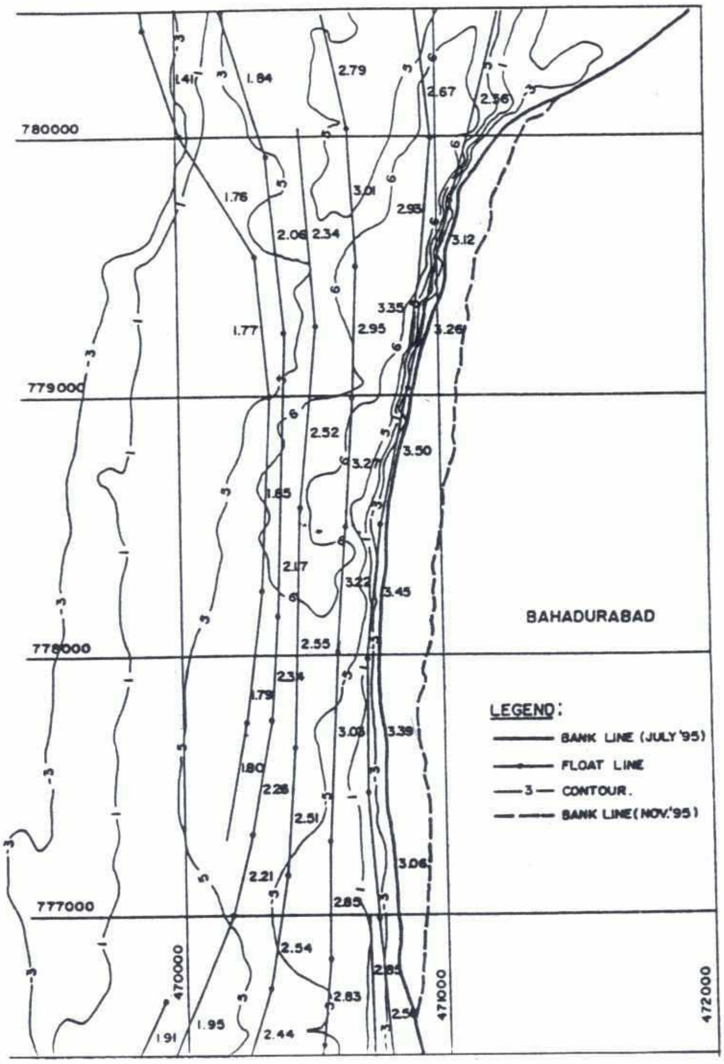


Figure 9.7 Float tracking at July 1995 near Bahadurabad and consequent bank erosion (July-November 1995)

In the Jamuna River, bank erosion may occur at places other than along the outer bends. The flow convergence due to impedance of flow by a comparatively harder river bank, or by a bank that has not yet sufficiently eroded, may cause comparatively high flows to occur very close to a river bank. Such high velocities near the river bank may cause bank erosion as well. As an example, the conditions near Bahadurabad in July 1995 may serve. The velocities measured via float tracking (see Figure 9.7) showed that a higher flow velocity (more than 3 m/s) occurred very close to the river bank due to flow impedance by Bahadurabad Ghat area. Due to these high velocities, substantial bank erosion occurred in the period of July-November 1995, see Figure 9.7. Evidently, such type of bank erosion occurs during the monsoon only.

The following interesting observations can be done on the basis of the above examples:

- Generally the shape of a cross-section is lagging behind the changes in flow structure.
- Bank erosion along the river bend downstream of Bahadurabad is not a simultaneous process with a uniform distribution of bank erosion along the bend, rather the location of maximum bank erosion appears to shift in time. Bank erosion processes similar to a meandering river bend are also present in the Jamuna River. (e.g. at Kamarjani).
- High bank erosion rate may introduce huge quantities of sediment in the system and together with the intermittent processes of the sediment transport are probably the cause of the rapid changing of the flow direction and the location of bank erosion in a river bend such as the river bend downstream of Bahadurabad.
- Different from a river bend of a meandering single-channel river, bank erosion may occur at places, where high flow velocities happen very close to a river bank due to impedance of flow by a not yet eroded bank, as in the Bahadurabad Ghat area.

9.4 Changes of the curvature and thalweg line of the eroding channel bend

In a meandering channel the curvature of a river bend is in first approximation a function of discharge. This can be shown by combining the Leopold and Wolman relation (Equations 3.3 and 3.5) and at-a-station relation derived for Jamuna River (Equation 3.10). This combination yields:

$$R = 43 * Q_b^{0.50} \qquad (9.8)$$

where R = radius of curvature (m) and Q_b = bankfull discharge (m^3/s).

It was observed from the previous section that the shape of the cross-section is lagging behind the flow; hence the curvature of the thalweg derived from the channel bathymetry is certainly different from the curvature of the flow. In absence of flow measurements during bathymetric surveys, the thalweg lines of the channels can be compared. In Figure 9.8 this is done for the river reach downstream of Bahadurabad and for two periods, notably Jun.-Nov.93 and Nov.94-Nov.95. This figure can provide an idea about the changes of the location of the thalweg and in the curvature of the channels with time and with the variation of the discharges. From Figure 9.8 it appears that only in 1993 there was a single channel in the river bend downstream of Bahadurabad; this channel was approaching the river bank and moved in time in downstream direction. In 1994 and 1995, due to flow division by bar formation in the channel, the processes became more complicated, as the smaller outflanking channels attacked the river bank at different locations. The discharge in the river was higher in August 1993 than June and November 1993 and, consequently, the curvatures in Figure 9.8 also show the similar type of variation.

In addition to the changes of curvature, also the shifting of the bend curvature has a significant effect on the bank erosion. The curvature of the bend downstream of Bahadurabad migrated in downstream direction from June to August 1993 due to the occurrence of a cutoff upstream (see Chapter 8). The migration continued in the following period. In 1994, the curvature of the bend had moved in downstream direction; at the same time an outflanking channel upstream of Bahadurabad became more prominent and continued to erode the bank, though to a lesser extent. After 1993 the eroding river bend was not a single channel; rather, it was a combination of two or more smaller anabranches. In 1995 these anabranches were almost at the same location as they were in 1994, although there was some variation in the curvature depending on the importance of those channels.

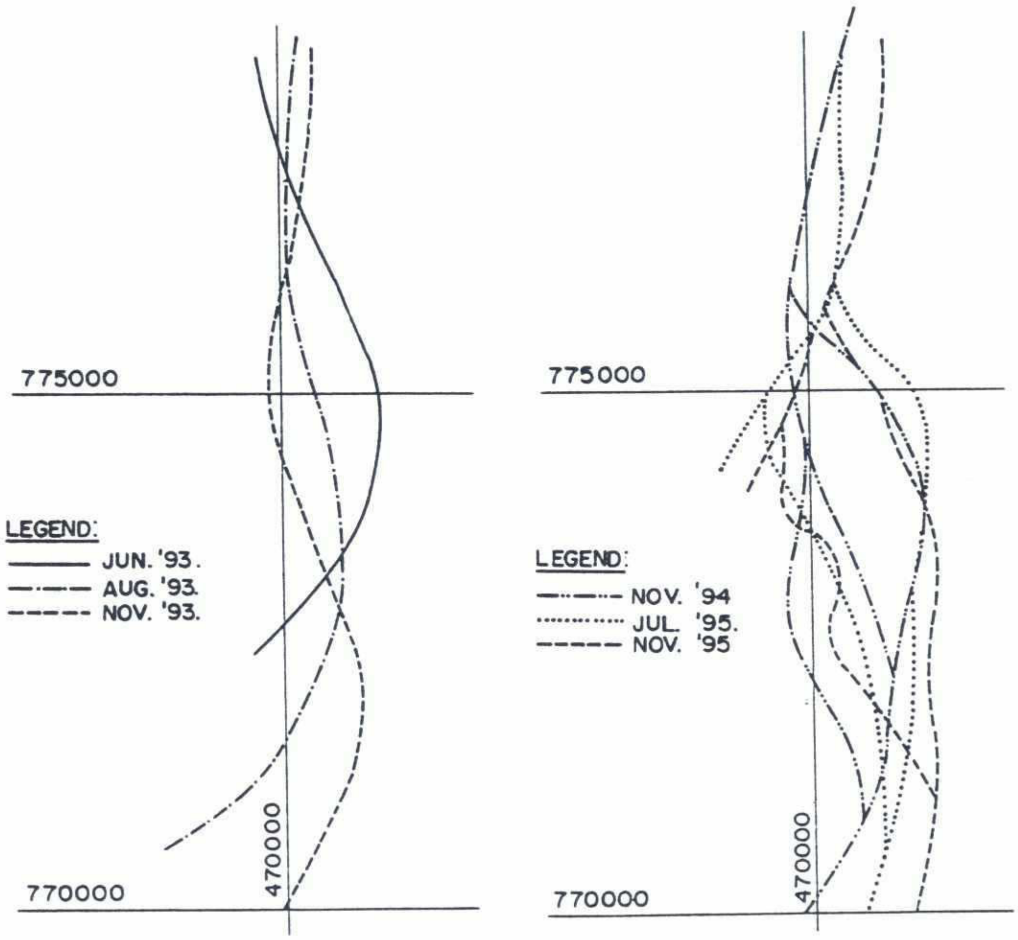


Figure 9.8 Changes of the curvature and shifting of the eroding bend in time downstream of Bahadurabad

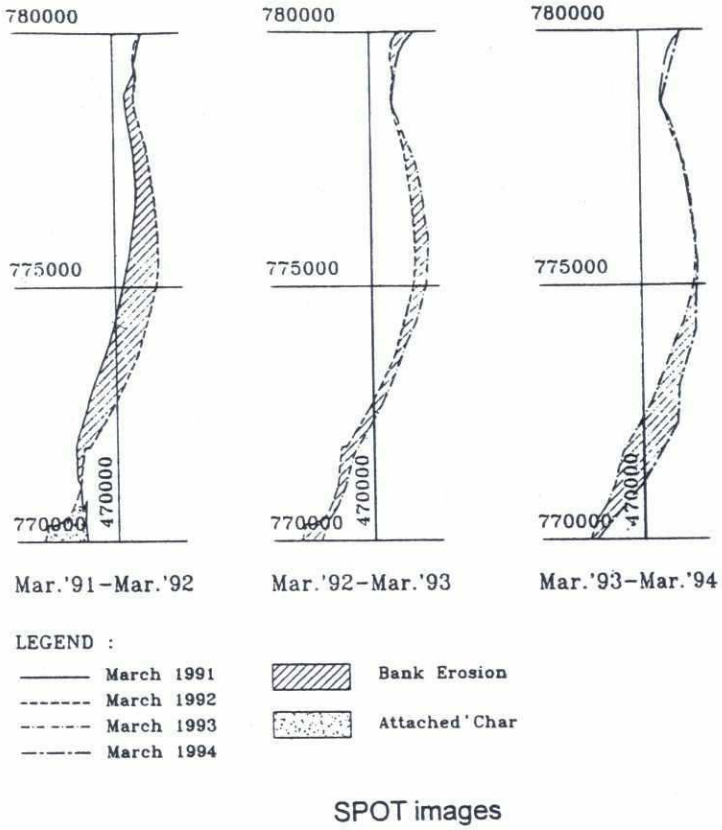
It appeared that a channel bend may migrate in downstream direction, but another outflanking channel may begins to develop and result in continued bank erosion upstream. The development of the outer bend channel during the period indicates that this bend was losing its importance and in the near future the bank erosion will stop, unless another marked planform change would occur upstream, which could change the conditions again seriously.

9.5 Bank erosion rates

The bank line migration of the left bank downstream of Bahadurabad during the period of June 1993 to November 1995 could be derived from RSP bathymetric surveys (see Figure 9.9). Bank erosion was also derived from SPOT images during the period 1991-1995 and these are shown in Figure 9.9 as well. The corresponding estimated bank erosion rates are presented in Tables 9.1 and 9.2. Due to differences in the positioning systems used by RSP and SPOT images, about 500 m needs to be added to the Northing of RSP surveys to have the bank erosion rates estimated from bathymetric surveys correspond to that from SPOT images at same location. The estimated erosion rates may still differ with some tenths of metres, due to errors in the grid system of the SPOT images, errors in locating the bank line on the SPOT images and the limited resolution of the satellite imagery.

The figures and tables indicate that the bank erosion rates vary along the bend and the maximum bank erosion occurred at the downstream end of the bend. As a result, the maximum erosion rate migrated 1.5 km in downstream direction from August 1993 to November 1995 (see Tables 9.1 and 9.2). The maximum yearly bank erosion rate at the river bend downstream of Bahadurabad (Northing 770000 to 776000) is about 800 m, which can be classified as an extreme event of bank erosion (Klaassen and Masselink, 1992). Within less than three years the maximum bank retreat was about 2 km. The maximum bank erosion rate along the inner bend near Bahadurabad (Northing 777000 to 780000) is about 400 m/year in 1995, which is almost half of the downstream river bend. The channel geometry, the structure of flow and probably the characteristics of the bank material are different at both locations (see Section 7.4, Figures 9.7 and 9.8). Probably due to different characteristics of the bank material the maximum bank erosion at Kamarjani is less (see Figure 9.6), although it is a well developed river bend.

The eroded areas and the eroded volumes during the period in-between the subsequent bathymetric surveys are shown in Table 9.3. To estimate the volume, the difference between the highest bank level and the average bed level along the eroding river bend was multiplied with the eroding area. The highest bank level is considered to be -7m SLW and the average bed level was estimated from the bathymetric surveys. The maximum eroded area downstream of Bahadurabad was 2.6 Mm^2 and the corresponding eroded volume was 24 Mm^3 in the period from November 1994 to November 1995, in which year the duration and magnitude of flood were comparatively higher than in the other periods. In contrast, the eroded area and volume were 1.1 Mm^2 and 10 Mm^3 respectively, in the period between November 1993 and November 1994, which was a relatively dry year. These guiding support the probable relation between the eroded area and the overall discharge through the river during the same period in the Jamuna River (Mosselman et al, 1993). The estimated total area yearly eroded along the whole Jamuna River varies according to Mosselman et al. between 2 to 5.5 Mm^2, which seems to be very low in view of the yearly eroded area found for the left bank at Bahadurabad location only.



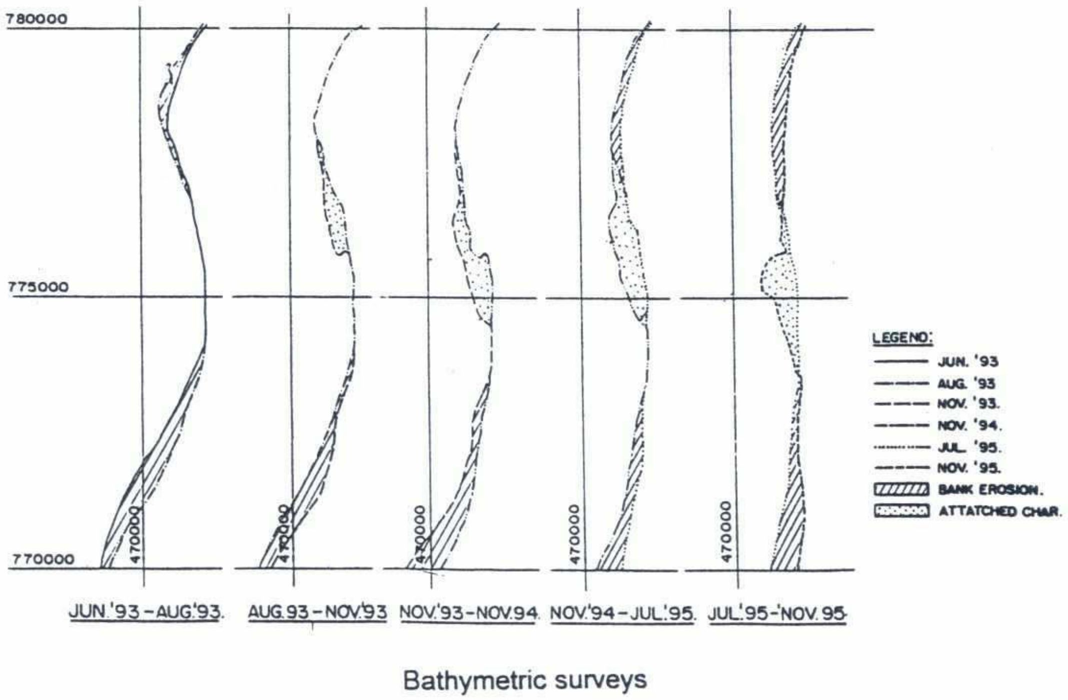


Figure 9.9 Bank erosion at Bahadurabad based on SPOT images and RSP bathymetric surveys

Norting	Bank erosion (m)			
	1991-92	1992-93	1993-94	1994-95
780000		250		
779000	130	30		100
778000	240	90		
777000	320	220		
776000	510	260		
775000	630	240	70	70
774000	600	190	320	180
773000	560	170	460	240
772000	310	210	720	380
771000		160	480	620
770000			110	190

Table 9.1 Bank erosion rates at Bahadurabad based on SPOT images

Northing	Bank erosion (m)						
	Jun-Aug.'93	Aug-Nov.'93	Nov'93-Nov'94	Nov.'94-Feb.'95	Feb.'95-Jul.'95	Jul.'95-Nov.'95	Jun.'93-Nov.'95
780000						150	150
779500	80				100	150	330
779000	150		50		150	200	550
778500	100		100		120	260	580
778000			50		150	250	450
777500					70	200	270
777000						70	70
776500							0
774500							0
774000	50						50
773500	120	130				100	350
773000	200	50	120		50	100	520
772500	300	100	150		120	120	790
772000	400	300	100		150	150	1100
771500	450	350	250		150	250	1450
771000	350	400	450		150	450	1800
770500	250	350	550		250	500	1900
770000	100	200	600		400	500	1800

Table 9.2 Bank erosion rates at Bahadurabad based on bathymetric surveys

The eroded areas and the eroded volumes during the period in-between the subsequent bathymetric surveys are shown in Table 9.3. To estimate the volume, the difference between the highest bank level and the average bed level along the eroding river bend was multiplied with the eroding area. The highest bank level is considered to be - 7m SLW and the average bed level was estimated from the bathymetric surveys. The maximum eroded area downstream of Bahadurabad was 2.6 Mm^2 and the corresponding eroded volume was 24 Mm^3 in the period from November 1994 to November 1995, in which year the duration and magnitude of flood were comparatively higher than in the other periods. In contrast, the eroded area and volume were 1.1 Mm^2 and 10 Mm^3 respectively, in the period between November 1993 and November 1994, which was a relatively dry year. These guidings support the probable relation between the eroded area and the overall discharge through the river during the same period in the Jamuna River (Mosselman et al, 1993). The estimated total area yearly eroded along the whole Jamuna River varies according to Mosselman et al. between 2 to 5.5 Mm^2, which seems to be very low in view of the yearly eroded area found for the left bank at Bahadurabad location only.

Period of survey	Bahadurabad Ghat		Along downstream river bend	
	Area (Mm^2)	Volume (Mm^3)	Area (Mm^2)	Volume (Mm^3)
Jun-Aug. 1993	0.2	2.4	1.1	12.0
Aug-Nov. 1993			0.9	8.0
Nov. 1993-Nov. 1994	0.1	1.4	1.1	10.0
Nov. 1994-Jul. 1995	0.3	4.0	0.6	5.0
Jul-Nov. 1995	0.6	8.0	1.1	7.0

Table 9.3 Bank erosion area and eroded volume at Bahadurabad

It is interesting to compare the volume of material originating from bank erosion with the average sediment transport volume in the left channel to see the significance of the bank erosion product with possible complications for river planform changes. During the period of Jun-Aug. 1993 the bank erosion volume is about 45% of the total sediment transport in the left channel and in the Aug-Nov. 1993 period it is more than 60%. This tremendous input of sediment from bank erosion might change the planform of the river bend within a short period. In the period between June to August 1993 the downstream bend had shifted. After then (in 1994) instead of a single channel at the bend, division of flow occurs due to formation of an attached bar, reduces the capacity of the curved channel, further bank erosion in 1995 almost abandoned the river bend. This type of rapid changes is in line with the observations by Klaassen and Masselink (1992) and Thorne et al (1993), when they observed that the duration of an aggressive bend is very limited. It is observed that tremendous volume of bank erosion product changes the planform of the river bend and also probably downstream, unfortunately the bathymetric survey boundary limited to see those changes.

9.6 Comparison with different predictors

The predictors mentioned in Section 9.2 can be compared with the data obtained from the Bahadurabad and Kamarjani locations. Here the two different types of predictors that were identified in that section are used for this comparison. In applying the Mosselman and DHI predictors it is required to calibrate the coefficients E_u, E_h, α and β (see Equations 9.1 and 9.2) for estimating the bank erosion along the river. These two predictors, different from the Hickin and Nanson (1984) method, are based on local parameters like u, s, h, and so on. Some detailed surveys provide these local data, and these can be used for the present comparison.

For the river bend downstream of Bahadurabad, the results of the RSP/UoN special surveys in May, August and September 1994 are used. For the river bend at Kamarjani, FAP 21/22 bathymetric surveys and ADCP data of RSP in August 1995 are usee. Average velocity (u) and near bank velocity u_b are determined from the ADCP discharge data; average depth h and near bank depth h_b are estimated from the measured transects and they are averaged for the consecutive surveys to link them to the bank erosion rate. For the Kamarjani location, the velocity once measured on 3 and 11 August 1995 at different transect transects, see Figure 9.6. The value of u and for the other surveys u_b were estimated by linking the velocity u with discharge Q using the at-a-station relations (see Equation 3.9 and 3.10) and the continuity equation of water. The following relation is found:

$$u :: Q^{0.26} \tag{9.9}$$

The values of h and h_b are estimated from the measured bathymetric surveys of FAP 21/22 in August, September and October 1995 at Kamarjani.

The predictor of the near-bank sediment transport was based on the sediment transport predictor derived for the Jamuna (Equation 3.23). The Shields parameter θ is replaced by u using the Chézy equation. In this form the sediment transport predictor reads:

$$\frac{s}{\sqrt{\Delta g D^3}} = \frac{80}{1-\varepsilon}\left(\frac{1}{C^2 \Delta D}\right)^{1.8} * u^{3.6} \tag{9.10}$$

Thus the near-bank sediment transport s_b can be estimated using the velocity u_b.

It is observed that the near bank depth in a transect at Bahadurabad location varies in time while usually it has a relatively small contribution to bank erosion rate. If Equation 9.1 is solved for E_u and E_h simultaneously for a section measured more than two times, different sections result in different values including some (unrealistic) negative values for the coefficients. Similar unrealistic values are found for the coefficients α and β in Equation 9.2. Therefore, the second term of equation 9.1 and first term of Equation 9.2 are neglected. Using at-a-station relations (Equations 3.9), and assuming in first approximation that h_b = 2h and u_b = 1.4 u (see Section 10.3), it is possible to express $\delta n/\delta t$ of Equations 9.1 and 9.2 in terms of u_b. The following expressions are found:

(a) based on Mosselman (1992)

$$\frac{\delta n}{\delta t} = E_u * 0.3 * u_b \tag{9.11}$$

(b) based on DHI (1996)

$$\frac{\delta n}{\delta t} = \beta * 10^{-4} * u_b^{2.7} \tag{9.12}$$

In this approach the terms related to the coefficients E_b and α are neglected, as mentioned earlier. The difference between these two methods is that in the Mosselman method bank erosion is linearly related to u_b and in the DHI method, the bank erosion increases with some power of u_b. Calibrating the parameters E_u and β using the observed average values (Table 9.2), the comparison of Mosselman (1992) and DHI (1996) method with the obtained data is shown in Figure 9.10.

Location	**Range of E_u 10^{-5} (-)**	**Av. E_u 10^{-5}(-)**	**Range of β (-)**	**Av. β (-)**
Bahadurabad	2.6-19	9.5	0.03-0.34	0.12
Kamarjani	3.6-11	7.2	0.11-0.19	0.15

Table 9.4 Estimated values for the coefficient related to bank erosion

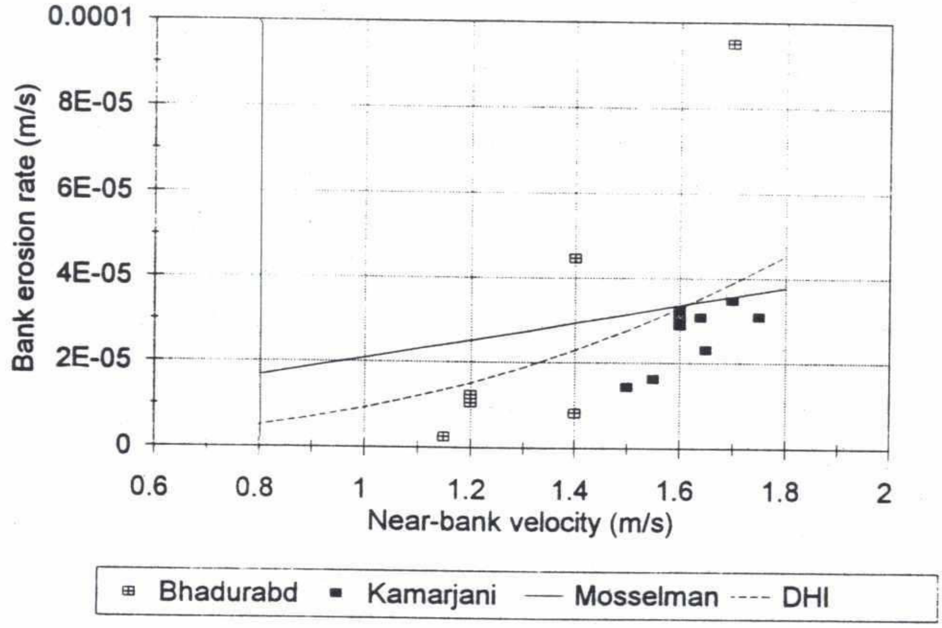


Figure 9.10 Observed bank erosion rates at Bahadurabad and Kamarjani location in relation with near bank velocities

From Figure 9.10, it appears that two data points from Bahadurabad seems to be outliers. These are points related to Section 7 in the period May-August 1994 and Section 8 in the period August-September 1994. In those cases the flow severely attacked the bank. Considering the other points, it seems that the non-linear relation corresponding to the DHI method appears to predict the bank erosion in the Jamuna River better. For extreme bank erosion events (however, for instance the river bank erosion along the bend downstream of Bahadurabad) additional studies are needed.

