FAP24

Government of the People's Republic of Bangladesh

Water Resources Planning Organization

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Delft Hydraulics

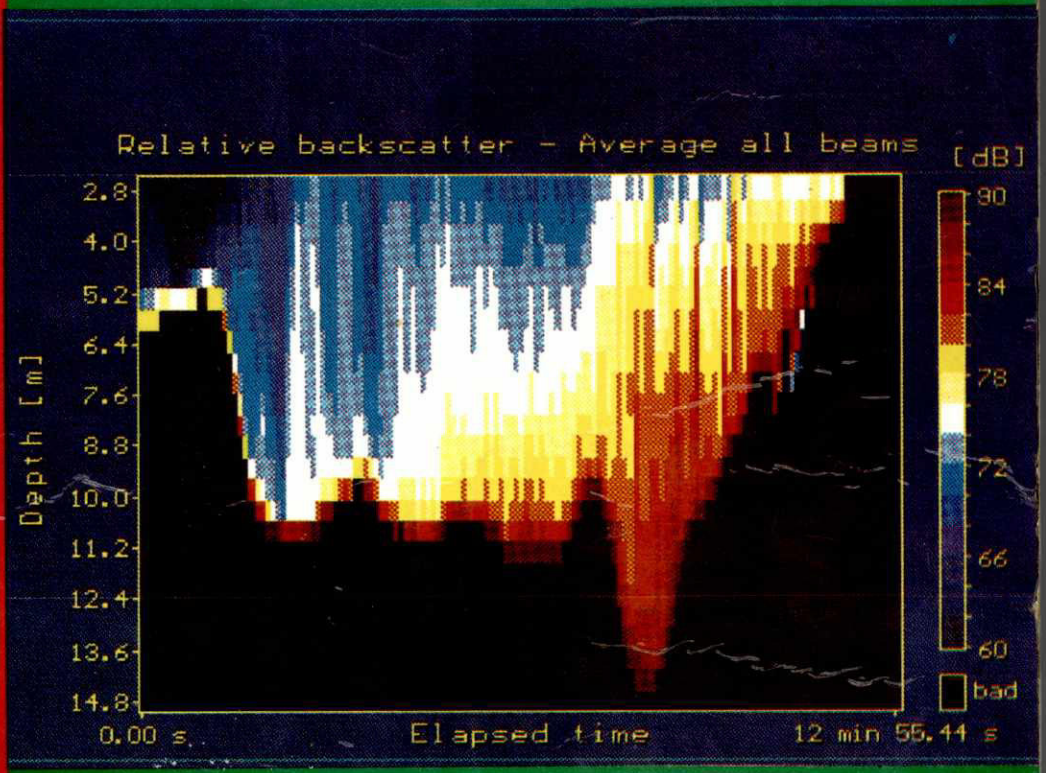
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Osiris

RIVER SURVEY PROJECT



Final Report – Annex 5

Morphological Characteristics

November 1996

Government of the People's Republic of Bangladesh:

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FAP 24

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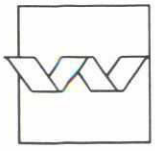
Final Report Annex 5

Morphological Characteristics of the Main Rivers of Bangladesh



November 1996

Delft Hydraulics



Danish Hydraulic Institute



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3.6 Mean daily discharge data collected by FAP24
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3.13 Dedicated tidal surveys
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3.22 Some statistical parameters of coarse sediment transport data measured by BWDB in Bahadurabad
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5.1 Average (1966-1993) high, low and mean level of the lower bank of a section of the Jamuna River
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5.4 Return period and non-exceedance frequency of bankfull discharge
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8.1 Source of data for monitoring bar growth and morphology, Bahadurabad, 1993-1996
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9.1 Maximum scour depth, area and volume (below SLW +6m) of the scour holes at Bahadurabad location in the period June 1993 - November 1995
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10.1 Bank erosion rates at Bahadurabad based on SPOT images
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12.1 Overview of the bathymetric maps of the left channel at Bahadurabad included in this study
12.2 The volume of the channels under different levels
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12.4 Local erosion and deposition in the period of August-November 1993 in the different branches
12.5 Measured and predicted adaptation length along the flow lines

13.1 Average width of the Jamuna River and centre line migration 1830 to 1992 (ISPAN, 1993)
13.2 Characteristics of the imagery used
13.3 Selection of type of model to be used
14.1 Proposed study topics on river morphological characteristics

Notation

A	Cross-sectional area; area	(m^2)
A_s	Conveying cross-sectional area	($m^{2)}$
B	Storage width; width	(m)
B_s	Stream width	(m)
C	Chezy coefficient	($m^{½}s^{-1}$)
c	Concentration	(mg/l)
c	Celerity	(ms^{-1})
C_D	Drag coefficient	(mg/l)
c_b	Celerity of bedform	(ms^{-1})
D	Numerical damping factor	(-)
D	Particle diameter	(mm)
D, D_M	Mean particle diameter	(mm)
D_g	Geometric mean particle diameter	(mm)
D_n	Diameter of particle such that n% of sample is finer	(mm)
D_{50}	Median particle diameter	(mm)
Fr	Froude number	(-)
$F(...)$	Function of	
$f(...)$	Function of	
f	Darcy-Weisbach friction factor	(-)
G	Weight	(kg ms^{-2})
g	Acceleration due to gravity	(ms^{-2})
H	Energy head; height of bedform	(m)
h	Depth of flow	(m)
h	Mean depth of flow	(m)
h_n	Normal depth of flow	(m)
h_c	Critical depth of flow	(m)
i	Mean slope of energy line	(-)
i_b	Mean slope of bottom	(-)
i_c	Critical mean slope of bottom	(-)
i_w	Mean slope of water surface	(-)
K	Diffusion coefficient	(m^2s^{-1})
k	Bed roughness	(m)
k	Wave number	(m^{-1})
k_1	Reciprocal of mean step length of single grain	(m^{-1})
k_2	Reciprocal of mean duration of rest period of single grain	(s^{-1})
L	Length, distance	(m)
l	Mixing length	(m)
L_m	Meander length of river length measured along thalweg	(m)
l_s	Straight distance between two points on the thalweg	(m)
N	Power	(kg m^2s^{-3})
N	Morphological time scale	(s)
n	Scale factor; numeral	(-)
n	Manning number	(S^{-1} $m^{0.33}$)
M	Manning coefficient	($Sm^{-0.33}$)
M	Mass (sample)	(kg)
m	Reciprocal of celerity (1/c)	($m^{-1}s$)
P	Wetted perimeter	(m)

$P\{...\}$	Probability; accumulative probability	
p	Pressure	(kg $m^{-1}s^{-2}$)
p	Mean pressure	(kg $m^{-1}s^{-2}$)
p	Pressure fluctuation *(P-p)*	(kg $m^{-1}s^{-2}$)
Q	Discharge	(m^3s^{-1})
q	Discharge per unit width	(m^2s^{-1})
R	Hydraulic radius; radius	(m)
R	Hydraulic resistance term	(ms^{-2})
Re	Reynolds number *(uh/v; wD/v)*	(-)
Re_*	Boundary Reynolds number *(u_*D/v)*	(-)
R_m	Radius of curvature of meander	(m)
r	Radial or cylindrical coordinate; radius	(m)
r	Distortion factor	(-)
r_C	Relative accuracy of concentration	(-)
S	Sediment transport	(m^3s^{-1})
S	Sum, estimation of standard deviation	(Various)
S_b	Bed load	(m^3s^{-1})
S_{bm}	Bed material load	(m^3s^{-1})
S_s	Suspended load	(m^3s^{-1})
S_w	Wash load	(m^3s^{-1})
S_t	Total sediment transport	(m^3s^{-1})or(kg s^{-1})
s_b	Bed load per unit width	(m^2s^{-1})or(kg s^{-1})
s_{bm}	Bed material load per unit width	(m^2s^{-1})or(kg s^{-1})
s_s	Suspended load per unit width	(m^2s^{-1})or(kg s^{-1})
s_w	Wash load per unit width	(m^2s^{-1})or(kg s^{-1})
s_t	Total sediment load per unit width	(m^2s^{-1})or(kg s^{-1})
s	Cylindrical coordinate in direction of flow	(m)
T	Period	(s)
T	Temperature	(°C)
t	Time; time coordinate	(s)
U	Flow velocity component in x-direction	(ms^{-1})
u,u	Time mean flow velocity component in x-direction; depth mean flow velocity in x-direction	(ms^{-1})
u	Turbulent flow velocity component in x-direction (U-u)	(ms^{-1})
u_*	Shear flow velocity in x-direction (z/g)	(ms^{-1})
u_l	Dimensionless flow velocity in x-direction *(xu/u_*)*	(-)
V	Flow velocity component in y-direction	(ms^{-1})
V	Volume	(m^3)
v,v	Time mean flow velocity component in y-direction; depth mean flow velocity in y-direction	(ms^{-1})
v'	Turbulent flow velocity component in y-direction	(ms^{-1})
W	Flow velocity component in z-direction	(ms^{-1})
w	Time mean flow velocity component in z-direction;	(ms^{-1})
w	settling velocity of particle (fall velocity)	(ms^{-1})
w'	Turbulent flow velocity component in z-direction *(W-w)*; sand flux fluctuation in x-direction *(W-w)*	(ms^{-1})
X	Dimensionless transport parameter($s_b/D^{3/2}{}^1g\Delta$)	(-)
x	Coordinate in main flow direction	(m)
Y	Dimensionless flow parameter *($\Delta D/\mu hi$)*	(-)

y	Coordinate in lateral direction	(m)
Z	Rouse number ($\kappa u_*/w$)	(-)
z	Vertical coordinate; level	(m)
z_0	Level of zero velocity or discharge	(m)
z_b	Bed level	(m)
z_w	Water level	(m)
α	Angle; correction coefficient for non-uniform flow in the vertical	(-)
α'	Correction coefficient for non-uniform flow in the entire cross-section	(-)
β	Angle	(-)
γ	Angle	(-)
Δ	Relative density $((\rho_s-\rho)/\rho)$; increment	(-)
δ	Thickness of viscous sublayer; depth of movement of bed load	m
δ	Angle	(-)
ϵ	Eddy viscosity	(m^2s^{-1})
ϵ	Porosity	(-)
ϵ	Mean error	($_{Various}$)
θ	Angle; dimensionless time $(K_z t)$; weighting factor	(-)
κ	Von Karman's constant	(-)
μ	Ripple factor; correction coefficient	(-)
ν	Kinematic viscosity	(m^2s^{-1})
ρ	Density of water	(kg m^{-3})
ρ_m	Densiy of material	(kg m^{-3})
ρ_s	Density of sediment	(kg m^{-3})
Σ	Summation	($_{Various}$)
σ	Standard deviation	($_{Various}$)
τ	Shear stress	(kg $m^{-1}s^{-2}$)
τ_b	Bottom shear stress	(kg $m^{-1}s^{-2}$)
τ_c	Critical shear stress	(kg $m^{-1}s^{-2}$)
τ	Tracer supply per unit width and time	(m^2s^{-1})
τ_*	Tracer supply per unit width	m^2
τ_{**}	Tracer supply	m^3
ϕ	Potential function	(m^2s^{-1})
ϕ	Angle of repose; angle	[-]
ϕ	Angle, angular coordinate; relative celerity (c/u)	[-]
ψ	Dimensionless shear stress $(\tau_b/(\rho_s-\rho)gD = u_*^2/\Delta gD)$;	[-]
ω	Angular velocity	[-]

List of symbols

Symbol	Meaning	Unit
B	Channel width	(m)
C	Chezy's roughness parameter	($m^{1/2}/s$)
D	Bed material size	(mm)
D_{50}	Median Particle diameter	mm
g	Acceleration due to gravity	(m/s^2)
h	Average water depth	(m)
i	River slope	(m/m)
i_v	Valley slope	(m/m)
k	Number of parallel channels of a braided river	(-)
L	Length of river reach	(m)
m	Coefficient in simplified sediment transport formula	(various)
n	Power of velocity in simplified sediment transport equation	(-)
p	Sinuosity, power of particle diameter in simplified sediment transport equation	(-)
Q	River discharge	(m^3/s)
Q_b	Bankfull discharge	(m^3/s)
R	Hydraulic radius	(m)
S	Sediment transport	(m^3/s)
s_t	Total sediment transport per unit width	(m^2/s)
s_b	Bed load per unit width	(m^2/s)
t	Time coordinate	(s)
u	Flow velocity	(m/s)
V	Sediment transport integrated over the year	(m^3)
x	Longitudinal coordinate	(m)
z_b	Bed level	(m)
α_Q	Correction for variability of the discharges in a river	(-)
ρ	Density of water	(kg/m^3)
Δ	Relative Density	(-)
ϵ	Porosity	(-)
μ	Ripple factor	(-)
ψ'	Effective dimensionless shear stress	($\mu\psi$)

Indices

b	bankfull
o	original situation (present state)
1	changed value (after FAP implementation)

1 General

1.1 Introduction into the River Survey Project

The River Survey Project (RSP, or FAP24) was initiated on June 9, 1992, and is scheduled for completion on June 8, 1996. The project has been executed by the Flood Plan Coordination Organisation (FPCO) under the Ministry of Irrigation, Water Development and Flood Protection. By end of 1995, FPCO merged with the Water Resources Planning Organization (WARPO) under the same ministry, whereby, at the same time, WARPO took over the project execution. Funding has been granted by the Commission of the European Communities. Consultants are DELFT-DHI joint venture in association with Osiris, Hydroland and Approtech. Project supervision is undertaken by a Project Management Unit with participation by FPCO/WARPO, a Project Advisor, and a Resident Project Advisor.

The goal of the project is to contribute to the basis for the FAP programme, as well as for other national planning, design, and impact evaluation activities within water resources and river engineering.

The project consists of three categories of activities:

- a survey component, comprising a comprehensive field survey programme of river hydrology, sediment transport, and river morphology
- a study component, comprising investigations of processes and effects within river hydrology, sediment transport, and river morphology
- a training component

The proceedings of the River Survey Project are described in several report series that cover the over-all progress, surveys, studies, general professional issues, and administrative matters. The final reporting is organised as follows:

- A main Final Report, which contains a summary of the background, a short overview of the activities within each project component, and over-all recommendations
- Annex volumes, covering
  1: Surveys
  2: Sustainable survey techniques
  3: Hydrology
  4: Sedimentological characteristics of Bangladesh's main rivers
  5: Morphological characteristics of Bangladesh's main rivers

A listing of all RSP project reports is given in the Main Report.

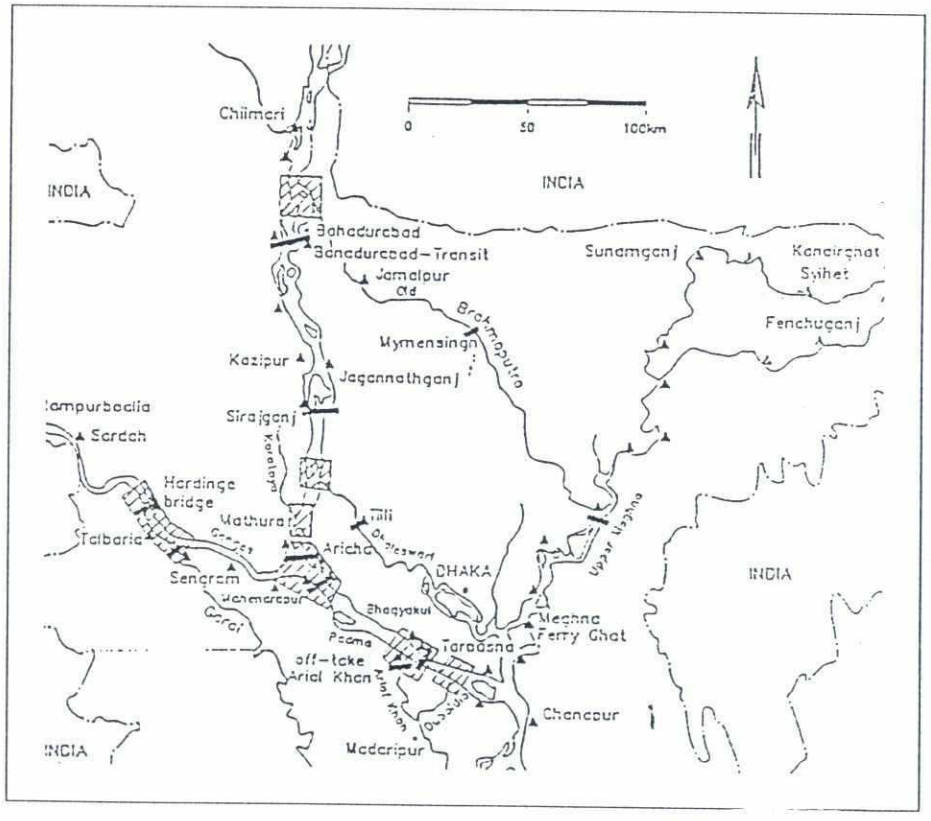
This Annex 5 specifically discusses morphological processes in the main rivers of Bangladesh. As river morphological characteristics of rivers are ultimately the result of morphologicalprocesses triggered by water flow and sediment transport, this Annex 5 should be read and appreciated in conjunction with the Annexes 3 (Hydrology) and 5 (Sedimentological characteristics of Bangladesh main rivers).

1.2 Scope of present Annex

This Annex is one of the three annexes dealing with the study component of the River Survey Project. The overall objective of the study component of this project is to improve the understanding of the behaviour of the main rivers in Bangladesh by studying the hydrological and morphological characteristics of the main river system.

The scope of the present Annex is to present and discuss the present understanding of morphological processes in the main rivers of Bangladesh. Explicitly it goes beyond a description of the surveys and studies carried out under the River Survey Project: its aim is to present a state-of-the-art of the understanding of river morphology of the main rivers of Bangladesh. Hence also the results of previous studies are incorporated and it is attempted to present an integrated view of all main rivers.

The study area of the project is the network of the Brahmaputra (Jamuna), Ganges, Padma, Old Brahmaputra, Dhaleswari and the upper reaches of the Meghna, Gorai and Arial Khan rivers, in accordance with the ToR. This network for the morphological data and characteristics is slightly different of the survey area of the project. The survey area in the context of this report, comprises the main river system of Bangladesh which includes partly the river basins of the Ganges, the Jamuna and the Meghna rivers. The survey area with the locations of bathymetric sites, sampling transects and Automatic Water Level Recorder (AWLR) locations is shown in Figure 1.1.



▲ Sites for water-level gauges

Cross-section, discharge and sediment measures
June-October : fortnightly; November - May : every six weeks

Indicative sites for pre- and post monsoon bathymetric surveys

Figure 1.1 Study area showing FAP 24 measuring locations

1.3 Previous work

The benchmark paper for the morphology of the main rivers of Bangladesh is Coleman (1969). Even now much of its contents remains unchallenged. Furthermore the paper by Morgan & McIntyre (1959) should be mentioned as giving for the first time a comprehensive overview of the geology of the basin of the main rivers in Bangladesh.

During and after these benchmark papers quite a number of studies have been carried out on the different main river system in Bangladesh, mostly within the frame work of a consultancy studies regarding the feasibility of proposed structures. During these studies use was made of the data collection programme of the BWDB. It should be stressed that it is through these data that most of the understanding is obtained. An overview of the available data on the morphological parameters is given in Study Report 3. All other data collection under specific projects usually was fairly short-term and scanty, with some exceptions where it was attempted to study a specific aspect in more detail (Jamuna Bridge study: outer bend scour, confluence scour, planform changes; FAP 1: bend dynamics, exchange processes; FAP 21/22: planform changes and combined scour; and FAP 16/19: char dynamics).

An overview of the most relevant consultancy studies with respect to sediment transport and morphology is presented for the main rivers in Table 1.1 and for the main distributaries in Table 1.2. Studies which are not directly related to structures in or near the rivers such as the study by the East Pakistan Water and Power Development Authority Master Plan by International Engineering Company (1964) and the sediment investigations in main rivers of Bangladesh by the BWDB (Water supply paper No 359) 1972 are not included in those tables.

The morphological aspects that were studied in the projects mentioned in Table 1.1 are summarized below.

Surveys of inland waterways and ports (NEDECO, 1968)
For the classification of the main rivers in Bangladesh (at that time East Pakistan) according to the behaviour of their water levels and the corresponding variations in the thalweg levels, many data on planform and thalweg location and depths were collected and some morphological aspects like sediment transport and the planform were studied.

Jamuna Bridge Project (RPT et al, 1987; 1988 and 1990)
BWDB cross-sections, BIWTA bathymetric maps and other data were collected and analysed, a.o. to identify location and cause of the deepest spots in the Jamuna and Padma River. Also bankfull dischrges were studied and regime and at-a-station-relationships were developed for the Jamuna River. A number of special field surveys was carried out in the southern part of the Jamuna River during the extreme flood of 1987, including a study of confluences and outer bends in some reaches. For the first time a systematic study into planform changes was done using satellite imagery. A stochastic approach to generate boundary conditions for the design of the river training works was applied on the basis of physical model studies.

Brahmaputra river training studies (FAP 1) (Halcrow et al, 1992)
Old maps and recent satellite imagery was used to demonstrate the westward movement of the Jamuna river along some reaches. This was also illustrated by the history of retirements of the Jamuna West embankement. The project included a systematic geomorphological survey of the right bank of the Jamuna River from the confluence with the Teesta River to the confluence with the Hurasagar River. Data previously collected on the planform and

cross-sectional characteristics were studied in detail. Satellite imagery was used for a study of bend dynamics. Sediment transport and channel dynamics were also studied in two test areas. Two test areas of the Brahmaputra River were selected for detailed measurements of morphologic characteristics. One test area covered the full width of the river over a 12 km long reach south of Sirajganj and contained both a major confluence and a bifurcation. The second covered the western channel with a sharp bend in the vicinity of Kazipur. For the first time a 2-d mathematical model for simulation of river morphology was used.

River	Period or year of publishing report	Consultancy report
Ganges River	1917-1918	Hardinge Bridge over the Lower Ganges, R.R. Gales
	1968	Surveys of inland waterways and ports, NEDECO
	1983	Rehabilitation Ganges-Kobadak Project, NEDECO
	1993	South West Area Water Resourdes Management Study, FAP 4
Brahmaputra River/ Jamuna River	1967	Surveys of inland waterways and ports, NEDECO
	1968-1970	East-West Interconnector Project, Acres International
	1975	Jamuna (Brahmaputra) river crossing, Northwest Hydraulic Consultants
	1974-1976	Feasibility Study Jamuna Bridge, JICA
	1986,1987, 1990	Jamuna Bridge Study, Phase I and II, RPT, NEDECO
	1991	Flood control and river trainig project on the Brahmaputra river, China-Bangladesh Joint Expert Team
	1993	FAP 1, Brahmaputra River Training Studies, Halcrow, DHI
	1992	FAP 3.1, Charland Study, Sogreah, Halcrow, Lahmeyer
	1993	FAP 21/22, Bank Protection and River Training project, RRI, CNR, DELFT, Lackner & Partner
Meghna river	1967	Surveys of inland waterways and ports, NEDECO
	1971	Protection Chandpur town, Prokaushali Sangsad
	1975	Chandpur irrigation project, erosion study, Northwest Hydraulic Consultants
	1992	FAP 9B, Meghna river bank protection short term study, Haskoning/DELFT
Padma River	1967	Surveys of inland waterways and ports, NEDECO
	1992	FAP 9B, Meghna River Bank Protection Short Term Study, Haskoning/DELFT

Table 1.1 Important studies which deal with the sedimentology of the main rivers in Bangladesh

River	Year of publishing report	Consultancy report
Old Brahmaputra River/ Lakhya River	1967	Surveys of inland waterways and ports NEDECO
	1992	FAP 3, North central Regional study, BCEOM, Euroconsult
	ongoing	FAP 6, North East Regional Study, Northwest Hydraulic Consultants
Dhaleswari River	1967	Surveys of inland waterways and ports, NEDECO
	1990	Jamuna Bridge Study Phase 2, Environmental Impact Study
	1992	Dhaleswari Mititation Study
Gorai River	1967	Surveys of inland waterways and ports, NEDECO
	1993	FAP 4, South West Area Water Resources Management Study, Halcrow, DHI
Arial Khan/Dubaldia Rivers	1967	Surveys of inland waterways and ports, NEDECO
	1993	FAP 4, South West Area Water Resources Management Study, Halcrow, DHI

Table 1.2 Important studies which deal with the sedimentology of the main distributaries in Bangladesh

Meghna River Bank Protection Short Term Study (FAP9B) (NEDECO, 1992)
The analysis of the morphological data, including satellite imagery, yielded interesting results with respect to planform changes in the Padma, the Upper and Lower Meghna River: the bank erosion along the Lower Meghna and the scour depths near Chandpur could be linked to the char developments in the Padma River. Also for the Upper Meghna bankfull discharge was determined and regime relations were established. The importance of subsidence for the Upper meghna was shown clearly.

Bank protection and Active Flood Plain Management pilot project (FAP 21/22) (RRI et al, 1993)
During the feasibility phase, in which mostly data collected in the past were collected, processed and analysed, two special studies were carried out. One was an extension of the remote sensing study done under Jamuna Bridge Study: a series of images almost covering every year since 1973 was obtained and an extensive analysis of planform changes was made. The other study dealt with the combination of different types of scour.

Environmental Impact and GIS study (FAP 16/FAP 19) (ISPAN, 1994; 1995).
Several char land studies were carried out by the combination of FAP 16 and FAP 19. Interesting information on char formation, mobility and age were obtained. In addition FAP 19 produced interesting results of a study into floodplain sedimentation.

In addition to the benchmark papers of Morgan & McIntyre (1959) and Coleman (1969), a number of publications is considered as relevant for this study, notably a series of papers published by Klaassen and his co-workers (Klaassen & Vermeer, 1988a and 1988b; Klaassen & Masselink, 1992; Klaassen et al, 1993; Mosselman et al, 1994), Bristow (1987), Goswami (1985), Thorne et al (1993) and van der Knaap (1993). These papers are mostly derivatives from consultancy studies or reports.

1.4 Summary of relevant activities carried out under FAP 24

The activities carried out under FAP 24 in relation to the morphology of the main rivers of Bangladesh can be divided into:

a Collection and storage of data previously collected
b Bathymetric surveys
c Special surveys
d Studies

Re a *Collection and storage of data previously collected*
All data on bed material sizes and sediment transport in the main rivers were collected from BWDB Hydrology. For some years also copies of the measuring forms were made for more detailed analysis. All data were entered in data bases.

Re b *Bathymetric surveys*
Bathymetric surveys are of particular interest for understanding the morphological characteristics of the main rivers. These surveys were made of a number of selected river reaches. Most bathymetric surveys were of the left part of the Jamuna River near Bahadurabad (in total 8 over the period 1993-1996), confluence of the Jamuna and the Ganges River (in total 9 over the period 1993-1996) and the offtake of the Gorai from the Ganges River (in total 4 over the period 1993-1996). Other bathymetric surveys were made near Kamarjani (5), Dhales wari offtake (3) Hurasagar outlet (4) Arial Khan offtake (5). The bathymetric data were presented as sounding maps, but were also introduced in a GIS by FAP19. This allowed for various types of further studies.

Re c *Special surveys*
The following special surveys were carried out that are relevant for an improvement of the understanding of the morphology of the main rivers in Bangladesh:

- occurence of bars;
- bar dimensions;
- main and secondary flow around a bar;
- internal structure of bars;
- development of bars in time;
- joint measurements of cross-sections;
- flow field measurements via float tracking;
- scour holes near FAP 21 test structures near Kamarjani.
- local slopes and discharge and sediment transport at the Gorai offtake.

Re d *Studies*
The following special studies were carried out to improve the understanding of the morphology of the main rivers in Bangladesh, mainly during Phase 2 of the project:

- quality check on BWDB cross-sections;
- floodplain levels;
- magnitude of bankfull discharges in the Jamuna and Ganges Rivers;
- (improved) regime equations for Jamuna and Ganges Rivers;
- at-a-station-relationships for Jamuna River;
- geomorphological controls along the Ganges River;

- application of improved Lane's balance to the main rivers;
- main and secondary flow around bars;
- bar formation and bar growth
- dimensions of bars;
- occurrence of scour holes;
- depths of scour holes;
- changes of scour holes over time;
- wandering of scour holes;
- bank erosion rates;
- possible causes of cutoffs;
- development of cutoffs;
- predictability of planform developments;
- hydraulic performance of Jamuna offtakes over the last 30 years;
- planform development of Old Brahmaputra offtake;
- (hydraulic) development of Gorai offtake in time;
- application of 2-d mathematical model of river morphology to study the Gorai offtake;
- bed level changes near confluences;
- planform changes at the Jamuna-Ganges confluence;
- flow patterns;
- flow adaptation;
- maximum flow velocities;
- exchange processes;
- transport, deposition and erosion of fine sediments;
- planform changes near Bahadurabad in the period 1993-1996
- bed topography changes near Bahadurabad in the period 1993-1996
- short-term prediction of bed topography changes.

This Annex provides a summary of the results obtained during these studies, making extensive use of the results of the bathymetric and special surveys.

1.5 Structure of present Annex

River morphology is the science of the form of rivers. Hence morphological characteristics are the characteristics of the form of the rivers. These characteristics are not constant in time, but they are changing in time and hence quite dynamic. This holds for rivers in general but even more so for the main rivers of Bangladesh. The reason for this is that they are flowing on top of a vast alluvial plain with only limited geomorphological constraints. At the same time the bed and bank material is made up of fine sands, which are known to provide least resistance to bank erosion (Nanson & Hickin, 1984).

Even though the rivers are quite dynamic, they can nevertheless be characterised by average values. Hence one may define some kind of average form for these rivers, on which dynamic changes are superimposed. Even the average form of the rivers may change in time as a response to changing environmental controls including in the case of Bangladesh the effect of geology, noticeable mainly in the form of subsidence.

Based on this concept of average conditions and superimposed dynamic changes, this Annex has been divided into four parts. The first part is Chapter 2, which gives the frame-work for

the analysis of the morphology of the main rivers in Bangladesh. It distinguishes between the environmental controls on the river systems and the dependent variables. The latter are divided into (i) primary dependent variables corresponding to the average river characteristics and (ii) the secondary dependent variables, which correspond to the superimposed dynamic changes.

The second part (Chapter 3) deals with the availability of data. Apart from an indication of the data collected in the past also the data collected under this project are listed. Furthermore the quality of the data is discussed on the basis of quality checks and joint measurements carried out together with the BWDB under this project as well.

The third part covers the Chapters 4 through 5. It is dealing with the average characteristics of the main rivers of Bangladesh. The independent variables in the different river reaches are discussed in Chapter 4. Best estimates for these variables for the different rivers are given. In Chapter 5 the resulting dependent variables are discussed. These dependent variables are slopes, channel dimensions and planform characteristics. Data on these characteristics are gievn as well. A simple approach (an improved Lane's balance) is used to check these data on consistency and to identify river reaches that are apparently behaving differently. This different behaviour is interpreted as not yet being adjusted to changed independent variables.

The last part, corresponding to the remaining Chapters 6 through 14 is dealing with the dynamics of the morphological system. The river morphology of the rivers in Bangladesh is strongly affected by the variations in discharge. Redistribution of sediment is taking place as a response to earlier discharge changes. Simultaneously the planforms of the rivers are changing over time, hence after a flood the river is not returning to its previous planform but it has to adjust to a changed planform as well. It is this complicated adjustment leading at any moment to erosion at some places and deposition at others that makes these rivers so dynamic.

At the same time the geometry of the rivers themselves is very complex. In particular in the Brahmaputra/Jamuna River, but to a smaller extent also in the other main rivers, many chars are present that migrate through the system. Depending on the stage these chars are either submerged or above the water level. The resulting flow patterns over and around them are strongly variable in time and in space. Erosion and deposition in these rivers shows the same variability. In interpreting the dynamics of the system the linkage between river morphology on the one hand and flow and sediment transport on the other hand should be kept in mind at all times.

The following dynamic elements are discussed:

- offtakes (Chapter 6);
- confluences (Chapter 7);
- bars and bifurcations (Chapter 8);
- scour holes (Chapter 9);
- bank erosion and cutoffs (Chapter 10).

In view of the strong interaction between flows and morphology of the rivers, typical flow patterns are discussed in Chapter 11. In these dynamic rivers there is a continuous exchange of sediment between channels, chars and floodplains. Some aspects of this are discussed in Chapter 12. Chapter 13 describes in more detail channel form changes and planform develop-

ment for some river reaches, concentrating mostly on an interesting series of bathymetric maps of the Jamuna River near Bahadurabad. This series allows to illustrate most of the points discussed in the previous Chapters. At the same time it serves to illustrate the advantages of the use of a GIS for the study of river morphological phenomena. Furthermore, this chapter deals with short- and middle-term prediction techniques for the main rivers in Bangladesh. The application of a prediction method, developed along the lines of a prediction technique described by Peters (1978) for the Zaire River, is shown.

This study, although covering a wide field and having produced interesting results allowing for an improved overview of the network of main rivers, at the same time demonstrates that still in many aspects our present understanding is too limited. Annex 5 therefore concludes with Chapter 14 in which suggestions are made for further studies. These will certainly increase the understanding of the morphological processes in the main rivers even more, but in Consultants' opinion the results obtained during the River Survey Project will have a major impact on any plans for improving and on a longer run "taming" the main rivers of Bangladesh in the greater interest of the country and the people of Bangladesh.

2 Frame-work for analysis

2.1 Introduction

This chapter sets the scene for the subsequent chapters by describing in general terms the specific characteristics of rivers. Key issues for this description are a systems approach to rivers as typical input-output-systems, dynamic equilibrium (long-time equilibrium with short term fluctuations imposed on it), adaptation of a river system to changes in its independent inputs and continuous changes of the river characteristics in time as a result of discharge variation.

2.2 Rivers as morphological systems

Rivers are dynamic systems. Here as frame-work for analysis of the main river system in Bangladesh, typically an input-output-system is used. An input-output system is a system where the output (read river characteristics) are completely determined by the inputs (read basin characteristics and human interference).

Every river can be described as a system that is responding to a number of independent inputs, the river characteristics being the resulting dependent outputs. For the subsequent discussion of the input and output parameters in a river basin reference is made to Figure 2-1, where these parameters are indicated schematically. A difference is made between the independent variables on catchment level, and the independent variables in a certain river reach.

2.3 Independent variables

On a very generalized level the independent inputs on the *catchment level* are the climate and the geology of the basin. The climate determines the (average) precipitation and the (average) temperature. The geological history is responsible for the rocks that in the present era are subject to weathering and hence ultimately the quantities and characteristics of the sediment that has to be transported by the river draining the catchment. In addition the geological history is determining the level differences in the catchment, and hence the energy available in the river system.

Geology and climate, however, do not in a straightforward way determine the discharges and the sediment transport rates in a river system. The picture is complicated by the role of the vegetation and the weathering processes.

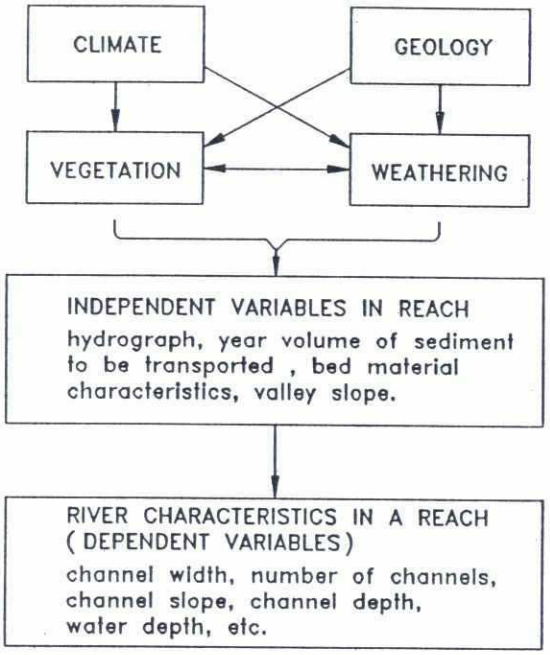


Figure 2.1 Input and output parameters in a river basin (adapted from Morisawa, 1985)

Vegetation is largely influenced by on the one hand the climate (generally high precipitation rates and moderate temperatures are favourable for the development of vegetation), but also the geology is important. The geology, in combination with the climate, determines the rate of weathering and this, again, has a significant influence on the growth of the vegetative cover. For more extensive discussions regarding the close interaction between geology, climate, vegetative cover and weathering reference is made to handbooks like Morisawa (1985), Richards (1987), etc.

The above close interaction, as illustrated in Figure 2.1, yields the independent inputs for the *river reach level*. In a particular river reach the inputs are:

- the discharge hydrograph (Q in m^3/s as function of t),
- the volume of sediment that has to be transported through the river reach, on say an annual basis (V in m^3);
- the characteristics of the sediment, consisting of coarse sediments (usually transported as bed material load, both as bed load and as suspended load) and fine sediments (transported as wash load, always in suspension);
- the slope of the valley.

The following observations are made regarding these independent variables:

- Each of them is different for different river reaches: e.g. a more downstream reach usually has to carry more sediment. Hence for all independent variables at the river reach level it holds that they are a function of the longitudinal coordinate x.
- A differentiation is made between bed material load and wash load. See also Figure 2.2, where the sediments transported in a river are distinguished as far as their origin and their mode of transport is concerned. In line with this the total volume of sediment that has to be transported is divided in V_b (bed material) and V_w (wash load).

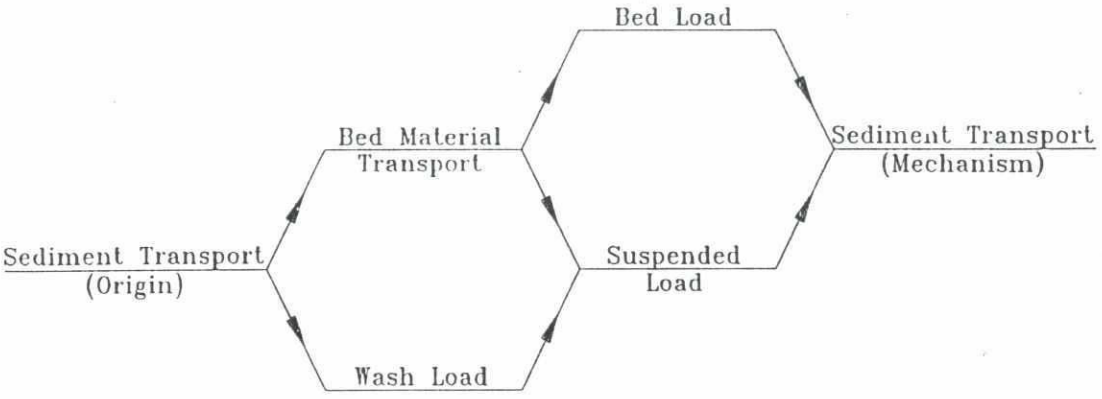


Figure 2.2 Different modes and origin of sediment transport (Jansen, 1979)

2.4 Primary dependent variables

The dependent variables in a particular river reach are the river characteristics, which are listed hereafter. A distinction is made between the morphological characteristics and the hydraulic characteristics:

- Dependent morphological characteristics:
— number of channels n
— average width of the channel(s) B_b, where the index b stands for bankfull conditions
— sinuosity p of the river channel(s)
— typical wave length of the curved channels L
— total width B_t occupied by the river channel(s)
— bankfull depth h_b of the river channel(s)
— slope of the river i_b

- Dependent hydraulic characteristics:
— average water depth in the main channel;
— "wet" width either in the main channel or including the floodplain;
— inundation depth of the floodplain;
— the roughness coefficient of the main channel and of the floodplains;
— the average velocity.

It is obvious that the dependent hydraulic characteristics are directly affected by the morphological characteristics, while the overall morphological characteristics are affected by the hydraulic characteristics only on a longer time span.

The independent and dependent variables in a river system are illustrated in Figure 2.3.

Often the concept of the "graded river" (Mackin, 1948) is used. For such a river the independent variables have been constant over a very long period. Hence equilibrium exists, implying that there is no overall aggradation and/or degradation. On a yearly basis on the average all sediment is transported through the river reach considered. Rivers being graded are also said to be "in regime". It may be assumed that for graded rivers all dependent variables have a fairly constant value in a particular river reach. See also the Sections 2.6 and 2.7.

Ideally all the dependent variables should be linked to the independent variables via relations well founded in river mechanics. The problem, however, is that for many of dependent variables no undisputed relations are available. Partly this is solved by the use of empirical relations, which may be different from one river to another, but when properly calibrated and verified can be of great help. For some other relations one has to rely on more speculative proposals like extremal hypotheses (e.g. "the river tends to maximise its sediment transport capability"). A state-of-the-art review of methods in use is provided in the Final Report of FAP 22 (Volume 2, Annex 1, Chapter 7). Annex 1 provides a complete set of equations, partly "sound", partly empirical and partly more speculative ones, that were used for impact assessment under FAP 22. It allows to determine the dependent variables. Also the impact of human interventions can be assessed using this frame-work. It provides insight into which relations have to be improved to arrive at better assessment of the physical impact of human interventions like FAP.

Finally it should be noted that the "nodes" of a river system, notably the offtakes and confluences, are considered to belong to the primary depended characteristics. These, often very dynamic locations of the river are further elaborated in the Chapters 6 and 7.

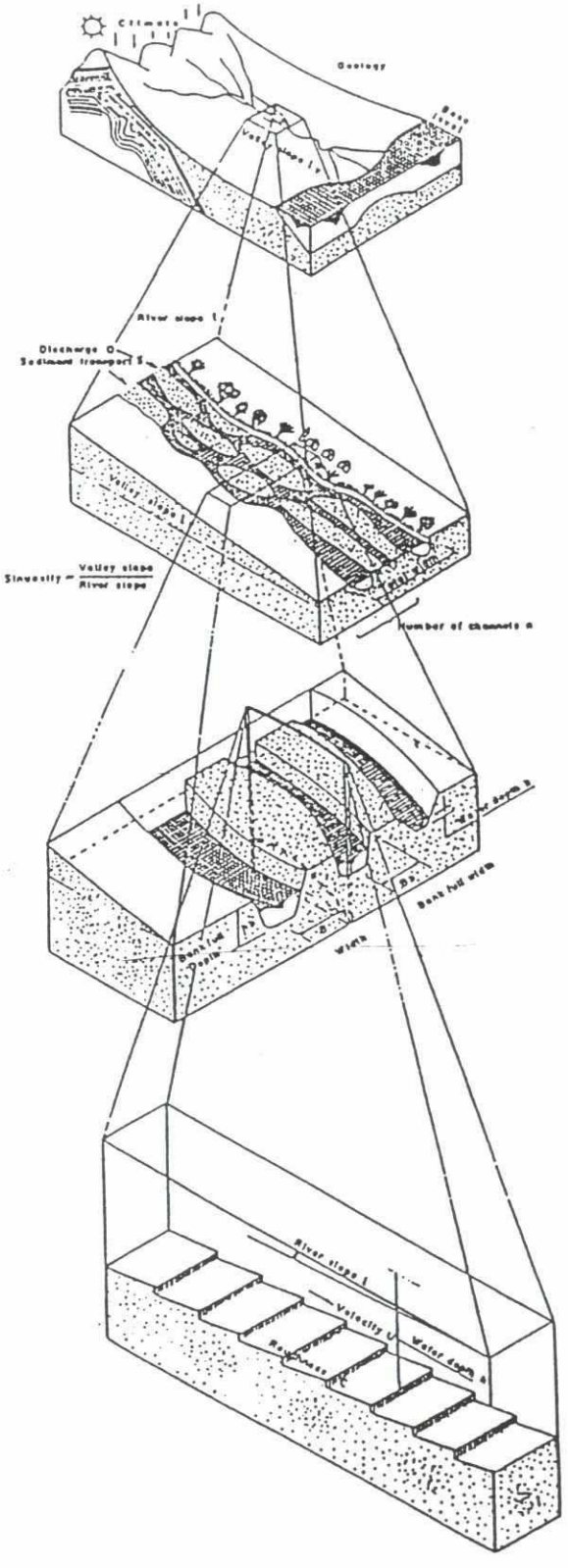


Figure 2.3 Independent and dependent variables in a river system. (FAP 21/22 Final Report)

2.5 Secondary dependent variables

The secondary dependent variables in a particular river reach are listed hereafter.

- bars (Chapter 8)
- bifurcations (Chapter 8)
- scour holes (Chapter 9)
- bank erosion (Chapter 10)
- cutoffs (Chapter 10)

These elements of the river are called secondary because they are more detailed, local, dynamic characteristics. As indicated in the above list the secondary depend variables are described in the Chapters 8 to 10.

2.6 Time-dependent aspects

This section comes in three parts in which the following time dependent aspects are discussed:

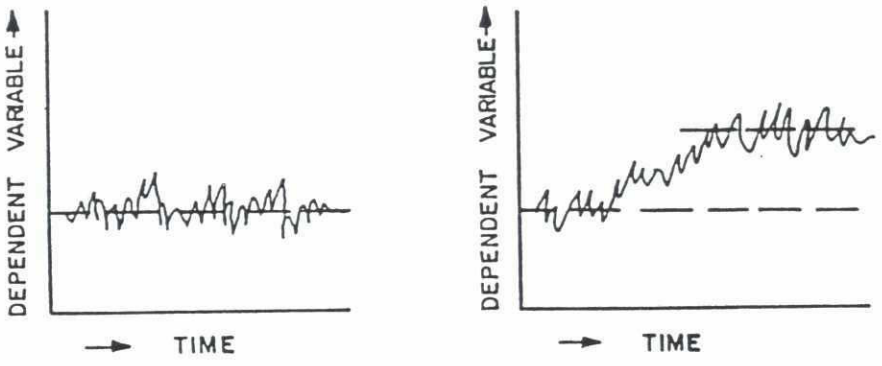
- dynamic equilibrium in case the independent variables like discharge, sediment volumes, sediment characteristics and valley slope can be considered constant over a very long time;
- changes due to variation in the independent variables
- the effects of the variable discharge.

2.6.1 Dynamic equilibrium

River characteristics like braiding index, river width, roughness, etc. are often described as if they are constants. This, however, is definitely not the case. Even for a river system for which the independent variables have been constant over a very long time, still variations are taking place constantly. This is caused by two reasons.

First of all the discharge in the river is not constant but it is usually varying in time. This means that, even if the morphological characteristics do not change significantly over a short period, the hydraulic variables may change rapidly as a reaction to the changes in discharge in time.

Secondly also the morphological characteristics are changing in time. This type of changes can be distinguished in (1) a direct response to variation in discharge, and (2) processes that continue in time and can be regarded as the integrated effect of the discharge hydrograph. An example of the first group are changes in channel dimensions due to the effect of major floods. Dramatic examples are given in Graf (1987) for ephemeral rivers, but similar behaviour is present in perennial rivers. The second group is related to processes like outer bend erosion and cutoffs. Outer bend erosion tends to increase the length of the river and hence increases its sinuosity. Cutoffs in meandering rivers reduce the length of the river, and hence result in a reduction of the sinuosity. Hence 'the' sinuosity of a river does not exist and only an average sinuosity can be defined.



(a) Dynamic equilibrium (b) Adaptation to new (dynamic) equilibrium

Figure 2.4 Behaviour of river characteristics in time

In other words: a real equilibrium does not occur in rivers, and it is better to speak of a *"dynamic equilibrium"*. This is indicated schematically in Figure 2.4(a), where the vertical axis stands for the river characteristic considered.

This indicates that many river characteristics are fluctuating around an average value, the average value being the value that is determined by the "average" value of the independent parameters. Even the independent variables, however, will usually fluctuate around a certain value and this in itself may cause some fluctuation in the dependent variables. As an example an earthquake can be mentioned, which will induce many landslides and hence increase temporarily the input of sediment in a river. As a consequence the bed levels in the river may rise locally. The hump of sediment in the river will travel in downstream direction, and remaining noticeable over a long distance.

The above also has consequences for field measurements and their interpretation. In analyzing field data always it should be kept in mind that results of measurements may not correspond to equilibrium conditions. A good example of this are the regime equations derived by Klaassen et al. (1988a) for the Jamuna River. In the derivation a substantial scatter was observed when plotting bankfull width versus bankfull discharge. One explanation of this is that it might be due to the fact that many of the studied channels might have been either aggrading or degrading.

2.6.2 Adaptation to changes in independent variables

As all river characteristics depend on independent variables, any change in these independent variables will result in changes in the river characteristics. These changes will not take place immediately, but they will adjust in time to the new conditions.

In the interpretation of river behaviour it is often assumed that the independent variables have been constant for a long time. In reality this might not have been the case. Hence the observed river characteristics may be related to a transition phase rather than an equilibrium phase. This holds especially for the rivers in Bangladesh, being located in a tectonically speaking very active area.

As an example the Brahmaputra River can be cited. Between 1780 and 1830 the river shifted its course from its former Old Brahmaputra course to its present Jamuna course. Before 1780 the Brahmaputra River (in its Old Brahmaputra course) was clearly braided (as is shown in the famous Rennell maps). In 1830 the planform of the river (known from maps by Wilcox) was meandering. Nowadays the river is again braiding with a braiding index of 2 to 3. It seems however that the Northern reach is more braiding (higher braiding index) than the Southern reach (Klaassen et al, 1988b). This may well be due to the fact that the river is still "underway" in establishing a new equilibrium in its new course.

The same holds for the Upper Meghna River. Previously this river carried the combined discharges and sediment transport of the Brahmaputra and the upper reaches of the present Meghna River (the Kushiara and the Surma Rivers).

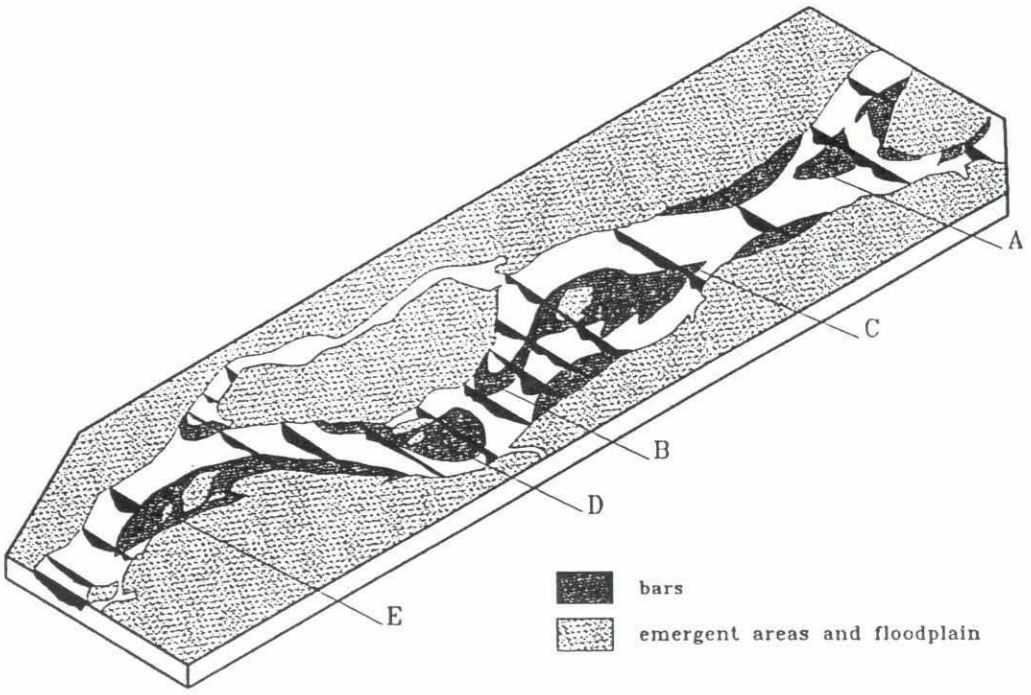
Nowadays it is fed mainly by these upper reaches with only a small input from the Old Brahmaputra. Considering the small quantities of sediment that have to be transported under the new conditions, the equilibrium state of the Upper Meghna will be a meandering river. The Upper Meghna River is adapting to its new conditions: it is transiting from a braided system to a more meandering one. This adaptation, however, is taking place very slowly, because nowadays the sediment transport in the Meghna River is very small (for more details see FAP 9B, Final Report, Volume B).

The adaptation towards a new equilibrium may take a substantial time. In the case of the Jamuna River the river is probably still adapting in its new course hence indicating that the adaptation time is several centuries. This is probably due to the fact that the adaptation takes place via bank erosion at selected reaches and that it is not a continuous process (see later). The adaptation of the Upper Meghna may take even longer: the transition to a meandering river takes place by deposition of sediment in the parallel channels and the deposition rate in the Upper Meghna appears to be fairly low. Hence the adaptation time varies per river considered and to have insight in this adaptation time is very important to conclude whether or not the characteristics of the river can be interpreted as fluctuating around an equilibrium (Figure 2.4(a)) or adaptation towards a new equilibrium. The latter is schematically illustrated in Figure 2.4(b). In this Figure it is also indicated that the adaptation takes place not at a continuous pace but that e.g. major flood events may demonstrate an accelerated drive towards the new (dynamic) equilibrium conditions.

2.6.3 Effect of variable discharges

One of the independent variables as identified in Section 2.3 is the hydrograph of a river. This should be understood as the average hydrograph of the river, may be obtained by averaging over a number of years. This average hydrograph, together with the other independent variables, determines the river characteristics like the number of channels and the width of the channels. In the geomorphological literature (see e.g. Bristow, 1987) these river variables are often referred to as the first and second order channels. The first order channel is then the river in totality, while the second order refers to the individual channels of the system.

In the river system there are however also higher order channels and phenomena. An example are the bars which very often can be observed in the 1st and 2nd order channels. These bars are divided in mid-channel bars, attached bars, etc. (see Figure 2.5). Also deep pools in outer bends, point bars in inner bends, crossings between two river bends, bars downstream of a confluencing tributary and deep pools downstream of confluences belong to these categories, although these are often referred to as fixed bars and pools. Figure 2.6 provides an overview of different types of bars and pools. Over the last decade many of these phenomena have been explained as instabilities (see e.g. Parker and Ikeda, 1989).



A first-order tributary bar, B second-order tributary bar, C first-order medial bar, D and E first-order point bars with subsidiary scroll bars and chute channels

Figure 2.5 Bars of different orders in the Jamuna River (Bristow, 1987)

An interesting aspect is that (given the channel dimensions, the characteristics of the bed material, etc.), the higher order phenomena are very much affected by the discharge itself. There appears to be a close relationship between the discharge on the one hand and the dimensions of these pools and bars. Large discharges allow for deeper holes, and longer and higher bars. The discharge in a natural river, however, is usually changing. This means that in many river systems the bars and pools are never in equilibrium with the momentaneous discharge but that there is delayed adaptation.

