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SPATIAL REPRESENTATION AND ANALYSIS OF HYDRAULIC AND MORPHOLOGICAL DATA

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Table of contents

Chapter 1 1

INTRODUCTION 1
1.1 Project Background and Overview 1
1.2 Objective 1
1.3 Study Area and River Surveys 2
1.3.1 Major Rivers of Bangladesh 2
1.3.2 BWDB Surveys 3
1.3.3 BIWTA Surveys 3
1.3.4 RSP Surveys 4
1.3.5 Map Projection and Coordinate System 6
1.4 GIS and Satellite Image Processing 7

Chapter 2 9

2.1 Introduction 9
2.2 Data Description 9
2.2.1 Introduction 9
2.2.2 Bathymetry Data 9
2.2.3 Land Topographic Data 11
2.3 Data Processing 13
2.3.1 Bathymetry Data 13
2.3.2 Land Surface Data 13
2.3.3 Merging of River Bed Topography with Land Surface 14
2.3.4 Depth-Area Statistics and Volumetric Changes 14
2.4 Results 14
2.5 Interpretation and Discussion 20
2.5.1 Features of Bed Topography and Evolution of Bed Morphology 20
2.5.2 Depth-Area Statistics 21
2.5.3 Sediment Balance 22

Chapter 3 23

3.1 Introduction 23
3.2 Data Description 23
3.2.1 Flow Data 23
3.2.2 Sediment Transport Data 24
3.3 Data Processing 24
3.3.1 Processing of Flow and Sediment Data by RSP 24
3.3.2 Float Tracking Data 25
3.3.3 Merging of River Bed Topography with Land Surface 25
3.3.4 Calculation of Sediment Concentrations from Flow Field 27
3.3.5 Short-term Prediction of Morphological Changes 27
3.4 Results 28
3.5 Interpretation and Discussion 34

8

3.5.1 Flow Velocity and Sediment Concentration Measurements 34
3.5.2 Short-term Prediction of Morphological Changes 34

Chapter 4 36

4.1 Introduction 36
4.2 Data Description 36
4.2.1 Hydrometric Data 36
4.2.2 Satellite Imagery 36
4.2.3 Cross-sectional Data 37
4.3 Data Processing 38
4.3.1 Water Levels 38
4.3.2 Land Cover Type 39
4.3.3 Land Age 39
4.3.4 Georeferencing of Cross-sections 39
4.3.5 Land Surface Elevation 43
4.3.6 Position of Median Conveyance Line 45

4.4 Results 45
4.5 Interpretation and Discussion 45
4.5.1 Land Surface Elevation, Cover Type and Age 45
4.5.2 Positions of Median Conveyance Line 49

Chapter 5 50

5 Conclusions and Recommendations 50

References 52

List of Appendices

Appendix A: Processing of Bathymetric and Topographic Data 53
Appendix B: Conversion from SLW to PWD Datum 55
Appendix C: Merging of River Bed Topography with Land Surface 56
Appendix D: Depth-area Statistics 57

Q/

List of Figures

Figure 1.1 Ganges, Brahmaputra and Meghna River Catchment Areas 2
Figure 1.2 Locations of RSP Ganges, Transects and Bathymetry Survey Areas 5

Figure 2.1 Summary of Data Flow, Bathymetric Surveys of RSP 12
Figure 2.2 Water Discharge at Bahadurabad during the survey periods from June 1993 to November 1995 15
Figure 2.3 Evolution of Bathymetry at Bahadurabad from July to November 1995 16
Figure 2.4 Evolution of Land Surface at Bahadurabad from July to November 1995 17
Figure 2.5 Depth Relative to SLW of Jamuna Left Channel at Bahadurabad from June 1993 to November 1995 18
Figure 2.6A Mean Water Depth vs Channel Width 19
Figure 2.6B Mean Depth below SLW vs Channel Width 19
Figure 2.7 Distribution of Sediment Erosion and Deposition in Jamuna Left Channel at Bahadurabad 19

Figure 3.1 On-line Data Flow for Routine Gauging by RSP Survey Units 24
Figure 3.2 Summary of RSP Data Flow 25
Figure 3.3 Concentration at Bahadurabad, July-December 1994 26
Figure 3.4 Erosion and Deposition as a Function of Local Flow Velocity and Water Depth 28
Figure 3.5 Depth-average Flow Velocities from ADCP Measurements at Bahadurabad in August 1993 29
Figure 3.6 Surface Flow Velocities and Flow Lines from Float Tracking at Bahadurabad in July 1995 30
Figure 3.7 Depth-averaged Sediment concentrations from ADCP Back scatter at Bahadurabad in August 1993 31
Figure 3.8 Comparison of Predicted and Measured Morphological Changes at Bahadurabad between August and November 1993 32
Figure 3.9 Comparison of Predicted and Measured Morphological Changes at Bahadurabad between July and November 1995 33

Figure 4.1 Georeferenced Cross-sections on Jamuna River in 19980 42
Figure 4.2 Determination of Average Elevation from Selected Cross-section 44
Figure 4.3 1994 Landsat Image, Land Cover Types and Cross-section Locations 46
Figure 4.4 Land Age Map and Class Statistics for the Jamuna River 47
Figure 4.5 Positions of Median Conveyance Line 48

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List of Tables

Table 1.1	Hydrological and Morphological Information on Ganges and Jamuna River in Bangladesh	3
Table 1.2	RSP Bathymetry Data Used in this Study	6
Table 1.3	Landsat satellite images of Jamuna River with corresponding discharges and water levels	8
Table 2.1	Bathymetric Survey by RSP, 1993 to 1995	10
Table 2.2	Standard Low Water (SLW) Level and Water Surface Gradiant	11
Table 2.3	Topographic Surveys by RSP	13
Table 2.4	Summary Statistics on River Bathymetry of Jamuna Left Channel for Bahadurabad Survey Area	18
Table 2.5	Volumetric Changes in the River Bed of Jamuna Left Channel at Bahadurabad	20
Table 2.6	Main Morphological Units in Study Reach	20
Table 3.1	RSP Measurements of Flow Trajectories by Float Tracking	23
Table 3.2	Assessment of Short-term Predictions of Morphological Changes at Bahadurabad	34
Table 4.1	Hydrometric Data Availability for Ganges-Jamuna River System	37
Table 4.2	Cross-sectional Data Availability for Jamuna River	38
Table 4.3	Location of 1994 BWDB Cross-sections in the Jamuna River	40
Table 4.4	Quality of Matching of 1980 Cross-sections for Jamuna River	43
Table D-1	Depth-area Statistics of Jamuna Left Channel at Bahadurabad	57
Table D-2	Depth-area Statistics of Jamuna Main Channel at Kamarjani	58
Table D-3	Depth-area Statistics of Ganges-Jamuna Confluence at Aricha	59
Table D-1	Depth-area Statistics of Ganges at Offtake	60

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The study was carried out by GIS specialists, river engineers and morphologists. Several individuals shared the responsibility for carrying out the study and writing the report: Ahmadul Hassan coordinated the entire study. Shamsuddin Ahmed processed and analyzed bathymetric data. Syed Iqbal Khosru, Hasan Ali and Minhajuddin Ahmed processed and analyzed cross-sections and hydrometric data. Maarten van der Wal, Gerrit J. Klaassen and Mominul Haque Sarker suggested possible approaches for data processing and developed a methodology for short-term morphological prediction based on a method proposed by J.J. Peters, Project Advisor for the River Survey Project. The bathymetric and most other data were collected by field staff of the River Survey Project, coordinated by Hans Hoyer and later by Kim K. Jensen. Erik Mosselman and Colin R. Thorn contributed to the report. Timothy Martin, EGIS Project Advisor managed the study and report.

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Acronyms

ADCP	Acoustic Doppler Current Profiler
ALLW	Average Lowest Low Water
BIWTA	Bangladesh Inland Water Transport Authority
BTM	Bangladesh Transverse Mercator
BUET	Bangladesh University of Engineering and Technology
BWDB	Bangladesh Water Development Board
DELFT	Delft Hydraulics
DEM	Digital Elevation Model
DGPS	Differential Global Positioning System
DHI	Danish Hydraulic Institute
EGIS	Environmental and GIS Support Project for Water Sector Planning
ERDAS	Earth Resource Data Analysis Systems
ESRI	Environmental Systems Research Institute
FAP	Flood Action Plan
GIS	Geographic Information System
GPS	Global Positioning System
ISPAN	Irrigation Support Project for Asia and the Near East
MIA	Morphological Impact Assessment
MPO	Master Plan Organization
MSS	Multi Spectral Scanner
PWD	Public Works Department
RMRIS	River Morphology and Resource Information System
RSP	River Survey Project
SLW	Standard Low Water (sloping datum)
SWMC	Surface Water Modeling Center
TIN	Triangular and Irrigation Network
TM	Thematic Mapper
UTM	Universal Transverse Mercator
WARPO	Water Resources Planning Organization

Chapter 1

Introduction

1.1 Project Background and Overview

GIS and image processing are powerful tools for characterizing and analyzing the morphology of the major rivers in Bangladesh. The morphological characteristics of these rivers are primarily determined by fluvial processes which involve water flow, sediment transport, bed material composition, bed topography changes and planform changes. To analyze these processes, GIS and image processing applications are being developed in the River Morphology and Resource Information System (RMRIS), an activity of the Environment and Geographic Information System Support Project for Water Sector Planning (EGIS).

The RMRIS project is establishing a computer-based system for storing, retrieving and manipulating information of the major rivers of Bangladesh. The system includes a database and mapping capability for storing and analyzing satellite images, historical maps, bathymetric data, hydrometric data, socio-economic and physical resources data, and other river morphology and resource information.

The database and analysis capability developed under this project will have applications to a number of on-going and planned development projects, including the Jamuna Multipurpose Bridge, the River Bank Protection Project, the Meghna Estuary Study. In addition, it will form a basis for the information and analysis needs of the proposed Morphology Impact Assessment (MIA) project.

The present report contains the results of a study on the spatial representation and analysis of hydraulic and morphological data, which is a part the RMRIS being established by EGIS. This report was prepared in cooperation with the River Survey Project (FAP 24). It includes the collection and organization of data on river bathymetry, hydrography (including water levels, discharges and sediment transport) and channel and char topography from surveys on the Jamuna and Ganges Rivers. The data are analyzed and presented to enhance their utility for interpretations of river morphology, including depiction of changes in river form and computation of sediment mass balance for selected reaches of river channel.

1.2 Objective

The goal of this study was to develop methods to visualize and analyze the huge number of hydraulic and morphological data of FAP 24 more efficiently by using GIS and image processing. One of the rationales behind this objective is that the FAP 24 data should also be easily accessible for potential users in the future.

More specifically, the following objectives were defined:

(i) River bathymetry mapping and change analysis (Chapter 2);
(ii) Analysis and presentation of fluvial data (water flow, sediment transport) in combination with bathymetry (Chapter 3);
(iii) Testing of a method of short-term morphological prediction (Chapter 3);
(iv) Development of a method to derive a land elevation map from satellite images (Chapter 4);
(v) A revised representation the 50 percent conveyance line of the Jamuna River (Chapter 4).

1.3 Study Area and River Surveys

1.3.1 Major Rivers of Bangladesh

Bangladesh occupies the lowest part of the Ganges-Brahmaputra basin. This basin is a low-relief plain between the Himalayan Alpine system in the north and the Gondwana Shield in the south (Murphy, 1992). Figure 1.1 shows the catchment of the basin, which has a total area of 1.76 million km^2. During floods, a water discharge in excess of 170,000 m^3/s flows from the basin into the Bay of Bengal, transporting approximately 13 Mton suspended load per day as a yearly average (Hannan, 1993).

The major rivers of Bangladesh are the Jamuna (Brahmaputra), the Ganges, the Padma and the Meghna. Some characteristic values of the hydrological and morphological parameters are given in Table 1.1.

Figure 1.1 Ganges, Brahmaputra and Meghna River Catchment Areas

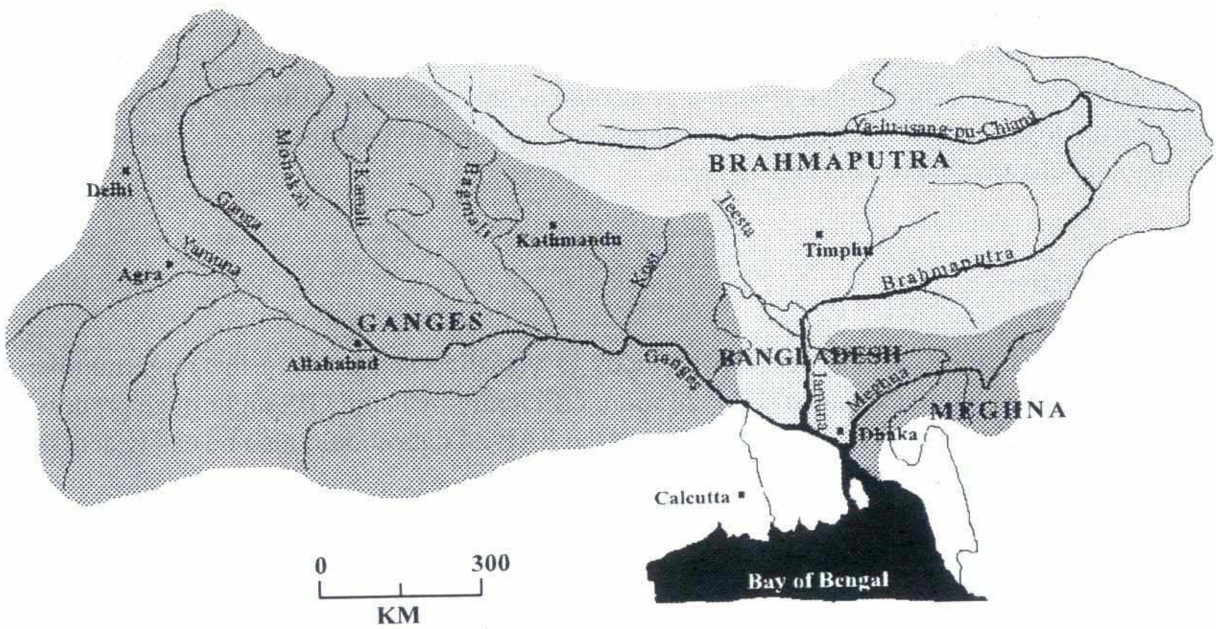


Table 1.1 Hydrological and Morphological Information on Ganges and Jamuna River in Bangladesh

Quantity	Ganges at Hardinge Bridge	Jamuna at Bahadurabad
Bankfull discharge (m^3/s)	40,000 to 45,000 [1/]	45,000 to 50,000 [1/]
Dominant discharge (m^3/s)		38,000 [2/]
Mean discharge (m^3/s)	11,000 [3/]	20,200 [2/]
Danger level (m+PWD)	14.25 [4/]	19.50 [4/]
Slope (m/km)	0.05 [5/]	0.076 [4/]
Average width (km)	5 [5/]	11 [4/]
Suspended transport (Mt/yr)	548 [4/]	590 [4/]
Average median grain size (mm)	0.12 [2/]	0.22 [2/]

1/ : RSP, 1996a
2/ : FAP 1, 1993
3/ : FAP 4, 1994
4/ : RSP, 1994
5/ : Hannan, 1993

1.3.2 BWDB Surveys

The Bangladesh Water Development Board (BWDB) has been monitoring the rivers of Bangladesh since the early 1950s, operating a network of staff gauges that covers the entire main river system of the country. The comprehensive routine gauging program of BWDB comprises flow measurements, sediment transport measurements and morphological monitoring at fixed standard cross-sections along the rivers. There are 607 standard cross-sections at an interval of about 6.4 km throughout the country. In total, 144 cross-sections are surveyed in the main rivers every year. In the medium and minor rivers 119 cross-sections are surveyed once in two years and 344 cross-sections once in three years. The cross-sections are measured during dry season. The dry part of the section is surveyed with a levelling instrument and a levelling staff, whereas the wet part of the cross-section is surveyed by an echo-sounder on a survey vessel. The positioning of the vessel along the transit line is determined by sextant or theodolite with respect to a known base line. A cross-section is defined by two to three pillars or monuments at one bank and at least one pillar or monument at the other bank. In case relatively high elevation islands (chars) are found in the cross-section it is necessary to define more temporary pillars at the char. The location of a pillar is fixed by a description of the plot of land in which it has been placed, the location of that plot in administrative maps and the geographic coordinates of the pillar. The direction of the cross-section is defined by the bearing, an angle measured with respect to the magnetic north.

1.3.3 BIWTA Surveys

The Bangladesh Inland Water Transport Authority (BIWTA) prepares bathymetric maps on the basis of surveys which are executed to monitor the least available depth (minimum draught) in inland navigation routes. In general, these soundings cover a short stretch of the river and not the full width. In the Jamuna river soundings are made almost every year in the routes of the ferries from Aricha to Nagarbari, Sirajganj to Bhuapur and Bahadurabad to Fulchari.

The position of the survey vessel is determined with a Decca positioning system. The accuracy depends on weather conditions, survey time and location of the river. The positioning error in average conditions is about 100 m. The channel depth is measured with echo-sounders and charted depths are given with respect to SLW (Standard Low Water) or ALLW (Average Standard Lowest Low Water). The relation between SLW, ALLW and PWD is established for several stations along the river. Hydrogaphic charted depth is given in 0.1 meter, and maps are drawn in standard scales 1:5,000 to 1:50,000.

1.3.4 RSP Surveys

The River Survey Project (RSP) is project number 24 of the Flood Action Plan (FAP 24). The objective of the surveys performed by FAP 24 is to collect reliable all-season hydrological, hydrographic and morphological data at key locations of the country's main river system.

As a supplement to the monitoring by BWDB, and in order to extend the information produced, RSP executed a routine gauging programme in the period from January 1993 to March 1996. The programme comprised water level gauging at 22 locations, routine transect gauging of flow and sediment transport at 11 locations, and repeated bathymetric mapping for the purpose of morphological monitoring of 7 areas distributed over the main river system of Bangladesh.

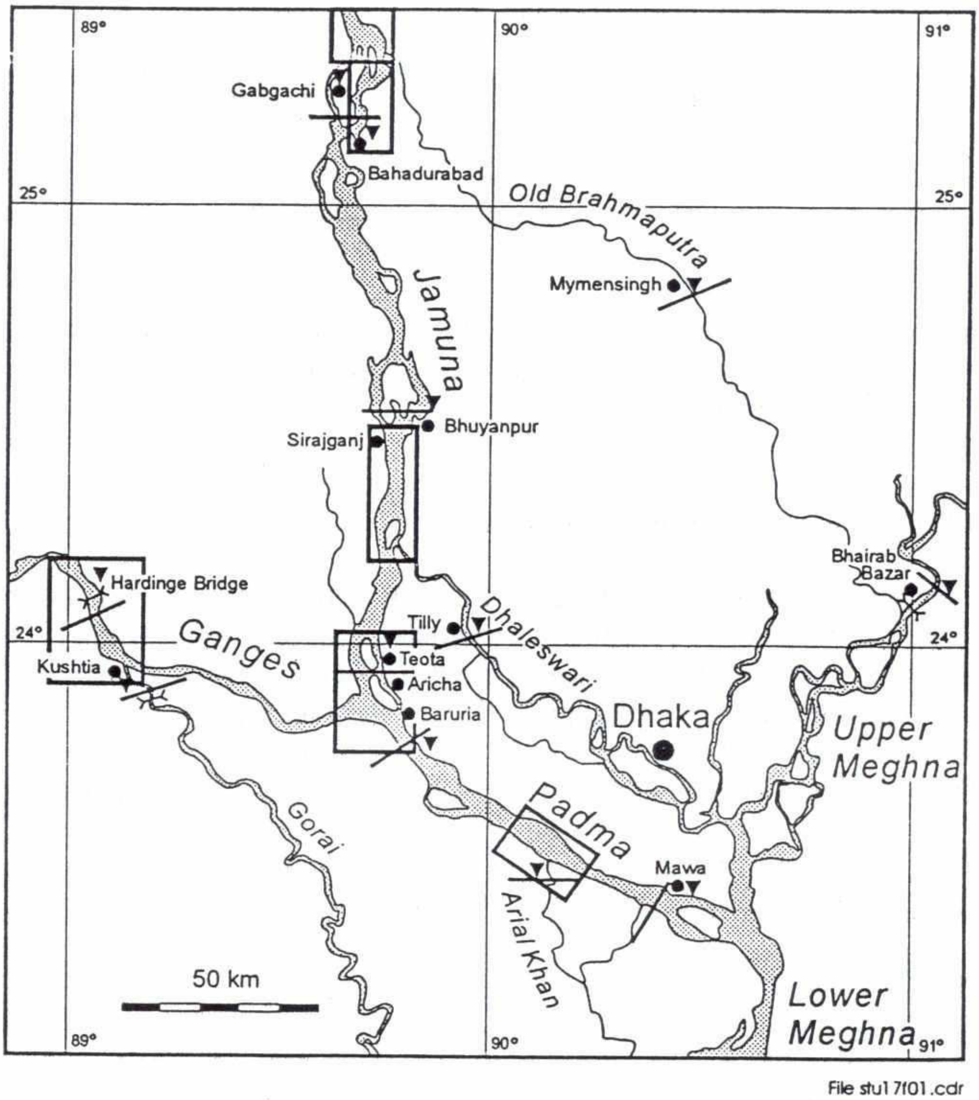
The locations of water level gauges, transects and bathymetry areas are shown in Figure 1.2. Nineteen bathymetric surveys at four sites, as shown in Table 1.2, were processed and analyzed with GIS under the present project.