Due to the apparent intermittent process of bank erosion along the river bend at Bahadurabad, the computed coefficients vary considerably, whereas the range of variation is comparatively less for Kamarjani (see Table 9.2). This is probably due to the fact that the river bank erosion occurred simultaneously along the whole river bend. It is interesting to note that the average value of β is only slightly higher than what DHI found during the calibration of the mathematical model for the Jamuna Bridge. Due to neglecting the effect of bed-level changes, it may be expected that the derived value of β will be higher in the present analysis.

Unlike the Mosselman (1992) and DHI (1996) method, it is not possible to express the Hickin and Nanson (1984) method in terms of some local flow or sediment transport parameters. The application of this method is also less straight forward for a braided river because of the parameter Q_5. In a braided channel, continuous changes are taking place in division of the discharge over the different anabranches. Under these circumstances the parameter Q_5 has little meaning for a braided channel. Moreover, assigning tentatively 50% of Q_5 of the Jamuna River to the eroding channels applications of the Hickin and Nanson (1984) method results in very small value of $E_{2.5}$, (about 20 m/year). Apparently the bank resistance of the bank material of the Jamuna River is far below what Hickin and Nanson estimated for different grain sizes, which raises some doubts on the general applicability of the Hickin and Nanson (1984) methods. See also Klaassen and Masselink (1992).

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The relation between the relative erosion rate and the relative curvature is presented in Figure 9.11. Only three data (from Bahadurabad 1993 and 1994 and Kamarjani in 1995) are plotted. The preparation of such a graph for braided rivers such as the Jamuna involves subjective judgement which largely influences the value of the estimated parameters. The curvature of the thalweg is difficult to estimate as it changes very quickly in time. The curvature of the bank line might not be representative as it is the result of number of sequences of bank erosion. Also the estimate of the river width depends on personal judgement. A very wide point bar platform, varying with the stages of discharge and also along the bend, introduce uncertainties in estimating the river width. Klaassen and Masselink (1992) used the low flow width derived from satellite imagery, which is possibly not the most appropriate measure to link with bank erosion rates. However, from the analysis of Klaassen and Masselink (1992) and the present analysis, it appears that (in conformity with Hickin and Nanson, (1984)), probably the highest relative bank erosion occurs if the relative curvature is around 2.5.

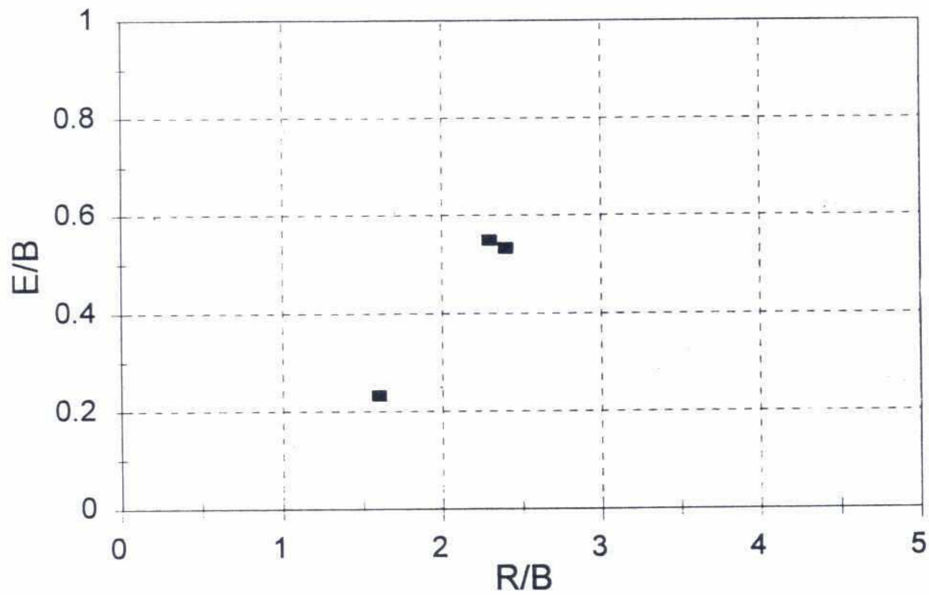


Figure 9.11 Relation between relative bank erosion and relative curvature of a bend

9.7 Summary

The results from the study of bank erosion processes along the Jamuna River can be summarized as follows:

- Two processes of bank erosion can be identified in the Jamuna River; one type is related to the flow structure in a normal river bend and another type of bank erosion may occur at a place other than river bends, where due to flow convergence or maybe other reasons, comparatively high flow velocities occur close to a river bank.

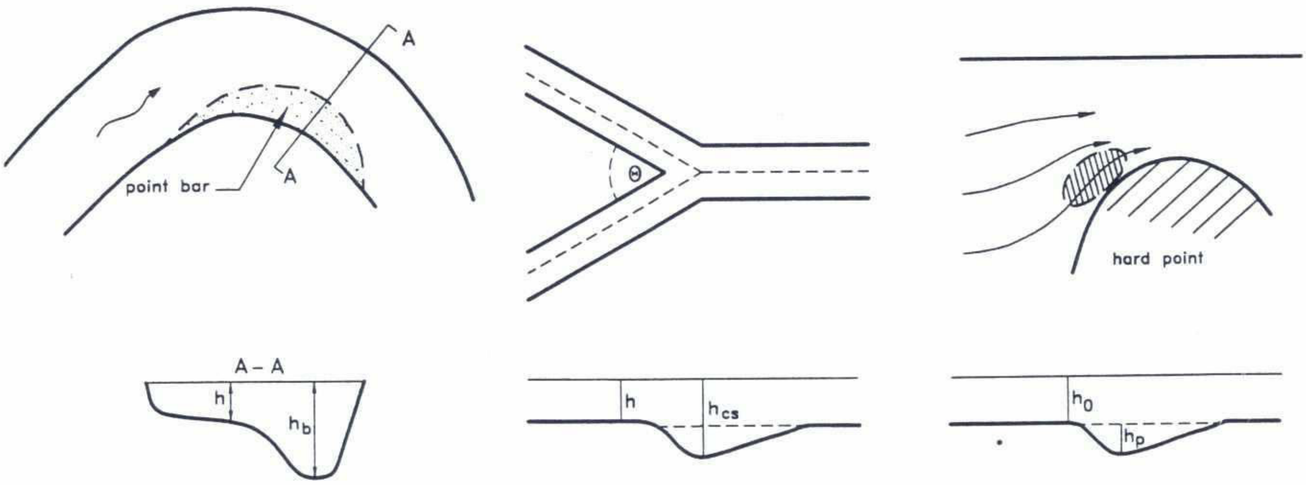
- In a river bend different types of bank erosion processes may develop depending on the erodibility of the bank material. Bank erosion processes are more chaotic and rapid in the case of highly erodible bank materials.
- Rapid planform changes are generally associated with high bank erosion rates, and may be due to the tremendous sediment input from the bank erosion.
- The bank erosion rates can be simulated in a 2-D mathematical model by using the DHI method, in the case of comparatively small erodible bends. The range of uncertainties is very wide in the case of the highly erodible bend.

10 Scour holes

10.1 General

During the RSP bathymetric surveying some very deep scour holes were observed. This chapter discusses these observations against the background of what is known about these scour holes. Scour holes are important for the design hydraulic structures, like bridges, revetment, groynes etc. Moreover, deeper scour holes may attract flow and thus may contribute to planform changes.

The reasons for the occurrence of scour holes are manifold: local flow condition or secondary flow locally, may generate larger (than average) shear stresses on the riverbed, causing bed scour or bed degradation. Also increased turbulence levels may cause deeper sections locally. Scour holes are often differentiated in constriction scour, bend scour, confluence scour, protrusion scour, bedform scour and local scour (occurring near hydraulic structures). In addition, general scour is often mentioned, but as this corresponds to long-term aggradation and degradation, it is not relevant here. In the Bahadurabad area there are no hydraulic structures and neither any types of natural constriction were observed during floods. From the RSP bathymetric survey, it is not possible to identify bedform scour due to the large interspacing of the transect lines (100 m) during bathymetric surveys. Therefore, the emphasis of this study is a bend scour, confluence scour and protrusion scour (see also Figure 10.1).



a. Bend scour b. Confluence Scour c. Protrusion scour

Figure 10.1 Different types of scour holes

In this Chapter (in Section 10.2) first the causes of scour holes mentioned above and the prediction methods of different types of scour holes are discussed next to identifying the different types. The development and the movement of the scour holes from the bathymetric maps is dealt with in Section 10.3. Dimensions and slopes of scour holes are discussed in Sections 10.4 and 10.5, respectively. The observed scour holes are compared using different predictors, in Section 10.6. Finally, a summary of the main findings of this study is presented in Section 10.7.

10.2 Causes of scour hole and prediction method

10.2.1 Introduction

Different hydraulic processes generate different types of scour holes in rivers and, accordingly, the scour holes can be classified. In some cases, the scour hole may be generated by a combination of different processes. For example, in an outer bend two braided channels may create a confluence, and the created scour hole may be the result of the combination of two different processes, notably confluence scour and bend scour. Scour holes created by a combination of different processes, are not analysed in detail here. Processes causing the formation of different scour holes are observed in the different bathymetric maps and existing prediction methods are discussed in the following sub-sections though.

10.2.2 Bend-scour

Bend scour develops in the outer part of a river bend and the scour hole is determined by the secondary flow associated with the curved flow. At the beginning of the bend some length is needed for the flow and sediment distribution to adapt to the new (curved) condition. After a sufficiently long distance along the bend, axi-symmetric flow conditions may develop. The spiral flow tends to transport particles towards the inner bend until a sufficiently steep lateral slope has formed and an equilibrium between lateral components of bed-shear forces and gravity forces is established (Van Bendegom, 1947). The bed level of a bend in transverse direction in an integrated form is given by Jansen (1979) as follows:

$$\left(\frac{1}{h_y}-\frac{1}{h_c}\right) = \left(\frac{1}{R_y}-\frac{1}{R_c}\right)\cdot\frac{1.5\ \alpha\ R_c\ i_c}{\Delta\ D} \qquad \textbf{(10.1)}$$

where h_y = the water depth at the transverse location y, h_c = water depth in the middle of the river, R_y = radius of curvature at the location y, R_c = radius of curvature in the middle of the river, α = a coefficient, i_c = water level slope in the middle of the river, Δ = relative specific density and D = size of bed material. This equation is derived assuming constant discharge, uniform bed material sizes, bed load transport and fixed banks. Certainly, these limitations will affect the potential for prediction of the bed topography in natural rivers. This holds in particular in Bangladesh, where suspended load is dominant over bed load.

Struiksma (1988) presented a graph (Figure 10.2) to estimate the maximum scour depth at the outer bend of curved channels in terms of cross-sectional average parameters. In the figure the relevant parameter h_{bs}/h is the ratio of the maximum scour depth and the average depth, B/R is the ratio of width and radius of curvature, θ is dimensionless Shield parameter and A is secondary flow coefficient which depends on the Chézy coefficient as expressed via:

$$A = 2\ \kappa^{-2}\left(1-\frac{\sqrt{g}}{\kappa\ C}\right) * 0.85 \qquad (10.2)$$

The prediction method based on transverse bed slope and transverse velocity distribution is valid for long circular bends. The transverse bed slope was expressed as:

$$\frac{\partial h}{\partial n} = A \sqrt{\theta} \frac{h}{R} \tag{10.3}$$

where $\delta h/\delta n$ represents transverse slope.

This graph is based on the same limitations as mentioned in the case of Equation (10.1). During the 'Meghna River bank protection short term study' (FAP 9B), Haskoning et al (1990) found that the prediction of the depth of the maximum scour hole by Struiksma is about three times higher than the actual value. Similar observations were made for the Jamuna River in the Jamuna Bridge Study, Phase 2 (RPT et al, 1989). One explanation for this difference can be the influence of suspended load. According to Ikeda and Nishimura (1986) suspended load increases the lateral slope for the axi-symmetric conditions. See also Ikeda and Nishimura (1985) and Talman (1992). In addition, due to the assumption of fixed banks, the influence of the bank erosion products on the bed level is neglected. In a natural river, where the bank erosion rate might be significant, it considerably reduces the maximum scour depth. Moreover, the parameters involved in the prediction method are not so well defined in a natural river compared to a curved channel in laboratory flume. Mosselman (1989) provided an expression for the influence of bank erosion product on the transverse bed slope in an axisymmetric case and modified expression of his equation is (Mesbahi, 1992):

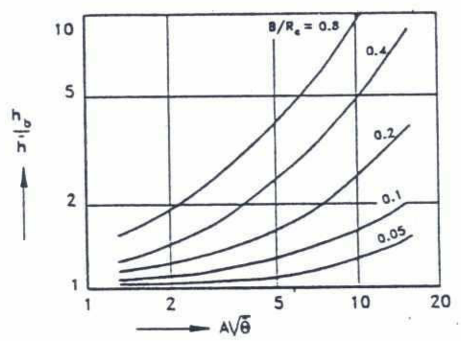


Figure 10.2 Method for finding the maximum bend scour depth (Struiksma, 1988)

$$\pi \frac{h'}{B} = f(\theta) \left(A \frac{h}{R_c} - \frac{1}{\pi} \frac{\eta h_b}{s_x} \frac{\partial n}{\partial t} \right) \tag{10.4}$$

where h' is first-order perturbation of h, varying with average flow direction only. It can be considered as: $h' = h_b - h_{avg}$, θ, A, h and R_c are similar as defined earlier, η = wash load factor, s_x = sediment transport in longitudinal direction and $\delta n/\delta t$ = bank erosion rate. The first part of this equation is similar to Equation 10.3. Input of bank erosion products (second part of the equation) reduces the scour depth and the reduction is very significant when the bank erosion rate is high. The effect of bank erosion products was studied recently by Shishikura (1996). He found that the effect of these products on the transverse slope is substantial in sand-bed rivers like the Jamuna River.

10.2.3 Confluence scour

Confluence scour occurs downstream of the confluences of two channels, either two separate rivers or two braided channels of a braided river. The confluence scour is characterized as an elongated reach of relatively high depth in the middle of the combined downstream channel. The probable reason for occurrence of scour hole at the confluence is (Mosley, 1976; Ashmore and Parker, 1983) back-to-back bend scour as caused by helical flow generated by the induced curvature of the stream lines (or increased turbulence due to the bouncing of the two confluencing water). Ashmore and Parker (1983), studying confluence scour in gravel bed rivers, postulated the following relation for confluence scour:

$$\frac{h_{cs}}{\bar{h}} = f(F_o, \bar{i}, \theta, \varepsilon) \tag{10.5}$$

where

h_{cs} = maximum scour depth
h = average depth of the upstream anabranches, defined as $h = (h_1 + h_2)/2$
F_0 = densimetric Froude number, defined as $F_0 = u_0/(\Delta\ g\ D_{50})^{0.5}$
u_0 = average anabranches velocity
D_{50} = average mean grain size of the upstream anabranches
i = average anabranch downstream water surface slope
θ = angle of incidence of anabranches of confluence
ε = $|(Q_1 - Q_2)| / 0.5\ Q_T$
Q_1, Q_2, Q_T = discharge in channel 1, 2 and total discharge downstream of confluence.

After analysing a number of data from field and laboratory tests, Ashmore and Parker found that the influence of F_0 and i on the relative scour depth (h_{cs}/h) is not significant and without discrimination for ε they obtained a relation between the relative scour depth and θ, which reads as follows:

$$\frac{h_{cs}}{\bar{h}} = 2.235 + 0.0308\,\theta \tag{10.6}$$

Klaassen and Vermeer (1988b) developed a similar relationship for sand-bed rivers on the basis of data from the Jamuna River. They observed the influence of ε on maximum scour depth while studying the confluence scour of the Jamuna River and they found that for $\varepsilon > 0.75$, no relation between h_{cs}/h and θ exists. Their study was based on the hydrographic surveys by the Bangladesh Inland Water Transport Authority (BIWTA) and special surveys in relation to the feasibility study of the Jamuna bridge. They estimated the discharge of the different confluencing anabranches with the help of at-a-station relations derived for the Jamuna River (Klaassen and Vermeer, 1988a). The following relation between relative scour depth and θ was obtained for the Jamuna River.

$$\frac{h_{cs}}{\bar{h}} = 1.292 + 0.037\,\theta \tag{10.7}$$

It was observed that the maximum scour depth in the Jamuna River is slightly smaller than the Ashmore and Parker (1983) predictor. This may be the influence of part of the bed material being carried in suspension as well.

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10.2.4 Protrusion scour

Protrusion scour occurs e.g. where flow is impeded by the channel bank due to occurrence of comparatively erosion-resistant material into the river. The scour hole is determined by the magnitude of obstruction of the flow. The protrusion forces the flow to concentrate within a smaller width, resulting in a higher unit discharge, which causes scour in the riverbed. This type of scour holes is similar to the scour hole in front of a hydraulic structure usually referred to as bridge abutment (Simons and Sentürk, 1977). The only difference is that the abutment is completely non-erodible, whereas the natural protrusion may consist of erodible material, but locally the resistance to erosion is comparatively higher than the average bank material. Also the bank might not have been eroded yet. Therefore, scour depth predictors for abutment scour can be applied to predict the maximum depth of this type of scour hole.

This type of scour is observed in the Jamuna River and also in the Meghna River. During the study on 'Meghna River Bank Protection Short Term Study' Haskoning et al (1990) analyzed this type of scour hole and they found that the relation proposed by Simons and Sentürk (1977) to estimate the scour near abutments is closer to the observed value. Based on the experience from the Mississippi, Simons and Sentürk (1977) derived the following empirical relation:

$$\frac{h_p}{h} = 4\ Fr^{0.33} \qquad (10.8)$$

where h = average depth, h_p = scour depth below the average depth (h), and Fr = froude number. This method is very simple as it needs only the estimation of the Froude number via the average flow velocity and the average depth of a channel.

10.3 Identifying the types, development and movement of the scour holes

Scour hole is generally defined as an area in a channel reach which is comparatively deeper than other areas of that reach. From the seven bathymetric surveys at Bahadurabad the identified scour holes are shown in Figure 10.3. Two types of scour holes are indicated in the figure, notably shallow scour holes, minimum bed level of which is above +6 m SLW and deep scour holes, minimum bed level of which is below +6 m SLW. In considering the channel geometry, three main types of scour hole can be identified: confluence scour, bend scour and protrusion scour. There are some other types of scour holes. The reason for their existence is not clearly known. Some of these scour holes moved through the system after their formation. These are named 'wandering scour holes'. However, the identification of the types, development and movement of the scour holes are presented below.

Bend scour

Scour hole I in the outer bend can be classified as a bend scour (Figure 10.3). Although in June-July 1993 three separate scour holes I_1, I_2 and I_3 were present, probably these scour holes were the remnant of a scour hole that had developed before the upstream cutoff. During the survey in June-July 1993 the direction of the flow was in transition due to the changing flow direction resulting from the cutoff process. After the further development of the cutoff through the New Main Channel an attached bar developed at the location of previous scour holes and the flow attacked the left bank farther downstream. This shifted the scour hole I about 1.5 km in downstream direction, increasing its scour depth from 8 m +SLW to about 16 m +SLW as can be seen from the August 1993 bathymetric survey. Bank erosion during the period of August to November caused the scour hole to move in an outward direction. Reduction of the flow in November resulted in an increase of the curvature of the scour hole (induced by changes in the flow lines) and a decrease in depth (Figures 10.6 and 10.7). The later survey in November 1994, showed that scour hole I had moved farther outward, following the bank erosion. The division of flow due of formation of bars over two channels approaching towards the bank, shaped the scour holes I_1 and I_2 to a combined scour hole.

The shallow bend scour C in June-July 1993 gradually diminished as the Old Main Channel lost its importance. In August 1993 the scour hole C split into C_1 and C_2 and later in November it further reduced its size. Scour hole H can also be classified as a bend scour hole, although it changes its shape and characteristics. Often it appeared as a combined (bend and confluence) scour hole.

Confluence scour hole
A confluence scour hole G exists in June 1993 as a result of the confluence of the Old Main Channel and the smaller channels bisecting the low char area north of Bahadurabad. Due to the development of the New Main Channel after the cutoff processes and the consequent reduced discharge in the Old Main Channel, the direction as well as the maximum depth of the scour hole reduced from 13.5 m +SLW to 10.5 m +SLW in August 1993, see Figures 10.4 and 10.5. Further deterioration of the Old Main Channel resulted in a further reduction of the scour depth to 8.5 m +SLW and the upstream part of the scour hole shifted about 1.5 km in downstream direction with considerable reduction in size.

The scour hole D in Aug-Sep 1993 was probably only a locally deepened reach of a degrading channel. The scour holes D_1 and D_2 in November 1993, November 1994 and February 1995 can probably be classified as confluence scour holes. These confluence scours were formed by the smaller braided channels, the flow of which was split after the emerging of low level bars. During the monsoon these scour holes diminish in size as can be seen from the July 1995 bathymetric survey.

Protrusion Scour
After the development of the cutoff, the main flow was directed toward the Bahadurabad Ghat and the flow through the left bank channel upstream of Bahadurabad experienced the Bahadurabad as an extended part of a bank which partly obstructed the flow. As a result, the scour hole F on the August 1993 bathymap developed can probably best be classified as a protrusion scour hole in view of the upstream channel geometry. Probably both protrusion and to some extent confluence scour effects (due to the shallow left bank channel) are reflected in scour hole F. During the lean season the protrusion effect of Bahadurabad diminishes due to complete drying up of the left bank channel and the scour hole moved over more than a km in downstream direction through the system. In November 1994, February 1995 and November 1995 the flow through the New Main Channel was directed toward the Bahadurabad bank with incidence angles ranging from 20° to 35°. It appeared that instead of formation of a bend, the flow was deflected by the comparatively harder bank at Bahadurabad, and as a result a scour hole formed at Bahadurabad can be considered as protrusion scour with the same resemblance to a local scour hole. However, the scour hole F in the July 1995 survey (when the left channel was active again) is similar to that of August 1993.

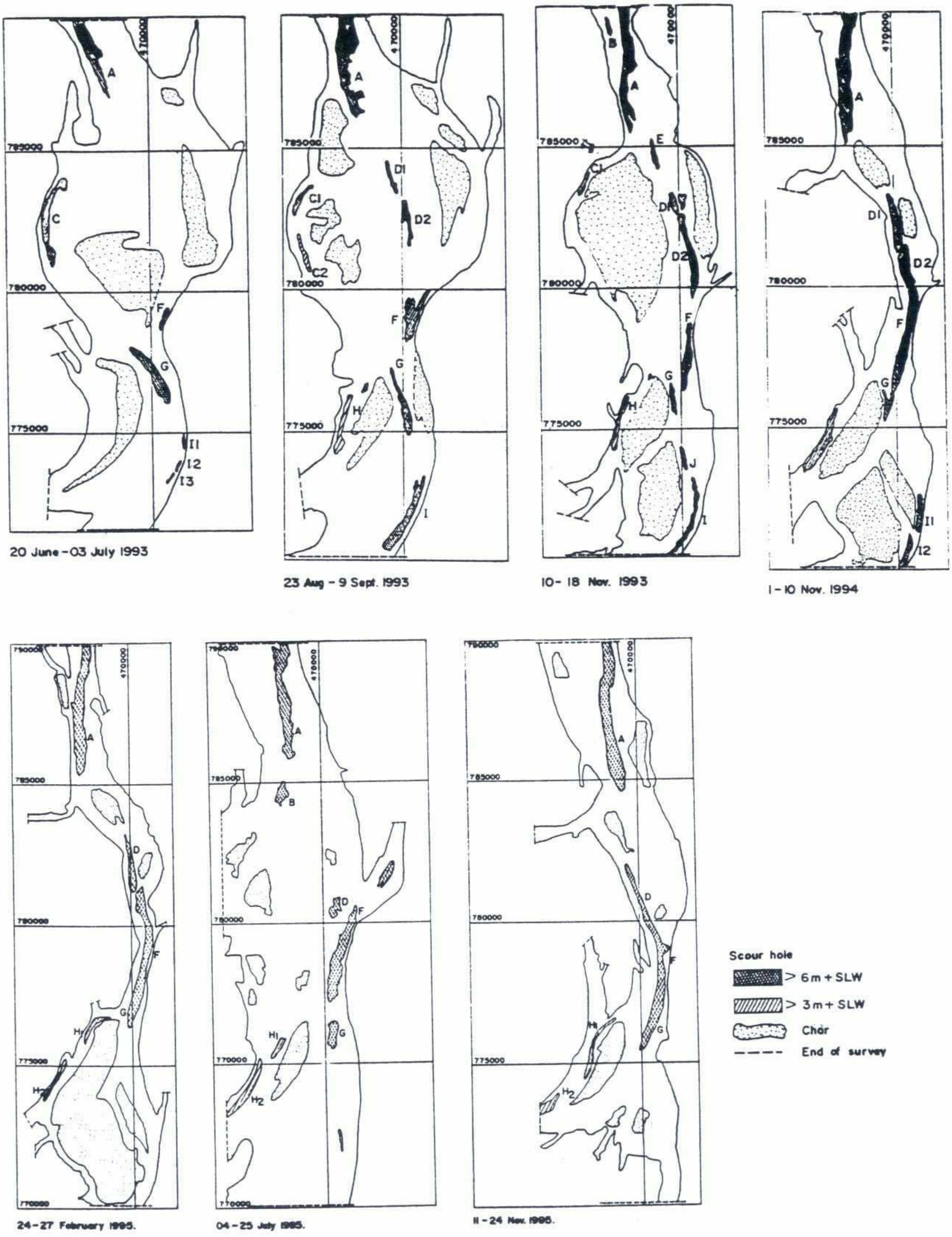

Figure 10.3 Scour holes at Bahadurabad identified in different bathymetric surveys

Wandering of scour holes

The scour holes D_1 and D_2 in August 1993 probably appeared due to the cutoff processes in the new channel and later in November, the scour holes E, D and F appeared in the system, probably due to the continuation of similar processes.