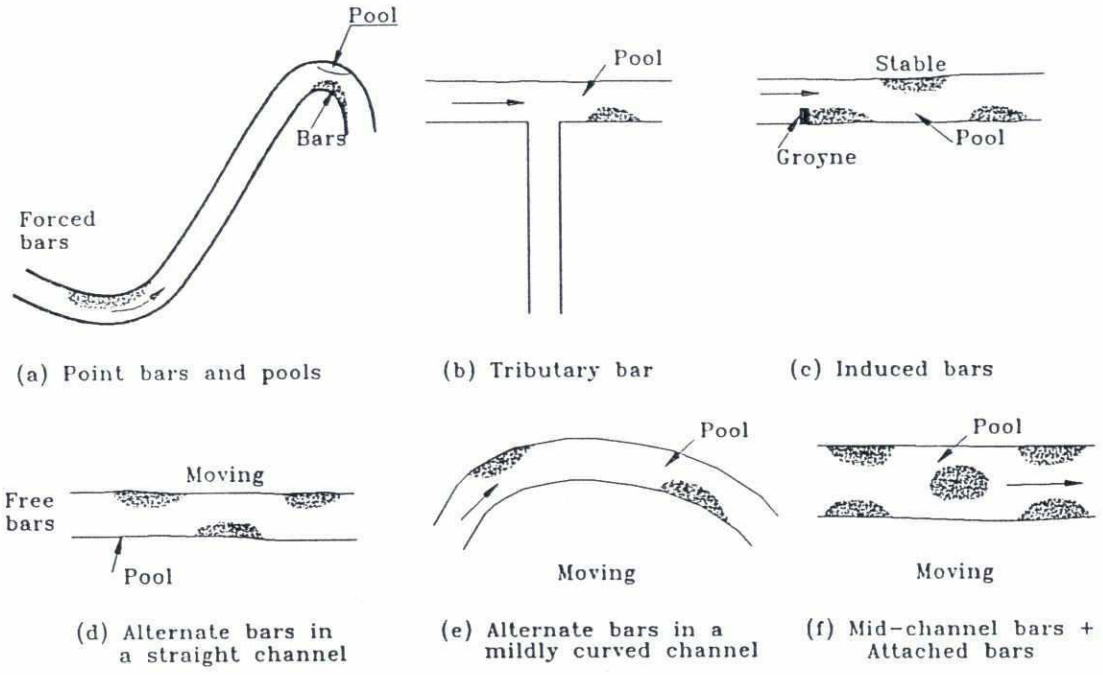


Figure 2.6 Overview of bars and pools in river systems

A similar phenomenon takes place at the still more detailed scale of the bedforms. The bedform dimensions are influenced by the local hydraulic conditions and these are affected by the discharge in the river channel. Also bedforms exhibit the typical delayed response behaviour, but here it is not certain whether the bedform dimensions are positively correlated with the discharge for all stages (see Klaassen et al, 1988b).

It is obvious that also this delayed response as discussed here should be taken into account when analyzing the river behaviour and the dimensions of phenomena like bars and bedforms, and observation of deep pools in rivers.

3 Data available

3.1 Introduction

This chapter presents a review of available data, both historical data collected from other projects, from agencies and organizations, from literature etc. (Sections 3.2 to 3.5) and data measured by the River Survey Project (Section 3.6). The last section describes data quality aspects.

3.2 Planform data

3.2.1 Topographic maps

For morphological studies recent topographic maps and historical maps are the most important categories of maps. First an inventory of available historical maps (all maps before 1950) is given next the topographic maps from 1950 onwards are described more in detail and finally some remarks are made on other types of maps relevant for morphological studies.

Historic maps

Probably one of the oldest available maps of Bengal and Bihar including the present Bangladesh geographical area and depicting the course of the main rivers is from Major James Rennell (1764 to 1776). The map was first published by the Asiatic Society, Calcutta and again published by T.H.D. LaTouche in 1910. This map has an approximate scale of 1:1,300,000 and is available in the library of Cambridge University, England. In 1765 James Rennel prepared a set of 5 maps covering the Brahmaputra's old course from the Meghna confluence to deep in Assam (India). This General Map of the River Brahmaputra has an approximate scale 1:130,000. A reproduction of this old map made in 1917 is also available from the India Office Map Room, London. The map is not plotted on a geographic coordinate system. Some adjustments are necessary if this map is compared with other maps.

In 1828 B.N.J.Wilcox prepared a map of the course of the Brahmaputra River in Assam, India, in an area approximately covered by 91 to 93° E and 26 to 27° N. This so-called Wilcox map shows the Jamuna River from the Bangladesh border with India at a scale 1 inch to 4 miles, corresponding to about 1: 253,440. This rather accurate map was plotted on a geographical coordinate system and covers only the river and a narrow strip on either side.
A river navigation map of the coastal zone with the whole southern region of Bangladesh was made by the British Admiralty in 1840.
Maps of the districts of Jessore, Faridpur and Dhaka showing the river courses of the Padma, the Ganges and the Gorai rivers are available for the period 1855 to 1860 at a scale 1 inch to 4 miles.
The Lower Provinces Revenue Survey map was published in the period 1867-1869.

Recently some historical maps with the banklines of the Ganges River have been compiled by BWDB for the years 1780, 1855 and 1886 for the reach from Indo-Bangladesh border to the Jamuna River (BWDB, 1978).

Sheets 118 and 119 of the Indian Atlas, made by J. Walker and published in 1866, cover the northern part of the Jamuna River. The scale of these maps is also 1 inch to 4 miles. Col. S.G. Burrard of the Survey of India issued 3 detailed maps of the complete Jamuna River in 1914 at a scale 1 inch to 4 miles. It is stated that these maps of 1914 are based on the maps of Walker which were surveyed from 1848 to 1866, and published in 1866. His surveys continued up to 1875. During 1911 to 1913 correction were made to these old maps.

Some maps, mostly of the Sirajganj area and not all of which show the Jamuna River, are available for the period 1914 - 1967. In total 17 maps are available with scales ranging from 1:50,000 to 1:250,000.

The Survey of India Quarter Inch Series, published in 1944, contain some information of the main river system in Bangladesh.

Many of these historical maps of Bangladesh made use of the India Zone IIB yards grid system. Only for the southern half of the Chitagong Hill Tracts, India Zone IIIB yards grid system was used. Both these grid systems are based on the Lambert Conformal Conical projection. This projection creates a conical surface that intersects the earth at the single standard parallel of 26° N (or 17° N for Zone IIIB). With this projection, distortions along east and west are minimized but the distortions increase with the distance north and south of the 26° N parallel. This projection was used by the Survey of India for creating maps of a vast east-west extent of the Indian sub-continent but is not optimal for Bangladesh, which is longer than it is wide and mostly lies south of the 26° parallel (FAP 19, 1992).

It is mentioned that during the 19th century, the longitude of Calcutta with respect to Greenwich was corrected. Therefore, the longitude on old maps can not be compared directly with the longitude on recent maps. It is recommended to identify "fixed" locations (mountain tops, lakes, important buildings etc) on old and recent maps and to use these "fixed" points as reference points for comparisons. Villages near the Jamuna River might have been shifted over centuries because of river bank erosion. Therefore, not all villages close to the river can be used as such a reference point.

Topographic maps since 1950

The Survey of Bangladesh, SoB, prepared standard topographic maps covering Bangladesh at a scale 1:50,000. An inventory of 198 of these maps used by various projects is presented in Tables 3.1 to 3.5, with the topographic identity numbers. Locations of these maps are shown in Figure 3.1 which relates the numbering system of the maps with a geographic coordinate system. Some maps are also printed on a large scale 1:250,000, see for example Table 3.1. The first versions of those maps were prepared during the fifties. In total 72 of these maps were revised in 1990/91 on the basis of information obtained from aerial photography of 1983 and verified on the ground with the help of ground control points, see their location in Figure 3.2. In February 1992, another 24 maps were on printing stage, numbers of others are on a proof-stage and the revision of all other maps is under cartographic completion.

Each standard topographic map covers square area of about 15 x 15 km. These areas are divided into nine standard sub-areas of which detailed maps with contour lines were prepared.

These detailed maps have a scale 4 inch to 1 mile or 1:15,837, see for example Tables 3.3 and 3.4 (FAP atlas, 1992). Some standard topographic maps are divided into 16 sub-areas with a scale 1:7,918, see Tables 3.2c and 3.3c, details are discussed later.

It is mentioned that SoB-datum is about 0.46 m (or 1.509 ft) above Public Works Department, PWD, datum (FAP 9B, 1992 and note Land Reclamation Project). The Great Trigonometrical Survey, GTS, datum, the Survey of Pakistan datum and the SoB datum, all refer to a common reference plane the Mean Sea Level, MSL. At the end of 1993 a revision of this MSL datum is prepared by SoB. It appears that the Bengal PWD was established during the British period independent of the MSL.

Some officials of SoB are of the opinion that PWD was defined to avoid negative contouring of ground levels.

Maps prepared under the responsibility of the SoB, are based on a "Lambert Conformal Conical Projection" (FAP 21/22, 1993). Some maps were prepared using the Universal Transverse Mercator (UTM) projection but these maps are outside the responsibility of SoB. The UTM projection portrays a series of horizontal cylinders tangent to the earth along equally spaced meridians. The UTM system divides the world into sixty such north-south zones, each 6 degrees wide. Bangladesh is divided almost equally between two UTM zones, one east of 90° E and the other one west of that meridian. Therefore the UTM projection requires use of two different transformations for dealing with spatial data from the two zones of Bangladesh. To reduce the average spatial distortion over a UTM zone, a horizontal Scale Reduction Factor is introduced. This factor effectively creates two north south lines of no-scale distortion, 'lines of true scale'. The overall effect is to balance the spatial distortion for the entire UTM zone. The standard scale reduction factor for a 6 degrees UTM zone is 0.9996. However, for new mapping, FAP 19 recommends the use Bangladesh Transverse Mercator, BTM, projection. (FAP 19, Technical Notes Series 1, 1992).

FAP 1 used 1:50,000 scale topographic maps published by SOB in 1951-57, 1967-69 and 1978-79 for studying the banklines of the Jamuna river prior to the commencement of satellite image coverage. It seems from FAP 1 report that the accuracy of those maps was sufficient for their purpose.

The Bangladesh Water Development Board, BWDB, also prepared topographic maps. From an area east of the Meghna river, detailed maps with contour lines at an interval of 1 foot were made recently at a scale 4 inch to 1 mile (1:15,837). For an area around Dhaka and the Ganges River detailed maps were prepared at a scale 8 inch to 1 mile (1:7,918) see Figure 3.3 (FPCO, 1992).

FINNMAP Oy/BWDB made topographic maps at a scale 1:8,000 and 1:16,000 of Gumti area (Gumti,Phase II), Madhumati-Nabaganga and Naogaon areas. In February 1992 FINNMAP Oy/BIWTA had been preparing maps at a scale 1:10,000 and 1:20,000 of the areas around Jamalpur, Sirajganj, Tangail and the coastal zone. These maps show contour lines with 0.25 m or 0.50 m interval, see Figure 3.4.

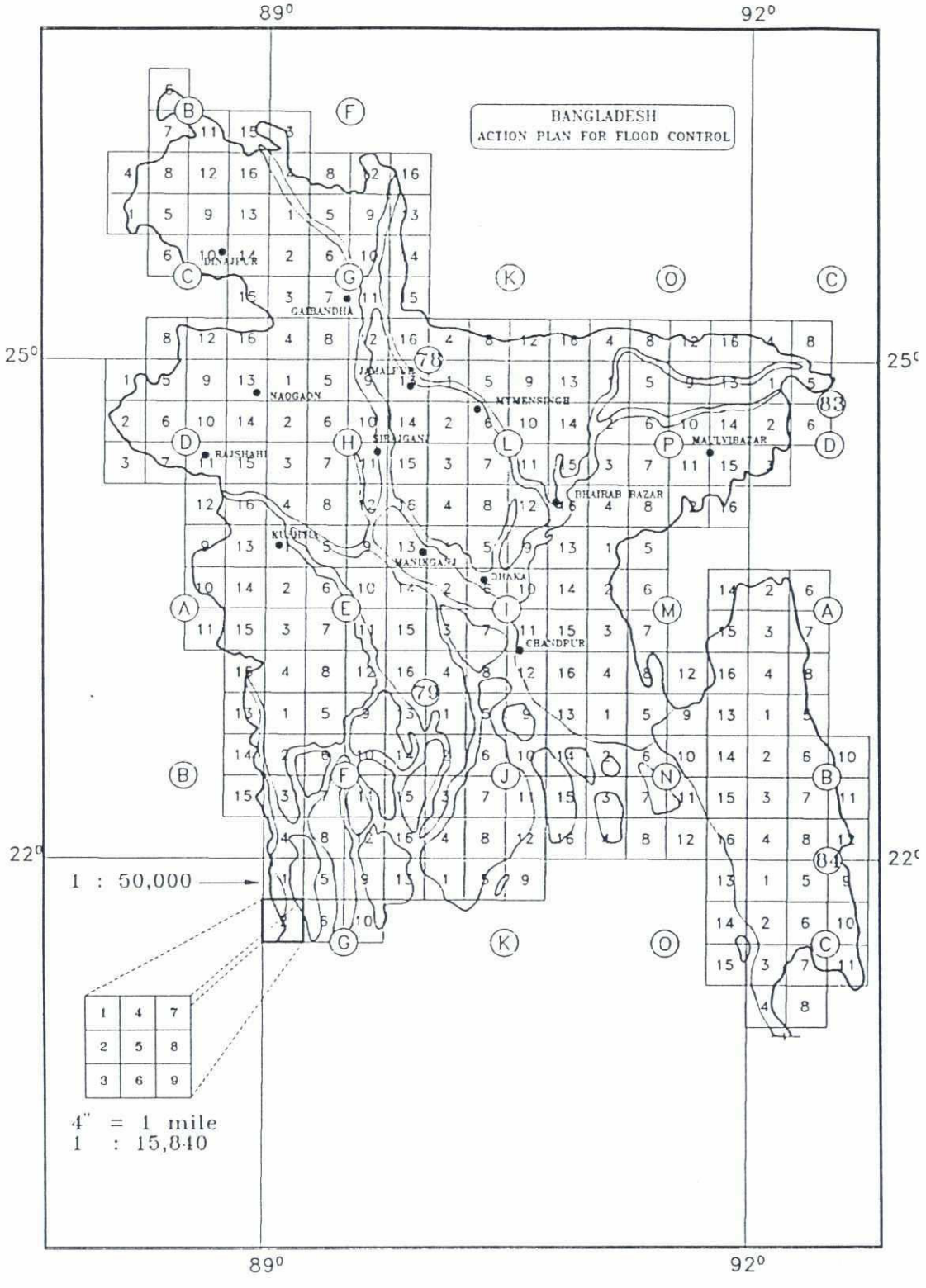


Figure 3.1 Numbering system of the maps with the geographic co-ordinate system

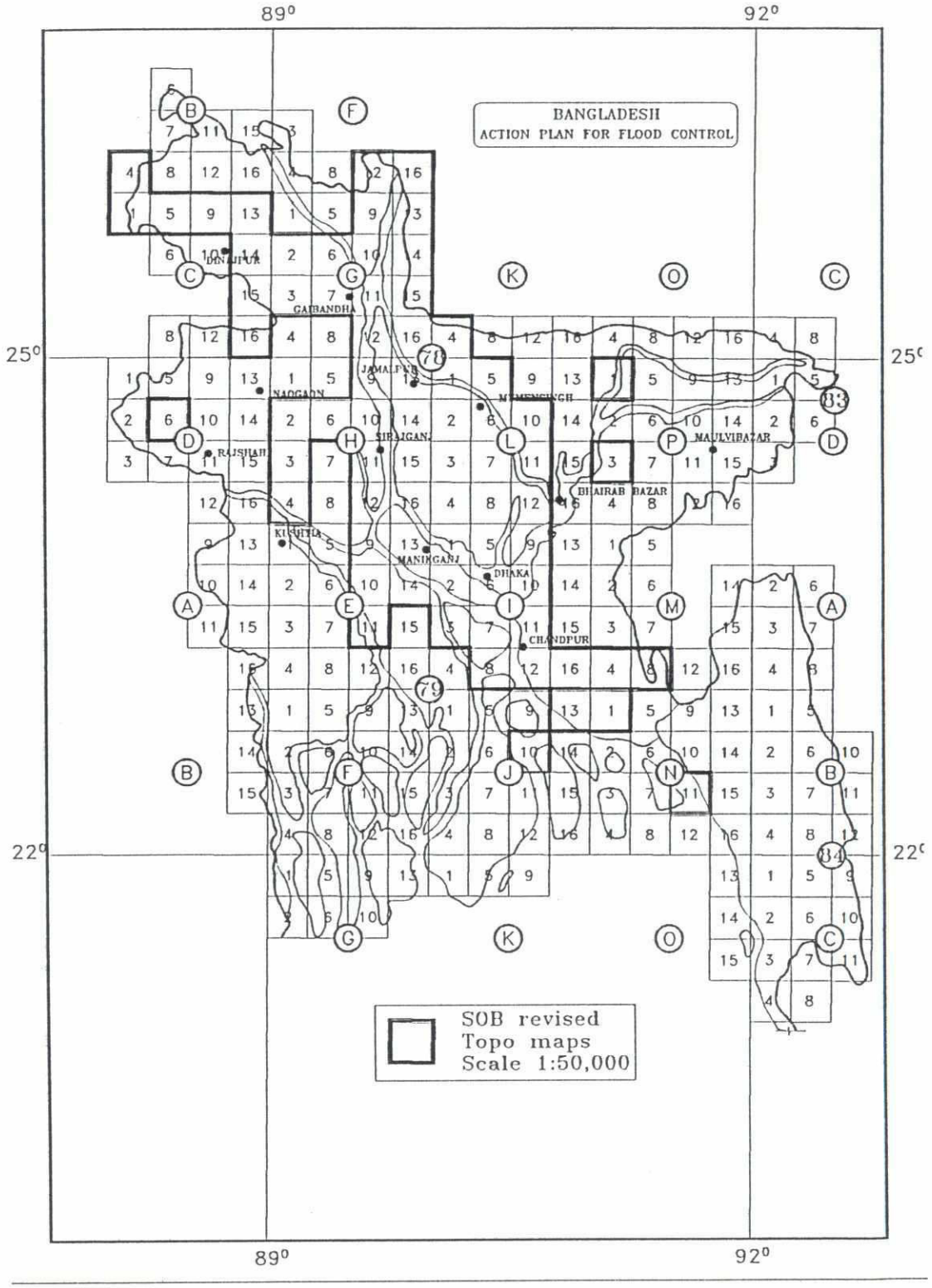


Figure 3.2 Revised topographic maps by SoB

Other maps

Not only topographic maps are of interest for morphological studies, but also maps presenting information in the field of (inland) navigation, geology, geomorphology, groundwater, land use and settlement mapping can be useful for detailed studies. For example, geological mapping can contain information on the constitution of the sub-soil, fault lines, scars of historic river plan-forms and the history of the alluvial sedimentation processes. This information is clearly presented in the structural geological map from 1964 and the Geological Map of Bangladesh published by the Geological Survey of Bangladesh, Ministry of Energy and Mineral Resources (Alam et al, 1990).

Bangladesh Inland Water Transport Authority, BIWTA, published maps for the inland navigation with all the navigable routes in Bangladesh. A chainage system which starts from the mouth of the rivers inside the distances in miles. This information is presented on the maps at a scale 1:250,000 with a geographic co-ordinate system. The older parts are based on surveys of 1943 and were updated with several revisions during the period from 1943 to 1965. Copies of these maps were collected by FAP 24.

3.2.2 Aerial photographs

According to the FAP ATLAS (FPCO, 1992), the Survey of Bangladesh has aerial photographs of entire Bangladesh from 1975 at a scale 1:30,000 and from 1983 at a scale 1:50,000. In December 1990 FINNMAP Oy/BIWTA made aerial photographs of the whole Jamuna river and prepared black and white photographic prints at scales 1:20,000 and 1:50,000 of a wide strip covering both sides of the Jamuna river, see Figure 3.5. This figure does not indicate the areas for which no photographic prints are available for FAP projects because of the security restrictions imposed by the Ministry of Defence. The permitted prints which cover the Jamuna River area only partially (about 60%), were used among others by FAP 1, FAP 3 and FAP 21/22. FAP 4 obtained aerial photographs of the Ganges, the Padma and the Gorai Rivers with exception of the Gorai mouth, because that area is classified. FAP projects can use aerial photographs through FPCO, and for selecting the required photographs a complete index of these photographs is available at the Survey of Bangladesh. The feasibility study of the Jamuna Bridge, (JICA, 1976), used aerial photographs of the Jamuna river in 1963.

In general, the spatial resolution of the aerial photographs is very high and small details can be detected from the aerial photographs. This resolution depends on the physical characteristics of the film, the focal length of the optics and the distance of the object. Stereographic photographs allow an impression of the variation in height of the objects.

To identify aerial photographs, a combination of line numbers and numbers along the flight lines are mentioned in each photograph. The identification numbers do not provide a direct relationship with a geographic co-ordination system. Each photograph covers an square area of about 4300x4300 m. Aerial photographs can be used for plan-form studies if a correction is made for the water-level at the time when the photographs were taken. Without this correction the bank lines based on these photographs should be considered cautiously. In addition, ground controls (at known places preferably with known coordinates) are necessary to interpret horizontal dimensions of the photographs.

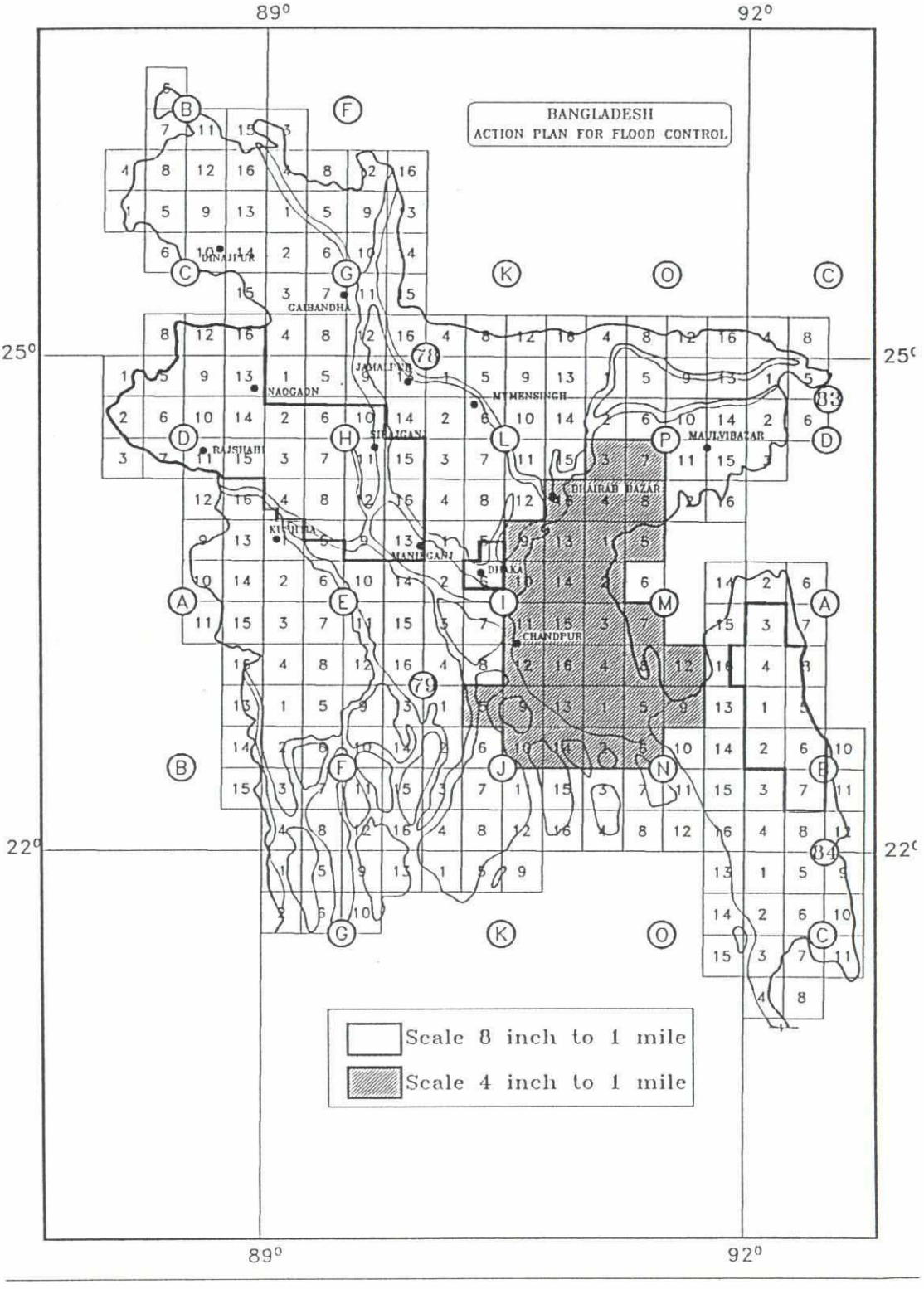


Figure 3.3 Detailed topographic maps on different scales

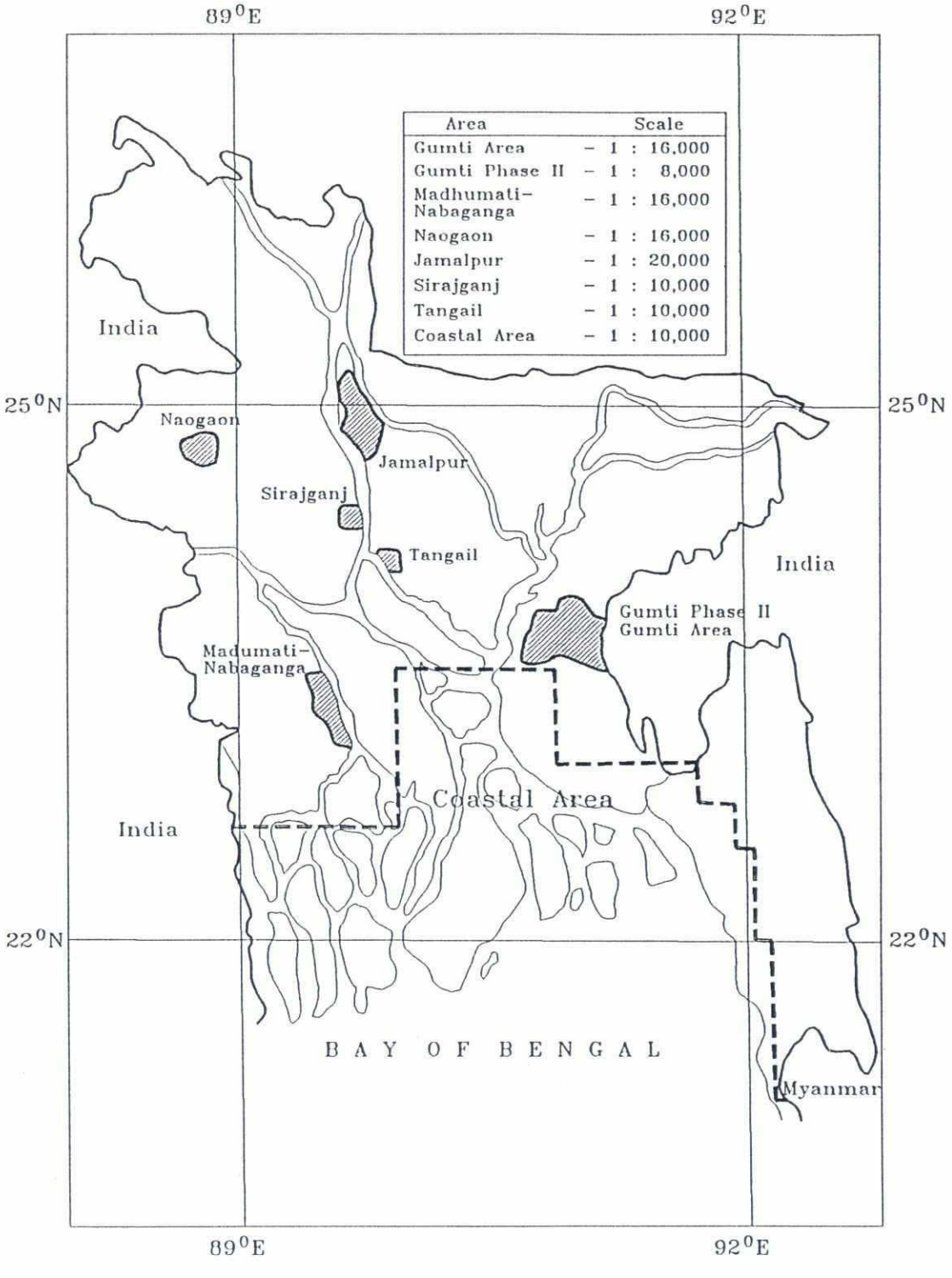


Figure 3.4 Recent detailed topographic mapping of project areas by BWDB/FINNMAP and BIWTA/FINNMAP

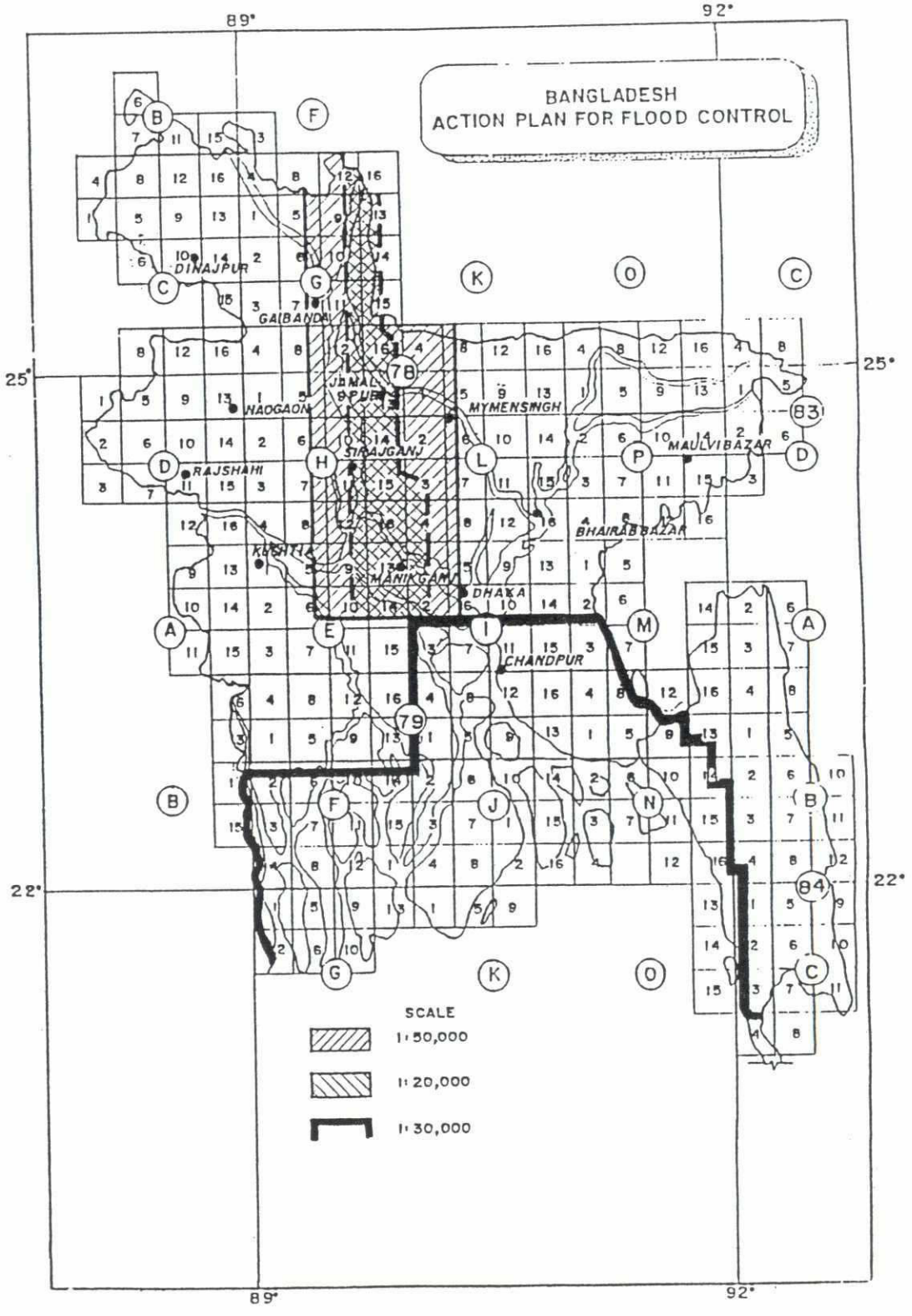


Figure 3.5 Aerial photography by BIWTA/FINNMAP

3.2.3 Satellite images

Various recent morphological studies have used satellite images from different origins, sensors and satellites. FAP projects can obtain satellite images by direct purchase or through SPARRSO (Space Research and Remote Sensing Organization), FPCO, or in some cases, through the Geographic Information System project (FAP 19).

The oldest available images of Bangladesh are LANDSAT images which are made by a Multi Spectral Scanner, MSS. The LANDSAT satellite was launched into orbit by the US National Aeronautic and Space Administration, NASA in July 1972. An inventory of LANDSAT images available with SPARSSO is presented in Table 3.6. The 16 ERTS/LANDSAT images which cover entire Bangladesh are indicated in Figure 3.6 (Bangladesh ERTS (LANDSAT) programme, 1977). The LANDSAT images are of the same size as the ERTS images, but a different numbering system has been used, see Figure 3.7 with the first number referring to the MSS images and the second referring to the more recent Thematic Mapper, TM, images. The location of some MOS-1 images are indicated in Figure 3.9. FAP 19 can process the computer compatible tapes, CCT's, of the satellite images. It also collected the more recent images from the TM, on-board the LANDSAT 4 and 5, from 1988 onwards and a few images acquired by the Marine Observation Satellite, MOS-1, during 1992 and 1993, see Table 3.7.

The Flood Plan Coordination Organization distributed prints of recent images from the French operated Systems Probatoire d'Observation de la Terre, SPOT, images starting from 1989 to 1993, to the different FAP projects, see Table 3.8 and Figure 3.8. The costs of acquisition and the digital tapes of those images are paid by the donor, C.D.F, of FAP 18. The processing of some of those images is paid by the E.C, from a FAP 24 budget, but outside the budget of the consulting consortium of FAP 24 (specifically the images of October 1991, March and October 1992, March 1993 and March 1995). FAP 19 received some SPOT images in digital form for research purposes. The minimum delivery time between the image being scanned by the satellite and the availability of a print of the image at FPCO is about two months. This delivery time is important because the study of the latest plan-form changes of the rivers after the monsoon flood can start earliest mid December to mid January. The two High-Resolution Visible instruments of the SPOT can be pointed so as to cover adjacent fields. In this configuration, the total swath width is of 117 km (nadir) and the two fields overlap by 3 km. The sensors provide high resolution imagery in the range of visible and infrared bands.

The main purpose of the Japanese satellite MOS-1 is to establish the fundamental technologies for earth observation and to carry out practical observations of the earth, primarily of the ocean. Its sensors operate in the visible, near infra-red, thermal infra-red and micro-wave bands. The MOS-1 images of the rivers in Bangladesh are also useful for studies of the plan-form of the rivers, see Figure 3.9.

The Indian IRS satellites provide high resolution imagery in a range of visible and infrared bands. Their primary objectives are national mappings of various resources.

A recent development is the use of radar images for the plan-form and the identification of the flooded areas during the monsoon. These Synthetic Aperture Radar, SAR, systems are based on active microwave sensors which are different from the LANDSAT and SPOT sensors in that the microwaves are capable of penetrating the atmosphere under virtually all conditions; i.e. microwave energy can "see through" haze, light rain, clouds and smoke.

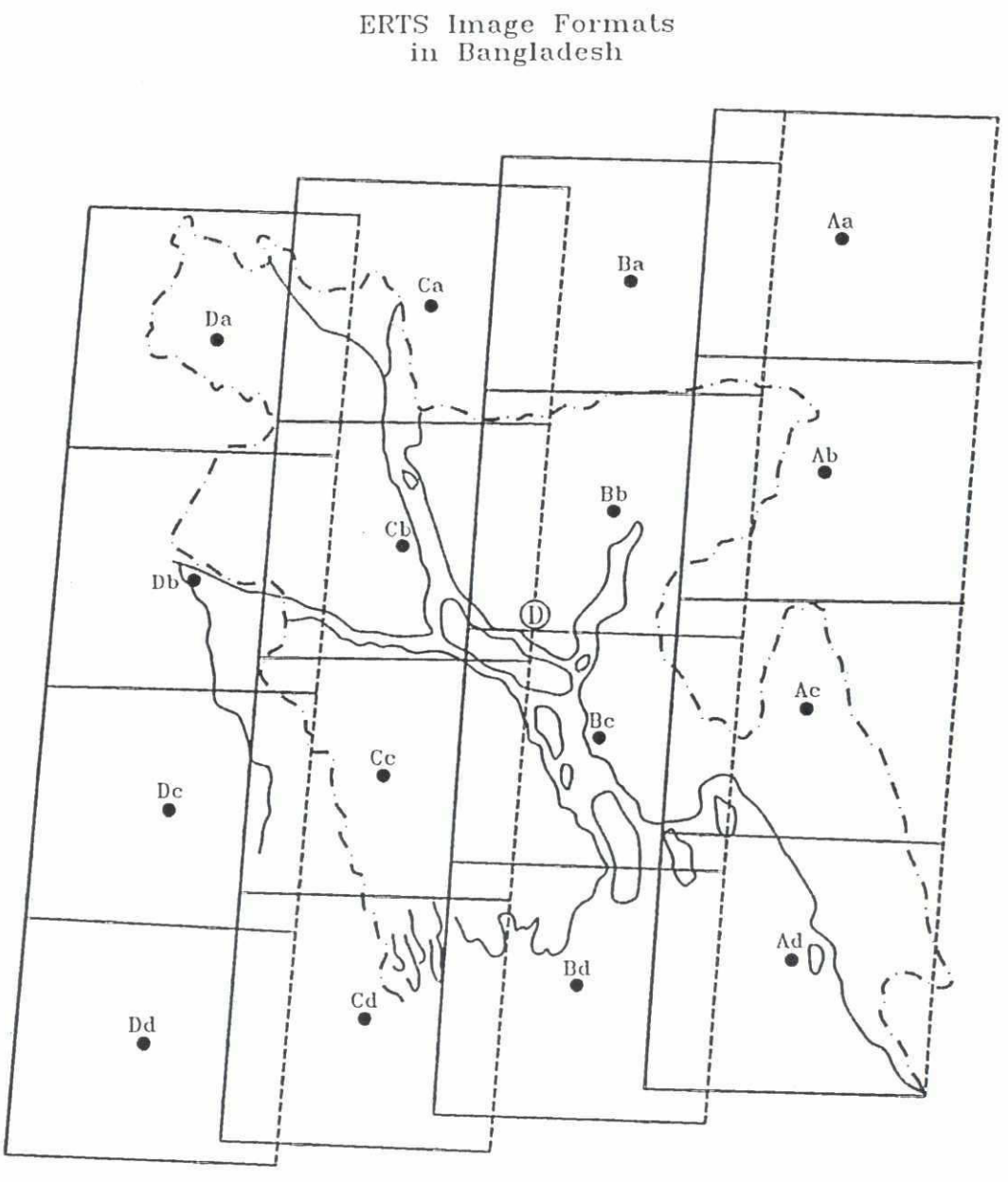


Figure 3.6 ERTS image formats in Bangladesh

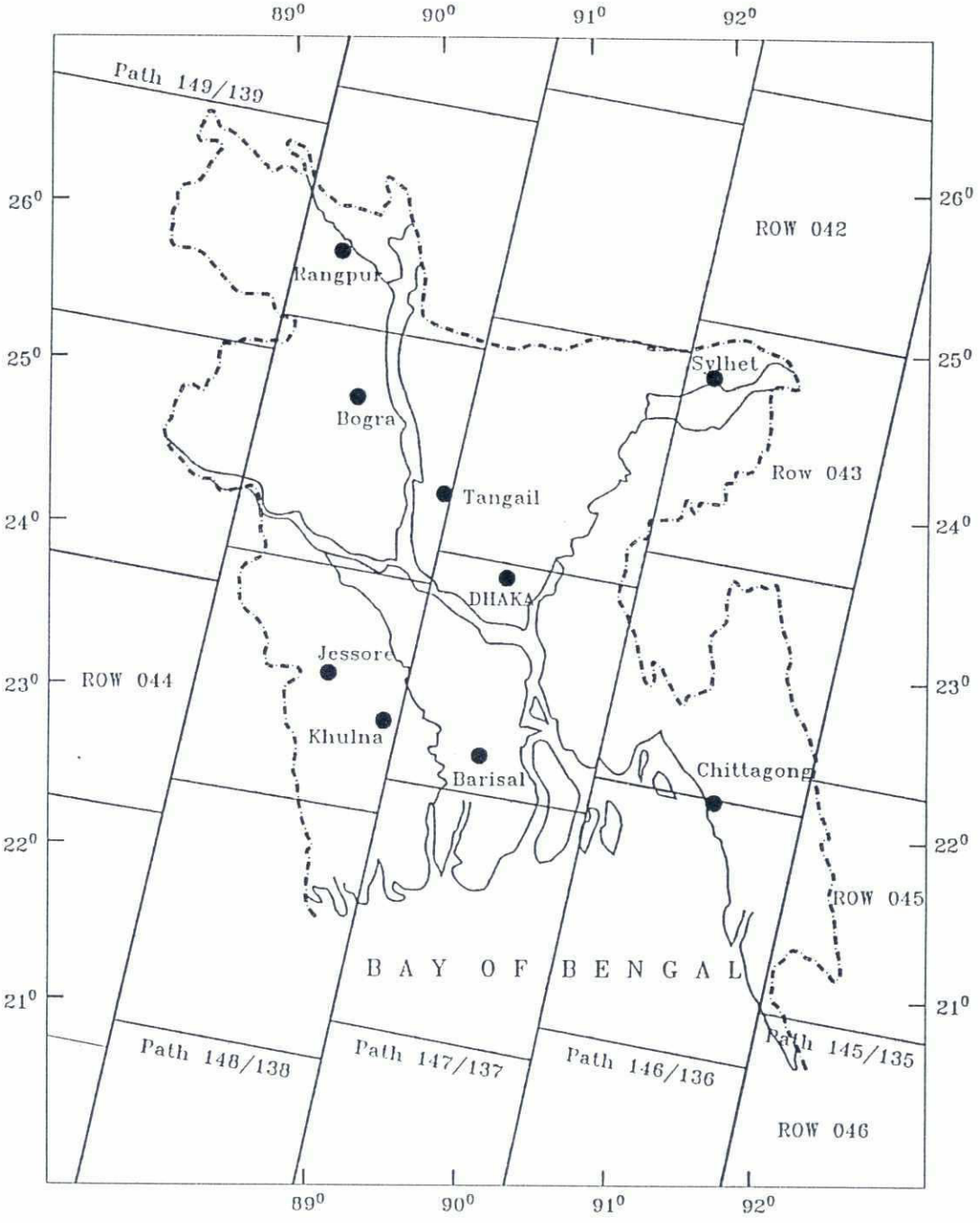


Figure 3.7 LANDSAT coverage of Bangladesh

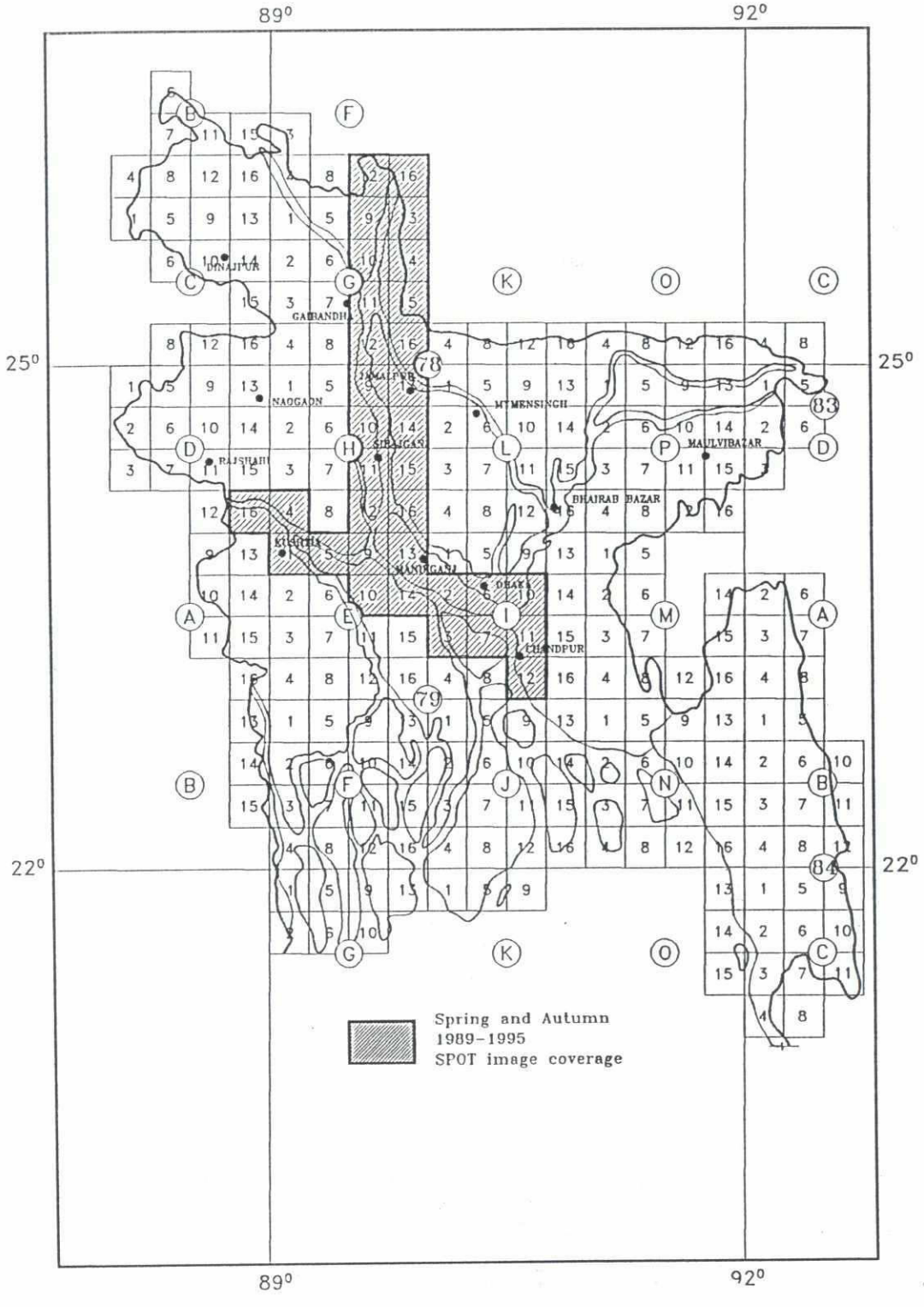


Figure 3.8 SPOT images 1991-93 for FAP projects

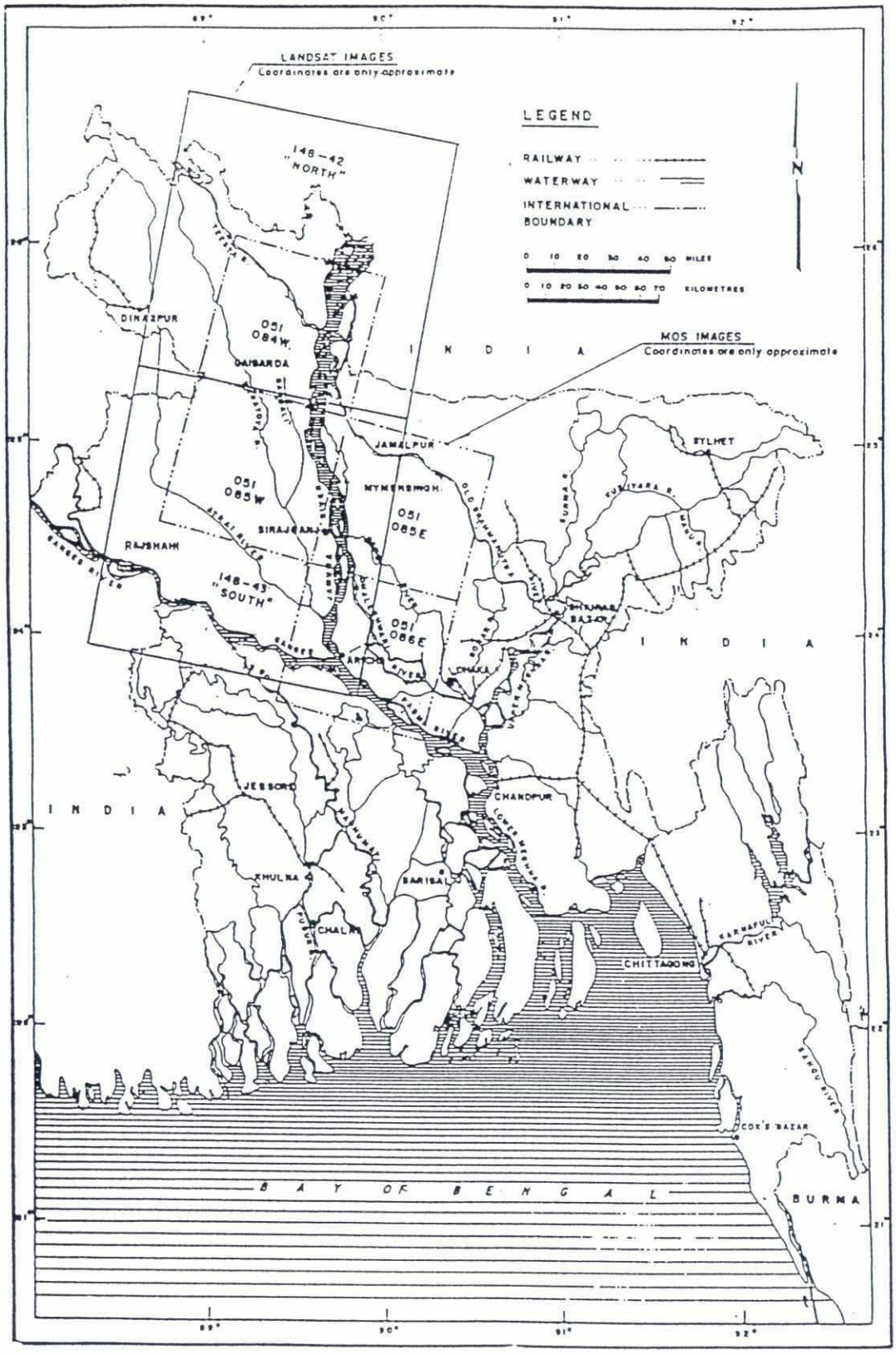


Figure 3.9 Coverage of LANDSAT and MOS satellite images of the rivers in Bangladesh

This property of the microwave energy allows the identification of flooded areas under a clouded sky during the monsoon. The ground resolution of these sensors is in the order of 10 to 25 m (Geographic Information System, Radar applications for the FAP, 1993).

Some information on the following relevant aspects of satellite images is presented: the resolution and the scale of the maps, the geometric correction, the projection system used for the map and the use of satellite images in morphologic studies.

Resolution and scale

The spatial resolution of satellite images varies depending on the different types of satellites. In general, the sensors of more recent satellites are able to take images with a higher resolution than the older sensors and satellites, see Table 3.1.

Satellite image	Scale of printed map	Resolution	Coverage	Period
LANDSAT MSS	1:250,000	80 by 80 m	-	1972-1988
LANDSAT TM1	1:250,000	30 by 30 m	185 by 185 km	1988-today
MOS-1	1:500,000	50 by 50 m	100 by 100 km	-
SPOT	1: 50,000	10 to 20 m	60 by 80 km	1989-today

Table 3.1 Scale, resolution and coverage of several types of satellite images.

On LANDSAT MSS images the geographical co-ordinates can be determined with an accuracy of about 80 m. If two LANDSAT images are compared the local erosion and sedimentation are determined with an accuracy in the order of 100 to 150 m.

SPOT images are corrected to maps using both a model of the imaging system and ground control points. This allows to associate estimated graphical co-ordinates to each image pixel. It is specified that the root mean square residual error between actual and estimated geographical co-ordinates for all the image points must be lower than 50 m. This error combines the error due to the ground control points and the error due to residual internal distortion. Verification checks have shown that the actual accuracy is about 20 m.

Geometric correction

In the Jamuna Bridge study, and in FAP 21/22 the Computer Compatible Tapes of LANDSAT, MSS and TM were processed by the National Aerospace Laboratory in The Netherlands by means of the Reseda processing system. The tapes were read and the data were subsequently geometrically corrected and resampled. The geometrical correction was done on the basis of some ten points which could be identified on the image of the Jamuna River of 1977 and from which the co-ordinates could be obtained from topographical maps. The accuracy of this correction was evaluated and the inaccuracy is not greater than the size of the pixel after resampling e.g. 50 m. All other images were corrected using the 1977 image as a base map.

The importance of this type of correction can be illustrated by some figures from the report Specialist Study, River Sedimentation and Morphology prepared by FAP 6 (FAP 6, 1993). The plan-form of the Upper Kushiyara River is studied by comparing topographic maps of 1952

and 1963 with a SPOT image of 1989. This study, which was carried out on a reconnaissance level, used this comparison to detect large scale changes in the plan-form of the rivers, such as new river courses (see example in Figure 3.10). For the detection of this type of changes no geometric correction of the maps is necessary. However for the detection of small scale changes in the plan-form of the rivers, such as bank erosion, and the development of a meander bend geo-corrected maps are needed. For example, in a stretch downstream of Fenchuganj, 4 cross-sections are presented (Figure 58 of FAP 6 report) showing minor shifting during the period 1969 to 1989. It very likely that the shifting of the river in Figure 3.11 is because of no correction has been applied and not because of morphologic processes during the period 1963 - 1969. Without a proper correction it is necessary to shift the map each time, compare for example the Baulai river between 270 and 280 km in Figure 3.12: in both figures the SPOT image was shifted to a different position compared with the topographic map of 1952. This example illustrates that an analysis of non-corrected images can easily result in misleading conclusions on the small-scale morphological processes. But as stated before, these maps and images can be used very well to detect large scale changes in the plan-form.

Projection

In general, mosaics of satellite images are prepared using different projections. Maps based on different projections can not be compared straight forward, but need careful transformations to the same projection before comparing them. For example, LANDSAT images which were used by FAP 19 for digital mapping are based on a Bangladesh Transverse Mercator Projection (BTM), and SPOT images are presented on Transverse Mercator Projection. This BTM is a cylindrical Transverse Mercator Projection combined with a map datum based on the Everest ellipsoid. This ellipsoid has been used on the Indian sub-continent for a long time and provides the 'best fit' with the earth surface for this part of the world. Rather than dissecting the country into two zones as with the UTM, the BTM takes 90 degrees as its central meridian and projects a 6 degrees wide zone on that meridian. Entire Bangladesh is contained within this zone, which extends from 87 to 93° E. The characteristics of different Mercator projections are listed in Table 3.2. FINNMAP (Topographic Mapping, FAP 18) and also FAP 19 recommends to use BTM projection for the preparation of maps of Bangladesh, especially within the projects of the Flood Action Plan. And FAP 19 will be pleased to assist other organizations in using BTM projection and in converting to/from other projections in use in Bangladesh, see Technical Notes Series No 1 of FAP 19 dated 24 May 1992.