The main locations for water level and discharge measurements on the Jamuna River are Bahadurabad and Sirajganj. The morphological analysis of the bathymetric surveys which were performed at Bahadurabad Left Channel showed that the morphological developments in this channnel depend on the conditions up to 20 km upstream. Therefore RSP decided to extend the Bahadurabad survey area about 20 km in the upstream direction to include the area known as Kamarjani survey area.

The Hardinge Bridge is the main station for hydrological and sediment transport measurements in the Ganges River. To study the influences of morphological conditions, such as the influence of bars in the Ganges River on discharges in the Gorai River offtake, RSP carried out various bathymetric surveys in the area of the Hardinge Bridge and the Gorai offtake.

36

Figure 1.2 Locations of RSP Gauges, Transects and Bathymetry Survey Areas



▼ Automatic water level recorder

— Transect for routine gauging of flow and sediment transport

☐ Bathymetric survey area

86

Table 1.2 RSP Bathymetry Data Used in this Study

Location	River Name	Study Area Coordinates [1/] (km, BTM)	Survey Date
Kamarjani	Jamuna	UL: 461E, 815N LR: 472E, 790N	Sep 94, Nov 94, Mar 95, Aug 95
Bahadurabad Left Channel	Jamuna	UL: 455E, 790N LR: 475E, 770N	Jun 93, Aug 93, Nov 93, Nov 94, Feb 95, Jul 95, Nov 95
Confluence	Ganges and Jamuna	UL: 454E, 652N LR: 480E, 630N	Oct 93, Apr 94, Dec 94, Apr 95
Gorai offtake/ Hdinge Bridge	Ganges and Jamuna	UL: 398E, 670N LR: 424E, 644N	Oct 94, Jan 95, May 95, Sep 95

1/: Upper Left (UL) and Lower Right (LR)

The confluence of the Jamuna River and the Ganges River is important for the water levels upstream in both rivers as backwater and drawdown effects occur. To study these effects, RSP surveyed the bathymetry of this confluence various times.

1.3.5 Map Projection and Coordinate System

Most maps prepared by SoB (Survey of Bangladesh) and BWDB use the India Zone IIB and Zone IIIB yards grid system based on a Lambert Conformal Conic projection. Some other maps of Bangladesh were prepared using the geocentric ellipsoid WGS84 and the Universal Transverse Mercator (UTM) projection. Maps in this projection are most accurate in tropical latitudes. The UTM system divides the world into sixty north-south zones, each 6° wide. The 90° E meridian divides Bangladesh almost equally between two such UTM zones. Hence, the UTM projection requires two different transformations for dealing with spatial data from Bangladesh. Therefore FAP 19 (1992) recommended a transverse mercator projection with a central meridian at 90°E, which implies a 3° shift with respect to the UTM zones.

Another important factor for mapping and digital databases is an appropriate map datum. Different models for the representation of the Earth Surface have been developed for different regions. The geocentric WGS84 model best represents the entire earth but with less overall accuracy for the Indian subcontinent. Historically, however, the Everest 1830 ellipsoid has been used on the Indian subcontinent and provides the "best fit" for this part of the world. Therefore FAP 19 (1992) recommends the use of the Everest 1830 ellipsoid.

The recommendations by FAP 19 (1992) have led to the Bangladesh Transverse Mercator (BTM) projection and coordinate system, which has the following specifications:

Ellipsoid	:	Everest 1830
Projection	:	Transverse Mercator
Central meridian	:	90° E
False easting	:	500,000 m
False northing	:	-2,000,000 m

All the thematic data and maps produced by EGIS are in the BTM coordinate system.

1.4 GIS and Satellite Image Processing

A GIS is a computer based technology for recording, manipulating , analyzing, and displaying data such as digital maps, images or other information with a spatial reference such as latitude and longitude. Techniques of GIS can be quite valuable in studying the river morphological behavior. The GIS output in the form of color contours, river form change maps, velocity gradient maps and other spatial products are very convenient for studies, for example to predict the morphological development. Thus, GIS is an important tool for inland navigation and for design and construction of river training works, for example.

Remote sensing techniques have been applied to geographical research, flood monitoring and assessment of natural systems in Bangladesh for more than two decades (ESCAP/SPARRSO, 1989). In order to obtain more historical data of changes in the Jamuna River, the use of satellite images from Landsat was considered. Landsat MSS and TM data were collected in the dry season from 1973 to 1996 as listed in Table 1.3 alongwith BWDB water levels and dischurge data computed by RSP. All the images were geometrically corrected in order to register them and to make change detection possible. Subsequently, the images were classified into the categories water, sand, cultivated soil and vegetation. The satellite imagery was used in this project to monitor the morphological changes within the braid belt of the Jamuna River, to help to georeference the cross-sections, to map the age of chars, and to examine the relation between land surface elevation, land cover and land age.

Table 1.3 Landsat Satellite Images of Jamuna River with Corresponding Discharges and Water Levels

Satellite Image Date	Sensor	Resolution (m)	Bahadurabad		Kazipur	Sirajganj
			Discharge (m^3/s)	Water Level (m+PWD)	Water Level (m+PWD)	Water Level (m+PWD)
21 Feb, 1973	MSS	80	3230	13.09	8.57	6.64
10 Jan, 1976	MSS	80	5240	13.54	8.93	7.14
22 Feb, 1978	MSS	80	4730	13.08	9.19	6.46
21 Feb, 1980	MSS	80	4410	13.53	8.41	6.65
5 Feb, 1983	MSS	80	4340	13.23	9.32	7.00
Feb/Mar 1/ 1984	MSS	80				
25 Feb, 1985	MSS	80	3950	13.36	9.31	6.72
7 Feb, 1987	MSS	80	5530	13.30	9.19	6.94
28 Feb, 1989	TM	30	6070	13.94	9.65	7.67
8 Mar, 1992	TM	30	4660	13.76	9.36	7.58
25 Jan, 1994	TM	30	5070	13.61	9.37	7.50
28 Jan , 1995	TM	30	N.A.	13.04	8.43	N.A.
31 Jan, 1996	TM	30	N.A.	13.53	N.A.	7.33

1/: Exact date is unknown
N.A.: Not available

The digital analysis in this project was performed on 486 DX microcomputers, using ERDAS and pcARC/INFO software for image processing, raster and vector GIS analyses.

29

Chapter 2

Bathymetry and Topography Mapping and Change Analysis

2.1 Introduction

The bathymetric data are used to map and compute changes in the bathymetry over time for visualizing, interpreting and predicting the evolution of river morphology. From bathymetry change maps, the sedimentation and erosion of the river bed can be quantified. Topographic information such as land elevation and land type from additional input can be used for computing the sediment mass balance and for better understanding of morphological changes.

2.2 Data Description

2.2.1 Introduction

Traditional monitoring of river morphological developments uses successive mappings of bed elevation contours, which are analyzed for level differences caused by accretion and erosion of the river bed in the period between the surveys. For routine purposes, bathymetric surveys can best be undertaken in the dry season, when the morphological developments proceed slowly or not at all. For studies of morphological developments, however, surveys in the flood season are more useful, but the surveys are rather time-consuming.

In the dry season, however, the stage is low, so a substantial part of the river sediment volume exposed to morphological change appears as dry land. Therefore, the mapping must, in some way, cover both the dry and the submerged part of the river bed. This requires a combination of bathymetric and topographic surveys. ***Bathymetry*** is referred to a declined surface and ***topography*** is referred to a horizontal surface.

Hereby not only are the relative and absolute accuracy of the leveling important; also the absolute positioning accuracy is crucial, because a positioning off-set between successive surveys can induce a substantial deviation with respect to the erosion and accretion rates, and, even more significant, with respect to the impact areas. During the bathymetric and topographic surveys for the present study, positioning was made by DGPS (Differential Global Positioning System), which in its dynamic mode has an estimated absolute accuracy of 3 m.

2.2.2 Bathymetry Data

Until the end of 1995, RSP completed 31 bathymetric surveys at 7 locations. These are listed in Table 2.1 (7 additional bathymetric surveys were made in early 1996). Out of these, the data from 19 bathymetric surveys at 4 locations were used by EGIS. The line spacing was 100 m and 200 m at Kamarjani, 100 m at Bahadurabad and 200 m at the Ganges-Jamuna confluence and the Gorai offtake. The horizontal survey spacing in the one but last column is an irregular interval between 1 and 5 m approximately.

The surveys were made along fixed run lines that were maintained by the DGPS system. To the extent possible, these run lines were retained from one survey to another, in order to allow for a good determination of the morphological development.

Table 2.1 Bathymetric Surveys by RSP, 1993 to 1995

Location	Start date	End date	Line spacing	Survey number
Bahadurabad	20-Jun-93	03-Jul-93	100 m	8001*
Bahadurabad	23-Aug-93	09-Sep-93	100 m	8002*
Confluence	15-Oct-93	31-Oct-93	200 m	8003*
Bahadurabad	10-Nov-93	18-Nov-93	100 m	8004*
Hurasagar	23-Nov-93	30-Nov-93	100 m	8005
Arial Khan Off-take	01-Jan-94	10-Jan-94	200 m	8006
Confluence	19-Apr-94	05-May-94	200 m	8007*
Kamarjani	01-Sep-94	26-Sep-94	200 m	8008*
Gorai Off-take	13-Oct-94	23-Oct-94	200 m	8009*
Bahadurabad	01-Nov-94	11-Nov-94	100 m	8010*
Kamarjani	10-Nov-94	20-Nov-94	100 m	9038*
Dhaleshwari Off-take	24-Nov-94	11-Dec-94	200 m	8011*
Confluence	13-Dec-94	25-Dec-94	200 m	8012*
Hurasagar	25-Dec-94	29-Dec-94	200 m	8013
Gorai Off-take	06-Jan-95	20-Jan-95	200 m	8014*
Arial Khan Off-take	04-Feb-95	13-Feb-95	200 m	8015
Bahadurabad	24-Feb-95	27-Feb-95	100 m	8016*
Kamarjani	06-Mar-95	13-Mar-95	100 m	8017*
Dhaleshwari Off-take	29-Mar-95	04-Apr-95	200 m	8018
Confluence	08-Apr-95	15-Apr-95	200 m	8019*
Hurasagar	18-Apr-95	20-Apr-95	200 m	8020
Arial Khan Off-take	27-Apr-95	07-May-95	200 m	8021
Gorai/Kushtia	28-May-95	12-Jun-95	200 m	8022*
Gorai/Kushtia	24-Jun-95	30-Jun-95	200 m	8023
Bahadurabad	03-Jul-95	25-Jul-95	100 m	8024*
Gorai Off-take	08-Aug-95	14-Aug-95	200 m	8025
Kamarjani	05-Aug-95	19-Aug-95	200 m	8026*
Gorai/Kushtia	08-Sep-95	24-Sep-95	200 m	8027
Gorai/Kushtia	16-Oct-95	20-Oct-95	200 m	8028
Bahadurabad	11-Nov-95	24-Nov-95	100 m	8029*
Kamarjani	25-Nov-95	13-Dec-95	100 m	8030

* processed and analyzed under this project

The reference level selected for the bathymetric mapping is Standard Low Water (SLW), which is defined by the water level that is exceeded 95 percent of the time. Interconsult (1991) computed SLW from daily registrations of the mean water level by assuming a log normal distribution. SLW is a nominal datum that has been defined only at locations where long-term water level records have been available for the purpose. The 'true' SLW datum, being a matter of definition, cannot be established elsewhere. For the purpose of the survey, however, the datum has been estimated to be parallel with the surface of the river at the time of the survey. The surface gradient (relative to PWD) is measured by staff gauges, so that a correction can be made for its variation from case to case, for example when comparing successive surveys. SLW along with the gradient variation of four study areas are shown in Table 2.2. During the surveys, banklines were mapped from the survey vessel by registering the distance between the end of the survey line and the river bank. The data flow is summarized in Figure 2.1

Table 2.2 Standard Low Water (SLW) Level and Water Surface Gradient

Location/River	SLW (m+PWD)	Water Surface Gradient (cm/km)	
		Maximum	Minimum
Kamarjani/Jamuna	13.87	9	8
Bahadurabad/Jamuna	12.03	9	5
Confluence/Jamuna-Ganges	2.31	4.2	3.6
Gorai offtake/Ganges	4.11	4	3

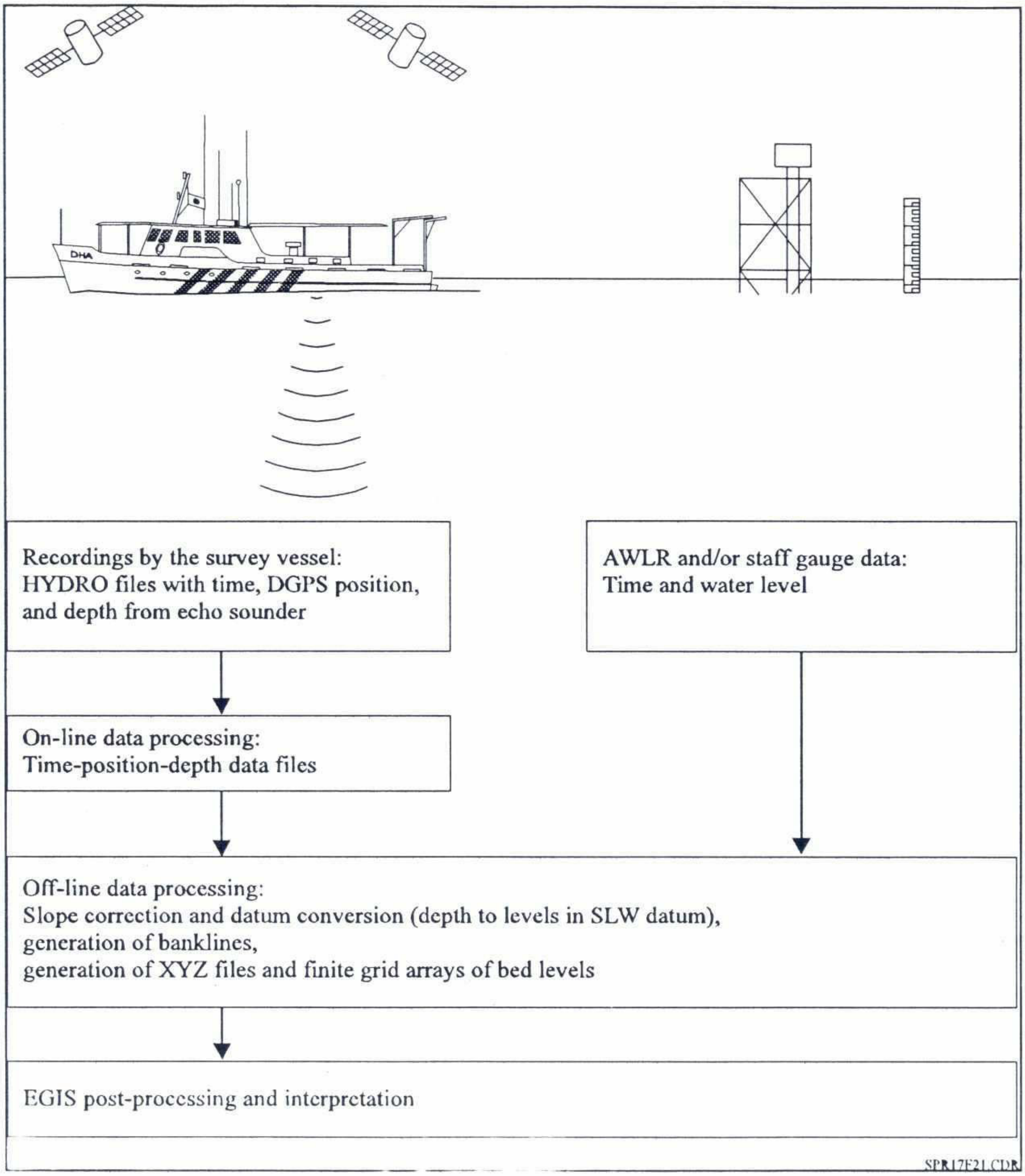
Source: RSP

2.2.3 Land Topographic Data

Topographic information on the exposed part of the river bed during the dry season is a key input for computing the sediment mass balance (FAP 19, 1995) and for understanding the morphological changes. Topographic surveys were carried out by RSP as indicated in Table 2.3. The surveys determined spot elevations along survey lines that were aligned with the bathymetric survey run lines. The line spacing was 500 m, and the point increment along each line was 100-200 m. The survey lines (and the positioning in general) were made by DGPS, whereas the leveling was made by a Topcon total station. With the procedures applied in the field, the accuracy is estimated at 3 m horizontally and 2-3 cm vertically. Over 2000 spots were surveyed on the banks, on the chars and even on the sand bars. This number of 2000 was not enough to generate a continuous surface, especially on the banks. Hence, more points on the banks and the chars were required. Such points were generated using the land slope, previous survey information and bankfull water level data.

The original survey lines did not cross land with different ages. In order to find, for each land feature, a correlation between elevation and age, three additional lines across land of different ages were surveyed by RSP near Bahadurabad in November 1995.

Figure 2.1 Summary of Data Flow, Bathymetric Surveys of RSP



22

Table 2.3 Topographic Surveys by RSP

Location	Start Date	End Date	Survey Number
Gorai Off-take	15-Jan-95	14-Feb-95	9044
Bahadurabad	25-Nov-95	20-Dec-95	8032 *
Bahadurabad	25-Dec-95	06-Jan-96	8032 *
Bahadurabad	09-Mar-96	14-Mar-96	8032 *
Kamarjani	07-Jan-96	16-Jan-96	8034
Kamarjani	15-Mar-96	18-Mar-96	8034
Ganges/Jamuna Confluence	22-Mar-96	31-Mar-96	8037

* used under this project

The surveys included a mapping of features, as a support to the interpretation of the satellite imagery. The topographic surveys used in this project also collected information on land cover and other features. This included in descriptions of crop type and height, soil texture and relative moisture, local relief and content and descriptions of infrastructure such as roads and embankments.

The land features were surveyed at more than 1200 locations in the area of Bahadurabad. The surveys included the registration of the minimum extent of land of a certain type and the elevation relative to the water level. Using the water surface slope and the water level reading at the station at Bahadurabad Ghat, all the relative elevations were converted to elevations above PWD datum. Only 57 of the survey locations were on sites larger than 0.4 ha, the minimum size established for comparison with November 1995 Landsat TM images, which have a 30 m ground resolution.

Information on the topography of bars, chars and banks is important for a better understanding of the sedimentation processes in the study area. It was not possible to estimate the total quantity of erosion and sedimentation from the bathymetry data only because the period between successive surveys varied from 3 months to one year. In this period important changes can occurs. For that, the river bed topography must be merged with land surface data.

2.3 Data Processing

2.3.1 Bathymetry Data

The processing of the bathymetric and topographic data consisted of data conversion, surfacing and recoding. The conversion transformed floating ASCII format data. The surfacing consisted of interpolation between data points as to obtain a continuous distribution of values over the area considered. The recoding consisted of several procedures to rescale or rename the continuous data values generated from the discrete data. Details of the processing are given in Appendix A.

2.3.2 Land Surface Data

Land surface data were first converted into GIS format and then into elevations with respect to PWD datum. The *conversion into GIS format* consisted of converting the land survey data of November 1995 into vector GIS with a point coverage. Using GIS software, a 50 m regularly spaced grid was

22

derived from the irregular point data through a Triangular and Irregular Network (TIN). Then, the land elevation was converted to PWD datum and transferred for use in raster processing.