During the cutoff processes a huge volume of sediment had to be removed from the riverbed of New Main Channel. The net volume corresponding to about $8*10^6$ m^3 inbetween the period of Aug-Nov. 1993 which could only be achieved if locally the sediment transport was increased considerably. The sediment transport and deposition is also responsible for the movement of these scour holes. These scour holes move through the system and disappear within a number of months. Later, in response to changes of the channel geometry and different flow condition, other types of scour hole appearing nearly the same location. The scour holes D and G in July 1995 can also be distinguished as wandering scour holes: scour holes which developed in earlier months and which travel through the system.

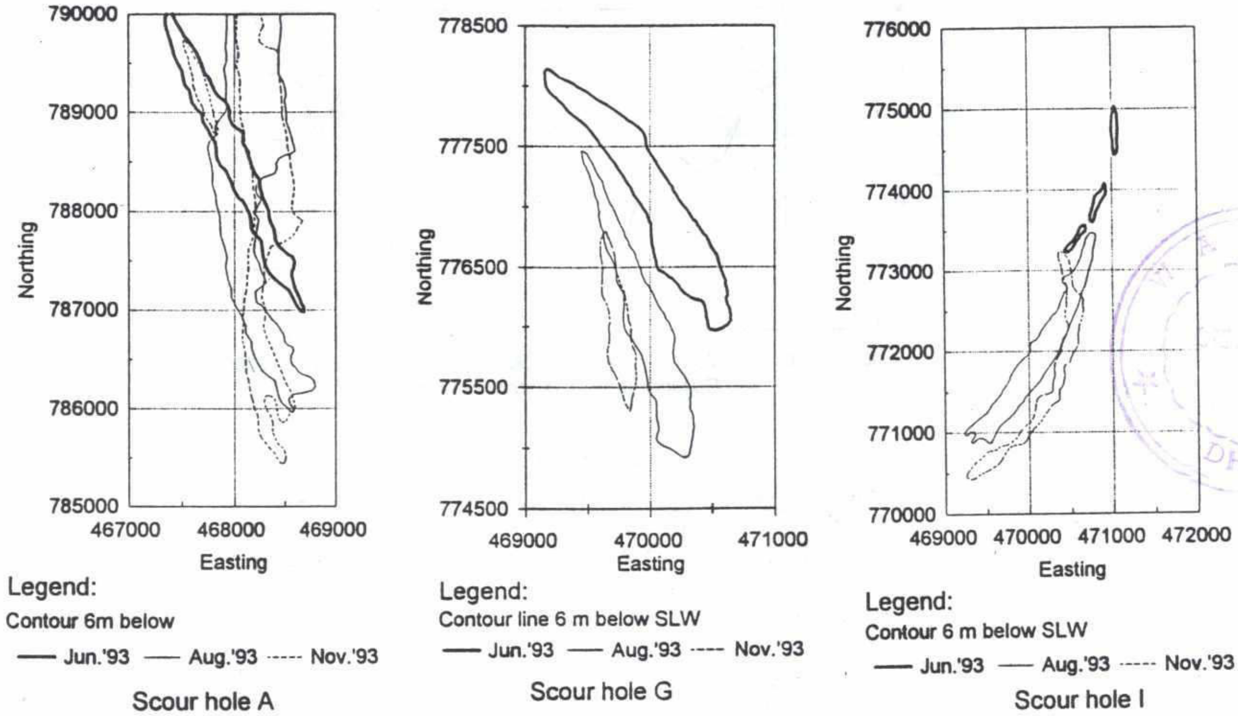

Figure 10.4 Shifting of the scour holes in time

Other scour holes

The scour hole A is present in all bathymetric surveys, although its size and shapes changes in time. The upstream part of this scour hole was not included in bathymetric surveys. But also from the satellite images in Figure 2.6, which cover the reach upstream of the bathymetric survey, it is difficult to identify the type of this scour hole. It is quite exceptional that this scour hole remains through the whole study period, both in monsoon and lean season, although it changed its size and shape while persistently migrating in east-ward direction. One of the reasons of the existence of this scour hole is that this reach of the river is comparatively narrow and straight probably due to convergence of flow.

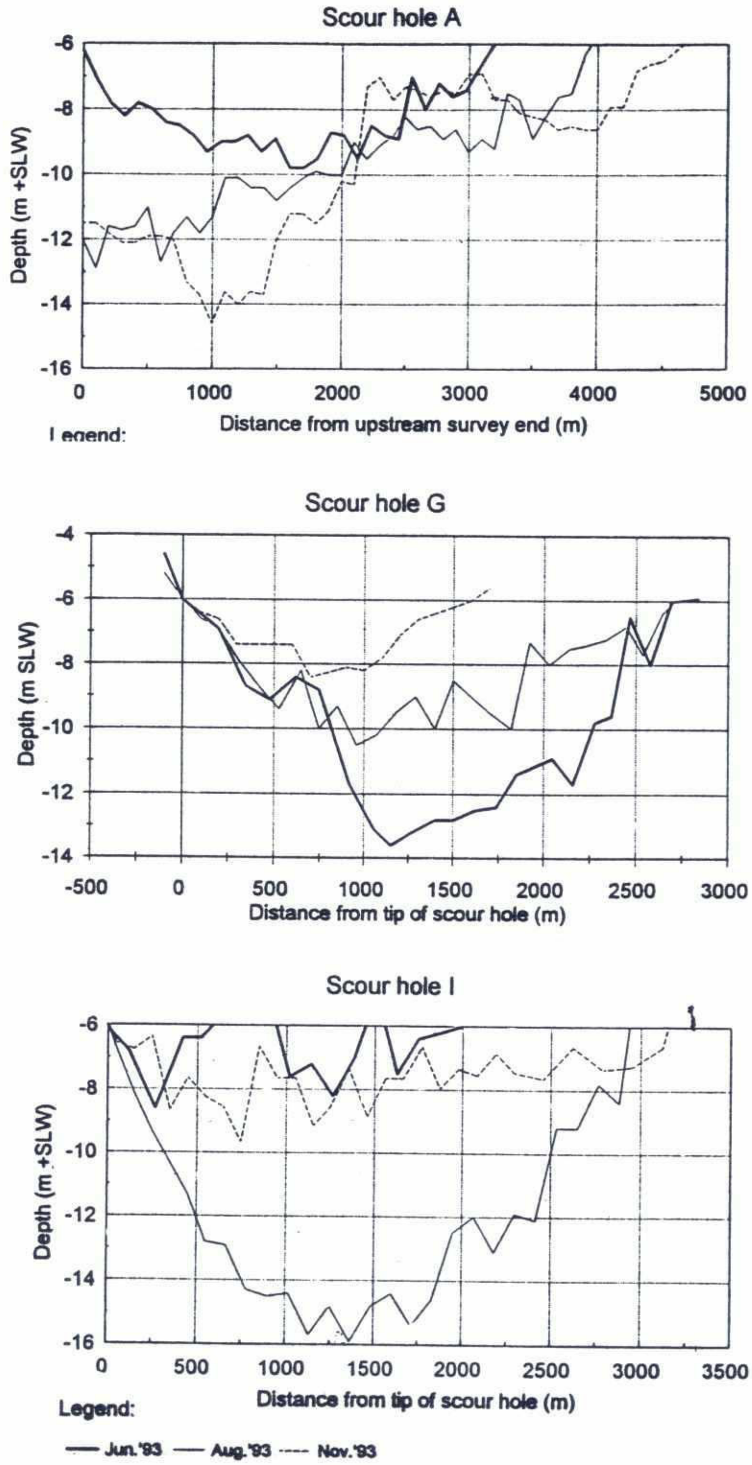

Figure 10.5 Changing of the long profiles of the scour holes in time

10.4 Dimensions of the scour holes

As indicator for the typical dimensions of the scour holes the maximum depth, area and volume below certain levels are analyzed here. The maximum depth is considered as a depth below SLW level; the area and volume are estimated below the +6 m SLW. These parameters are presented in Table 10.1. The maximum depth presented in the table is not the maximum depth of the scour holes, rather it indicates the relative lowest bed levels of the holes. The maximum scour depth observed at the Bahadurabad location is 17 m +SLW of the scour hole F during the lean season survey, the maximum observed area and volume are found for the scour hole A in November 1995, notably 2.6 Mm^2 and 8 Mm^3 respectively. The shift of the scour hole A from June to August 1993 involved about 6 Mm^3 of riverbed erosion, which is about 25% of the total transported volume of sediment through the left channel at Bahadurabad during that period (see Table 5.1). Therefore, it can be concluded that the shifting of scour holes, which takes place continuously, involves huge amounts of sediment via deposition and erosion of the riverbed and probably has a significant contribution to the changing of the planform of the river.

The maximum depth, area and volume of the scour depth change continuously in response to the changing upstream channel geometry and the changing flow conditions. For example, confluence scour hole G changed with the changing of the significance of an upstream confluencing channel.

Unlike what is suggested in Breusers (1991a) the monsoon surveys do not show an increase in scour depth during the passage of floods. On the average the maximum scour depth, area and volume do not change with the season, see Figure 10.6. Due to the disappearing of a few scour holes, for example scour hole D during the monsoon, on the average comparatively overall deeper channels exist during the lean season.

10.5 Slope of the scour hole

During the shifting and also during the development or diminishing of a scour hole, it maintains almost constant upstream and downstream slope, see Figure 10.5. The upstream slopes are ranging from 1 to 100 to 1 in 200, while the downstream slope is varying from 1 in 250 to 1 in 400. These values indicate very mild slopes at both ends of the scour holes. They are also much milder than the scour hole slope found by Breusers (1991b) for scour holes downstream of hydraulic structures. The mild slope is probably due to the large contribution of the suspended sediment transport to the total bed material transport.

The inner bend slopes of scour hole I from the three bathymatric surveys of 1993 are shown in Table 10.2 (see also Figure 10.7). The radius of curvature (Rc) is estimated from a line draw through approximate 50% conveyance line of the reach of the river bend. The maximum slope occurred in August 1993 and varied through the bend. The highest scour depth occurred, where the transverse slope is highest (see Figure 10.7). The slopes of scour hole I in June and November 1993 have much lesser value. The magnitude of the inner bend slope is to the interaction between the transverse bed-shear stress due to the secondary current profile and the gravity forces of the grains. However, the outer bend slope varies from 1:2 to 6, probably depending on the bank erosion intensity of the bend and the characteristics of the bank materials.

Scour holes

Scour hole	Jun.1993				Aug. 1993				Nov. 1993			
	Max. depth		Area	Volum	Max. Depth		Area	Volume	Max. Depth		Area	Volume
	Below SLW		Below 6 m SLW		Below SLW		Below 6 m SLW		Below SLW		Below 6 m SLW	
		(m)	(Mm²)	(Mm³)		(m)	(Mm²)	(Mm³)		(m)	(Mm²)	(Mm³)
A		10	1.2	2.2		12	2.6	6.6		14	1.6	5.1
B										7	0.06	0.05
C		5			C1	6			C1	4		
					C2	6				3		
D					D1	7	0.3	0.2		7	0.2	0.3
					D2	9	0.4	0.9		10	0.8	1.3
F		8	0.06	0.1		10	0.8	1.6		10	0.6	1.3
G		13	0.9	2.5		8	0.6	1.3		8	0.2	0.2
E										7	0.3	0.4
H					H1	5				7		
					H2	8	0.05	0.1		8	0.05	0.1
I		7	0.1	0.1		15	0.9	3.6		9	0.5	0.6
J										8	0.2	0.3

Scour hole	Nov. 1994				Feb. 1995				Jul. 1995				Nov. 1995			
	Max. Depth		Area	Volume	Max. Depth		Area	Volume	Max. Depth		Area	Volume	Max. Depth		Area	Volume
	Below SLW		Below 6 m SLW		Below SLW		Below 6 m SLW		Below SLW		Below 6 m SLW		Below SLW		Below 6 m SLW	
		(m)	(Mm²)	(Mm³)		(m)	(Mm²)	(Mm³)		(m)	(Mm²)	(Mm³)		(m)	(Mm²)	(Mm³)
A		11	2.2	5.7		10	1.8	4		10	1.6	3.4		13	2.6	8
B																
C																
D		10	0.5	0.3		10	0.5	1.6						9	0.8	1.7
		12	0.5	0.6		11	0.3	0.8								
F		17	1.6	6.6		17	1.5	6.3		13	1.8	5.2		14	1.4	4.8
G		7	0.2	0.2		8	0.2	0.2		10	0.5	0.9				
E										7	0.3	0.6				
H		8	0.1	0.2		6				9	0.1	0.2		8	0.1	0.2
		8	0.2	0.4		8	0.1	0.2		6						
I	I1	8	0.2	0.3		8	0.1	0.2								
	I2	8	0.3	0.6												
J																

Table 10.1 Maximum scour depth, area and volume (below SLW +6m) of the scour holes at Bahadurabad location in the period June 1993 - November 1995

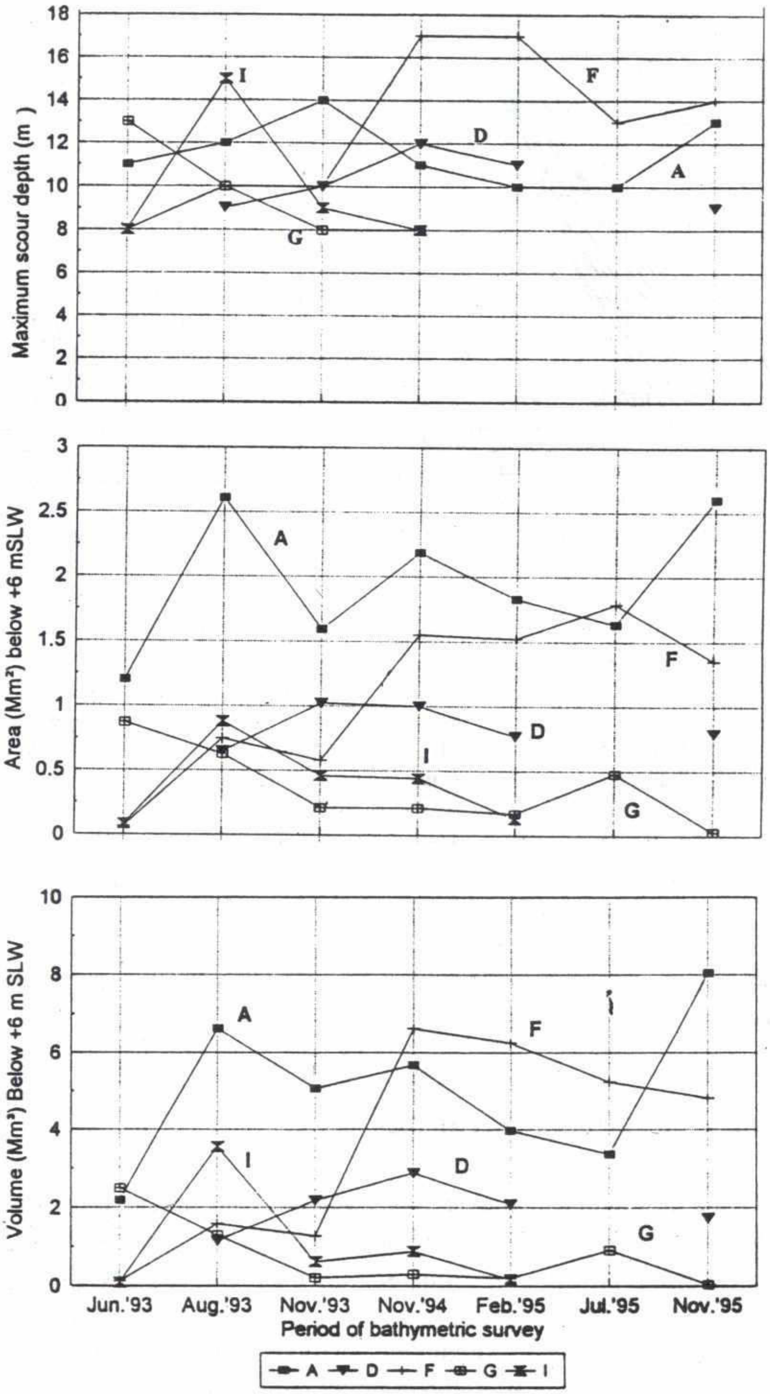

Figure 10.6 Variation of maximum depth, area and volume of different scour hole at Bahadurabad location in time

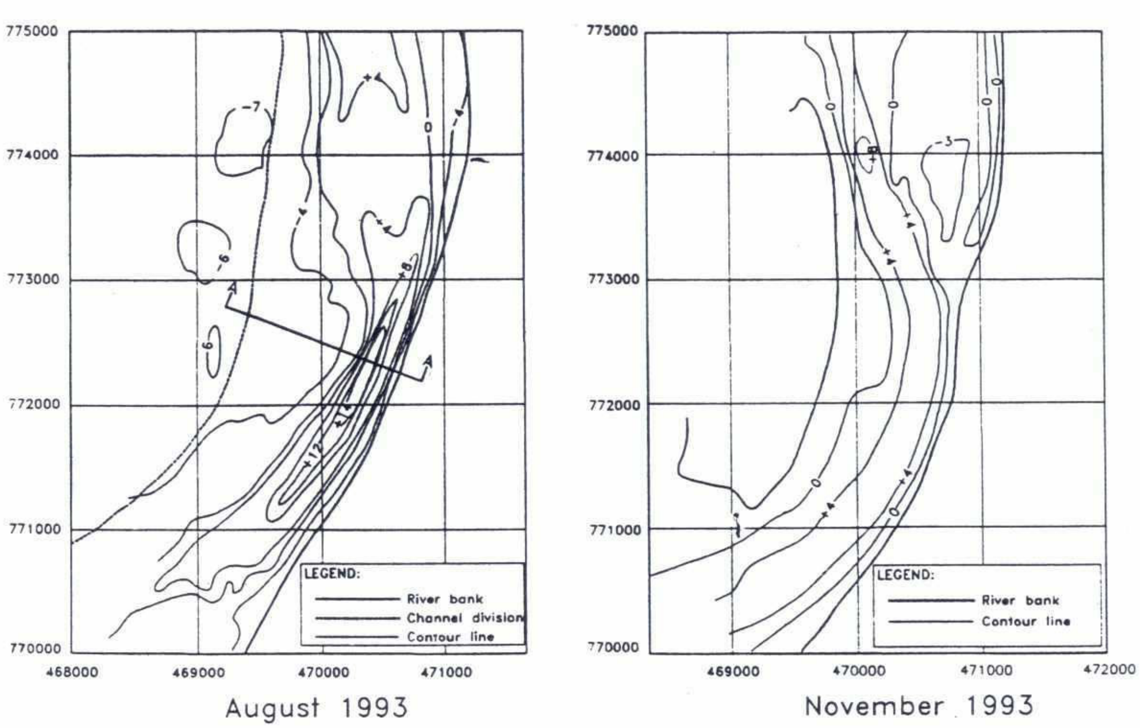

Figure 10.7 Scour hole I in August and November 1993 bathymetric surveys

Bathy surveys	Av. width (km)	h (m)	Rc (km)	Actual slope
Jun. 1993	1.15	6.8	2.8	1:25 to 1:60
Aug. 1993	1.7	7.8	3.7	1:15 to 1:25
Nov. 1993	0.85	5.8	2.5	1:40 to 1:60

Table 10.2 Average width, depth, radius of curvature and inner bend slope of the bend scour hole I, 1993 at Bahadurabad location

10.6 Comparison with different predictors

There are a number of predictors available for predicting the maximum scour depth. Here the predictors are limited to those which were previously used in the main rivers of Bangladesh under earlier studies. The different predictors for estimating the maximum scour depth mentioned in Section 10.2 are compared with the observed scour hole data. Here the main difficulty encountered is in estimating the parameters related to the prediction methods. Unlike a flume, in a natural river no parameters like B, h, R, i, u etc. are well defined, and they vary in space and time. Moreover, in the Jamuna River the range of variation of these parameters is quite high. In this study, B and h are estimated by averaging relevant stretches of a river, average radius of curvature is considered a representative of R, for i the average slope of the river at Bahadurabad is used and for the cross-sectional velocity u is derived from the measured discharge. In estimating B, h and R subjective judgement influences the derived parameters. In addition, the possible time lag of the riverbed with respect to flow increases the range of uncertainty in the prediction method.

Bend scour

According to the Struiksma method the relative bend scour depth (h_{bs}/h) increases with the increasing of the product of the secondary flow parameter and the square root of the Shield parameter ($A\sqrt{\theta}$), and with the increasing of the ratio of the width and radius of curvature (B/Rc). The secondary flow parameter A of Equation (10.3) was estimated here by assuming a constant Chézy's C value 70 $m^{1/2}/s$. This value was suggested by Klaassen et al (1988b) for the Jamuna River during monsoon flow. For the average slope (i) a value of $7*10^{-5}$ is used.

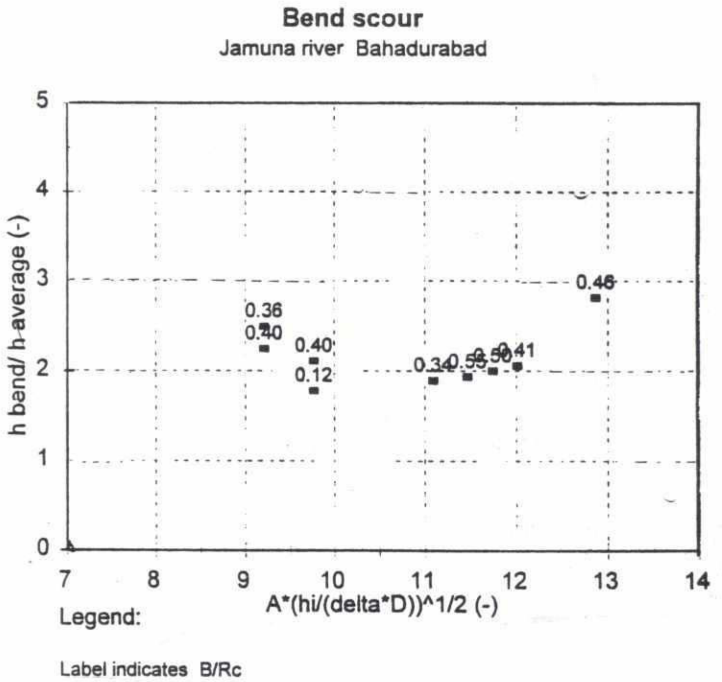

Figure 10.8 Maximum relative bend scour depth plotted according to the Struiksma (1988) design graph

Although there are some uncertainties in estimating the parameters related to the prediction method, it can be observed in Figure 10.8 that relative scour depth hardly shows any variation with the parameter B/Rc and ($A\sqrt{\theta}$). Like the observation of Haskoning (1990) in the Meghna River, the maximum bend scour depth is almost 3 to 4 times smaller than the predicted depth by Struiksma (see Figure 10.9). The average relative bend scour hole h_{bs}/h is about 2.4, which is higher than the Meghna River. This significant difference between the observed and the predicted depth can be seen via Figure 10.10, where cross-section A-A (see Figure 10.7) is compared with a cross-section derived using Equation (10.3), based on the parameters of the section A-A (Table 10.2). There are a number of reasons for these high differences, notably, (1) the estimated river width used here may be higher than a width where an axisymmetric flow condition prevails and (2) the Struiksma method was developed for bed load transport, suspended sediment may have some effect in reducing transverse bed slope, (3) the Struiksma method is strictly speaking only appropriate for axi-symmetric conditions (but considering the conditions at the beginning of a bend would lead to an increase rather than a decrease of scour depth), (4) the bank erosion product is not considered in Struiksma's method. Moreover, a number of other factors like the time-scale of the development of the scour hole as indicated by Klaassen (1988), the erodibility of the bank near the bend, intensity of the flow, the variation of width and radius of curvature along the bend might cause that the scour depth is fairly insensitive to the parameter B/Rc. More studies are needed to better identify possible causes of this discrepancies. Clearly the prediction of the scour depth in bends of rapidly eroding sand-bed rivers still has to be improved considerably.