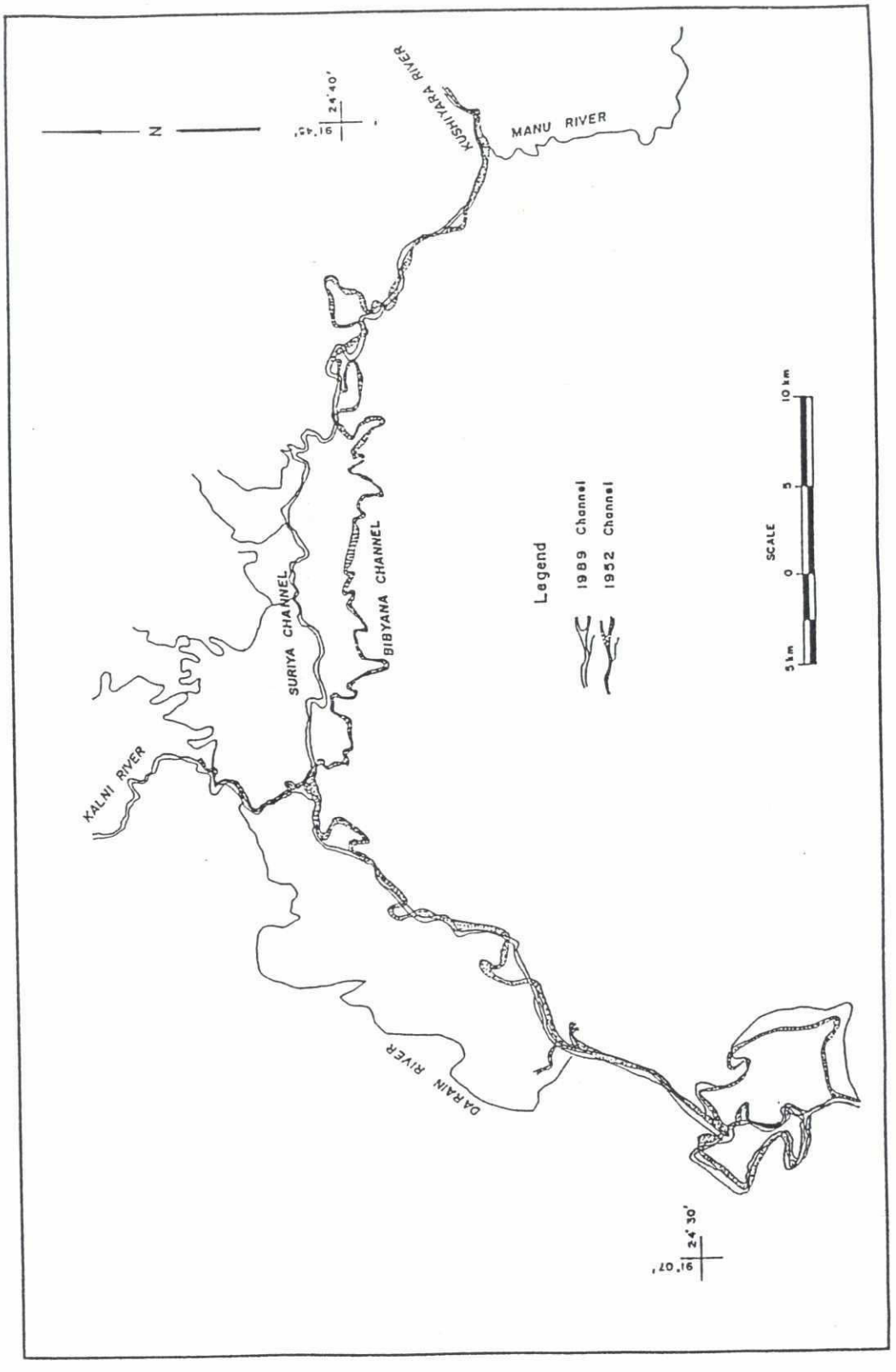


Figure 3.10 Examples of the use of not geo-corrected satellite images for comparing the plan-form changes of Kushiara river

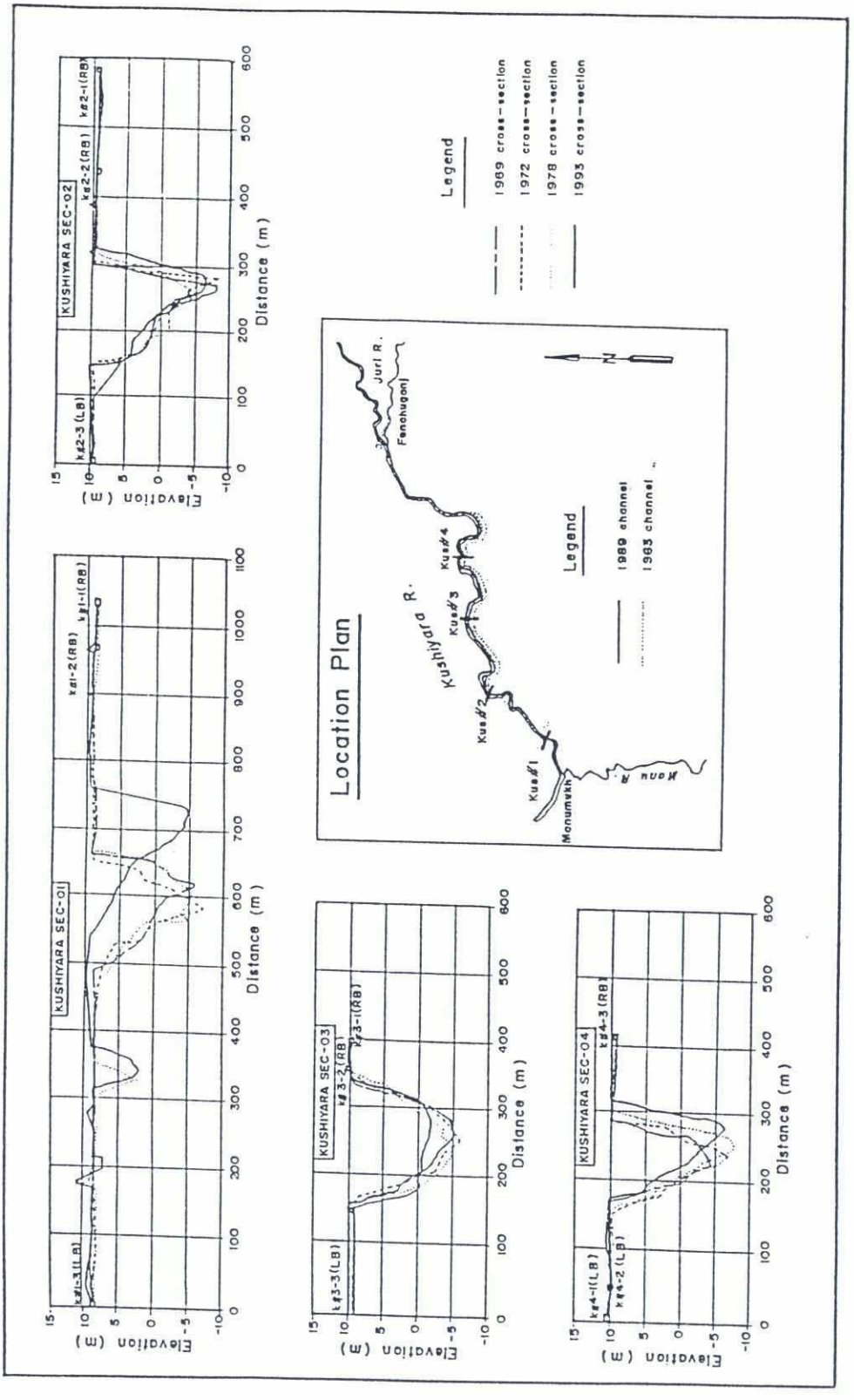


Figure 3.11 Example of the use of not geo-corrected satellite images for comparing the shifting of cross-section of Kushiara river

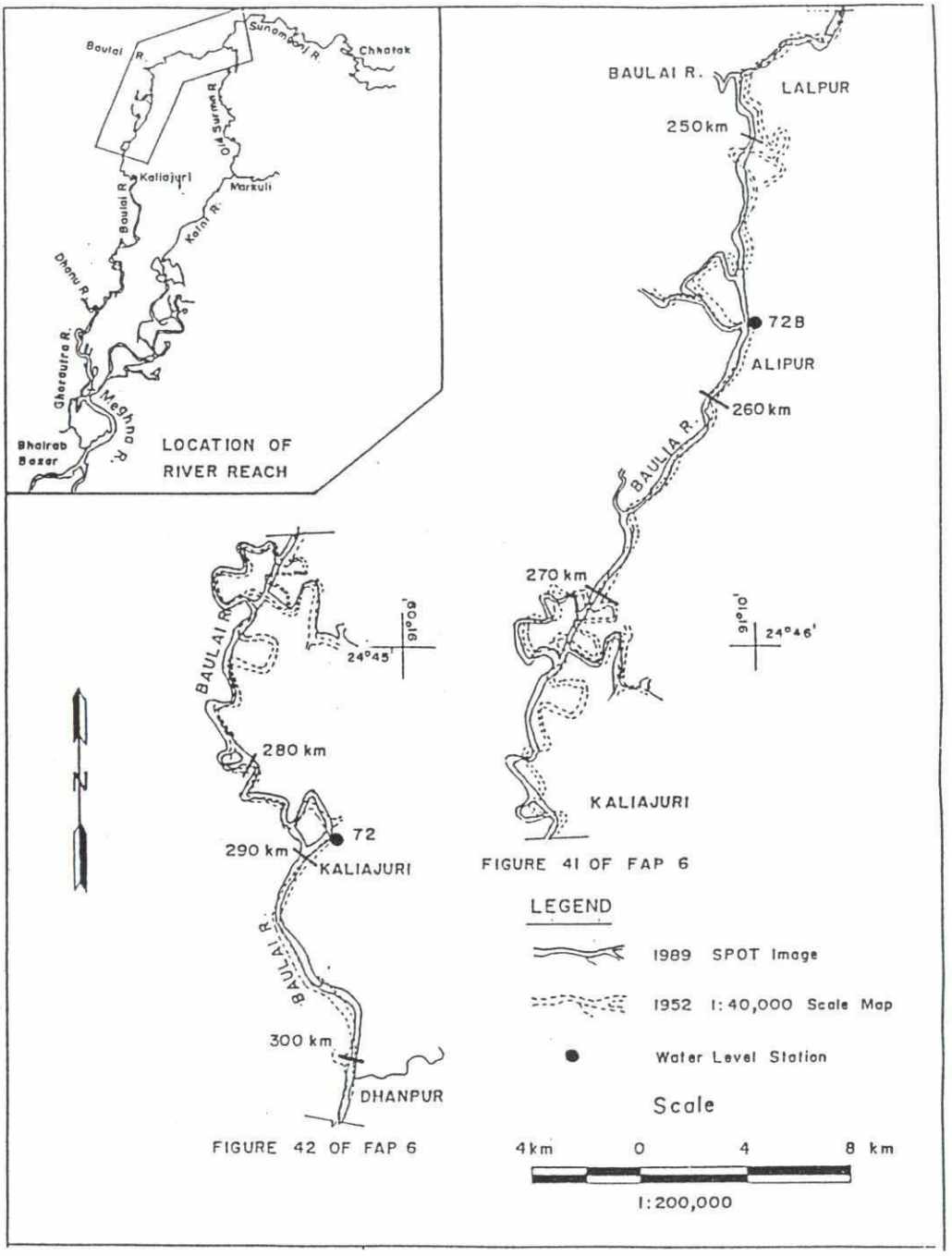


Figure 3.12 Example of the use of not geo-corrected satellite images for comparing the plan-form changes of the Baulai river

LANDSAT TM image data can be geo-coded in the projection of Space Oblique Mercator (SOM) or Universal Transverse Mercator.

The available maps of MOS-1 images are based on SCMP projection, and include an indication of the geographic coordinate system.

Parameters	Universal Transverse Mercator Projection (UTM)	Bangladesh Transverse Mercator Projection (BTM)	SPOT Transverse Mercator Projection (SPOT TM)
Projection	Transverse Mercator	Transverse Mercator	Transverse Mercator
Ellipsoid	WGS 84	Everest 1830	Everest spheroid
Scale Factor	0.9996	0.9996	0.9998
Central Meridian	87/93 degrees	90 degrees E	90 degrees E
Latitude of Origin	equator 0 degr	equator 0 degr	equator 0 degr
False Easting	500,000 m	500,000 m	500,000 m
False Northing	0 m	-2,000,000 m	0 m
UTM zone	45/46	-	-

Table 3.2 Comparison of different Transverse Mercator Projections, according to FAP 21/22 and FAP 19.

Use for morphological studies

The satellite images were used in FAP projects to study the plan-form of the rivers in Bangladesh. For example bank erosion, the growth and the erosion of chars, and the location of natural cutoffs can be determined accurately from dynamical composites of images of different years. The geometric characteristics of the braided belt, confluences, bifurcations, off-takes and bends can be measured from images. For flood protection and flood control studies information on the flooded area at intervals of 2 to 3 weeks during the monsoon period is very important. In some special cases valuable information on flow lines and on the mixing of water from different channels at a confluence can be obtained from satellite images. The orientation of possible faults in the river-bed and in the floodplain can be determined with an analysis of satellite images. It might be expected that the use of satellite images for morphologic studies will be developed further in the near future.

3.3 Data on cross-sections

3.3.1 Introduction

The main river system of Bangladesh is covered by a network of standard cross-sections which are surveyed by BWDB regularly (Subsection 3.3.2). BIWTA makes irregular soundings of the deepest part of the channels of the main river system to inform the inland navigation on the available depth in navigation routes (Subsection 3.3.4), this information is also useful for morphological studies.
In addition to these cross-sections and soundings irregular cross-section soundings are made for special purposes or according to special project requirements. The inventory of these irregular soundings is not complete, but includes some examples, which can be useful for morphological studies. It includes Jamuna Bridge soundings (Subsection 3.3.5) the soundings by the Railway Department (Subsection 3.3.3) and Consultant soundings (Subsection 3.3.5).

3.3.2 BWDB soundings

The BWDB established a river survey network covering all main, medium and minor rivers in the whole country during the past 25 years. This network comprises a total of 607 standard cross-sections at an interval of about 6,436 m (4 miles). In total, 144 cross-sections are surveyed every year in the main rivers, see Figure 3.13. 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 the dry season when the water-level is below the level of the chars. The dry part of the cross-section is surveyed with a levelling instrument and a levelling staff, while 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. The BWDB feels that for appropriate analysis of morphological changes in the river system it is necessary to survey the cross-sections also during the monsoon season and to densify the network with more standard cross-sections in future (Hoque, 1993).

Out of a total of approximately 1,000 cross-sections which have been surveyed in the Jamuna River from 1964 up to 1991, FAP 1 could locate approximately 700 which have been stored in a database. Most of the remaining 300 cross-sections which cover the period 1970 to 1976 could not be located despite extensive efforts by FAP 1 and BWDB staff. Only 24 cross-sections from that period could be located and this resulted in a very sparse coverage of 2 to 8 cross-sections for any individual year of that period (FAP 1, draft final report, Annex 2 Morphology, 1993).

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 high chars develop, 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 it is placed, the location of that plot in the Mauza maps and by the geographic co-ordinates of the pillar. The direction of the cross-section is defined by the bearing, an angle measured with respect to the magnetic north. In general, a cross-section is measured from the pillar (or the embankment) at one bank to the pillar (or the embankment) at the other bank. This means that not only the channel(s) and the chars are surveyed but often also a part of the flood plain. Preferably the cross-section is perpendicular to the river axis or the main flow direction in the river, but after some time the river axis may have changed as part of the changes in the plan-form of the river and the angle between the cross-section and the river axis is no longer perpendicular. If the pillars are eroded it is necessary to place and define new pillars with a new bearing. This can result in minor shifts in the location of a cross-section.

Jamuna River

In the Jamuna River, the oldest cross-sections were measured in 1964-65 at an interval of about 8 miles for the study of a barrage near Bahadurabad. Since 1965-66, this interval was reduced to about 4 miles. This interval was further reduced to about 1 mile since 1969-70, but these soundings were not performed regularly, and only in smaller stretches of the river (see Table 3.9).

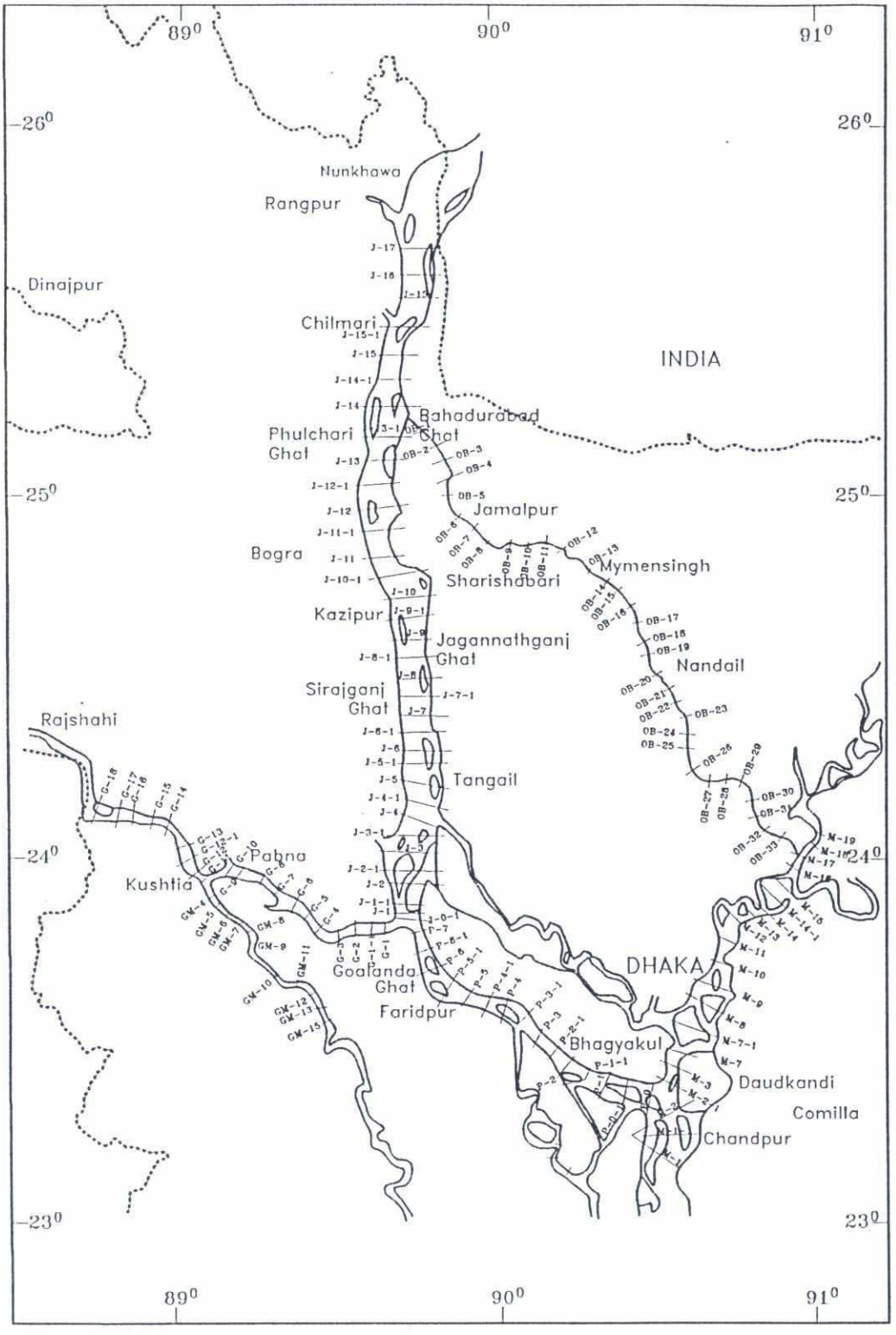


Figure 3.13 Standard BWDB cross-sections in the main river system

River	Total length (miles)	Number of standard cross-sections
Jamuna River	163	34
Ganges River	82	18
Padma River	65	15
Meghna River from Markul to Chandpur	158	45
Old Brahmaputra River	124	36
Dhaleswari River	90	23
Gorai River	124	32
Arial Khan River	72	32
Total	878	235

Table 3.3 Number of standard cross-sections per river of the main river system (1 mile = 1609 m).

Ganges River

The eighteen cross-sections have been extended with four more during 1965 to 1967, see Tables 3.3, 3.10a and 3.10b. All cross-sections were measured from 1966-67 to 1984-85 with a few years without surveys, especially, cross-sections G10 to G18. Probably, the inventory is not complete for recent years.

Meghna River

The 38 cross-sections in the Meghna River have been extended with 7 more during 1965-68, (see Tables 3.3 and 3.11). The approximate location of the standard cross-sections of the Meghna River is given in Figure 3.13 and a more accurate location in a more recent plan-form is given in Figure 3.14. During 1964 to 1968 only a few cross-sections were surveyed. All cross-sections have been measured with intervals from 1968-69 to 1993.

Distributaries

The cross-sections in the Old Brahmaputra River (since 1966), the Dhaleswari River with the Kaliganga (since 1965), the Gorai River (since 1968) and the Arial Khan River (since 1965) are measured much less frequently than the cross-sections in the main river system, see Tables 3.12 to 3.16.

3.3.3 Other soundings

WARPO (MPO)

The level of the flood plains can be estimated from the spot levels which are available at a 1 km spacing from the WARPO (MPO) square kilometre grid, (SWMC, General model Verification report, 1992). This information is additional to the described cross-section data.

Railway Department

Not only the BWDB, but also the Railway Department carries out cross-sectional soundings at a more or less regular basis. The Railway Department surveys the river-bed in a small strip

on either side of the following three railway bridges: Hardinge Railway bridge, Gorai Railway bridge and Bhairab Bazar Railway bridge. These surveys are part of the monitoring of the bridge stability. A few maps with soundings near the Bhairab Bazar Railway Bridge from 1989 and 1990 could be traced, see Table 3.17 a.

The routes of the railway ferries crossing the Jamuna River between Bahadurabad and Fulchari and between Jagannathganj and Sirajganj are also sounded regularly. It is mentioned that on the maps of those surveys all levels are related to a educed datum (= MSL) which differs from the PWD-datum. The oldest sounding map dates from 1946, but most available maps were prepared in the 80's, see Tables 3.17 a, b, and c. It is recommended that the Railway Department collects all their sounding data in one office, stores their sounding data in an archive and prepares inventory lists of their maps. Because the presented inventory in Tables 3.17 and is probably far from complete.

3.3.4 BIWTA soundings

The Bangladesh Inland Water Transport Authority, BIWTA, prepares bathymetric maps on the basis of surveys which are executed in the framework of the monitoring of the least available depth in inland navigation routes. In general, these soundings cover a short stretch of the river and not the full width of the river. The position of the survey vessel was determined with a Decca Navigation system. Its accuracy depends on the weather conditions, the survey time (morning or evening) and the location of the river (or the oblique of the angles between the connecting lines of the beacons). Under optimal conditions a rather high accuracy of about 30 m for the position fixing in any direction (FAP1, Annex 1 Sediment analysis) can be obtained, but under average conditions a lower accuracy of about 100 m is realized. The channel depth is measured with echo-sounders and charted depths are given with respect to SLW or ALLW. ALLW level stands for average lowest low water-level and in the BIWTA Hydrographic charts the average of 3 to 5 years lowest low water-level is taken. SLW level represents for standard low water-level which was first established by Nedeco in 1967. After a decade or more, BIWTA started using ALLW level for reduction of sounded depths. The relation between ALLW and PWD is established for several stations along the river.

In the Jamuna river these soundings started with a first small sounding in 1967, but from 1975 onwards almost every year a sounding was made in the route of the ferry from Aricha to Nagarbari. In the ferry routes from Sirajganj to Bhuapur, from Bahadurabad to Fulchari the frequency of the soundings is less, see Table 3.18. In the Ganges-Padma River these soundings started with an irregular frequency at 1969, see Table 3.4, and most soundings were made from Goalundo to Mawa, see Table 3.19. The BIWTA made soundings in the Upper Meghna River from 1964 and in the Lower Meghna River from 1964 with more or less regular intervals, see Table 3.20.

River	Starting year
Jamuna River	1967
Ganges and Padma River	1969
Upper Meghna River	1964
Lower Meghna River	1962

Table 3.4 Starting year of the BIWTA soundings in the main rivers

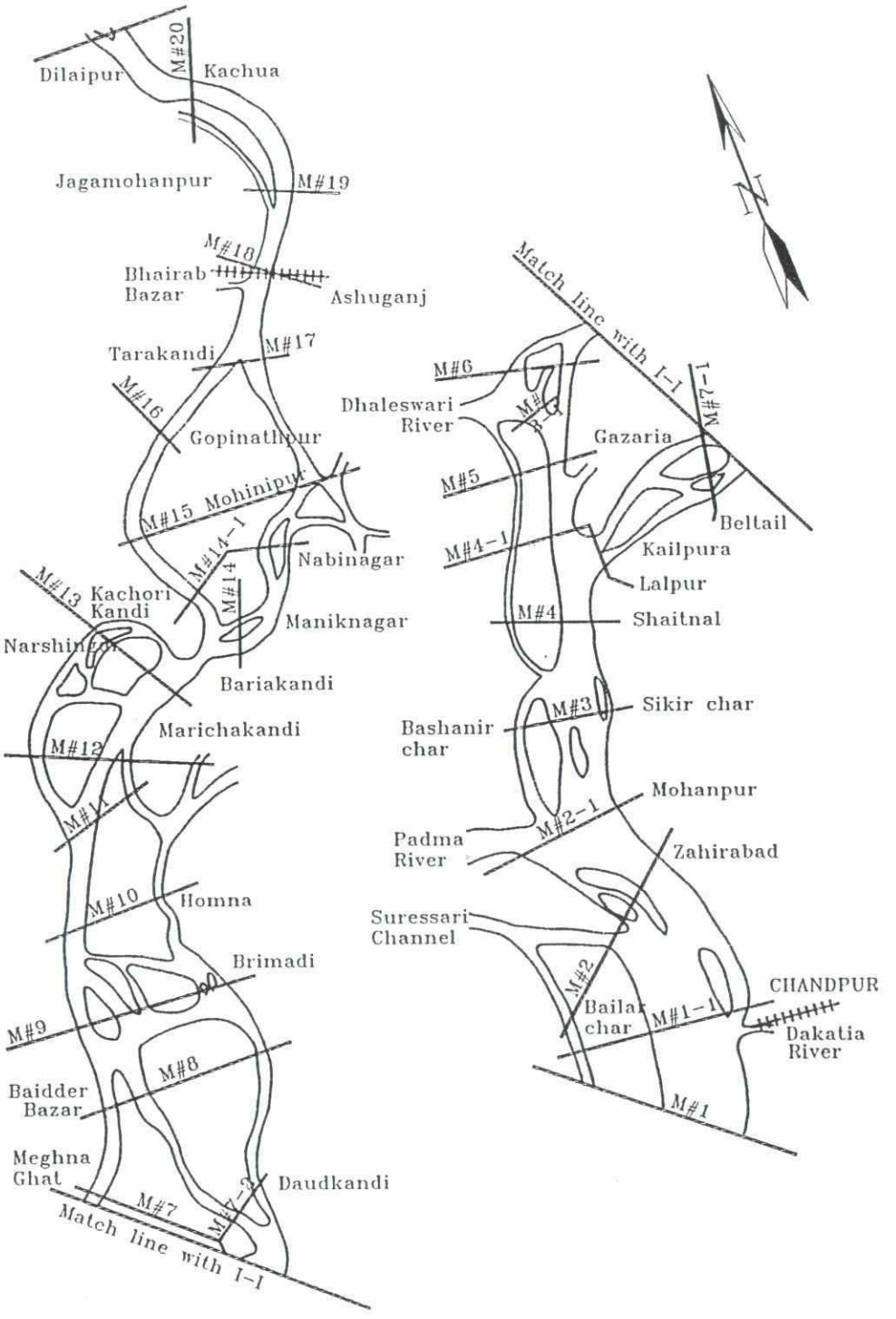


Figure 3.14 Location of the standard BWDB cross-sections in the Meghna River

The maps show the charted depth in 0.5 feet or 0.1 meter, and the maps are drawn at standard scales 1:5,000 to 50,000. Generally for thorough survey of the navigational route 1:25,000 or 1:50,000 scale are used and for special purpose, say for dredging or bandalling, surveys are presented in maps at a scale of 1:5,000 to 1:10,000. Most of these surveys do not cover the full width of the channel but only show the dredging or bandalling areas. This type of survey is not covered in the inventory. For the area near Sirajganj, Old Brahmaputra, the Gorai river a few maps are available at a scale 1:12,500. Some older ones of the Meghna River were made of a scale 1:100,000.

In the Old Brahmaputra, Dhaleswari and Arial Khan rivers only very few (1 to 5) soundings are available, see Tables 3.21 to 3.23.

Some contour lines are added to the map, especially to indicate the bank lines with some important locations (town, ferries, energy towers etc) but also of small settlements, villages. Those locations can often be found on the topographic maps of the SoB.

3.3.5 Other, irregular soundings

In recent years, several feasibility and design studies were performed including one or more bathymetric surveys of a very specific stretch of the rivers of the main river system. The presented inventory of these irregular surveys and soundings is probably not complete, because this information has been collected by bits and pieces. No systematic index could be used to search for this type of information.

The *Jamuna Multipurpose Bridge* is planned about 13 km downstream of Sirajganj town. Three survey campaigns by the Morphology Division of the BWDB at Jamalpur were executed during a period February/March 1990, October/November 1990, and February 1991. After February 1991, probably two more survey campaigns were executed.

The survey covered a stretch of the Jamuna River with a length of about 5 km. In this stretch 9 special parallel cross-sections were defined JMBP 1 to 9 which were numbered from downstream to upstream at an interval of 500 m. Cross-section JMBP 3 is parallel to the bridge axis and about 107 m downstream of this axis, indicated by a flag on both sides of the river. No coordinate system is mentioned on the maps, only the bridge axis is mentioned in the maps of the first survey report. However, monument 1 of cross-section J#6-1 at the right bank is indicated at a map in the report of the second campaign during October and November 1990.

The survey method and the presentation of the results in maps at a scale 1:10,000 is similar to the standard BWDB soundings.

In the frame-work of the *Meghna River Bank Protection Short Term Study*, FAP 9B (Hydroland, 1991), Hydroland made a bathymetric survey in February-March 1991, from Mawa at the Padma to Haimchar at the Lower Meghna River, and in August 1991 from the confluence of the Upper Meghna river with the Lower Meghna river near Eklashpur up to Haimchar. A cross-section for the entire length of 50 km in the Lower Meghna river from 5 km downstream of Haimchar to 5 km upstream of the confluence with the Padma river were carried out from bank to bank at an 500 m interval. From this confluence upto Mawa this interval was increased to 2000 m. A bathymetric survey in two areas near Chandpur and

Eklashpur (7000 m in the length, 2000 m in width) was carried out with a sounding interval of 100 m. The Decca positioning system and an echo sounder resulted in a reasonable accuracy of the surveyed bathymetry.

After the completion of the *Meghna Roads and Highways Bridge* in 1990, Pacific Consultants (1992) studied the bank erosion at the left bank upstream of this bridge. This study could use the 15 cross-sections which were surveyed in April 1989, January 1990, January and June 1992. These cross-sections cover a stretch of about 11 kilometre and the entire width of the river. In addition a detailed survey of 46 sections with a width of 700 m near the bridge site and along the left bank was performed. Contour maps at a scale 1:3000 were prepared. The report included also a contour map of the river-bed near the old ferry ghat from 1984.

The *River Training Studies of the Brahmaputra River,* FAP 1, defined 2 test areas in the Jamuna River. This project surveyed test area 1 which is an area south of Sirajganj during the surveys in June, July and November 1990. This area has been selected because it contains both fairly straight and wide reaches as well as one major confluence and one bifurcation. This project also surveyed the bathymetry of test area 2, which area covers the sharp bend near Kazipur, in December 1990 and August 1991. The aim was to monitor the development of bend scour and bank erosion in a well developed bend. (Halcrow/DHI, Draft Final Report, Technical Annexes, Annex 1 Analysis of sediment data, January 1993). Contour maps were prepared and individual cross-sections with fixed and well defined positions were analyzed. The 50% conveyance of a cross-section was determined. For the positioning fixing a Decca system was used.

FAP 1 made a cross-sectional sounding at a small interval of about 1 to 4 km for almost the entire length of the Jamuna River in 1986/1987.

The *Bank Protection and River Training (AFPM) Pilot Project* commissioned Hydroland and The Surveyors and The Realters to survey the preliminarily selected test-areas for a pilot project for bank protections along the Jamuna River in April/May 1992. These test areas were located near Kamarjani (north of the Manos Regulator), downstream of Bahadurabad ghat, Chandanbaisa and Nakalia. In October 1992, an additional survey was made at Kamarjani and at Bahadurabad. In November 1992, additional surveys were executed at Kazipur and at Sariakandi. In the survey area the cross-sections were surveyed at an interval of 200 m, see Table 3.5. The land part of a cross-section survey had a length of about 1500 m and the water part of a cross-section had also a length of about 1500 m. This means that the surveyed cross-sections did not cover the entire width of the Jamuna River, but only the width of an outflanking channel. The cross-sections were drawn at a distorted scale: a horizontal scale 1:2,000 and a vertical scale 1:100 and contour maps were prepared at a scale 1:5,000. These maps give detailed information on the topography of the bank, the bathymetry of the channel near the bank and of the dynamic changes in the river channels in a rather short period of time.

Test area	Length surveyed
Kamarjani	5 km
Bahadurabad	12 km
Chandanbaisa	10 km
Nakalia	12 km
Kazipur	6 km
Sariakandi	6 km

Table 3.5 The Jamuna River stretch surveyed in various test areas of FAP 21/22.

The *Southwest Area Water Resources Management Project*, FAP 4, surveyed the Gorai river from the mouth to the Kamarkhali bridge in the dry and in the monsoon season and the mouth of the Arial Khan with 8 cross-sections in the Padma river near the off-take in the period 1992 - 1993. Long profiles with continuous depth measurement and position fixing by GPS were run from the Ganges to Khulna through the Gorai and from the Padma River via the Arial Khan river to Khulna.

3.4 Bed and Bank material

3.4.1 Introduction

For morphologic studies of the main river system of Bangladesh often some samples of bed material were analyzed. In addition, samples of the sub-soil of the river banks were analyzed in many projects related to the design of the foundations of structures in or along the rivers. These data are also useful for morphologic studies, but no comprehensive database of these data is available at the moment. The search for these data has resulted in a most probably incomplete data collection, but still useful for an overview of the bed and bank material characteristics, see for example Table 3.24.

A short introduction in the geology of Bangladesh in Subsection 3.4.2 provides a general understanding of the composition of bed and bank material in the main river system. The availability of analyzed samples of river-bed material are presented in Subsection 3.4.3 and the boreholes along the main rivers are summarized in Subsection 3.4.4. The rather general presence of some mica flakes in the alluvial sands of Bangladesh is an interesting aspect. The consequences of these mica flakes for engineering projects and bank erosion phenomenon are described in Annexure 1.

3.4.2 General geology

The drainage area of Ganges, the Jamuna and the Meghna rivers is located in one of the geologically most active areas of the world. The plain of the north-east Indian sub-continent is bounded to the north by the Himalayas and to the east by the range of mountains running North-South through Burma. On a geological time scale the northern Indian plate structure is sliding under the South-East Asian Plate, forming the Himalayas and in doing so undergoes considerable warping and shearing. On the East the two plates are rubbing against each other. Hence the Bengal Basin and its adjacent area is an active tectonic area. The Bengal Basin with

the main river system of Bangladesh has been in filled by sediments washed down from the surrounding mountains, especially from the Himalayas, where the mountains have steep slopes and the rocks are not so consolidated. It is estimated that the depths of sediments in the delta may be some 8 km, see Figure 3.15. These sediments are mostly fine sand and silt with a more or less horizontal stratification and these sediment are underlain by very old rocks. North of the Upper Meghna River these old rocks crop up as the Meghalaya Plateau, but the courses of the main rivers in Bangladesh are not influenced by outcrops of these rocks. The bed and bank material of the main river system consists therefore of alluvial sediments : mostly fine sand and silt.

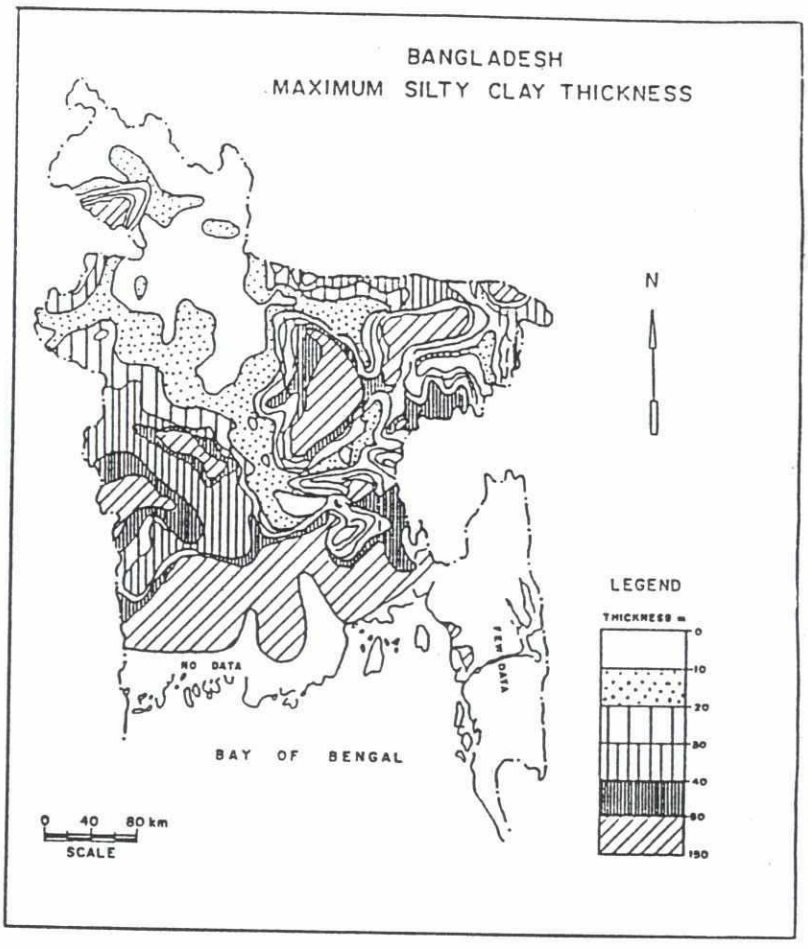


Figure 3.15 Thickness of recent alluvial deposits (Source : MPO, 1987b)

3.4.3 Riverbed material

The analysis of the riverbed material is often done by the analysis of small surface samples which were taken from the river-bed.

For morphological studies the most important parameters to be determined in this analysis are (Vanoni, 1976):

- size frequency distribution or sieve curves from which D_{10}, D_{16}, median size D_{50}, D_{60}, D_{84} and D_{90} and the geometric standard deviation can be determined,
- type of material: sand, silt or clay,
- frequency distribution of the fall velocities of the particles,
- density and specific weight.

D_{50} is defined as the grain-size of which 50% of the weight of the total sample has a smaller diameter by sieving.

In general, the following properties are of secondary importance from morphological point of view:

- porosity and permeability,
- critical slope angle or angle of repose,
- shape of the grains or angularity,
- homogeneity, stratification, compaction, flocculation and chemical composition.

The sample analysis for the design of foundations include more specific soil characteristics than the above mentioned, for example, the plasticity index determined by the Atterberg Limits, shear strength parameters, critical and in-situ density.
Susceptibility for liquefaction may be of some interest for studying bank erosion as part of a morphologic study. The susceptibility for liquefaction is indicated by a comparison of the critical density under the condition exhibiting zero-volume change with the measured in-situ densities (e.g. from triaxial test samples). Critical density tests are carried out on reconstituted samples at varying dry density to establish at what density zero volume change occurs as a result of induced shear stresses, see the final report of FAP 9B (1992) and Delft Geotechnics (1988).

An inventory of the samples from the riverbed which have been collected and analyzed on a regular basis by BWDB, is given in Tables 3.25 and 3.26. An inventory of those samples collected by several projects at irregular intervals is presented in Table 3.27.

Jamuna River

During the survey of inland waterways and ports from 1963 to 1967, the grain-size distribution of about 14 to 17 samples of the Jamuna River were analyzed. From these grain-size distributions D_{90} was determined and found to be ranging from 0.05 to 0.33 mm (NEDECO, 1967).

During the appraisal study for Jamuna Multipurpose Bridge an inventory was prepared of existing data of soil samples from Chilmari to Aricha for the period 1965 to 1977 (see Table 3.28). In this table, also the D_{16}, D_{84} and an estimation of the standard deviation of the mean particle diameter are given. No new samples were collected from the river at that time. The samples analyzed by the River Research Institute were a main source of information for this inventory on bed material of the Jamuna River. In the description of these analysis, the depth of the sampling location, and the grain-size distribution were mentioned.

Bristow (1987) reports the analysis of some sediment samples from the upper reach of the Jamuna river near Chilmari. No more details are given in his article.

The River Training Studies of the Brahmaputra River (Halcrow, 1992) took 76 samples in July and 19 samples in November 1990 from the river- bed in a test area south of Sirajganj. In the report two maps are included with the location of the samples in the test areas. The mean diameter, 0.15 mm and the geometric standard deviation, 2.8 have been determined from the grain-size distribution. The spatial variation of the D_{50} over the test area was rather small of the July samples and considerable of the November samples may be due to differences in grain sorting.

During the surveys in August 1991 this project also analyzed some samples from the river-bed in the second test area in the sharp bend near Kazipur. At depths less than 4 m a grab type sampler was used to take the sample of the bed. At depths greater than 4 m a US-GS sampler with a scoop released by a spring was used during the July survey. These samples were analyzed by the River Research Institute (Halcrow/DHI, 1993 and Halcrow/DHI, 1991). The quality of the sediment data depends mostly on the correct identification of samples and the accuracy of the grading analysis, which involves relatively small quantities of material. At the site the samples should be clearly and indelibly labelled to guarantee the correct identification later.

Meghna River and Padma River

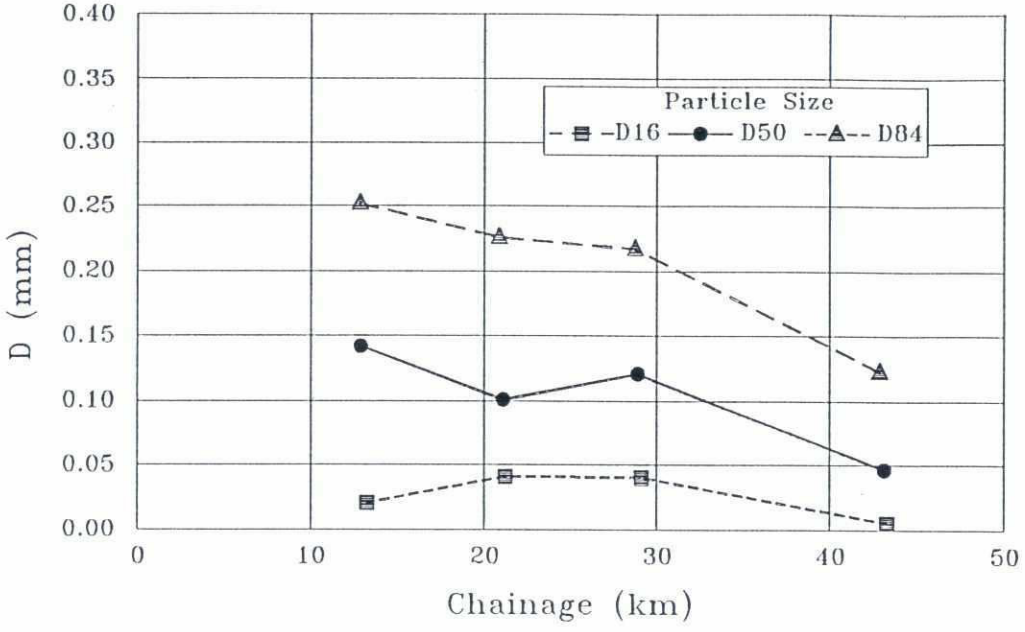
Within the frame-work of FAP 9B in total 126 bed samples taken with a grab sampler in the stretch from 5 km downstream of Haimchar upto Mawa and 5 km upstream from the confluence in the Upper Meghna river. The grain-size distribution and the density were determined in the analysis of these samples, see Figures 3.16 and 3.17. The analysis of samples revealed the predominance of fine sand with traces of silt. Along the chainage, the D_{50} reduces in the downstream direction. In the area practically all encountered fine sand layers contain a fair quantity (5%) of recognizable mica flakes, their dimensions often exceeding 3 to 5 times the D_{50} of the sand (Haskoning, 1992).

Other rivers

Bed samples were collected from the Gorai River at the mouth, at the Kamarkhali bridge and at two places more downstream by FAP 4 (Halcrow, 1992-1993).

3.4.2 Sub-soil material

The analysis of the sub-soil is often done by borings, which results in a characterization of the stratification in the sub-soil of the alluvial delta. The Groundwater Circle of BWDB conducts sub-soil investigations and geo-technical analysis on commercial basis for foundation engineering. Every year this department explores a total length of 12,000 to 16,000 m bore holes. In total, the BWDB has executed 108 deep test drilling (300 to 450 m below ground level) and 409 shallow test drillings down to 50 to 210 m below ground level to study the lithological characteristics of different aquifers. Disturbed soil samples by split spoon, undisturbed samples by Shelty tube and piston samplers and wash samples are collected at 1.5 to 3 m vertical interval and at the change of strata. In general, these soil samples are analyzed in the laboratory of the River Research Institute.



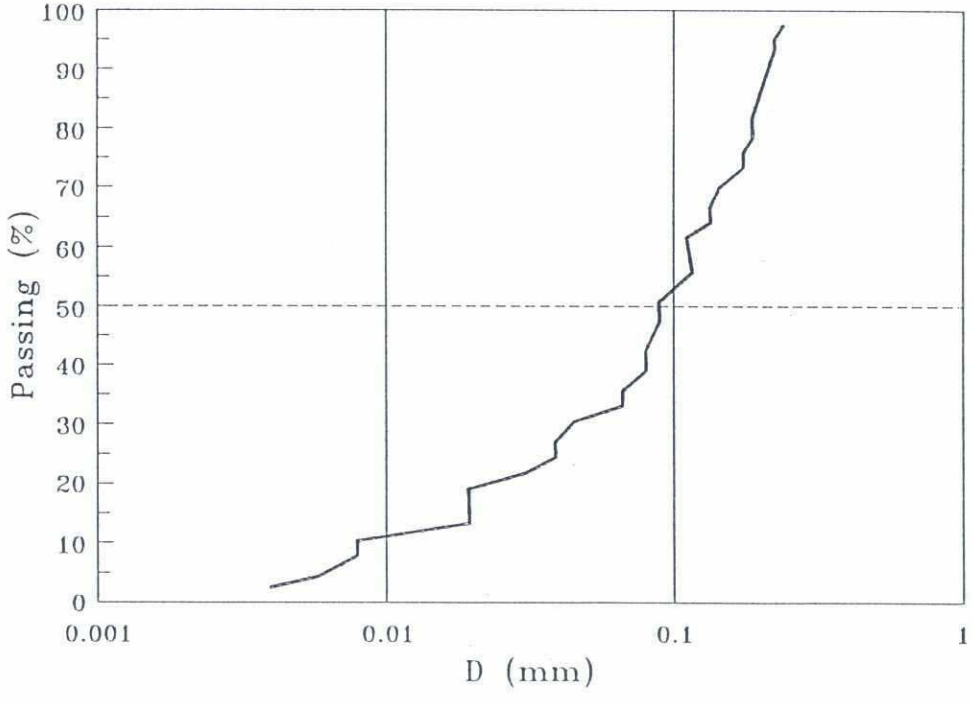
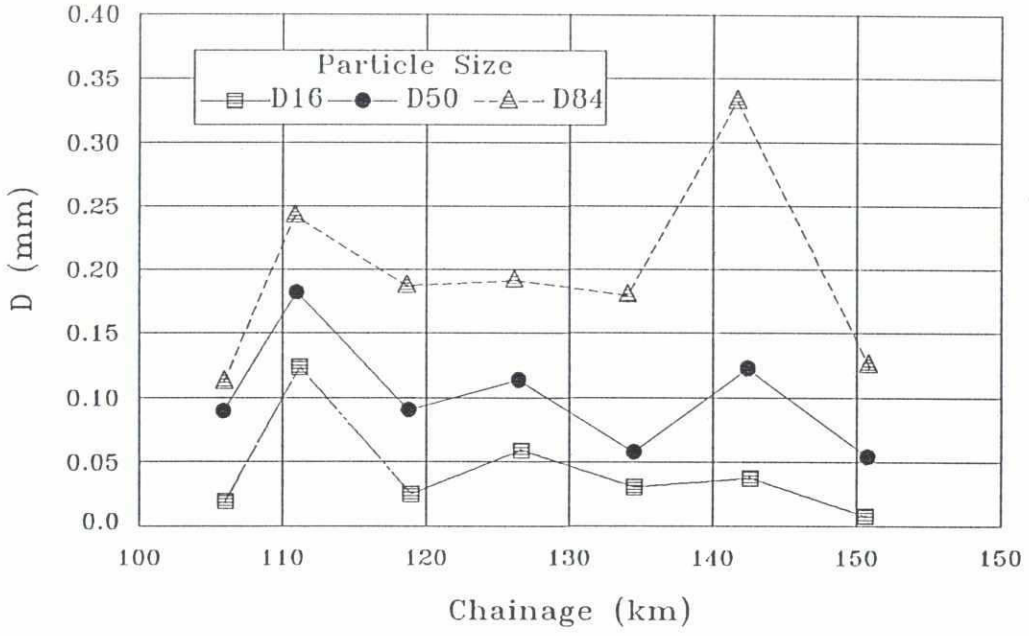


Figure 3.16 Sediment characteristics of the Padma River (FAP 9B)



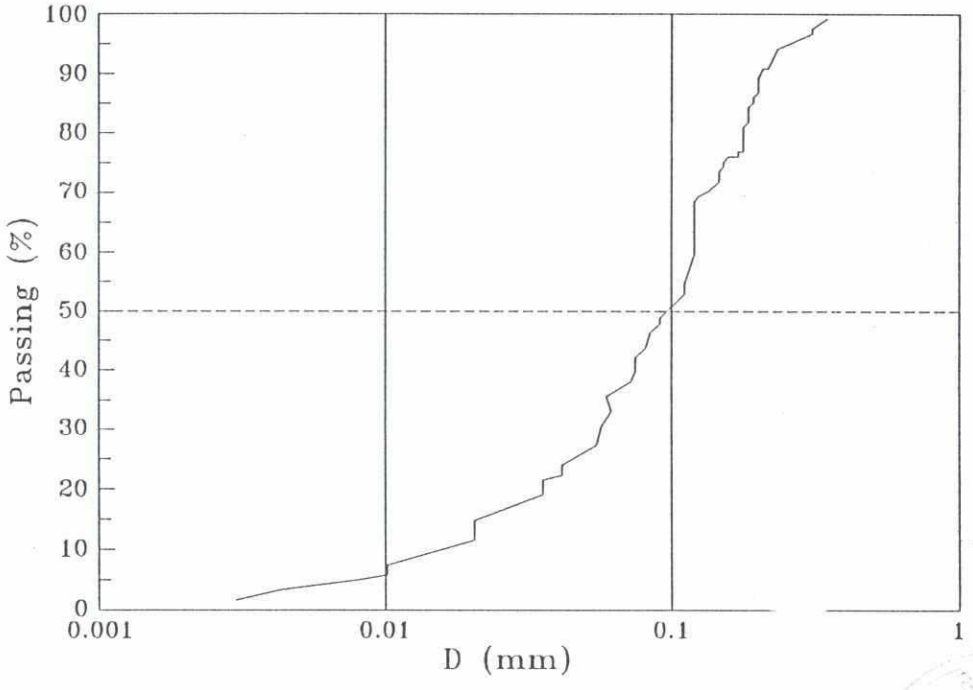


Figure 3.17 Sediment characteristics of the Lower Meghna River (FAP 9B)

Jamuna River

As part of the soil mechanical investigation to assess the sensitivity for liquefaction of the sub-soil near the Jamuna Bridge, 3 bore holes were sunk. One at the right bank down to 40 m below ground level and two at the left bank down to 40 and 120 m below ground level. The grain-size distribution of the samples taken from the borings are included in an annex of the report (Delft Geotechnics, 1988), with interesting photographs of the grains to illustrate the variation in shape of the grains.

The soil-mechanical investigation by FAP 21/22 for the foundation of the test structures for bank protections in the test areas near Kamarjani, Bahadurabad, Chandanbaisa and Nakalia consisted of about 15 boreholes. These boreholes were sunk down to a depth of 20 to 25 m below the ground level and one boring down to 40 m below ground level. The grain- size distribution, the moisture content, the specific density, Atterberg limits and the unit weight were determined. Also compression tests and consolidation tests were conducted.

Deep borings near Sirajganj and Aricha have produced evidence of wood fragments from depths around 100 m below present land levels. A carbon dating analysis estimated that the wood fragments near Sirajganj at 100 m depth date from 28,000 years before present and along the East-West Interconnector at a depth of 85 m the wood fragments were estimated to be 10,700 to 25,000 years old.

Meghna River

In the upper 10-15 m layer fine sand with sandy silt is found, while deeper layers consist mainly of fine sand. The grain-size gradually increases with depth. Along the whole river traces of mica are found.

For the improvement of the protection of the railway bridge near Bhairab Bazar after the 1988 flood, Development and Design Consultants made 8 boreholes.

In May 1989, during the feasibility study for Gumti phase II sub project several boreholes were made, of them 2 went down to 33 m below ground level near Maniknagar.

During the feasibility study for the Meghna Road and Highways Bridge in the Dhaka-Chittagong highway 4 boreholes (50 to 60 m deep) were made. Of these four borings two borings were sunk in the river-bed, one was sunk at the right bank and one at the left bank.

In a report dated 1977 and prepared by C.K.C. from Japan, data bases on boreholes down to 33 m below ground level were presented. These boreholes were located near pumping stations north and south of Eklashpur for Meghna Dhonagoda Irrigation project. For this irrigation project three boreholes were carried out down to a depth of 18 m below ground level by BWDB during 1986.

In 1971, two bore holes were sunk in Chandpur, of which one is at Nutan and the other one at Puran Bazar.

For the Chandpur Irrigation project two boreholes were made down to a depth of 16 m below the ground level by BWDB in 1977.

FAP 9B made 2 boreholes at each of the following 4 locations along the Meghna River: along the right bank near Bhairab Bazar, near the Meghna R&H Bridge, Munshiganj and Chandpur (1 in Nutan bazar and 1 in Puran Bazar) (FAP 9B, 1992).

The results of the analysis of the samples from all these bore holes can be found in the respective reports.

Other rivers

No information on the sub-soil materials from other rivers in Bangladesh was found in the reports available with FAP 24.

3.5 Data on flow stages, discharge and sediment transport

3.5.1 Flow stages and discharge

The major source of hydrological data is the Directorate of Surface Water Hydrology-II of BWDB. Most of the historical BWDB-data was, however, available in computerized form at FAP25 from where they were procured. The remaining data required, especially for the recent years after 1989 and for some additional stations, were procured directly from BWDB.

Despite that most of the data were readily available from FAP25, the procurement procedures, the necessary processing and checks on availability of the data and following collection of additional data made the establishment of a data base to a very time consuming process. Some of the data procured directly from BWDB were in a form of hard copies only while others were in computerized form but in various formats. The transfer of these data into the FAP24 data base required development of several computer programmes.

Up to date detailed overview of all historical hydrological data collected by FAP24 were made see as examples Tables 3.6 and 3.7. All the data collected are basically original BWDB-data even though the major part of the data were procured from FAP25. The data series cover basically the period from 1966 to 1992, but there are several gaps, e.g. data for the hydrological year 1971 are not available at all. For details, please refer to RSP SR2 Appendix 1.

In short the collected data are Stage-Discharge Data:
Results from discharge measurements including stage and derived discharge (Q-h measurements) were collected for the six permanent discharge stations in the main rivers. Available BWDB-rating curves for these stations were also procured from BWDB.

Mean Daily Discharge

The mean daily discharge time series derived by BWDB from water-levels and established rating curves were collected for the six discharge stations in the main rivers.