Land feature information from the survey was also used to verify the classified 1994 satellite image. The agreement was over 80% for vegetated areas and about 70% for dry and wet sands.

2.3.3 Merging of River Bed Topography with Land Surface

The bathymetry of Jamuna left channel at Bahadurabad, given with respect to the sloping SLW datum, was converted to a bed topography with respect to the horizontal PWD datum. The formulas of the conversion are given in Appendix B. Bed topography of July 1995 and November 1995 were then merged with land surface data of November 1995. The procedure is given in Appendix C.

It was found that the minimum elevation of the river bed topography was -2 m+PWD in July 1995 and -3 m+PWD in November 1995. The highest land surface elevation was 21 m+PWD.

2.3.4 Depth-Area Statistics and Volumetric Changes

The area occupied by each depth class was calculated from raster GIS output of the river bathymetries at different times. This yielded the frequency of occurrence of depths in the area and is referred to as ***depth-area statistics***. Changes in depth-area statistics represent volumetric changes of sediment. The depth-area statistics are hence useful for the evaluation of the sediment balance.

The volumetric changes of the river bed were computed with two different methods, one based on elevations relative to PWD datum and one based on depths relative to SLW. Computation of changes in volume over time should be based on a constant datum or reference level. The SLW datum varies with change in water surface slope, but can still be used when there is a relatively small variation in slope between surveys. If the slope changes considerably then a conversion to a fixed datum such as PWD is required. In most areas the method with SLW was acceptable because the fluctuations of the water slope were very small, i.e, ±1 cm/km. Only at Bahadurabd a conversion to PWD datum was necessary because the water surface slope varied substantially from 5 to 9 cm/km as shown in Table 2.2. The formulae of the conversion are given in Appendix B.

Erosion and deposition in the period between two surveys were computed using raster GIS modeling techniques with the following procedures:

- computation of erosion and deposition class value by taking symmetric differences and intersections of the two sets of elevation data covered by both bathymetric survey areas;
- recalculation of the erosion and deposition by recoding the above class values, and delineation of the areas of each class of erosion and deposition.

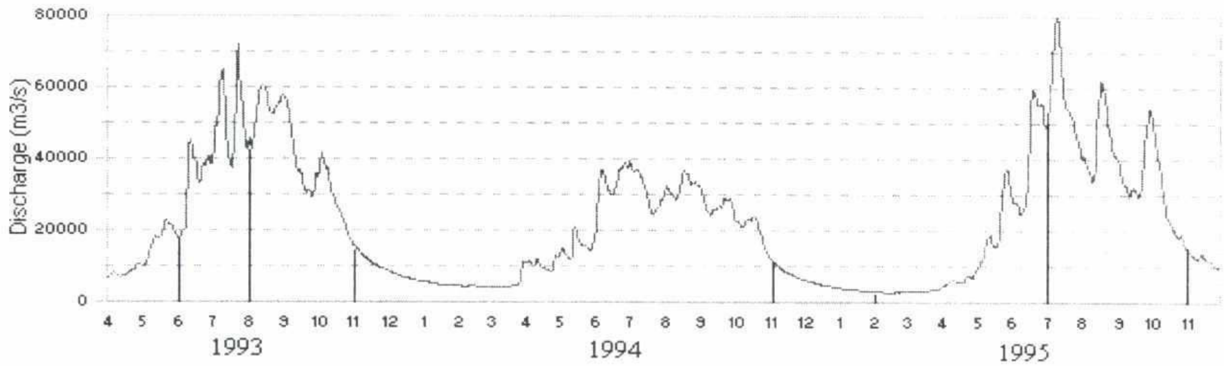
2.4 Results

Contour slice bathymetric maps were prepared for all 19 of the RSP surveys shown in Table 1.2. These bathymatric maps were used to produce erosion and deposition maps for each consecutive pair of bathymetric surveys and for other selected periods. These maps and assembled data are available with the EGIS Project and WARPO. The water discharge during the period of surveys at Bahadurabad are shown in Figure 2.2.

Figure 2.2 Water Discharge at Bahadurabad during the Survey Periods from June 1993 to November 1995

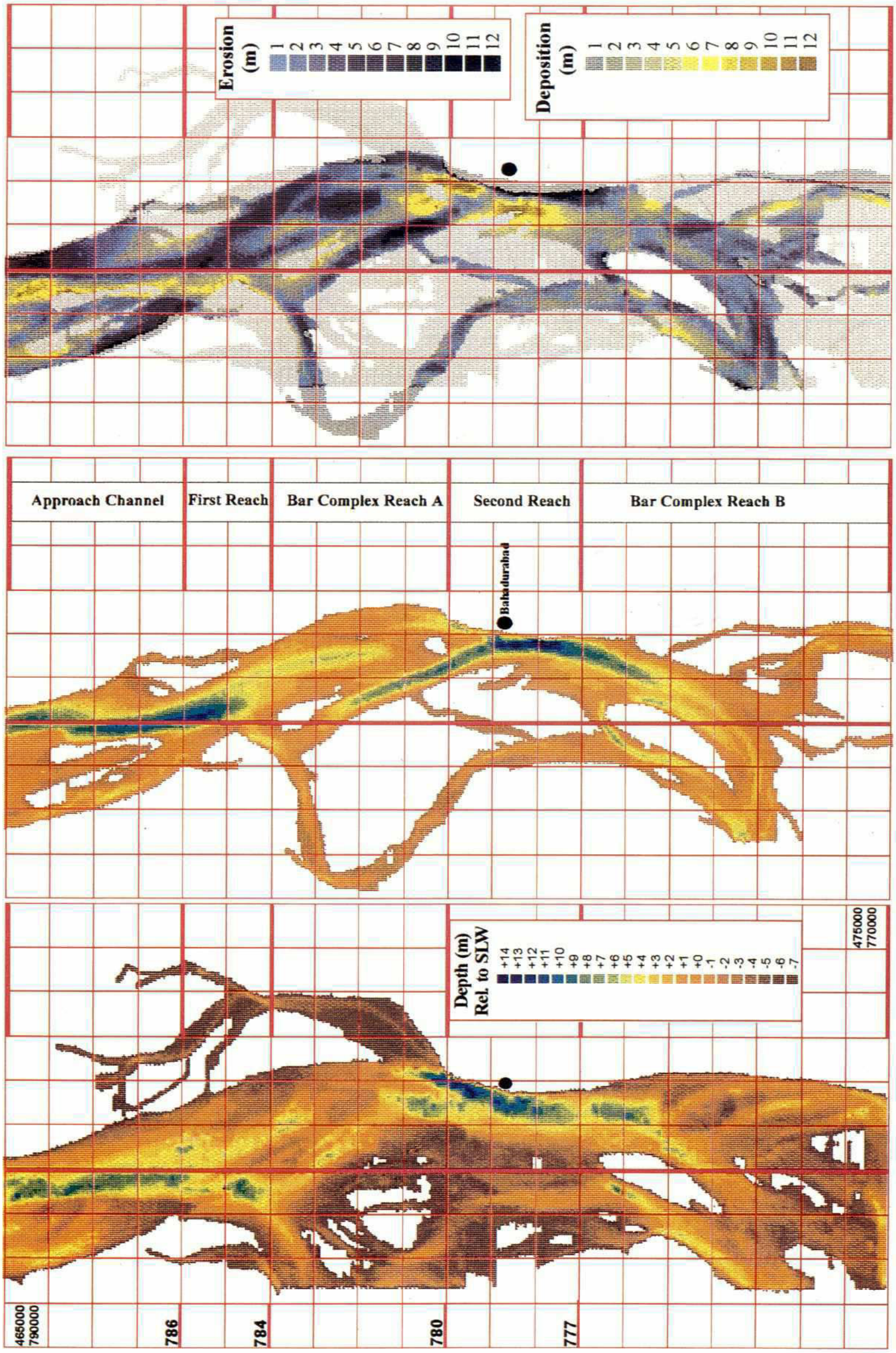
The bathymetric maps of July 1995 and November 1995 were also combined with land surface data to create a land surface contour map. Furthermore, they were used to construct a planform change map. All maps of July 1995 and November 1995 are shown in Figures 2.3 and 2.4. They reveal interesting features of bed topography and evolution of bed morphology which are discussed in Section 2.5.1.

The depth-area statistics of the Jamuna main channel at Kamarjani, the Jamuna Left Channel at Bahadurabad, the Ganges-Jamuna confluence at Aricha and the Ganges at the Gorai offtake are shown in Appendix D. Summary statistics on the bathymetry of the Jamuna Left Channel at Bahadurabad shown in Table 2.4, reveal the maximum and minimum average width of the left



channel at Bahadurabad are 4.03 km in July 1995 and 1.24 km in February 1995 respectively. These widths are the average distance between certain contour limes in a selected reach, see for more information SPR24 morphological processes in the Jamuna River, Section 7.3. The maximum and minimum depths relative to SLW at Bahadurabad are also shown in Figure 2.5. These results are discussed in Section 2.5.2.

Figure 2.3 Evolution of bathymetry at Bahadurabad from July to November 1995

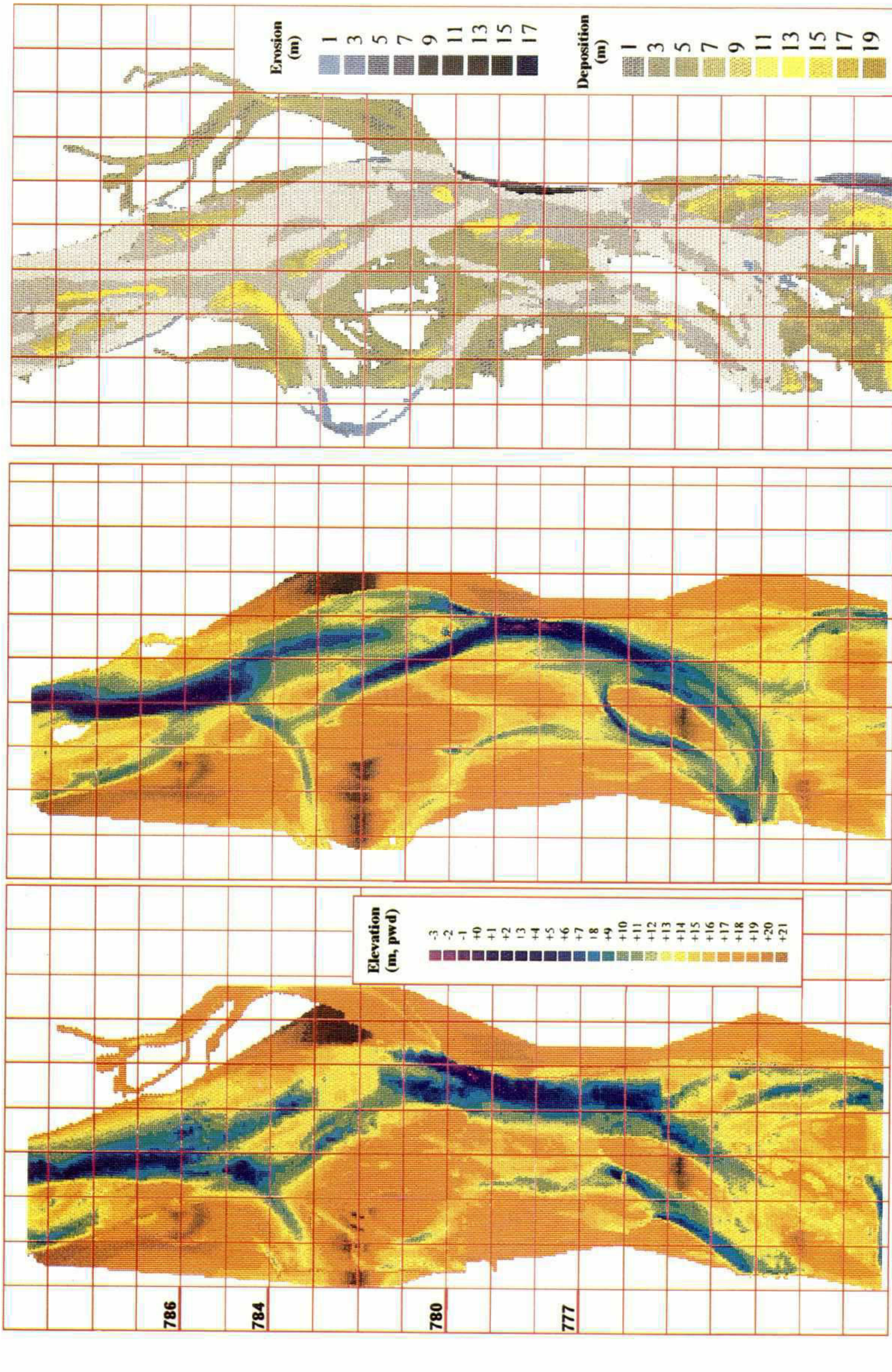


C. Bed erosion and depositon, July to November 1995

B. Bathymetry contour slice of November 1995

A. Bathymetry contour slice of July 1995

Figure 2.4 **Evolution of topography and planform at Bahadurabad from July to November 1995**



A. Land and bathymetry surface of July

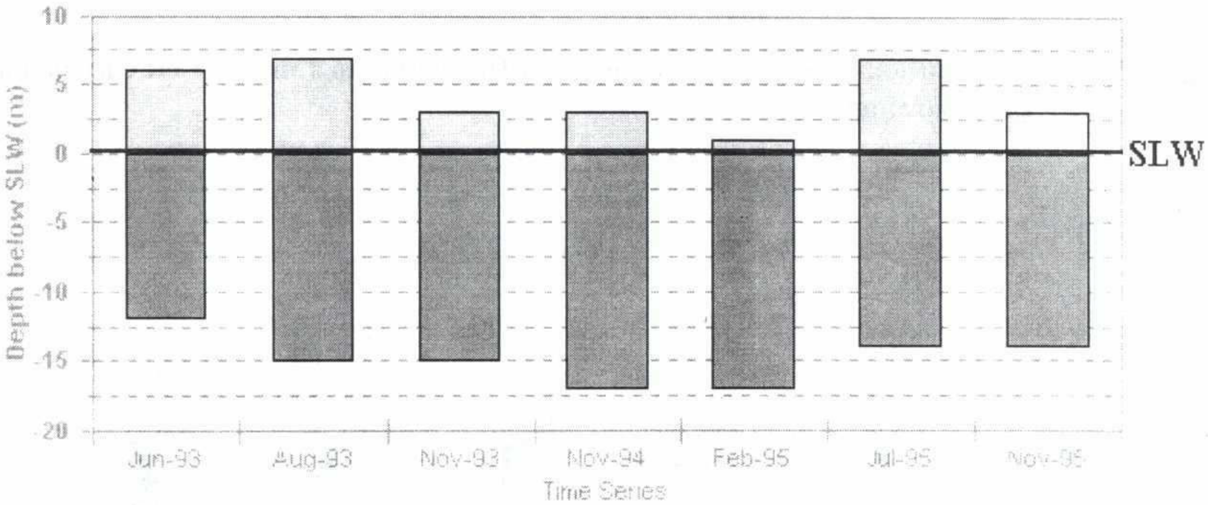
B. Land and bathymetry surface of November

C. Land surface changes, July to November

Table 2.4 Summary Statistics on River Bathymetry of Jamuna Left Channel for Bahadurabad Survey Area

Statistic	Jun93	Aug93	Nov93	Nov94	Feb95	Jul95	Nov95
• Depth (m)							
Maximum (SLW)	12.00	15.00	15.00	17.00	17.00	14.00	14.00
Minimum (SLW)	-6.00	-7.00	-3.00	- 3.00	-1.00	-7.00	-4.00
Mean (SLW)	-1.27	-1.05	0.94	1.70	3.19	-1.56	0.96
Standarddeviation(SLW)	1.59	1.67	1.71	1.76	1.67	1.73	1.63
Mean water depth	5.73	6.95	4.94	5.70	5.19	6.44	4.96
• Average width (km)	3.43	3.90	2.51	1.98	1.26	4.03	2.42
• Water surface area (ha)	6862	7805	5017	3958	2522	8066	4832

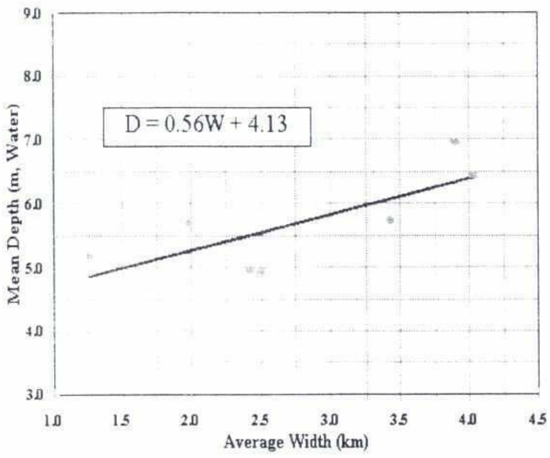
Figure 2.5 Depth Relative to SLW of Jamuna Left Channel at Bahadurabad from June 1993 to November 1995



Relations between depth and channel width are shown in Figures 2.6a and 2.6b. Those are also discussed in Section 2.5.2. The amounts of bed erosion and deposition at Bahadurabad are shown as a function of time in Figure 2.7 and Table 2.5. It should be noted that these results apply only to the part of the bed which was submerged in July as well as November 1995. The results are discussed in Section 2.5.3.

Figure 2.6A Mean Water Depth vs Channel Width

Figure 2.6B Mean Depth below SLW vs Channel Width



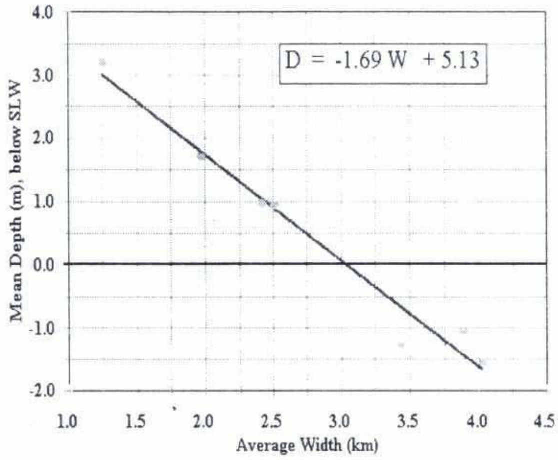


Figure 2.7 Distribution of Sediment Erosion and Deposition in Jamuna Left Channel at Bahadurabad

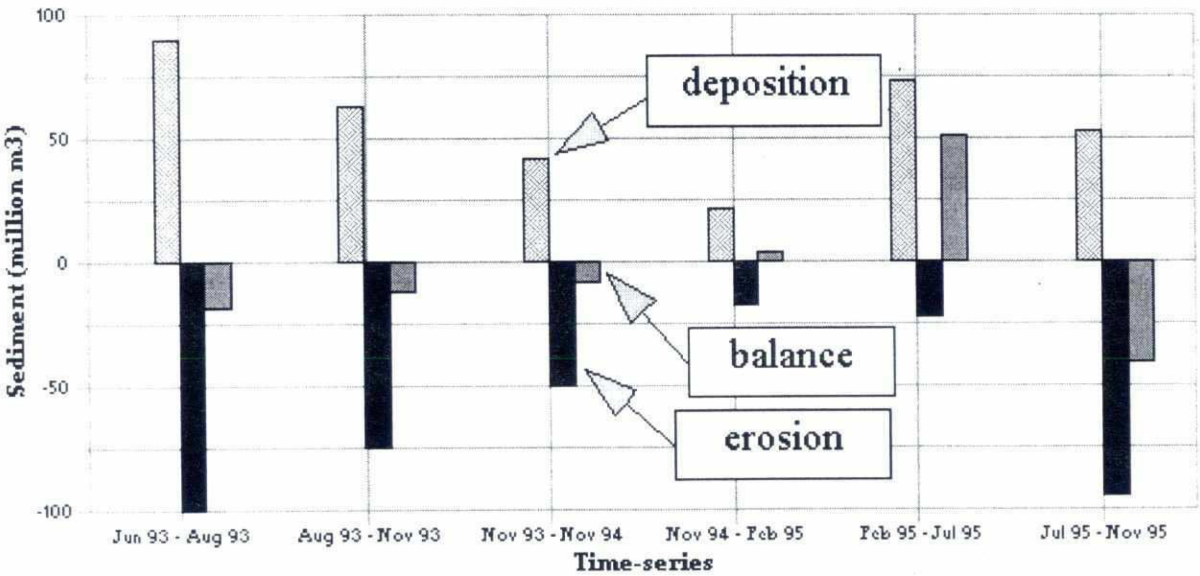


Table 2.5 Volumetric Changes in the River Bed of Jamuna Left Channel at Bahadurabad

Bed-level Changes in	Compared with	Erosion million m^3	Deposition million m^3	Balance million m^3
Aug-1993	Jun -1993	108.19	89.85	-18.34
Nov-1993	Aug-1993	74.39	62.56	-11.83
Nov-1994	Nov-1993	49.94	41.74	- 8.20
Feb- 1995	Nov-1994	17.18	21.17	3.90
Jul - 1995	Feb -1995	22.59	73.22	50.63
Nov-1995	Jul - 1995	93.95	53.01	-40.94

2.5 Interpretation and Discussion

2.5.1 Features of Bed Topography and Evolution of Bed Morphology

The study area comprises a reach of the left bank anabranch of the Jamuna. It covers five morphological units that can be seen to persist over the full study period from June 1993 to November 1995, although their size, shape and geographical location evolve through time. These five main units are given in Table 2.6.