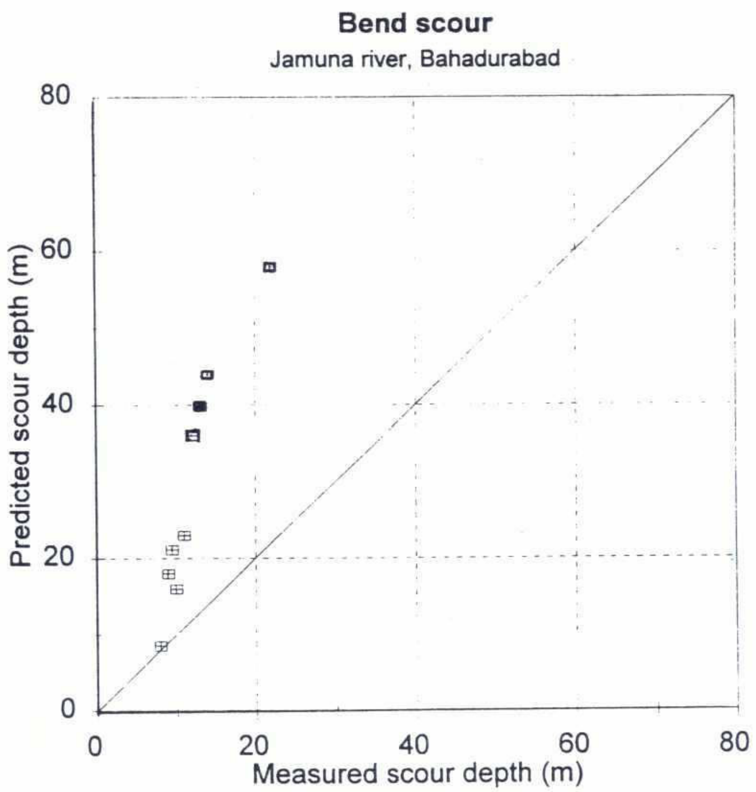

Figure 10.9 Comparison between observed and predicted (Struiksma, 1988) bend scour depth

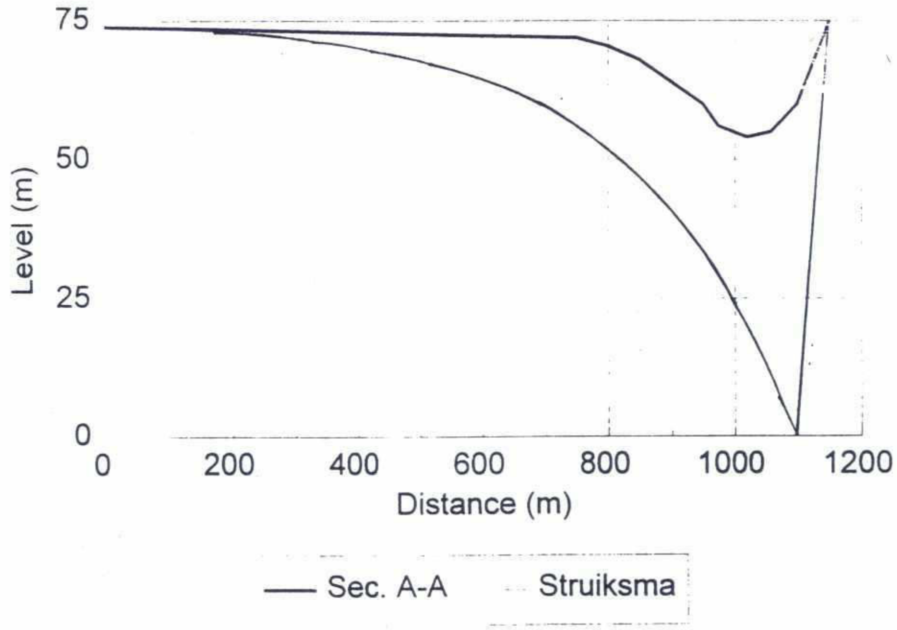

Figure 10.10 Comparison cross-section A-A (see Figure 10.7) and the predicted cross-section based on Struiksma (1988)

However, for the Jamuna River to predict the bend-scour depth an average value of relative scour depth can be considered. In Figure 10.8, it is observed that the relative bend-scour depth varied within a range of 2 to 2.8, the average value can be selected as 2.4.

Confluence scour

The relative scour depth (h_c) of the confluence scour increases with the angle of incidence (Θ) of the confluencing channel (see Equation 10.7). To apply the Klaassen and Vermeer (1988) prediction method for confluence scour, the average depth of the upstream channels has to be estimated, and this can only be done with limited accuracy. To estimate the value of ε the discharge of the confluencing channels are estimated from the RSP measured discharges and discharges obtained from rating curves. Klaassen and Vermeer (1988) used at-a-station relations for estimating the discharge. In Figure 10.11 can be observed that the measured confluence scour holes near Bahadurabad are in good agreement with the Klaassen and Vermeer (1988) prediction. During the derivation of Equation (10.5) Klaassen and Vermeer (1988b) excluded scour holes for which $\varepsilon > 0.75$, because they observed that for the higher values of ε, no relation existed between h_{cs}/h and Θ, probably due to the diminishing of the confluencing effect. However, the Bahadurabad data suggest that the confluencing effect is probably also significant beyond the mentioned range of ε.

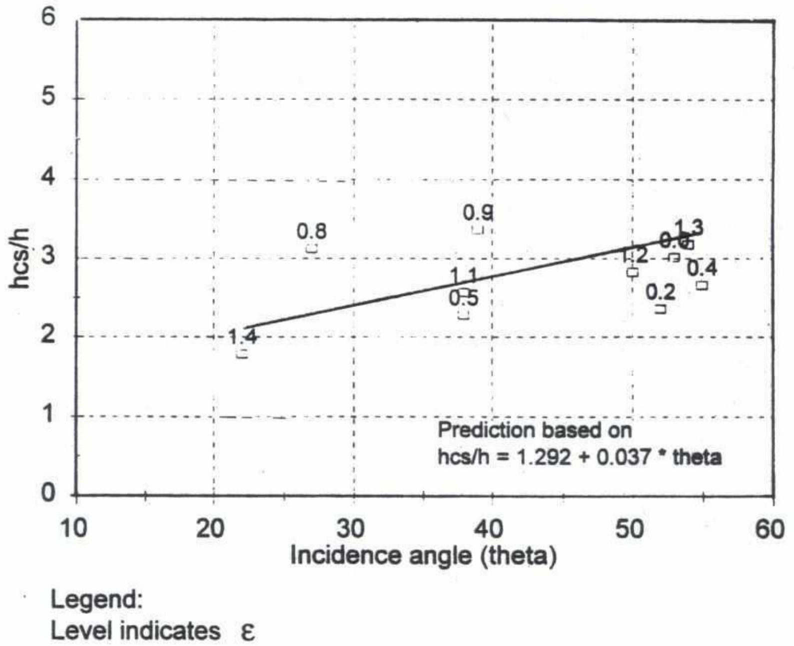

Figure 10.11 Relation between the relative confluence scour depth and the incidence angle

Protrusion scour

Comparing the observed scour depth with Simons and Sentürk (1977) prediction method for abutment scour, it was found that the predicted depths are slightly higher than the actual values, (see Figure 10.12). The average observed value of $4*Fr^{0,33}$ is 2.1, where as the average h_p/h is about 1.8. One possible explanation is that in the case of abutments the sediment supply from the bank completely ceases, while in the case of a natural protrusion as at Bahadurabad, the bank is erodible. Consequently there is sediment supply from the bank, which might reduce the scour depth. In the Meghna River the protrusion scour holes are similarly related to the Froude number, indicating that the protrusion scour holes in the main rivers of Bangladesh can be fairly well predicted by the Simons and Sentürk (1977) method.

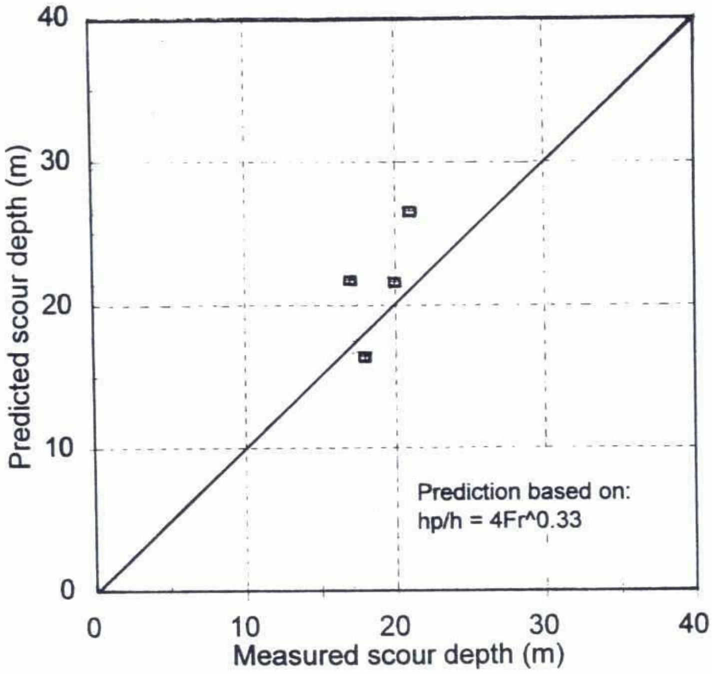

Figure 10.12 Observed and predicted (Simons and Senturk 1977) protrusion scour depth

10.7 Summary

The results from the study on the scour holes of the Jamuna River can be summarized as follows:

- The different types of scour holes could be studied in this study using more reliable riverbed data, flow and other parameters than in any previous study, although uncertainties remain in estimating some of the parameter used in the prediction method.
- The development and movement of the scour holes in the Jamuna river are extremely dynamical processes and they are mainly related to the rapid changes of the upstream planform. The formation, movement and diminishing processes of a few scour holes are also related to the seasonal variation of discharges.
- The shifting of the scour holes is generally associated with major aggradation and degradation of the riverbed which may involve up to 25% the total sediment transport (coarse fraction) volume.
- The upstream and downstream slopes of the scour holes are comparatively very mild, which is probably the large contribution of the suspended bed material load to the transport in the river.
- The dimensions of the scour holes i.e. the maximum scour depth, area and volume change time, but on average no seasonal variation of scour hole dimensions are observed at Bahadurabad over the observation period.
- The prediction method by Klaassen and Vermeer (1988b) can be used to estimate the confluence scour in the Jamuna River. For protrusion scour the Simons and Sentürk (1977) method can be applied for the Jamuna River. For bend scour depth an average relative scour depth (h_s/h) can be considered as 2.4 for the Jamuna River.

11 On prediction method and predictability

11.1 General

One of the aims of this study was to derive prediction methods for river erosion and deposition on the riverbed, for channel development or abandonment, for bank erosion rate and for depth of scour hole. A number of prediction methods are available for predicting the changes of the various morphological phenomena in the Jamuna River. Those prediction methods were developed by using satellite images, BWDB standard cross-sections measurements and BIWTA sounding maps. A significant range of uncertainties exists in almost all the prediction methods. It was felt that by using the more reliable data on bed topography and hydraulic and sedimentary data obtained during the monsoon as well as during the low flow season; those prediction methods could be improved. Also it might be possible to derive improved prediction methods as a step towards a better prediction of the planform changes of Bangladesh rivers. An attempt was made to derive different prediction methods and the previous prediction methods available for predicting various morphological changes are evaluated, by using more reliable and relevant data collected by the RSP. The derivation of new predicting methods and the evaluated previously methods are discussed in the following sections.

11.2 Erosion and deposition

The erosion and deposition processes in the Jamuna River are discussed in Chapter 7, in relation to the flow and sedimentary processes of the river observed in the RSP data. Erosion and deposition on the riverbed can be described by the two-dimensional sediment continuity equation including changes in sediment concentration (see equation 7.3), as it was observed that the adaptation of the suspended sediment transport plays an important role in changing the bed topography. For this type of equation the development of additional predictors for the adaptation of suspended sediment verticals for a particular river are needed, to be able to use it for modelling purposes. Besides the prediction of the river bed-level changes by modelling, simpler prediction methods can be made visual. Peters (1988) derived for the Zaire River a method for predicting the location of erosion and deposition on the riverbed (see Figure 3.3) on the basis of a simple graphical relation. In addition, local slope and prevailing bedforms were used for predicting local erosion and deposition in the river bed for Zaire River (Peters Starling, 1976 and Peters et al, 1977).

In principle, two possible prediction methods can be considered, the difference between them being the measure of detail. One prediction method uses detailed information, e.g. via the GIS grid. If for each point some relevant data are given, then these can be used to indicate whether in each point deposition or erosion may occur. Another method is to do the prediction not in a detailed grid, but rather to consider whole river branches, with a length of several kms. The prediction method to be developed should indicate whether a branch will develop further or whether it will be abandoned.

The first method on the basis of detailed information is discussed first. It was developed to predict erosion and deposition on the basis depth-averaged velocity and water depth in line with the Peters method. To predict the location of erosion and deposition on the riverbed a number of transect measurements during August 1993 survey are used for estimating the depth-averaged velocity and the water depth. During the August 1993 survey the ADCP was used for a number of river reaches and hence both parameters are available. The corresponding erosion and deposition is found by comparing the August-November 1993 surveys. The result obtained from this analysis is shown in Figure 7.8.

Instead of a linear relation between the water depth and the velocity (in conformity to Peters), for the Jamuna River the relation between the velocity and square root of the depth yields a good demarcation line between the erosion and deposition area (see Figure 11.1). It is also observed that the demarcation lines between erosion and deposition for the Zaire River are below the Jamuna River "lines" over the largest range. This is slightly amazing as the bed material of the Zaire River is coarser than the Jamuna River.

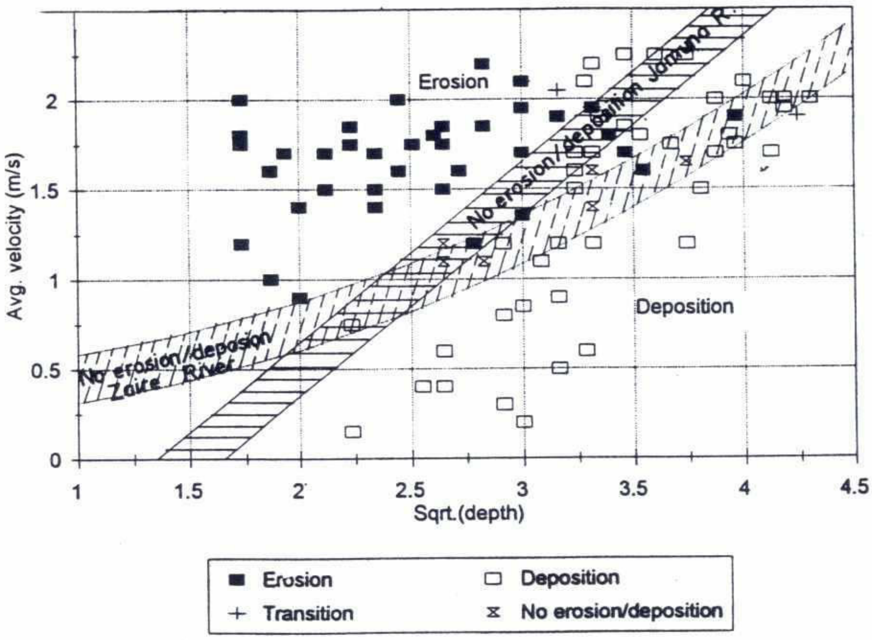

Figure 11.1 Erosion and deposition on the riverbed in relation with depth average velocity and square root of depth

The observed erosion and deposition in relation to depth and velocity is the result of a combination of different processes, and is in principle based on physical laws (Peters,1988). One probable explanation for getting this type of relation is that the involved process is an adaptation process. The bed topography (or possibly the cross-section) is lagging behind the flow pattern (see also Chapter 7). It is trying to adjust to changing conditions flow, by eroding and depositing on the riverbed. For example, the velocity measured at location "A" in August is very small compared to the water depth (see Figure 7.7). Before the August measurement the channel around area A was more active, but after the development of the cutoff the flow shifted more towards the right attacking the shallow area 'B'. Later both areas A and B react differently to the changes of the flow condition: deposition occurred in area A and erosion occurred in B.

The prediction method for the erosion and deposition that derived from Figure 11.1 can be described as:

$$u > \sqrt{h} - 1.35 \qquad \textit{Erosion}$$

$$\sqrt{h} - 1.35 \leq u \leq \sqrt{h} - 1.65 \qquad \textit{Transition} \qquad (11.1)$$

$$u < \sqrt{h} - 1.65 \qquad \textit{Deposition}$$

where h = water depth and u = depth-averaged velocity. Transition is defined as erosion/deposition < 1.0 m.

For verifying, the above developed method data from Aug.-Nov. 1993 and July-Nov. 1995 are used. The depth-averaged velocity obtained from ADCP and surface velocities from float tracking in Aug.93 and Jul.95 respectively (see Figures 5.10 and 5.11), and from corresponding bathymetric surveys were available in addition to water depths and areas of erosion and deposition. The results are shown in Figure 11.2 and 11.3. It is observed from the figures that the predicted transition area is comparatively covering a larger area than for the measured case. Redefining of transition for: erosion/deposition < 0.5 m rather than < 1.0 m probably can offer a better agreement between the predicted and measured transition area. There are locations where the prediction is opposite to the measured erosion/deposition and it is of interest to study these for a possible improvement of the prediction method. In both figures it is observed that the prediction method is unable to predict the shifting of scour holes (at the upstream end of the survey). It can be observed in Figures 7.10 and 7.11 that in 1993 the processes of over and underloading of sediment in this area was very high. Peters (1988) already pointed out that this type of prediction method can only be applied at areas where the actual sediment transport is near the sediment transport capacity. This implies that in addition to the velocity, sedimentary processes like overloading also have a considerable influence on the processes of erosion and deposition (as already observed in Chapter 7). Moreover, changes of flow direction can affect this prediction method as well. Nevertheless, it is observed that a good agreement exists for more than 60% for the Aug-Nov. 93 period and more than 50% for the Jul-Nov.95 period. This also indicates that the length of time over which the prediction has to be made is important. It should be noted here that the real accuracy is higher than shown in these figures and improvement can be achieved by redefining the transition for the measured case as indicated earlier. Furthermore it is noted that in principle the method can be extended to indicate also the magnitude of erosion and deposition. Finally, it is stressed that further improvements of the method can be achieved by:

- developing a method based on $\frac{\partial u}{\partial x}$ rather than on a relation between u and $\sqrt{h}$ (see RSP, 1996c);
- including information about sediment transport patterns, which e.g. can be derived from ADCP backscatter.

This short-term prediction method can be applied for assisting in the maintaining the navigation route in the Jamuna River, as it can give indications where dredging or bandalling might be effective. This short-term prediction of channel shifting can be very helpful for estimating the requirement for the dredging of bandalling works. Moreover, this method can provide a better based decision on the location where bandals could be placed and it can assist in making decision as to the best location and alignment of dredging work.

The second prediction method is rather 1-D than 2-D (as the previous one is). The net erosion and net deposition in downstream direction can be related to the average velocity and average depth over the cross-section. In Figure 11.4 the average depth is estimated for one kilometre long reaches of the river and the average velocity is estimated by dividing the discharge of the channel by the average channel area of the same reach. The discharge measured in August 1993 in different channels is used in estimating the average velocity. Figure 11.4 is showing a similar type of relation of erosion and deposition as Figure 11.1 and demonstrates the potential of applying the Peters (1988) method to larger reaches as well. This type of relation can also be extended to whole branches (see Figure 11.5) and the figure shows that the relation holds also if whole branches are considered. Although this is a preliminary analysis, it nevertheless indicates that this type of relation can be developed for predicting the development of the different anabranches of the river on short-term basis.

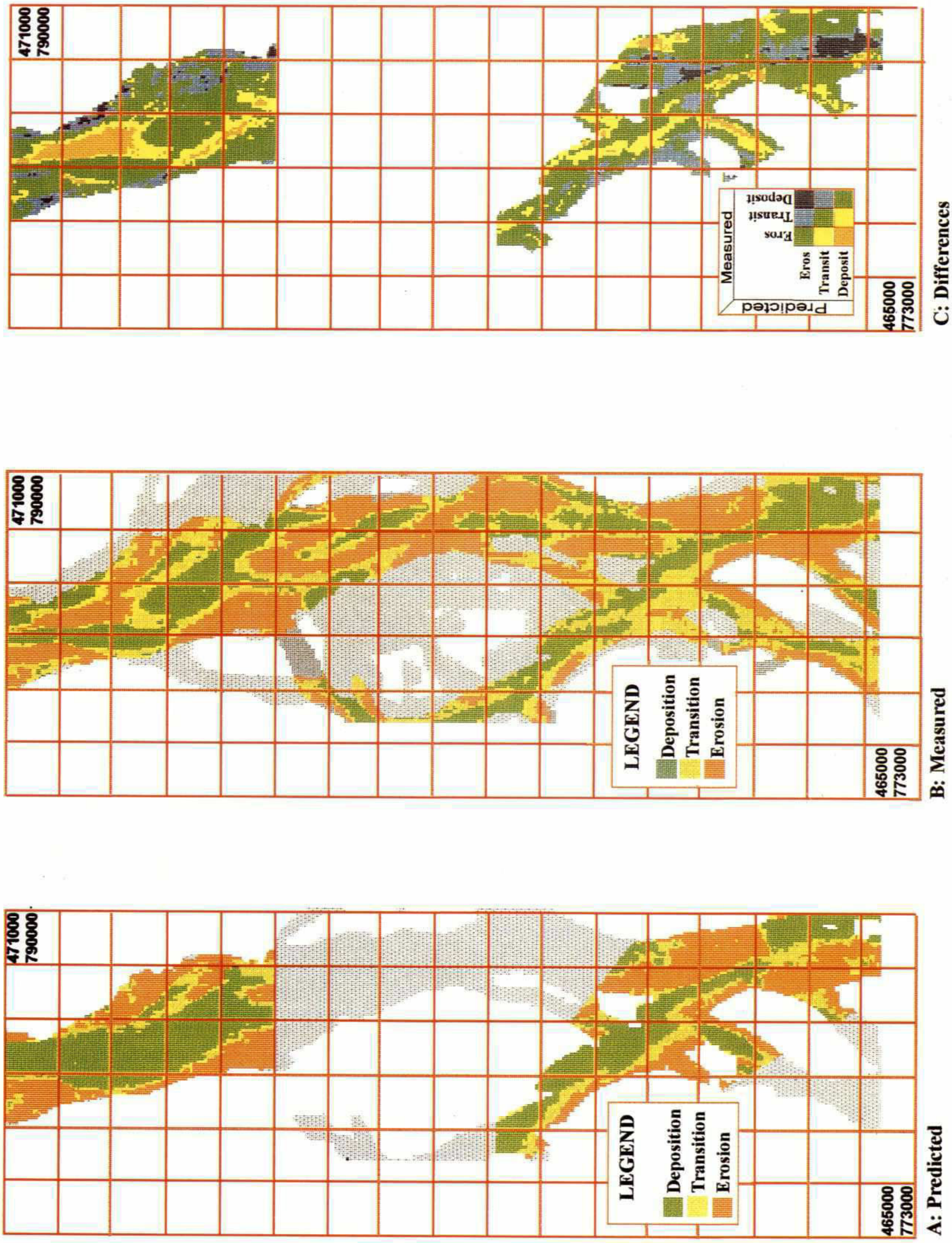

Figure 11.2 Comparison of predicted and measured erosion and deposition in the period of Aug-Nov.93