MEAN DAILY DISCHARGE DATA collected by FAP 24

1/2

WATER YEAR (April–March)	STATION: 46.9L Bahadurabad		STATION: 90 Hardinge Bridge **		STATION: 91.9L Baruria		STATION: 93.5L Mawa (tidal)	
	Status	Source	Status	Source	Status	Source	Status	Source
64	–	–	H	F	–	–	–	–
65	H	F	H	F	–	–	H	F 186
66	H	F*	H	F*	H	F*	H	F
67	H	F*	H	F*	H	F*	H	F
68	H	F*	H	F*	H	F*	H	F
69	H	F*	H	F*	H	F*	H	F
70	H	F*	H	F* 11	H	F*	H	F 7
71	–	–	–	–	–	–	–	–
72	H	F*	H	F*	H	F*	H	F
73	H	F*	H	F*	H	F*	H	F
74	H	F*	H	F*	H	F*	H	F
75	H	F*	H	F*	H	F*	–	–
76	H	F*	H	F*	H	F*	H	F
77	H	F*	H	F*	H	F	H	F
78	H	F*	H	F*	H	F	H	F
79	H	F	H	F*		Only parameters available	H	F
80	H	F*	H	F*	H	F*	H	F
81	H	F*	H	F*	H	F*	H	F
82	H	F*	H	F*	H	F*	H	F
83	H	F*	H	F*	H	F*	H	F 41
84	H	F*	H	F*	H	F*	H	F 43
85	H	F*	H	F*	H	F* 2	H	F 98
86	H	F*	H	F*	H	F* 39	H	F 90
87	H	F*	H	F*	H	F*	H	F 218
88	H	F*	H	F*	H	F*	H	F 224
89	H	F* (B)	H	F* (B)	H	F* (B)	H	B 224
90	H	B	H	B	H	B 13	H	B 219
91	H	B	H	B	H	B	L	B
92	–	–	–	–	–	–	–	–

Status: H = Data transfered to HYMOS
L = Data available in spreadsheet format.

– = DATA REQUIRED

Source: B = data available from BWDB (with number of missing days)
F = data available from FAP 25
(1st source mentioned is used for analysis)

* Rating curve parameters also available
** Also available 60 – 63

Table 3.6 Mean daily discharge data collected by FAP24

MEAN DAILY WATER LEVEL DATA collected by FAP 24

STATION NO.	NAME OF STATION	TYPE	NAME OF RIVER	STATUS OF DATA	WATER YEAR (april 1 – march 31)																											
					64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92
								L				L				L				L				L				L				
15J	Muthurpara		Brahm. Jamuna																											B	–	
45	Noon Khawa		Brahm. Jamuna																											B	–	
45.5	Chilmari		Brahm. Jamuna	H	–	F	F	F	F	F	F 33	F 79	F	F	F	F	F	F	F	–	F	–	–	F	F	F	F	F 60	F	FB	FB 1	B	–
46	Kamarjani		Brahm. Jamuna																											B	–	
46.7L	Kholabarichar		Brahm. Jamuna	H	–	F	F	F	F	F	F	–	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	FB	B	B	–
46.9L	Bahadurabad		Brahm. Jamuna	H	F	F	F	F	F	F	F	–	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	FB	FB	B	B 121
46.9R	Fulchharghat		Brahm. Jamuna																											B	–	
48	Jagannathganj		Brahm. Jamuna																											B	–	
49	Shirajganj		Brahm. Jamuna	H	F	F	F	F 1	F	F	F	–	F	F	F	F 1	F	F	F	F 1	F	F 61	F	F 1	F	F	F	F 1	F	FB	FB	B	–
49A	Kazipur		Brahm. Jamuna	H	–	–	–	F	F	F	F	–	F	F	F	F	F 13	F	F	F 2	F	F	F	F	F	F	F	F	F	FB	B	B	–
50	Porabari		Brahm. Jamuna	H	F	F	F	F	F	F	F	–	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	FB	B	B	–
50.3	Mathura		Brahm. Jamuna	H	–	F	F 4	F 1	F	F	F	–	F	F	F	F	F	F 7	F	F	F	F 122	F	F	F	F	F	F	F	FB	B	B	–
50.6	Teota		Dhaleswari																											B	–	
88	Rampur Boalia		Ganges																										B	B	–	
89	Sardah		Ganges																											B	–	
90	Hardinge Bridge		Ganges	H	F	F	F	F	F	F	F 11	–	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	FB	FB	B	–
91	Talbaria		Ganges																											B	–	
91.1	Sengram		Ganges	H	F	F	F	F	F 7	F	F	–	–	F	F	F	F	F	F	F	F	F	–	F	F	F	F	F	F	FB	FB	B	–
91.2	Mahendrapur		Ganges	H	hc	F	F	F	F	F	F	–	F	–	F	F	F 1	F	F	F	F	F 16	F	F	–	F	F	F	F	FB	FB	B	–
91.9L	Baruni		Padma	H	F	F	F	F	F	F 2	F	–	F	F	F	F	F	F	F	F	F	F	F 2	F	F	F 2	F	F	F	FB	FB	B	–
91.9R	Goalundo Transit		Padma	H	F	F	F	F	F	F	F	F 1	F	F	F	F	F	F 43	F 34	F 131	F 132	F 121	F 185	F	F	B	B	B	F 201	FB	B	B	–
93.4L	Bingyakul	T	Padma	H	–	–	–	–	F	F	F	F	F	F	F	F	–	F	–	–	–	F	–	F 1	F 1	F	B	B	B	B	B	B	–
93.8L	Mawa	T	Padma	H	–	F 61	F	F	F	F	–	–	F	F	F	F	F	F	F	F	F	F	F	F	F	F 122	F	B	F	FB	B	B	–
94	Tarpasha	T	Padma																											B	–	
95	Suroshwar	T	Padma																											B	–	
99	Goal Railway Bridge		Goal	H	F	F	F	F	F	F	F 4	–	F	F	F	F	F	F	F	F 1	F	F	F	F	B	B	F	F 91	F	FB	B	B	–
230.1	Bhairab Bazar Rly. Br.	T	Old Brahmaputra	H	F 114	F	F	F	F	–	F 11	–	F	F 1	F	F 122	F	F	F	F	F	F 4	F	F	F	F	F	F	B	B	B	B	–
272	Madna	T	Surma – Meghna																											B	–	
272.1	Austigram	T	Surma – Meghna																											B	–	
273	Bhairab Bazar	T	Surma – Meghna	H	F	F	F	F	F	F	F 11	–	F	F 8	F	F	F	F	F	F	F	F	B	F	F	F	F	F	F	FB	B	B	–
274	Narsingdi	T	Surma – Meghna																											B	–	
275	Baidyer Bazar	T	Surma – Meghna	H	–	–	–	–	F	F	F	F	F 1	F	F	F	F	F	–	F	F	F	F	F 1	F 1	F	F	–	F	FB	B	B	–
275.5	Meghna ferry ghat	T	Surma – Meghna	H	–	–	–	–	F	F	F	F 47	F 1	F 1	F	F 1	F	B	–	–	F	B	B	B	B	–	F	F	F	FB	B	B	–
276	Sutnal	T	Surma – Meghna																											B	–	
277	Chandpur	T	Surma – Meghna																											B	–	

= DISCHARGE / WATERLEVEL STATION

TYPE : T = Tidal station
STATUS : H = Data transfered to HYMOS

Remarks: – In case of incomplete years, additional data are not available at BWDB.

WATER YEAR: L = Leap year

= DATA AVAILABLE FROM: B = BWDB (with number of missing days)
F = FAP 25
(1st source mentioned is used for analysis)

= DATA REQUIRED

Table 3.7 Mean daily water level data collected by FAP24

92

Mean Daily Water Levels

Mean daily water level time series were collected for a number of stations along the main rivers to provide the basis for checking of water level time series at the six discharge stations. For a selected recent year 1990 additional data from a number of water level stations were collected to provide the basis for plotting of water surface profiles along the main rivers. For this purpose information on the chainages of the various stations were also collected from the Surface Water Modelling Centre (SWMC).

FAP24 data base for historical data

All the historical time series mentioned above have been transferred from various file-formats (lotus-files, BWDB-file-formats and hard copies) into the HYMOS data base of FAP24. The HYMOS software package has been used extensively for data validation, development of rating curves and statistical analyses.

When modifying the original data series due to data-corrections, new rating curves etc. as described in the next Chapter 5, the procedure has been to maintain the original data series in the original files and create new files with the modified data. Thus the FAP24 HYMOS data-base in fact consist of two parallel data bases, the first one with the original BWDB-data procured from FAP25/BWDB and the second one with all the updated FAP24 time series.

3.5.2 Historical review on the available sediment data

In the sixties the improvement of the sediment data collection received a high priority and the "Food and Agriculture Organisation-United Nations Special Fund" (FAO-UNSF, 1969) Hydrological Survey Team started an extensive sediment investigation using improved techniques. However it was limited to suspended sediment only, as it was practically impossible at that time to measure the bed load transport in the main rivers on a regular basis (including the monsoon period).

As per the programme initiated by FAO-UNSF, ten stations were selected within the priority area for sediment measurements. These stations are mentioned in Table 3.6.

Station No	Name of Station	River
46.9L	Bahadurabad	Jamuna
90	Paksey	Ganges
91.9L	Goalundo	Padma
91.9R	Baruria	Padma
93.5L	Mawa	Padma
99	Gorai Railway Bridge	Gorai
228.3	Kamarkhali	Gorai
137a	Mymensingh	Old Brahmaputra
68.5	Taraghat	Kaliganga
273	Jagir	Dhaleswari

Table 3.8 FAO-UNSF measuring stations along the main rivers

During the period 1966 and 1967, the sediment data collection at the stations mentioned in Table 3.8 was carried out at an interval of one week during the period from the beginning of April to the end of November. These data are published in the report "FAO-UNSF Second Hydrological Survey in East Pakistan, Dhaka, April 1969 (FAO-UNSF, 1969).

In 1968, at all the 10 stations suspended sediment data were collected during the period from April to November, and in 1969 weekly during the entire Hydrological year, that means from April 1969 to March 1970. These data are published in the report "Sediment Investigations in Main Rivers of Bangladesh 1968 and 1969, BWDB, Dhaka, December 1972".

At Bhairab Bazar the suspended sediment sampling was started in 1960 and it continued until 1963. No data is available for the period 1965-1969 probably because the sediment transport in the Upper Meghna river is relatively small. It seems likely this was the reason that Bhairab Bazar was not selected as one of the 10 stations in Table 3.6. Again in 1972, BWDB has started sediment measurements at Bhairab Bazar gauging station on a regular basis for the period from May to November.

Recently, Surface Water Hydrology II (SWH II) of BWDB made a computerized data-base of suspended sediment data. The data for most of the stations are processed until October 1992, for few stations they are processed until October 1993. All these processed data of BWDB were collected by the River Survey Project.

The BWDB is the only organization which is carrying out sediment measurements on a weekly basis all over Bangladesh. According to the inventory of Surface Water Hydrology (BWDB, 1986), BWDB is also taking measurements at stations along the smaller rivers. The Surface Water Modelling Centre also carried out the following sediment transport measurements for the calibration of their General Model, 5 samples were collected in 1992 at Mymensingh, and 6 samples were collected in 1992 at Taraghat.

3.5.3 Suspended bed material load

Since 1965, the suspended sediment samples collected from the rivers in Bangladesh have been divided into two fractions:

1. The suspended bed material load or sand fraction with particle diameter bigger than 0.05-0.063 mm and
2. the clay and silt fraction with the particle diameter smaller than 0.05-0.063 mm.

In general the distinction between bed load transport and suspended sediment transport has not been defined sharply.

The sediment samples consisting of bed material and wash load material, are collected at the time of the discharge measurements at the above stations. A "Brinkley Sampler" was used for the collection of the sample. The samples are collected from a number of verticals in a transect at a gauging section and from several points in each vertical. The one litre sample which is collected with the "Brinkley Sampler" is quickly transferred to the conical elutriator for the separation of the sand fraction. This fraction is collected in a tube at the bottom after 100 seconds.

The coarse sediment transport data (expressed in tons per day) are available for the period 1966-1969. Since 1970, the data are presented as sediment transport expressed in kg/s. The conversion of the sediment transport or the sediment concentration into different units is mentioned here:

1 PPM	=	1 mg/l,
1 ton/day	=	$1.157*10^{-4}$ kg/s.
in which PPM	=	parts per million.

The periods of suspended bed material data available with SWH-II and FAP 24 are mentioned in Table 3.9. At most stations suspended bed material measurements are not available for the period 1970-1975.

No	Name of Station	River	Hydrological Period
1	Bahadurabad 46.9L	Jamuna	1966-1969 & 1976-1992
2.	Hardinge Bridge 90	Ganges	1966-1969 & 1976-1992
3.	Baruria 91.9L	Padma	1968-1969 & 1976-1992
4.	Goalundo 91.9R	Padma	1966-1969,1976-1978 & 1980-1982
5	Mawa 93.5L	Padma	1966-1970,1976 & 1980-1993
6.	Gorai Railway Bridge 99	Gorai	1966-1969, 1989-1992
7.	Mymensingh 228.3	Old Brahmaputra	1966-1969 & 1988-1991
8.	Taraghat 137a	Kaliganga	1967-1970 & 1972-1993
9	Jagir 68.5	Dhaleswari	1967-1969
10.	Bhairab Bazar 273	Upper Meghna	Nil

Table 3.9 Suspended bed material records available with SWH-II and FAP 24

3.5.3 Wash Load Transport

The wash load is defined as the transport of material finer than the bed material. The wash load depends on the amount of fine sediment which erodes from the upstream catchment area and the wash load is almost independent of the transporting capacity of the river. A practical distinction between wash load and bed material transport is that the particles of the wash load has a diameter D_{50} which is smaller than 50 to 63 micron and the particles of the bed load transport has a D_{50} > 50 to 63 micron. For most rivers sediment concentration of the wash load is almost uniformly over the vertical.

In the laboratory, the sediment left in the elutriator after 100 seconds of fall is called by approximation wash load or fine sediment.

The wash load data available with SWH-II and as well as with FAP 24 are indicated in Table 3.10.

No	Name of Station	River	Hydrological Period
1	Bahadurabad 46.9L	Jamuna	1966-1969 & 1972-1988
2.	Hardinge Bridge 90	Ganges	1967-1969 & 1973-1988
3.	Baruria 91.9L	Padma	1968-1969, 1972-1978 & 1983-1986
4.	Goalundo 91.9R	Padma	1966-1969,1977-1979 & 1981-1982
5.	Mawa 93.5L	Padma	1966-1970 & 1974-1978
6.	Gorai Railway Bridge 99	Gorai	1967-1969
7.	Mymensingh 228.3	Old Brahmaputra	1966-1967
8.	Taraghat 137a	Kaliganga	1967
9	Jagir 68.5	Dhaleswari	1967
10.	Bhairab Bazar 273	Upper Meghna	1959-1963 & 1972-1988 Except 1976,1977 & 1982

Table 3.10 Wash load data available with SWH-II and FAP 24

For the period 1966-1970, the fine sediment transport data are expressed in tons/month. Since 1970, the data are presented as sediment concentration in Parts Per Million, ie. the ratio of the dry weight to total weight of the water-sediment mixture. In general the sediment transport is the sediment concentration multiplied by the water discharge.

3.5.4 Bed load

Bed load transport is characterized by the movement of bed material by rolling, sliding and small jumps. Bagnold (1956) defines the bed load transport as the sediment transport in which the successive contacts of particles with the bed are strictly limited by the effect of gravity, while the suspended sediment transport is defined as that in which the excess weight of the particles is supported by random successions of upward impulses imported by turbulent eddies. Einstein (1950) had defined the bed load transport as the transport of sediment particles in a thin layer of 2 particles diameters thick just above the bed by sliding, rolling and sometimes by making jumps with a longitudinal distance of a few particle diameters. The bed layer is considered as a layer in which the mixing due to turbulence is so small that it cannot influence the sediment particles, and therefore suspension of particles is impossible in the bed load layer. Einstein's description of bed load transport is based on a rather low sediment transport intensity and is useful for the phenomena in laboratory flumes but less useful for the phenomena in the field. Van Rijn (1984) had defined the bed load transport as all the sediment transport below the crest of the ripples or dunes. This is a more practical definition than an accurate characterization of the physical phenomena.

The measurement of the bed load transport is difficult at high sediment transport intensities of fine sediment. The bed load transport can be measured by various methods such as: various types of trap samplers, the dune tracking method and methods using optical and ultra-sonic instruments. Each of these methods has its own advantages and disadvantages. During the monsoon, the depth average flow velocity in the Jamuna river is often more than 3.0 m/s and under those flow conditions the sediment concentration near to the bed is very high. The optical measuring method is less suitable for sand particles and the ultra-sonic measuring

method is not accurate in the range of a high sediment concentration. Trap samplers are not convenient in the high flow velocity range and the actual period of measurement is difficult to determine and this is more critical in a situation with high flow velocities. Moreover, a trap sampler does not trap fine sediments as the mesh size is bigger than it. In the above three methods, the placement of sampler in a correct position close to the river-bed needs always careful attention. The dune-tracking method is limited to situations with two-dimensional dunes, but in nature dunes are often three-dimensional and not uniformly distributed in transverse direction. In nature dunes have a limited life-time and after travelling some distance in the order of a dune length a dune gets faded and destroyed. In the Jamuna river and the Lower Meghna river it has been observed that if the depth averaged flow velocity is higher than 3 m/s the bed-forms disappear and the river-bed becomes flat. Therefore the dune tracking method can be applied successfully in only special selected situations in the main river system of Bangladesh.

It seems to be that the dunes in the Jamuna River migrate much faster than would be expected from any known bed load transport formula (FAP 1, 1993). It is suggested that probably a substantial proportion of the suspended sediment is deposited in the lee of the sand dunes and this proportion contributes to the dune movement.

Until now, no attempt has been made to measure bed load transport in the main river system of Bangladesh. Instead, the bed load transport is estimated by various prediction methods. In the Jamuna River the bed load transport is estimated at about 10 percent contribution to overall sediment transport. In 1992 FAP 24 started bed load measurements on an experimental basis using a trap sampler (Helley-Smith) and the dune-tracking method. Further testing of alternative equipment is envisaged to select the most optimal measuring techniques.

3.6 Data measured under this project

3.6.1 Introduction

The extent of the survey programme was largely defined in the Terms of Reference of the Project. The programme was executed with certain adjustments, as deemed advisable on the basis of the detailed planning and the experience gained in the early stage of the work, and as agreed with the Client, the RSPMU and the funding agency. Funds were for example reallocated to special surveys for the collection of data for specific studies undertaken under RSP. The modifications are listed in *RSP Final Report Annex 1: 'Surveys'*.

The present chapter gives a summary of the results of the surveys. Please refer to the *RSP Data Books* for a complete inventory of the data collection and for key findings of each survey.

3.6.2 Water-level gauging

The water-level gauging of RSP began in Phase 1 of the project with establishment of a staff gauge at Gobindi (near Bahadurabad) in November 1992. AWLRs at Bahadurabad and Gabgachi were established in June/July 1993, together with a network of additional staff gauges in the same area for measurements of local water-level slopes.

Another ten AWLRs were set up in May/August 1994, distributed over the entire project area. The station network is shown in Figure 6.1. Most of the stations were located near a BWDB gauge, from where long-term data are available. In addition to the AWLR stations, several separate staff gauges were deployed on a short-term basis for registration of backwater effects or local water-level slopes at Bahadurabad and at Gorai Offtake.

The placement of the AWLRs was quite difficult. The primary concern was a suitable hydraulic regime, where local irregularities do not influence the registration significantly, so that the data have a good validity in relation to the general hydrodynamics of the river section. AWLRs cannot easily be shifted on a routine basis during the year, so the location must cover the entire flood season hydrograph and, wherever possible, the entire annual water-level range. The planform stability and the extent of local erosion or sedimentation were considered, and also the logistical requirement that the station be accessible for inspection, data downloading, servicing, and repairs.

The AWLR stations were demobilised in May 1996. Between them, they were in operation for 303 station-months (Table 3.11).

The data series were partly validated early 1995 and the remainder after completion of the programme, as described in Section 5.4 of the main report. The water-level gauging programme and the related data validation are described in *RSP Special Report 2: 'Water-level gauging'*. Summary presentations of the results are given in the *RSP Data Books*, and all results are stored in the HYMOS database.

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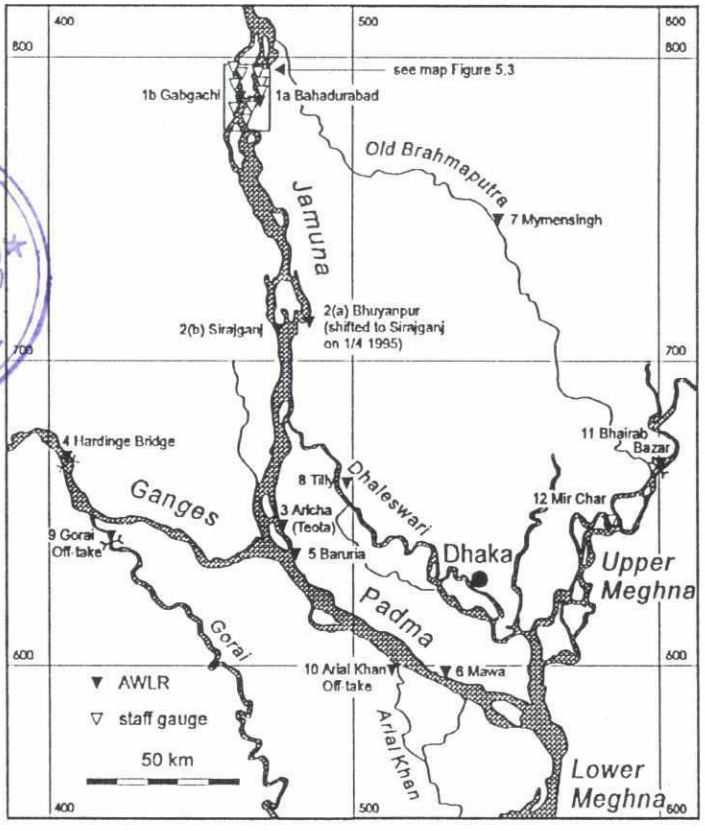


Figure 3.18

Water-level gauging stations (three additional staff gauges near Gorai as shown)

Station	River	Operation period	Station-months
1L Bahadurabad	Jamuna	6/6/93 -31/5/96	34.3
1R Gabgachi		15/7/93 - 31/5/96	33.5
2 Bhuyanpur/ Sirajganj		29/5/94 - 30/4/95 1/4 95 - 26/5 96	11.0 + 13.9
3 Aricha (Teota)		13/5/94 - 23/5/96	24.4
4 Hardinge Bridge	Ganges	21/7/94 - 31/5/96	22.3
5 Baruria	Padma	28/5/94 - 24/5/96	23.9
6 Mawa		10/5/94 - 30/5/96	24.7
7 Mymensingh	Old Brahmaputra	29/6/94 - 24/5/96	22.8
8 Tilly	Dhaleswhari	28/5/94 - 23/5/96	23.8
9 Gorai	Gorai	22/7/94 - 31/5/96	22.3
10 Arial Khan	Arial Khan	3/6/94 - 31/5/96	23.9
11 Bhairab Bazar	Upper Meghna	24/7/94 - 28/5/96	22.1
		Total	302.9

Table 3.11 Summary of data collection, water-level gauging (6 staff gauges at Bahadurabad and Gorai for shorter periods not included)

3.6.3 Routine gauging of flow and sediment transport

Basic programme

The objective of the RSP routine gauging was to produce detailed and accurate information about the flow and sediment transport through a cross-section of a river, including the cross-sectional distributions.

The locations of the RSP transects for routine gauging were defined in the ToR. Several of them are also covered by BWDB's routine gauging programme. Their exact location was selected on the basis of a field reconnaissance, which considered to the extent possible the flow regime, the regularity of the channel, and its morphological stability. In general, however, ideal gauging transects are rare in the river system of the project area, and the basic demand of data production imposes a need of compromising. In many cases, the geometry changed considerably in the span of one single flood season (see for example Figure 6.5), so continuous adjustments of the cross-section locations were necessitated. The flow pattern could, from case to case, be influenced by adjacent cross-section shifts, shifting channels, bedforms, and other depth irregularities. The transect locations are shown in Figure 3.19.

The first routine gauging survey took place in January 1993, and the last one was made in March 1996. The survey routine is briefly described in Section 5.2, and is elaborated in *RSP Final Report Annex 1: 'Surveys'*. The extent of the programme is summarised in Table 6.2, which shows that the RSP completed a total of 252 routine gauging surveys at 11 transects. Summaries of results of each survey are presented in the *RSP Data Books*, together with a description of the exact place and time of each measurement, and a complete listing of the raw data files and processed data files. The detailed results are stored in the PSD24 database.

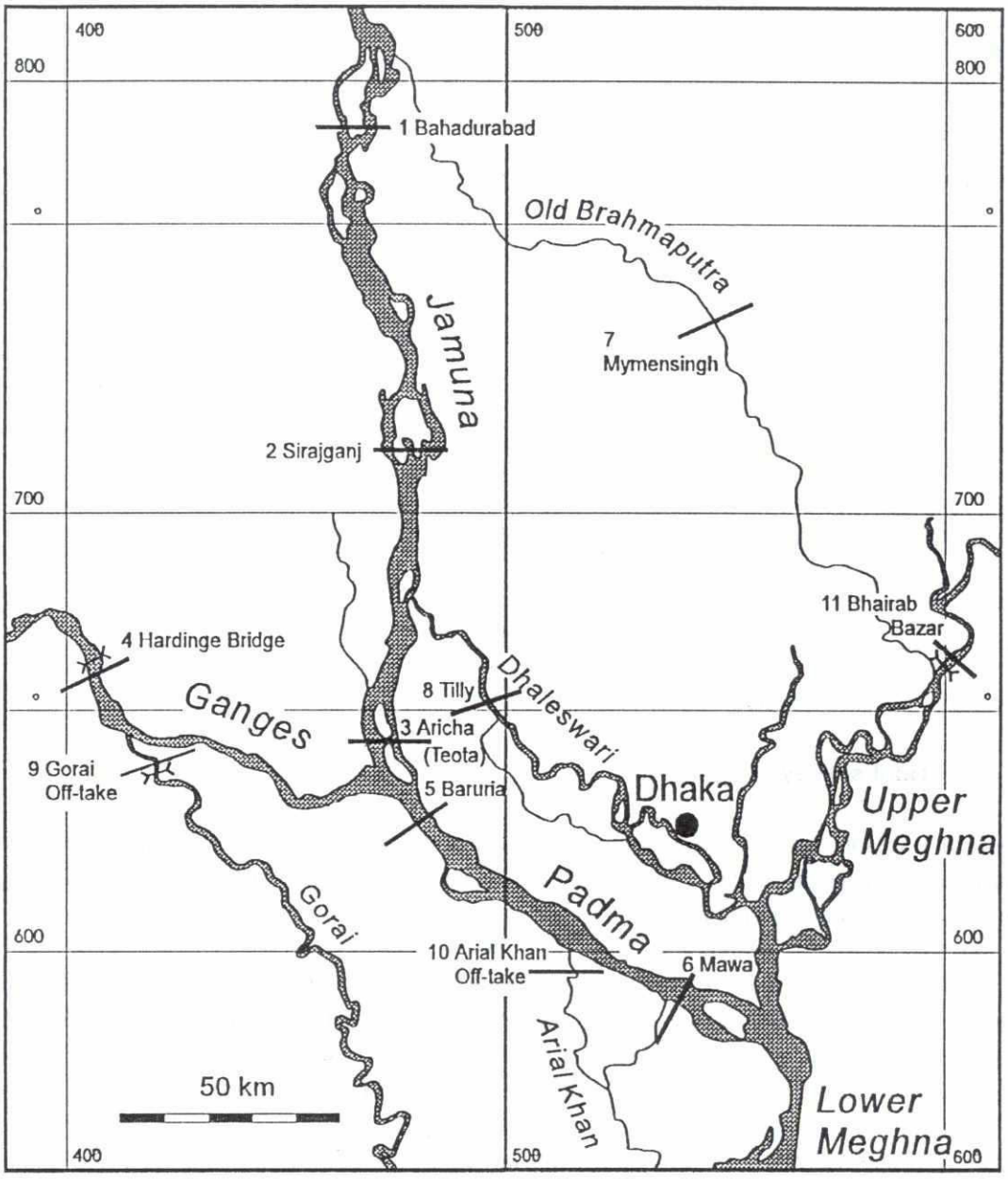


Figure 3.19 Transects for RSP routine gauging of flow and sediment transport

	Year	93		94		95		96	Total
	Season	lean	flood	lean	flood	lean	flood	lean	
1	Bahadurabad	3	4	6	7	6	9	8	43
2	Sirajganj		3	5	6	7	7	6	34
3	Aricha		1		2	0	4	0	7
4	Hardinge Bridge		1	5	7	6	7	5	31
5	Baruria		4	5	7	6	7	5	34
6	Mawa		1		2	1	3	2	9
7	Mymensingh			3	4	3	5	3	18
8	Tilly		1	3	4	3	5	3	19
9	Gorai Off-take		1	3	4	3	6	3	20
10	Arial Khan Off-take		1	3	4	3	5	2	18
11	Bhairab Bazar	1	1	3	3	4	4	3	19
	Total	4	18	36	50	42	62	39	252

Table 3.12 Summary of data collection, routine flow and sediment transport gauging

Tidal surveys

In the dry season, the astronomical tide can extend up to several of the RSP standard transects: Baruria, Arial Khan Off-take, and Mawa in the Padma River, and Bhairab Bazar Railway Bridge in the Upper Meghna.

A number of extended surveys of tidal-influenced flow was carried out by the Project, as listed in Table 3.13. During these surveys, the flow was monitored over periods of 13 or 26 hours. Specific procedures were implemented that aimed at describing the time and space distribution of the flow in more detail than it was done during the routine flow gauging.

The surveys aimed at a providing an appropriate time resolution of the tidal flow and, at the same time, a reasonably detailed resolution of the cross-sectional distribution of flow and sediment transport. Two or three vessels were deployed for the purpose. One vessel was repeatedly shifting its position during the survey, doing regular (hourly) flow and depth contour measurements along and across the river, while one or two vessels were anchored doing continuous single point (EMF) current-recordings, and regular (hourly) single vertical current-profiles by ADCP/EMF and S4. Also, the near-bed sediment transport was measured every hour by the anchored vessels, with Helley-Smith and Delft Bottle.

The tidal measurements at Mawa in early 1996 were compared with simultaneous measurements by BWDB. The standard tidal survey routine of BWDB comprises 15-hours measurements every two weeks.

Bhairab Bazar (Upper Meghna)	26-28/4 1993 10-12/2 1994 18-19/3 1995
Baruria (Padma)	21/3 1994
Arial Khan Off-take (Padma)	18-19/4 1994
Mawa (Padma)	17-18/2 1995 30-31/1 1996 7-8/2 1996

Table 3.13 Dedicated tidal surveys

Overland flow and floodplain sedimentation

As a supplement to the routine gauging, a separate programme of overland flow and floodplain sedimentation measurements was carried out during the 1995 flood season, which was the only flood season with flow and stages above median (flood conditions) within the flood seasons covered by the RSP field programme.

The measurements were made on the left bank of Jamuna, southeast of Bahadurabad. The study built on previous work in the same area by FAP19 (the Geographic Information System Project). The study area covered part of the Active and Young Jamuna Floodplains and part of the Older Jamuna Floodplain.

The measurements and the results are summarised in *RSP Final Report Annex 5: 'Morphology'*, and are elaborated in *RSP Special Report 15: 'Overland flow and floodplain sedimentation'*.

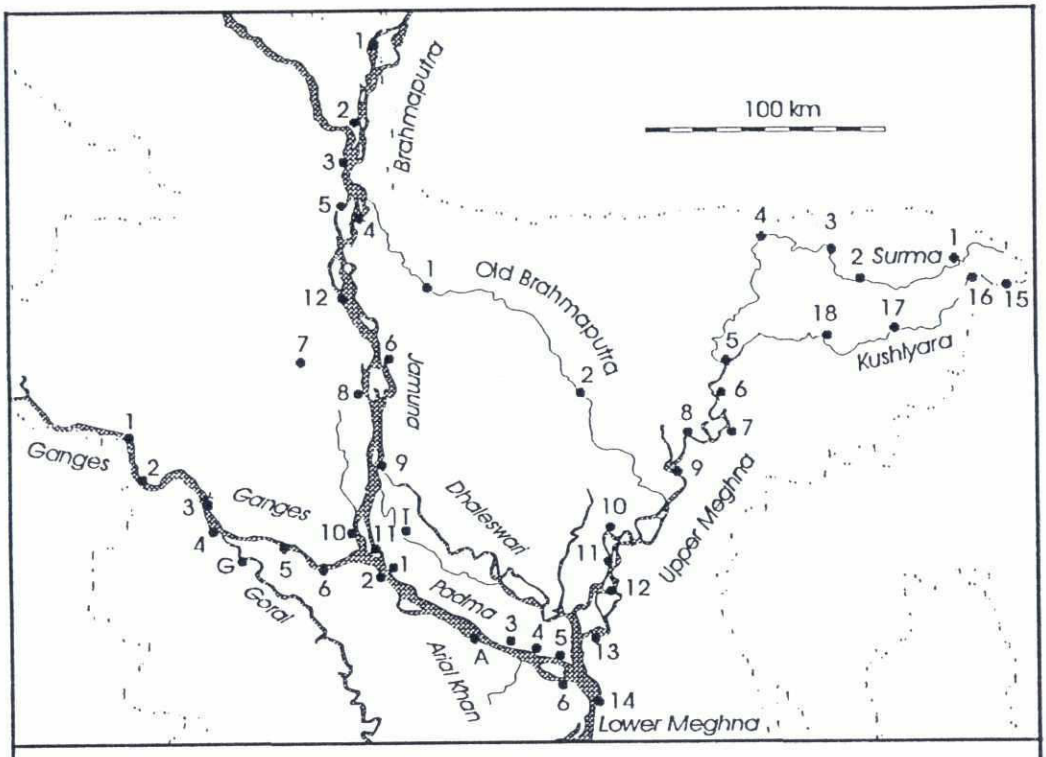
3.6.4 Geodetic, bathymetric and topographic surveys

Validation of BWDB bench marks

One of the tasks of RSP was to verify the zero levels of 47 selected BWDB water-level gauges by second order levelling. The stations are shown in Figure 6.3. The work was executed in early 1993. It included a level crossing of Jamuna River at Bahadurabad, which was done by traditional land surveying during an extremely low stage in the dry season of 1992/93. The results are reported in *RSP Special Report 1: 'Validation of staff gauge bench marks'*. This report compares the applied zero levels of the gauges with the levelling results of the RSP, as well as certain deviations that were identified between the BWDB and the FINMAP bench mark networks.

Bathymetric surveys

The bathymetric survey programme comprised repeated mappings of 7 areas. The original extent, as described in the ToR, was to carry out the surveys before and after each monsoon season. In the course of the project, however, a demand was felt of more detailed information about the morphological processes, so the RSPMU recommended to supplement the programme with certain flood season surveys, which improved the time resolution of such processes.



Brahmaputra/Jamuna

1	45	Noonkhawa
2	45.5	Chilmari
3	46	Kamarjani
4	46.9L	Bahadurabad
5	46.9R	Fulcharighat
6	48	Jagannathganj
7	49.A	Kazipur
8	49	Sirajganj
9	50	Porabari
10	50.3	Mathura
11	50.6	Mathurapara

Ganges

1	88	Rampur Boalia
2	89	Sardah
3	90	Hardinge Bridge
4	91	Talbaria
5	91.1	Sengram
6	92.1	Mahendrapur

Padma

1	1.9L	Baruria
2	91.9R	Goalunda
3	93.42	Bhagyakul
4	93.5L	Mawa
5	94	Tarpasha
6	95	Sureshwar

Dhaleswhari

T	68	Tilly

Old Brahmaputra

1	225	Jamapur
2	228.5	Mymensingh

Arial Khan

A	9A	Arial Khan Off-take

Gorai

G	99	Gorai Railway Bridge

Upper Meghna including Kushiyara

1	266	Kanairghat
2	267	Sylhet
3	268	Chattak
4	269	Sunamganj
5	270	Markuli
6	271	Ajmiriganj
7	272	Madna
8	272.1	Austagram
9	273	Bhairab Bazar
10	274	Narsingdi
11	275	Baidder Bazar
12	275.5	Meghna Ferryghat
13	276	Satnal
14	277	Chandpur
15	172	Amalshid
16	173	Sheola
17	174	Fenchuganj
18	175.5	Sherpur

Note: First number or letter is map reference - second number is BWDB reference number

Figure 3.20 Location of BWDB water-level gauges selected for zero level validation

The bathymetric survey areas are shown in Figure 3.21 and are described in Table 3.14. The work programme is summarised in Table 3.15. Results of these surveys were presented on A0 sounding plans and contour maps. The data collection and processing are described in *RSP Special Report 3: 'Bathymetric surveys'*.

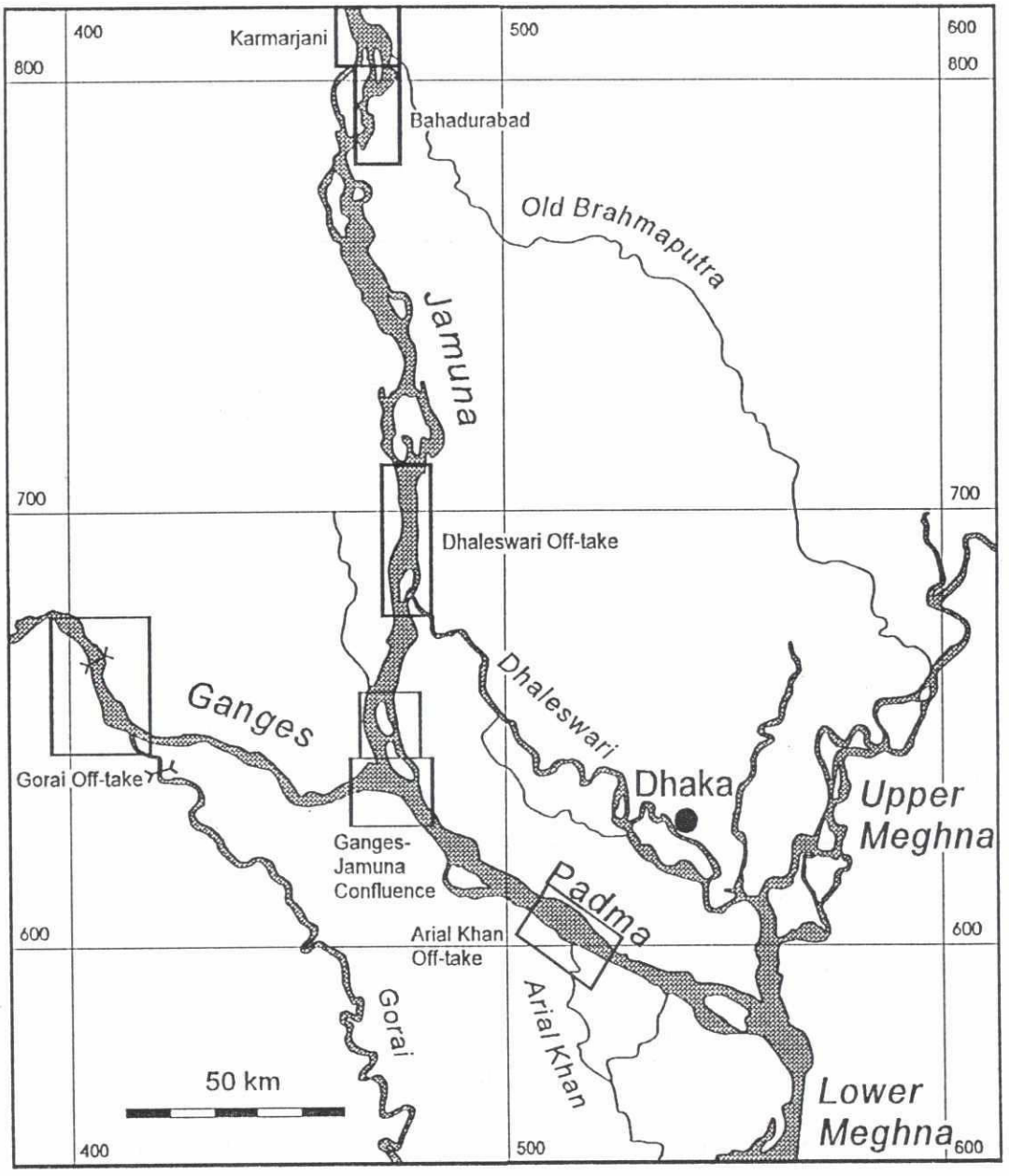


Figure 3.21 Bathymetric survey areas

River		Location	Area 1)	Line spacing
Jamuna	1	Bahadurabad	29 - 91 km²	100 m
Jamuna	2	Karmajani	50 - 160 km²	100 m or 200 m
Jamuna	3	Dhaleswari Off-take	60 - 85 km²	200 m
Jamuna	4	Hurasagar Outlet	15 - 21 km²	200 m
Ganges	5	Gorai Off-take	4 - 107 km²	200 m
Jamuna/Ganges	6	Confluence	73 - 107 km²	200 m
Padma	7	Arial Khan Off-take	79 -99 km²	200 m
1): The actual net area varies from one survey to another				

Table 3.14 Description of bathymetric survey areas

	Year	93		94		95		96	Total
	Season	lean	flood	lean	flood	lean	flood	lean	
1	Bahadurabad		2	1		2	1	2	8
2	Karmajani				1	2	1	1	5
3	Dhaleswari Off-take					2		1	3
4	Hurasagar Outlet			1		2		1	4
5	Gorai Off-take				1	2		1	4
6	Jamuna/Ganges Confluence		1	1		2	4	1	9
7	Arial Khan Off-take			1		2		2	5
	Total		3	4	2	14	6	9	38

Table 3.15 Bathymetric surveys carried out by RSP

Char topography

A char topography programme was carried out in the final stage of the project. These surveys included a mapping of topographic features, as described in Chapter 5. An outline of this programme is given in Table 3.16. The extent of the data collection and presentations of the results are given in *RSP Special Report 3: 'Bathymetric Surveys'*, and the findings are elaborated in *RSP Special Report 17: 'Spatial representation and analysis of hydraulic and morphological data'*.

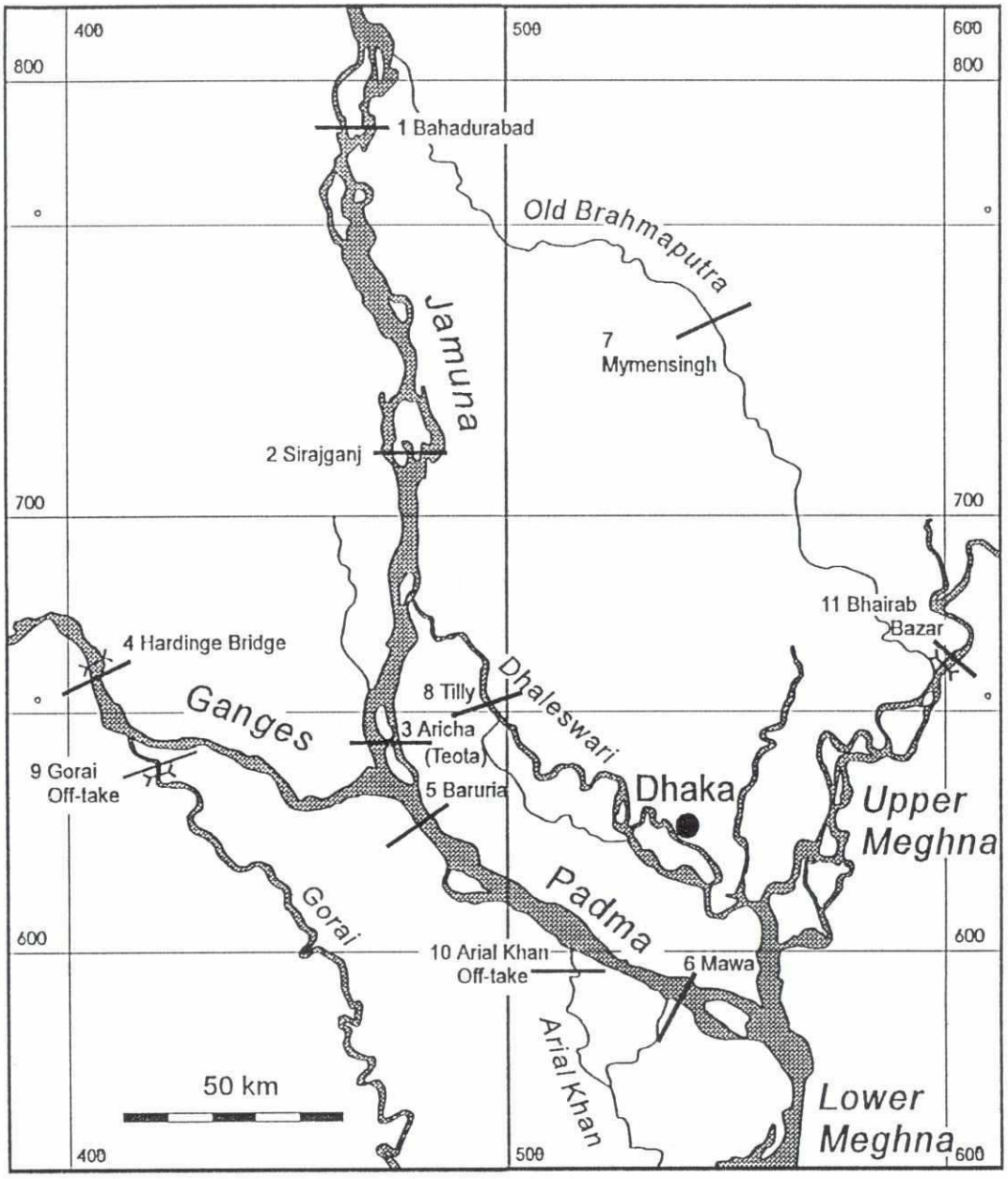


Figure 3.22 Examples of bathymetric surveys, Bahadurabad, left channel

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

F): Feature classification was included in this survey

Table 3.16 Topographic mapping of chars

3.6.5 Special surveys

The extent of the special surveys were not specified in the ToR of the project, which only mentioned '... some supplementary surveys'. The special surveys programme was recommended on and approved by the RSPMU. These surveys served a variety of demands of specific river data that were identified in connection with the study activities. They can be divided into three categories:

- Additional flow measurements at Bahadurabad (carried out on 28 occasions);
- a so-called bedform inventory programme, comprising repeated recordings of longitudinal depth contour profiles (carried out on 28 occasions): and
- a variety of other purposes (carried out on 43 occasions).

Many of the special surveys supported several study activities at the same time, while most of the study activities in turn were based not only on the special surveys, but also on the results of the routine gauging programme (and also to a high extent on data produced by BWDB). Results of the special surveys are reported in the 9000-series of Survey Bulletins and are included in the *RSP Data Books* and in the PSD24 database.

Flow measurements at Bahadurabad

The objective of the additional flow measurements at Bahadurabad was to improve the data coverage of the routine flow gauging, for several good reasons, one being to allow for a detailed inter-calibration and a mutual validation of the BWDB and the RSP rating curves at that key location. These flow recordings were made by the same procedure as that of the routine gauging, except that sediment transport measurements were omitted. The surveys were scheduled so that they, together with the routine gauging, provided a good coverage of the hydrograph. The extent of these recordings is indicated in Table 3.17. Please refer to *RSP Final Report Annex 1: 'Surveys'* for a complete inventory.

Year	94		95		96	Total
Season	flood	lean	flood	lean		
Number of surveys	16	7	5			28

Table 3.17 Additional flow measurements at Bahadurabad

Bedform inventory programme

The bedform inventory programme supplied data to the studies of bars and bedforms. Like the other special surveys, this activity was not included in the ToR, but was recommended by the PA. It comprised repeated recordings of longitudinal depth contour profiles in the Jamuna River between Aricha, Sirajganj, and Bahadurabad. Hereby, a supplement was provided to the information about the time and space variation of bedforms produced by a number of special surveys at Bahadurabad. As compared to these surveys, the bedform inventory programme covered the entire downstream reach from Bahadurabad to Aricha, hereby highly extending the spatial coverage of the detailed measurements at Bahadurabad with respect to frequency of occurrence, spatial variability and geometry of bars and dunes.

The measurements were more frequent than the ones at Bahadurabad, but only one longitudinal line was recorded, and the positioning (by ordinary, or 'non-differential' GPS) was less accurate than for the bathymetric surveys. Therefore, and also due to the shifting positions of channel and bars, the transect direction was not always aligned with the main bar and dune axes, and the transects were not the same during successive mappings. The recordings were made while transferring between routine gauging transects.

An outline of the data collection is given in Table 3.18, and a complete inventory is included in *RSP Final Report Annex 1: 'Surveys'*. Results of the programme are presented in the related RSP study reports and special reports, and particularly in *RSP Special Report 9: 'Bars and dunes in Jamuna River'*.

Year	94		95		96	Total
Season	flood	lean	flood	lean		
Number of surveys	11	10	7			28

Table 3.18 Bedform inventory programme

Other special surveys

These surveys were targeted at specific analyses and were in many cases carried out by adaption of elements of the routine procedures. In other cases, measurements were carried out by methods that were selected for the purpose. For example, geological investigations of river deposits were made by vibro-coring, seismic surveying, and by ground penetrating radar. The equipment for this work was supplied and applied by the research institutions involved in the study component of the project. The scope of this category of non-routine surveys covered a variety of subjects, such as for example:

- surface slope mapping;
- flow dynamics at constrictions, off-takes, bifurcations, and confluences;
- hydrodynamic effects of planforms and bedforms;
- examination of survey techniques (hydraulics and sediment transport);
- bed material characteristics;
- comparative measurements with BWDB (hydrology and morphology);
- length and time scales of flow and sediment transport;
- geological mapping of river deposits.

The extent of this activity is indicated in Table 3.19. Please refer to *RSP Final Report Annex 1: 'Surveys'* for a complete inventory. Results of the programme are presented in the series of RSP Special Reports. The comparative measurements with BWDB are elaborated in the following Section 6.6.

Year	94		95		96	Total
Season	flood	lean	flood	lean		
Number of surveys	15	6	16	6		43

Table 3.19 Other special surveys

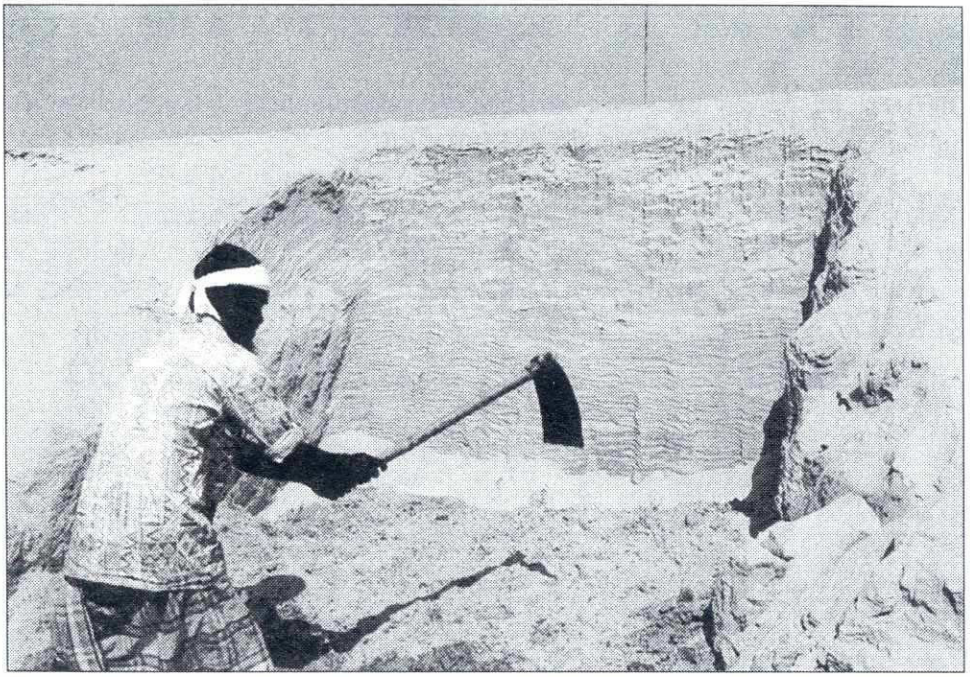


Figure 3.23

Profile wall for geological dating of chars (Special Survey no. 9097, Bahadurabad, February 1996)

3.6.6 Comparative measurements with BWDB

Flow and sediment transport

In 1993, a comparison between BWDB and RSP flow gaugings at Bahadurabad indicated a systematic difference, RSP measuring lower discharges than BWDB during high stages. A *'Committee on Shift in the Rating Curve at Bahadurabad'* was established to examine the matter, with representatives from BWDB (Surface Water Hydrology I & II), FPCO, BUET, and RSP. One recommendation of this committee was to carry out a series of comparative BWDB and RSP measurements, in order to investigate such possible systematic deviations that could be related to the different instrumentation or the different procedures applied by BWDB and RSP.

As shown in Table 3.20, the techniques applied by the two programmes were based on rather different principles, and they were therefore well suited for examining the performance of each other. As BWDB's monitoring is permanent, while the RSP survey component was a fixed term project, the comparison was intended mainly for the purpose of BWDB, and the work was planned and reported accordingly. The programme of joint measurements is shown in Table 3.21.

BWDB:	Positioning by sextant, depth registration by wire length, 2-point current measurements by propeller type (non-directional) current meter, no anchoring, suspended sediment sampling by Binckley trap sampler
RSP:	DGPS positioning, registration of measuring/sampling depth by pressure cell, water depth registration by echo sounder, flow gauging by ADCP moving boat method or by 6-point measurements by S4 electromagnetic current meter, vessel anchored during vertical profiling, suspended sediment sampling by pump system or by integrating bottle

Table 3.20 Inter-comparison of BWDB and FAP24 instruments and methods

107	Bahadurabad	17/-23/10 94	routine gauging
134	Mawa	17-18/2 95	routine gauging (tidal)
139	Bhairab Bazar	17-20/3 95	routine gauging (tidal)
9070	Bahadurabad	16-20/7 95	special comparative survey
9086	Hardinge Bridge	3/10 95	special comparative survey
9089	Mawa	19-22/10 95	special comparative survey
9092	Bahadurabad	7-8/11 95	special comparative survey

Table 3.21 Joint BWDB/RSP measurements

The results are presented in *RSP Special Report 19: 'Joint discharge measurements'*, where the following aspects are evaluated:

- Anchoring and positioning;
- depth control of instruments and sediment samplers;
- determination of cross-section profile geometry;
- accuracy of current velocity measurements;
- significance of the flow direction;
- the horizontal and vertical resolution; and
- the sediment sampling procedure.

Further, the report contains observations and suggestions in relation to the techniques applied in the BWDB routine gauging.



Figure 3.24

The catamaran used by BWDB for flow gauging

Morphology

Similarly, on one occasion, a comparative survey was made between BWDB, Morphology and Research Circle, and RSP. This survey took place in the period March 24-26, 1995, at the BWDB standard cross-section at Bahadurabad (cross-section J#13_1). The joint activities comprised both the field measurements and the data processing.

The RSP did not carry out morphological monitoring in a way that was directly comparable with the BWDB procedure. The RSP did repeated surveys of a few selected areas, as described in Section 6.4, whereas BWDB undertakes long-term monitoring of a large number of cross-sections. Therefore, a special RSP survey was made for the purpose of evaluating the techniques applied by BWDB. This was done by comparison with the corresponding RSP routines for positioning on land and on the river, for topographic and bathymetric surveys, and for data processing.

The study is described in *RSP Special Report 20: 'Joint measurements, morphology'*. The data analysis for the joint survey comprised (1) a comparison between the BWDB and the RSP results, (2) a comparison between both surveys and SPOT imagery from March 24, 1995, and (3) a comparison with BWDB surveys from 1993 and 1994. The following aspects were examined:

- The horizontal and vertical control;
- positioning on land and on the river;
- procedures for measuring the dry part of a cross-section;
- procedures for sounding of the water part of a cross-section;
- the data documentation and processing routines applied by BWDB.

On the basis of the analyses, recommendations were made on adjustments of the field and data processing procedures applied by BWDB.