Table 2.6 Main Morphological Units in Study Reach

Morphological Unit	Northing (km)	Comments
Approach Channel	790 - 786	
First Nodal Reach	786 - 784	University of Leeds Study Bar
Bar Complex Reach A	784 - 780	
Second Reach	780 - 777	Bahadurabad Ghat and FAP 21/22 test site for bank revetments
Bar Complex Reach B	777 - 770	Includes Roy's Bar (studied by University of Nottingham)

The morphological development in this study area were described for the period 1992-1994 by Peters (1994) in a study of SPOT satellite images. In continuation, the morphological developments in 1995 are described in the following.

As can be observed from Figure 2.4 (A and B), the thalweg of the Approach Channel crosses the channel from the east bank to the west bank with a south heading. After July 1995 it migrates eastward. The channel divides twice in the First Nodal Reach, producing a west channel, a center channel and an east channel. The first bifurcation shifts downstream from Northing 786.1 in July 1995 to 785.1 in November 1995, the second from Northing 784.3 in July 1995 to 783.8 in November 1995. Both bifurcations display a typical downstream Y-shaped scour pattern. In the divided reach around Bar Complex A, the center channel is the largest. The west channel follows a strongly curved path with an arc angle of 120° and joins the other channels within Bar Complex B. Its previous strongly asymmetrical cross-profile with deep scour at the outer, flanking bank and a shelving bar at the inner bank has become less pronounced, but in the sharp turn at Northing 782.8 in November 1995 such a cross-profile is still visible.

The center channel and the east channel were both growing between July and November 1995, producing marked erosion 'hot spots' on the map of erosion and deposition (Figure 2.4C). The nature of the growth, however, is different for the two channels. The growth of the center channel is related to retarded scour during the falling limb of the discharge hydrograph, when continuous low-water channels are carved through shallow crossings and other areas of locally diverging flood flow. The growth of the east channel is related to the formation of a new major channel by cutting a deep path through the river bed, advancing from upstream to downstream. It is induced by the eastward migration of the Approach Channel. The deep path of the east channel is expected to meet the center channel during the fall of the flood in 1996, causing deep confluence scour in front of Bahadurabad Ghat. East of these channels another system of channels can be seen on the maps of July 1995. These channels are much shallower than the other three and follow an old embayment cut into the left bank.

The center channel and the flow from the east channel meet in the Second Nodal Reach. The combined action of constriction scour, confluence scour and bend scour results here in a very deep channel. This channel forms a clear bend in November 1995 and displays the typical cross-profile asymmetry with deep scour at the outer bank and a shelving bar at the inner bank. It divides at Northing 777 around the upper bar of Bar Complex B. This upper bar has two characteristic downstream wings at Northing 774.0 and 774.6 on the map of July 1995. Secondary flow plays an important role in shaping these wings, though, interestingly, the wings are already present at incipient bar growth when the effect of secondary currents is negligible.

The longer eastern wing is an indication that the channel along the eastern side is more important than the channel along the western side. The land surface contour map of July 1995 shows that this is indeed the case. The eastern wing grows further after July and captures the western wing. On the maps of November 1995 the western wing is no longer visible. The dominant eastern wing has the shape of a spit or sand arrow which on satellite images and aerial photographs serves as an indicator of ongoing sedimentation. This complies with the sedimentation shown on the map of erosion and deposition (Figure 2.4C).

2.5.2 Depth-Area Statistics

Figure 2.5 shows that the bed level is generally lower during the dry season than during the flood season. This is due to two effects. Firstly, some areas are submerged during the flood season but exposed during the dry season. Hence those areas do not contribute to the determination of the minimum depth in the dry season, which leads to reporting of higher values of the minimum depth relative to SLW. Secondly, the main channels tend to become incised more deeply in the dry season due to retarted scour during the fall of the flood. This leads to higher values of the maximum depth. Thus Figure 2.5 displays clear seasonal effects. An overall trend of changes through the years is not found.

Figures 2.6A and 2.6B show that there is a significant correlation between the channel width and the water depth (positive) or the depth below SLW (negative). Figure 2.6A reflects that channels do not have a rectangular cross-section but one in which the width increases with elevation. Figure 2.6B, reflects the trend from Figure 2.5 that the average level of the submerged bed is lower during the dry season when the widths are smaller. Lower bed levels imply a larger depth below SLW

These relations were also studied in Study Report 7 of RSP (1996) where the average depth and width as function of the channel discharge were presented to establish regime equations for the different rivers.

2.5.3 Sediment Balance

Figure 2.7 shows for danger parts of the river that net erosion occurs in during the period from the beginning of the flood to November, net deposition occurs from November to the beginning of the next flood season. The largest amounts of erosion and deposition occur during the flood season. This can be seen when comparing the erosion and deposition between June and August 1993 with the erosion and deposition between November 1994 and February 1995.

A comparison of the changes between August 1993 and November 1993 with the changes between November 1993 and November 1994 suggests that the net erosion and the net deposition are smaller over a full year than over a few months of the flood season. An explanation is that the bed may be considerably reworked during the flood, but that retarded scour during the fall of the flood re-creates a bed topography which resembles to a large extent the topography of the previous year due to forcing by the planform. The unusually large amount of deposition between February and July 1995 is likely caused by channel shifting since part of the deepest channels of July lies in areas which were not submerged in February.

The sediment balance would be more complete if topographic data of the land surface were included. If time permits this will be completed later in 1996 under Activity 4C of the RMRIS project. For the bathymetric surveys before the flood of 1995, however, no land surface data are available.

Some error is introduced to sediment balance computations by the way the original survey data were interpolated into values on a 50 m grid using post processing software of the MIKE 21 package. The procedure in MIKE 21 is not a simultaneous interpolation between three or more surrounding points, but a series of two-point interpolations in different directions. This leads to inaccuracies, particularly in case of missing data.

92

Chapter 3

Water flow, Sediment Concentration and Prediction of Morphological Changes

3.1 Introduction

Flow velocity and ADCP backscatter data for the Bahadurabad study reach in August 1993 and July 1995 were used to map flow fields and sediment concentration fields so as to visualize and interpret the fluvial processes in the river. The flow velocity data are combined with bathymetry data to develop and test a prediction method for short-term morphological changes along the lines of Peters (1988).

3.2 Data Description

3.2.1 Flow Data

Flows were recorded by RSP with different methods during the bathymetric surveys of August 1993 and July 1995:

- *Cross-sectional flow distribution measurements by ADCP (Acoustic Doppler Current Profiler)*: Recording of the vertical flow profile by determining the phase lag between an emitted and a reflected sound wave while cruising across the river (moving boat method) in a both survey.
- *Float tracking of surface flow trajectories:* Recording of the time development of the position of a float on the water surface. This provides a Lagrangean description of the flow as distinguished from the Euleran description given by single-point measurements of the time variation of the velocity vector at a fixed position.

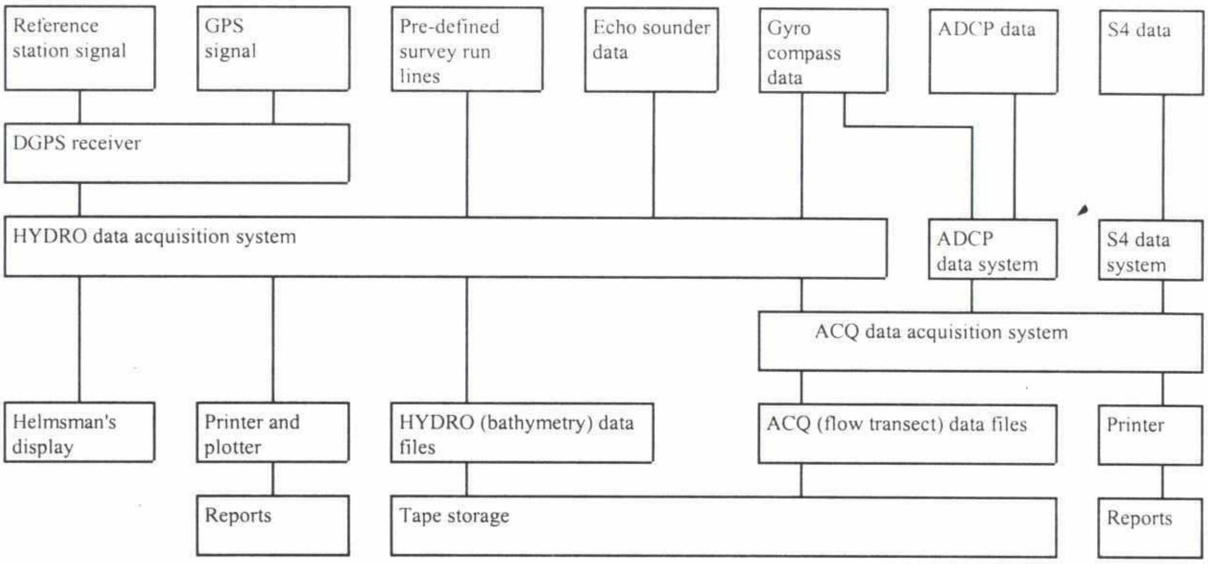
The ADCP transect measurements were applied using the moving boat method. The on-line data flow for RSP stationary ADCP vertical measurements are shown in Figure 3.1. The float tracking was carried out in July 1995 within the 'special survey program' as shown in Table 3.1.

Table 3.1 RSP Measurements of Flow Trajectories by Float Tracking

Location	Start date	End date	Survey number
Bahadurabad [1/]	26-Jul-95	31-Jul-95	9071
Gorai Off-take	11-Aug-95	14-Aug-95	9077
Gorai Off-take	11-Oct-95	15-Oct-95	9080
Bahadurabad	18-Nov-95	23-Nov-95	9094
Kamarjani	05-Dec-95	19-Dec-95	9095
Confluence	25-Jan-96	04-Feb-96	9096

[1] used in this study

Figure 3.1 On-line Data Flow for Routine Gauging by RSP Survey Units



3.2.2 Sediment Transport Data

Sediment transport data were obtained by sampling in combination with the traditional area-concentration method, but also from ADCP measurements.

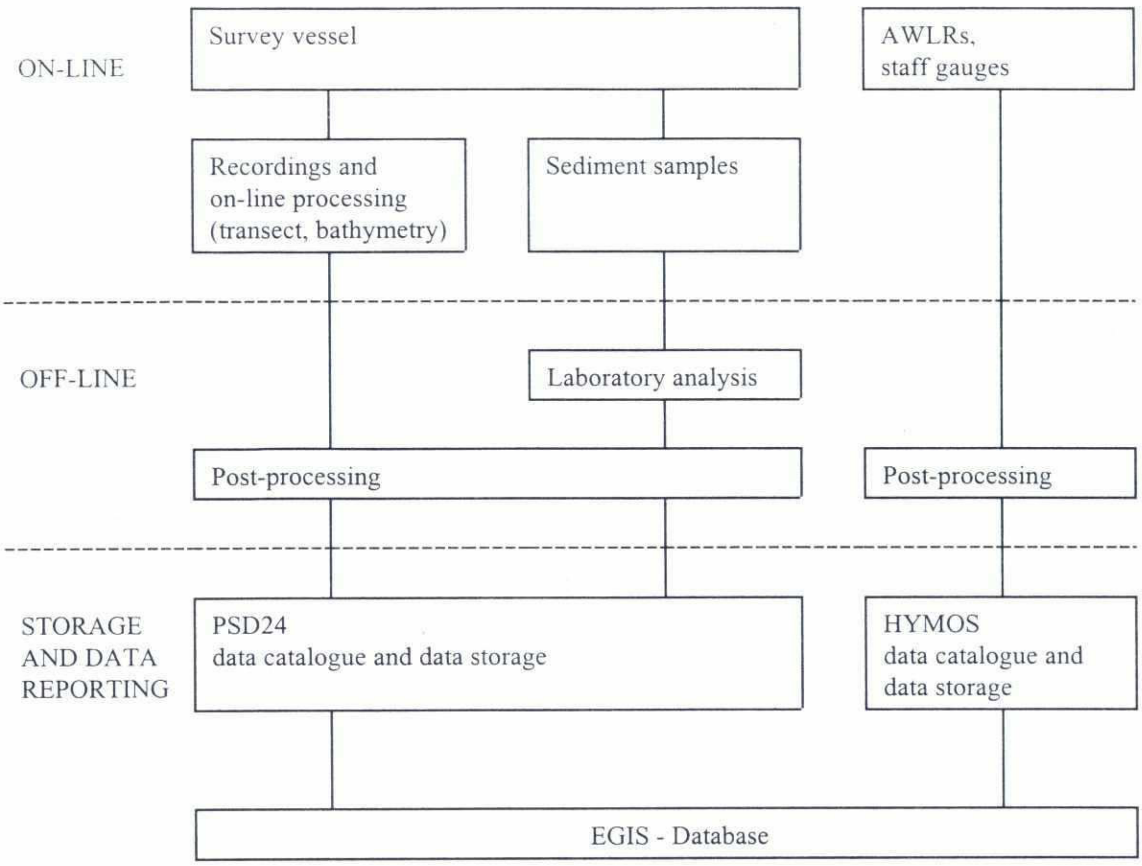
An ADCP instrument registers the phase lag and the intensity of a reflected sound wave. The phase lag provides information on the flow velocities treated in Section 3.2.1. The intensity is called 'backscatter' and, for a given ADCP sound signal frequency depends on the sediment concentration and the sediment grain size distribution. In theory, if either the concentration or the grain size distribution is known, the other quantity can be determined from the backscatter. For some of the RSP bathymetric surveys, the ADCP backscatter signal was registered together with the ADCP flow transect measurements and the sediment transport measurements.

3.3 Data Processing

3.3.1 Processing of Flow and Sediment Data by RSP

The routine processing of RSP data consisted of data conversion and compression, calculation of flow and sediment transport rates and distributions, plotting for quality checks, data reporting, listing of files in a data catalogue and storing of data in three databases. Water level data were stored in a HYMOS database, routine transect flow data and backscatter data were stored in a Paradox/Quattro Pro database called PSD24 (Processed Survey Data of FAP24) and sediment analyses were stored in a separate Quattro Pro database. The results of the routine gauging were presented in RSP Data Books. The overall data flow is shown in Figure 3.2.

Figure 3.2 Summary of RSP Data Flow



3.3.2 Float Tracking Data

Non-routine data processing for the purpose of the present study consisted of analysis and presentation of the float tracking data. These Lagrangean data were analyzed together with the Euleran data from the single-point flow measurements. The hydrodynamic information from these two complementary methods was integrated.

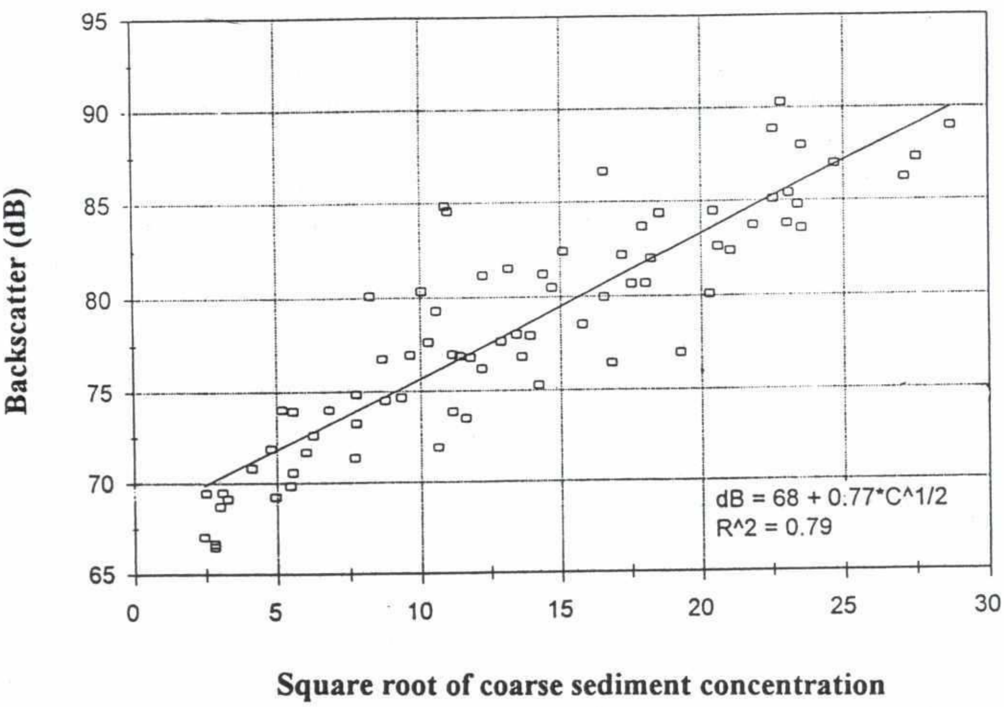
3.3.3 Calculation of Sediment Concentrations from ADCP Backscatter

A relation between ADCP backscatter (at 300 kHz) and coarse sediment concentrations in Bahadurabad in the period 1993 - 1995 had been found empirically in previous studies by Delft Hydraulics/DHI (1996). Coarse sediment is defined as particles with a sieve diameter > 0.0063 mm. Some of the observations are shown in Figure 3.3. The relation is given by

$$dB = 68 + 0.77\, c^{0.5} \qquad (3.1)$$

in which dB is the backscatter value in decibels and c is the concentration of the sand fraction of the sediment. This relation was used to derive vertically averaged sediment concentrations from ADCP backscatter measurements. For the silt fraction the data was more scattered and no relation could be established. More information about theoretical backgrounds and measurements in the Jamuna River is given by Sarker (1996).

Figure 3.3 Comparison between ADCP Backscatter and Suspended Bed Material Concentrations at Bahadurabad, July-December 1994



3.3.4 Calculation of Sediment Concentrations from Flow Field

Vertically averaged sediment concentrations were also calculated from the flow field with the following sediment transport formula:

$$c = \propto \frac{u^{2.6}}{h} \qquad (3.2)$$

in which c denotes concentration, u denotes flow velocity, h denotes water depth and $\propto$ is a coefficient. GIS was used to determine a best-fit value of $\propto$ by comparing the resulting sediment concentration map visually with the map derived from ADCP backscatter measurements.