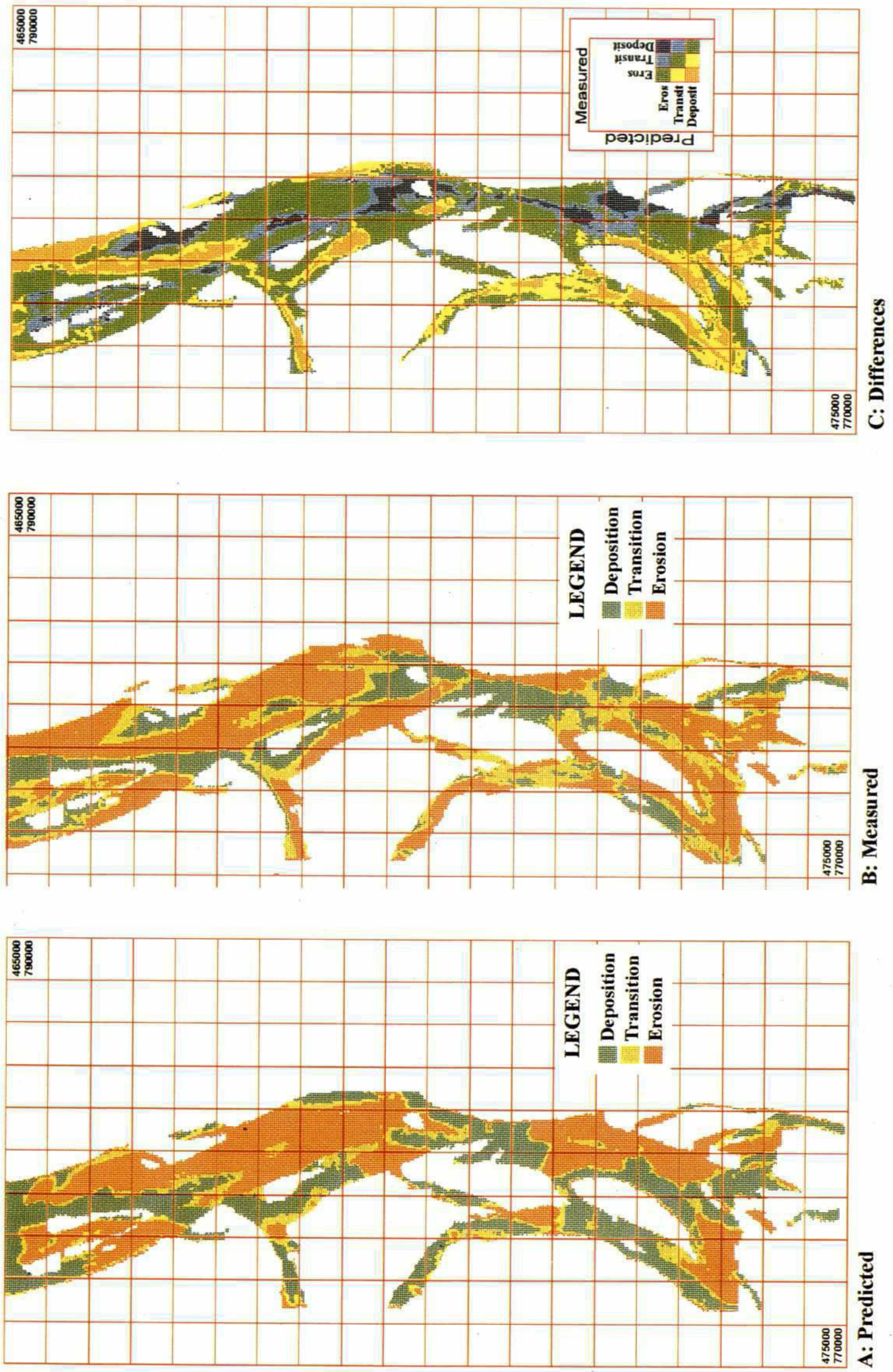

Figure 11.3 Comparison of predicted and measured erosion and deposition in the of Jul-Nov.95

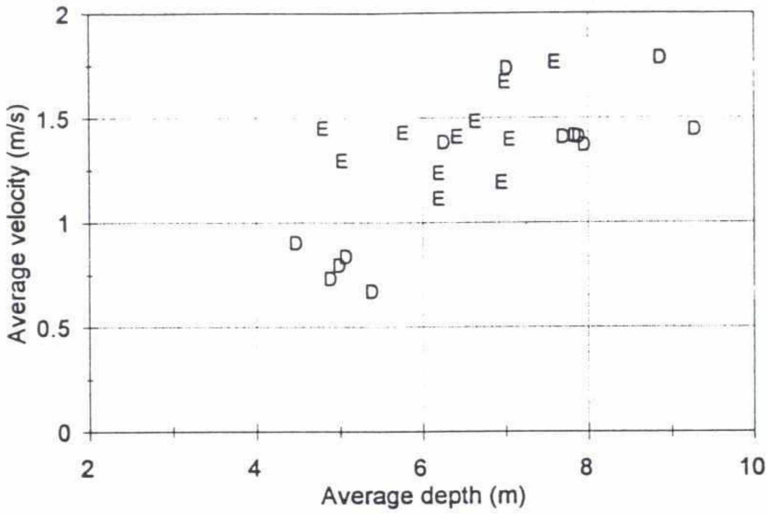

Figure 11.4 Net erosion and deposition in reach of 1 km length in relation to the average depth and velocity

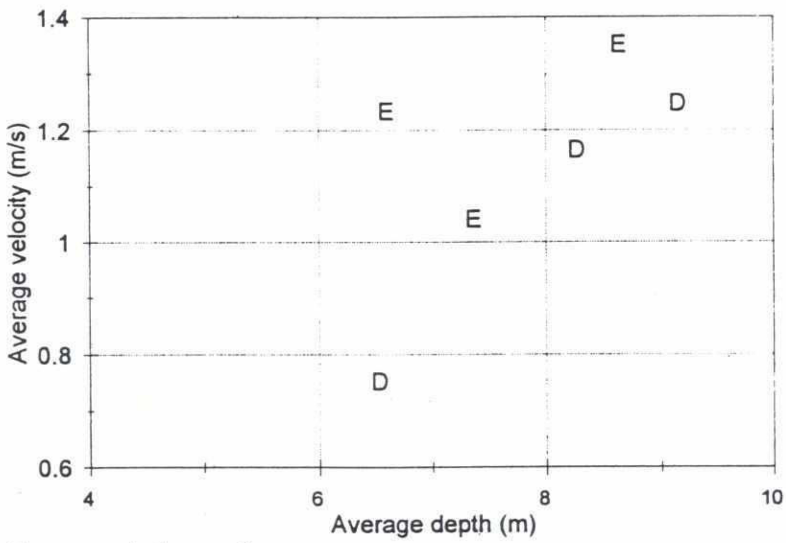

Figure 11.5 Net erosion and deposition in different branches in relation to the average depth and velocity

11.3 Cutoff processes

The development of a cutoff upstream of Bahadurabad in 1993 was described in Chapter 8. The available two prediction methods for predicting the cutoff in the Jamuna River such as Klaassen and Van Zanten (1989), are here simplified to a criterion for the cutoff ratio. Klaassen and Masselink (1992), and Mosselman (1994) based on the deviation angle of the curved channel compared to the upstream channel direction. In the former prediction method the threshold value 1.25 and for the latter method the threshold value of deviation angle is 40°. During the cutoff processes in 1993, the threshold values for both predictive methods were reached. It was observed that the deviation angle varied in a wide ranges above its threshold value during the development of the cutoff processes. It appeared that Mosselman (1994) is probably a more sensitive criterion for the cutoff process and can probably better be used to make predictions.

There is much uncertainty in both methods for predicting the development of cutoff. Applying the relation shown in Figure 11.5 in association with these prediction methods can help to predict the cutoff process with better accuracy.

11.4 Bank erosion

This study confirmed that bank erosion rates along the Jamuna River are very high. During the analysis of the bathymetric surveys, it was observed for a river bend downstream of Bahadurabad that the radius of curvature and the location of bank erosion changes very frequently during the monsoon even within a period of a month which makes accurate predictions even more difficult. It was also observed that even a smaller and fairly shallow outer bend eroded the river bank quite considerably. In addition to dimensions the sizes of the river bend, the rate appears to depend on the characteristics of the bank materials. It is imperative to have an idea of the bank material characteristics to make a fair prediction of the bank erosion rate. From the present analysis, it is concluded that the prediction of bank erosion is only possible with a fair accuracy where the bank erosion rate is comparatively small, like the observed bank erosion at the Kamarjani location with probably comparatively less erodible banks.

In this study the period over which data were available is fairly small; in particular, this holds for Kamarjani where data are only available for a period of four months. For Bahadurabad the observation period is a little larger, notably 2.5 years. Therefore, a full judgement of the prediction methods of Klaassen and Masselink (1992) and RRI (1993) is not justified. It is obvious though that inherent inaccuracies for those types of prediction method for bank erosion are quite high, as is also pointed out by the authors. From the present analysis of bank erosion rates and via comparing them with equations that can be used in 2-D models, the DHI (1996) method is found to be acceptable for predicting bank erosion rate, in cases when the bank erosion rate is moderate. To predict the bank erosion rate for reaches comparable to the reach downstream of Bahadurabad, the flow structure, the changes in the channels and the influence of bank erosion products must be taken into consideration.

11.5 Scour holes

Here were studied different types of scour holes as identified during the bathymetric surveys at the Bahadurabad location. The various predictors were evaluated as well and they were compared with the observed data. It was found that confluence scour can be predicted by the relation (10.7) proposed by Klaassen and Vermeer (1988b). The protrusion scour depths observed at the Bahadurabad location can be predicted by a relation (Equation 10.8) for abutment scour, derived by Simons and Sentürk (1977). For predicting the bend scour depth, no suitable predicting method was found. The bend scour in the Jamuna River can be estimated to be about 2.5 times of the average depth of water at the river bend. This includes a reduction of the scour depth due to the input of bank erosion products. Recent research (Shishikura, 1996) has demonstrated that the scour depth may increase considerably when bank protection works are constructed (in conformity with the experiments of Mesbahi (1992) and recent field observations by RRI et al, (1993).

11.6 Overall channel development

Overall planform development is related to the changes of the different morphological features discussed above. The predictability of the planform development also depends on the availability of reliable prediction methods for predicting the various morphological features of the river. Prediction methods can be differentiated to their time scale: how far ahead a method can predict changes with a certain accuracy. Accordingly, the methods can be identified as short-term, medium-term and long-term prediction methods, see Figure 11.6. Understanding of a river is a prerequisite for every type of prediction methods. For planform development a probabilistic medium-term prediction method was developed by Klaassen et al (1993) for the Jamuna River, as discussed in Chapter 3. The prediction method is based on integrating the different prediction methods for various components of the river planform, such as channel dimensions, bank erosion rate, cutoff development etc. The results of the present study can contribute to improving a few of the components of planform model. The short-term prediction method (Equation 11. 1) for the erosion/deposition on the riverbed can provide a fair idea about the lateral shifting of the channels. Probably the channel development in the lean season by retarded scour can also be predicted by this method. For the development or abandonment of a channel the relation shown in Figure 11.5 may be attractive to be included.

From the present study it appeared that the Jamuna River is very dynamic and its often chaotic behaviour makes it difficult to predict planform changes even on a medium-term time scale. The stochastic nature of the boundary conditions like discharge and sediment input (depending as they are on the meteorological conditions) is partly the cause of this. The present study had contributed to the development of the medium-term planform prediction method. More studies are required for improved understanding of the river processes active in this large braided sand-bed river, to develop in due course improved prediction methods for the Jamuna.

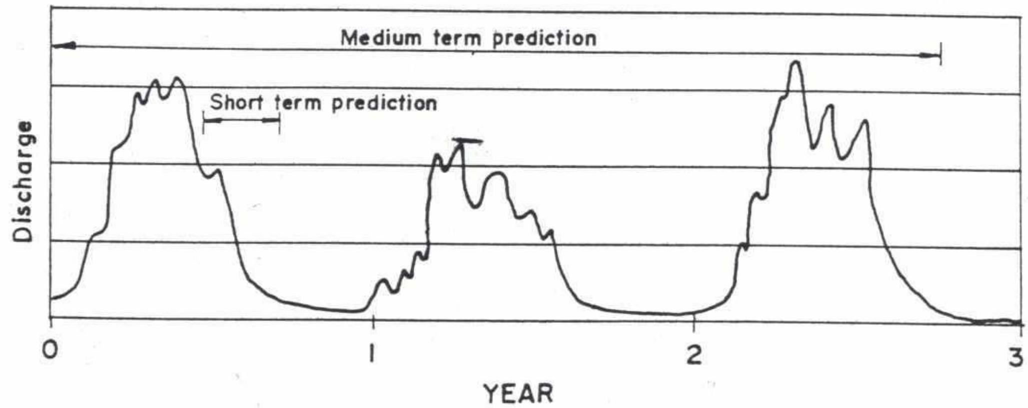

Figure 11.6 Different types of prediction methods

12 Discussions

12.1 Introduction

This study is mainly based on the analysis of RSP bathymetric surveys performed in the Jamuna River near Bahadurabad. Flow and sedimentary data are also used to relate them to the observed changes in bed topography as derived from consecutive bathymetric surveys. In the previous chapters various observations, analyses and results regarding the morphological processes of the river from the analysis are presented. In this chapter, a number of questions are addressed, notably; what we did, how we did it, and with what accuracy; what we learnt from the RSP surveys and from our studies; what the limitations of our studies are and how we can proceed to improve our understanding of the river processes. The discussions are divided in a number of issues that correspond to the different sections, RSP surveys, measuring concentration of suspended bed material using ADCP backscatter, use of GIS, increased understanding of the morphological processes and prediction methods.

12.2 RSP surveys

Accuracy of RSP Surveys

The methods and instruments used under the River Survey Project are quite sophisticated and the accuracy of the surveys is quite good (see Chapters 4 and 5). Measurements of the flow velocity by ADCP provide the three components of the velocity while the backscatter intensity of ADCP provides information about the sediment concentration. The use of the Differential Global Positioning System (DGPS) provides accurate positioning and this allows very good spatial links between the bed topography and flow and sediment transport processes. The bathymetric surveys provide accurate information on changes of bed topography, shifting of the bars, movement of thalweg, changes and movement of scour holes, shifting of the location of bank erosion. In the past three years RSP collected a large amount of various types of hydrological and morphological data from the main rivers of Bangladesh. Proper application of these data can contribute to an improvement of the understanding of morphological processes in Bangladesh's main rivers.

RSP data compared with data used in the past

Previous studies on the various morphological aspects of the rivers (like Klaassen and Vermeer, 1988; Klaassen and Masselink, 1992) are mainly based on satellite images obtained during the dry season, the standard cross-sections surveyed once a year during the dry season by Bangladesh Water Development Board (BWDB) and BIWTA bathymetric maps. There are, however, some limitations regarding the usefulness of these data. Major changes in the rivers occur during the flood season. The changing processes are comparatively slower in the dry season. The dry season images are the end result of the changes which occurred during the passage of the monsoon flood. Therefore, it is not possible to observe in detail the phenomena occurring in the river, which produces the planform which can be observed in the satellite images. Moreover, satellite images can provide only two-dimensional information only, and no information is provided on what is submerged. Furthermore, BWDB standard cross-sections are spaced at distances of about 6 km interval along the rivers. Therefore, the data collection in the past has limitations both temporally and spatially.

RSP bathymetric surveys during the monsoon as well as in the dry season provides three-dimensional information about the bed topography with fair accuracy. Thus it makes possible to quantify the changes that occurred inbetween surveys. The surveys provide an idea about the type of the changes that occurred and how the be topography and planforms developed during the monsoon resulting in the bed topography during the dry season. Furthermore, the flow and sediment transport data obtained from the ADCP and other data from the bathymetric surveys, provide a framework to relate the changes in the bed topography of the river to the hydraulic and morphological parameters.

Limitation of RSP data
Although the RSP surveys do have a number of advantages, the instruments and the methodology followed result in a number of limitations. The ADCP is unable to sample a significant part of the water mass column. No data are available on the upper 2,7 m and the lower 0.5 m. On the average this corresponds to more than 25% of the vertical. The RSP survey vessels were unable to measure in very shallow areas, while during flood some of these areas become very active in changing of the planform and the bed topography of the rivers. The major limitation of the bathymetric surveys is, however, that they cannot provide any information about the char levels above the water level prevailing during the survey, unless simultaneously a land survey is performed. Only a bathymetric survey during which all the chars are flooded, can cover the whole area of the riverbed which participates in the processes of changing the planform bed topography. The using after a survey in the monsoon a subsequent survey in dry season without land survey, it is not possible to quantify the changes that have taken place above the dry season water level. It should be mentioned here that a land survey was carried out at Bahadurabad during the Nov 95 bathymetric survey. This survey, however, was not used here due to time limits. In this respect, the satellite images have an advantage over the bathymetric surveys; they can at least provide some qualitative information about the bar and bank levels above the dry season water level. In addition, satellite images can provide information about the shallow and dry channels, which bathymetric surveys cannot cover.

A part of bathymetric surveys of Aug 93 was done while at the same time an ADCP was used to measure flow and sediment concentration (via backscatter). Later, during the Jul.95 and Nov.95 bathymetric surveys float tracking was performed. In addition, a part of the survey area of Nov.95 was covered by ADCP measurements. The ADCP data have a number of advantages over the other methods of measuring the velocity and its direction: it can provide information or velocities and sediment concentration and also it can provide information about the flow direction and about secondary flow in channels. More ADCP data during the bathymetric surveys can provide information about all the interacting processes which are involved in changes in bed topography and planform development of the river.

Additional studies
As stated earlier a huge amount of various types data has been collected by the RSP. These data have the potential of providing more information about morphological processes in the Jamuna River than could be explored in the present study. Within the time frame and scope of this study, here only a part of the strong potential of the available data could be explored. More and more detailed analyses are possible with the available data, notably:

- flow and sediment distribution in the dry season by using ADCP data as measured in Nov 95.
- the distribution of sediment among chars/bars and channels by using the land survey data of Nov. 95.
- verification of the derived prediction method for bed-level changes using dry season bathymetric surveys, such as Nov 95 and Feb 95.
- more detailed analysis of overall planform development during the period 1993-1996 by using the bathymetric surveys and satellite images.

12.3 Measuring concentration of suspended bed material using ADCP backscatter intensity

A correlation between the ADCP backscatter intensity and suspended bed material concentration was developed in this study (see Annex 2). The relation was derived by correlating suspended sediment measurements with a pump bottle sampler. Although the relation deviates slightly from what can be expected theoretically (Weiergang, 1995), the verification of the relation by comparing it with the different sets of suspended bed material concentrations measured by pump bottle sampler showed encouraging results. Deviation of the obtained relation from the theory of Weirgang is mainly due to spatial and temporal variation of particle sizes of suspended sediments. During the analysis of the present study it appeared that the method is quite powerful in studying the spatial variation of suspended sediment distributions. It can provide the link between the flow and sediment transport processes in the river with the observed changes in planform. It is also powerful in identifying areas with overloading.

The present method of correlating the ADCP backscatter intensity with the suspended bed-material concentration has some limitations (more about this is presented in Annex 2). The ADCP that was used for surveying at the Bahadurabad location had a 300 kHz frequency. The present relation was obtained by using this frequency, which enables to separate the suspended bed material from the finer silt fraction. The present relation is only valid for an ADCP having 300 kHz. The ADCP backscatter intensity is very sensitive to the particle sizes which are in the Rayleigh's scatterer range. To apply this method to another location or in other rivers where the suspended sediment sizes differ considerably from the sediment sizes in the Jamuna River, it is required to derive another but similar type of relation between backscatter intensity and sediment concentration. Therefore, more study is required for generalizing the method for obtaining sediment concentration using backscatter. Also the effect of particle size and its variation in space and time on the backscatter should be studied in more detail.

12.4 Use of GIS

GIS has been developed to analyses spatial data. In this study the GIS was used for presenting the bathymetric surveys, for carrying out various analyses and for presenting the obtained results. The analyses performed by GIS are: preparation of overall and local balances for sediment distribution, manipulation of depth-averaged ADCP velocity data, interpolation and manipulation of velocities from float tracking, and manipulation of sediment concentration from ADCP backscatter intensity. In addition, GIS was used to observe the range of variation of spatial velocities from the predicted velocities estimated by using the Chézy's momentum equation (assuming a constant slope and roughness). Furthermore, to identify overloading of sediment, GIS was used for locating and quantifying areas with overloading. GIS was also used for comparison of the results of the prediction for bed-level changes with the measured ones. The variety of methods for analysing and presenting used here, provides an idea about the large potential of GIS for use in morphological studies.

In the present study, the use of GIS was introduced for the first time in a study of the bathymetry, flow and sediment transport data in a river. Methods had to be developed for the preparation of sediment balances. GIS was found to be quite powerful in doing this. It was found that when the wet volume of different bathymetric surveys under different levels are compared, it results in an inconsistent overall balance of sediment among the bathymetric surveys. This is rather due to the morphological processes than to the use of GIS (see Chapter 7). If however overall balances are made by considering the local balances for different reaches and branches, that are common in both surveys, a fair overall of sediment balance could be obtained. A disadvantage is that this type of balance does not included bars, chars, shallow and dry channels; only a balance can be made below the lowest water level of the two successive surveys considered.

In addition to the use of GIS in the present study, additional use of GIS can be envisaged especially for the migration of bank lines, quantifying volume of bank erosion, shifting of scour holes etc. Due to limitations in time and resources, this could not be explored in the present study. However, the GIS application in the present study showed that use of GIS can improve the processing, analysing and presenting of bathymetric surveys, spatial flow and sediment transport data for arriving at improved understanding of morphological processes in Bangladesh's main rivers.

12.5 Increased understanding of the morphological processes

General

The limitations of previous studies were discussed earlier when describing studies on the morphological processes of the Jamuna River that were performed earlier. In view of these limitation there was hardly scope for relating the changes of the various morphological features to observed flow and sedimentary process. The range of uncertainty of relations that were developed for the different parameters like bank erosion are quite high (see Chapter 3). The behaviour of the river often appeared to be chaotic. It was felt that more reliable and relevant data can help to develop improved understanding of the morphological processes of the Jamuna River, which might help in improving prediction methods.

On the basis of the understanding on the Jamuna River previously developed, the study present aimed at developing more insight into the various morphological processes by exploring the potential of the RSP bathymetric surveys and supplementary flow and sediment data. The bathymetric survey provide a fair estimate of the sediment redistribution involved in changes of the different morphological features like bank lines and scour holes. Using bathymetric survey data has an additional benefit that it is possible to quantify the significance of certain morphological processes in changing the overall planform. ADCP data provide an opportunity to have an impression of the flow processes in the river in two or even three dimensions. In addition, especially after obtaining a fair relation between ADCP backscatter and the suspended sediment concentration, it became possible to get an idea about the sediment transport processes in two dimensions as well.

It should be stressed here that this study has attempted to study a number of morphological processes in the river rather than study a simple process in much more detail (e.g. by using mathematical models to test emerging understanding). The advantage of such an approach is that it can provide a quick impression about the potentials of a new and reliable set of data (like the RSP surveys) to explore the river behaviour. However, such an approach limits the possibilities for more detailed investigations as there is always a time limit for a study. Therefore, the observation made and the results obtained here should not necessarily be considered as valid for the overall processes of the Jamuna River. Rather the results should be considered as indicative, showing the possibilities to improve the observations made here in future.

The improved understanding of the morphological processes of the Jamuna River, which we gained from the present study, are discussed in this section. In addition, the limitations of our studies are discussed as well.

Flow and sediment transport processes in the river in relation to erosional and depositional processes
To study the flow and sediment transport processes in the Jamuna River, ADCP flow and backscatter data measured in August 1993 are used. It was observed that the spatial distribution of depth-averaged velocity are often not in line with the bed topography (see Figures 3.16 , 7.7 and 7.9). It appeared from the float tracking during the Nov.95 bathymetric surveys (Figure 5.8) that in the low-flow season the deviation of the flow distribution from the bed topography is comparatively less than during the monsoon. Processing of the ADCP flow velocity measured during the Nov.95 bathymetric surveys would have been very relevant for comparing the differences in velocity distribution in the monsoon and in the low-flow season. Due to the rapid shifting of the flow direction in the monsoon, there are larger deviations of the flow distribution from the bed topography compared to the low-flow season. These deviations can be explained by three probable causes, such as: (1) the flow is far from uniform: the adaptation process of flow governed by the typical adaptation length of the flow defined by: $\lambda_w = C^2h/2g$ corresponding to adaptation lengths in the range of several km; due to the larger adaptation length in the monsoon the deviation is larger, resulting in a continuing process of adaptation; (2) due to the spatial variation of roughness and slope and (3) due to changes in momentum of the flow with the variation of the discharge. Combined with the highly mobile bed material, the bed topography attempts to adjust to the changing flow distributions, resulting in a rapid erosion and deposition on the riverbed. However, these rapid morphological processes again generate disturbances of the flow. This type of interactive adaptative processes probably continues throughout the whole monsoon period. Even during low-flow redistribution it is locally important.

It appeared that using the average value of Chézy's roughness coefficient as estimated by Klaassen et al. (1988) together with the average slope for estimating the average velocity, can only be done for simplified one-dimensional cases. Figure 7.8 shows that if the average value of roughness and the average slope are applied for estimating the spatial (2-D) depth-averaged velocity field, then the differences can often exceed 50 to 100% indicating, in addition to the effect of adaptation, possibly also the spatial variation of the roughness and the local slope.

It is observed that the spatial variation of the sediment concentration is quite high. For the same velocities, 200% to 300% of variation in sediment concentration is observed from the present analysis. The reason of such a variation may be due to the fact that the sediment transport in large sand-bed rivers is seriously affected by the three-dimensional process, as already indicated by Peters (1990). Convergence and divergence of flow due to spatial variation of the bed topography also have an influence on sediment transport pattern. From the present analysis it appeared that where the sediment concentration rapidly increased, the size of the bedforms at that location were prominent. The bedforms offer higher roughness to the flow and produce additional turbulence (boils) depending on the size and shape of the bedforms, and can thus contribute to high sediment transport rates. This indicates that the bedforms in large braided sand-bed rivers, like the Jamuna River, may have a substantial contribution via higher roughness and higher turbulence to the higher sediment transport rates compared with locations where the bedforms are less prominent. It apparently contradicts the observation of Klaassen et al. (1988) in the Jamuna River, and Lukanda et al. (1992) in the Zaire River. It should be mentioned here that the analysis of Klaassen et al (1988) was based on a one-dimensional case, for which their result is probably relevant. Another issue which needs clarification is the reason for the appearance of such bedforms, which are probably the cause of high sediment concentration at the upstream part of the bathymetric survey in August 1993 (see Figures 5.13 and 7.13). Similar flow conditions were prevailing also at other places, but there such high sediment concentration was not observed. Not in all cases where the bedforms are prominent, are the sediment concentrations high. There is a need for prediction methods for the appearance of bedforms, for their size and shape, and their contribution to roughness to the flow under two-dimensional conditions. For deriving such prediction methods, ADCP flow and sediment transport data can be very much helpful.