3.7 Data quality

3.7.1 Introduction

After the collection of the survey data in the field, they have to be processed and stored in the office. Before using the data in studies it is important to validate them. The validation is to assess the reliability and accuracy of the data in the light of the objectives of the data collection. To some extent the expectations of the users of the data should be considered in the validation process. In practice, the common survey strategies aim at the collection of the most accurate data with the available instruments and the applied methodology. The need for improvement of the data validation is illustrated by the preliminary results of a response study with the users of data collected by government agencies (Shamsul Hoque, 1993). These results show that in 1990 only 30 to 40% of the users are of the opinion that the data are adequate and reliable. Since the data of the Hydrology organization form an important part of all the data collected by government agencies, it is expected that these results are also more or less valid for the hydrological data collection. In the mean time improvement has been achieved with the establishment of linkages with SWMC and FAP studies and the assistance provided by a UNDP project to the hydrology organization.

In this chapter an overview is given of the results of validation activities done by the project or others of the different types of hydrological and morphological data.

3.7.2 Water-level gauging

BWDB measurements

The BWDB measures the water levels in a network of staff gauges and automatic water recorders. Data from staff gauges are read and recorded by gauge readers, who are members of the regular establishment of the BWDB, Hydrology organization. The monthly recorded data are routed through the sub-divisions to the processing unit of SWH-2. In that office the data are stored after checking and processing. Similarly, data of automatic gauge recorders are also transferred to the processing unit in graph sheets or data logger cassette (Shamsul Hoque, 1993).

The RSP checked the quality of the data and validated it, using HYMOS software. In this software the validation is done by examining the data in several steps, called screening, time-series graphs, relation curves, double-mass analysis and series homogeneity tests. In the screening of data series, some statistical parameters were computed and the outliers were detected. In the time-series tests, residuals, residual mass curves and moving averages were computed so as to detect errors. Relation curves between the two series of data were used to detect random and systematic errors. Other facilities of the software, such as double mass analysis technique and the series homogeneity tests, were not used.

Some typical inaccuracies found in water levels measured by staff gauges are described in the following.

Sometimes frequent raising and lowering of the staff gauges is necessary to follow quick changes in the water level. This is likely to introduce errors, particularly if several shifts take place between two check-levellings. In principle, a shift of the gauge should immediately be

followed by a relevelling. The Flood Modelling and Management Project (FAP25) stressed the importance of frequent check-levellings of staff gauges.

Near an eroding bank it might be necessary to shift the gauge to a new location at some distance from the previous one. Average water-level slopes in the main rivers are about 5 to 8 cm per km. Hence, shifting the gauge over distances as far as one kilometres may introduce significant differences in simultaneous water-level readings. This should be described in detail in the relevant documents.

Some gauges have been located near bridge piers or bridge abutments, where high velocities are experienced during floods. In general, at those locations the riverbed will erode during floods and silt up during the lean season. This implies that the velocity head for equal discharges can be different, depending on the season and hence a time varying stage-discharge relation results. Furthermore, it is recommended to correct the measured water level for the varying velocity head.

RSP measurements

Validation of RSP water-level data was directed at obtaining the correct data from simultaneous AWLR and staff gauge readings. It was performed in two principal ways; in the field while offloading the AWLR data, and later in the office. Upon retrieval of data in the field, the data are visualized in a graphical representation of the readings versus time. Distinct errors such as sensor over-range, recording of error codes, and spikes in the data can then be recognized by visual inspection.

In-office data validation is done by examining the data on some criteria. These are physical limits of the recorded data, time-window, and consistency and difference check between the simultaneous records.

Physical limits

Firstly, the data have to be within a certain limiting range reflecting certain physical limitations. For the AWLR, the limits are -0.50 and +0.50 m and for the staff gauge 0.0 and 2.0 m. The associated reference levels which are set in the reference file, must also fall within the fixed limits. This also allows the operator to enable or disable the use of a certain data source.

Time window

When the recorded data pass the physical tests, they are subjected to a time test. During processing, the program advances through the data files. At each processing step, the time is increased to the time associated with the next valid sample in either AWLR or the staff gauge file, or both in case of coinciding sample times. The sample time stamp must fall within a window of -1.5 and + 1.5 minutes around the processing time. In other words, only data for which the time stamp differs less than 1.5 minutes from the current data processing time are accepted for further use. Due to the mechanism of advancing through the files, always at least one sample coincides with the processing time.

Difference

If samples of both data sources pass the physical and time tests, they are subjected to the difference test. If the difference falls within the margin as set in the reference file, the AWLR level is regarded as valid, otherwise the staff gauge level is adopted. If both AWLR and staff gauge level pass the test, the AWLR level will be used. The data collection interval of the AWLR is 30 minutes, whereas that of the staff gauge is 180 minutes. Hence, only one out of six AWLR samples can be tested according to the time criterion as described before, which could result in a wastage of data. To overcome this problem, a linear interpolation procedure is applied to the staff gauge data, provided that these data passed the time and range tests. For each AWLR sample time, the AWLR level is compared with the associated interpolated staff gauge level. If the difference falls within the margin that has been set in the reference file, then the AWLR value is regarded as valid.

In this way consistent and validated time series of daily water levels were prepared for eleven stations by the project.

3.7.3 Discharge measurements

Discharge measurement data were validated in two principal ways. One is done by plotting the h (water level) and Q (discharge) and visually identifying the outliers. From a cluster of data, if some data deviate from the trend shown by the majority, they were detected. The detected data are examined for possible mistakes in data-punching from field sheets, field recording and possible physical reasoning. If no explanation is found from these tests, the detected data are considered as unacceptable measurement errors and discarded.

Secondly, the discharge data are examined for consistency with hydraulic geometric properties of the transect. These were done by plotting cross-sectional area as function of water level, velocity versus water level, discharge versus cross-sectional area and discharge versus average flow velocity. Again visual checks were applied to detect outliers. In the anabranched Jamuna River, the consistency check was also applied between the individual channels.

3.7.4 Sediment transport and other sedimentological measurements

The collection of suspended sediment transport data began in the fifties at Bhadurabad, Hardinge Bridge, Gorai Railway Bridge and Bhairab Bazar. These data were not analyzed by the RSP because some confusion exists on these data, whether the samples include only the coarse fraction, only the fine fraction or both. This illustrates the importance of complete documentation and storage of old survey data.

The sampling of the suspended sediment transport and the bed-material sampling were extended considerably since 1966. However, the bed-material sampling stopped somewhere in late seventies but the suspended sediment transport measurements were continued. The RSP has done sediment transport measurements at the major gauging stations for about three years, 1993 until the end of 1995. A BWDB and RSP joint sediment transport measurement was carried out in the Jamuna River near Bahadurabad. In this section, main focus is pointed at the validation of the BWDB suspended sediment transport data for the major stations and the results of the joint measurements by BWDB and RSP.

Methods

A simple validation method is checking for consistency of sediment transport data series taken in one station and using the same sampling method. This can be done with a trend analysis with data covering a period of many years. One of the criteria, which has been selected initially for validation of the sediment transport data, is the discrepancy ratio i.e. deviation of each measured point from the rating curve. A relative measure as discrepancy ratio should be used in combination with an absolute measure for the deviation of the observed value from the average trend.

Another validation method is to compare the measurements with measurements by other instruments or measurements done within the framework of other gauging strategies but taken at the same location and in the same period.

Results

The results of the validation of sediment transport data are discussed per main station: Bahadurabad, Hardinge Bridge and Baruria.

Bahadurabad

All the available suspended coarse sediment data from Bahadurabad gauging station for the period 1966-1993 are plotted against discharge in Figure 8.1. The discrepancy ratio for all the data of Bahadurabad station is presented in Figure 8.2. The maximum value of this ratio is 22 for low to moderate discharges and it falls below the range 4-5 for moderate to high discharges. Therefore, the data are relatively more scattered at low to moderate discharges than at moderate to high discharges. This trend does not hold for the absolute differences, which are rather constant. This scatterness in the 1966 to 1993 data set might be caused by physical phenomena and does not necessarily indicate erroneous data.

However, this scatterness reduces if the data are split in separate periods of a few consecutive years. The data for the period 1989-1991 are very scattered, partly because the accuracy of the measured discharges had fallen below the normal level during that period. Therefore, the data of this period were removed from the analysis.
Furthermore, the data shows a decreasing trend in sediment transport over the period 1966-1993. An explanation for this decreasing trend could be a change in measurement technique. A joint measurement of the BWDB and the RSP was carried out at Bahadurabad in July 1995. Between these two measurements, a good agreement in sediment transport of the silt and clay fraction (fine fraction) was found, but the sediment transport of the sand or coarse fraction differed significantly in channels with high flow velocities (exceeding 2 m/s). Under those conditions the BWDB measured significantly less sediment transport than the RSP did. Next a comparison was made with the routine gauging sediment samples from the RSP and the BWDB for the period 1994-1995. The result shows that during the monsoon the sediment transport measured by the BWDB was up to ten times less than the sediment transport measured by the RSP. In the lean period, the BWDB measured the same sediment transport of sand fraction as the RSP. This confirmed the result of the joint sediment transport measurements. The most probable explanation for the underestimation of the sediment transport during the monsoon period is the large deflection angle of the Binckley silt sampler supporting cable in high flow velocities, if the survey vessel maintains position by dynamic positioning.

Without a correction for this deflection angle the sample was taken in a higher position in the vertical than the required depth. During the joint measurement it was observed that the technique which was recommended by the survey team sent by the United Nations in 1966 for avoiding a large deflection angle, was not followed up (Special Report 19, RSP, June 1996). This means that the underestimation of sediment measurement could have been existing for a longer period. Another comparison was made between the BWDB data 1966-1970 and RSP data 1994-1995 and it shows no significant decreasing trend in sediment transport particularly at high discharges (Figure 3.27). In that figure the RSP data at low discharges concave downward that maybe due to the natural scour hole present in the left channel at Bahadurabad. The conclusion is that the coarse sediment fraction was not measured sufficiently accurate during the high flow velocities and during a long period between 1974 and 1995. The measurements of the fine sediment fraction were not much affected by this change in field technique.

At Bahadurabad, the exponent to the flow velocity of the sediment rating curve is within the normal range 3-5. This indicates that the measuring site at Bahadurabad is good if no deep scour hole is present in the measuring transect.

Station	Sediment Rating Curve Data Period	Mean	Percentage of data in the range		Standard deviation	No of data
			0.50-1.50	0.10-1.90		
Bahadurabad	1966-1993	1.81	59	78	2.59	661
	1966-1970	1.01	87	98	0.34	126
	1976-1982	1.01	93	99	0.31	216
	1983-1988	0.98	99	100	0.20	178
	1993	0.78	100	100	0.26	35

Table 3.22: Some statistical parameters of coarse sediment transport data measured by BWDB in Bahadurabad

Hardinge Bridge

All the available coarse sediment transport data for Hardinge Bridge station are plotted in Figure 8.1. The trend in the data is slightly concave downward at low discharges. That graph shows that the scatterness of the data is constant for various discharges and also constant for sub-sets of data covering different periods 1966-1970, 1976-1982 and 1983-1988. This indicates that the scatterness of the data is homogenously distributed in time.

The scatter in sediment transport data is possibly due to the location of the Hardinge Bridge gauging station in an artificially constricted reach of the Ganges river. In general, a scour hole develops in a constricted reach. At low to moderate discharges such a scour hole functions as a sediment trap, and at high discharges the deposited sediment is washed away (Special Report 18, RSP, 1995). This phenomenon give rises to an increased variability in the sediment transport. The sediment transport curve at a constriction has its largest slope at low discharges and its smallest slope at the highest discharge, so that the curve is concave downward.

The conclusion is that these coarse sediment transport data are sufficiently accurate and internally consistent, but that in an analysis of these data this scour hole effect should be taken into account. In this sense the location of the measuring transect is not optimal.

Baruria

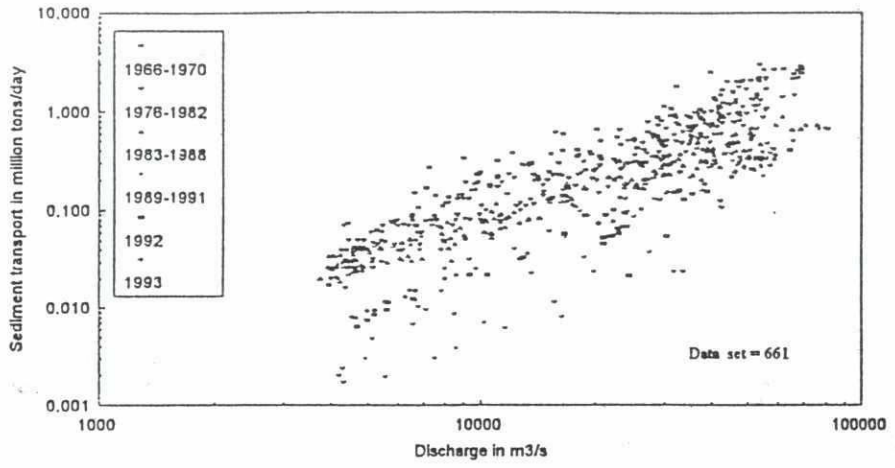
The available coarse sediment transport data for Baruria station are plotted in Figure 3.25. The data are very scattered and the trend in the data is concave downward at low discharges. This scatterness did not improve when the data were separated in different periods. In Figure 3.26, the discrepancy ratio is high up to 16 at low discharges. The Baruria gauging station is located downstream of the confluence of the Jamuna and the Ganges rivers. The 1-D model results (Special Report 18, RSP, 1995) show that at the confluence the sediment transport is highly variable, while further downstream, the variability reduces. That model calculated also a concave downward trend in the sediment rating curve. At the confluence of the Ganges and the Jamuna River one or two big scour holes are present most of the time. The same effect as described for Hardinge Bridge, occurs also in the sediment data of Baruria.
That model also shows that the reaches upstream of a confluence are continuously adjusting, but at the same time fluctuating around an average bed level, and hence the system is in a dynamic equilibrium. At the rising stage, the riverbed is degrading at the confluence, whereas during falling stage it is aggrading. The late flood in the Ganges River causes a backwater effect in the Jamuna River. This effect causes some seasonal aggradation of the riverbed. It can be seen from the model that also downstream of the confluence, alternating aggradation and degradation of the riverbed occurs. These changes of bed levels in different branches near the confluence are the main reason of the variability in the coarse sediment transport data measured at the Baruria transect.
The conclusion is that these coarse sediment transport data are sufficiently accurate and internally consistent, but that in an analysis of these data scour hole effects as well as the seasonal aggradation and degradation of the riverbed should be taken into account. In this sense the location of the measuring transect is not optimal.

Bed material

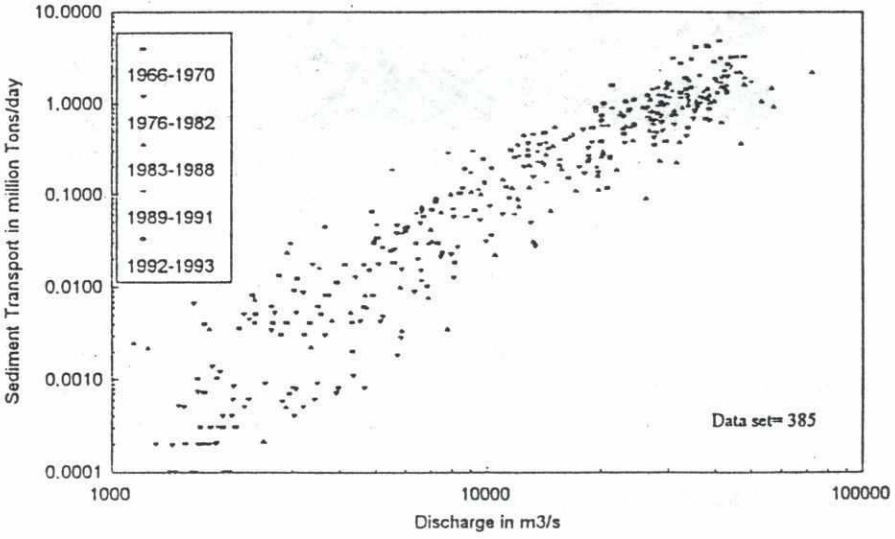
Bed material samples were taken since 1965 from the main rivers. A simple method to validate the data is to check on coarse outliers and on the general trend in the data taken from different places along the river.

Some samples taken with the Van Veen sampler at locations with deep water and high flow are less reliable, because part of the fine fraction of the sample can have been washed out during hoisting of the sample. In general, other samples were found reliable, especially the samples taken by the USBM.

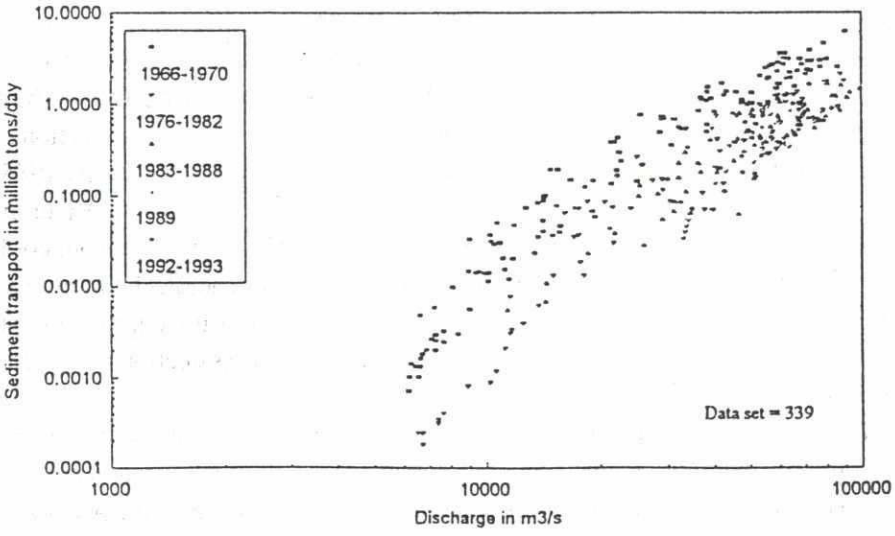
The bed-material samples are taken to determine the grain-size distribution of the bed material. The variability in the grain-size distributions of different samples is large if some samples with a high percentage of silt are included. It is recommended to separate the samples in samples with less than 40% silt and in samples with more than 40% silt.



a) Jamuna River at Bahadurabad



b) Ganges River at Hardinge Bridge



c) Padma River at Baruria

Figure 3.25 Suspended coarse sediment data measured in Bahadurabad, Hardinge Bridge and Baruria

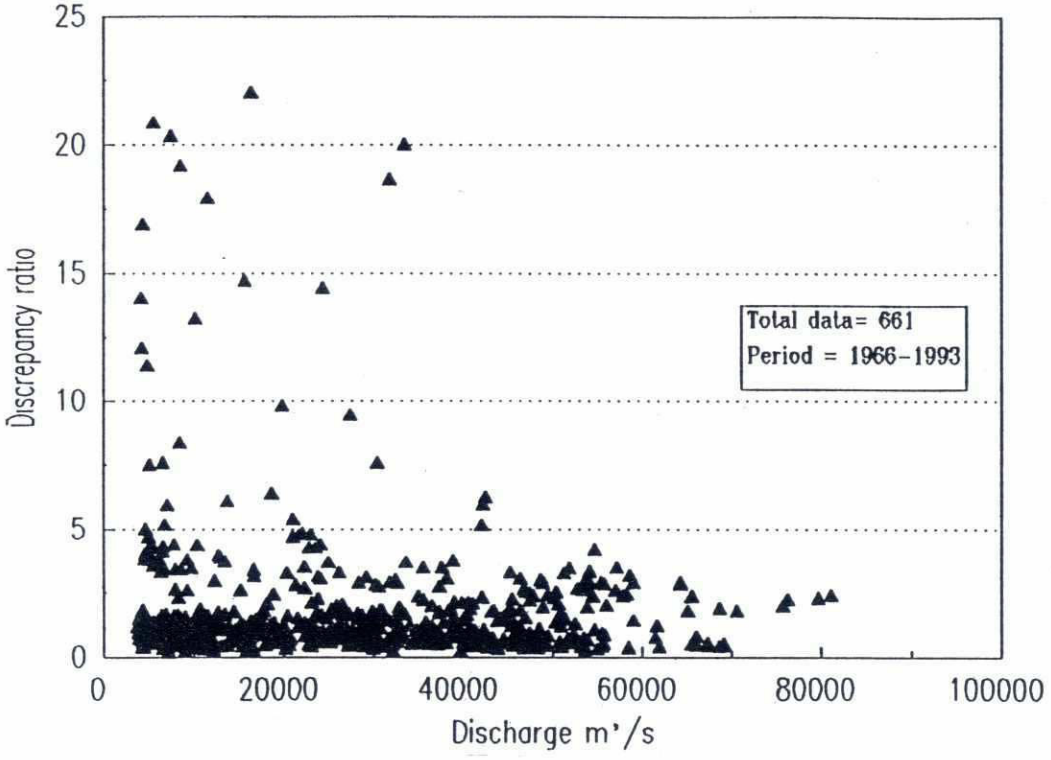


Figure 3.26 Discrepancy ratio of suspended coarse sediment data

In the past sometimes only a few samples of the riverbed were taken and analyzed. Because of the variability in the grain-size distributions of the samples it is recommended to take at least ten samples to determine a reliable average grain-size distribution.

3.7.5 Cross-sectional data (BWDB)

Since the sixties the BWDB had measured cross-sections in a large network covering the main rivers and also the smaller rivers with only a few interruptions. These data were used in many studies. Various users of these data have checked their quality often in a non-systematic way and by visual inspection of graphs with a strong distortion of the vertical scale. The effect of a distorted vertical scale is illustrated in Figure 8.4. During the study of the Jamuna Bridge, after checking the history of the bench marks of the cross-sections a selection of validated cross-sections were used for their study (Klaassen and Vermeer, 1988). A few years ago FAP1 digitized all the available BWDB cross-sections of the Jamuna River and stored them in a data base. They assessed the quality of those data (Halcrow, 1993) but could not improve the quality by removing inconsistencies in these data. In general, the previous users of these data tend to conclude that their quality is not good enough for engineering studies. At this moment still no database with accurate and validated cross-sections measured by BWDB is available.

The RSP attempted to estimate the inaccuracies in BWDB cross-sectional data by checking them against satellite images, against soundings from other organizations and by inter-comparison of BWDB standard cross-sections surveyed in consecutive periods (see RSP, 1994, 1996a and 1996b). In 1995, the RSP participated in a joint cross-sectional survey with the BWDB Morphological Circle in the Jamuna River to get an impression of the applied methodology and, if necessary, to recommend on measures for improving the quality of these measurements (see RSP, 1996c).

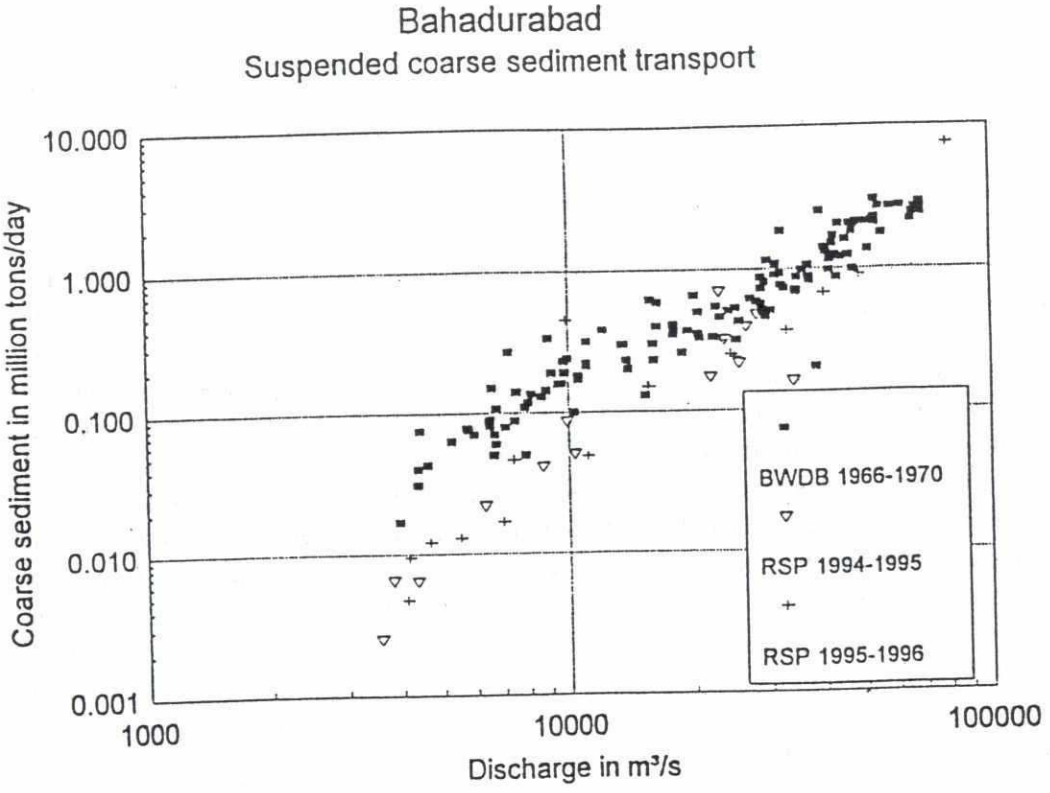


Figure 3.27 Comparison of BWDB and RSP sediment transport measurement in verticals of transects

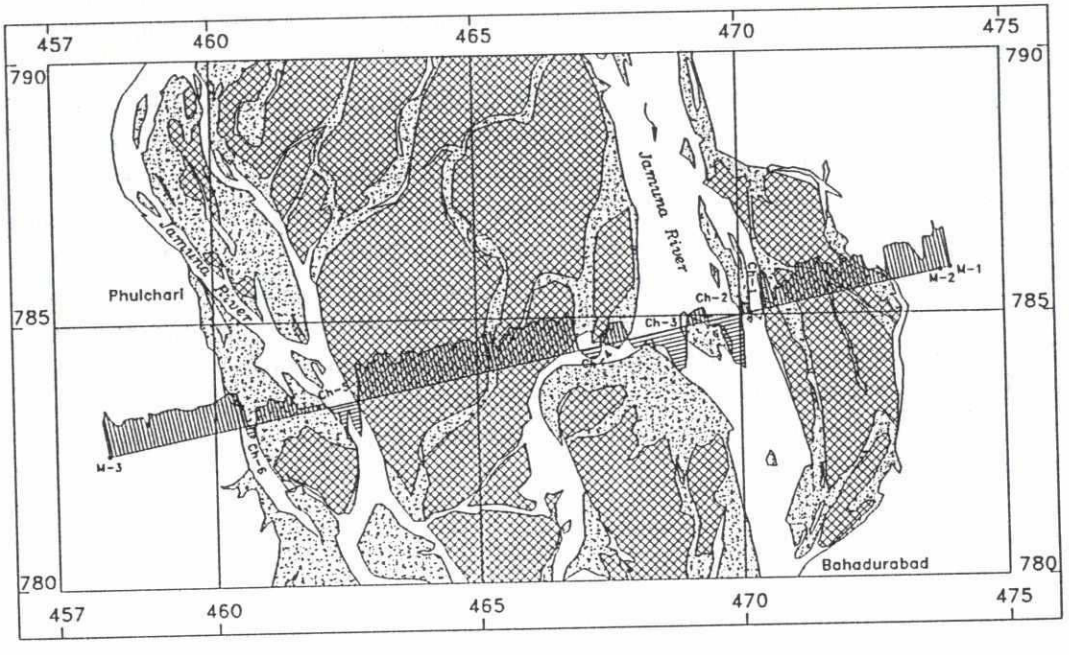


Figure 3.28 Location of the entire BWDB cross-section J#13_1 in the planform as seen on a SPOT image

Data validation methods

Two main aspects of validation methods for cross-sections are the positioning (alignment, bearing, start of the cross-section line) and the vertical levels of the cross-section.

Geographic location of cross-sections

Cross-sections have been compared with the planform of the river on satellite images. This comparison is a very powerful tool for validation of the positioning of cross-sections, see for example Figure 3.28 with cross-section J#13_1 projected on the planform as seen on a SPOT sheet. Preferably, images taken during the lean season and shot a short time before or after the cross-section survey, should be selected for this comparison. LANDSAT images are available without a geo-referenced coordinate system and, therefore, these are less suited for this purpose. The SPOT sheets show more details while also having a coordinate system.
The graph of the cross-section can be projected on the satellite image, if the horizontal scale of the cross-section graph is the same as the scale of the image sheet. The water level at the day the image was made can be drawn in the cross-section graph. The validation method consists of checking the water line in the cross-section with the land/water lines on the satellite image. This can be done visually by shifting and rotating the cross-section graph. The validation of the geographic location of cross-sections will be far less effort if a DGPS system is used for positioning.

Vertical levels

The benchmarks in the field should be checked to eliminate possible inaccuracies in the common reference plane, often PWD. In general, the RSP checked all the benchmarks for the water-level gauges, but this checking did not include specific benchmarks for the standard cross-sections.

The vertical levels can be checked by comparing the same cross-section measured in different years. If the geographic position of the cross-section was not changed then the height of the embankments or of a part of the flood plain has probably not changed either. The comparison of the floodplain level and the height of the embankments can indicate an erroneous shift in vertical direction. For this comparison a part of the adjacent floodplain should be measured; fortunately this is often the case, see example of a Jamuna River cross-section J#13_1 in Figure 8.?. (block c). Also a sudden constant shift of the level of a char indicates an error. In the example the floodplain has been measured probably along the same alignment in 1993 and 1994 and it might have been shifted in 1995. A common error is a spike, which means an error in a individual measurements. Spikes are also found by visual inspection of a graph.

Results

The RSP checked the inconsistencies in a number of selected cross-sections of the Jamuna, Ganges and Padma rivers, see Special Report on 'Floodplain level and bankfull discharge of the Jamuna, Ganges, and Padma Rivers'. The results of an earlier validation of some cross-sections in the Jamuna river downstream of Sirajganj were presented in RSP, Study Report 3. Finally, this validation of the Jamuna river cross-sections was extended by EGIS project using GIS techniques, see Special Report 17.

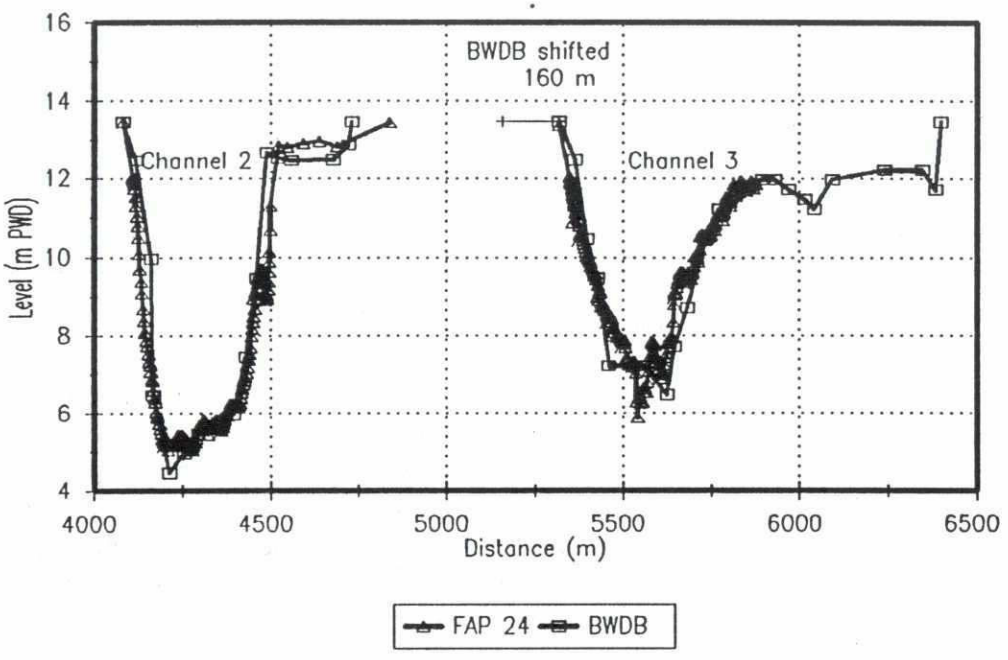


Figure 3.29 Comparison between the RSP survey and a part of a BWDB cross-section survey in J#13_1

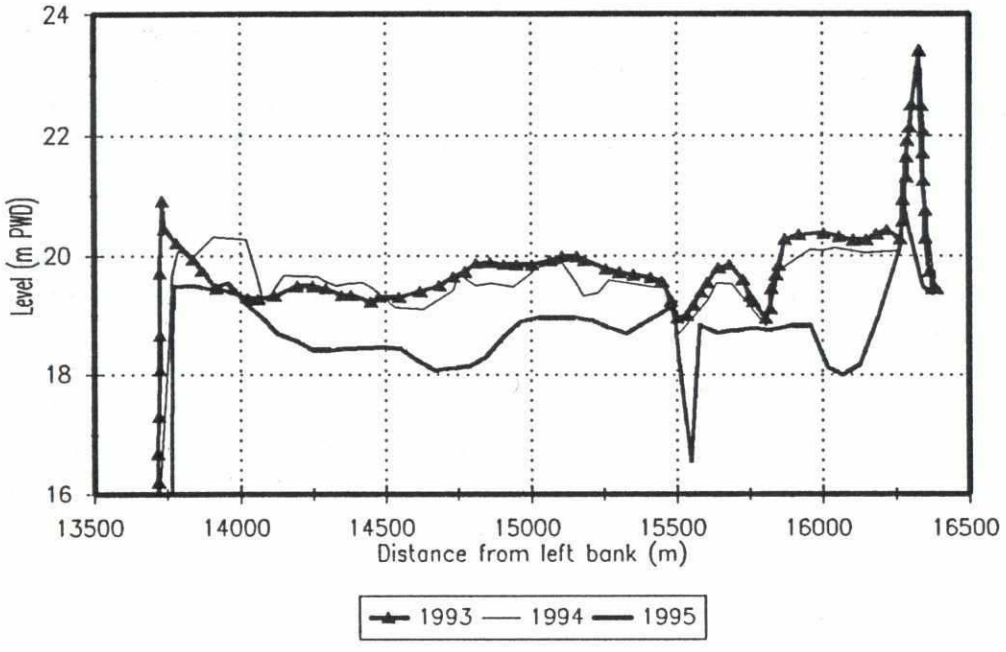


Figure 3.29a

River	Number of standard cross-sections	not available	not consistent	vertically consistent	total
Jamuna	16	183 (39%)	104 (22%)	177 (38%)	464 (100%)
Ganges	14	174 (43%)	25 (6%)	207 (51%)	406 (100%)
Padma	11	100 (31%)	34 (11%)	185 (58%)	319 (100%)

Table 3.23 Some results of the validation of cross-section measurements by BWDB

The overall conclusion of these validation exercises was that the consistency of the cross-sections of the Ganges river is comparatively better than the consistency of the cross-sections in the Padma and the Jamuna rivers. In the Jamuna river the cross-sections are longer than in the other rivers and the number of channels in a cross-section is higher. Furthermore, the morphological changes in the Jamuna River are faster than in other rivers. Rapid migration of the river banks has washed away monuments or pillars of several cross-section in the last decades. It seems likely that these circumstances are responsible for a reduced accuracy of these cross-section surveys.

These exercises have also shown that after detection of an inconsistency in a cross-section it is often uncertain how to remove an inconsistency (except spikes). This makes correction of cross-section data cumbersome and often impossible.

In recent years an UNDP aided project has been proceeding in improving the survey techniques and modernisation of survey equipments of the BWDB Morphological Circle. It can be expected that in the near future the quality of BWDB cross-section survey will be improved. From experiences in the BWDB cross-section validation of the main rivers, and from the experiences in the joint measurement, a few recommendations can be made:

- The validation of the cross-sections should include an assessment of the accuracy of the data, because the required accuracy is not constant, but depends on the purposes of the study.
- All cross-sections, especially the monuments of the cross-sections, should be defined by geographic coordinates or by any other projection. The height of the monuments/-pillars should be reconnected to the newly established network of bench marks. Both the new and old values should be published for the user of BWDB cross-sections.
- Introduction of an adequate data validation system using GIS in BWDB could improve the quality of the survey data.

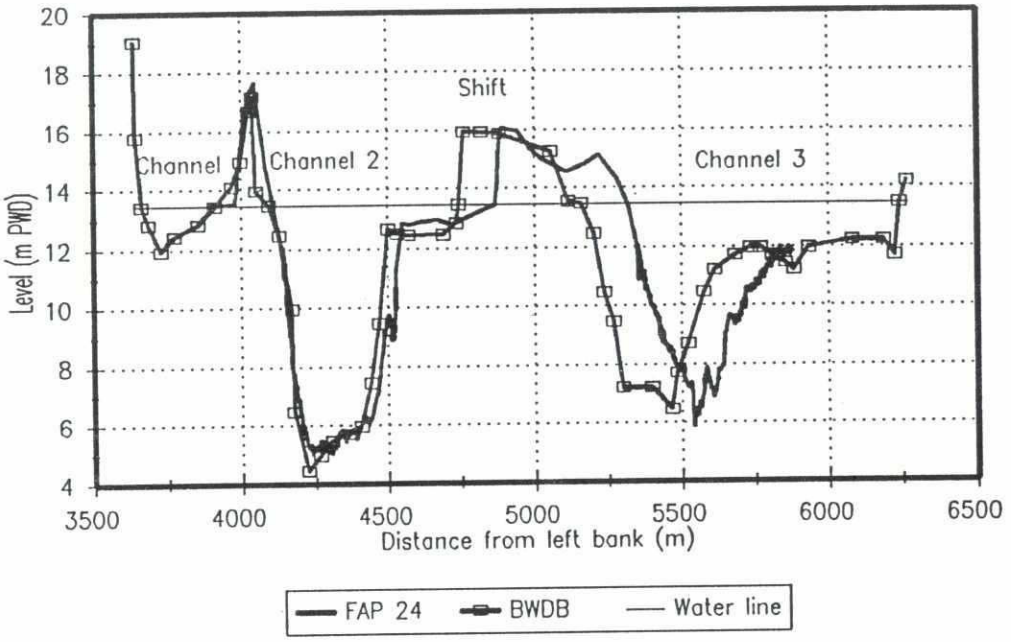


Figure 3.30 Example of shift in the land survey over a char, joint measurement BWDB and RSP

3.7.6 Bathymetric maps

Bathymetric maps of selected reaches of the main rivers were prepared by the BIWTA and also by RSP. The main purpose of the bathymetric surveys done by BIWTA is to monitor the least available depth in inland navigation routes. The RSP bathymetric surveys cover certain stretches of a river which are aimed at the study of morphological processes and planform studies. The quality of these surveys depends on the quality demands for the purposes it is prepared. The BIWTA bathymetric surveys are for monitoring navigational routes but they can also be used in the study of morphological processes of a river (Klaassen et al 1988; Klaassen and Vermeer, 1988b, Haskoning et al, 1990 etc.).

Data validation methods

The validation of the planform of the bathymetric map can be done by checking some known distances between special features in the map. A more thorough method is to project the bathymetric map onto a satellite image of the same area, and shot nearly at the same time as the time of the survey. If the water levels are the same, then the pattern of bank lines should be the same in the bathymetric map and in the satellite image. Differences can occur because of a different projection. This type of differences are often easily recognisable in maps of a sufficiently large area.

At this moment no thorough methods are available for the validation of the measured depths and the reduction to a common datum. An easy method is to check for internal consistency of the data in a bathymetric map: outliers can be detected visually and be removed.
If a standard cross-section measured by BWDB is located in the area of the bathymetric survey then that cross-section can be compared with a cross-section along the same transect line and derived from the bathymetric map.

Results

The RSP compared only six cross-sections picked up from BIWTA bathymetric charts surveyed in 1990 in the Jamuna River downstream of Sirajganj, with the BWDB cross-sections (see RSP, Study Report 3, 1994). These BIWTA cross-sections were plotted together with the BWDB cross-sections in the same plot, for an accurate comparison. The BIWTA surveys were done in January 1990 and the comparison with the BWDB surveys of April and May 1990 showed considerable differences, mainly because of the morphological changes in the river. For validation and checking of the bathymetric surveys it is recommended to make such comparisons with the BWDB cross-sections if both surveys were done in the lean season and the time lapse between the surveys is less than two months.

The RSP projected the BIWTA bathymetric chart surveyed in January 1990 onto the SPOT image of 16 March 1990 of the Jamuna River downstream of Sirajganj, see RSP, Study Report 3 1994. It was observed that BIWTA surveys are rather accurate and consistent with the SPOT images if the coordinates are shifted over a small distance because of the different projections used by SPOT and BIWTA, see for example Figure 3.31.

The BIWTA bathymetric survey plots are presented with respect to average lowest low water level (ALLW), which is determined by averaging of 3 to 5 years records from the adjacent water level gauges of BIWTA and BWDB. As mentioned for the case of BWDB cross-sections, the errors related to the bench marks and water-level gauges is also applicable to the BIWTA bathymetric surveys. The accuracy of the Decca Chain system used in BIWTA survey is on average about $\pm$ 30 m, but it may increase up to $\pm$100 m depending on the location of the river (and the angles between the connecting lines of the beacons). The depth is measured by echo sounder. The interspacing between two survey lines varies from 50 to 500 m and the spacing of the charted depth varies from 25 to 250 m along a survey line depending on the scale of the survey. Hence a BIWTA survey map presents smooth contour lines. The BIWTA is mainly interested in areas with shallow depths, i.e. in the case of bed forms the water depth at the crest of a bedform is considered for plotting in the chart only. Therefore, the BIWTA bathymetric charts results always show shallower depth than the actual river depths, the magnitude depending on the presence of bed forms and their heights.

The accuracy of the DGPS positioning system used in RSP bathymetric survey is about $\pm$ 5 m. For vertical controls, the bench marks and zero value of the water-level gauges used were reconnected from the recently established geodetic bench marks network for some locations where available, otherwise old SoB bench marks were used for reconnection. The interspacing of survey lines vary from 100 to 200 m depending on the location of the survey and the spacing along each survey line is about 2 to 5 m only. The resolution of an echo sounder is about 0.02 m but the character of the river bed (hard, soft, moving or not) may affect the result and enhance the uncertainty of the result. This, however, is more a physical uncertainty regarding the position of the bed than an uncertainty related to the instruments. The bank lines in the bathymetric maps of lean season surveys follow the bank lines on SPOT images sufficiently accurate for morphological studies.

The accuracy of the river-bed relative to the PWD reference plane varies from a few centimetres to a few decimeters because of the variation of local water-level slope. The magnitude of this variation depends on the distance of the survey area to the water-level gauge considered and the difference between the local water-level slope and the estimated slope.

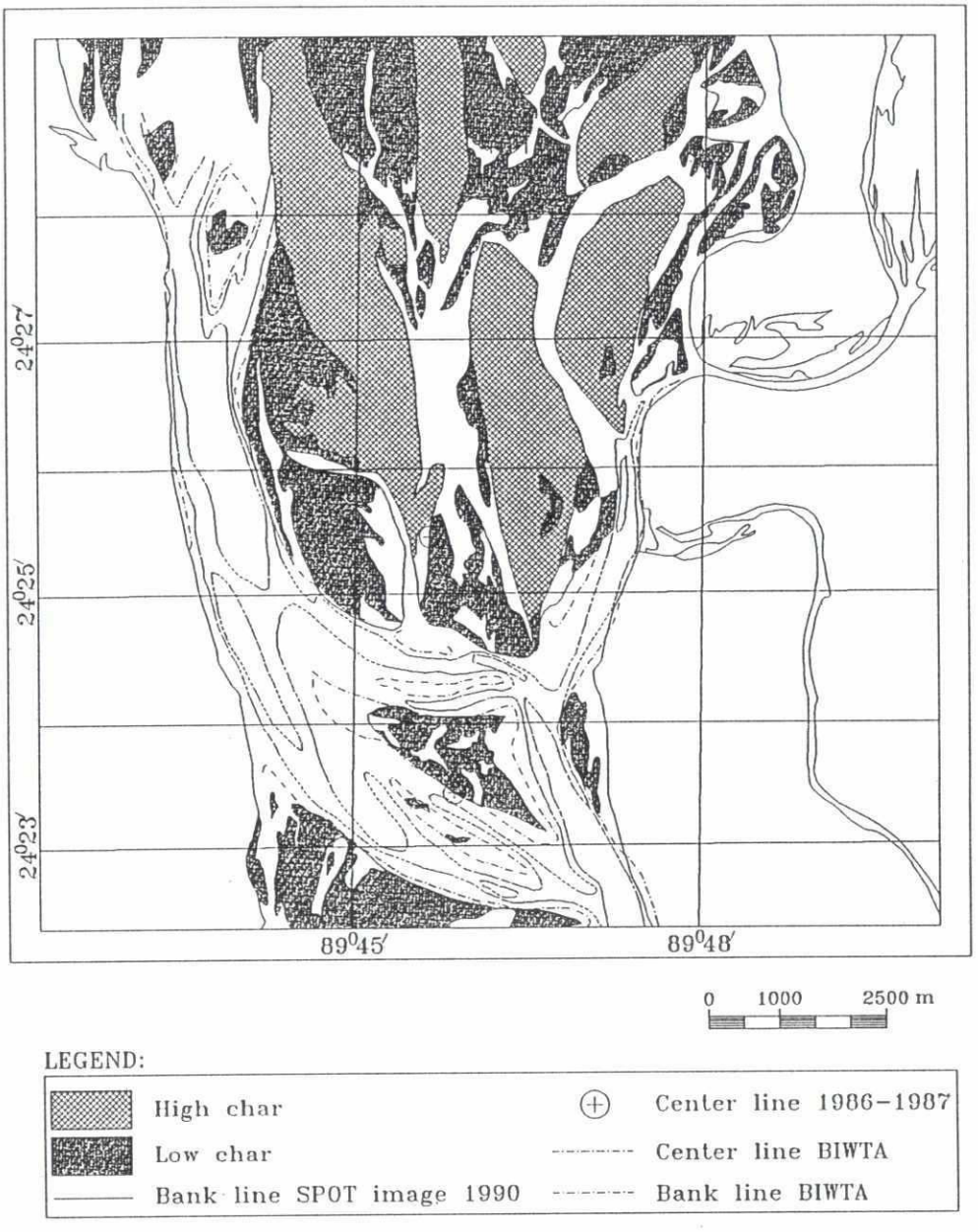


Figure 3.31 BIWTA bathymetric chart (1990) and SPOT images (1990)

4 Independent variables

4.1 Introduction

As said before (Section 2.3) the independent variables of the river catchment are determined by the climate and the geology of the basin, but not directly; also the vegetation, the weathering processes and human interference play a role. In this chapter, factors are discussed, which ultimately result in variables like discharge, sediment volumes, sediment characteristics and valley slopes. These factors are:

- climate: precipitation, temperature, evapotranspiration, humidity (Section 4.2)
- hydrology: water-levels and discharges versus major river shifts (Section 4.3)
- topography: relief versus sediment concentrations (Section 4.4)
- geology: tectonics, faults, soil type and sediment yields (Section 4.5)
- base-level changes: sea level rise versus sedimentary structures (Section 4.6)
- human interference: deforestation, sediment transport (Section 4.7).

This chapter gives a discussion about the factors behind the variables and not quantitative information about the variables.

4.2 Climatic factors

The climatic factor is an important geomorphological control of a river system because it governs the amount of rainfall, snowfall and the melting of snow in the Himalaya mountains, and consequently the surface runoff and river discharge. The climate determines the extent and intensity of basin denudation and indirectly the sediment yield. The important climatic factors in this regard are the precipitation, temperature, evapotranspiration and humidity. The climatic region of the Ganges and the Brahmaputra basin can be broadly categorized under humid tropics with major portions subclassified under humid subtropical warm climate, and a small part of Bangladesh in the south and eastern region has a tropical rainforest climate (Trewartha, 1992). The climatic conditions are characterized by the reversal of the monsoon. The predominant wind field in the basin is characterized by the northeast monsoon in the winter due to the presence of a high pressure (~ 1032 to 1038 mb) zone in the Asian Highlands (50° N, 105° E) near the Gobi desert and the southwest monsoon in summer due to the presence of a low pressure (~ 996 to 1002 mb) zone in central Asia (30°N, 70°E) near Thar desert. Figure 4.1 shows the dynamics of the southwest monsoon.

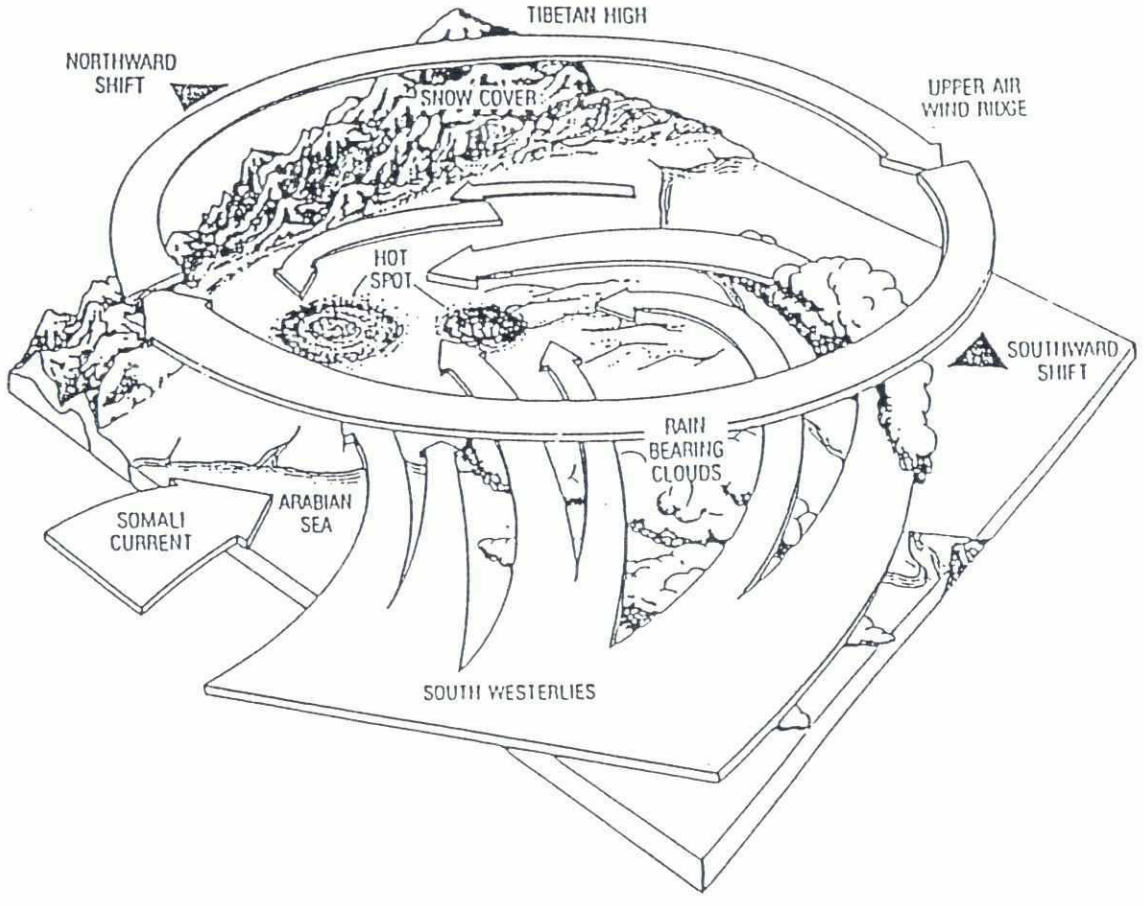


Figure 4.1 Dynamics of the Southwest Monsoon (Source : India Today, 30 June 1988)

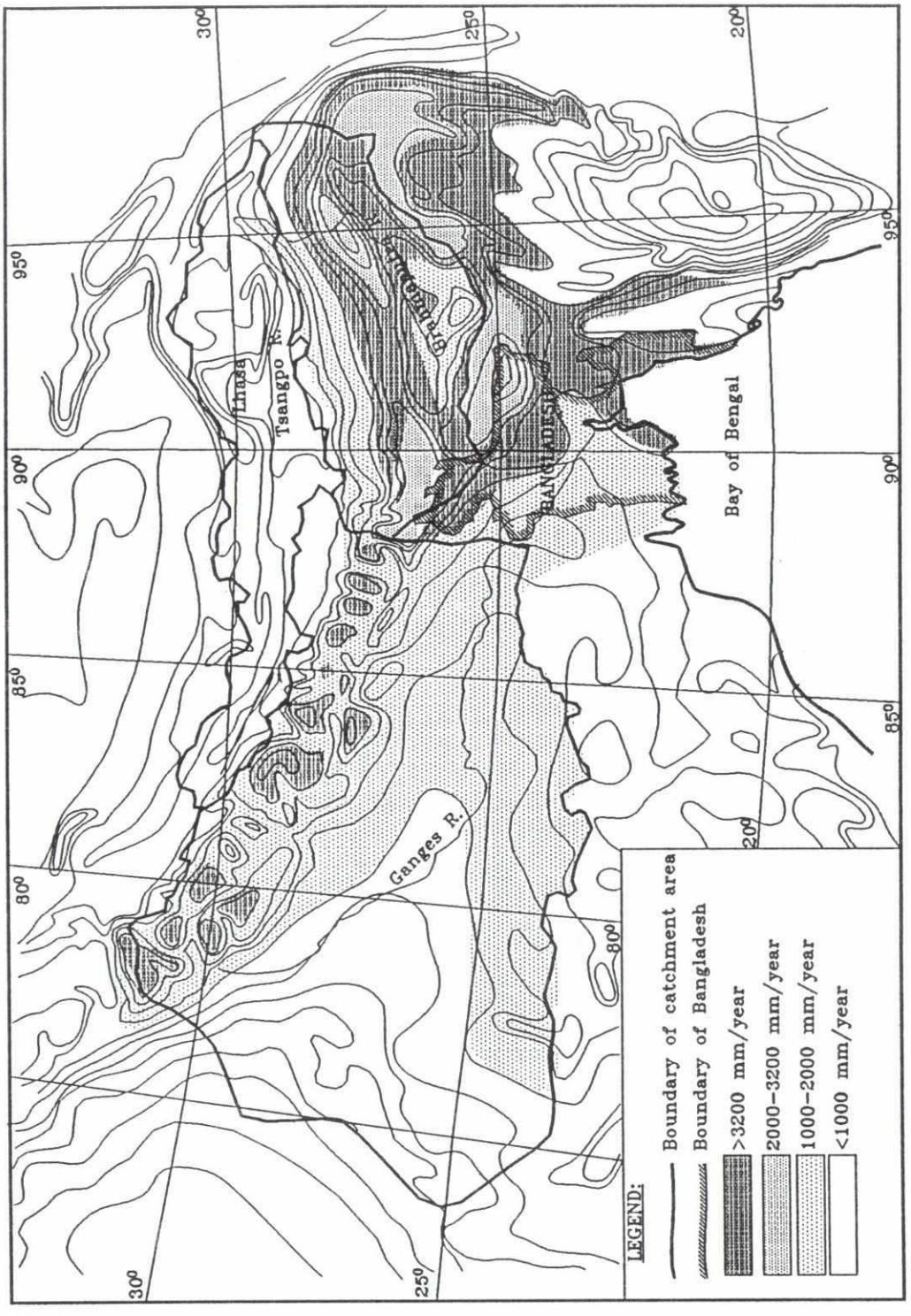


Figure 4.2 Catchment boundary and mean annual rainfall distribution in the Ganges-Brahmaputra River basin (Source : Barua et.al., 1993)

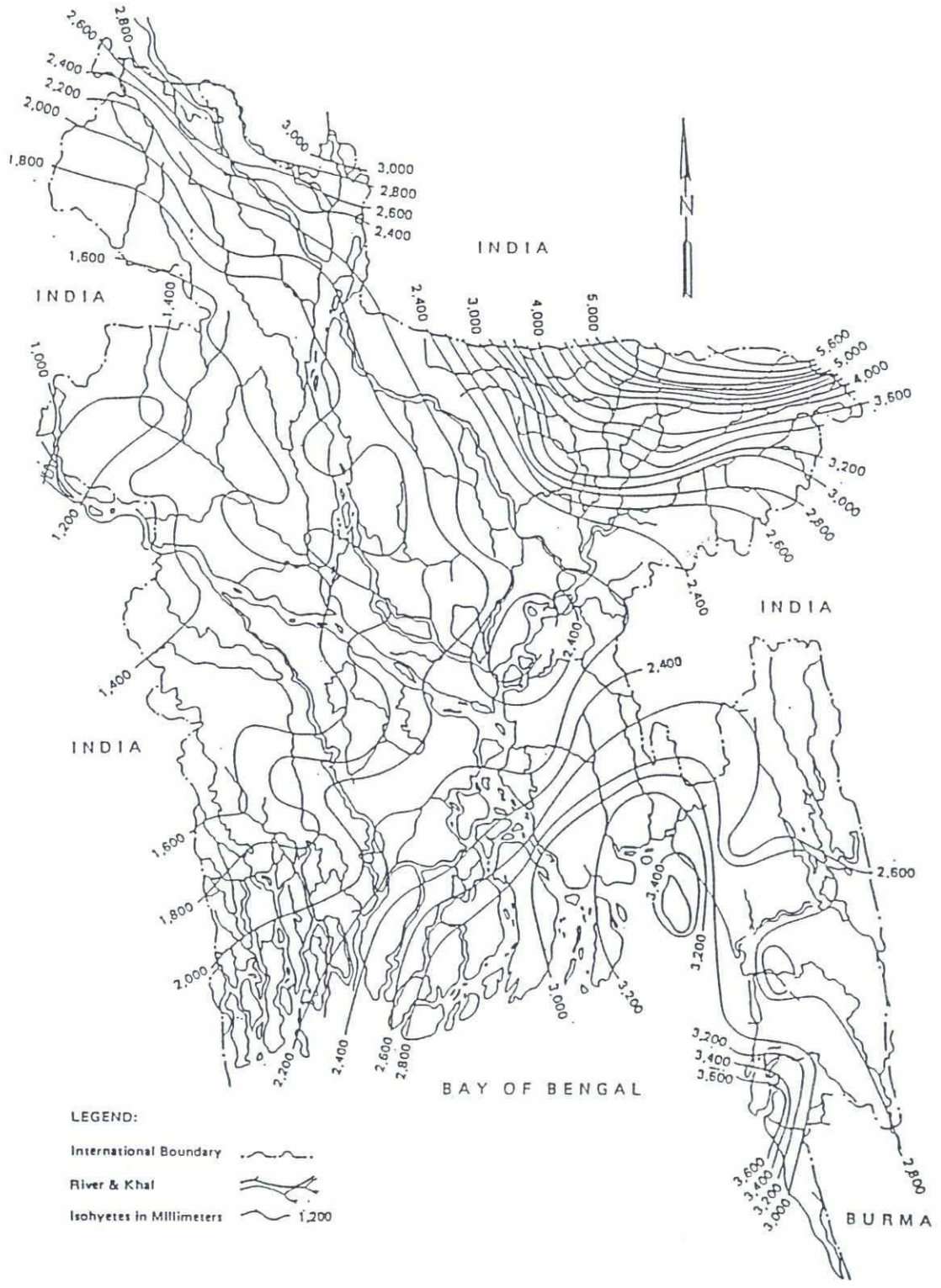


Figure 4.3 Isohyetal map for Bangladesh. (Source : MPO, 1985)

The average precipitation in the river basin range from over 1000 mm during May - October to 120 to 250 mm during November-April. The catchment boundary and annual rainfall distribution in the Ganges-Brahmaputra river basin is shown in Figure 4.2. More locally, in the Bangladesh region, the annual distribution of rainfall can be described in three periods resulting from different wind-patterns (Islam and Miah, 1981; Rashid, 1991). The western depressions of the winter occur in January-February with light rainfall of about 25 mm. The early summer thunderstorms known as North-Westers occur in March-May with a rainfall of about 90 mm in the northwest to about 420 mm in the northeast. Heavy rainfall occurs during the monsoons from June to September. The rainfall during this period varies from the highest of 5000 mm in Sylhet to the lowest of about 1220 mm at Rajshahi, see the mean annual rainfall distribution in Bangladesh in Figure 4.3. While such an annual distribution is well-established, long-term trend in rainfall distribution is not clear. Statistical analysis of 150 years of monthly rainfall data at 11 sites in the lower reaches of the Ganges River basin suggests no long-term trend in the regional monsoon rainfall nor any statistically significant cycles or periodicities (Rogers at al, 1989a), see also 150 years of total annual rainfall at Calcutta in Figure 4.4. Although, spatially, a 1989 analysis of regional rainfall data confirms an east-west alternation within the basin whereby droughts over central and northwest India take place in years of excess rainfall over northeast India/Bangladesh and vice versa (Shukla, 1987). Despite this uncertainty in the long-term trend in rainfall distribution, world-wide climatic modelling and future projection indicates that rainfall in the catchment may increase by about 9% by the year 2030 (Gates et al, 1992) due to global warming.