3.3.5 Short-term Prediction of Morphological Changes

Peters (1988) developed a short-term prediction method for morphological changes in the Zaire River in Africa based on the idea that erosion and deposition tend to establish an equilibrium relation between water depth and flow velocity. Erosion is expected where flow velocities are too high in view of the local water depth, deposition where flow velocities are too low. A similar method for the Jamuna River was derived from a part of the measurements at Bahadurabad in August and November 1993. The results in Figure 3.4 gave the following erosion and deposition model:

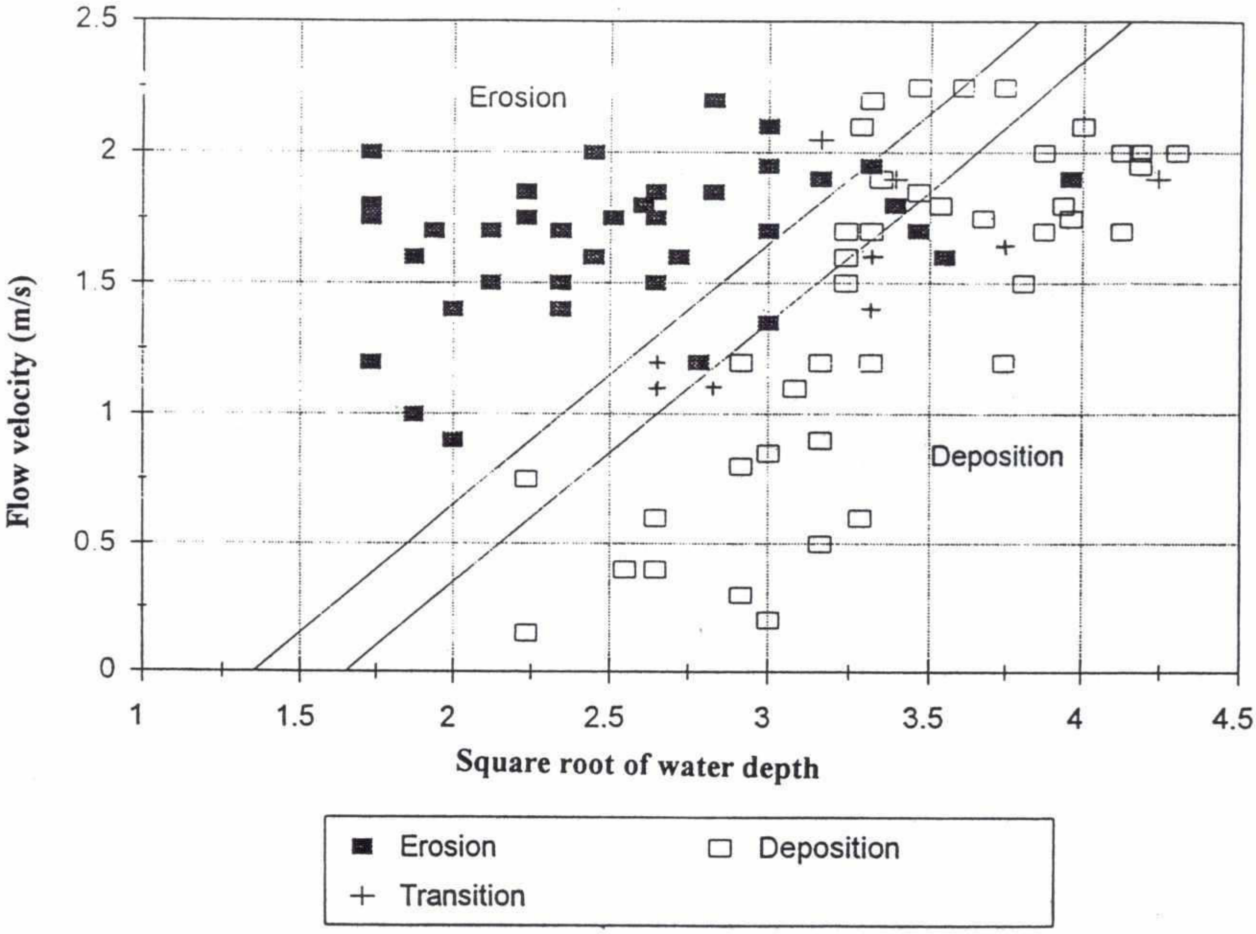
$$u > \sqrt{h} - 1.35 \qquad \textit{Erosion}$$

$$\sqrt{h} - 1.35 \leq u \leq \sqrt{h} + 1.35 \qquad \textit{Transition} \qquad (3.3)$$

$$u < \sqrt{h} + 1.35 \qquad \textit{Deposition}$$

in which u denotes flow velocity and h denotes water depth. The transition zone is defined as the zone where the bed level changes less than one meter. The above formulas were used to process depth and velocity data into a map of expected erosion and deposition.

Figure 3.4 Erosion and Deposition as a Function of Local Flow Velocity and Water Depth



3.4 Results

A color contour map of depth-averaged flow velocities derived from ADCP data is given in Figure 3.5. There are a lot of missing data due to the limited extent of the survey. A color contour map of surface flow velocities and flow lines derived from float tracking is given in Figure 3.6. A color contour map of sediment concentrations from ADCP backscatter is shown in Figure 3.7. Maps of sediment concentrations calculated from the flow field with the tentative sediment transport formula (3.2) were also produced for several values of $\propto$, but the agreement with concentrations from backscatter measurements was very poor. Those maps are not shown here.

Short-term predictions of erosion and deposition at Bahadurabad are compared with measurements in Figures 3.8 and 3.9. The flow data of August 1993 in Figure 3.8 were derived from ADCP measurements, the flow data of July 1995 in Figure 3.9 from float tracking.

Fig. 3.5 **Depth-average Flow Velocities from ADCP Measurements at Bahadurabad in August 1993**

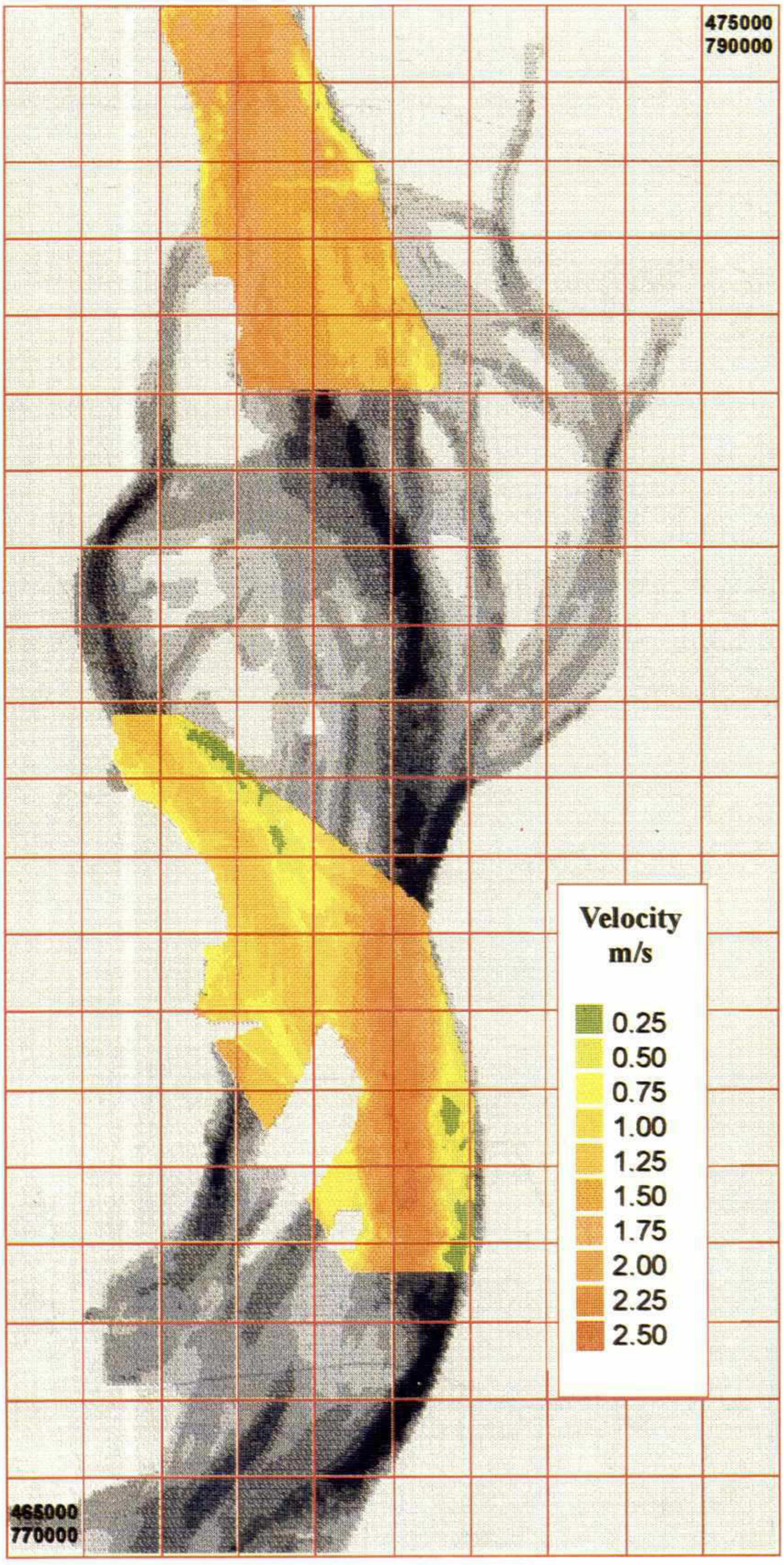


Fig 3.6 **Surface Flow Velocities and Flow Lines from Float Tracking at Bahadurabad in July 1995. The dashed line represents a correction of an error in the float tracking.**

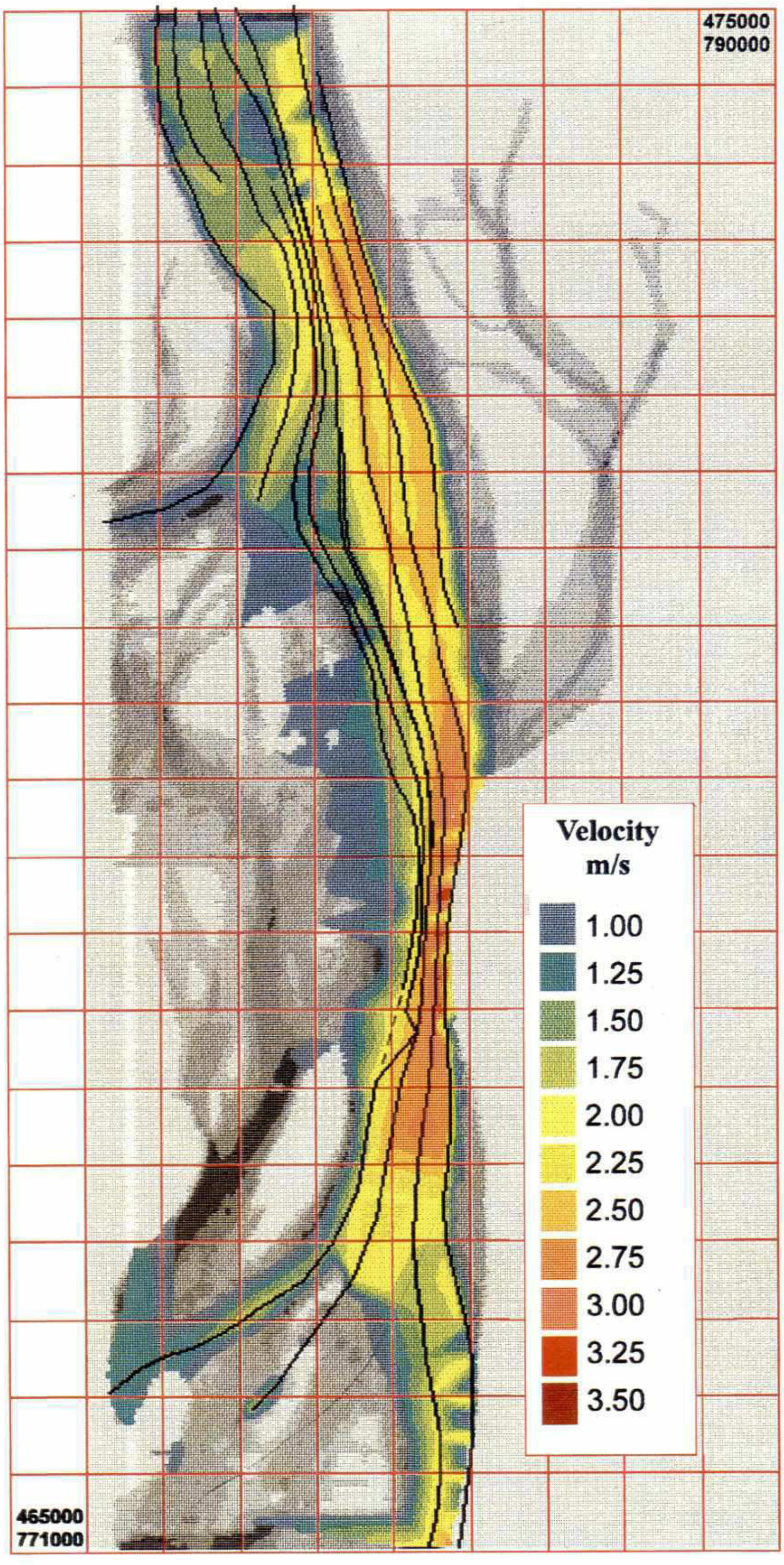


Fig 3.7 **Depth-averaged Sediment Concentrations from ADCP Backscatter at Bahadurabad in August 1993**

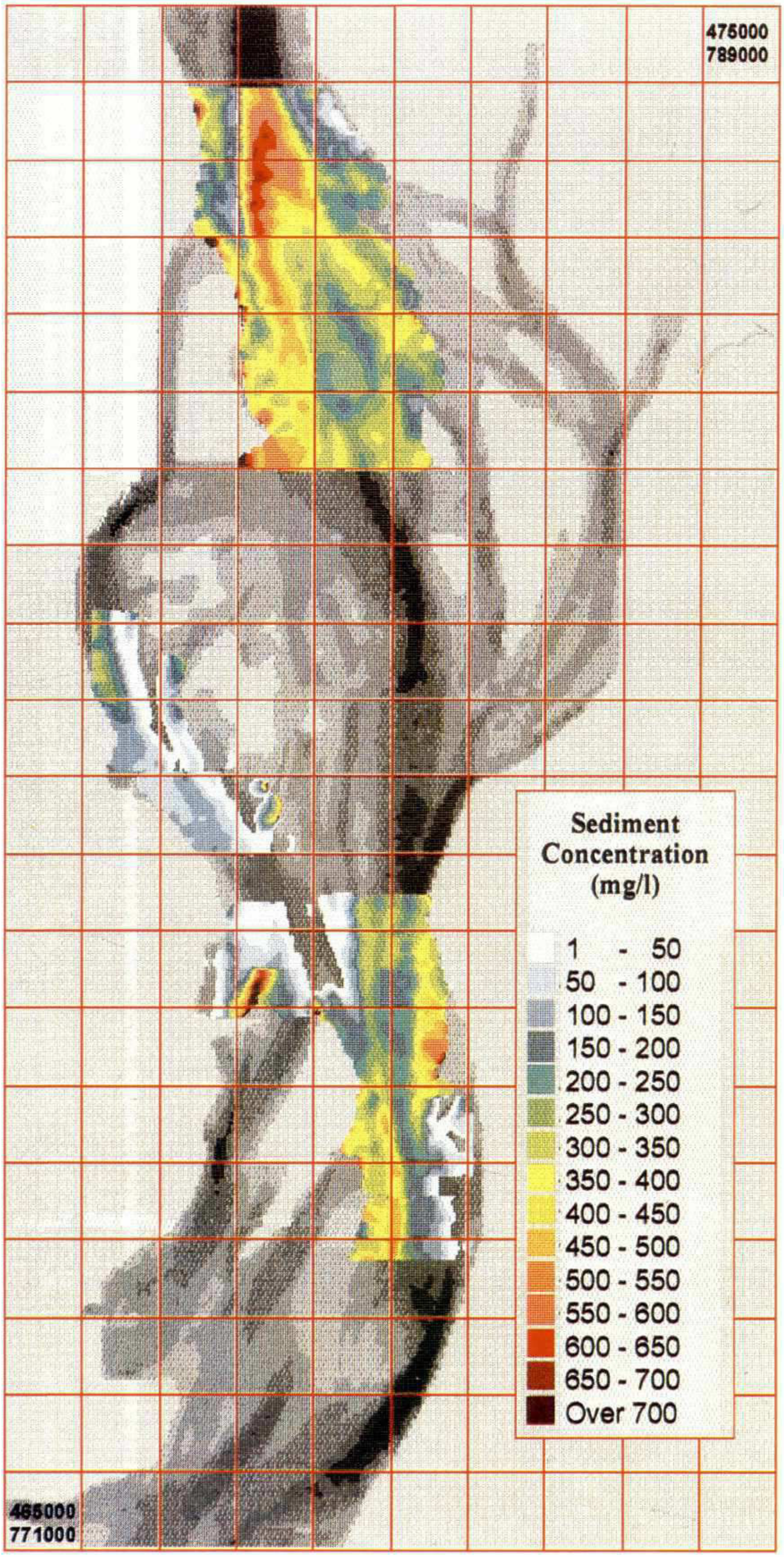


Fig 3.8 **Comparison of Predicted and Measured Morphological Changes at Bahadurabad between August and November 1993**

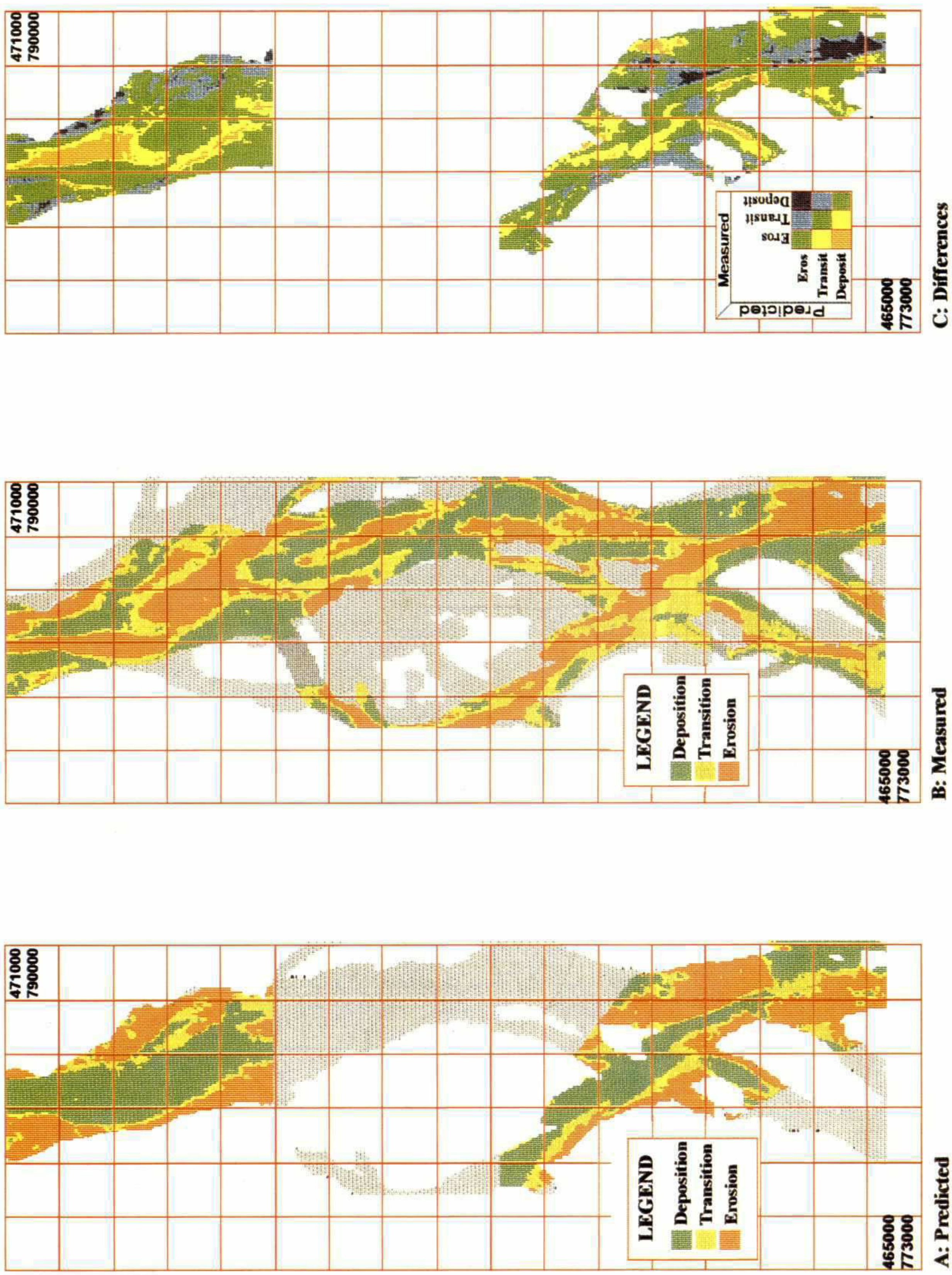
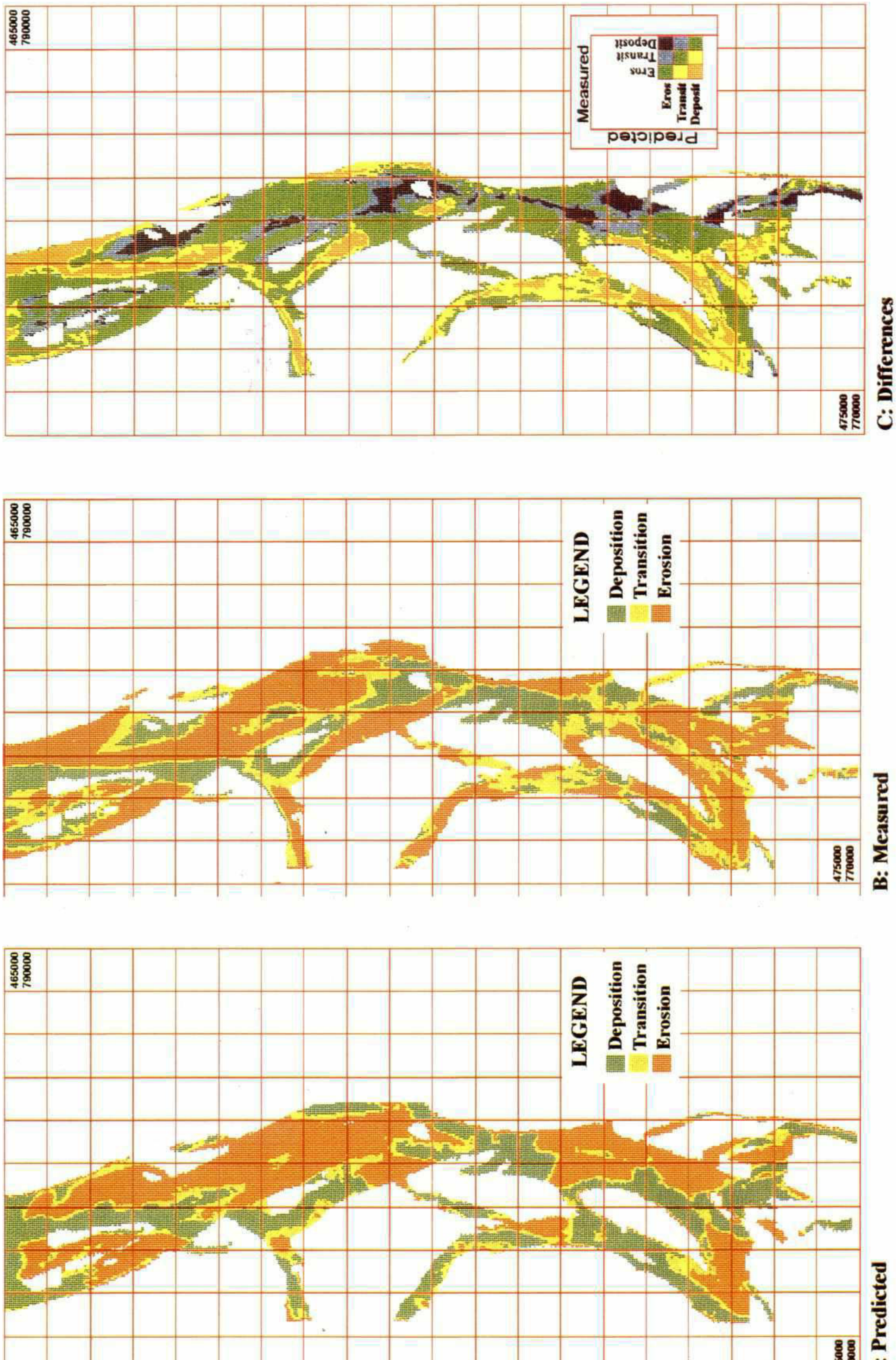