Overloading and underloading contributes to the processes of erosion and deposition on the riverbed (Peters, 1993). It also appeared that the prediction method of Van Rijn (1987) for the adaptation length of suspended sediment for overloading processes has a good agreement with the observed processes in the Jamuna River, although the parameters involved in prediction methods (like depth along a flow line, grain sizes of the suspended sediment) are highly variable in a natural river. This introduces also uncertainties in the estimation of the magnitude of the overloading.

The above observations of the flow and sediment transport processes in the river are based on analysing a few cases only. The overall processes may deviate from the present analysis. In this regard a 2-D mathematical model can help in improving the interpretation of the present observations.

Measured bathymetric surveys at one time are momentary realizations of the complicated process of interaction between flow and sediment that generates the riverbed topography. The erosion and deposition observed from the comparatively frequent surveys like series of Jun-Aug-Nov 93 and Feb-Jul-Nov 1995 surveys may not be a result of unidirectional processes of erosion and deposition. More frequent surveys in the monsoon can provide better answers. The river shows a high spatial variation of erosion and deposition within a short period; the magnitude of erosion and deposition in some places is more than 10 m (see Figure 5.14). It is observed from the present analysis that during the monsoon and over a few kms only more than 50% of the average sediment transport in the river does contribute to the erosional and depositional processes on the riverbed. The observed contribution of sediment transport in erosion and deposition has a significant implication for sediment transport measurements in these rivers. In addition to the uncertainties due to errors in the instruments and the followed methodology, this process can add differences in the measurement of up to 100% depending on the location of the sediment gauging.

During the above studies only the suspended bed material was considered for estimating the contribution of the sediment transport to the erosion and deposition process, which may result in an over-estimation of the contribution to the sediment transport. However, when the observed erosion and deposition processes are not the result of one sequence, but rather the result of more than one sequence of process (which is likely), then our observation underestimate the contribution of the average sediment transport to the erosion and deposition on the riverbed. Hence, for the time being our observation are considered as a fair estimate. It appeared from the present observation that the processes of the river are very dynamic; in fact much more than ever can be derived from satellite images taken during the low-flow season. The river may even be more dynamical than could be observed from the bathymetric surveys. To have an idea about the dynamics of the processes, more sequential and possibly even more frequently bathymetric surveys during the monsoon might be needed.

Cutoff processes in the Jamuna River

Only one cutoff development was observed from the bathymetric surveys at Bahadurabad location A. Cutoff in a braided river is different from a meandering river. In a meandering river cutoff develops through a floodplain and the most important criterion is that the shear stress on the floodplain exceeds the critical shear stress, so that a cutoff channel may form. In a braided river cutoff of a curved channel generally develops through a smaller channel or through a recently deposited sediment such as bar or char. Essential is that the sediment supply to this potential cutoff channel is less than the

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transport capacity (Klaassen and Van Zanten, 1989). Hence, the main criterion for the development of a cutoff in a braided river is related to the sediment distribution in the offtake as this governs the process. This depends on the deviation angle of the curved channel from the upstream (Mosselman et al, 1994).

It was observed during the present analysis that the deviation angle of the curved channel varied over a wide range in a short period: in one monsoon (March-June-August-November 1993) a variation from 50° to 90° and back was observed and similarly the location of the offtake moved considerably. It is interesting to see the variation of the sediment distribution at the offtake during the development of cutoff processes. According to the rough estimate the sediment distribution coefficient σ of the offtake varied with the observed deviation angle of the curved channel. Here the values of σ are 2.9 and 1.5 were estimated for deviation angles of about 90° and 50°, respectively. This supports the concept that the sediment distribution at the offtake depends on the deviation angle of the curved channels. It was observed that the criteria for cutoff development (Equation 8.3) of Klaassen and Van Zanten (1989) were fulfilled during the cutoff process.

From the satellite images it appeared that the maximum values of the cutoff ratio for the cutoff development as indicated by Klaassen and Masselink (1992) and for the deviation angle (Mosselman et al, 1993) were both reached in 1993. Probably the process was already initiated during the monsoon of 1992. From the satellite images of early 1992, the threshold values of both prediction methods for cutoff development were not yet reached. The changes due to upstream bank erosion during 1992-1993 changed the orientation of the offtake. This type of interlinked processes (bank erosion and a potential cutoff) adds uncertainties to predicting its behaviour.

In most cases, at the beginning of the development of cutoff channel, the channel first deepens and only later widens. In a meandering river this is generally the case as the channel develops the more cohesive floodplain soils. In a braided river this type of adjustment process was also observed by Chien (1961) in the Yellow river. From the present analysis it was found that the adjustment of depth and width in both cutoff and abandoned channel are almost simultaneous. The possible reason behind this behaviour is that during the development and abandonment of the channels, simultaneously lateral shifting of the channels occurred that contributed to the simultaneous adjustment of the depth and the width.

Bank erosion processes

The bank erosion processes along the outer bend of the curved channel were studied for two outflanking channels, one downstream of Bahadurabad (using RSP bathymetric surveys) and the other at Kamarjani slightly upstream of Bahadurabad (using FAP 21/22 bathymetric surveys). The study period was two and a half year downstream of Bahadurabad and a few months for Kamarjani. The maximum bank erosion rate of 800 m/year was observed downstream of Bahadurabad. From the satellite images it appeared that the maximum bank erosion rate at Kamarjani is about 200 to 250 m/year. The curvature of the bend and the width of both channels are almost same. This indicates that probably due to difference in erosion resistance once of the bank material, the magnitude of bank erosion rate can vary significantly. From the data presented by Klaassen and Masselink (1992) on the bank erosion rate along the curved channel in the Jamuna River, it appeared that the average rate is 200-300 m/year, although they observed a wide range of variation in bank erosion between 0 and 1000 m/year. This indicates that the uncertainties involved in predicting the bank erosion rate along an outer bend of a curved channel in the Jamuna River are quite high. One of the probable reasons is apparently the variation of bank material characteristics. Another probable reason is the very unstable nature of the

Jamuna river: as observed from the Jun.93 to Aug.93 surveys upstream planform changes shifted the bank erosion location about 2 km downstream. Similar differences in attack might also be the cause of a part of the variation of the bank erosion rates.

From the bank erosion history downstream of Bahadurabad it is observed that the life span of a highly erodible curved channel is fairly short, i.e. about 2 to 3 years. This supports the observation by Thorne et al (1993). The massive input of bank erosion products, in two cases during the period of Jun-Aug 93 and Aug-Nov 93 corresponding to about 50% of the average suspended bed material transport over the period considered, can change the planform of the downstream curved channel within a short period (see Chapter 9). It is also observed that the bank erosion along a quickly eroding river bend is not a simultaneous process along the whole outer bend. Rather, it appears as an intermittent process (see Figure 9.4). Figures 9.3 and 9.4 indicate that the bank erosion processes at such highly erodible bank are probably determined by the flow structure as well as by the changes of the planform possibly due to the bank erosion products. On the other hand, where the bank erosion rate is moderate such as Kamarjani, the bank erosion process is almost simultaneous along the whole outer bend (see Figure 9.5) and the possible life time of such an outer bend is also longer than of the river bend downstream of Bahadurabad.

Bank erosion may also occur at other locations than reaches with typical bank erosion like along the outer bank of a curved channel. The bank erosion at Bahadurabad Ghat is a typical example. Probably due to comparatively erosion-resistant bank materials or the delayed process of bank erosion, the bank line at Bahadurabad Ghat appeared like a protrusion to the flow, causing (due to flow convergence) very high flow velocities. High near-bank velocities can be observed from the float tracking during July 1995, see Figure 9.6. This type of high near-bank velocity is probably the cause of eroding the bank about 250 m within a short period (July-November 1995).

From the above discussion it can be concluded that bank erosion processes along the Jamuna River is quite complicated, especially at locations where the bank material is highly erodible. For predicting the bank erosion rate a method like Hickin and Nanson (1984) does not appear to be suitable. Because of the large variability of parameters like width, depth, curvature of the bend and bank erosion rate itself, the inherent level of uncertainty of such a predictive method is substantial. For the moderate case (like Kamarjani) the bank erosion rate can be estimated using the DHI (1996) method. Bank erosion rates probably do not have a linear relation to near-bank velocity (see Figure 9.9). Probably the bank erosion rate increases with some power of (excess) near-bank velocity. It should be noted that the parameter near-bank velocity as a basis for estimates of the bank erosion rate could only be determined with limited accuracy (see Chapter 9). Therefore, the present observation should be considered as based on a preliminary analysis only. Much more study in bank erosion processes is needed.

From the present study it appears that for predicting a bank erosion rate with a fair accuracy, knowledge about bank material characteristics is essential. In this respect it is surprising that the bank material of the Jamuna River, although not extremely diverse, yields such differences in erosion coefficient. Analysis via satellite images can be helpful for locating highly erodible bank material.

During the present study the sediment transport processes near eroding river banks could not be observed due to lack of data. A series of flow and sediment transport data of a highly erodible bank can provide a better understanding of rapid bank erosion processes and their effects.

Scour holes
The scour holes, which were observed in the RSP bathymetric surveys at the Bahadurabad location, were studied. In the bathymetric surveys, the development shifting and disappearing of the scour holes could be identified. It appeared that scour holes are extremely dynamic phenomena during the monsoon. The reason is that these scour holes are greatly influenced by changes in the upstream reaches, in particular planform changes which take place with changing stages. During the dry season, the changes are less. The shifting of scour holes is linked to major sediment re-distribution, which could be studied under the present analysis in particular owing to the application of GIS. In one case about 6 Mm^3 sediment was involved (scour hole A in Jun-Aug.93). This amount corresponds to about 25% of suspended bed material transport during that period, indicating the significant role scour holes may play in the planform development of the river.

It was observed that different types of scour holes react differently with the variation of the discharges. The variation of the planform also influences the variation of scour depth, area and volume in time. Therefore, no seasonal variation of the scour depth, scour area or scour volume was observed in the present analyses.

During the comparison of the observation with the different predictors for predicting maximum scour depth, it became clear that uncertainties in estimating the parameters involved are influencing the prediction substantially. Estimates have to be made of parameters like the average depth, average width and curvature of a curved channel, incidence angles for channels at confluence, etc. While applying the Struiksma (1988) method for estimating the scour depth in outer bends it was even more difficult to estimate the relevant parameters. The Struiksma method was developed for axisymmetric condition of flow in long circular bends and for a well-defined channel. In applying it to the Jamuna River very high scour depths were found more than three times of the observed depth. The major difference is due to the estimation of the width of the river bend. In the Jamuna River a very wide point bar is present during the monsoon. If the channel width is considered while excluding the submerged point bar, then the mentioned deviation would be less. The question remains as from which point it should be defined as "the" inner bank to be used for estimating the considerable width of a river bend. See also Shishikura (1996), who addressed this aspect more specifically.

Although a only few cases of confluence and protrusion scour could be studied, it appeared that the Klaassen and Vermeer (1988b) method for predicting confluence scour depth and the Simons and Sentürk method (1977) for predicting protrusion scour depth in the Jamuna River can be applied. The method of Simons and Sentürk was derived for predicting abutment scour, but as the flow impedance by an abutment and by a natural protrusion are almost similar, this prediction method is applicable here as well.

12.6 Prediction methods

One of the aims of this study was to derive improved prediction methods for predicting bed topography changes and changes in the planform of the river. Based on the Peters (1988) method derived for the Zaire River, a prediction method for the changes of the riverbed was derived and verified for the Jamuna River. Via a simple relation involving local water depth and local depth-averaged velocity, it is possible to predict with fair accuracy the location of erosion and deposition on the riverbed during the recession of a flood. The dividing lines used for differentiating zones of erosion and deposition were selected on the basis of first estimates (see Figure 11.1). By trial and error, the method can be improved by changing the slope of the lines or by slightly shifting the lines. In this respect, the use of GIS can be very helpful. In some areas, especially at the upstream part of the bathymetric surveys in Aug.93, this method is unable to predict the shifting of scour holes, see Figure 11.2. It is noticed from Figure 5.13 that this area was highly active with major sediment overloading and underloading. This supports the Peters (1988) observation in the Zaire River that this type of prediction method only yields good results when the sediment transport is not deviating too much from the sediment transport capacity. This also implies that, in addition to the water depth and depth-averaged velocity, inclusion of sediment transport process can improve the prediction method. On a routine basis, sediment concentration can be measured by ADCP. From the verification of the method, it is observed that the shorter the time over which the prediction is made the better prediction is. One of the limitation of this method in its present state is that only a qualitative changes of bed level can be estimated by this method, it is not possible to get a quantitative estimation from this method. It seems, however, possible to include in the method velocity gradients and this may enable more quantitative predictions.

By using a similar type of relation it is probably possible to predict the aggradation or degradation of different branches or anabranches of the river (Figure 11.6), although this type of prediction still needs formal verification, such a prediction method can help in improving the prediction method for the changes of planform. Especially for predicting the channel development or abandonment, the uncertainty inherent in prediction methods like Klaassen and Masselink (1992) and Mosselman (1994) are quite large (see Chapter 8). Applying the method as indicated in Figure 11.6 simultaneously with the above methods, it might be possible to predict the changes of planform with improved accuracy.

The evaluation of the previous prediction methods such as predicting methods for bank erosion, scour, etc., was already discussed above. From this study it appeared that by using accurate data like the RSP measurements, it is possible to increase the understanding of the processes of the river and, hence, in the near future the prediction methods for the planform changes can be improved. For medium- or long-term prediction methods the limitations imposed by the boundary conditions, as indicated by Klaassen et al. (1993) such as the water and sediment input in the system, will still be present. Uncertainties in boundary conditions, in combination with internal processes only marginally understood, limits the accuracy of the prediction methods. Moreover, the sensitivity of the system in that small changes upstream can be cause of enormous changes downstream, also limit the possibilities for accurate deterministic prediction. It demonstrates the partly chaotic behaviour of the system, and underlines the logic of accepting stochastic modelling (see Klaassen et al, 1993).

13 Conclusions and Recommendations

13.1 Conclusions

In the past, studies on the morphological behaviour of the Jamuna River were mainly performed by using the dry season satellite images and the BWDB standard cross-sections routinely measured also in the dry season. The maximum changes in channel bathymetry occur during the monsoon, and only their overall effect can be assessed using the low-flow data. Moreover, from the data available in the past it was not possible to link the occurrence of changes to the flow velocities and the sediment transport. In this study various analyses on the different aspects of the morphological processes are performed by using a comparatively reliable and all season data collected by the River Survey Project, which provides more insight into the morphological processes of the river.

From the analyses discussed before and observations made during the present study, the following conclusions can be drawn:

- *The Jamuna River is an extremely dynamic river.*
  The Jamuna River is an extremely dynamic river: it is much more dynamic than previously conceived. Changes in upstream reaches are able to cause enormous changes in the downstream river reaches. Moreover, from studying a series of bathymetric maps it follows that developments that have been observed from either satellite images or from standard cross-sections yearly measured by the Bangladesh Water Development Board (BWDB), are probably not "uni-directional"; rather these changes are the result of a sequence of events and changes, varying in time and with space.

- *During the flood: major changes*
  The Jamuna River is characterised by a flood season (June-September) and a low flow season (December-April). During all stages morphological changes take place, owing to the bed material consisting of fine sand. Morphological changes during the flood season are rapid. During this period (1) submerged channels and scour holes move laterally over distances of more than 1 km and they may change their direction, (2) large bars may be formed or move over several kilometres, (3) cutoffs take place and channels are abandoned, (4) major bank erosion occurs and (5) the location of bank erosion shifts over distances of several kilometres during one flood.

- *Several bathy maps are better than one low-flow satellite image for interpreting morphological processes*
  In the recent past morphological changes were interpreted on the basis of satellite images obtained during the low-flow season (see e.g. Klaassen & Masselink, 1992). In this study several bathymetric maps made in one flood season were available. These have shown that the overall morphological changes observed after one year may be the combination of several different developments throughout the flood season. Only several bathymetric maps made during the flood season with an interval of 1 or 2 months can explain the overall changes taking place.

- *Bathy maps and satellite images complementary*
  For an interpretation of changes taking place both chars and channels are important. Only if the total overall bed topography is considered in relation to the momentary stage (which chars

are flooded?), is a good interpretation of morphological changes possible (in accordance to Peters, 1993). Both bathymetric maps and satellite images have their specific advantages and disadvantages in this respect. Bathymetric maps do not show char levels unless supplementary land surveying is done. Present satellite imagery does not provide information on the submerged bed topography and makes it difficult to asses changes due to submerged features.

- *Use of ADCP backscatter intensity for measuring concentration of suspended bed material*
  A method was developed for correlating ADCP backscatter with suspended bed material concentration. Although the relationship deviates slightly from what can be expected theoretically (which can be explained from variations in particle size), the method is quite powerful in (1) studying spatial distributions of sediment concentration and (2) identifying areas with overloading.

- *Use of GIS for data presentation and study*
  In this study GIS was used for data presentation and for correlating spatial data on depth, velocity, sediment concentration and bed-level changes. In particular the latter application proved quite powerful in improving the understanding of morphological processes.

- *Several bathy maps per flood yield substantially improved understanding*
  Owing to the detailed study of the repeated bathymetric soundings at Bahadurabad increased insight into the following morphological processes was obtained: erosion and deposition (Chapter 7), occurrence of cutoffs (Chapter 8), bank erosion and its prediction (Chapter 9), and types of scour holes and their dimensions (Chapter 10).

- *Deposition and subsequent erosion of sediments very important*
  In this wide, braided and untrained sand-bed river, deposition and erosion of sediment takes place on a major scale. During successive soundings up to 50% of the total bed material sediment transported in that period may deposit or may be eroded in reaches with a length of a few kilometres only.

- *Prediction method for short-term morphological changes of bed topography*
  A prediction method was developed for predicting morphological changes during the recession of a flood. This method, which is based on a method developed by Peters (1988) for the Zaire River, essentially consist of measuring simultaneously depth and velocity and, via correlating these data, identifying areas prone to deposition or erosion. Other additionally collected data, like areas of overloading via ADCP and slope measurements, probably can be used to make better predictions.

- *Future planform changes difficult to predict*
  By hindcasting the planform development near Bahadurabad over the period 1992-1995 it became clear that planform developments are caused by a chain of (upstream and local) events and phenomena, that are not easily identifiable on low-flow satellite imagery. Hence there is more scope for the stochastic type of planform prediction as proposed by Klaassen et al (1993) than for deterministic modelling of planform changes.

13.2 Recommendations

On the basis of this study and the conclusions listed in the previous section, the following recommendations can be made for improving the understanding of the morphological processes in the Jamuna River:

- *More frequent bathymetric sounding campaigns in combination with satellite imagery.* It appeared that the changes in the river observed from the bathymetric surveys may not be a sequence of changes. To link the changes to flow and sedimentary parameters, it is essential to identify the sequence of changes. For this purpose more frequent bathymetric surveys are needed. Preferably also flow and sediment transport data should be collected (e.g. via using an ADCP). To get an impression of the changes that take place above the water level, satellite images are necessary.

- *GIS as standard tool for presentation and study of spatial data* For further analysis of the bathymetry and ADCP data, continued use of GIS can improve the processing and analyzing of the data and presentation of the results. GIS can offer a quick analysis of spatial data and it is better able to visualize the result than any other means.

- *Further studies on relation between backscatter intensity and sediment concentration.* The correlation method to link the backscatter and the suspended bed material as developed here is only valid for the Jamuna River and especially around the Bahadurabad location, as the variation of grain sizes (which is not included in the present method) is important. Further studies are needed to generalise the relation between the backscatter intensity and the sediment concentration for different grain sizes and their distribution, and for different frequencies of ADCP as well.

- *More studies on sediment re-distribution process.* This study is one of the first which deals with the sediment re-distribution processes. There are some limitations due to the methodology used in this study in particular in relation to the re-distribution processes between bars and channels. Further elaboration and use of the November 1995 land survey might assist in getting a better understanding of these processes.

- *Improved understanding of morphological phenomena required.* In a number of cases the present study is unable to provide more insight into some of the observed processes, like the reasons for overloading of sediment, the adaptation processes of flow and riverbed, sediment transport processes near eroding bank etc. Moreover, this study only provides indicative results. As it is felt that the understanding of the morphological phenomena is still limited, it is essential to improve the understanding by doing different studies.

- *Use of mathematical models for improved interpretation.* A 2-D mathematical model for flow, sediment transport and morphology can help in interpreting the present observations and thus can improve the understanding of the morphological processes in the Jamuna river.

- *Improvement of prediction method.* Probably the prediction method developed for the bed-level changes during the recession of the flood can be improved by combining it with measurements of the sediment transport and probably the local slope. In addition, similar prediction methods should be developed for the other locations and other rivers as well.

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Annexes

Annex 1

Classification of the river patterns

There are number of methods available in the literature about the prediction of river patterns. Different channel pattern classification are discussed here to understand the causes of braiding of a river. Leopold and Wolman (1957) classified the channel pattern on the basis of the channel slope and the bankfull discharge (see Figure 1) in which the demarcation line between the braided and meandering reads as:

$$i = 0.0125\ Q^{-0.44} \tag{1}$$

where i = channel slope (-) and Q = bankfull discharge (m^3/s). If the actual channel slope is higher than i for given Q, the river will be braided, whereas a lesser slope will lead to a meandering river. Similar types of empirical classification were derived by a number of Authors (Lane, 1957; Bray, 1982 etc.). Later comparison with the data from natural rivers are not satisfactory (Bettess and White, 1983).

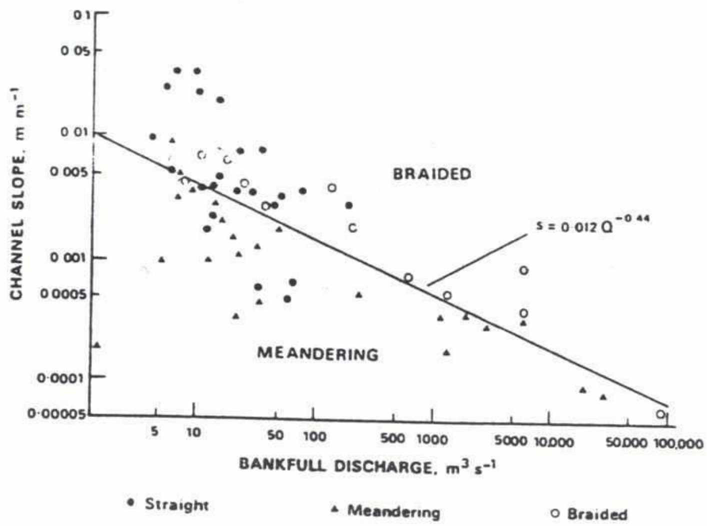


Figure 1 Channel classification diagram (Leopold and Wolman, 1957)

Even for the Jamuna River Equation 1 yields a slope of $1.01*10^{-4}$, which is higher than the actual slope of the river, indicating a meandering planform instead of a braided one. Ferguson (1984) proposes to include the bed material size of the alluvial channels as additional parameter and his relation reads:

$$i = 0.042\ Q^{-0.49}\ D_{50}^{0.09} \tag{2}$$

where D = bed material size in mm. Struiksma and Klaassen (1988) found that Ferguson classification is compatible to their classification method based on linear stability analysis.

Chang (1988) introduced the bed material sizes, the bed material transport and discharge to determine the slope based on extremal hypothesis (Chang, 1976), and related the channel slope to the valley slope to classify the river planform. The channel slopes expressed as:

$$\frac{i}{\sqrt{D}} = 0.28 * \frac{Q_s^{0.58}}{Q^{0.75}} \qquad for\ 0.000704 * Q^{-0.55} \geq \frac{i}{\sqrt{D}} \tag{3}$$

$$\frac{i}{\sqrt{D}} = 2.28 * \left(\frac{Q_s}{Q}\right)^{0.87} \qquad for\ 0.00763 * Q^{-0.51} \leq \frac{i}{\sqrt{D}} \tag{4}$$

where i = channel slope, Q = discharge (m^3/s), Q_s = bed material discharge (m^3/s) and D = bed material size (mm). The slope estimation was based on the minimum power expenditure per unit channel length, i. e. minimum γQi, where γ is the unit weight of the water-sediment mixture. If the channel slope estimated from Equation 3 or 4, is higher than the valley slope, the river needs to lose its power by braiding but if the channel slope is less than the valley slope, the river will meander to achieve its required slope. This criteria depends on the slope estimated by the minimum stream power (extremal hypothesis) and also the valley slope. According to the criteria, for a given Q, Q_s and D the braiding or meandering only depends on the valley slope and in that case meandering is likely for a higher valley slope. However, the criteria is not validated with the field data, the applicability remains questionable.

Recent work on the classification of channel pattern was performed on the basis of linear stability analysis such as Fredsoe (1978), Blondeaux and Seminara (1983) and Struiksma and Klaassen (1988).