The annual temperature ranges from mild in the winter (January temperature 10°C to 20°C) to hot in the summer (July temperature 21°C to 32°C) (Parkins, 1992).

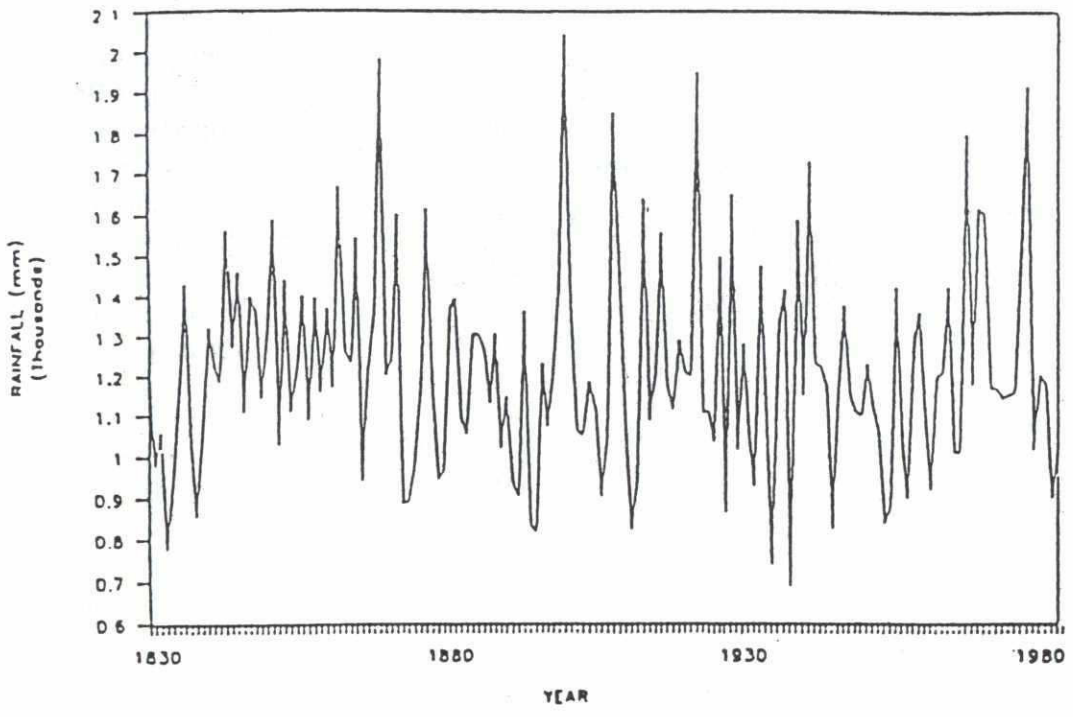
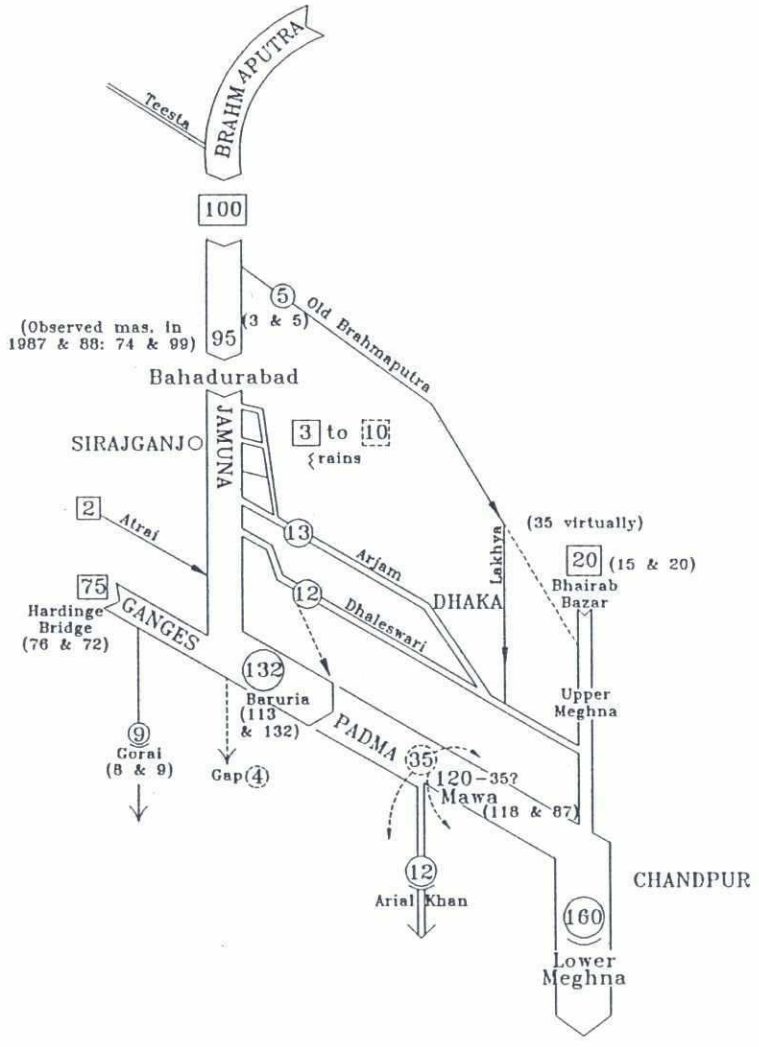


Figure 4.4 Long-term monsoon rainfall at Calcutta (Source : Rogers et al. 1989a)

4.3 Hydrological factors

In fluvial geomorphology such hydrological factors as water-level and discharge are important parameters. But low frequent catastrophic floods are important episodic events which may change the characteristics of a river behaviour. Historic shifting of the Brahmaputra River from its previous course along the east of Modhupur Jungle to its present course is attributed to a series of events which started with the 1787 flood according to some investigators. La Touche (1910b) suggested that the changes took place rapidly in 1787 as a result of a rapid increase in water volume in the Brahmaputra river. Mahalanobis (1927) agreed with La Touche and claimed that a catastrophic flood in 1787 caused the Brahmaputra to abandon its old course. Hirst (1916) agreed with the hypothesis but indicated that the change took place gradually between 1720 and 1830. More recently, Galay (1980) showed major changes of the Ganges-Jamuna confluence at Aricha due to 1974 flood. The route and distribution of a peak flood along the major river system of Bangladesh is shown in Figure 4.5.



Some hydrological aspects of the occurrence of a catastrophic flood need some discussion here because of the importance of the confluences in creating a flood in Bangladesh. Figure 4.6 shows the 1987 and 1988 hydrographs of the Ganges-Brahmaputra rivers. During these two years, although the individual flood peaks through the two rivers were similar, Bangladesh experienced severe flood in 1988 just because of the coincidence of two floods coming through the two rivers.

Figure 4.5 Schematic distribution of flood flows along Bangladesh rivers (Source : F.E.C, 1989)

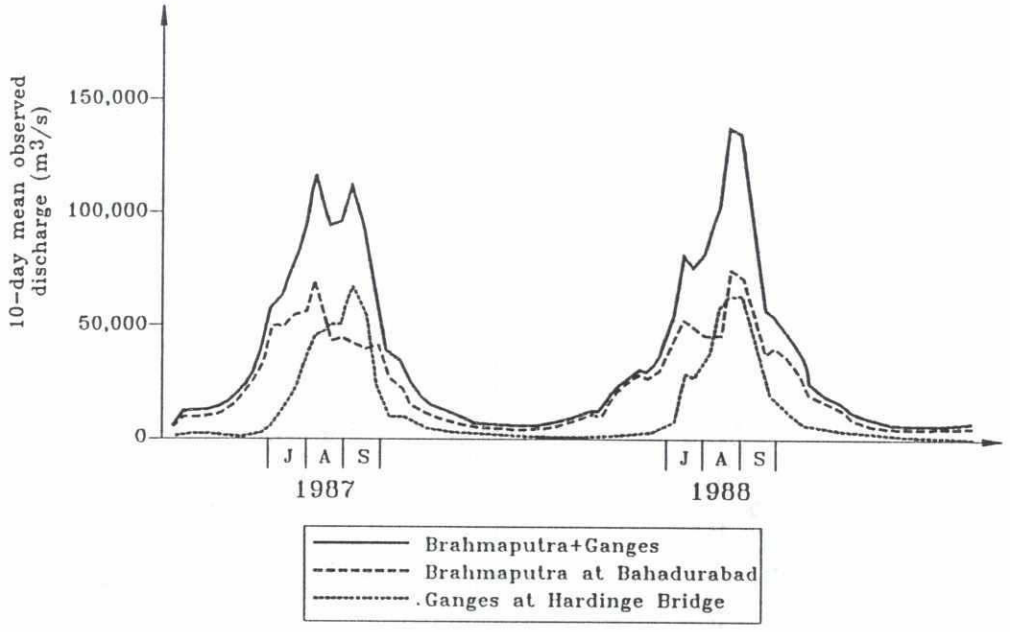


Figure 4.6 1987 and 1988 flood hydrographs of the Ganges and the Brahmaputra rivers (Source : F.E.C, 1989)

4.4 Topographical factors

Milliman and Syvitski (1992) indicated the importance of topographical relief on the sediment load of rivers. They showed that a certain basin area with a high mountainous river yields significantly higher sediment concentrations than a coastal plain river.

The Ganges-Brahmaputra river basin is a low relief plain (< 100 m) sandwiched between the Himalayan Alpine system in the north to the Gondwana Shield in the south (Murphy, 1992). The watershed of the rivers extends to both of this hilly and mountainous regions. The Himalayan mountains have a local relief (> 600 m) and the Indian Shield hills have a local relief between 100 m and 600 m, see Figure 4.7. It includes areas from the higher Himalayas to the peninsular Indian Shield. The general relief map of Bangladesh with its hypsometric characteristics is shown in Figure 4.8.

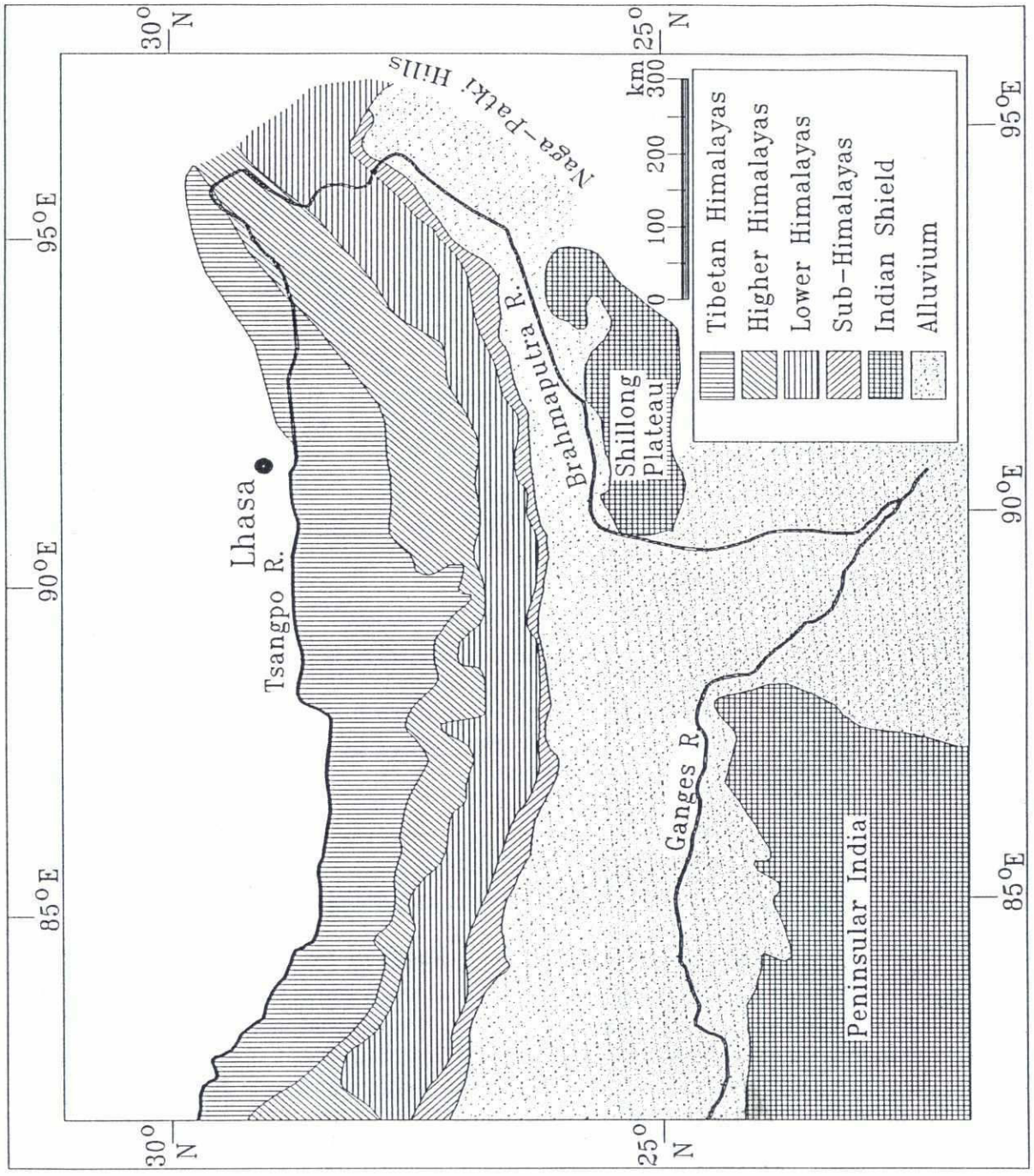


Figure 4.7 Eastern Himalayas and the Brahmaputra basin (Source : Gansser, 1964)

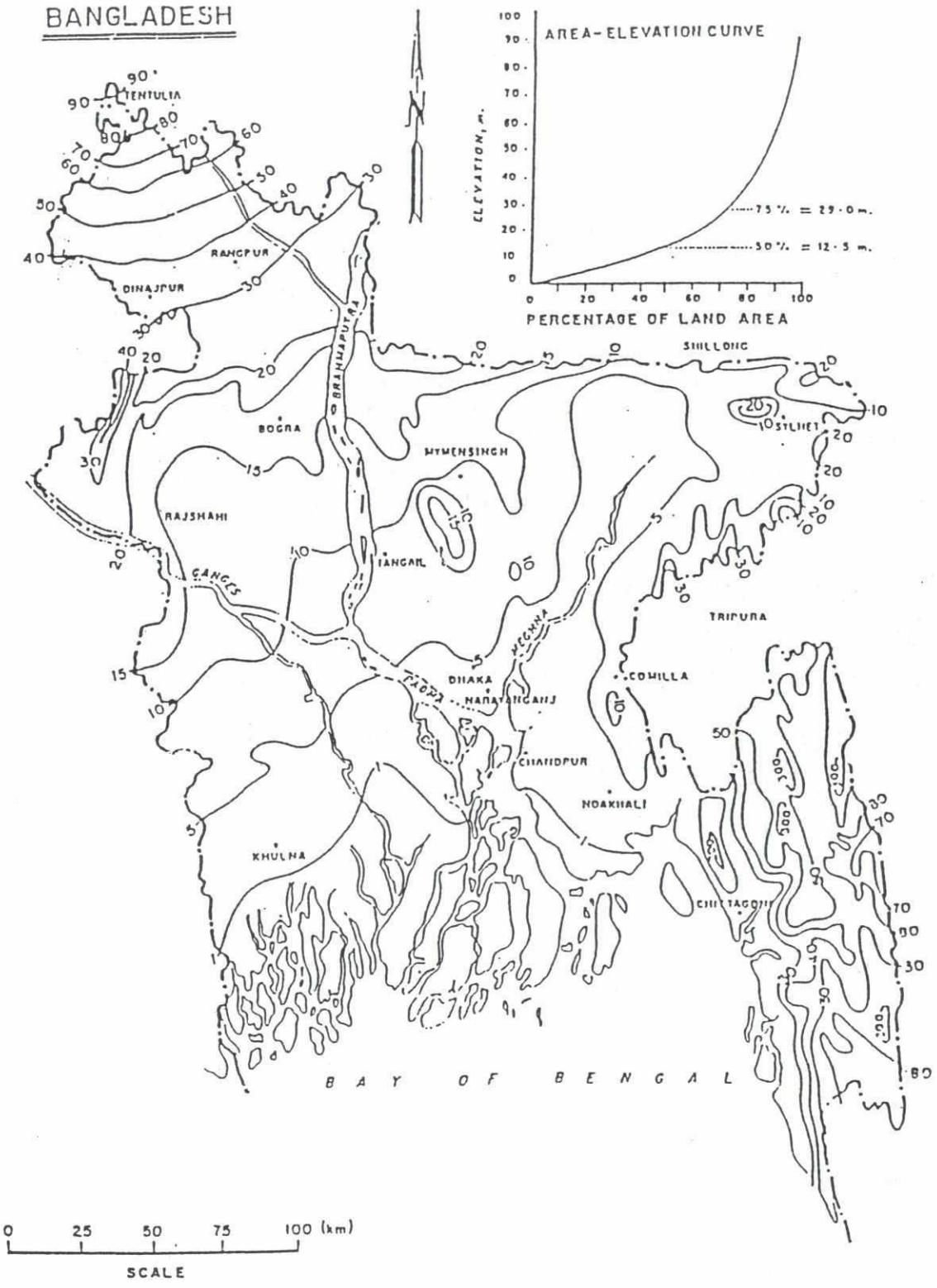


Figure 4.8 Generalized relief map and hypsometric characteristics of Bangladesh (Source : MPO, 1987b)

4.5 Geological factors

During the late Eocene epoch about 40 million years ago, the Indian plate began to meet and pass underneath the Eurasian plate at its southern edge Tibet at a rate of about 5 cm per year (Molnar, 1986). This collision elevated the Tibetan plateau and created the still geologically young and erodible Himalayan mountain range consisting of scrapings from the forward edge of the Indian plate forced back over the advancing mass. In the process, Himalayas rise by about 1 cm per year in altitude, and slippage in the process generates "a roughly annual moderate earthquake and the rare, but all too frequent great earthquakes" (Molnar, 1986). The north Indian plain consists of a great geological trench running below the very young Himalayas and filled to a depth of several kilometres by alluvium eroded from the mountains. Although moving at a geologic pace, the process is an active and dynamic one. Tectonic movement continues to raise the mountains, and massive and complex erosional process continue carrying the mountains' mass in the form of sediment toward the valley and the sea. For the general geologic characteristics of the region at different stages of plate collision, see Figure 4.9. Under this overall setting, the Bengal basin geological structural situation is presented in Figure 4.10. Rivers flowing through this type of active tectonic regions, respond to any structural deformation of its basin either by shifting of its course or by river bed aggradation or degradation.

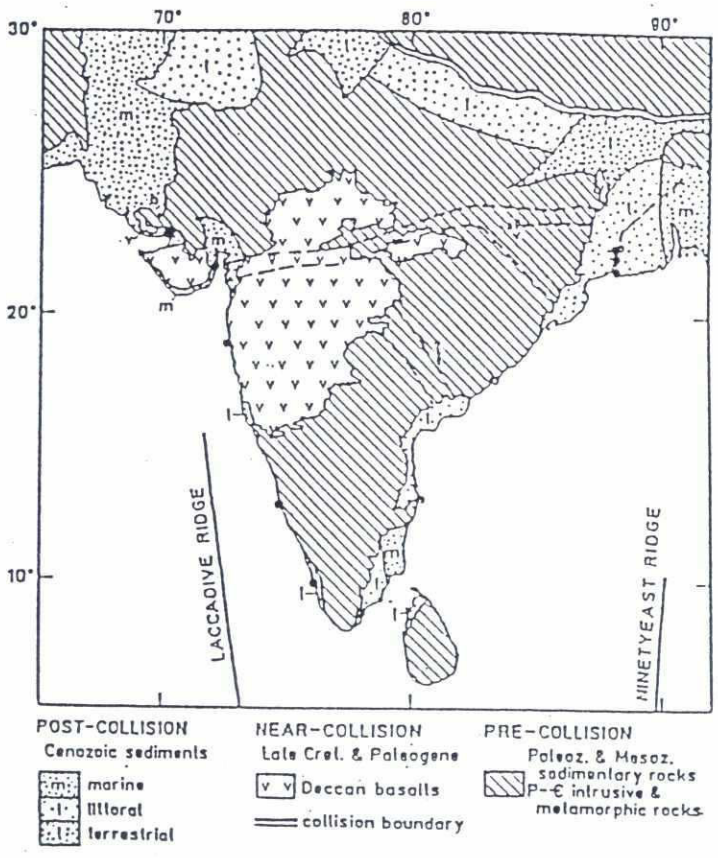


Figure 4.9 Generalized geological map of the region (Source : Emery and Aubery, 1988)

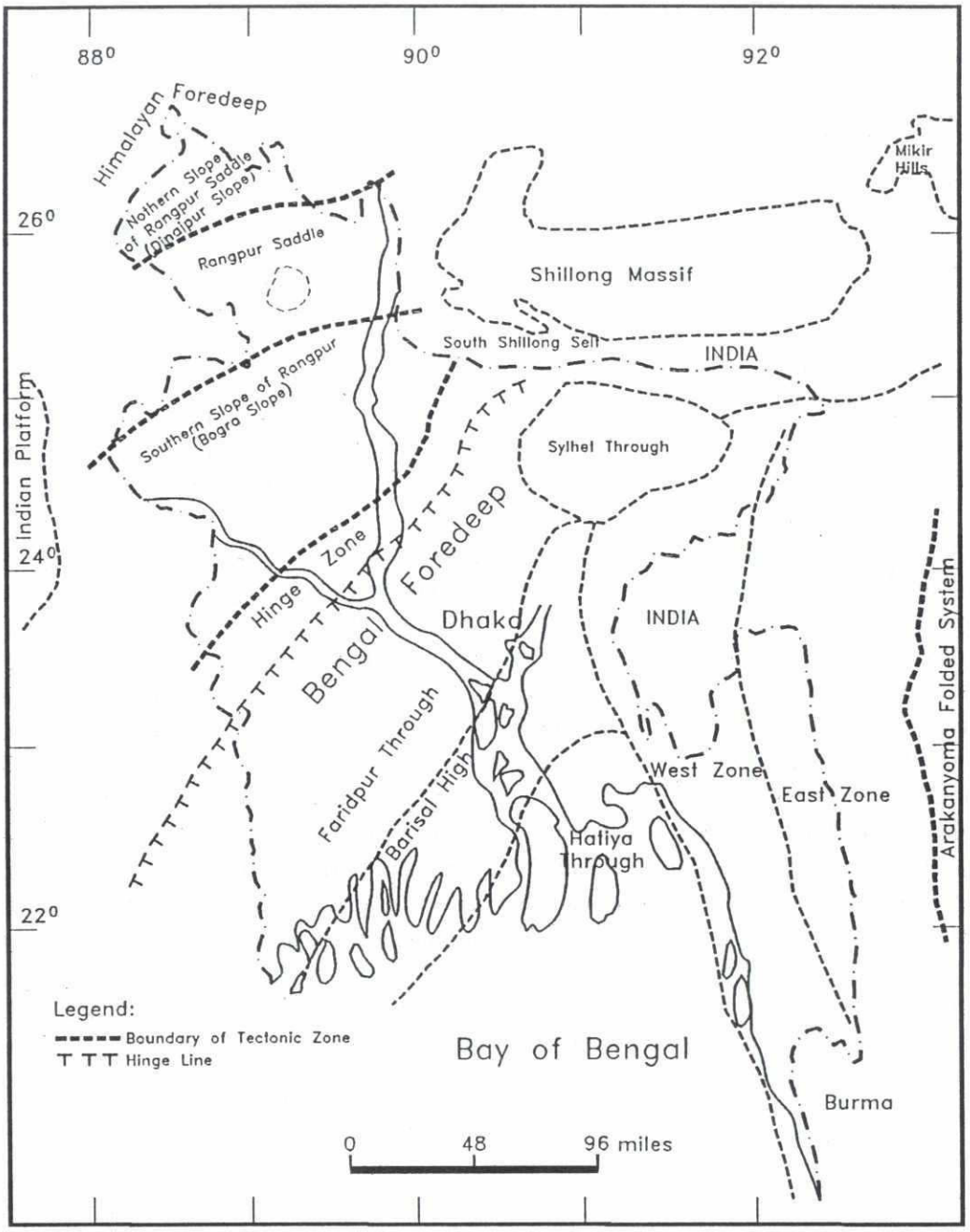


Figure 4.10 Tectonic classification of the Bengal basin (Source : MPO, 1987b)

About the present and the preferred course of the Ganges-Jamuna-Padma rivers, Fergusson (1863), Hirst (1916) and Morgan and McIntire (1959) suggested a structural "zone of weakness" along the present course of the Ganges-Jamuna-Padma rivers due either to a subsiding trough or to a single major fault at depth. Morgan and McIntire presented 4 major evidences in favour of it, they include (1) changes in the stream courses, (2) an assumed insignificant growth of the delta during the last two centuries, (3) the tilting of the north-eastern flank fault of Barind surface towards northeast, and (4) the presence of a gap between Garo Hills of the Shillong Plateau and Rajmahal Hills of peninsular India (Hora, 1944; Auden, 1949; Dey, 1949 and Krishnan, 1953).

Auden, 1949; Dey, 1949 and Krishnan, 1953).

In addition to this structural control on river migration, episodic earthquakes may change the river characteristics in the form of an episodic event. The 15 August 1950 earthquake in Assam with a magnitude of 8.6 caused considerable changes in the Brahmaputra River basin. During this earthquake a 40 m high slip-dam was built on the Subansiri River, a tributary of the Brahmaputra River (Bapat, 1988). Consequently, rapid river bed aggradation took place in that stretch of the Brahmaputra River (Goswami, 1985). This aggradation is probably moving slowly in downstream direction as a sand wave on the river bed. The height of this sand wave is gradually dampened.

Basin lithological type is determined by the type of natural vegetation. The natural vegetation in the Ganges-Brahmaputra river basin is broadleaf forests with evergreen to descidious and semi-decidious trees (Kuchler, 1992). The overall basin-soils are primarily inceptisoils aquepts which are immature, weakly developed soils and are seasonally saturated with water.

Bangladesh consists of three major geomorphological zones (Brammer, 1971). These are (1) Hill areas, (2) Terrace areas and (3) Floodplains. The first two topographical high areas are important in determining the course of a river, migration and sediment transport. Major parts of the Bengal Basin consists predominantly of recent alluvial and deltaic sediments (Morgan and McIntire, 1959). In the upper valley (land above tidal inundation) these deposits are composed primarily of silts and sands; in the lower delta they are principally silts, clays and peats. Because they were recently deposited, they contain a high water content, they are commonly loosely compacted, and they are generally grey. Because of the shifting nature of the Ganges and Brahmaputra rivers, the geomorphic relationships of the various sedimentary units are highly complex. A detailed lithological description of the recent alluvium is provided by Alam et al (1990). They can be broadly discussed under deltaic deposits, paludal deposits and alluvial deposits. The deltaic deposits mainly cover the southwestern region, with deltaic sand crevasse splay and deltaic silt deposits more in interior areas. The paludal deposits characterized by marshy clay and peat occupy the swampy areas of the Sylhet depression in the northeast, the Atrai basin in the northwest, the Goplagonj depression, and some in some minor depressions. The alluvial deposits covering Ganges-Brahmaputra-Meghna floodplain contain flood sand to overbank silt and ponded clay.

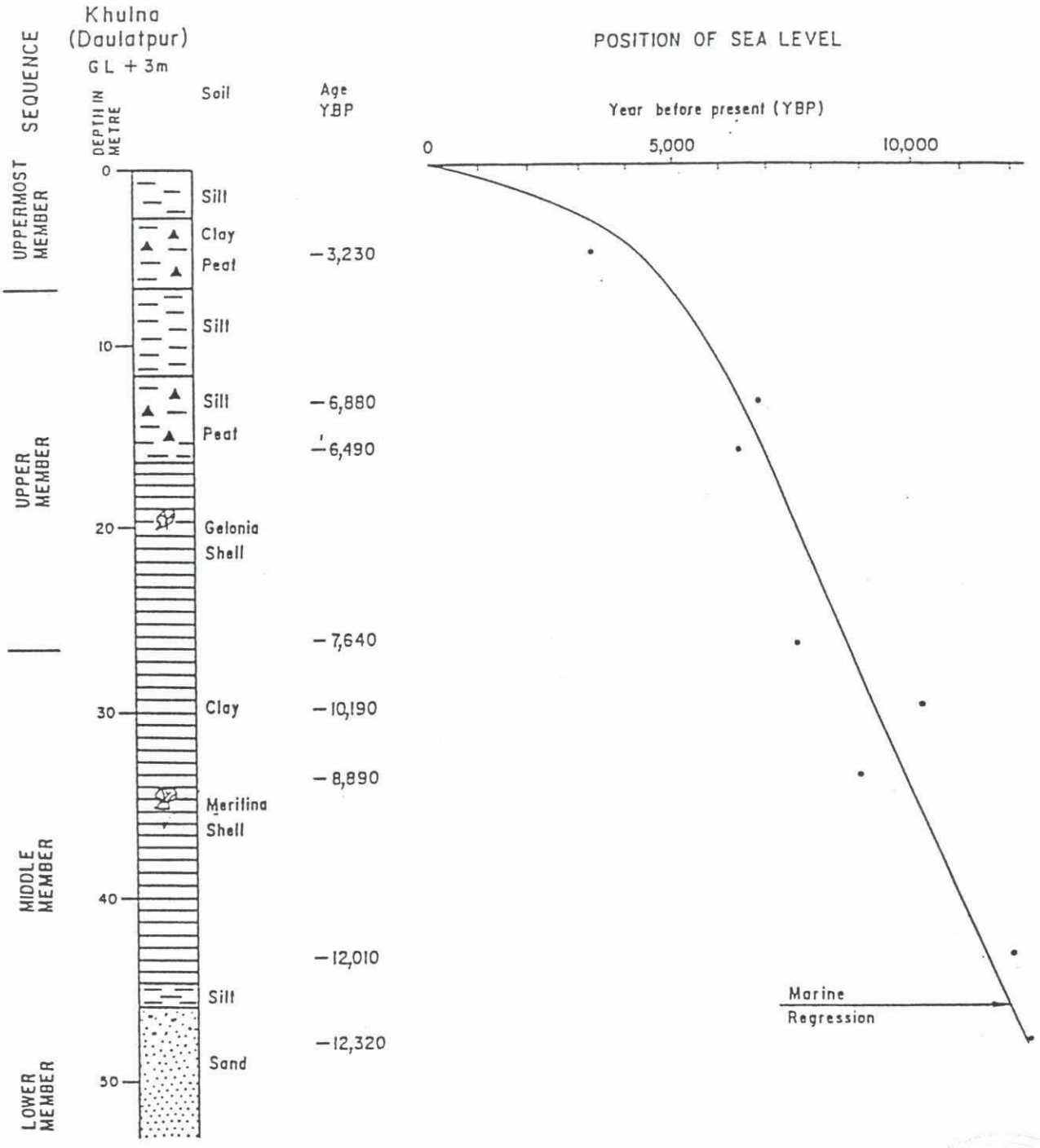


Figure 4.11 Sedimentary sequence and position of sea level (Source : Umitsu, 1993)

4.6 Base-level changes

The sediment transport capacity of a river and the type of deposits are dependant among others, on the rise and the fall of the base level. In the case of a tributary, the water level of the main river is a base level. The ultimate base level of all rivers, however, is the sea level. In the deltaic reaches of a river system, the sea level variation has a far reaching effect, specially on a geologic time-scale. During the historic time, there were changes in the sea level, followed with the periods of glaciation and anti-glaciation. The present Holocene Transgression started in about 18,000 years ago with eustatic sea level rise of about 0.10 m per century (a graded time-scale). In case of Bangladesh coast, this rise of the sea level is reconstructed by Umitsu (1993), see Figure 4.11. During this process the characteristics of channel deposits changed. Over-the-depth variation of lithological evidence investigated by Umitsu (1993) indicate that as the Holocene Transgression started, the lithological structure changed from coarser to fine sedimentary structures. The delta building of the Ganges-Brahmaputra rivers during the Transgression period is shown in Figure 4.12. The generalized geological map of India (Emery and Aubrey, 1988) shows that the Bengal basin is composed of marine and littoral Cenozoic sediments.

For this region of the world another interesting factor in sea level variation is important. That involves the seasonal variation in sea level following the southwest monsoon. Analyses of 10 years of water level data at Chittagong indicate that sea level rises by about 0.8 m in August as shown in Figure 4.13.

4.7 Anthropogenic controls

In general a rapid human growth accelerates the exploitation of the resources in a river basin, and consequently the river responds to that. This acceleration of his exploitation are in the form of growing extensive and intensive deforestation and cultivation of watershed areas, water management initiatives, floodplain developments, etc. The influence of these factors, however, on river behaviour is often only qualitatively known, but it can induce very important changes in the river system (Coleman, 1969; Goswami, 1985 and Milliman and Syvitski, 1992). Some qualitative indications by Hossain (1992) show that the sediment transport through the Ganges River is decreasing but the same is increasing for the Jamuna River. He attributed this development to the watershed management programmes on the Ganges basin and deforestation on the Brahmaputra basin.

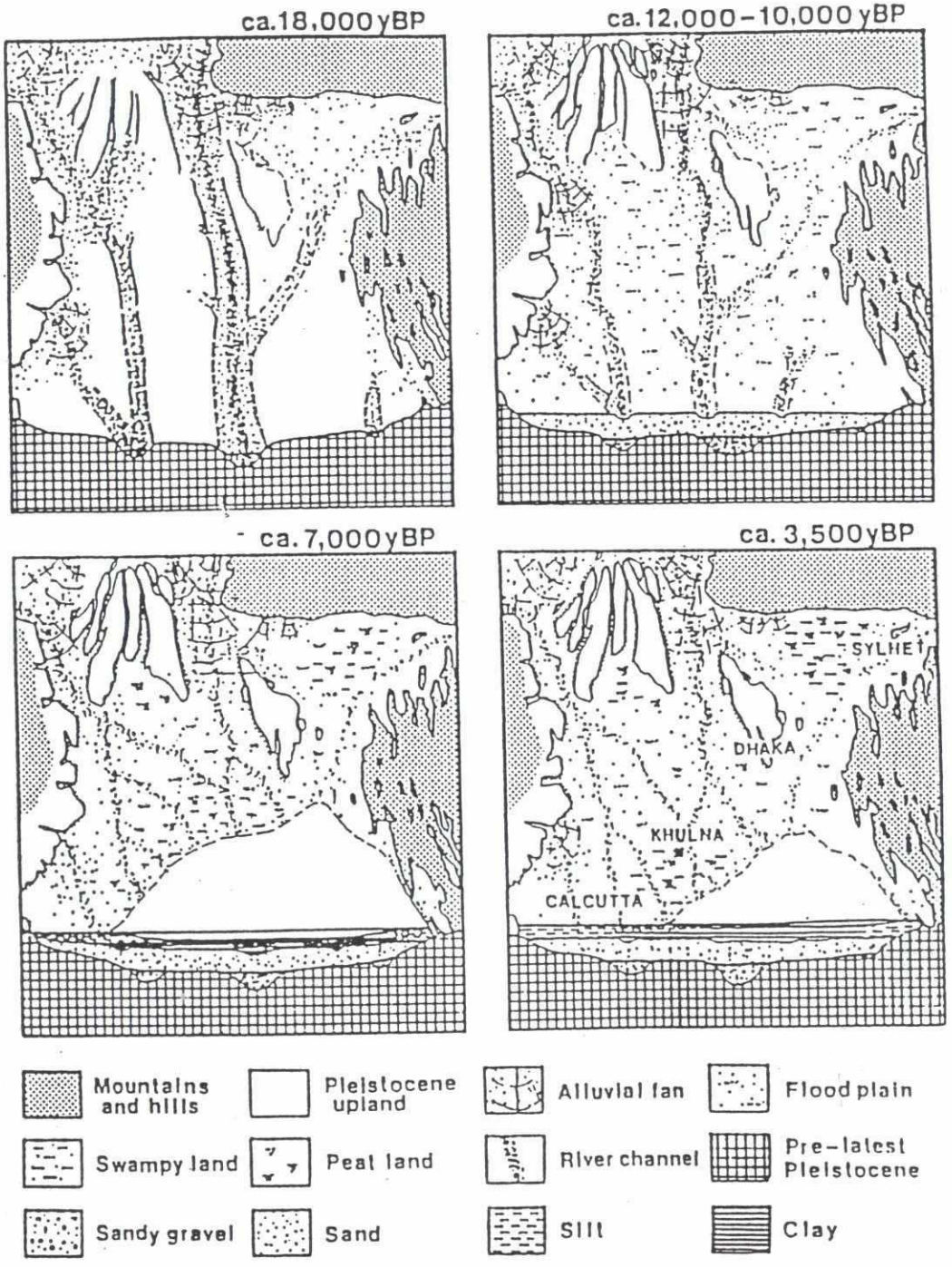


Figure 4.12 Paleo-geographic maps of the delta (Source : Umitsu, 1993)

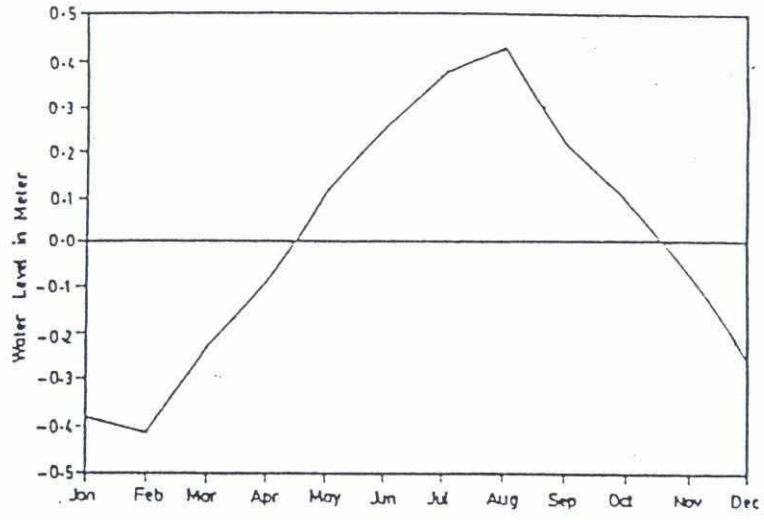


Figure 4.13 Seasonal sea-level variation at Karnaphuli river (Source: Barua, 1991)

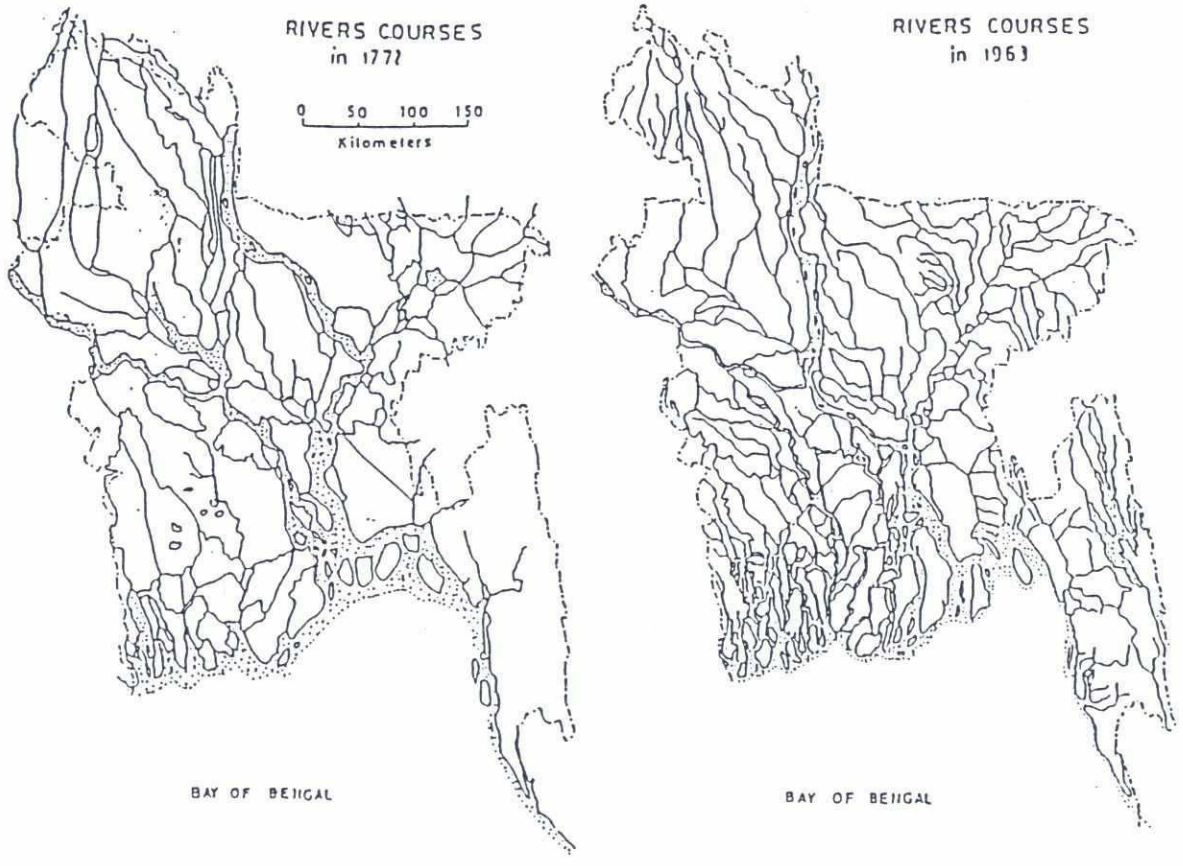


Figure 4.14 Changed courses of the rivers between 1772 and 1963 (Source: Universities Research Center, 1987)

5 Slopes, channel dimensions, and planform characteristics

5.1 Introduction

In the previous Chapters the independent variables that ultimately determine the characteristics of a river were outlined and discussed. In particular in Chapter 4 climatic, hydrological, topographical and geological factors plus base-level changes and anthropogenic controls on the main rivers in Bangladesh were reviewed. Due to the influence of these controls in the present era, but - probably even more important - their effect in the past as reflected in the present "form" of the river, the different characteristics of the main rivers of Bangladesh have taken shape. In this Chapter some of the dependent river characteristics, as far as studied under this project, are discussed. In the discussion also use is made of the results obtained during some earlier studies, in which the different partners of the Consortium were involved. In this way a fairly complete picture of these characteristics is obtained.

The characteristics discussed in this Chapter are:

- floodplain levels (and bankfull discharges) (Section 5.3),
- slopes (Section 5.4),
- planform characteristics (Section 5.5), and
- channel dimensions (Section 5.6).

These are considered as the primary dependent river characteristics as they are related to the first-order channel (Bristow, 1987; see also Chapter 2). Here the discussion of these primary dependent river characteristics is preceded by a discussion on dominant discharges (Section 5.2), as the determination of the "representative" discharge for some river characteristic is not without problems.

Also secondary characteristics have been studied. Typically these secondary characteristics are characteristics that are of importance when more local (2-nd order and higher) conditions are studied. Secondary characteristics of relevance for the main rivers of Bangladesh, studied under this project and discussed in this report are bars and bifurcations (Chapter 8), scour (Chapter 9), bank erosion and cutoffs (Chapter 10), maximum velocities (Chapter 11) and local exchange of sediments (Chapter 12).

It is important to stress here that probably there is no single-valued relationship between the imposed variables and the dependent river characteristics. In the case of the main rivers in Bangladesh, this is caused by at least two reasons.

One reason is that a different "history" of the river system can lead to different values of some dependent characteristics. Some insight in the different possible responses to imposed changes is obtained when considering the effects of an increase in a parameter characterizing flow strength, such as flow velocity, stream power or shear stress. The excess flow strength will lead to bed degradation when the banks are fixed. This bed degradation will increase the water depth and reduce the longitudinal slope until the flow strength reaches a value which matches the transport of the sediment supplied from upstream.

When the banks are erodible, there are three additional modes of adjustment. Firstly, the river can become wider. Secondly, the longitudinal slope can be reduced by increasing the sinuosity through the expansion of meander loops. Thirdly, new channels can be carved in the floodplain at discharges above bankfull, which leads to an anabranched system. The vertical response of rivers with fixed banks is rather unambiguous, but the distribution of the horizontal response over the three modes of adjustment depends on the initial state of the river and the time series of discharge and sediment supply during the transition to a new equilibrium. Moreover, even the equilibrium values of one single mode of horizontal response, namely width adjustment, are multi-valued (Delft Hydraulics, 1996). This multi-valuedness of equilibrium planform properties and consequent dependence on history might explain why Mosley (1987) found that cross-sectional dimensions and longitudinal slope have a high correlation with discharge magnitude, discharge variability, sediment character and bank erodibility, whereas sinuosity and braiding index seem to be completely independent of the supposed controlling variables.

The second reason for the fact that for the same imposed variables substantial differences in river characteristics are found is the specific character of an active braided river. In a river like the Jamuna River often channels do not continue to exist over a longer period. Initially channels tend to develop, but after some time their function is taken over by others and hence they slowly decay via sedimentation during flood. As a consequence channels can be in different stages of development and this determines the variability of their characteristics. An extreme example is the Upper Meghna River, which typically can be classified as an "underfit" stream, of which the planform (braided) does not fit to the presently imposed variables. Similar examples can be found in the Jamuna River.

Hence, a dependent variable is usually not characterized by one single value. Rather quite some scatter may be present in these variables.

5.2 On dominant discharges

The dependent variables will be discussed hereafter in relation to the imposed variables. Some of these imposed variables are "easy", as they are given as one single value. This holds for the yearly sediment load (see Chapter 10 of Annex 4) and for the bed material characteristics. The discharge however is an imposed variable that is continuously changing in time. To avoid the burden of the changing discharges as reflected in discharge hydrographs, often it is attempted to replace the (average) hydrograph (or duration curve) by a constant value, the so-called 'dominant discharge' or 'formative discharge', terms which according to Blench (1969) seem to have been originated by Inglis (1949).

There are several ways to determine such a single discharge, though all problematic:

- Dominant discharge = bankfull discharge
  The disadvantages of this definition are that the bankfull discharge is not independent of channel morphology, can be hard to define in braided rivers and can be misleading in incised rivers (Ferguson, 1987).

- Dominant discharge = discharge with a certain frequency of occurrence
  Church (1992) argues, however, that there is no universally consistent relation between flow frequency and effectiveness in creating morphological changes. Large rivers flowing in fine sediments may be shaped predominantly by frequently recurring flows, whereas boulder or cobble-gravel channels may be subjected to major disturbance only during much more extreme events. Church (1992) adds that, nonetheless, regionally consistent combinations of these circumstances and hence regionally consistent relations between discharge frequency and morphological effectiveness may occur.

- Dominant discharge = constant discharge which gives the same results in morphological computations as the full discharge hydrograph
  However, the constant discharge for the equivalent reproduction of one phenomenon, for instance meander formation, is usually not the same as the one for the equivalent reproduction of another phenomenon, such as self-adjustment of slope and transport of the annual sediment supply (NEDECO, 1959; Blench, 1969; Prins & de Vries, 1971; Mosselman et al, 1995).

- Dominant discharge = median of incremental discharge class responsible for transporting the most sediment in the long run
  This definition is proposed by Biedenharn & Thorne (1994). The latter acknowledge, however, that the range of effective flows should be considered as well, thus departing from a strict application of the dominant-discharge concept.

The latter two definitions are better than the first ones because they are based on the full discharge frequency distribution and the amounts of sediment transported at each discharge. For calculation purposes, however, none of these definitions is fully satisfactory, so that 'dominant discharge' remains a very imprecise concept. For other river characteristics probably a different definition of dominant discharge would be appropriate.

Preferably, the full discharge hydrograph has to be considered with due account of the possible influence of extreme events. The standard method of Jansen et al (1979) for the assessment of the vertical morphological response of rivers accounts for discharge variations. Though being used frequently, the concept of 'dominant discharge' should be abandoned for an analysis that takes into account the variation of the discharges and their sequence. For many phenomena this is not possible. Hence in the remaining part of this Chapter 'dominant discharges' are used, but the reader should be critical regarding the use of this concept.

5.3 Floodplain levels and bankfull discharges

5.3.1 Introduction

The floodplain level is related with the bankfull discharge, which is utilised as a parameter for the prediction of channel dimensions and plan-form characteristics of the major rivers in Bangladesh. The objectives of this section are as follows:

- To obtain an impression of the variability of the floodplain level and any changes of floodplain level during the last few decades
- To determine the bankfull discharge of the Jamuna, the Ganges and the Padma Rivers
- As different studies on the Jamuna River have reported different values for the bankfull discharge, one objective of the present study is to estimate the range of variation of the bankfull discharge of the Jamuna River with changes of the definition of the bank level.

This section is based on the contents of RSP Special Report 6, in which more details can be found.

5.3.2 Floodplain level

Floodplain

According to Volker (1981), the floodplain can be classified into three zones: Natural levee, transition zone, and backswamp. During flood flow, the river spills over the banks and flows over a strip of land along the river. This strip of land is known as natural levee. It is topographically elevated, due to the relatively coarser fraction of sediments depositing over this area. The natural levee accretes both laterally and vertically. The width of natural levees vary within a range of one-half to four times of the width of the river (Allen 1970) and the height may be as much as 3 to 4 m (Volker, 1981). Along the Jamuna, Ganges and Padma Rivers, backswamp is not a common feature, except for a few places. Rather, the flood basin is wide, see Figure 5.1.

Coleman (1969) observed the formation of the natural levee of the Jamuna and the Padma Rivers. He noted that flood spills occur in two ways. One (the predominant way) is diversion of the flood water into the basin through distinct funnel-shaped flood channels, which also convey the sediment from the river. This type of diversion of flood water has little influence on the formation or change of the floodplain level adjacent to the river. The second type of spill of flood water over the bank results in well-defined crevasse splays, which lead the water into the adjacent basin. Such crevasse splays account for the vertical accretion and irregularities in the vertical and the lateral direction of the natural levee. Crevasse splays mostly consist of fine sand capped with finer deposits, see Coleman (1969). It is not so that overbank flow always contributes to aggrading the floodplain. Leopold et. al. (1964) pointed out that irregularly distributed flood flows over a floodplain sometimes could induce scour, rather than deposition.

Leopold et. al. (1964) classified the floodplain sedimentation into two types: One is the overbank deposition, and the other is the lateral deposition within the river. They noticed that the lateral accretion dominates the process of the sediment deposition over the floodplain.

For rivers like the Jamuna, Ganges and Padma, where the rates of bank erosion and migration of the channels are relatively high, it is evident that the lateral accretion will be the dominating process.