Fig 3.9 Comparison of Predicted and Measured Morphological Changes at Bahadurabad between July and November 1995



3.5 Interpretation and Discussion

3.5.1 Flow Velocity and Sediment Concentration Measurements

The flow patterns in Figures 3.5 and 3.6 resemble the corresponding bathymetry maps; flow velocities are higher in deeper areas. Flow strips between adjacent flow lines in Figure 3.6 show that flow velocities increase between converging flow lines and decrease between diverging flow lines. The maps can be used together for more information. For example, the pattern of high velocities at the upstream side of the bar in the upper part of Figure 3.5 is similar to the corresponding pattern of high sediment concentrations in Figure 3.7. Together they indicate that the upstream side of the bar is eroding.

3.5.2 Short-term Prediction of Morphological Changes

Predicted morphological changes, measured morphological changes and a comparison are shown in Figures 3.8 and 3.9. In the comparison maps, green indicates a correct prediction, yellow shows prediction of too high a bed level and blue shows prediction of too low a bed level. The overall quality of the predictions is quantified in Table 3.2.

Table 3.2 Assessment of Short-term Predictions of Morphological Changes at Bahadurabad

Period	Time Span (months)	Percentage of Area		
		Correct prediction	Predicted bed level too high	Predicted bed level too low
Aug - Nov 1993	3	60%	20%	20%
Jul - Nov 1995	4	49%	29%	22%

The three months (1993) predictions are better than the four months (1995) predictions. There are two explanations for this. First, the formulas of the prediction method were derived from the data of 1993; second, the period in 1995 includes more of the peak of the flood, for which Coleman (1969) observed that the shifting of the thalweg is less gradual and more erratic than during the receding limb of the hydrograph.

The method of Peters (1988) identifies the location of erosion and deposition but they are not quantified. This makes assessment of the prediction method difficult. Peters' method can be made quantitative, however, by modifying it into the following predictor:

$$\Delta z_b = \Delta t \cdot k_1 \cdot \left(1 - \frac{u}{k_2 \sqrt{h}} \right) \tag{3.4}$$

where

Δz_b = bed level change (m)

Δt = time span of prediction (s)
k_1 = coefficient to be derived from the data (-)
k_2 = coefficient to be derived from the data, in theory equal to the product of Chézy coefficient and square root of river slope (-)
u = flow velocity (m/s)
h = water depth (m)

This predictor (3.4) retains the original idea of Peters (1988), because it results in erosion when $u > k_2\sqrt{h}$, in deposition when $u < k_2\sqrt{h}$ and in minor bed level changes when $u \approx k_2\sqrt{h}$.

It might also be interesting to test another prediction method which is closer to the physical-mathematical description of the processes involved. In this method bed level changes would be assumed to be proportional to flow velocity gradients. A final selection of a method for operational use might be based on a trade-off between improved predictions, increased amount of work and the prediction time span.

Chapter 4

Land Surface Elevations and Median Conveyance Lines

4.1 Introduction

Satellite images provide information on the river bed in a horizontal plane whereas cross-sections provide information in vertical planes. A more complete picture of the river bed is obtained when information from satellite images and cross-sections is merged. This merging of planes or dimensions requires spatially referenced hydrometric data for the same time as recording of the satellite images.

The geo-referencing of cross-sections is described in this chapter. It serves three purposes. First, it is a method to validate the cross-sections because cross-sections which fit the satellite image well can be assumed to be more reliable than cross-sections which do not fit. Second, it allows the positioning of median conveyance lines on the satellite images; study of the movements of the median conveyance line might reveal overall trends in river channel migration. Third, it assists in the construction of a digital terrein model (DTM) of the entire extent of the braid belt of the river.

4.2 Data Description

4.2.1 Hydrometric Data

The complex nature of the hydro-morphological conditions of Bangladesh makes the collection of water related data from the field very difficult. The Surface Water Hydrology section of BWDB has been reading water levels 5-7 times a day at 314 stations since 1960. Discharges have been recorded weekly, fortnightly or monthly at 104 stations since 1964. Six water level stations and one discharge station are located on the Jamuna River.

Table 4.1 shows which digital water level data and discharge data from BWDB were used in this study. All data are available in spreadsheets created by RSP. Hence, water surface slopes, widths and depths can be computed from cross-sectional data and these water level and discharge data.

4.2.2 Satellite Imagery

The Landsat MSS and TM satellite images at EGIS are listed in Table 1.3. All images were processed, but only the images of 1978, 1980, 1987 and 1994 were used for the study on land surface elevations and median conveyance lines. These dated were selected because the stages at Bahadurabad, Kazipur and Sirajganj were always about 13.0, 9.0 and 6.8 m+PWD, respectively. All the images show the Jamuna River during low-flow conditions. The images were geometrically corrected (with ± 80 m error), so that cross-sectional and other geographically corrected information could be overlaid for comparison.

Furthermore, hardcopies of SPOT satellite images of 1994 on scale 1:50,000 were provided by RSP. These were used for georeferencing of the cross-sections of 1994.

Table 4.1 Hydrometric Data Availability for Ganges-Jamuna River System

Hydrometric Station	Type[1/]	Available Water Year (April to March)						
		1964	1965	1966	1967-1990	1991	1993	1994
Ganges R.								
Hardinge Bridge	WL	∩	∩	∩	∩	∩	∩	∩
	Q		∩	∩	∩	∩		
Sengram	WL	∩	∩	∩	∩	∩	∩	
Mahendrapur	WL	∩	∩	∩				
Jamuna R.								
Bahadurabad	WL	∩	∩	∩	∩	∩	∩	∩
	Q		∩	∩	∩	∩	∩	
Kazipur	WL			∩	∩	∩		
Sirajganj	WL	∩	∩	∩	∩	∩	∩	∩
Porabari	WL	∩	∩	∩	∩	∩	∩	
Mathura	WL	∩	∩	∩	∩	∩	∩	
Padma R.								
Baruria Transit	WL	∩	∩	∩	∩	∩	∩	
	Q		∩	∩	∩	∩		

1/: WL = water level, Q = discharge

4.2.3 Cross-sectional Data

The cross-sectional characteristics of the river were studied on the basis of soundings made by BWDB since 1966. Out of the 144 cross-sections of major rivers surveyed by BWDB every year, 34 are located on the Jamuna River. Table 4.2 gives an overview of the available cross-sectional data.

In this study only cross-sections from 1978, 1980, 1987 and 1994 were used. The data had originally been recorded in graphical form. They were digitized by FAP1 and provided in the form of a database. Furthermore, data on 22 cross-sections surveyed in 1994 were collected from SWMC and BWDB.

Table 4.2 Cross-sectional Data Availability for Jamuna River

BWDB	75	76	77	78	79	80	81	83	84	85	86	88	89	91	92	93	
X-Section Number		76	77	78	79	80	81	82	84	85	86	87	89	90	92	93	94
J#0_1	∩	∩	∩	∩	∩	∩	∩	∩		∩			∩	∩			
J#1	∩	∩	∩	∩	∩	∩	∩	∩	∩	∩			∩			∩	
J#1_1	∩	∩	∩	∩	∩	∩	∩	∩		∩	∩			∩		∩	
J#2	∩	∩	∩	∩		∩	∩	∩	∩	∩	∩	∩	∩	∩			
J#2_1	∩	∩	∩	∩	∩	∩	∩	∩	∩	∩	∩	∩	∩	∩	∩		
J#3	∩	∩	∩	∩	∩	∩	∩	∩	∩	∩	∩	∩		∩	∩	∩	
J#3_1	∩	∩	∩	∩	∩	∩	∩		∩	∩	∩	∩	∩	∩			
J#4	∩	∩	∩	∩	∩	∩	∩	∩	∩	∩	∩	∩	∩	∩	∩		
J#4_1	∩	∩	∩	∩	∩	∩	∩		∩	∩	∩					∩	
J#5	∩	∩	∩	∩	∩	∩	∩	∩	∩	∩	∩	∩	∩	∩	∩		
J#5_1	∩	∩	∩	∩	∩	∩	∩		∩	∩	∩	∩	∩	∩	∩		
J#6	∩	∩	∩	∩	∩	∩	∩	∩	∩	∩	∩	∩	∩	∩	∩		
J#6_1	∩	∩	∩	∩	∩	∩	∩			∩	∩	∩	∩	∩	∩		
J#7	∩	∩	∩		∩	∩	∩	∩	∩	∩	∩		∩	∩	∩		
J#7_1	∩	∩	∩		∩	∩	∩			∩	∩	∩	∩	∩			
J#8	∩	∩	∩	∩	∩	∩	∩	∩	∩	∩	∩	∩					
J#8_1	∩	∩	∩	∩	∩	∩	∩			∩	∩					∩	
J#9	∩	∩		∩	∩		∩	∩	∩	∩	∩					∩	
J#9_1	∩	∩	∩	∩	∩	∩	∩			∩	∩					∩	
J#10	∩	∩	∩	∩	∩	∩	∩	∩	∩	∩	∩	∩				∩	
J#10_1	∩	∩	∩	∩	∩	∩	∩	∩			∩	∩				∩	
J#11	∩	∩	∩	∩	∩	∩	∩	∩	∩	∩	∩	∩				∩	
J#11_1	∩	∩	∩	∩	∩	∩	∩	∩		∩	∩	∩					
J#12	∩	∩	∩	∩	∩	∩	∩	∩	∩	∩	∩					∩	
J#12_1	∩	∩	∩	∩	∩	∩	∩	∩	∩	∩	∩					∩	
J#13	∩	∩	∩	∩	∩	∩	∩	∩	∩	∩	∩		∩			∩	
J#13_1	∩	∩	∩	∩		∩		∩	∩	∩							
J#14	∩	∩	∩	∩	∩	∩	∩	∩	∩	∩	∩						
J#14_1	∩	∩	∩	∩	∩	∩	∩		∩	∩	∩		∩			∩	
J#15	∩	∩	∩	∩	∩	∩	∩	∩	∩	∩	∩					∩	
J#15_1	∩	∩	∩	∩	∩	∩	∩			∩	∩						
J#16	∩	∩	∩		∩	∩	∩	∩	∩	∩	∩		∩				
J#16_1	∩	∩	∩	∩	∩	∩			∩	∩							
J#17	∩	∩	∩	∩	∩	∩	∩	∩	∩	∩	∩	∩	∩				

4.3 Data Processing

4.3.1 Water Levels

Local water levels were calculated from the water levels at hydrometric stations by using the local slope of the water surface. This slope was not constant, but varied from reach to reach and also from season to season. In addition to the local slopes, the overall slope from Chilmari down to Mathura near the confluence with the Ganges was determined for each month. It was found to vary from 0.065 m/km in the monsoon to 0.075 m/km in the dry season. The average slope for the Jamuna was calculated as 0.070 m/km from the historical data.

4.3.2 Land Cover Type

The full series of satellite images from 1973 to 1994 was classified according to the type of land cover. All images were first histogram matched to the 1976 image in order to standardize the classification procedure. This histogram matching allowed the use of the same signature file for the classification of all images, with the exception of the 1980, 1992 and upper 1990 image for which a slightly different signature file was used.

Unsupervised classification was applied to all the images. First a series of tests was carried out using the ERDAS clustering and classification programs with different input parameters. The selected routines and variables were used to classify all the images into four classes: water, sand, cultivated soil and vegetated land.

4.3.3 Land Age

The cultivated soil and vegetated land classes were combined and digitally recoded as `land'. The age of the 1994 charlands was then determined by considering the land classes on the images of previous years using ERDAS raster modeling techniques. If a part of the 1994 land class emerged as land in, say, 1980 and remained 'land' throughout all the more recent images, then the area was considered to be 14 years in age. More information is given by FAP16 and FAP19 (1995).

4.3.4 Georeferencing of Cross-sections

The BWDB cross-sections were georeferenced on 1:50,000 scale hardcopies of the SPOT satellite images of the corresponding year, starting with 1994. For this purpose each cross-section of 1994 was plotted at the same scale on a transparency along with a line showing the local water level on the day of the satellite image recording. Each cross-section was then matched with the hardcopy satellite image by moving the transparencies up and down while keeping the bearing of the cross-section constant. This cross-section matching procedure started from the positions specified by SWMC. The UTM coordinates of the eventual best-fit locations were measured from the SPOT image and transformed into BTM coordinates as shown in Table 4.3. These February-March 1994 coordinates served as the starting points for the matching of the cross-sections from other years. A computer program was developed to convert the cross-sectional data (distances and bed elevations) into an ARC/INFO GIS coverage including the locations of the ends of the survey lines.

8f

Table 4.3 Location of 1994 BWDB Cross-sections in the Jamuna River

No	Cross Section Number	Left Bank Coordinates (BTM, meter)	Right Bank Coordinates (BTM, meter)
1	J1_1	477204, 641471	471806, 635571
2	J2_1	472905, 647720	464808, 647067
3	J3	478658, 650145	465007, 655768
4	J3_1	476603, 660863	467410, 664066
5	J4	480084, 667739	469557, 669213
6	J4_1	488345, 679913	467008, 675713
7	J5	486247, 681411	469511, 681209
8	J5_1	484502, 685610	470506, 686562
9	J6	487497, 689860	470760, 689811
10	J6_1	482308, 698260	470905, 698159
11	J7	483999, 706658	471654, 706010
12	J7_1	484749, 710106	469008, 710554
13	J8_1	481104, 721006	467107, 721654
14	J9	481652, 725352	465661, 724907
15	J9_1	479255, 731501	466109, 724754
16	J10	478653, 735162	463060, 730950
17	J10_1	476605, 744754	462958, 738202
18	J11	472155, 751449	461159, 743448
19	J13	471243, 778555	458243, 776499
20	J13_1	474127, 784888	457668, 782640
21	J14_1	472727, 801324	461732, 801339
22	J15	475146, 810849	460915, 810395

The processing of the cross-sections of 1994 involved much of time and labor. Therefore, the following more efficient processing method was developed for georeferencing of the cross-sections of 1978, 1980 and 1987:

i. start with 1994 location of cross-section
ii. convert cross-sectional data (distances and elevations) into ARC/INFO coverage with a line corresponding to the water level on the day of recording the satellite image

iii. draw cross-section on corresponding image using ARCEDIT sub-system of ARC/INFO and Live Link facility of ERDAS
iv. determine the best-fit location of cross-section by moving it up and down on the image
v. update of the location and save it as GIS coverage.

An example of georererenced cross-sections is given in Figure 4.1. The figure shows that not all the cross-sections fitted the satellite image equally well. For example, the fit of cross-sections J6 and J6-1 is quite good but the fit of J7 and J8-1 is rather poor. The sloping trend of cross-section J7 with respect to the water surface suggests that the data of this cross-section are erroneous. The fit of cross-section J5-1 can be seen as an intermediate case of moderate quality. The fit of all cross-sections was assessed visually in this way. The results are summarized in Table 4.4.

The georeferenced cross-sections were used to determine land elevations and to determine the position of the discharge median or 50% conveyance line. This is explained in sections 4.2.5 and 4.2.6 respectively.