Based on the work of Struiksma et al (1985) regarding bed topography analysis, Struiksma and Klaassen (1988) arrived at a predictive discrimination method between meandering and braiding. During the bed topography analysis, in axisymmetric condition, Struiksma et al (1985) considered a non-uniform but steady perturbation and bed load transport. The linear perturbation analysis showed that the damping length L_D and wave length L_p are related to the ratio of λ_S/λ_W, where λ_S is the adaptation length of the bed topography and λ_W is the adaptation length of the flow. These terms are expressed as:

$$\lambda_S = \frac{1}{\pi^2}\left(\frac{B}{h}\right)^2 f(\theta)\, h \tag{5}$$

$$\lambda_W = \frac{C^2}{2g} h \tag{6}$$

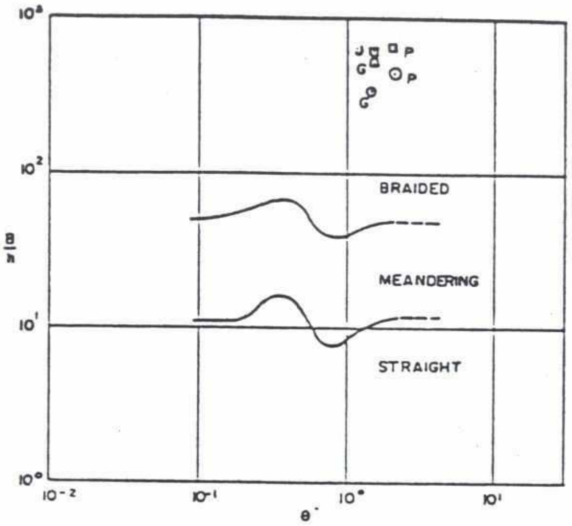
Thus

$$\frac{\lambda_S}{\lambda_W} = \frac{2}{\pi^2} * \frac{g}{C^2} * \left(\frac{B}{h}\right)^2 * f(\theta) \tag{7}$$

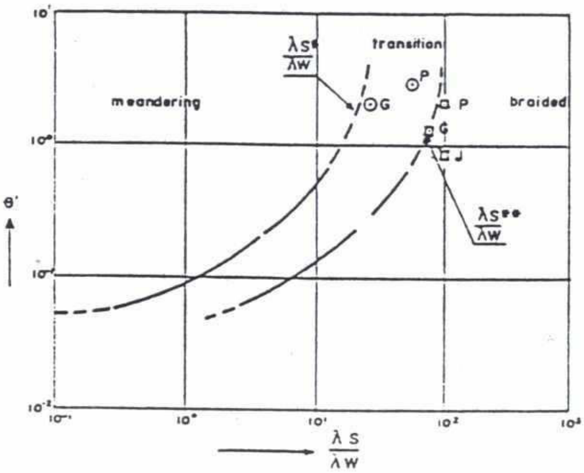
where B = channel width, h = channel depth, C = Chézy's coefficient, g = acceleration of gravity and an improved expression of $f(\theta)$ reads:

$$f(\theta) = 0.85\,\theta^{0.5} \tag{8}$$

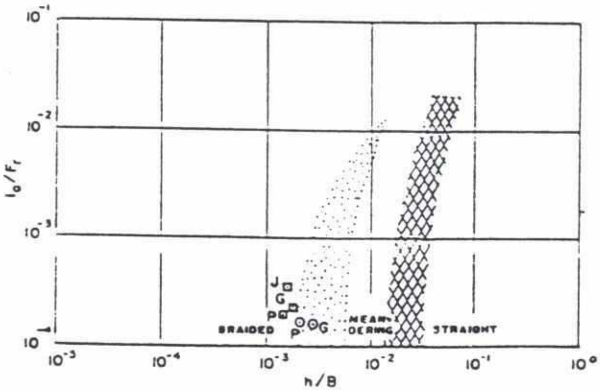
where θ = Shields parameter defined as θ = hi/ΔD, i = slope, D = grain size and Δ = relative density of sediment.



a. Fredsoe (1979)



b. Struiksma and Klaassen (1988)



c. Blondeaus (1993)

LEGEND:

- □ Braided stretches of river
- ⊙ Constricted stretches of river
- J Jamuna river.
- P Padma river.
- G Ganges river

Figure 2 Channel classification diagrams based on stability analysis and the position of the different stretches of the Jamuna, Ganges and Padma rivers in Bangladesh

Generally, the perturbations are damped in downstream direction for $\lambda_W/L_D > 0$. If $\lambda_W/L_D < 0$, the perturbations will grow in downstream direction generating instabilities in the riverbed and braiding is likely in that case. This is the basis of classification and the diagram is shown in Figure 9. The diagram is based on θ' and λ_S/λ_W, in which θ' is defined as:

$$\theta' = \frac{u^2}{C_{90}^{\ 2} * \Delta * D} \qquad \textbf{(9)}$$

where $C_{90} = 18 \log (12h/D_{90})$. The term λ_S/λ_W is also influenced by width-depth ratio (Equation 6).

The channel pattern classification diagrams based on linear stability analysis of Fredsoe (1978) and Blondeaux and Seminara (1983) are also presented in Figure 2. These two prediction methods were also based on linear stability analysis and considering the bedload transport. All the parameters used in the classification diagrams are defined earlier, except the Froude number, $F_r = u/(gh)^{1/2}$. In all the classification diagrams (Figure 2) the width-depth ratio is common. This ratio has the dominant influence on the type of river pattern and on the stability limits (Diplas et al, 1988). The other parameter shield stress (θ) plays an important role in predicting the channel pattern. Figure 2, here presented from (RSP, SPR-7, 1995) where these three classifications were examined and found in good agreement with Struiksma and Klaassen (1988) and Blondeaux and Seminara (1983) for the Jamuna River and different stretches of the Ganges, Padma rivers.

From the above, it can be seen that braiding is likely for higher slope, discharge, grain size, width-depth ratio and, sediment transport. However, width-depth ratio is interdependent on sediment size, slope, sediment transport and on the characteristics of the bank material.

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Annex 2

Estimation of suspended sediment concentration from ADCP backscatter

1 Introduction

The River Survey Project (RSP) performed many bathymetric surveys at different locations in the major rivers. A difference plot of two consecutive bathymetric surveys from same river reach provides information on the morphological changes in the period in-between. During two of these surveys Acoustic Doppler Current Profiler (ADCP) discharge and corresponding backscatter measurements were made for a number of channel sections at Bahadurabad in the Jamuna river. This creates an opportunity for linking the morphological changes of the river in this reach to the flow and sediment transport data using this ADCP discharge and backscatter data. This can only be done if a relation exists between the backscatter data and the sediment concentration. Therefore, an attempt was made to calibrate the ADCP backscatter data using sediment data simultaneously.

The theoretical basis underlying the method of estimating sediment concentration by ADCP backscatter is still in the developing phase. A number of researchers (Jansen 1977; Thorne et al, 1991 and 1994; Christopher, 1990; Weiergang, 1995) are working on this subject. They have attempted to relate the backscatter signal to the concentration of sediment for different sizes of particles and in different environments. Based on the work of these researchers, an attempt is made here to relate the backscatter signal to the sediment concentration measured in the Jamuna river at the Bahadurabad location.

The principle of backscattering is presented briefly in Chapter 2, followed by a description of the survey method using ADCP as employed in RSP (Chapter 3). The data used (Chapter 4), data analysis and results (Chapter 5), validation (Chapter 7), discussions (Chapter 8) and conclusions (Chapter 7) are presented below.

2 Principle of ADCP backscatter for measuring sediment concentration

Acoustic Doppler Current Profiler (ADCP) is designed for measuring currents by the Doppler shift of a sound wave which is transmitted and received again after reflection from scatterers in water. In water scatterers are generally the sediment particles. The number of sound echoes returning to the receiver is a function of the amount of scatterers in water, i.e. the sediment concentration. This is the basic principle of estimating the sediment concentration by ADCP backscatter. The key features of the backscattering of sound wave for estimating the sediment concentration are discussed below.

The sound wave emitted from the transmitting device spreads with distances and some of it is absorbed by water. The amplitude of acoustic backscattered signal P_b from a single particle can be written as (Thorne et al, 1991):

$$P_b = \left(\frac{k_1}{r^2}\right) * e^{-2r\alpha_w} \quad (1)$$

where k_1 is a constant, r is the distance of particle from the ADCP and α_w is the attenuation coefficient of the acoustic beam due to absorption by water. The attenuation coefficient is a parameter that can be computed from via (Fisher and Simons, 1977):

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$$\alpha_w = (55.9-2.37*T+4.77*10^{-2}T^2-3.84*10^{-4}T^3)*10^{-3}f^2 \tag{2}$$

where f is acoustic sound wave frequency in mHz and T is water temperature in degrees Celcius. The attenuation coefficient α_w increases with the square of sound wave frequency.

For a number of particles the value of the backscatter intensity P_b can be estimated from the following equation (Thorne et al, 1990):

$$\langle P_b \rangle = k_o([\tau c C(r)]^{1/2}/r)e^{-2r(\alpha_w+\alpha_s)} \tag{3}$$

where C(r) is the sediment particle concentration at a distance r from transducer, τ is pulse length, c is speed of sound in water, k_o is a constant and α_s is an attenuation coefficient and α_s= f[r, C(r), a_s], where a_s is the equivalent sphere radius of the sediment particles.

Hence, the backscatter signal is a function of the square root of the sediment concentration, pulse length and the exponent of the attenuation coefficient. The P_b value is very much sensitive to the exponent α_s for high concentration of sediments. The value of α_s depends on the sediment sizes: finer particles reduce α_s.

The above Equation (3) is valid when $ka_s \geq 1$, in which a_s is sediment particle radius and k the acoustic wave number which can be expressed as $k=2\pi/\lambda$, where λ is the wavelength. The term $ka_s=2\pi a_s/\lambda$ expresses the ratio of circumference of sediment particle to the wavelength. For $ka_s<1$ the particles are 'Rayleigh scatterers' (Rayleigh, 1945). Within the Rayleigh's range sound wave scattering cross-section exhibit a linear relationship with the product of $k^4a_s^6$. An upper limit of the validity of Rayleigh scattering law as suggested by Utrick (1983) is $ka_s=0.5$.

Weiergang (1995) derived a relation between backscatter signal with the sediment concentration of sediment particles within Rayleigh scattering range. In his relation the backscattering signal strength is expressed in decibels (dB) and it is considered that the attenuation due to absorption is adjusted in the built-in soft-ware of ADCP. The Weiergang relation is written as:

$$dB=10*\log\left[(3/4)k^4\Sigma_{i=1}^{i=m}C_i\alpha(a_s)_i^3\right] \tag{4}$$

where C_i is the partial concentration of size class i having class median diameter $(a_s)_i$ and α is a material parameter. This α is expressed (Greenlaw, 1979) as:

$$\alpha = 4\left(\frac{1-mn^2}{3\ln^2} + \frac{1-m}{1+2m}\right)^2 \tag{5}$$

where m is the ratio of the density of the scattering particle to that of the surrounding medium and n is the ratio of the speed of sound in the particle to the one in the surrounding medium.

For 300 kHz frequency of ADCP (used in RSP) the upper limit diameter of sediment particles of 'Rayleigh scatterer' range as suggested by Urik (1983) is 800 μm. In the Jamuna river suspended sediment sizes range from 1 μm to 500 μm (see Figure 1), i.e. all the particles are in the Rayleigh scatter range. Considering the size of the sediment of the Jamuna river, the ADCP frequency and the backscattering value (dB) expressed in the built-in software used in RSP, Equation 4 is relevant.

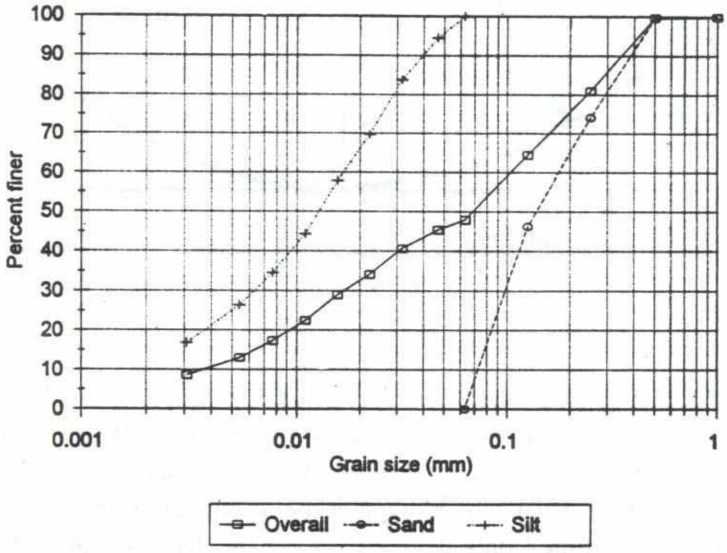

Figure 1 Average grain-size distribution of suspended sediment based on the analysis of 12 number of (25 liter) samples collected on 12 and 13th August, 1994 in the Jamuna river at Bahadurabad

3 Method of survey using ADCP by the RSP

During the survey the ADCP is mounted on board of a survey vessel close to the water surface. Four beams of monochromatic sound pulses are emitted through the water column. The beams are oriented in a so-called Janus configuration, i.e. each with a downward orientation of 20 degrees from the vertical. The projections of the four beams on the horizontal plane are oriented at 90 degrees interval. At any depth the speed of water can be determined by measuring the doppler shift of sound wave along the beam axis. The combination of four beams yields the three spatial velocity components.

There are two ADCPs mounted on two vessels of the River Survey Project. One ADCP having 300 kHz sound frequency and the other 600 kHz. The selection of the ADCP frequency by the RSP is mainly based on the capability of measuring velocity in deeper water. During the discharge measurement in a river the survey vessel sails from one bank to the other bank, the data from the ADCP is stored at certain time interval and the corresponding position (from DGPS) is added by the built-in software of the on-board computer. Later off-line processing is needed. During the processing of the ADCP, backscatter value in decibels (dB) is recorded with the 0.50 m interval in vertical direction. The minimum depth of water, in which the RSP of 300 kHz can measure, is 2.66 m due to the ADCP position in the vessel and the ADCP clearance distance, see Figure 2. An ADCP is also not able to measure the last 6% of the water depth from the riverbed, because of its orientation. The latter is a serious drawback in view of the shape of sediment concentration profiles (see also Chapter 7).

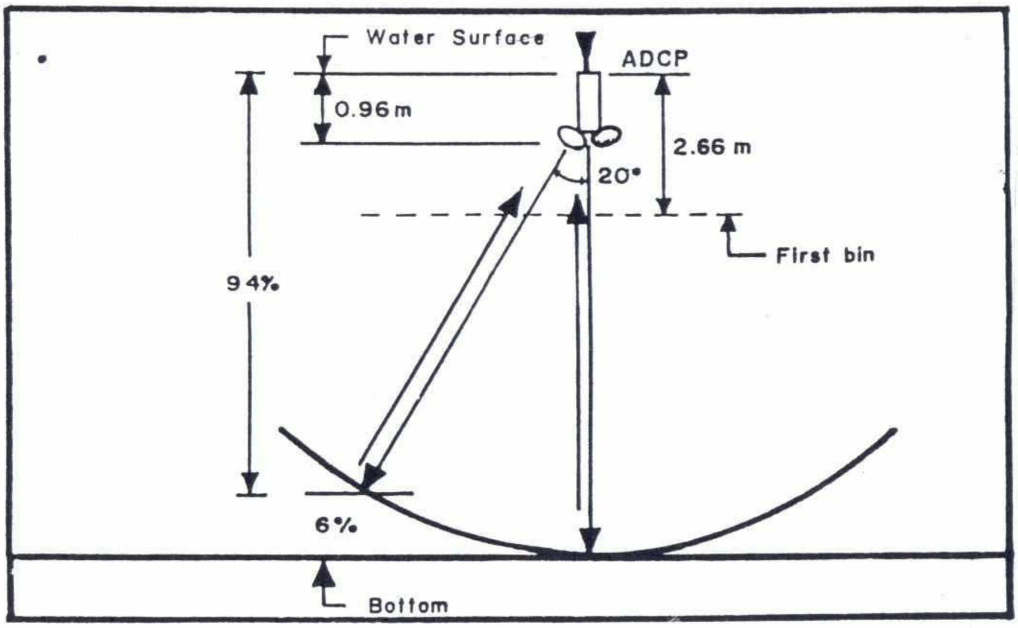

Figure 2 The configuration of ADCP mounted on RSP survey vessel

In almost all cases an ADCP of 300 kHz is used during sediment gauging at Bahadurabad. In the ADCP built-in software used by the RSP, the backscatter value is expressed in dB and attenuation of sound wave due to absorption by water is adjusted for water with a temperature of 4 °C. Due to the low frequency (300 kHz) the absorption coefficient α_w (equation 2) is not very sensitive to the temperature. The Backscatter value (P_b) in equation 3 only deviates 2% for the depth variation 5m to 10m, if the prevailing temperature of water in the Jamuna river (25 °C) would be taken into account. If the small influence of the temperature is neglected, then it can be considered that the ADCP backscatter value (dB) is directly reflecting the backscattering strength from the sediment particles.

Different methods of measuring suspended sediment concentration have been applied by the RSP, such as point-integrated sampling, depth-integrated sampling. Point-integrated sampling by pump-bottle sampler are considered the most accurate. During the point-integrated sediment sampling ADCP backscatter signal values were also recorded for different depths. A number of data of point-integrated pump-bottle sampling are available at the location of Bahadurabad for calibrating the backscatter signal value to the suspended sediment concentration.

4 Data used

To calibrate the ADCP backscatter value with the sediment concentration, sediment gauging at Bahadurabad is used only. This limiting approach was accepted because Bahadurabad is the study location where the calibrated backscatter data will be used. The expectation is that for the same location grain sizes and gradation of sediment particles will be similar and hence a fair correlation between sediment concentration and backscatter values is likely possible. At other locations, due to variation of grain sizes, the relation between the suspended sediment concentration and backscatter may be different.

The result of the sediment concentration for 1993 sediment gauging by the RSP is expressed in total concentration only, i.e. the sand and silt concentration were not analysed separately. During the sediment gauging in 1994, the concentration for sand and silt fraction is separately determined. To get an impression of the influence of silt and sand particles on backscatter value (dB), the suspended sediment gauging data of 1994 are used. For the calibration of the backscatter, data is used where simultaneously sediment concentration measured by pump bottle at different depth and backscatter values were recorded. The data used is shown in Table 1. The dB value is linearly interpolated to obtain the sediment concentration of same depth. Moreover, to see the variation of grain sizes of suspended sediment related to depth, 12 suspended samples collected in August 1994, are also used. For these samples grain sizes were analysed.

Channel	Date of Survey	Vertical	Depth of Vertical (m)	Sample depth (m)	Interpolated Backscatter (dB)	Sand fraction Concetration (mg/l)	Wash load Concetration (mg/l)	Total Concetration (mg/l)
Left	15/7/94	6	12.60	2.80	77.98	194	363	557
			12.60	5.70	82.42	228	380	608
			12.60	8.50	86.66	274	419	693
			12.60	11.40	90.32	522	376	608
Right	14/7/94	2	7.56	1.70	74.03	27	373	400
			7.56	3.40	74.52	77	450	527
			7.56	5.10	78.54	249	501	750
			7.56	6.80	82.64	425	542	967
Right	9/8/94	7	10.25	4.00	69.47	6	307	314
			10.25	6.10	70.82	17	353	370
			10.25	8.10	73.94	31	350	381
Left	6/8/94	8	14.30	2.80	71.70	36	342	378
			14.30	5.70	74.67	87	337	424
			14.30	8.60	79.31	112	367	479
			14.30	11.40	84.60	121	395	516
Left	24/6/94	3	10.00	4.30	80.68	325	604	929
			10.00	6.40	85.11	509	623	1132
			10.00	8.60	89.01	825	660	1485
Right	25/6/94	2	7.41	3.00	78.06	181	517	699
			7.41	4.50	80.49	216	564	780
Left	3/9/94	10	15.42	3.10	69.15	11	310	321
			15.42	6.20	69.85	30	331	361
			15.42	9.30	73.25	60	372	432
			15.42	12.40	77.66	106	423	529
Left	23/9/94	7	14.20	2.80	76.83	139	333	472
			14.20	5.70	79.98	274	342	615
			14.20	8.50	83.71	321	345	666
			14.20	11.40	88.00	554	380	934
Right	25/9/94	1	8.22	3.28	71.90	113	331	444
			8.22	4.92	73.85	124	339	463
			8.22	6.56	76.19	149	355	504
Right	27/9/94	5	6.82	3.10	71.36	59	329	388
Left	19/10/94	6	15.00	2.80	77.69	166	330	496
			15.00	5.60	80.67	307	366	673
			15.00	8.40	84.40	343	381	724
			15.00	11.20	88.90	509	400	909
Right	22/10/94	3	4.85	2.94	76.46	283	376	659
			4.85	3.92	81.99	332	341	673
			4.85	4.10	83.83	531	363	894
Left	8/11/94	3	12.65	4.80	76.97	93	175	268
			12.65	7.20	80.33	101	218	319
			12.65	9.60	84.87	119	218	337
Right	26/11/94	2	10.78	4.30	66.50	8	158	166
			10.78	6.50	69.49	10	153	163
			10.78	8.60	71.88	23	163	186
Left	27/11/94	3	11.10	4.40	74.00	46	156	202
			11.10	6.60	76.77	75	174	249
			11.10	8.80	80.09	68	171	239
Left	8/12/94	3	5.70	3.40	74.87	60	181	241
			5.70	4.60	76.90	130	185	315
		4	7.70	3.10	69.26	24	132	156
			7.70	4.60	70.57	31	141	172
			7.70	6.20	72.61	39	137	176
		5	6.90	2.80	66.68	8	113	121
			6.90	4.10	67.05	6	112	118
			6.90	5.50	68.74	9	129	138
Left	17/8/94	1	10.00	6.00	77.00	124	480	604
			10.00	8.00	81.50	173	484	657
		2	6.60	3.92	83.75	478	500	978
			6.60	5.30	87.00	610	472	1082
		3	7.00	4.20	83.55	554	504	1058
			7.00	5.60	86.24	735	535	1270
		4	7.60	4.56	85.40	534	549	1083
			7.60	6.08	87.30	758	555	1313
		5	4.30	2.58	80.10	412	661	1073
			4.30	3.44	82.38	443	650	1093
		6	5.00	3.00	73.50	135	739	874
			5.00	4.00	75.30	202	826	1028
		7	7.00	5.60	77.00	371	1250	1621
Left	18/8/94	1	6.30	3.78	76.85	186	520	706
			6.30	5.40	81.20	207	421	628
		2	5.60	3.36	82.20	296	461	757
			5.60	4.48	84.80	548	492	1040
		3	6.20	3.72	81.15	150	495	645
			6.20	4.96	84.50	418	511	929

Table 1 Data used to calibrate the backscatter value (dB) with the suspended sediment concentration, measured in the Left and Right channel of the Jamuna river at Bahadurabad

5 Data analysis and results

To calibrate the backscatter intensity, two types of analysis were performed. One is based on the theoretical approach expressed in Equation (4) and the other is an empirical relation. Both relations are compared and evaluated on the basis of their correlation and their consistencies in predicting the concentration.

During the analysis of the data it is assumed that the contribution of the attenuation coefficient (α_s) is negligible. The basis of this assumption is that al though the concentration of sediment in the Jamuna river is high, the contribution of the particles in impeding the sound wave through the column of water is negligible as the particles are in 'Rayleigh scatterer' range. The size of particles $(a_s)_i$ of different fraction of concentration (C_i) of suspended sediment are not analysed. Therefore, in applying Equation (4), a single size is assumed for the concentration of sediment.

The backscatter value (dB) is related to the logarithm of the sediment concentration (10*logC) of the same depth. The backscatter value is related both to the total sediment concentration and to the concentration of sand fraction. Both relations were evaluated on the basis of their correlation. The relation between backscatter (dB) and the logarithm of the total sediment concentration is shown in Figure 3. The data are showing two distinct separate relations. To study this further, the data were marked according to the concentration of silt fraction and also the period of measurement (Figure 4). This figure indicates that data measured in November and December when the silt concentration is within the range of 100 to 200 mg/l are showing a different relation than the data measured in the early and late monsoon having higher silt concentration. The relation between the backscatter (dB) and concentration of sand fraction (see Figure 5) is less scattered and does not show any difference in respect to their period of measurement. A linear relation between backscatter value (dB) and 10*log(C) is found having a correlation coefficient (R^2) of 0.80, indicating a fair correlation between the backscatter value (dB) and suspended sand fraction concentration. The relation between backscatter and concentration of sand fractions can be expressed as:

$$dB = 58.2 + 0.96 * 10Log(C) \qquad (6)$$

where C is the sand concentration. According to Equation 4 the slope of the regression is 1, where in Equation 6, the slope is 0.96 near to 1, which shows a good agreement between the regression equation and the theoretical equation. It seems, however, that in spite of a linear relation between dB and 10*log(C), that the data in Figure 5 rather suggest a curvilinear theoretical relationship.