River dynamics

Jamuna River has followed its present course for the last 200 years, and Ganges for approximately 500 years (ISPAN, 1993), while the Padma, carrying the joint volumes of water of the Jamuna and Ganges, has followed its present course since the avulsion of the Jamuna River.

During the last few centuries, the rivers have been in the process of adjusting their floodplain and plan-form. The Jamuna River, after its avulsion, has migrated within a 20 km wide sand body (Bristow, 1987), which is known as the active corridor. The Jamuna as a highly active braided river, continuously eroding and depositing its secondary and tertiary channels.

The Ganges and the Padma are wandering rivers (ISPAN, 1993). They are in a transition between meandering and braiding, and are often changing their plan-form locally within the different river stretches.

The banks of all these three rivers are highly erodible, the erosion rate exceeding 1000 m/-year in extreme cases (Klaassen and Masselink, 1992). The near-bank floodplain of these river are in a process of continuous lateral deposition and erosion. FAP 4 found that the Ganges and Padma Rivers, while shifting laterally, confine their migration within an active corridor (FAP 4, Final Report, Volume 3, 1993).

Limitation of data used

The standard cross-sections surveys of BWDB follow a fixed alignment, and the length of each section is limited by a fixed monument or by pillars. The length of the floodplain covered by BWDB cross-section surveys is mainly determined by the eroding or receding bank of the river. In most of the cases, it was observed that if any one bank of a cross-section is stable for a few years, BWDB reduces their length of the survey over the floodplain from a few km to a few tens or hundreds of meters. Hence, the BWDB data only represent the bank level and a part of the developing floodplain adjacent to the existing bank. However, in a few cases, the characteristic shapes of floodplain features, such as the natural levee with its depressed flood basin, or a part of the backswamp, can also be observed from the data, when the bank is stable for a period of time (see Figure 5.2).

Data analysis and discussion

The floodplain and river surveys of FAP21/22 in the Jamuna River are shown with a 0.5 m contour interval, see example in Figure 5.3. From this figure it is observed that within a distances, like 5 km, the level differs more than 2 m. Local irregularities of the floodplain level are observed both along and in the transverse direction of the river, see Figure 5.4. As mentioned earlier, Coleman (1969) pointed out that crevasse splays account for the irregular boundary of the toe of the natural levee. Also, formation and dying of spill flood channels and irregular flow over the floodplain may contribute to these irregularities.

Due to the instability of the bank of these rivers, the existence of a matured natural levee (developed over a long period of time) is not possible along the existing bank of the river. For banks which are free from erosion or deposition for a period of time, for example the left bank of cross-sections G#2 and G#3 of Ganges River, the shape and size of the developing natural levee can be observed clearly. For section G#2, the surveys of 1965 and 1969 were compared. At this section, the natural levee eroded with time, and, at the same time, a lateral accretion occurred during the four years period, so that little change can be observed at the toe of the levee or flood basin, see Figure 5.2a. For cross-section G#3, the BWDB surveys of 1968, 1972 and 1976 were compared. No large changes of the natural levee of this section were observed in the eight years period, only a few decimeter vertical accretion at the toe of the natural levee is seen, Figure 5.2b. Figure 5.2 shows that the width of the natural levee is 1.50 km, and that the relative height of the levee is more than one meter for section G#3, while the width is 1 km and the relative height is nearly two meters for section G#2. The widths of both levees are smaller than the range described by Allen (1970). The continuous migration of the river course, restricting the development of the natural levee, may be one of the causes of the difference in width as compared with Allen (1970).

In Figure 5.5, the time variation of the floodplain/bank level is shown for different BWDB cross-sections from the Jamuna, Ganges and Padma Rivers. No significant changes of floodplain/bank level is observed from this figure, though the year-to-year variation is considerable, especially at sections G#7 and G#10 (which are both at the left bank of the Ganges) and at sections P#3_1 and P#7 (at the right bank of the Padma), and at both banks of section P# 1 of the Padma. Changes of floodplain/bank level within two to four year are in the range of 0.5 to 1 m. These changes are associated either with bank erosion or with bank receding. For the former case, see for example Figure 5.6a, at section P#3_1. Here, after 1975, erosion of the right bank continues until 1984. Erosion of the higher part of the natural levee shifted the bank at the toe of the previous levee from 1975 to 1979, and the right bank level continues to decrease as the erosion proceeds, see Figure 5.6a. The section of 1984 shows that after ceasing of the erosion, the right bank raised nearly up to the position of 1975. For the latter case, see for example Figure 5.6b, at section P#7, where the right bank receded towards the river. A raising of the attached bar from 1974 continued up to 1989, till the level nearly reached the bank level of 1974.

Figures 5.5 and 5.6 show examples where bank erosion or deposition into the river have changed the level of the near-bank floodplain, but within a few years, the level raised again nearly up to its previous level. More often, overtopping of flood water result in a rapid sedimentation over the low-laying floodplain. Another reason of apparent small year-to-year variations of the floodplain, as seen in Figure 5.1, is related to the survey procedure, as the length of the survey over the floodplain is the not same, and also, the levelling points during the survey are not same every year. This can influence the average impression of the level of a highly irregular floodplain.

For banks that are free from erosion or deposition for a long time, almost no change in the level is observed from Figures 5.5 and 5.6. This suggests that if any net aggradation or degradation phenomena occur on the matured floodplain, they cannot be detected from the applied type of data, neither with respect to time scale nor quality. The analysis shows that the processes of lateral deposition and erosion are predominant in these rivers, without any net aggradation or degradation trend of the floodplain.

5.3.3 Bankfull discharge

Method to determine the bankfull discharge

The bankfull discharge can be estimated by an indirect method based on the breaking point of the rating curve at high stages. This method is best suited for a primary estimate. Drawbacks of this method are as follows: (i) the breaking point of the rating curve may reflect the 'char' level rather than the bank level; (ii) the range of variation of the breaking point is quite high, and may reflect both the local morphological changes and changes of the char level. A bank-full discharge estimated by this method represents only the specific section of the discharge gauging station for which the rating curve was made, as the bank level profile may not conform with water level profile for the whole river reach.

The method that was used in the present study is to estimate the bank level over a certain river stretch, and to compare this bank level with the water level profile at different discharges. Estimation of the bank level is based on the bank elevation at a number of fixed locations distributed at a fixed distance along the river, and for estimation of the water level profile, the same procedure is followed. Drawbacks of this method are as follows: First, the bank level along the river is not a regular feature, and the water level profile, though not as irregular as the bank level, still does not maintain a fixed slope over a long distance, but varies with time and space. Secondly, the bankfull discharge derived by this method is sensitive to the estimation of the bank and water level. Still, this method can provide a better estimate than the former, which is highly influenced by the local morphological features.

Definition of the parameters

In order to determine the bankfull discharge, two parameters are significant. One is the bank level, and the other is the longitudinal water level profile at different discharges. For the purpose of this study, the bank level is defined as the average of the bank level as estimated from BWDB survey data for about the last three decades. For the Jamuna River, the bank level data have been analyzed in a slightly different way than for the Ganges and the Padma Rivers. The reason for this is an aim to examine range of variation of the bankfull discharge of the Jamuna River due to changes of the definition of the bank level. Hence, for the Jamuna River, two levels, high and low level, were marked at both banks of each of the BWDB cross-sections, see Figure 5.7. High points, like roads or embankments, were not considered, and low depressed points on the floodplain were also neglected. The mean bank level is defined as the average of the high and low levels (1966-1993), while the average high bank level is defined as the average high levels from the period. The 'high' and 'mean' bank levels of the lower bank of a section (see Table 5.1) are then compared with the water level profile.

For the Ganges and Padma Rivers, the bank level is defined as the average of the mean level (1966-1993) of the near-bank floodplain (see Tables 5.2 and 5.3). Unlike the Jamuna River, the mean bank level is directly estimated from the BWDB cross-section, without estimating the low and the high level. For comparing the water level profile at different discharges with the bank level, both bank levels were plotted for these two rivers.

Cross-section	Chainage,(1989) km	Average bank level (m PWD)		
		High level	Low level	Mean level
J#17	25	25.27	23.77	24.40
J#16	37	23.74	22.70	23.22
J#15	56	22.16	21.55	21.85
J#14_1	63	21.58	20.74	21.17
J#13	85	19.36	18.51	18.93
J#12_1	84	18.90	17.72	18.31
J#11	118	16.73	15.89	16.32
J#10_1	127	15.73	15.07	15.43
J#9	142	15.23	13.97	14.65
J#8	150	14.01	13.52	13.77
J#7	162	13.88	12.85	13.35
J#6_1	171	12.76	12.03	12.39
J#6	178	12.75	11.88	12.31
J#5	188	11.87	10.75	11.27
J#4	201	11.04	10.11	10.57
J#2_1	220	9.17	8.44	8.80

Table 5.1 Average (1966-1993) high, low and mean level of the lower bank of a section of the Jamuna River

Cross-section	Chainage (1992-93) km	Average bank level (m PWD)	
		Right bank	Left bank
G#17	-32.5	15.71	16.07
G#16	-27.5	15.41	15.71
G#15	-19.5	15.36	15.38
G#14	-10.5	14.90	15.50
G#13	2.9	13.94	14.08
G#12	8.7	12.28	13.54
G#11	13.7	13.22	12.97
G#10	19	12.80	12.69
G#9	26	13.00	12.51
G#8	31.5	12.15	12.10
G#7	36.5	11.75	11.53
G#6	39.5	11.65	11.29
G#5	45	11.39	10.69
G#4	53	10.53	10.67
G#3	58	10.20	10.43
G#2	65	9.85	10.12
G#1	79	10.00	8.70

Table 5.2 Average (1966-1993) bank level of the Ganges River

Cross-section	Chainage (1992-93) km	Average bank level (m PWD)	
		Left bank	Right bank
P#7	0	8.26	7.56
P#6_1	5.4	7.01	7.10
P#6	11	6.68	6.83
P#5	21.5	6.83	6.98
P#4_1	28.5	6.67	6.66
P#4	36.5	6.67	6.86
P#3_1	49	6.50	5.94
P#3	55.5	5.51	5.69
P#2	67	5.00	5.40
P#1_1	72	4.91	5.38
P#1	77	5.10	5.28

Table 5.3 Average (1966-1993) bank level of the Padma River

The water level profile for each discharge is not a constant line. It varies from year to year, and also within one single year, due to hydrological and local morphological phenomena. Specific gauge analyses of the discharge stations at Bahadurabad of the Jamuna, at Hardinge Bridge of the Ganges, and at Mawa of the Padma River, were done by FAP 24, see Figure 5.8 (from Hydrological study phase 1, 1993). For each of the discharge stations, the year-to-year variation of the stage is considerable, the maximum range of variation being up to 0.50 m. To have an average impression of the stage for the same discharge, two years were selected for each river, where the stage variations were above and below the average line, and with almost the same magnitude for the higher discharges. Years 1990 and 1991 were selected for the Ganges and Padma Rivers, and 1984 and 1985 for the Jamuna, see Figure 5.8.

Assumption

Within the study reaches of the rivers, the discharge is not the same, due to the presence of tributaries and distributaries (see Figure 5.9). For simplicity, however, it has been assumed that the discharge at Bahadurabad represents the Jamuna River, Hardinge Bridge the Ganges, and Baruria the Padma River.

5.3.4 Data analysis

Jamuna River

As mentioned earlier, two bank levels, high bank and mean bank level, were estimated for each cross-section, and both were compared with water level profiles in order to asses the range of the bankfull discharge of the Jamuna River. The mean bank level profiles of the left and the right bank of this river are shown in Figure 5.9. The range of variation of levels between two banks is 0.05 m to 0.35 m. The mean level of the lower bank of a section was compared with discharge profiles of 45,000 m^3/s and 50,000 m^3/s for the years 1984, 1985 and 1990, see Figure 5.10. This figure indicates that the bankfull discharge varies with time,

and that the variation is higher at the downstream reach of the Jamuna, where backwater from the confluence affects the water level profile. The figure suggests that the average bankfull discharge is somewhere in between 45,000 m^3/s and 50,000 m^3/s, if the mean bank level is considered. The high bank level is compared with the water level profile of 55,000 m^3/s in Figure 5.9c. The average bankfull discharge is around 55,000 m^3/s, if the high bank level is considered.

Bank surveying of FAP 21/22 and FAP 1 was also utilised to asses the bankfull discharge, see Figure 5.10d. This figure indicates that the average bankfull discharge is within the range of 45,000 m^3/s and 50,000 m^3/s, a mid value of 48,000 m^3/s would be reasonable, if the mean bank level is considered. It is to be noted here that the mean bank level estimated from the BWDB cross-section surveys complies well with the mean elevation of the FAP 21/22 and FAP 1 data.

Now, the question arises, what will then be the most relevant bankfull discharge of the Jamuna River. It can be firmly concluded that it is not as high as in 60,000 m^3/s or more. One typical BWDB cross-section is shown in Figure 5.11, with marking of the high bank level and the mean bank line, as estimated for this analysis as a helping tool for approaching a conclusion. If the high bank is assumed to determine the bankfull discharge, almost all the floodplain and high 'chars' will be inundated during the bankfull discharge. On the other hand, if the mean bank is considered, only the low lying part of the floodplain is inundated during the bankfull discharge, and secondary channels can well be identified. Moreover, the mean bank level, which is just below the bank, is in line with the definition of Keith Richards (1980), mentioned in Chapter 2.

Ganges River

Unlike the Jamuna River, one mean bank level was estimated for each bank for each of the BWDB cross-sections of the Ganges River. In order to determine the bankfull discharge, the bank level profile was compared with discharge profiles of 40,000 m^3/s, 45,000 m^3/s and 50,000 m^3/s, for the years 1990 and 1991, see Figure 5.12. Two features are noted in this figure. From chainage -20 km to 40 km, the bank levels are relatively high, and the bank level downstream of chainage 40 km is inundated even at a discharge of 40,000 m^3/s, in both years. The backwater effect of the Ganges/Jamuna confluence at least partly accounts for this inundation. However, Figure 5.12 indicates that the average bankfull discharge of the Ganges is within the range from 40,000 m^3/s to 45,000 m^3/s. In between, any value could be selected, depending on individual judgement.

Padma River

For the Padma River, 70,000 m^3/s, 75,000 m^3/s and 80,000 m^3/s discharge profiles for the years 1990 and 1991 were compared with the bank level profile, see Figure 5.13. It was observed that the bank level at the mid portion of the river is relatively elevated. This feature, which may be due to the local geology or the plan-form of the river, was not investigated in the present study. However, the average bankfull discharge can be estimated at around 75,000 m^3/s, and in the range from 70,000 m^3/s to 80,000 m^3/s (Figure 5.13).

5.3.5 Results and discussion

Previous studies

Recent studies have produced different estimates of the bankfull discharge for the Jamuna River. For example, JBS determined the value for the bankfull discharge at 44,000 m^3/s, while FAP 1, referring to BWDB, mentions a value of more than 60,000 m^3/s. Hossain (1989) has examined the bank level near Bahadurabad and discharge rating curves and has determined a value of 38,000 m^3/s. The present study confirms that the bankfull discharge of the Jamuna River cannot be as high as 60,000 m^3/s. The value determined by JBS is rather close to the value found by the present study.

For the Ganges and Padma Rivers, no other recent studies exist of the bankfull discharge. The Meghna River Bank Protection Study (1990) tentatively estimated the bankfull discharge at 72,500 m^3/s for the lower part of the Padma River, which is close to the results found for the Padma in the present study.

Bankfull discharge predictors

In literature, a number of predictors have been reported for estimating the bankfull discharge. Among those, a few have been compared with the results of the present analysis, the intention being to investigate whether any common expression exists that can describe the bankfull discharge of the main rivers.

Leopold et. al. (1964) observed a remarkable similarity in the recurrence frequency of bankfull discharges of various types of rivers, as the frequency varied in the interval from 1 to 2 years. They also noticed that for stations on well-defined floodplain and with an accurately known elevation, the recurrence interval is closer to 1 than to 2 years. The recurrence interval of bankfull discharge of the Jamuna and the Padma is nearly 1 year and for the Ganges River, the recurrence interval is closer to 1 than 2 years, see Table 5.4. Hence, the findings of the present study are within the range suggested by Leopold et. al. (1964), but the range from a 1 year to a 2 years recurrence flood is large for each of the rivers, see Table 5.4.

Rivers	Return period	Non-exceedance
Jamuna	1 year	10%
Ganges	1.40 year	5%
Padma	1.05 year	8%

Table 5.4 Return period and non-exceedance frequency of bankfull discharge

Chang (1979), using data published by Schumm (1968) and Charlton (1965), developed a relation between the annual mean discharge and the bankfull discharge, see Figure 5.14. In this figure, the bankfull discharge of the Jamuna, Ganges and Padma Rivers are plotted with respect to their mean annual discharge. The values are higher than predicted by Chang (1979), see also Table 5.5. The graphical relation presented by Chang is simple to use, but gives a value that is too low for the three rivers.

Williams (1978) derived a regression equation for the bankfull discharge, using 233 sets of data from active floodplains and valley flat sites, which reads as:

$$Q_b = 4\ A^{1.21}\ i^{0.28} \qquad (1)$$

where Q_b is the bankfull discharge (m^3/s), A is the cross-sectional area (m^2), and i is the water surface slope. Values computed by this equation are compared with values of the present study in Table 5.5. It is interesting to see that the bankfull discharges of the Ganges and the Padma are nearly the same as computed from this regression equation. However, for the Jamuna River, Equation 1 gives a much higher value than the results of the present study.

Author(s)	Predictors	Predicted bankfull discharge		Obtained bankfull dis	
Chang, 1979	Graphical relation:	Jamuna:	33,000 m^3/s	Jamuna:	45,000-50,000 m^3/s
Williams, 1978a	Q_b=	Jamuna:	68,000 m^3/s		
Inglis, 1968	50% of Q_{max}	Jamuna:	48,000 m^3/s	Ganges:	40,000-45,000 m^3/s
Wolman and	1 to 2 year return	Jamuna:		Padma:	75,000 m^3/s

Table 5.5 Comparison of different bankfull discharge predictors

Inglis suggested that the bankfull discharge would simply be 50% of the maximum discharge. If the discharge of 1988 is considered as the maximum discharge, then values predicted by Inglis come close to the findings of the present study, see Table 5.5.

The recurrence period of the bankfull discharge varies from 1 to 2 years, and the non-exceedance frequency from 5% to 10%, see Table 5.4. From the above comparison and discussion, it is clear that some of the predictors provide results that are close to the determined value.

5.3.6 Conclusions

- The floodplain level near the bank of the river is quite variable, the variation being typically 1 to 2 m within a short distance. Under natural conditions, this may be explained by the presence of crevasse splay, or by formation and decaying of flood spill channels. Also, because of the agricultural use of the floodplain, many manmade elevation variations are found (drainage, footpaths, levees, housing on small hills).

- A matured natural levee can only exist outside the active corridor of the river, or where the floodplain remains free from erosion or deposition for a long period of time. Along the main rivers in Bangladesh, bank erosion occurs frequently, so that a natural levee can develop only at a few locations. For estimating the size and the shape of a natural levee, two cases were analyzed, with a width between 1 to 1.5 km, and a height of 1.5 m to 2.5 m.

- For a study of the changes of the floodplain with time, a long and reliable series of data with a good coverage of the floodplain is required. In the present analysis, no major changes nor any trends have been observed of the level of the floodplain over the last three decades. The erosion of the floodplain near an outflanking or meandering river channel is often compensated by sedimentation within a few years.

- The bankfull discharge of the Jamuna River is about 48,000 m^3/s (between 45,000 m^3/s and 50,000 m^3/s), for the Ganges River it is about 43,000 m^3/s (between 40,000 m^3/s and 45,000 m^3/s), and for the Padma River it is about 75,000 m^3/s.

- The bankfull discharge as predicted according to Inglis, and also according to Wolman and Leopold, is accurate within about ± 5000 m^3/s for the main rivers of Bangladesh. The predictors of Williams and Chang are not suited for those rivers.

- **Average discharge, bankfull discharge and discharge that carries most of the sediment transport**

It is of interest to compare the different values obtained for the bankfull discharge with the average discharge and the value of the dominant discharge, when defined as the discharge (class) that carries most of the sediment transport in the river. Data on these discharges in the different main rivers in Bangladesh are given in Annex 4, this Annex (and RSP Special Report 6), Haskoning (1992), Thorne et al (1993) and Halcrow (1993).

These data are presented in Table 5.6:

River	Average discharge (10^3 m^3/s)	Bankfull discharge (10^3 m^3/s)	"Dominant" discharge (10^3 m^3/s)
Jamuna River	20.4	45 - 50	38
Ganges River	10.6	40 - 45	38
Padma River	28.4	75?	70
Upper Meghna River	4.5	8	11
Lower Meghna River	33?	82.5	80

Sources: Haskoning (1992), Thorne et al (1993), Halcrow (1993) and this study

Table 5.6 Characteristic discharges of the main rivers in Bangladesh

From an inspection of this table it can be concluded that for most rivers it holds that the dominant discharge, as defined here as the discharge (class) that carries most of the sediment, is between the average discharge and the bankfull discharge. Only the behaviour of the Upper Meghna is different. It has been argued (Haskoning, 1992) that this is due to active tectonics combined with very low sediment transport rates in the Upper Meghna River.

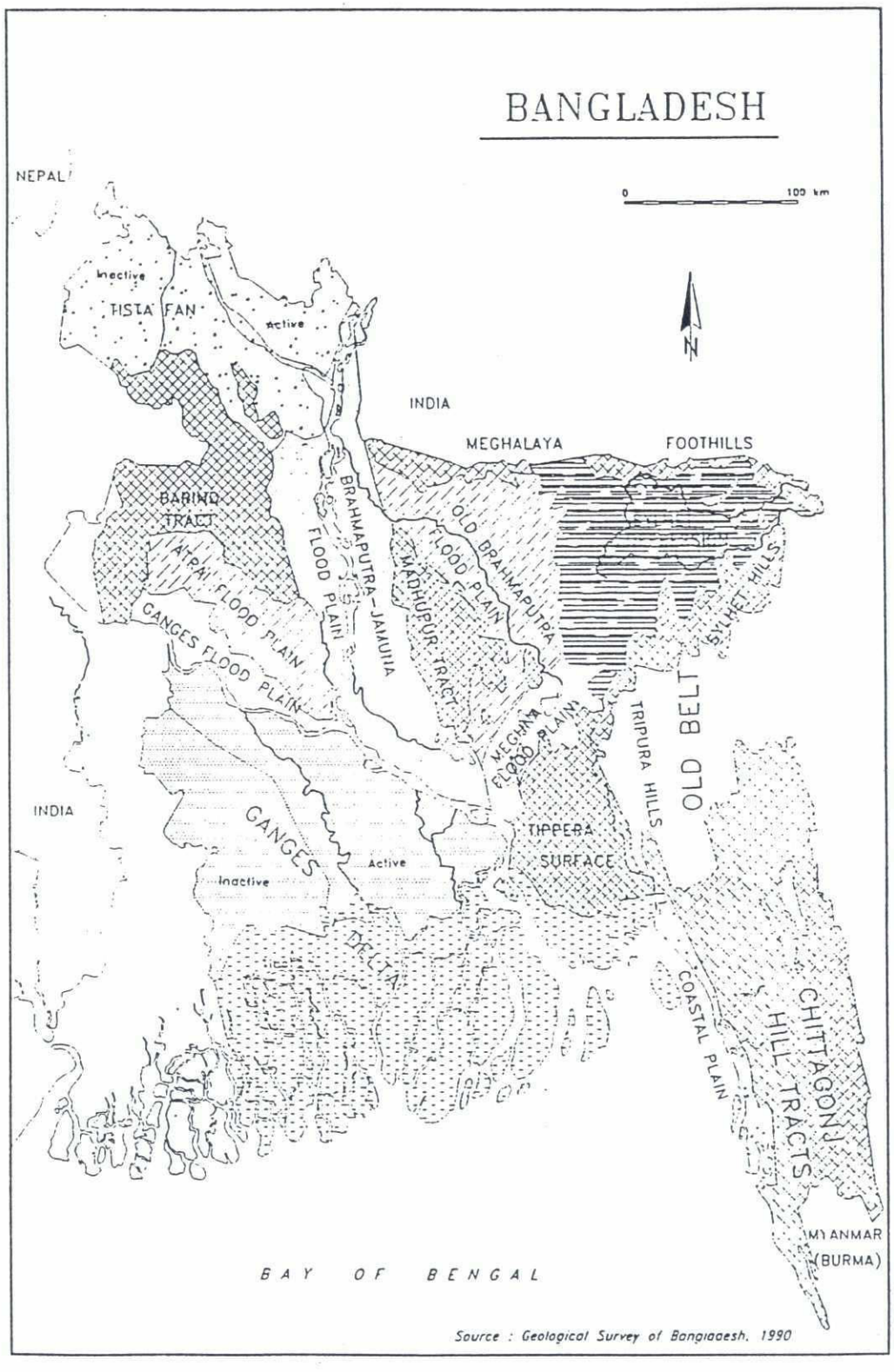
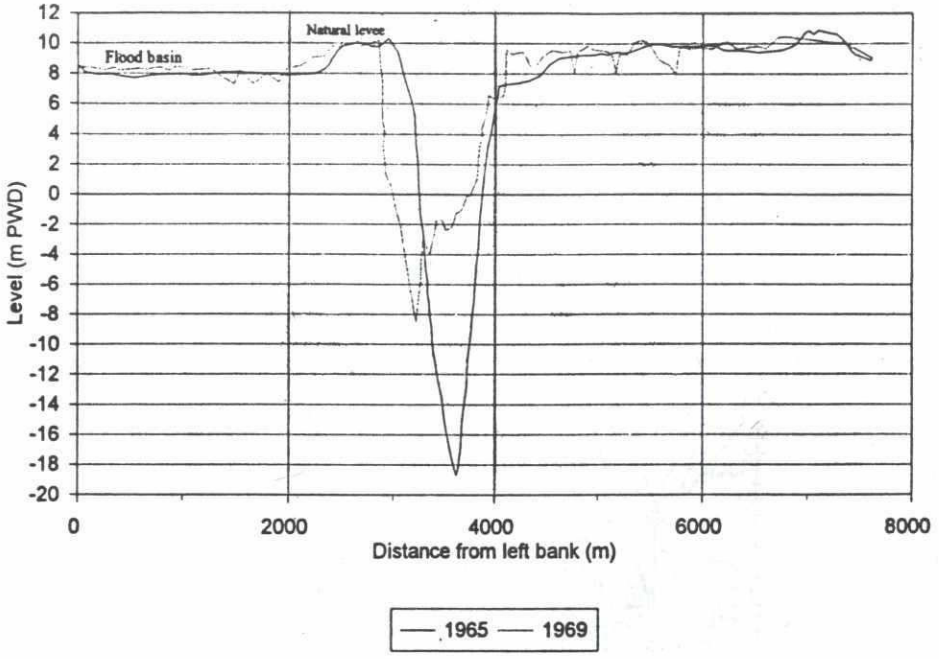
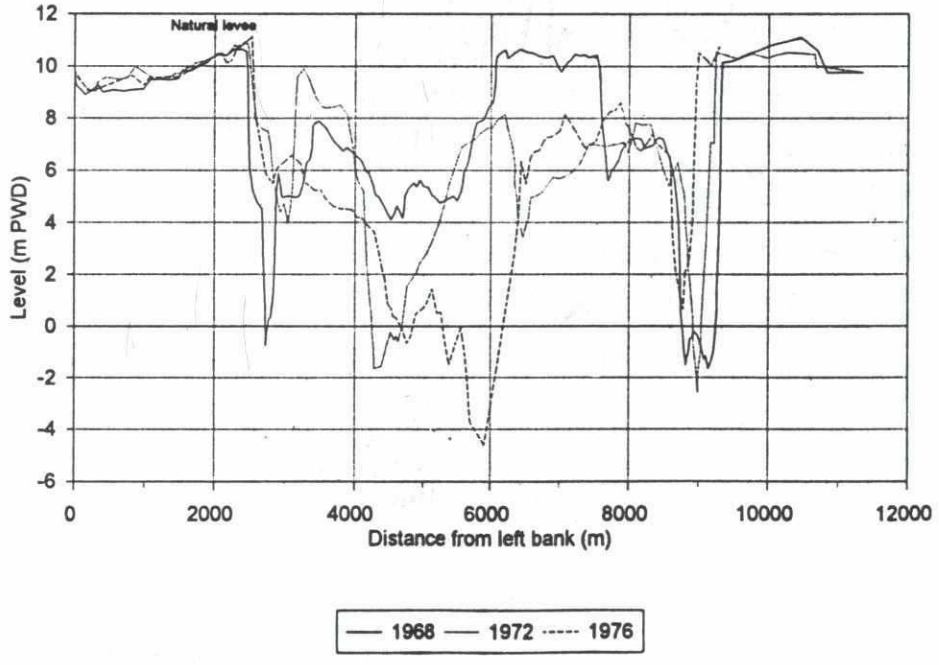


Figure 5.1 Generalised physiographic map of Bangladesh
(Geological survey of Bangladesh 1990)



a. BWDB standard cross-section: G#2



b. BWDB standard cross-section: G#3

Figure 5.2 Flood plain features and their changes with time, Ganges River

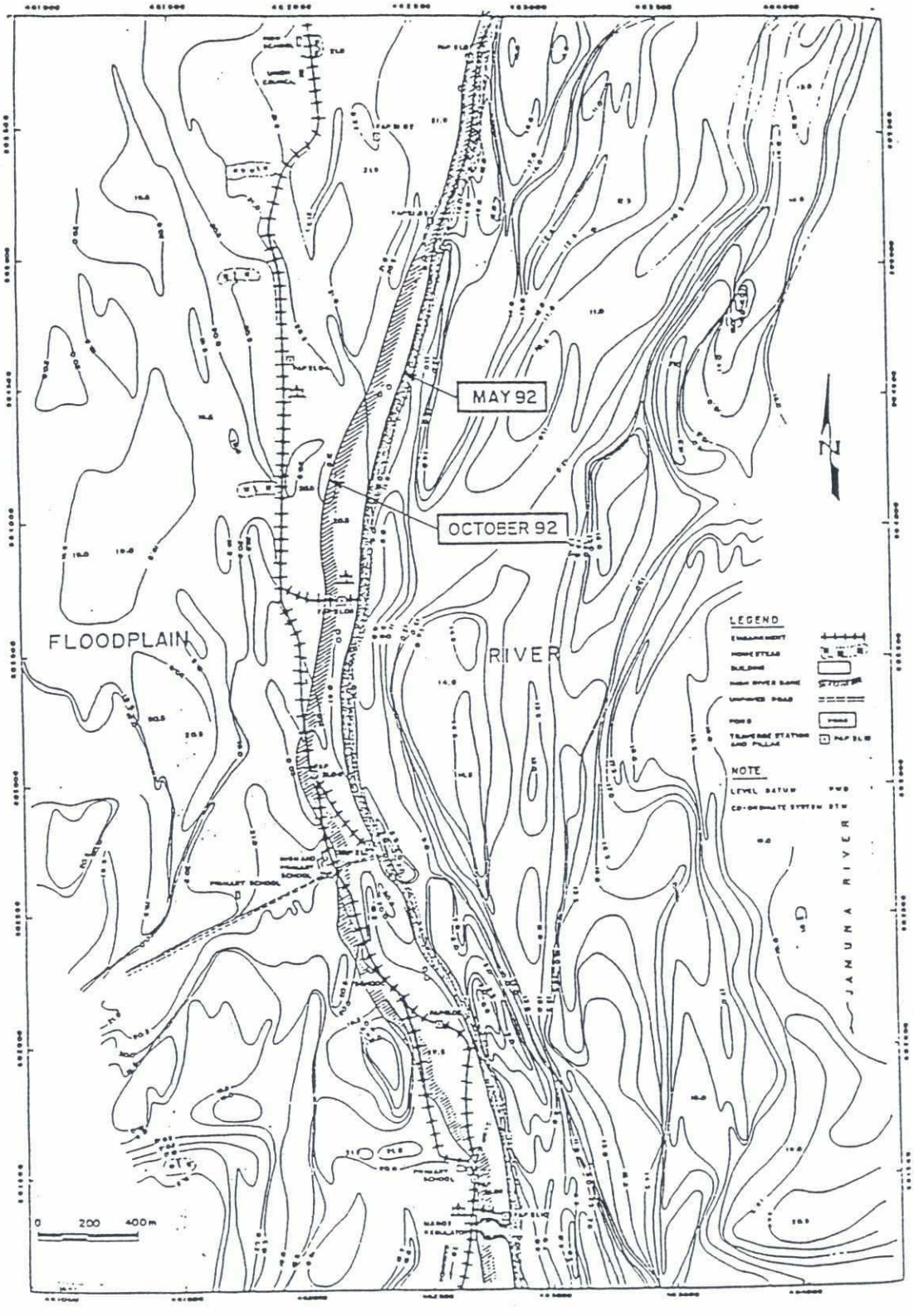


Figure 5.3 A typical topographic contour map of floodplain and river at Kamarjani, surveyed and presented by FAP 21/22

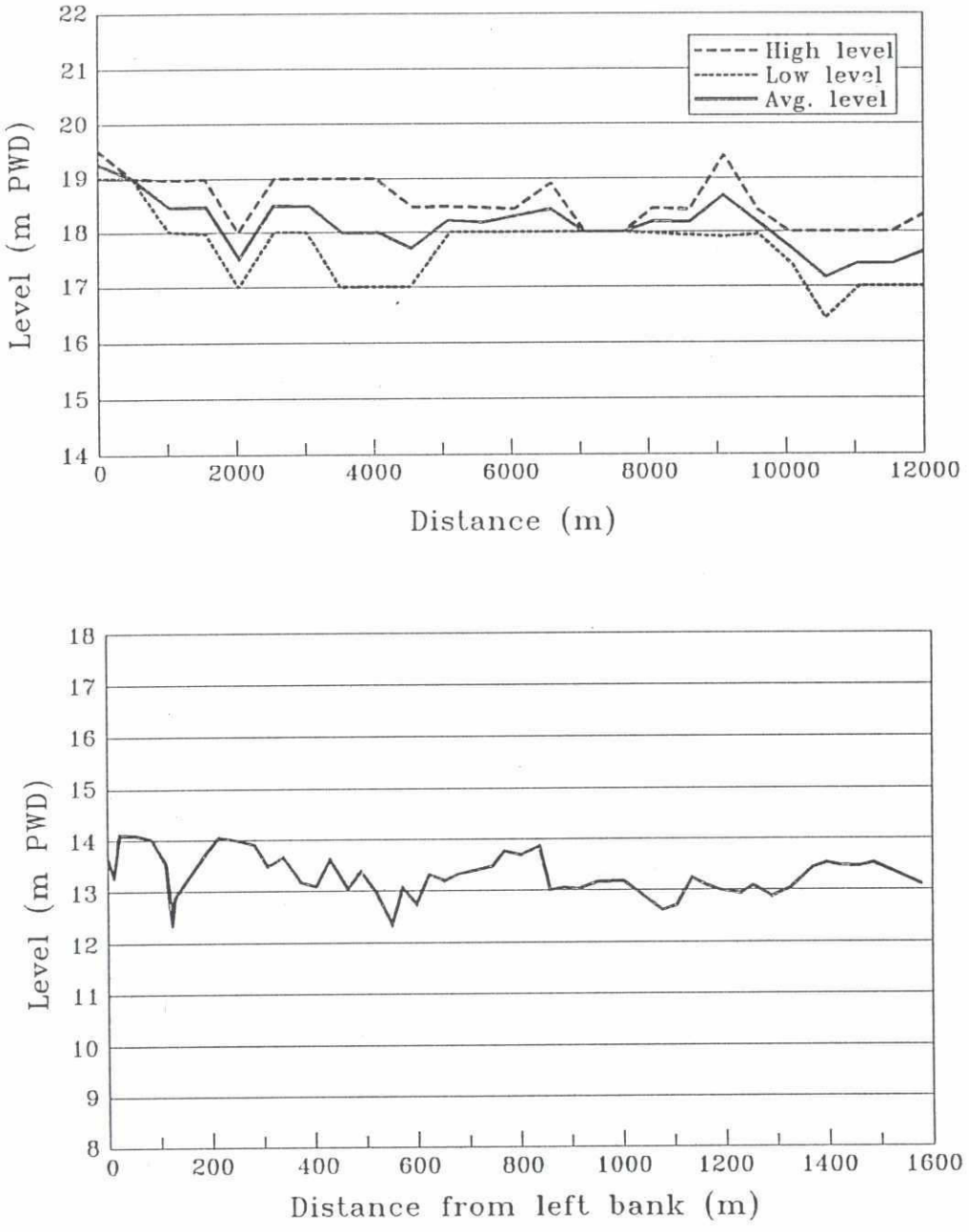
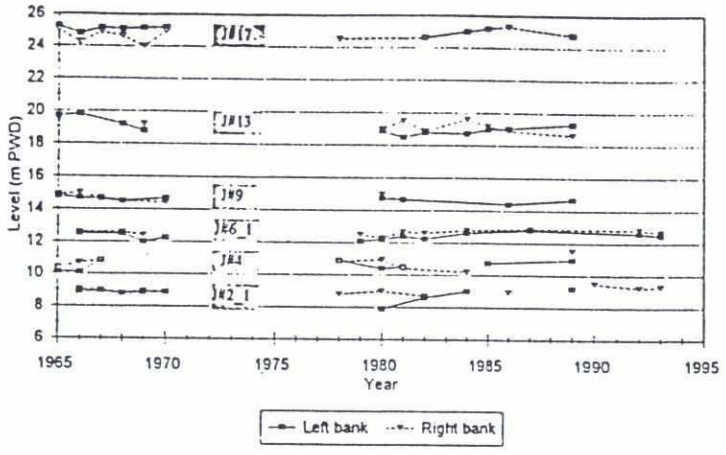
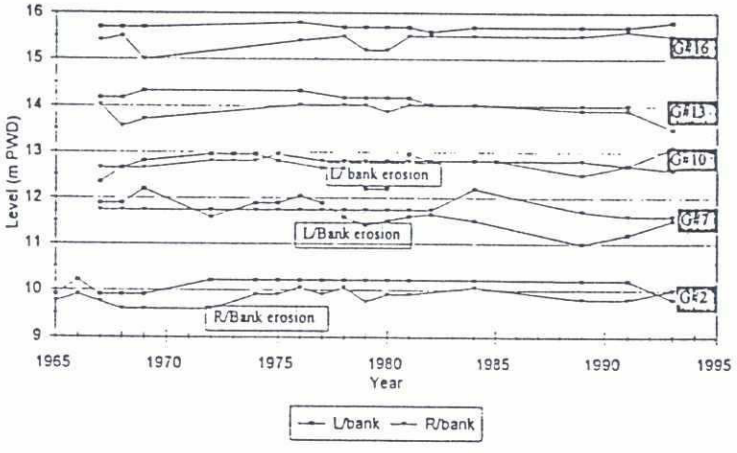


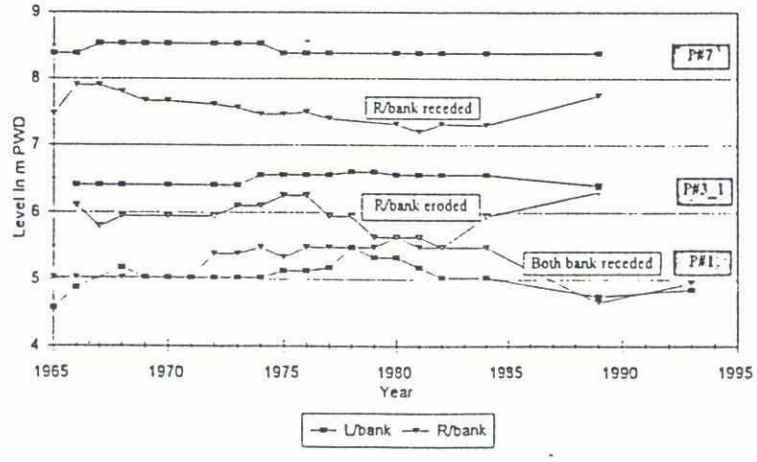
Figure 5.4 Floodplain level variability along with and in the transverse direction of the river, based on FAP 21/22 and FAP 1 surveys



a. Jamuna river

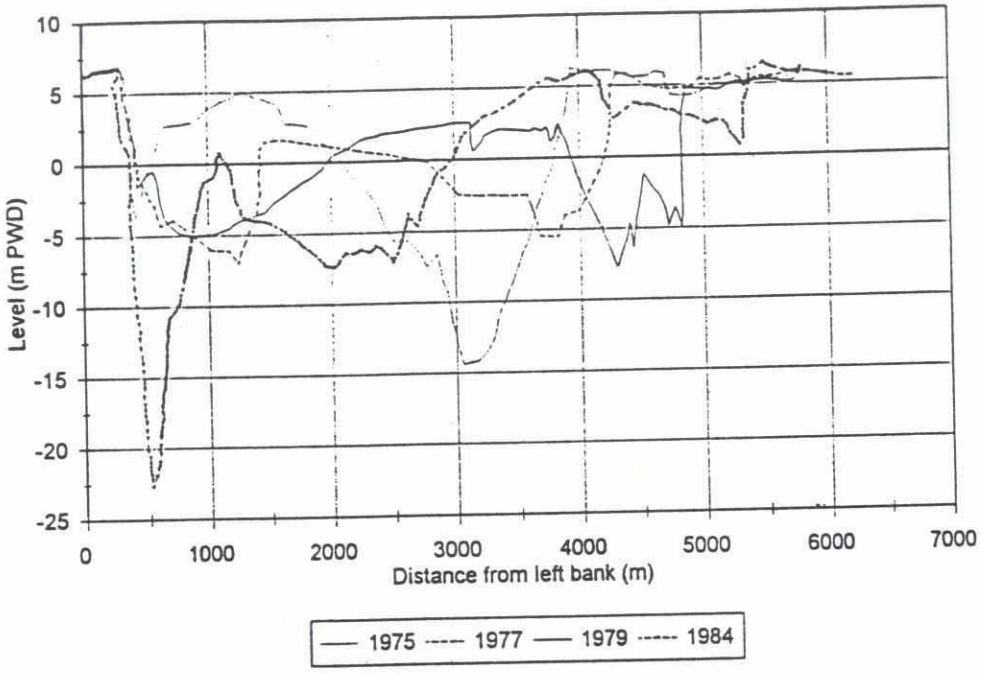


b. Ganges river

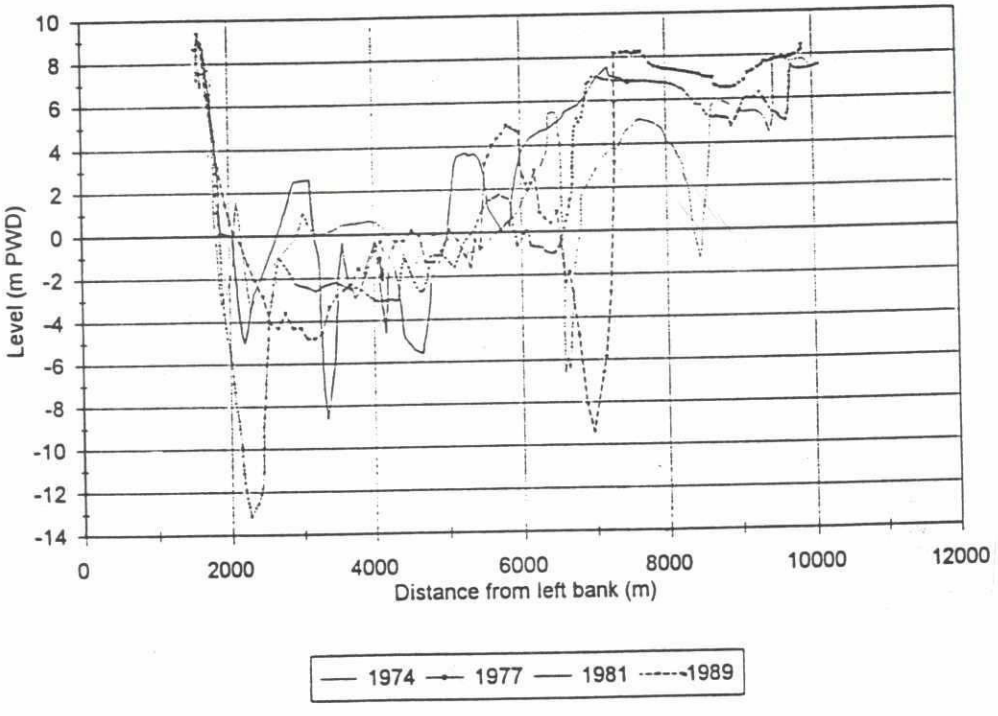


c. Padma river

Figure 5.5 Changes of floodplain level with time



a. BWDB standard cross-section: P#3_1, Padma river.



b. BWDB standard cross-section: P#7, Padma river.

Figure 5.6 Bank level change due to bank erosion and bank receding

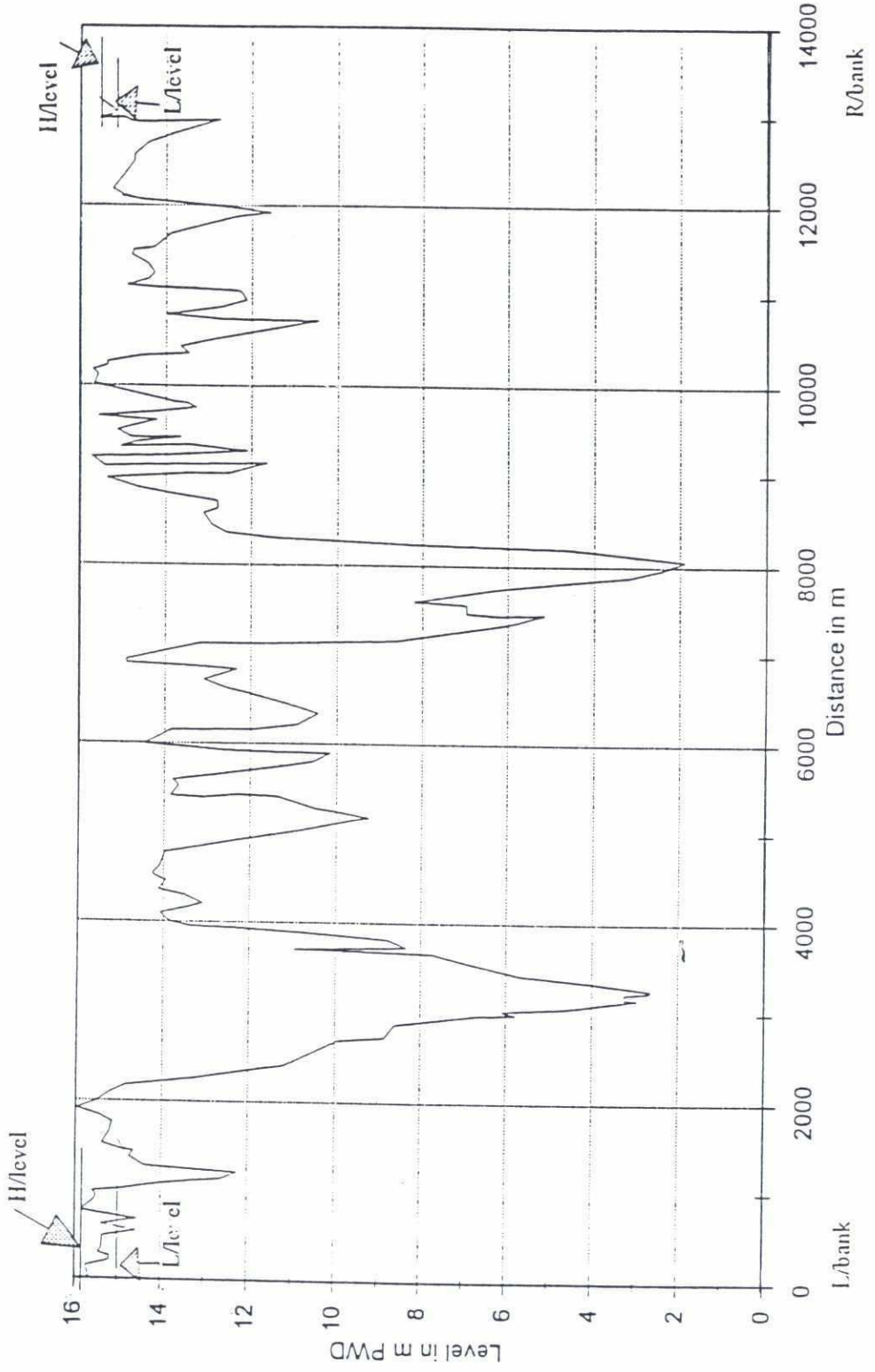
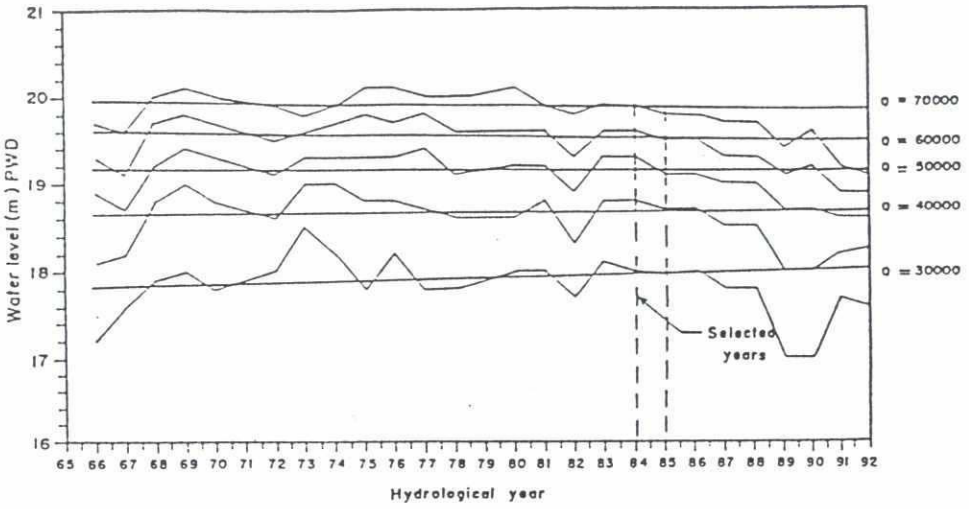
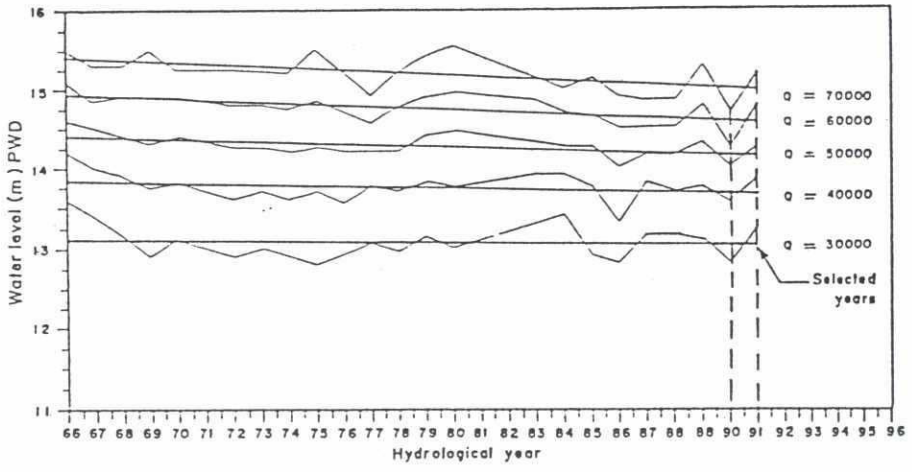