Figure 4.1 Geo-referenced Cross-sections on Jamuna River in 1980

Table 4.4 Quality of Matching of 1980 Cross-sections for Jamuna River

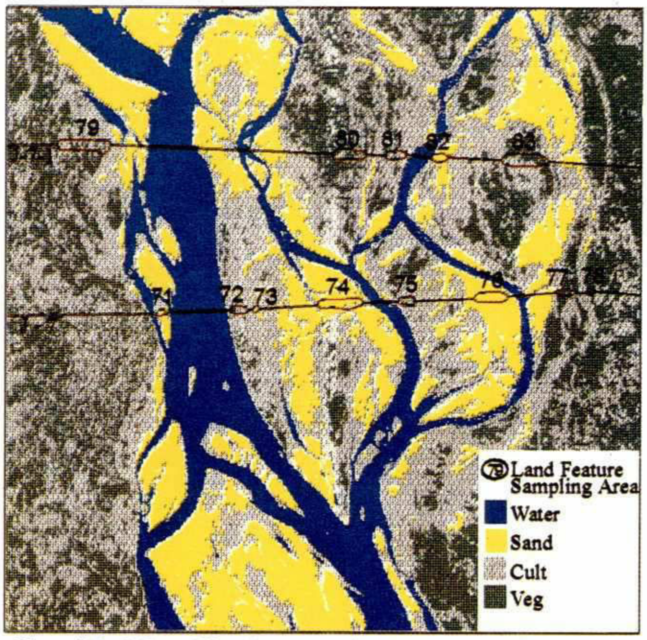
Cross-section	1978	1980	1987	1994
J1_1	–	–	+	+
J2_1	+	–	+	+
J3	–	+	+	0
J3_1	0	+	+	+
J4	0	0	+	–
J4_1	0	0	–	+
J5	+	0	–	0
J5_1	0	0	–	0
J6	+	+	0	0
J6_1	+	+	–	+
J7	0	–	–	+
J7_1	+	N.A	–	0
J8_1	+	–	0	–
J9	+	–	+	–
J9_1	+	–	0	0
J10	+	–	0	0
J10_1	–	–	0	0
J11	+	+	+	+
J12	+	0	+	N.A
J12_1	+	–	+	N.A
J13	0	0	+	+
J14_1	+	+	+	+
J15	+	+	0	+
J17	–	0	0	+

+ Good, 0 Moderate, – Poor, N.A data not available

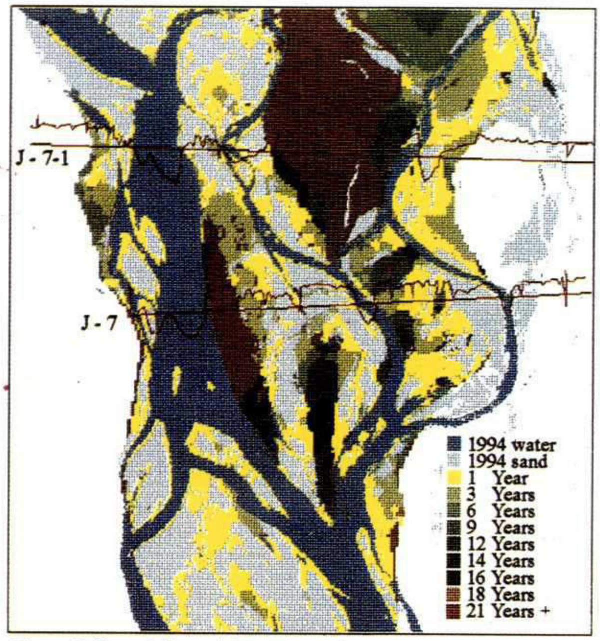
4.3.5 Land Surface Elevation

On the 25 January, 1994 satellite image 122 small areas along or adjacent to the georeferenced cross-sections were selected. Each area selected had relatively uniform spectral intensity, and was assigned the average elevation of the cross-section portion corresponding to the location of the area. The water level surface for each selected area were also computed, as illustrated in Figure 4.2. Furthermore, land cover type and land age of the area were derived from the corresponding GIS overlays. This allowed an examination of correlation of relative land height with cover type and age of the land surface. RSP conducted special surveys near Bahadurabad to collect land elevations for lands with different age. As found in Figure 4.4C, there is a similar relation between age of the land and elevation.

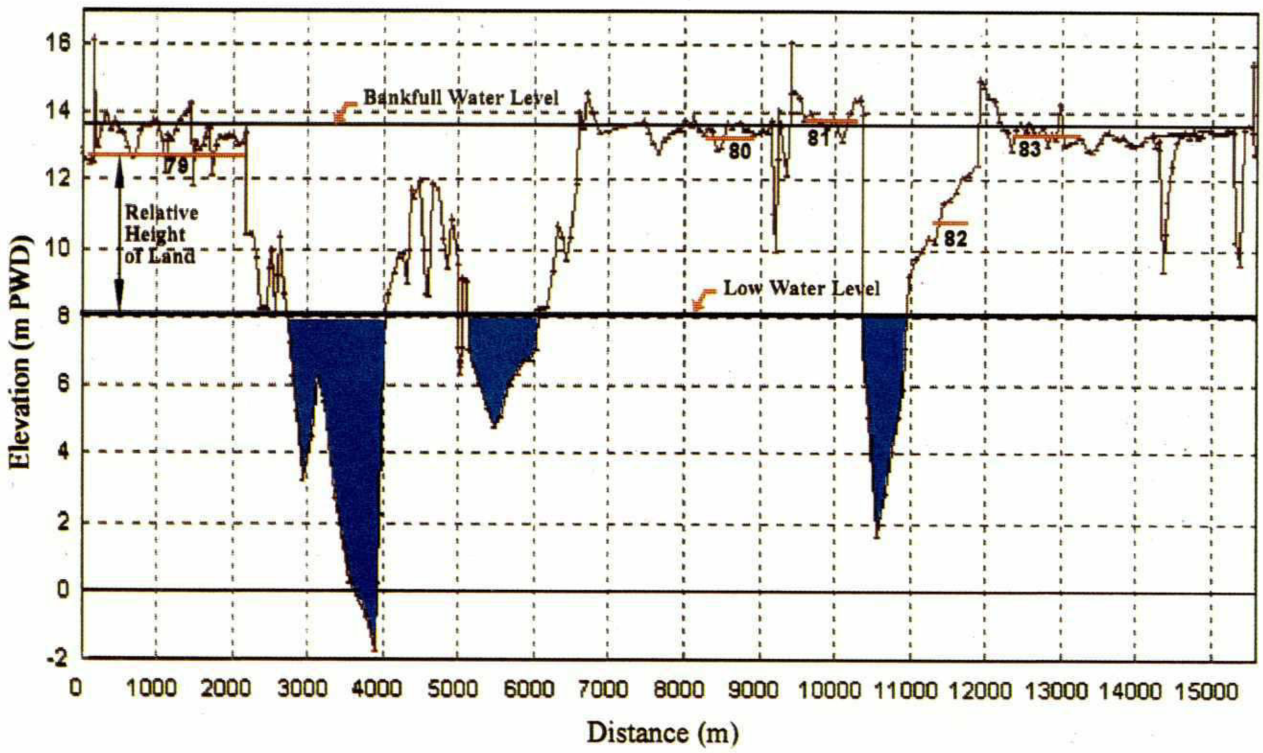
Fig. 4.2 Determination of Average Elevation from Cross-section for Selected Areas



Classified Satellite Image of 1994 (Fig. 4.2 A)



Land Age Map of 1994 (Fig. 4.2 B)



BWDB Cross-Section J-7-1, Jamuna River, 1994 (Fig. 4.2 C)

4.3.6 Position of Median Conveyance Line

A computer program of Delft Hydraulics was used to determine the point which divides a cross-section into halves of equal conveyance. The point thus found in a georeferenced cross-section was plotted on the corresponding satellite image. Connecting this point with those from other cross-sections yielded the median or 50% conveyance line. The conveyance of an incremental part of a cross-section was defined as $h^{3/2}\Delta y$, in which h is the water depth and Δy is a width increment. This definition implies that the Chézy coefficient of hydraulic roughness was assumed to be independent of stage. The 50% conveyance location was computed for all cross-sections of 1978, 1980, 1987 and 1994.

4.4 Results

The land cover types in 1994 are shown in Figure 4.3, together with the georeferenced cross-sections. The land ages in 1994 are shown in Figure 4.4A. The graphs of Figures 4.4B to 4.4E give statistical information on the distribution of land surface elevation and land age for different land cover types as well as the relationship between land surface elevation and age. These graphs are discussed in Section 4.5.1.

Figure 4.5 displays the positions of the median conveyance line in different years at two stages: bankfull on the left and low water is shown on the right. The bankful discharge is defined by Richards (1980) as 'the flow which just fills the range of the section of the alluvial channel without overtopping the bank'.The low flow condition shows water levels for the day of recording the corresponding satellite image which was during the low flow months of January-March for the various images. The positions of the median conveyance line are discussed in Section 4.5.2.

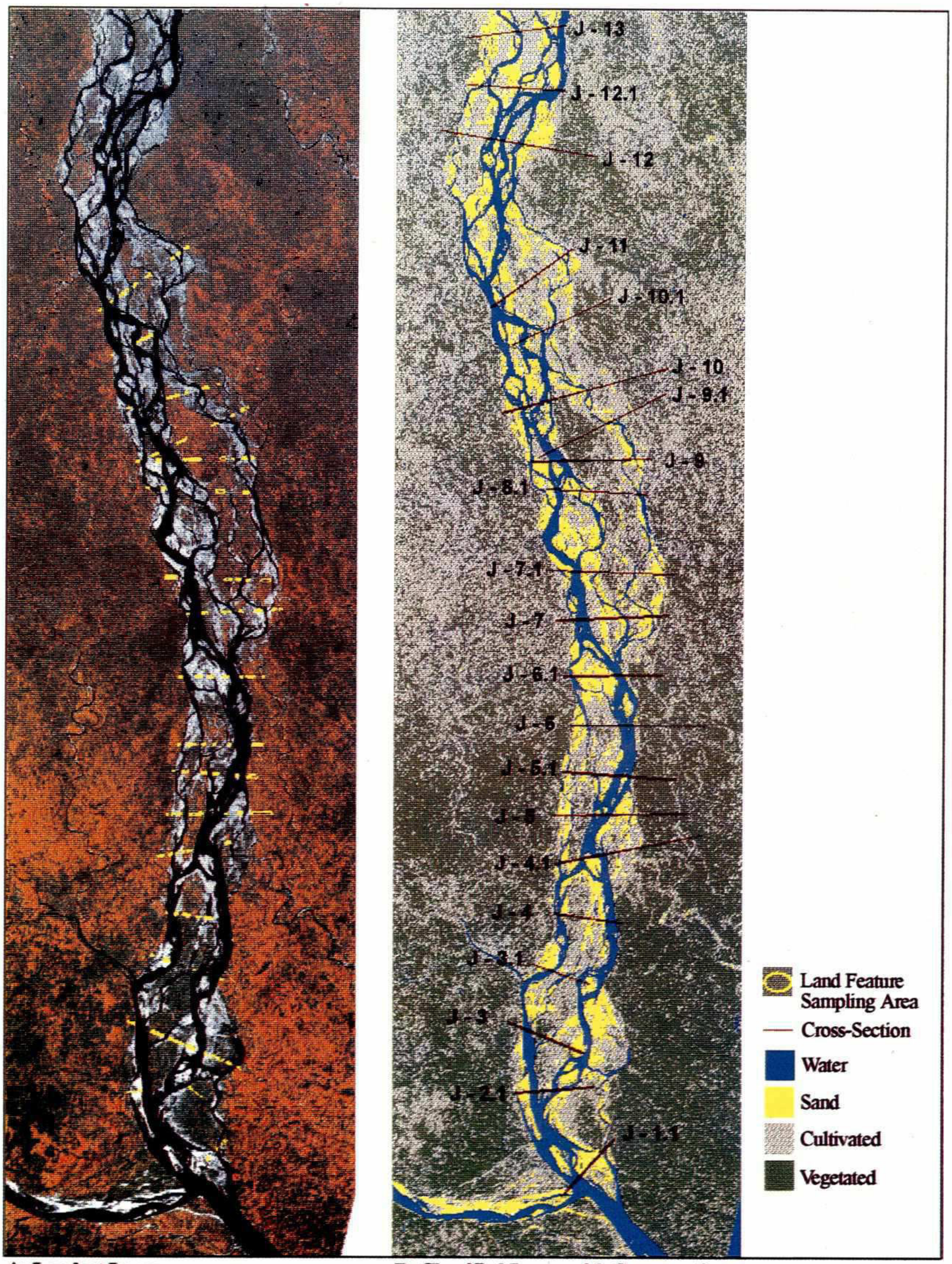
4.5 Interpretation and Discussion

4.5.1 Land Surface Elevation, Cover Type and Age

Figure 4.4B shows a distinction between the elevation distributions of sand, cultivated soil and vegetated area. The median elevations above the low-water level of the satellite image dates are 3.4 m for sand, 4.8 m for cultivated soil and 5.8 m for vegetated land.

The relationship of land elevation to land age are shown in Figures 4.4C and 4.4D. Elevations above PWD are used in Figure 4.4C and elevations above the low-water level in Figure 4.4D. Both graphs show considerable scatter, but nonetheless a trend of increasing elevation as the land becomes older.

Fig. 4.3 Land Cover Types



A: Landsat Image **B: Classified Image with Cross-sections**

Fig. 4.4 Land Age Map and Land Class Statistics

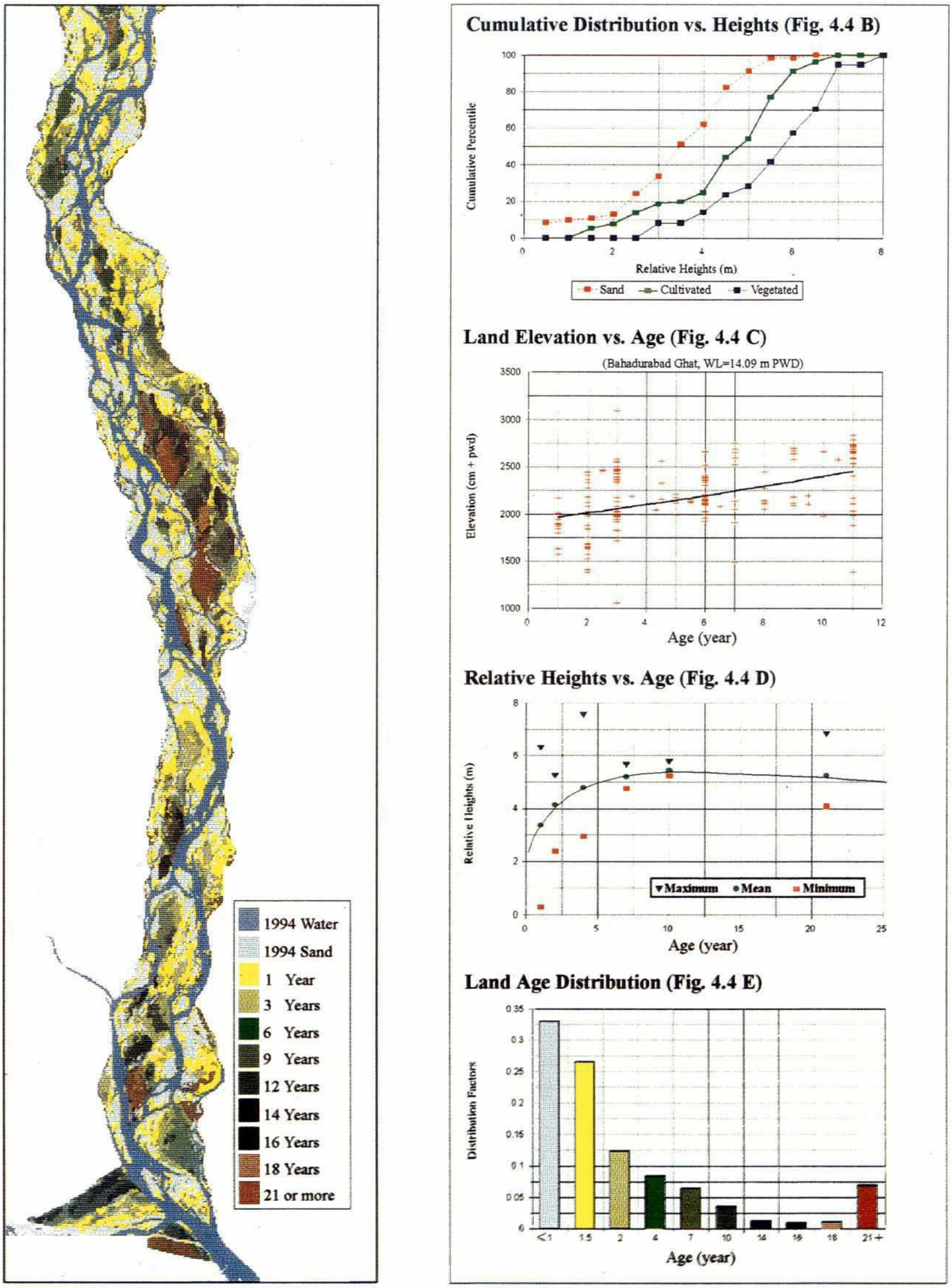
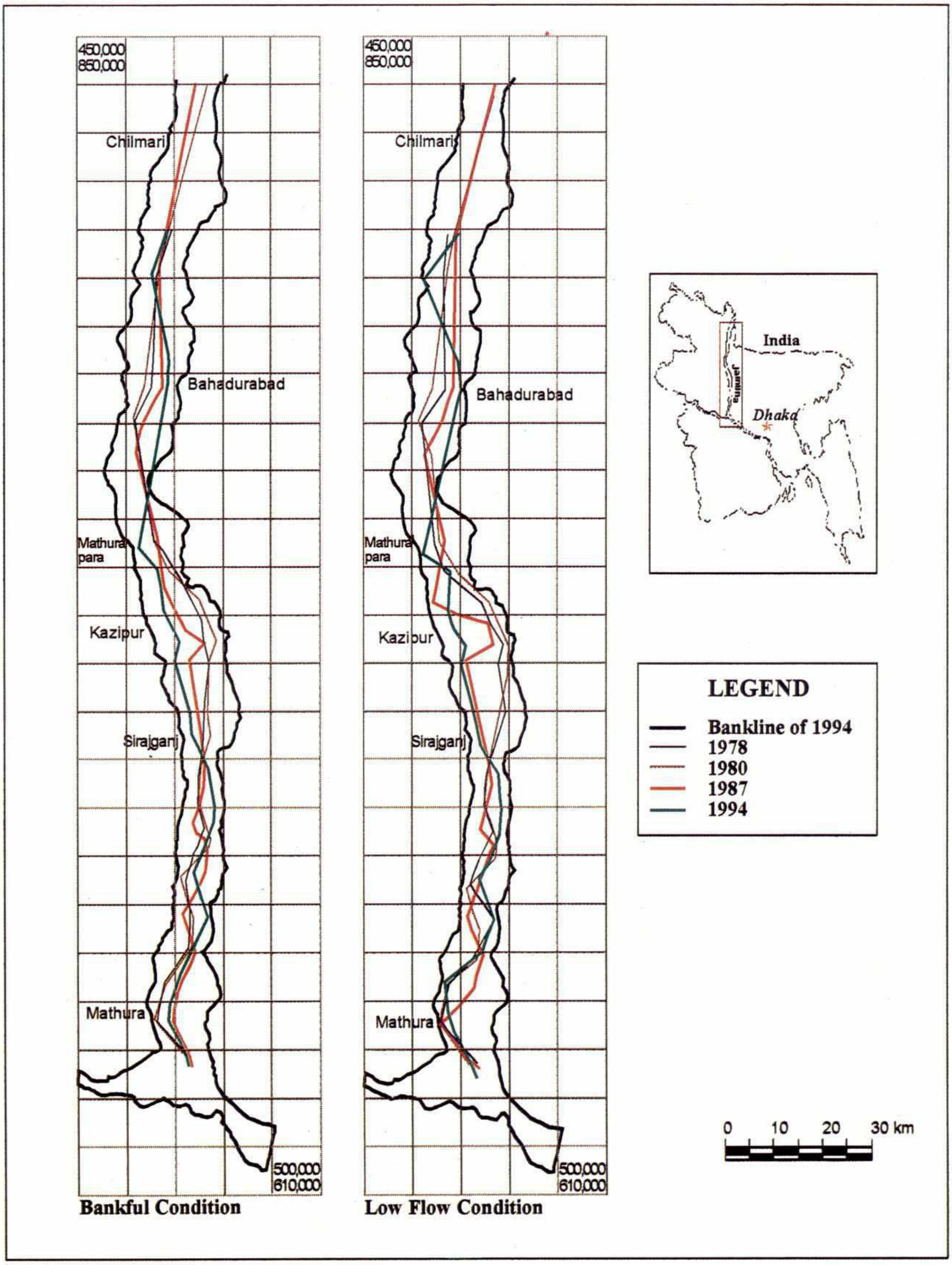


Fig. 4.5 Positions of Median Conveyance Line



Figures 4.4B to 4.4D imply that elevations cannot be correlated accurately with land cover type or land age alone. It was also tried to base a predictor on a combination of cover type and age, but the results of that are inconclusive. Research in this direction will be continued under Activity 4C of the RMRIS project.

The distribution of land age in Figure 4.4E shows that more than 75% of the char areas within the Jamuna River is younger than five years.

4.5.2 Positions of Median Conveyance Line

Figure 4.5 shows that the position of the median conveyance line changed considerably between 1978 and 1994. Three locations, however, appears as a type of hinge where the median conveyance lines of different years more or less coincide. The first two hinges, at approximately 8 km upstream of Mathurapara and approximately 5 km downstream of Sirajganj, occur at locations where the river is constricted locally by a convex eastern bank line. The third hinge is located close to the confluence with the Ganges River.

The hinges correspond to the nodal points identified by Coleman (1969), who suggests locally more resistant banks and local widening due to island formation as possible explanations. Bristow (1987) argues, however, that nodal points are not really fixed but transient on a scale of tens of years, which implies that differences in bank material composition cannot be responsible for the presence of nodal points. Van der Wal (1994) infers from the bathymetric surveys of FAP 24 that the stabilizing effect of confluence scour holes could also be an explanation for the nodal points.