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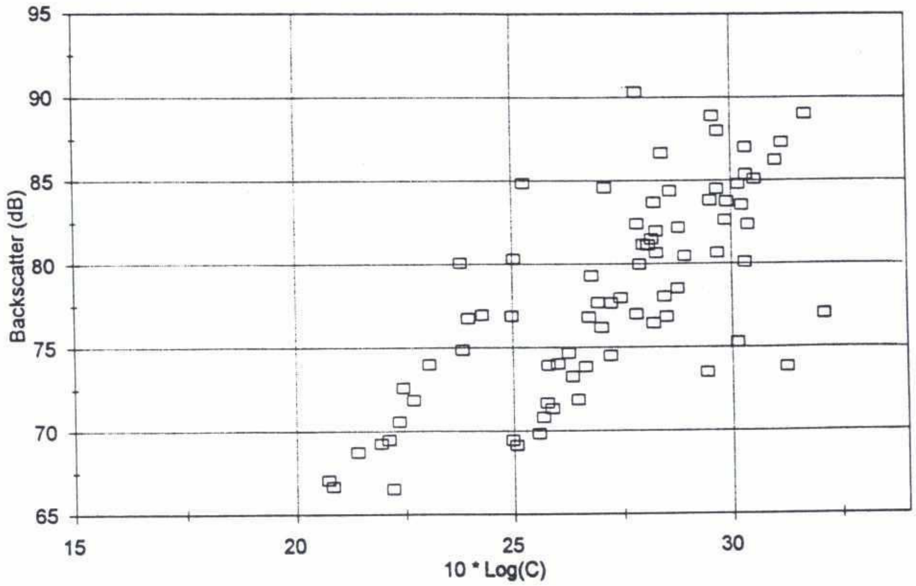
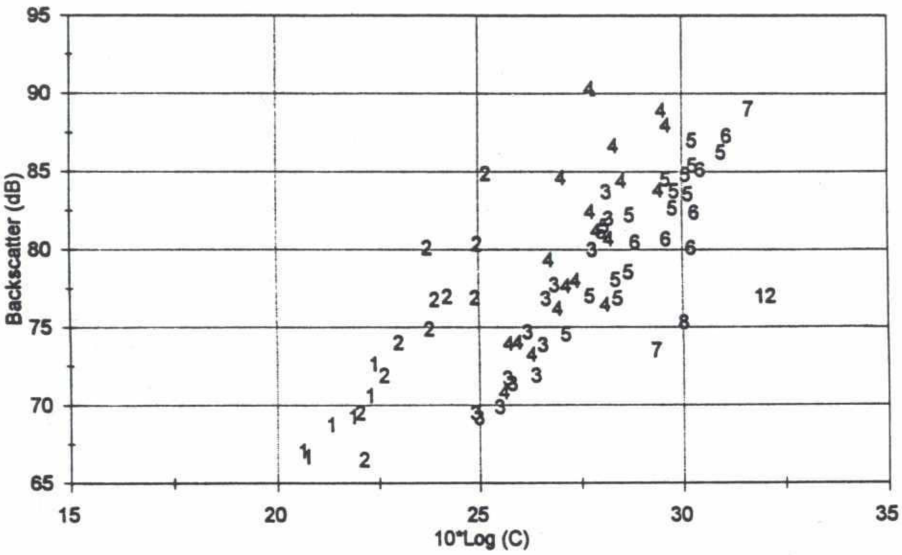
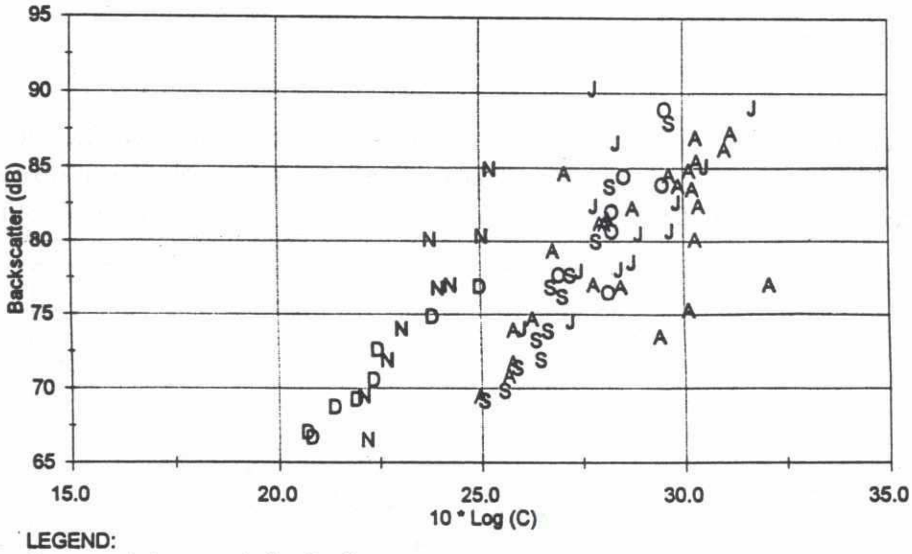


Figure 3: Relation between total suspended sediment concentration and backscatter value dB



LEGEND:
C represents for concentration (mg/l)
Number indicates the concentration of silt (100 mg/l) in the sample



LEGEND:
C represents for concentration (mg/l)
Letter indicates the month of gauging.
For example, J represents for the month of June and July

Figure 4: Relation between total suspended sediment concentration and backscatter with indication of the concentration of silt and the period of measurement of the samples

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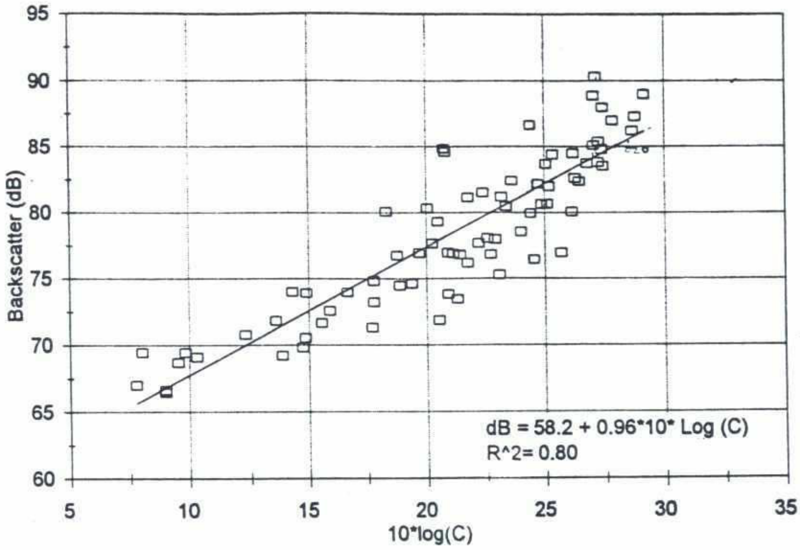

Figure 5: Relation between the suspended sediment (sand fraction) concentration (10*logC) and the backscatter value dB

To determine an empirical relation better fitting this "curved" relation the backscatter values in (dB) are plotted versus the square root of the concentration of sand particles, (see Figure 6). The regression equation can be expressed as:

$$dB = 68 + 0.77 * (C)^{0.5} \quad (7)$$

The correlation coefficient (R^2) is 0.79, approximately the correlation coefficient from Equation 6. Equation (7) shows zero concentration of sand fraction sediment particles at dB value 68, which is not correct. For dB value near the value of 68, Equation (7) yield inconsistent estimates of the sand concentration.

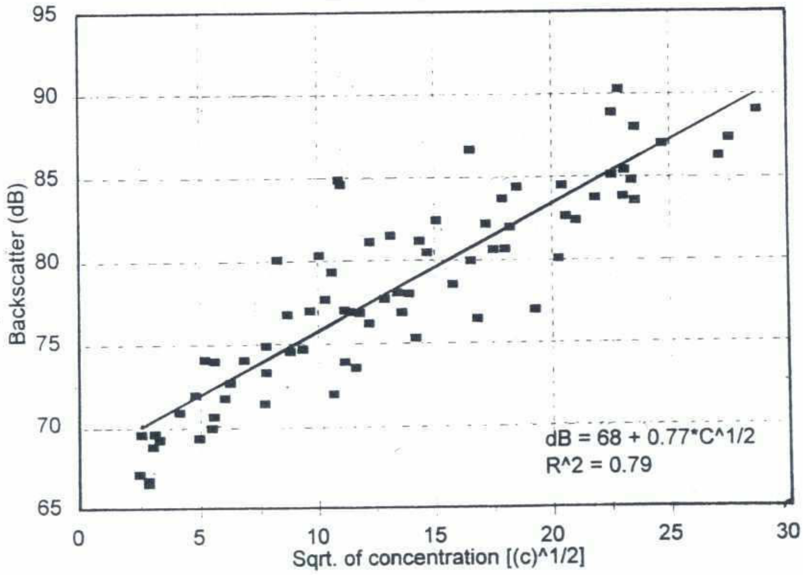

Figure 6: Relation between the square root of suspended sediment (sand fraction) concentration and the backscatter value dB

Both relations (Equations (6) and (7)) are showing fair correlation and are evaluated by comparing the measured sediment concentration with the predicted concentration, see Figure 7. During the comparison the same data set as used for deriving the relations is used. The comparison between the measured sand concentration and the predicted concentration-based Equation (6) (see Figure 7a) shows a good agreement up to a certain range of concentration. For higher concentration, say above 600 mg/l, Equation (6) predicts significantly higher concentration of sediment than the measured one. According to the equation 600 mg/l corresponds to a dB value 85. The probable reason for this deviation is discussed in the next chapter.

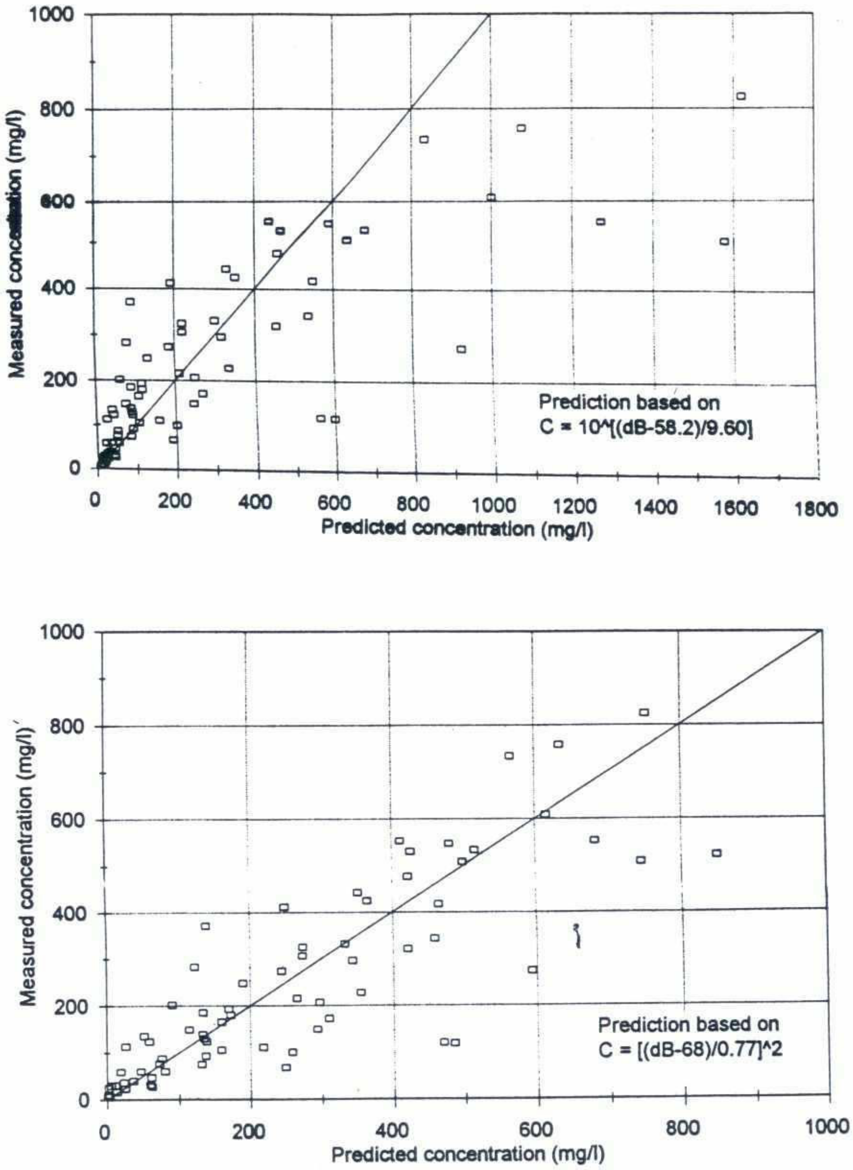

Figure 7: Relation between the measured and predicted concentration of suspended sediment (sand fraction)

A similar comparison between the measured sand fraction concentration and the concentration predicted on the basis of Equation (7) (see Figure 7b), shows a good agreement over almost the full range of concentrations, except for a few high scattered points and in the lower range of concentration.

6 Validation

Figure 7 shows that Equation (7) can better estimate the suspended sediment (sand fraction) concentration than Equation (6). Here the applicability of Equation (7) is checked by comparing a number of suspended sediment samples by pump bottle sampler in the Jamuna River near Bahadurabad in July 1995 with backscatter data (see Figure 8). It is observed that the concentration estimated with Equation (7) is gradually increasing with increasing depth with no exception. The sediment concentrations measured by the pump bottle sampler also shows a clear trend of increasing towards the depth, but a larger scatter in the data is observed. This scatter is probably due to either turbulence or some inconsistency of the measurements. The effect of turbulence can not be observed in the backscatter intensity. Although the scatter in the concentration measured by pump bottle is substantial, it is interesting to observe that the average of these concentrations have a fair agreement with the concentration estimated from backscatter intensity.

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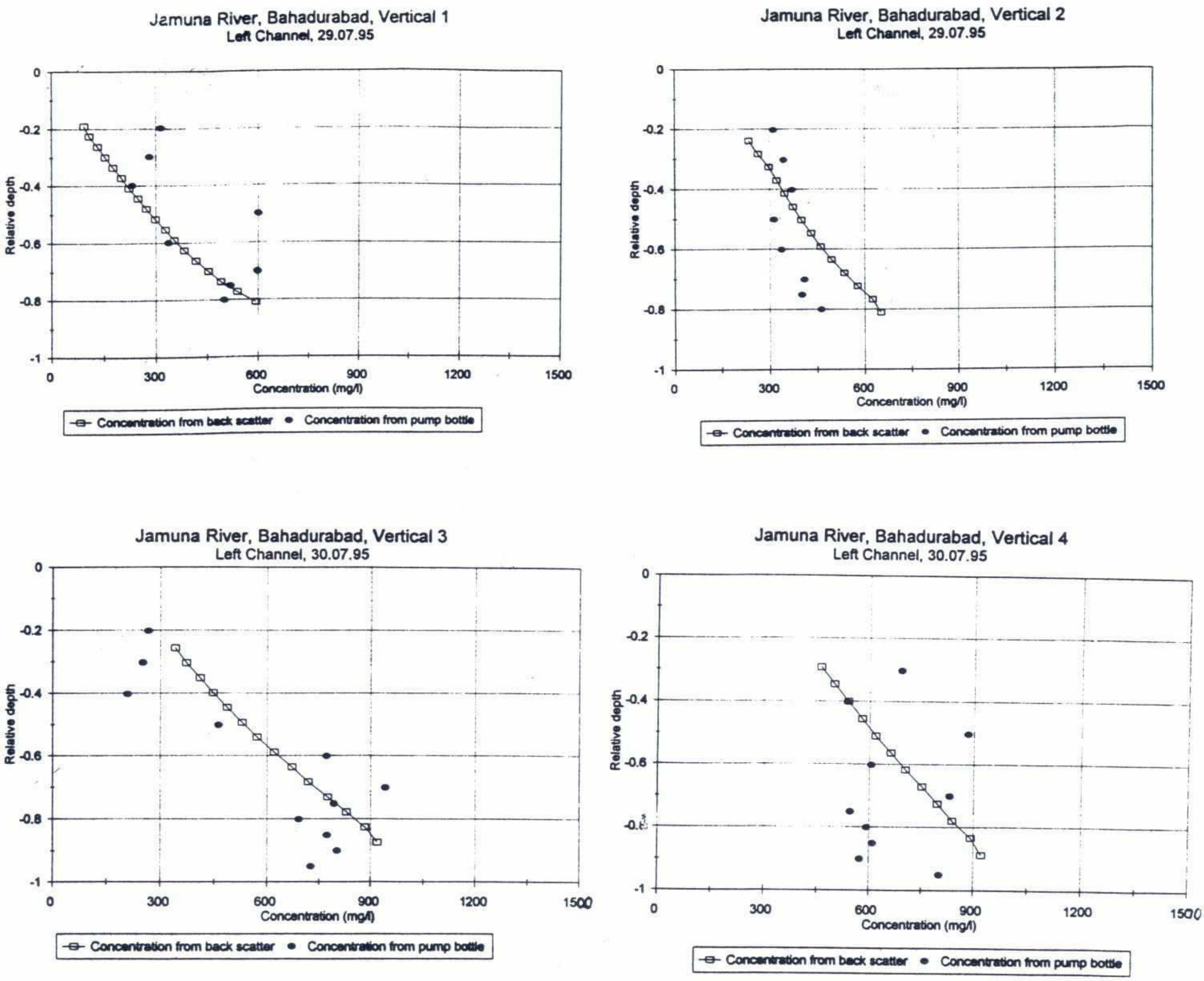

Figure 8 Comparison of estimated sediment (sand fraction) concentration with the measured concentration at different verticals using pump bottle sampler

7 Discussion

Considering the acoustic sound wave frequency of the ADCP used by the RSP, all the suspended grain sizes are in 'Rayleigh scatterer' range. Therefore, the analysis was based on the relation derived by Weiergang (1995) for 'Rayleigh scatterer' range of particles. It is observed that the backscatter intensity (dB) is almost insensitive with the increasing of the concentration of silt fraction of suspended sediment. This can be explained as follows.

The average median grain size of the suspended sand fraction is about 130 μm, whereas the median size of the silt fraction is about 12 μm, see Figure 1. According to Equation (4), the backscatter scales with the cubic power of the diameter. Hence, for the same concentration of sand and silt fraction, the contribution of silt in scattering the sound wave is more than 1000 times less than that of the contribution of sand. In the data the concentration of silt fraction varies in a wide range from 15% to 98%. The silt fraction in the sediment sample contributes to increase the backscatter and hence the apparent concentration but due to its insignificant contribution in scattering the acoustic sound wave, the change in backscatter value (dB) with an increase of silt concentration is negligible. Probably this is the reason why the relation between dB and total concentration is rather poor.

It is observed that the coefficient correlation using the Weiergang relation (Equation (6)) is quite good, but while comparing it with measured concentrations (Figure 7), in particular the higher range of concentration the agreement is rather poor. The probable reason is explained below:

The size of the sand fraction of the suspended sediment varies with the depth and also from location to location. For example, the variation of the median grain size (sand fraction) of the suspended sediment with the relative depth is shown in Figure 9. Median size of sand varies significantly with the relative depth. J. J. Peters, (1994) observed a similar variation of the particle diameter in the Jamuna river. In view of this expected that for the same concentration, the backscatter intensity will be higher for the deeper samples. Of course it would be more elegant to have a backscatter-concentration relation which differentiates for particle sizes. This necessitates to have a predictor for particle size as well. For the time being the acceptance of the curvilinear equation appears to be more simple. This is illustrated in Figure 10 where it is observed that the higher backscatter values are related to a larger relative depth. This is the probable reason, why the data in Figure 5 apparently show a curvilinear relationship between dB and 10*log(C) and also why the predicted concentration using Equation 6 deviates at the high concentration levels.

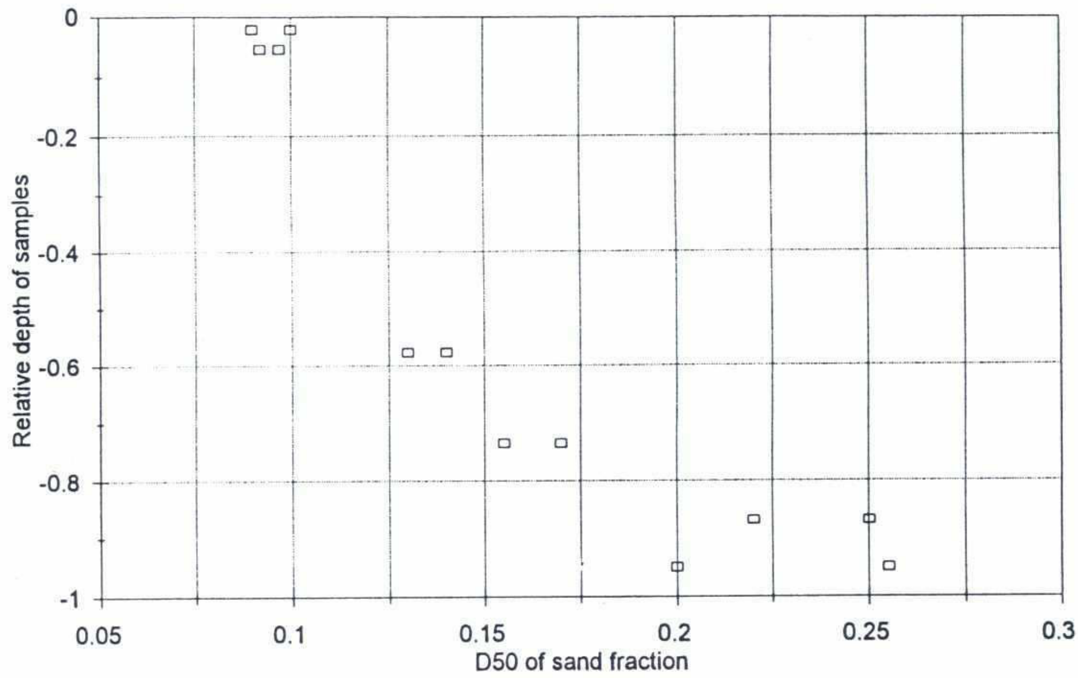

Figure 9 Variation of median grain size of suspended sediment (sand fraction) with the relative depth

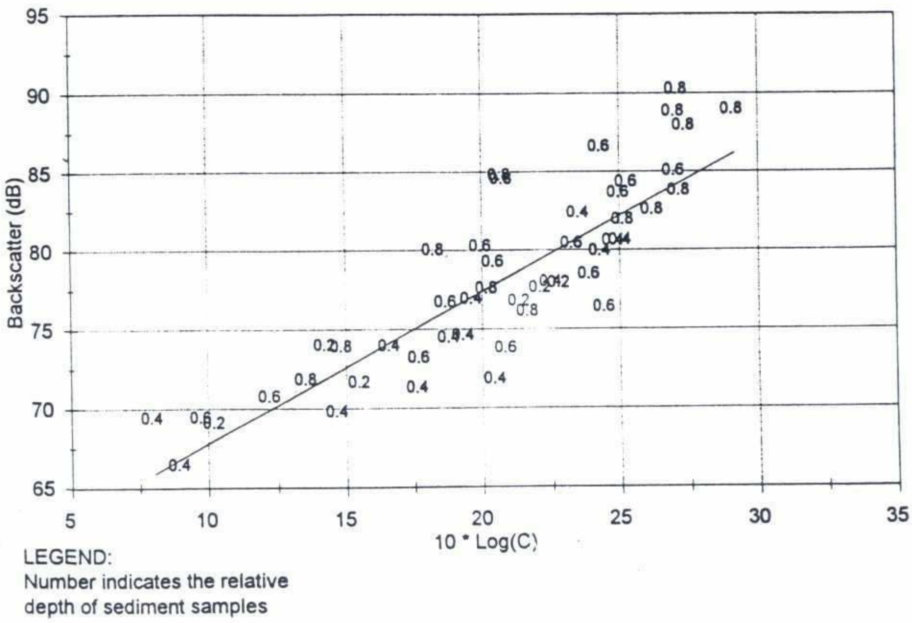

Figure 10 Relation between dB and 10*log(C) with the indication of relative depth of the samples

Although the empirical relation (Equation 7) is only partly based on theoretical considerations, the prediction is still fair, except in the lower range of sand fraction concentration. An alternative would be to apply both relations for the prediction of the sediment concentration in combination. The relation based on Weiergang, 1995 (Equation (6)) can be applied up to a certain range of concentration, i.e. about 600 mg/l, which corresponds to dB value 85. The empirical relation (Equation (7)) should not be applied at the lower range of dB values, because the relation is showing zero concentration at dB values equal to 68. This is not correct. Therefore, at the lower range of dB value the relation yields unreliable results. To obtain consistent results, it is suggested not to use Equation 7 for the dB value lower than 70.

For the ADCP frequency of 300 kHz all the sediment particles of the main rivers in Bangladesh are in 'Rayleigh scatterer' range, within which the backscatter value dB is highly sensitive to the size and gradation of the suspended particles. Therefore, the relations derived here can only can be applied for the Jamuna river, especially at the location around Bahadurabad. Also backscatter data from an ADCP having a frequency other than 300 kHz cannot be used for predicting sediment concentration by the derived relations.

8 Conclusions

Based on the principle of ADCP backscatter, data analysis, validation and subsequent discussions the following conclusion, can be drawn:

- An empirical relation is derived for estimating the suspended sediment concentration (sand fraction) from backscatter intensity.
- The backscatter value of the low frequency (300 kHz) ADCP can only be correlated to the concentration of the sand fraction of sediment.
- The derived relations are valid only for the Bahadurabad location where the grain sizes and gradation of the particles are similar to those for which the relation was derived. To estimate the concentration of suspended sediment (sand fraction), at other locations and for different rivers similar relations should be derived.
- The preference for a relation between the dB value and $C^{0.5}$ can be shown to be caused by vertical sorting of sediments: bigger particles near the bed cause a larger backscatter value.

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