The hinge points divide the river into three reaches with a distinct migration pattern. The median conveyance line migrates mainly eastward in the reach upstream of the hinge near Mathurapara and strongly westward in the reach between the hinges of Mathurapara and Sirajganj. In the downstream reach the line exhibits fluctuations around an average alignment rather than unidirectional migration.

The median conveyance concept has the disadvantage that it is always located within a channel. This location is very sensitive to small changes when a river divides into two major anabranches of approximately equal conveyance. The center of conveyance concept considers the land between anabranches and thus would not have this disadvantage. Using the center of conveyance instead of the median conveyance location would reduce the oscillations of the lines in Figure 4.5.

Chapter 5

Conclusion and Recommendation

Maps of river bathymetry, land surface topography, bed level changes, water flow velocities, suspended sediment concentrations, georeferenced cross-sections and median flow conveyance lines have been constructed and analyzed. They demonstrate the utility of spatial analysis tools, particularly GIS and image processing, for the *spatial representation, analysis and prediction* of the morphology of the major rivers in Bangladesh.

Although development of the computer-based tools took substantial time and effort, once established they proved to be highly efficient and innovative. In some cases, the spatial information processing methods enabled an exceptionally revealing presentation or the digital analysis capability yielded entirely new and very useful results. The benefits of spatial information systems for storing, representing and analyzing river survey and related data for understanding and predicting river morphology are firmly established. Full integration of these tools in future river survey and morphological program is strongly recommended.

The digital bathymetry maps were used for an evaluation of the *sediment balance*. In the deeper parts of the river, erosion dominates during the flood season whereas deposition dominates during the dry season. The largest amounts of erosion and deposition occur in the flood season. The net erosion and net deposition over a full year seem smaller than those over a few months of the flood season alone. An explanation is that, notwithstanding considerable reworking of the bed during the flood, the bed topography of the previous year is re-created during the fall of the flood due to forcing by the planform.

The sediment balance would be more complete if topographic data of the land surface and were included for both before and after flood conditions. This approach is recommended for future studies.

The detailed digital bathymetry and topography data developed in this projects are not available on a routine basis. It would be very useful if a DEM could be constructed from more obtainable data such as satellite images, hydrometric data and a limited number of cross-sections. For this purpose, cross-sections have been georeferenced on satellite images and relations between elevations of terrain units crossed by the cross-sections and corresponding land cover type and land age have been analyzed. Trends have been found in those relations, but also considerable scatter which implies that elevations cannot be correlated accurately with land cover type or land age alone. A predictor based on a combination of cover type and age has been tried as well, but the results of this are still inconclusive. Further research into this direction is recommended.

The georeferencing of cross-sections was very useful for validation of cross-sections and for positioning of median flow conveyance lines on satellite images.

Maps of the *median conveyance lines* in 1978, 1980, 1987 and 1994 reveal three locations which appear as a kind of hinge where the position of the lines did not change significantly. The hinges correspond to the nodal points identified by Coleman (1969). They divide the river into three reaches with a distinct migration pattern.

The median conveyance location has the disadvantage that it is always located within a channel. This location is very sensitive to small changes when a river divides into two major anabranches of approximately equal conveyance. It is recommended to repeat the analysis for the center of conveyance, which does not have this disadvantage.

The maps of this study have been used for *morphological predictions* in two ways. Firstly, the development of a confluence scour hole in front of Bahadurabad Ghat during the flood of 1996 has been predicted by a visual interpretation of the bathymetry and topography maps of July and November 1995. This prediction should be verified in the lean season 1996-1997.

Secondly, the distributions of erosion and sedimentation in the area of Bahadurabad in November 1993 and November 1995 have been predicted from the bathymetry maps and flow velocity maps of August 1993 and July 1995, respectively, using a prediction method based on Peters (1988). The idea behind this method is that erosion and deposition tend to establish an equilibrium relation between local water depth and flow velocity. A comparison with the observed morphological changes has shown that the predictions have been correct for 50% to 60% of the areas. The comparison is difficult, however, because the method only identifies areas of erosion and deposition without quantifying the corresponding bed level changes.

It is recommended to make the method of Peters (1988) quantitative with Equation (3.4) without violating Peter's original idea. Furthermore it is recommended to test a prediction method based on flow velocity gradients as well.

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APPENDICES

Appendix A: Processing of Bathymetric and Topographic Data

The processing of the bathymetric and topograhphic data consisted of data conversion, surfacing and recoding.

The *data conversion* was carried out in three steps:

a) floating ASCII format data were formatted into Z-X-Y ASCII (DOS) text format. Here, Z represents the identity (ID) for a depth and X-Y represents the corresponding coordinates in BTM;

b) a point topology was generated from the Z-X-Y forms using ARC/INFO vector GIS. Since both ARC/INFO and ERDAS do not allow values less than or equal to zero for spatial attributes, all values were transformed with the following equation:

$$C = G*10 + 100 \qquad \text{(A.1)}$$

where

C = converted value
G = actual value
10 is a factor to convert values in meters to decimeters
100 is an arbitrary constant added to ensure that no C value is negative or zero

c) vector data were rendered into raster GIS using a conversion module of ERDAS. The output was in DIG format.

The *surfacing* consisted of interpolation between data points so as to obtain a continuous distribution of values over the area considered. It was based on mathematical operations such as evaluation of a distance function including a search radius and surface calculation incorporating a weighting factor. Previously several trials were made to fit a best water surface with SURFER, pcTIN of ARC/INFO and the TOPO module of ERDAS software. In terms of data handling capability, the ERDAS TOPO module was found to be the most useful of all for the generation of surfaces and post-analyses. At the beginning the DIG format data were processed with the SORT command of ERDAS. A block size of 650 m was used, which provided processing of 99 percent of the data. The output files, with the default extension .BLK, were then used to generate a continuous surface using the SURFACE program of the TOPO module in ERDAS. The SURFACE program determines the influence a data point has on computed pixel values by processing groups of distinct 3-dimensional points and creates a continuous surface stored in ERDAS LAN format (FAP 19, 1995). The output raster image was stored as a dataset with the file extension name .GIS. In calculating the raster GIS pixel values, the point-to-surface transformation process was optimized through the functions defined below:

- **Weighting Factor:**

$$W = (1 - d/s)^2 \qquad (A.2)$$

where

W = weighting factor
d = distance from subject pixel to input data point

s = search radius i.e.maximum distance from subject pixel to input data point

- **Pixel value:**

$$V = \frac{\sum (W_i E_i)}{\sum_{k=1}^{n} W_k} \qquad (A.3)$$

where,

V = output pixel value
W_i = weighting factor of point i within the search radius
E_i = elevation of point i within the search radius
n = number of data points within the search radius

The *recoding* consisted of several procedures to rescale or rename the continuous data values generated from the discrete data. The following procedures were employed:

- GISMO of raster GIS modelling module;
- RECODE of Core module in ERDAS to rescale the data values;
- CLASNAM to add a description for each data value.

The description delineates contours of the river bathymetry surface. A composite color scheme of 29 classes comprising red, green and blue was also defined. The classes were given in descending order and ranged from 21 m to -7 m depth below SLW. A total of 19 bathymetry color-coded contour slice maps was produced on four survey study areas in the Jamuna and the Ganges River. The study area locations and time-series of the RSP river surveys are shown in Table 1.2. Parameters of the bathymetry mapping are shown in Table A.1.

Table A.1 Parameters of Bathymetry Mapping

Survey Area	Area	Coordinates (km)	Pixel Size	Number of	Horizontal & Vertical spacing (m)	
Location	(km^2)	Northwest Corner	m^2	rows and column	Survey	Mike21 interpolation
Kamarjani	25 x 11	461, 815	30 x 30	834, 375	1-5, 100	50, 50
					1-5, 200	
Bahadurabad	20 x 10	465, 790	30 x 30	669, 335	1-5, 100	50, 50
Confluence	23 x 16	464, 653	30 x 30	767, 534	1-5, 200	50, 50
Gorai offtake	26 x 26	398, 657	30 x 30	865, 867	1-5, 200	50, 50
						100, 100

1/ RSP prepared initially some bathymetry map using MIKE 21 post processing software.

Appendix B: Conversion from SLW to PWD Datum

- Calculation of absolute water level:

$$W_{Abs} = D_{SLW} - (W_{Avg} - SLW) \qquad (B.1)$$

where

W_{Abs} = Absolute water level relative to PWD datum
D_{SLW} = Depth relative to SLW
W_{Avg} = Average water level in PWD datum

- Fixing of PWD datum:

$$Z_{PWD} = [W_{Avg} + (Y - y).S/100000\ ] - W_{Abs} \qquad (B.2)$$

where

Z_{PWD} = Land/Bed level in with respect to PWD datum
S = Water level slope
Y = BTM reference in y' direction
y = pixel location in y' direction

Appendix C: Merging of River Bed Topography with Land Surface

The bathymetry of Jamuna Left Channel at Bahadurabad, given with respect to the sloping SLW datum, was converted to a bed topography with respect to the horizontal PWD datum. This bed topography was integrated with the land surface according to the following procedure:

- delineation of the area for unifying the river bed and the land surfaces;
- combination of the two surfaces with ERDAS modelling program GISMO;
- recoding of the heights above and below PWD datum.

The two surfaces were amalgamated through a raster GIS modelling program using the following simple conditional statement:

O = CONDITIONAL
{ (B > 1) B
(B <= 1 AND E > 0) E + 200 };

where

O = the combined file as output
B = file containing bed elevations of the river bathymetry
E = file containing land elevations of the land surface topography

1 is a unique value for background in the input files and 200 is an arbitrary number added to distinguish the land surface area in the output file.

Appendix D: Depth-area Statistics

Table D-1 Depth-area Statistics of Jamuna Left Channel at Bahadurabad

(Area in hectares)

Depth (m)	Jun 1993		Aug 1993		Nov 1993		Nov 1994		Feb 1995		Jul 1995		Nov 1995	
below SLW	Area	Percent	Area	Percent	Area	Percent	Area	Percent	Area	Percent	Area	Percent	Area	Percent
17	3.51	0.09	3.51	0.14										
16	3.51	0.09	3.33	0.13										
15	2.61	0.03	0.18	0.00	6.12	0.15	3.78	0.15						
14	5.58	0.07	1.44	0.03	7.02	0.18	5.85	0.23	0.90	0.01	2.70	0.06		
13	5.22	0.07	7.74	0.15	6.93	0.18	6.84	0.27	3.42	0.04	6.03	0.12		
12	4.14	0.06	8.91	0.11	10.89	0.22	8.73	0.22	8.91	0.35	6.84	0.08	11.70	0.24
11	6.12	0.09	20.34	0.26	13.50	0.27	18.00	0.45	11.61	0.46	12.15	0.15	23.31	0.48
10	7.47	0.11	35.64	0.46	20.34	0.41	41.49	1.05	23.13	0.92	19.08	0.24	47.43	0.98
9	18.00	0.26	55.62	0.71	30.96	0.62	73.35	1.85	46.35	1.84	36.09	0.45	79.65	1.65
8	41.04	0.60	85.05	1.09	45.81	0.91	118.71	3.00	88.20	3.50	88.92	1.10	101.79	2.11
7	47.79	0.70	136.62	1.75	128.61	2.56	151.20	3.82	126.54	5.02	109.44	1.36	107.37	2.22
6	109.62	1.60	207.72	2.66	214.29	4.27	171.99	4.35	162.00	6.42	165.96	2.06	115.92	2.40
5	162.54	2.37	216.63	2.78	254.07	5.06	199.08	5.03	216.72	8.59	240.12	2.98	217.62	4.50
4	255.15	3.72	280.08	3.59	274.86	5.48	235.98	5.96	297.09	11.78	313.92	3.89	225.45	4.67
3	367.74	5.36	359.73	4.61	350.19	6.98	289.98	7.33	346.23	13.73	371.07	4.60	299.25	6.1
2	416.52	6.07	418.41	5.36	408.33	8.14	377.73	9.54	357.84	14.19	439.56	5.45	452.43	9.3
1	521.19	7.60	519.84	6.66	574.47	11.45	479.16	12.11	391.59	15.53	447.30	5.55	604.80	12.5
0	595.44	8.68	573.84	7.35	625.68	12.47	576.36	14.56	265.59	10.53	510.03	6.32	642.96	13.3
-1	647.64	9.44	645.21	8.27	861.48	17.17	539.28	13.62	157.05	6.23	628.11	7.79	663.12	13.7
-2	712.53	10.38	767.07	9.83	909.81	18.13	366.12	9.25			726.21	9.00	626.49	12.9
-3	910.98	13.28	967.86	12.40	284.40	5.67	283.86	7.17			883.35	10.95	603.63	12.4
-4	851.22	12.41	1075.95	13.79							1018.17	12.62		
-5	664.56	9.69	913.68	11.71							869.22	10.78		
-6	521.82	7.61	361.35	4.63							648.63	8.04		
-7			141.93	1.82							527.94	6.54		
Total	6861.51	100.00	7804.89	100.00	5017.05	100.00	3958.11	100.00	2522.16	100.00	8066.43	100.00	4831.65	100.0
Percent	34.31		39.02		25.09		19.79		12.61		40.33		24.16	

Table D-2 Depth-area Statistics of Jamuna Main Channel at Kamarjani

Depth (m) below SLW	Sep 1994* Area (ha)	Sep 1994* Percent	Nov 1994 Area (ha)	Nov 1994 Percent	Mar 1995 Area (ha)	Mar 1995 Percent	Aug 1995 Area (ha)	Aug 1995 Percent
17			6.75	0.15			·5.94	0.07
16			3.60	0.08			6.03	0.07
15			3.78	0.08			11.79	0.14
14	0.72	0.01	3.24	0.07			9.72	0.12
13	8.10	0.07	2.97	0.07	0.63	0.02	14.49	0.18
12	8.19	0.07	4.77	0.11	0.36	0.01	13.05	0.16
11	11.07	0.10	9.63	0.22	2.25	0.06	29.70	0.36
10	12.15	0.11	14.58	0.33	4.14	0.12	40.50	0.50
9	25.11	0.23	36.90	0.83	17.82	0.51	59.76	0.73
8	54.72	0.50	62.37	1.40	44.73	1.29	92.07	1.13
7	97.11	0.88	108.18	2.42	83.97	2.42	117.09	1.43
6	154.89	1.40	222.03	4.97	180.72	5.21	188.82	2.31
5	286.38	2.60	324.81	7.27	354.42	10.21	234.72	2.87
4	429.66	3.90	464.04	10.39	554.85	15.99	346.77	4.24
3	540.45	4.90	513.09	11.49	584.37	16.84	497.16	6.08
2	788.58	7.15	649.08	14.54	714.24	20.58	701.46	8.57
1	981.45	8.90	760.23	17.03	592.29	17.06	875.88	10.71
0	1216.89	11.04	613.98	13.75	336.15	9.68	1040.40	12.72
- 1	1442.61	13.08	380.79	8.53			1021.59	12.49
- 2	1608.93	14.59	279.99	6.27			945.27	11.55
- 3	1577.25	14.31					751.23	9.18
- 4	1090.98	9.89					540.18	6.60
- 5	690.39	6.26					346.86	4.24
- 6							290.70	3.55
Total	11025.63	100.00	4464.81	100.00	3470.94	100.00	8181.18	100.00

* Sep 1994 Bathy survey area covered whole width of Jamuna with less area

Table D-3 Depth-area Statistics of Ganges-Jamuna Confluence at Aricha

Depth (m) below SLW	Oct 1993 Area (ha)	Oct 1993 Percent	Apr 1994 Area (ha)	Apr 1994 Percent	Dec 1994 Area (ha)	Dec 1994 Percent	Apr 1995 Area (ha)	Apr 1995 Percent
21	56.25	0.41	19.71	0.20	35.46	0.46	42.75	0.61
20	12.87	0.09	9.54	0.09	16.47	0.21	8.46	0.12
19	17.91	0.13	18.36	0.18	20.43	0.26	10.71	0.15
18	20.25	0.15	22.68	0.22	21.06	0.27	12.60	0.18
17	29.43	0.21	25.29	0.25	27.81	0.36	20.79	0.30
16	30.60	0.22	23.04	0.23	42.12	0.55	29.88	0.43
15	33.21	0.24	24.84	0.25	60.84	0.79	54.72	0.79
14	41.13	0.30	30.96	0.31	83.79	1.08	63.72	0.91
13	74.43	0.54	28.89	0.29	109.89	1.42	72.54	1.04
12	92.61	0.67	40.32	0.40	108.36	1.40	108.45	1.56
11	96.57	0.70	56.61	0.56	73.53	0.95	97.38	1.40
10	126.63	0.92	81.54	0.81	85.86	1.11	77.22	1.11
9	177.66	1.29	113.85	1.13	113.67	1.47	101.25	1.45
8	234.36	1.70	193.41	1.91	202.05	2.62	160.56	2.31
7	325.26	2.36	378.00	3.74	291.06	3.77	251.28	3.61
6	460.98	3.35	457.02	4.52	362.61	4.70	379.17	5.44
5	658.44	4.78	611.82	6.06	520.38	6.74	450.81	6.47
4	872.28	6.33	834.93	8.27	843.57	10.92	797.85	11.45
3	1099.62	7.98	1135.98	11.25	1245.51	16.13	1118.34	16.06
2	1224.99	8.89	1512.72	14.97	1549.98	20.07	1322.37	18.98
1	1328.67	9.64	1583.37	15.67	1465.92	18.98	1398.96	20.08
0	1547.46	11.23	1547.73	15.32	442.53	5.73	385.56	5.54
- 1	1611.72	11.70	1101.60	10.90				
- 2	1561.14	11.33	249.75	2.47				
- 3	1179.99	8.56						
- 4	696.15	5.05						
- 5	166.95	1.21						
Total	13777.56	100.00	10101.96	100.00	7722.90	100.00	6965.37	100.00

Table D-4 Depth-area Statistics of Ganges at Gorai Offtake

Depth (m) below SLW	Oct 1994*		Jan 1995		May 1995		Sep 1995*	
	Area (ha)	Percent	Area (ha)	Percent	Area (ha)	Percent	Area (ha)	Percent
21	80.01	0.93	56.25	0.41	56.25	0.41	46.89	0.49
20	17.28	0.20	12.87	0.09	12.87	0.09	21.78	0.23
19	17.46	0.20	17.91	0.13	17.91	0.13	24.48	0.26
18	21.69	0.25	20.25	0.15	20.25	0.15	25.29	0.27
17	23.13	0.27	29.43	0.21	29.43	0.21	22.59	0.24
16	23.58	0.27	30.60	0.22	30.60	0.22	26.64	0.28
15	24.84	0.29	33.21	0.24	33.21	0.24	28.80	0.30
14	25.92	0.30	41.13	0.30	41.13	0.30	32.67	0.34
13	25.92	0.30	74.43	0.54	74.43	0.54	34.65	0.36
12	25.83	0.30	92.61	0.67	92.61	0.67	36.09	0.38
11	34.47	0.40	96.57	0.70	96.57	0.70	42.39	0.45
10	45.72	0.53	126.63	0.92	126.63	0.92	49.41	0.52
9	67.95	0.79	177.66	1.29	177.66	1.29	66.78	0.70
8	87.21	1.01	234.36	1.70	234.36	1.70	78.12	0.82
7	114.84	1.33	325.26	2.36	325.26	2.36	98.91	1.04
6	139.23	1.61	460.98	3.35	460.98	3.35	137.43	1.45
5	206.91	2.39	658.44	4.78	658.44	4.78	186.66	1.96
4	321.48	3.72	872.28	6.33	872.28	6.33	254.43	2.68
3	481.32	5.57	1099.62	7.98	1099.62	7.98	393.84	4.15
2	550.71	6.37	1224.99	8.89	1224.99	8.89	547.38	5.76
1	632.25	6.31	1328.67	9.64	1328.67	9.64	625.05	6.58
0	705.69	8.16	1547.46	11.23	1547.46	11.23	755.73	7.95
- 1	963.54	11.15	1611.71	11.70	1611.72	11.70	874.53	9.21
- 2	1147.05	13.27	1561.14	11.33	1561.14	11.33	977.13	10.28
- 3	1278.63	14.79	1179.99	8.56	1179.99	8.56	1061.73	11.18
- 4	780.21	9.03	696.15	5.05	696.15	5.05	1073.61	11.30
- 5	801.45	9.27	166.95	1.21	166.95	1.21	881.46	9.28
- 6							726.57	7.65
- 7							369.54	3.89
Total	8644.32	100.00	13777.56	100.00	13777.56	100.00	9500.58	100.00

* includes the Gorai river with the Ganges R.