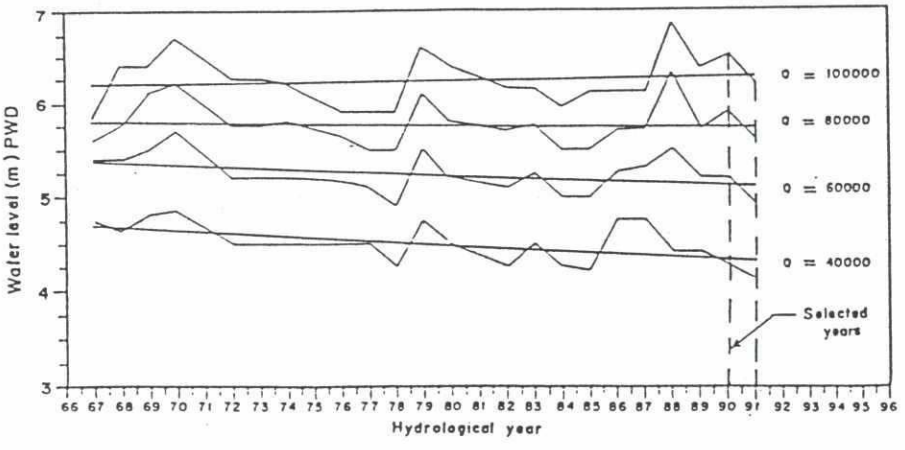
Figure 5.7 A typical cross-section survey in the Jamuna River and the definition of high and low bank-level



a. Bahadurabad



b. Hardinge Bridge



c. Mawa

Figure 5.8 Specific gauge analysis by FAP 24

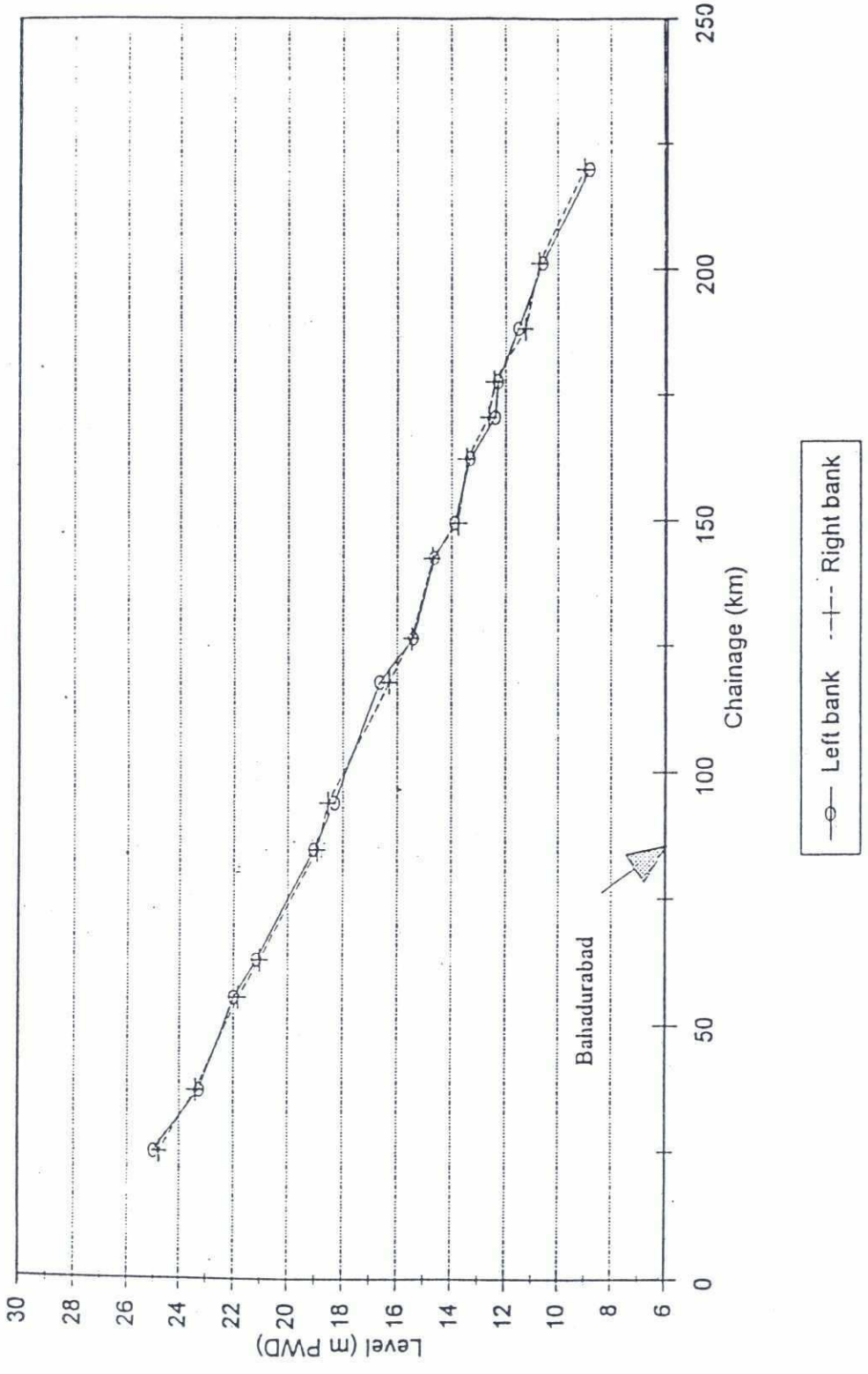


Figure 5.9 Mean bank level profiles of the Jamuna River

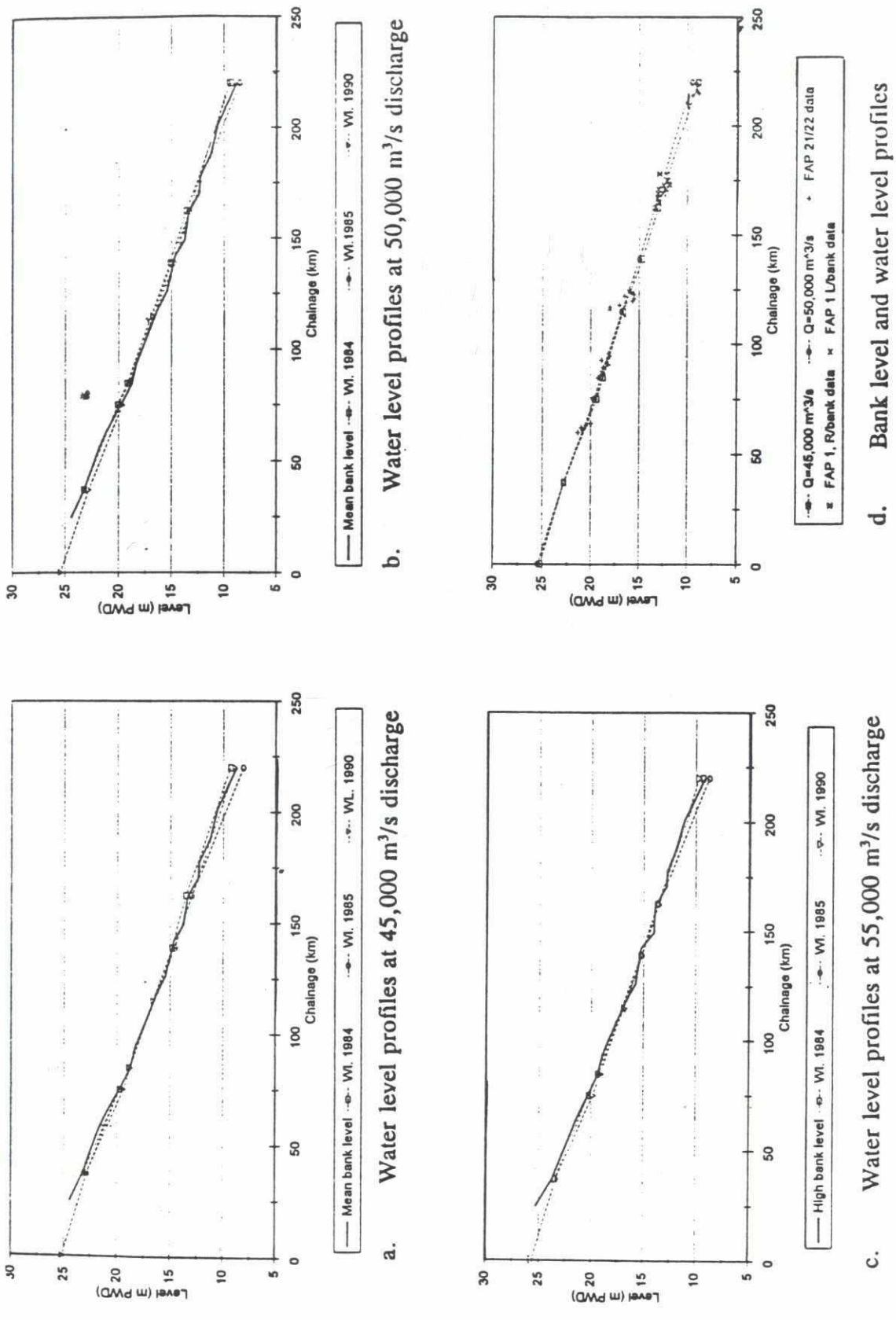


Figure 5.10 Comparison of bank level and water level profiles at different discharges, Jamuna River

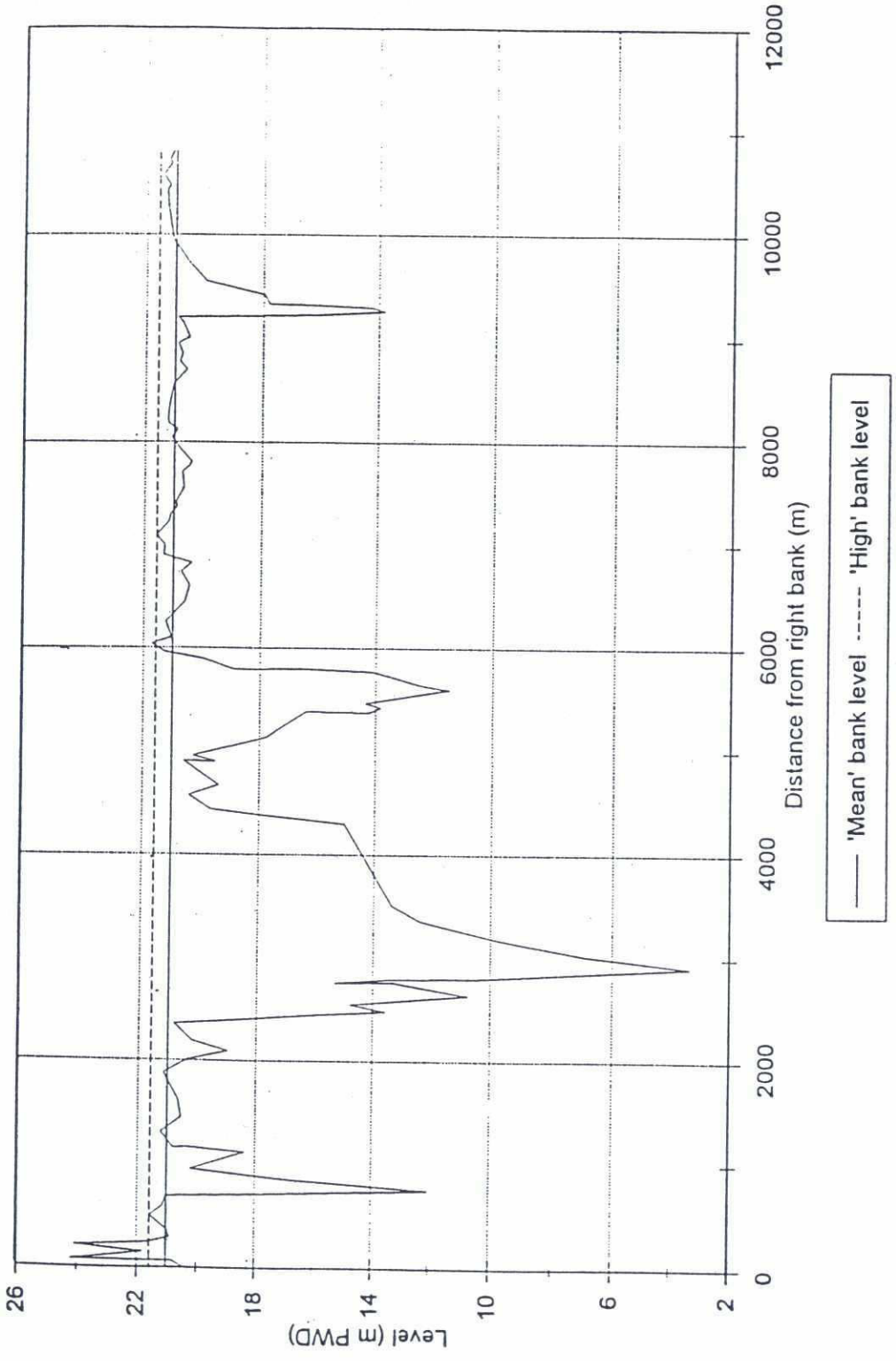
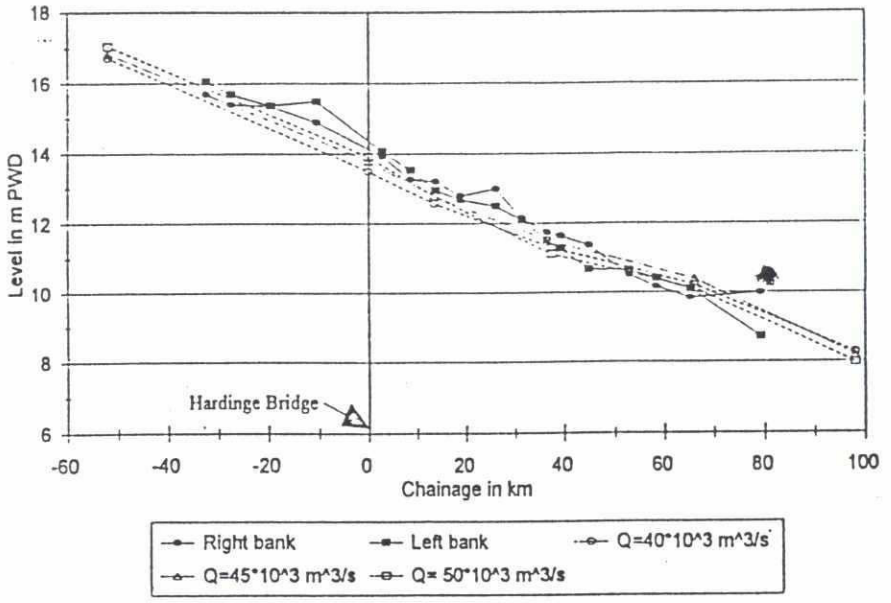
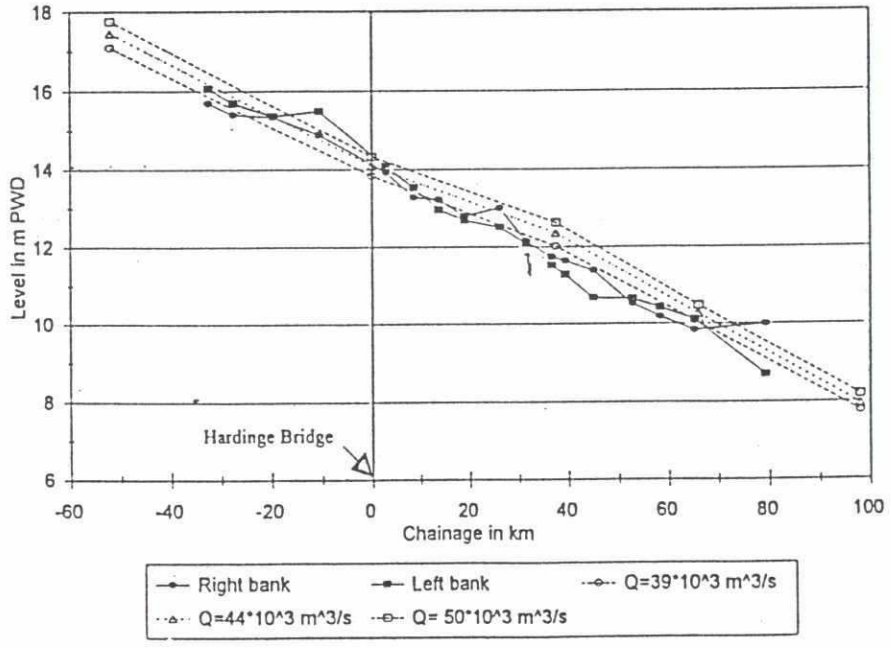


Figure 5.11 High and mean bank line on a cross-section, Jamuna River

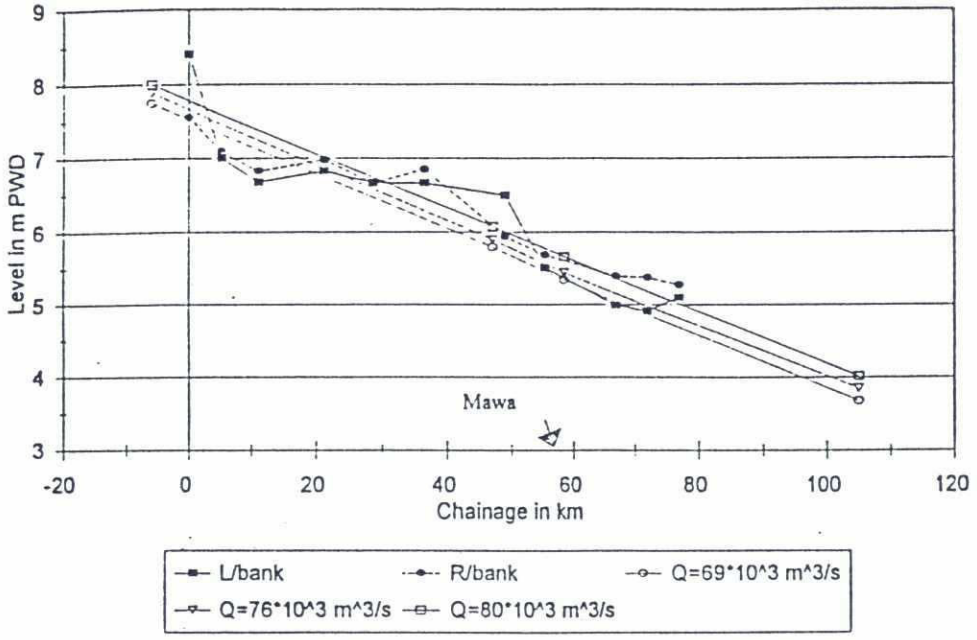


a. Water level profiles, 1990

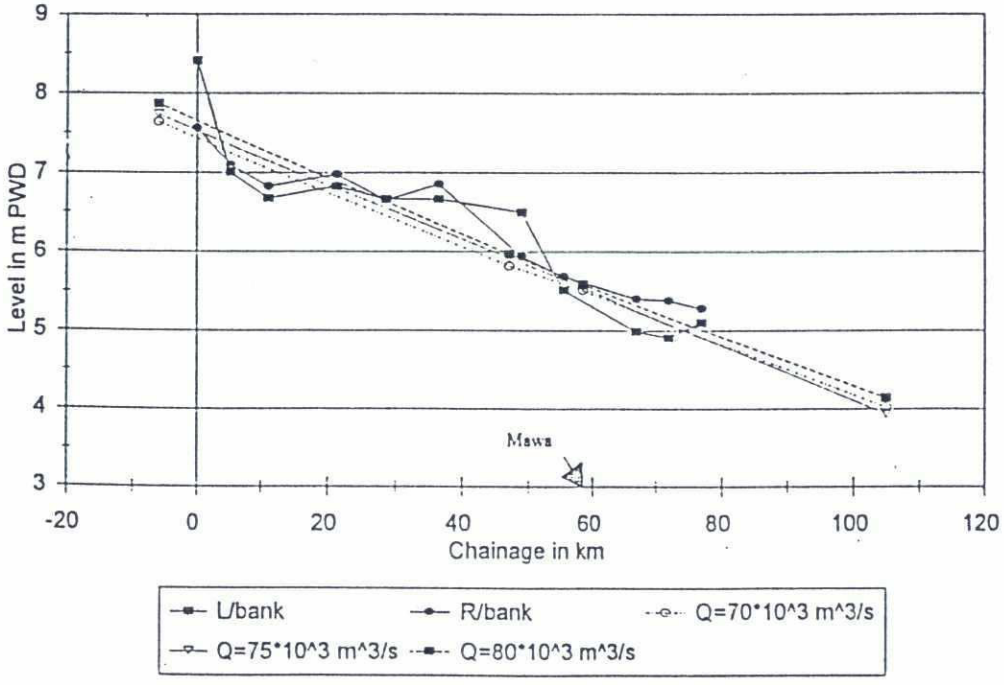


b. Water level profiles, 1991

Figure 5.12 Bank level and water level profiles at different discharges, Ganges River



a. Water level profiles, 1990



b. Water level profiles, 1991

Figure 5.13 Bank level and water level profiles at different discharges, Padma River

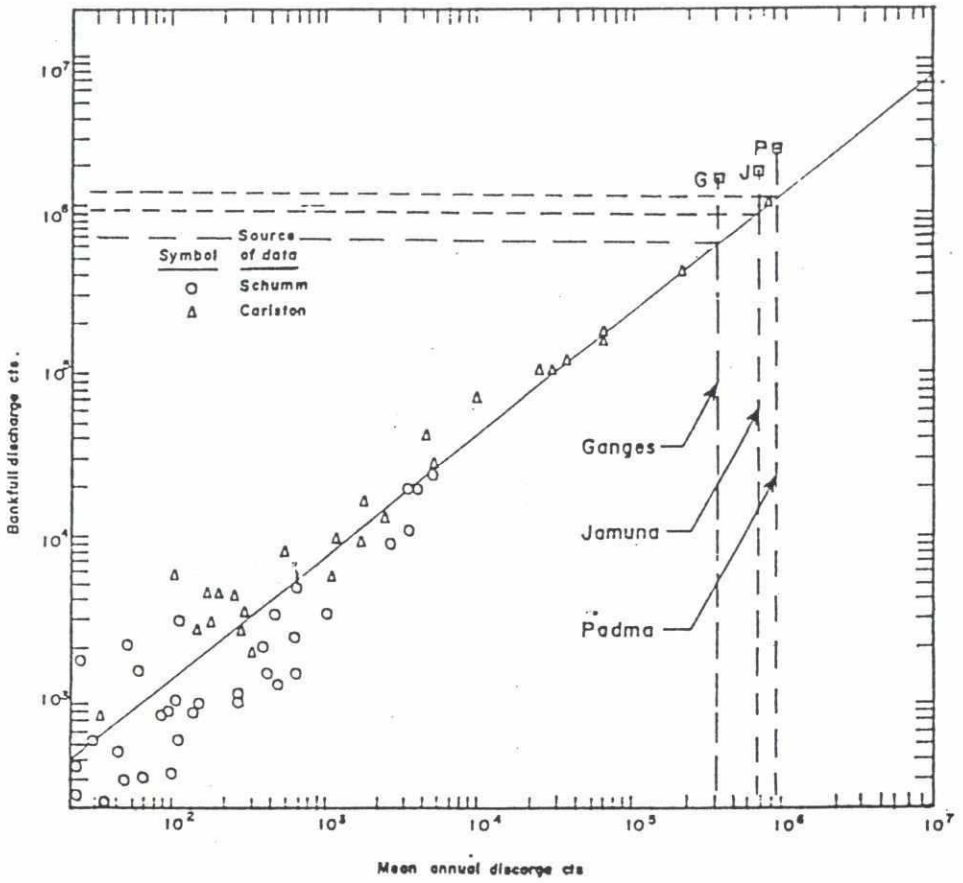
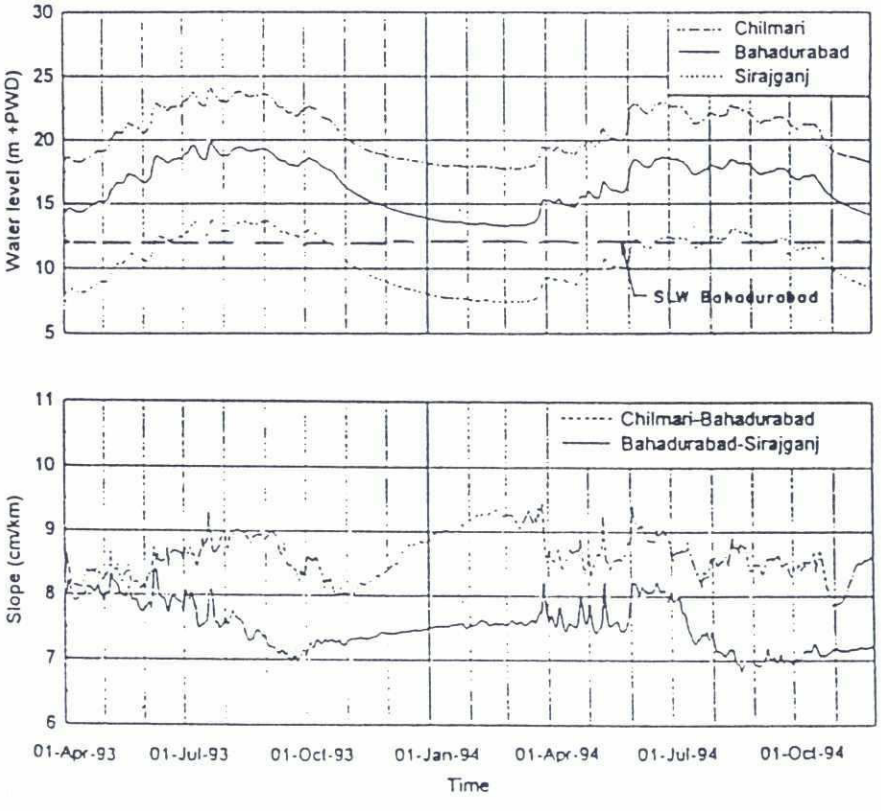


Figure 5.14 Relation between mean annual discharge and bankfull discharge, after Chang (1979)

5.4 Overall slopes

Water levels are routinely measured by BWDB on a daily basis in among others Chilmari (at the right bank about 47 km upstream of Bahadurabad), Bahadurabad and Sirajganj (also at the right bank and about 78 km downstream of Bahadurabad). For the period considered the observed stages are presented in Figure 5.15. In general, the hydrograph has a very regular receding limb towards the lean season, but the monsoon discharge shows much more variability. The water-level variation through the flood season of 1993 at Bahadurabad was about 6.5 m. In the figure also Standard Low Water Level (SLW) is indicated. SLW is the water level that is on the average exceeded during 95% of the hydrological year. The relation between PWD and SLW was determined by the Bangladesh Inland Water Transport Authority (BIWTA), and in Bahadurabad the SLW corresponds to 12.03 m +PWD. It can be concluded that the 1993-1994 lean season was not very dry.

From the observed stages the overall water-level slope between these stations can be calculated. The results for the two reaches Chilmari-Bahadurabad and Bahadurabad-Sirajganj are presented in Figure 5.15 as well. Apparently the overall water-level slope between Bahadurabad and Sirajganj varies between 0.07 to 0.08 m/km with the lower value being representative for the end of the flood whereas during the lean season the overall slope slowly increases again. There is evidence that the water-level gauge data from Chilmari are less reliable than from the other gauges, therefore the relatively high values of the overall slope between Chilmari and Bahadurabad may be less doubtful.



(figuur inplakken)

Figure 5.15 Observed water level and overall slopes: Chilmari-Bahadurabad and Bahadurabad-Sirajgang

5.5 Planform characteristics

5.5.1 General

Planform characteristics of braided streams can be divided in: (1) characteristics of the network of channels, and (2) characteristics of the individual channels

Howard et al, (1970) have introduced a number of topological and geometrical indices for networks of braided channels. Their approach and definitions were used in the analysis of the Jamuna planform characteristics. Details are provided in Section 5.5.3. Planform characteristics of individual channels relate to radii of curvature of bends in relation to channel widths, the total arc length of bends and channel directions. These parameters and their correlation are discussed in Section 5.5.4. The data used in the analysis are described in Section 5.5.2. This section is based on Klaassen & Vermeer (1988) with additions from more recent studies (Haskoning, 1992; Halcrow, 1993)

5.5.2 Available data

For the analysis discussed here the main source of information are satellite images, notably LANDSAT-scenes. These images are available from 1973 onward. For the older images the smallest details that can be identified in these images have approximate dimensions of 80 x 80 m^2. For these large rivers with channel widths in the order of kilometres, this is quite sufficient. A selection of relevant LANDSAT-images was made. Images from different years, covering the full period between 1973 and 1987, were used in the present analysis.

As the satellite images cover a rather short period only, attempts were made to use older data too. In particular, old maps were consulted. Looking at the drawn channel configurations it had to be concluded, however, that most probably the maps were not based on quantitative information but should be characterized as a rough impression of what the river looked like from the banks. These maps were subsequently discarded. No older aerial photographs were obtained either, leaving the LANDSAT-images as the only source of reliable information. Figure 5.17 provides a print of a satellite image of the lower reaches of the Jamuna River in February 1973. Also the other selected satellite images are related to low-flow conditions, allowing for a mutual comparison on realistic terms. A disadvantage of using low-flow images is that the width that can be observed on the scenes does not correspond to bankfull stages.

5.5.3 Braiding indices

Braiding indices are used to characterize channel networks of braided streams. Howard et al., (1970) have proposed a number of parameters, partly from a geometrical nature. In doing this, they made a distinction between channel segments, nodes where segments branch or join, and islands enclosed by segments. The following parameters are used:

- E average number of segments bisected by the cross-lines at the ends and interior of a river reach (-)
- E_i excess segments index, defined via $E_i = E - 1$ (for a purely meandering river $E_i = 0$) (-)
- N total number of segments entirely within the river reach and entering the reach from a lower numbered reach (-)
- C average width of the stream between the outermost segments within the section (km).

Howard et al., (1970) have proposed additional parameters (including average segment length, average wave length, etc.) and have also used derivative scale free parameters. Here these parameters are not used, because it is felt that in particular observed channel widths are subject to a considerable bias as they are related to low flow conditions.

For the analysis of the Brahmaputra (Jamuna) River the total length of the river in Bangladesh from the Indian border to the confluence with the Ganges River (see Figure 5.17) was divided in six reaches, each about 30 km long. For each of these river reaches braiding indices were determined on the basis of LANDSAT-images. The derived indices for the parameters defined before are listed in Table 5.6 for four years (1973, 1978, 1981 and 1987). No data are available for the upper reaches in the years 1973 and 1978, as no satellite image was available.

The following observations can be made regarding the data provided in Table 5.7:

- The degree of braiding decreases in downstream direction. This may be in line with the observed decrease in valley slope (conform Leopold et al, 1967 and Struiksma and Klaassen, 1988).
- After 1981 the degree of braiding has increased, while the total width of the braiding pattern has not changed substantially. In particular reach 4, just upstream of Sirajganj (see Figure 17), has experienced substantial changes. The 1986 data (not included in Table 5.6) support the change in braiding characteristics. At present there is no explanation for the change. Attempts should be made to correlate the braiding pattern to the flood discharges in previous periods. A first try by Steel (1995) appears to be promising.

5.5.4 Bend characteristics

The LANDSAT-images were also used to study the characteristics of bends in individual channels, being part of the braided network. Some results are provided in the Figures 5.18 and 5.19. Figure 5.18 is related to the relation between radii of curvature, channel widths (B) and arc lengths (ψ). A plot of radii of curvature versus channel widths for the year 1977 (see Figure 5.18(a)) shows considerable scatter. In the figure also a relation derived from Leopold et al, (1964) for meandering channels was plotted. This relation reads:

$$R = 2.35\ B^{0.99} \qquad (5.1)$$

Leopold et al, (1967) have not suggested this particular relation but it can be derived from their empirical relations between meander length, channel width and radius of curvature. The large deviation between Equation (5.1) and the data. As is shown in Section 5.6, the width of the channels varies with the discharge to the power of about 0.5. Average low-flow discharges in the Jamuna River are a factor 10 lower than bankfull discharges (RPT/NEDECO/BCL, 1987), data. In Figure 5.18(a) a corrected relation is plotted taking into account this factor 3. It may be concluded that for the present braided river the radii of curvature are on the average smaller than for meandering channels. This analysis does not take into account the possibility that the radii of curvature may change during the transition from flood to low flow stages.

A much better relationship is obtained when the arc length of the bends is plotted against the radii of curvature. For the low-flow period of 1983/84 this relationship is plotted in Figure 5.18(b). From this figure it may be concluded that rather extended bends are only possible for small radii of curvature, and thus for smaller channels only. Thus the major channels are less curved than the smaller ones.

Channel directions for the year 1983/84 are presented in Figure 5.19. Here the observed channel directions (according to the definition shown in the figure) are plotted against the radii of curvature, as it was anticipated that the channel directions (expressed as the deviation from the overall valley slope) would decrease when the conveyance of the channels would increase. Taking into account the relationship between R and B (and thus the conveyance, see also Section 5.6.5), this is substantiated by Figure 5.19.

5.6 Channel dimensions

5.6.1 General

Apart from planform data, also cross-sectional characteristics should be studied. For the Jamuna River this was done on the basis of soundings which have been carried out by the Bangladesh Water Development Board (BWDB) since 1966/67.
The analysis carried out was aiming mainly at the identification of any consistent changes in channel location, but as side product also the variation in wet area and in conveyance in longitudinal direction and over the years was obtained. Furthermore, regime equations were derived for the channels in the Jamuna River and a comparison was made with a regime equation derived for (smaller) stable channels with low sediment transport rates.

The structure of this Section is as follows. The available basic data (i.e. BWDB soundings) are described in Section 5.6.2. Data on channel conveyance and wet area and their variation in place and time are provided and discussed in Section 5.6.3. Section 5.6.4 is considering the dimensions of individual channels (notably widths and average depths), and an attempt is made to correlate them to the bankfull discharge of the channels.

The present analysis expands on work by Ullah (1987), who compared soundings of 1965\66 with more recent ones from 1983\84. By including soundings from other years, here a better insight is obtained into the fluctuations over the years in relation to any trends in bed levels and channel locations. Within the present study channel dimensions were studied as well. Results, which deviate significantly from the results presented here, can be found in RSP Special Report 7.

5.6.2 Available data

Cross-sectional soundings of the Jamuna River have been made since 1965/66. Initially these measurements were done every year, but they were interrupted in 1970 due to the Independence War. In 1975/76 the soundings were taken up again, although not every year the Jamuna River was included in the country-wide morphological measurements. In the period between 1965/66 and 1986/87 for most of the cross-sections in total some ten soundings are available for analysis.

The soundings were carried out during the low flow season. Both the submerged areas and the dry islands (locally called "chars") in between the braids were sounded. The bed levels are related to the local Public Works Datum (PWD). The horizontal distance was measured from monuments. Sometimes the monuments got lost either by bank erosion of by other causes. Consequently, for a number of cross-sections it is not possible to make a quantitative comparison of channel location in the horizontal direction.

Initially, the distance between the cross-sections was 4 miles, but gradually more cross-sections have been introduced over the years. Figure 5.20 provides an overview of the sounded cross-sections.

In the present study twelve cross-sections were selected for detailed analysis considering:

1 conveyance
2 width (of channels and chars)
3 depth (average and maximum)
4 average cross-section level.

Cross-sections J5, J5-1, J6, J6-1, J8 were selected in view of their location close to the proposed bridge site (J6-1), the others to investigate possible changes in channel characteristics upstream and downstream of the bridge site.
Figure 5.21 provides the results of soundings of two cross-sections (notably J13-1 and J6-1) for a number of years. Other cross-sections may have a total width of more than 15 km.

In a braided river the channel directions may deviated considerably from the direction of the valley slope (see Section 5.5.4), while furthermore this direction will change over the years. Consequently, the channel width of individual channels may be too large when derived from the sounded cross-sections.

5.6.3 Processing of cross-sectional data

The cross-sectional data contain important information on channel characteristics and horizontal and vertical stability. To isolate this information, the cross-sectional data have to be processed further. A computer program was developed for this purpose. This program uses the sounded data as input, and subsequently the following processing is being done per cross-section:

- for three discharge levels (44,000 m^3/s approximately corresponding to bankfull stage, 12,000 m^3/s and 4,000 m^3/s representing average low-flow conditions in the Jamuna River) stages are plotted in the sounded cross-sections, and channels and sand bars (chars) are differentiated;
- the total wet area for each of the three discharge levels is computed;
- going from the left (Eastern) bank to the right (Western) bank monument the cumulative conveyance is computed as a function of the distance to the left bank monument; in a second step this relationship is made dimensionless by dividing it by the total conveyance for that particular cross-section and stage (for an example of the obtained results see Figure 5.23);
- the width and the average levels of the individual channels in each cross-section is determined, together with the average char level, the average channel level averaged over all channels and finally the average bed level of the whole sounded cross-section, including both the parts above the water and the submerged parts.

It is of interest to study the results of the computation of the wet area and the conveyance of the river for bankfull conditions. In Figure 5.22 the computed values of these two parameters are plotted for some cross-section. From this figure it may be concluded that both the wet area and the conveyance do vary considerably over the years, There is no trend in the computed values, so apparently the variation is inherent to the river's behaviour. Including the direction of the different channels and thus reducing the computed values does not result in a reduction of the scatter. It should be stressed here that the underlying assumption for the figures in Figure 5.22 is that the low-flow cross-sections are representative for bankfull stages also. The scarce information available on changes of the cross-section through the year seems to support this assumption.

5.6.4 Regime equations for Jamuna channels

Regime equations were originally developed for stable canals on the Indian subcontinent. Lacey (1930, 1947) derived the following equations for the wetted perimeter p and the hydraulic radius R of a stable channel:

$$p = 2.67\ Q^{1/2} \tag{5.2}$$

$$R = 0.47\ (Q/f)^{1/3} \tag{5.3}$$

where Q = bankfull discharge and f = silt factor, defined via:

$$f = 1.59\ D_{50}^{1/2} \tag{5.4}$$

where D_{50} = diameter of the bed sediment in mm. All the other parameters are expressed in imperial units. Simons and Albertson (1963) extended the regime equations to include the effect of the soil properties of the banks. For canals with sand banks and beds they found:

$$p = 3.3\ Q^{0.512} \tag{5.5}$$

pointing at slightly larger widths for channels with sandy banks. Some others, e.g. Stevens (1986), have shown that the above equations hold for small sediment charges only. For larger charges the width may be larger.

It is of interest to attempt to compare the characteristics of the individual channels of the braiding Jamuna River to these regime equations. This was done for bankfull discharge (44,000 m^3/s). When it is assumed that the roughness and the energy slope of each channel in a cross-section is about the same, the total discharge in a cross-section can be distributed over the channels according to their conveyance. Next, the width B and the average depth $\bar{h}$ of the individual channels can be plotted against their discharge. The result is presented in Figure 5.27. The plotted data can be described by the following relations:

$$\bar{h} = 0.23\ Q^{0.32} \tag{5.6}$$

$$B = 16.1\ Q^{0.53} \tag{5.7}$$

Both relations are in S.I. - units. The Lacey equations, expressed in these units and assuming $p = B$ and $R = \bar{h}$ for these very wide channels, read:

$$\bar{h} = 0.47\ (Q/f)^{1/3} \tag{5.8}$$

$$B = 4.81\ Q^{1/2} \tag{5.9}$$

As $D_{50} \cong 0.2$ mm, $f = 1.13$, so Equation (5.9) can be written as:

$$\bar{h} = 0.45\ Q^{1/3} \tag{5.10}$$

Comparison of the Equations (5.8) and (5.10) to the Jamuna Equations (5.6) and (5.7) yields the following conclusions:

- the exponent of the discharge is approximately the same in both comparable equations;
- the Jamuna channels are substantially wider and more shallow than the stable channels of Lacey; also the relatively small increase of the width indicated by Simons and Albertson (1963) is irrelevant for the Jamuna channels.

Apparently large sediment loads (in the Jamuna River up to 10,000 ppm for the total load, wash load included) result in very wide, shallow channels. The aspect ratio of the Jamuna River is about 750, which is extremely high.

Furthermore the following remarks are made:

1 The substantial scatter in Figure 5.24 is at least partly due to the channel direction not being perpendicular to the cross-section. However, also other factors will play a role.
2 Lacey proposed a third equation for the slope of a stable channel. Introducing the relevant figures in this equation results in a slope which is 20% smaller than the actual slope of the Jamuna River.

Under the Haskoning (1992) study of the Padma and the Upper and Lower Meghna Rivers the channel dimensions of the Padma/Lower Meghna system were compared with the regime equations derived for the Jamuna River by Klaassen & Vermeer (1988) and given by the Equations (5.6) and (5.7). It was observed that the channels of the Padma/Lower Meghna system are on the average narrower and deeper than Jamuna channels. Possible explanations could be (1) the presence of clay deposits along some reaches of the river, (2) the very pronounced bend in the Lower Meghna upstream of Chandpur, and (3) the impact of the bank protection works at Chandpur. Clearly more study of the width and depth of Bangladesh's main rivers is needed before a full explanation for the very wide channels and the mutual differences can be given.

Average depths and widths of the Jamuna River were also derived for lower stages. For this, and also for the previous analysis, it is assumed that the cross-sections sounded during low flow conditions do not substantially differ from cross-sections for higher stages (see Figure 5.25). Under this assumption the average depth and width are described by:

$$\bar{h} = 0.56\ Q^{0.23} \tag{5.11}$$

$$B = 18.9\ Q^{0.51} \tag{5.12}$$

It is remarkable how similar these at-a-station relations equations are to the equations which relate to bankfull discharge only (Equation (5.6) and (5.7)). Apparently the Jamuna channels can to some extent be considered as regime channels for lower stages also, possible indicating that morphological processes in the Jamuna River are relatively fast.

Date		21 February 1973				22 February 1978				27 December 1981				27 February 1987			
Parameter		E (-)	E_1 (-)	N (-)	C (km)	E (-)	E_1 (-)	N (-)	C (km)	E (-)	E_1 (-)	N (-)	C (km)	E (-)	E_1 (-)	N (-)	C (-)
Reach	1	-	-	-	-	-	-	-	-	3.2	2.2	16	7.5	3.7	2.7	21	8.0
	2	3.2	2.2	19	8.5	3.0	2.0	20	8.0	3.3	2.3	19	12.0	3.8	2.8	21	8.0
	3	3.3	2.3	31	8.5	3.3	2.3	19	8.0	3.5	2.5	26	10.0	3.8	2.8	27	10.0
	4	2.8	1.8	12	10.5	2.8	1.8	16	8.0	2.9	1.9	12	10.0	4.3	3.3	25	10.0
	5	1.9	0.9	18	4.5	1.6	0.6	9	5.0	1.7	0.7	8	6.5	2.7	1.7	22	6.0
	6	1.9	0.9	8	6.0	2.2	1.2	14	6.5	1.8	0.8	4	6.0	2.6	1.6	9	8.0

Table 5.7 Braiding indices of the Jamuna River, Bangladesh over the period 1973-1987

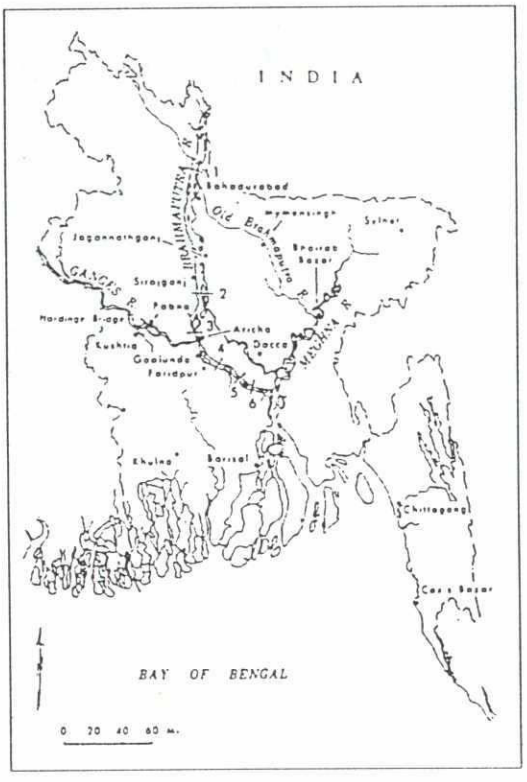
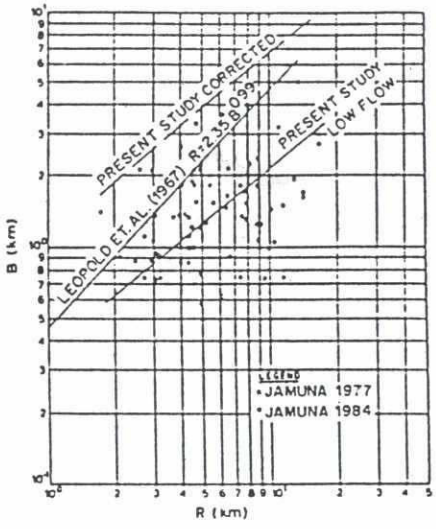


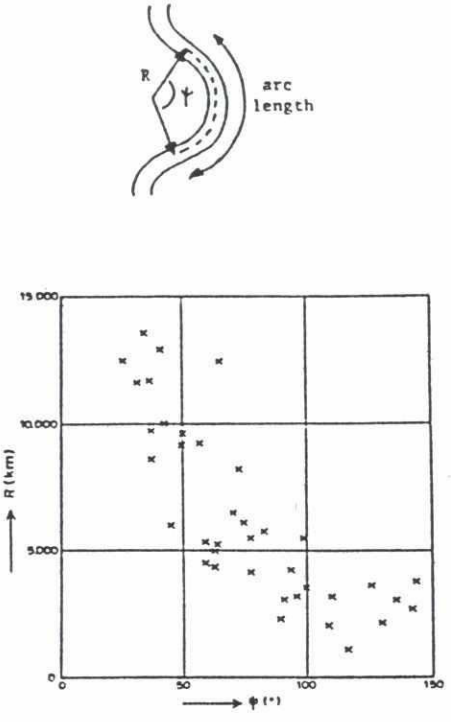
Figure 5.16 Index map of Bangladesh with major rivers (Coleman, 1969)



Figure 5.17 LANDSAT-image lower reach of the Jamuna River, date 27-2-1973 (scale 1:1,000,000)

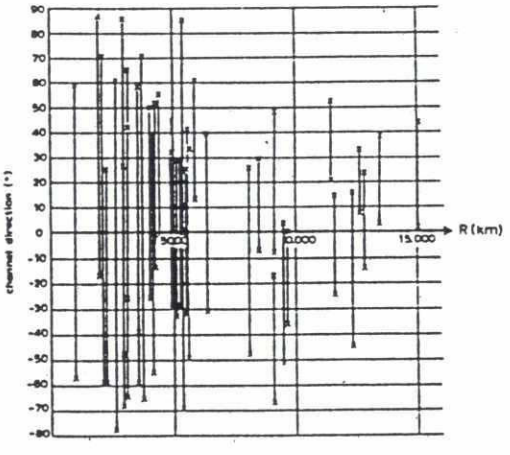


(a) Width versus radius of curvature for low flow data 1977



(b) Arc length versus radius of curvature for low flow data 1983/84

Figure 5.18 Bend characteristics of the Jamuna River



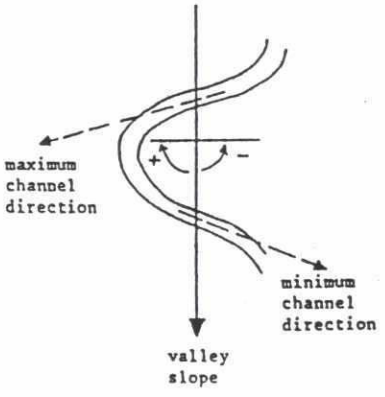


Figure 5.19 Channel direction versus width for the Jamuna River for the low flow season 1983/84

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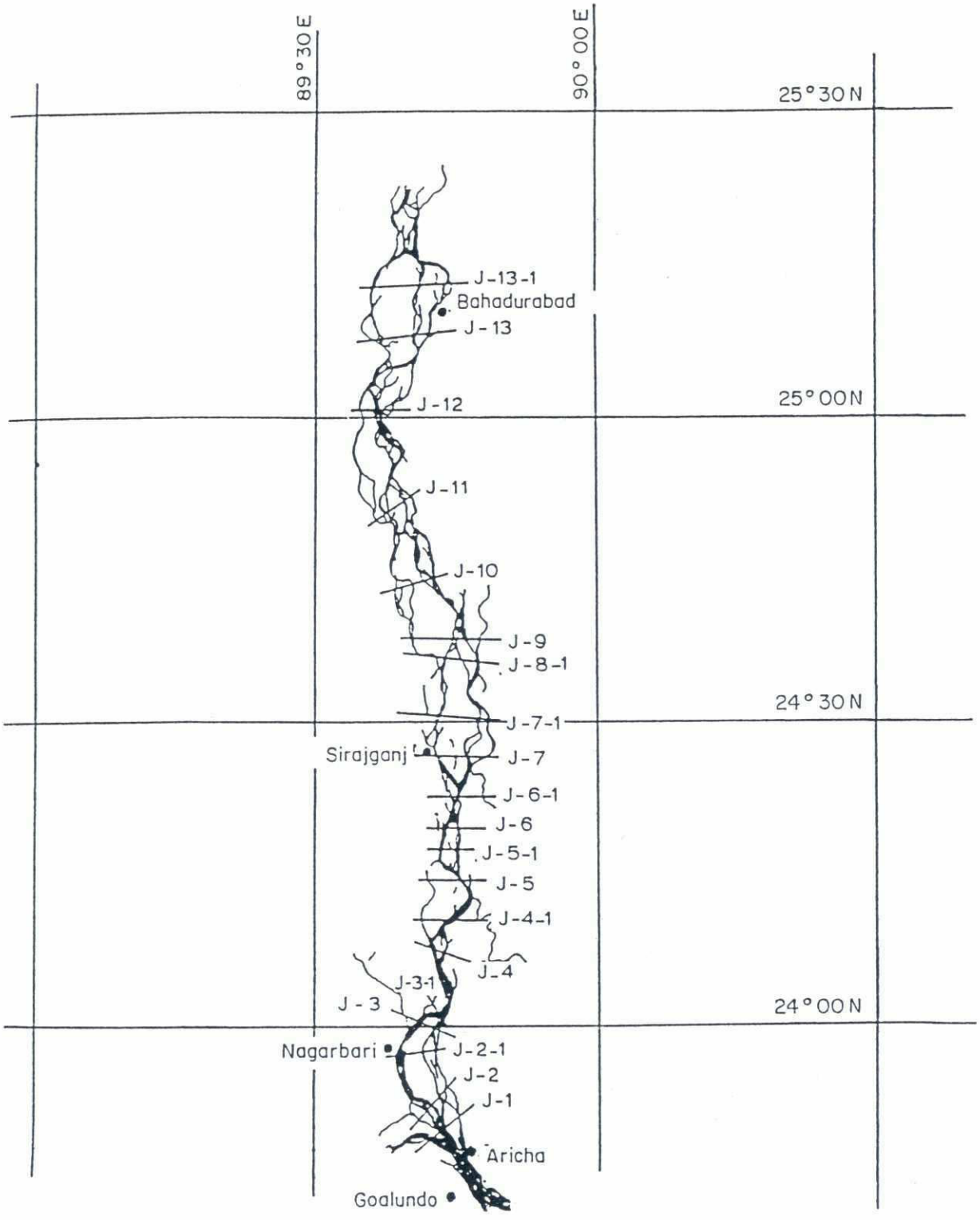


Figure 5.20 Cross sections measured by BWDB in the period 1966-1987

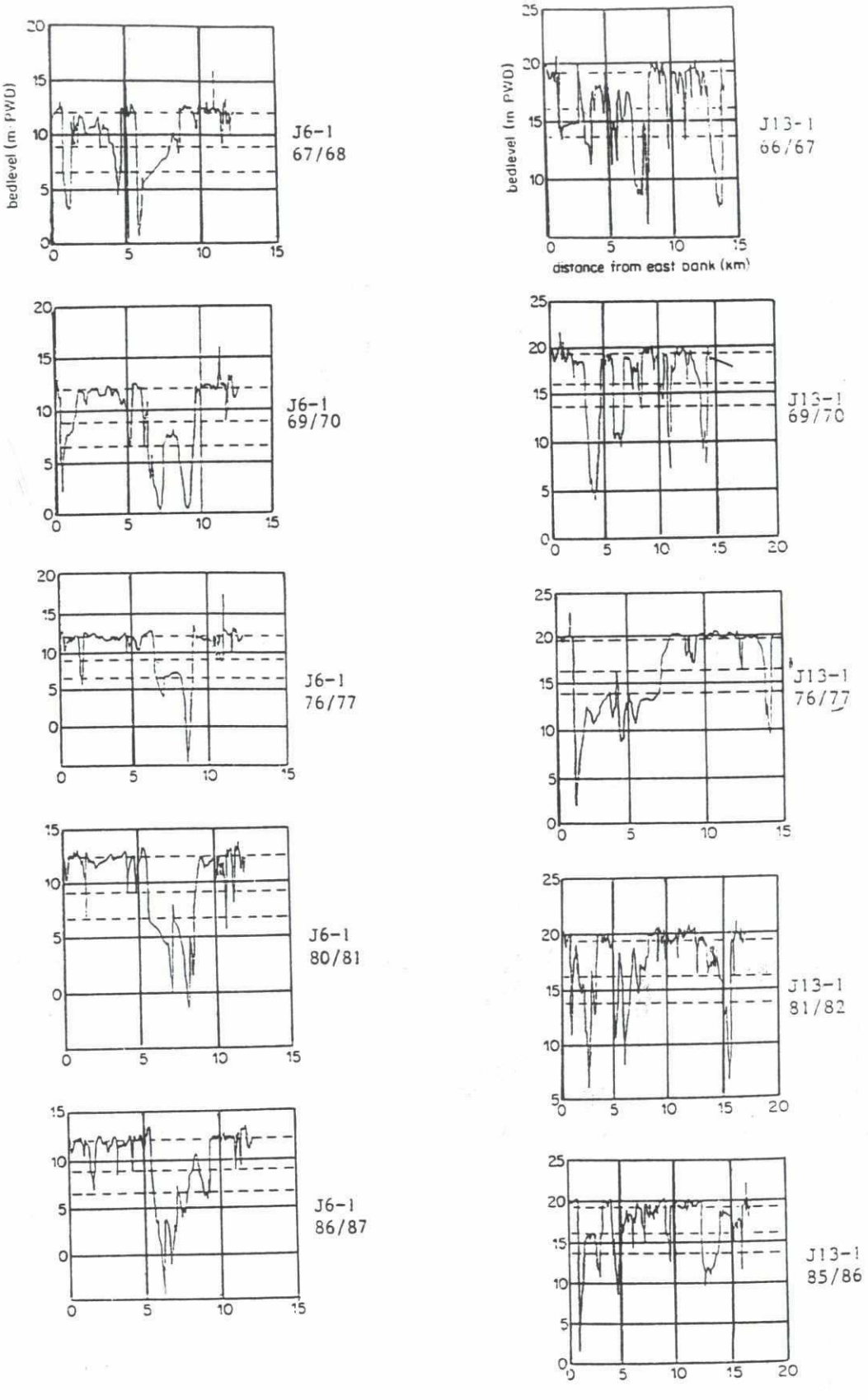


Figure 5.21 Two cross-sections of the Jamuna River and their variation in time

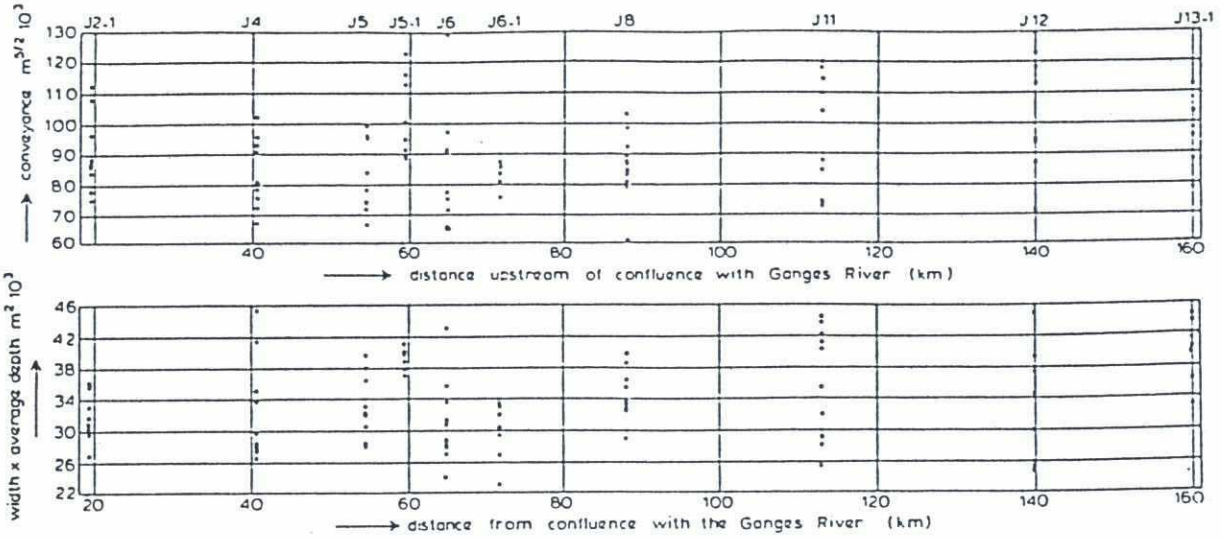


Figure 5.22 Variation of wet cross sectional area and conveyance along the Jamuna River

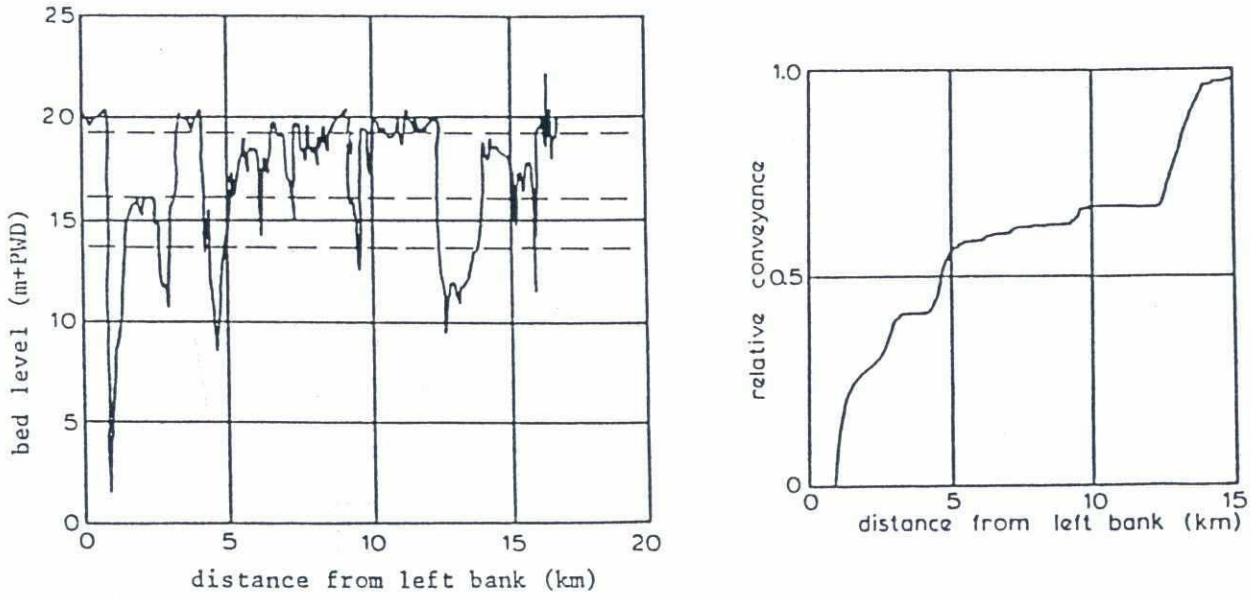
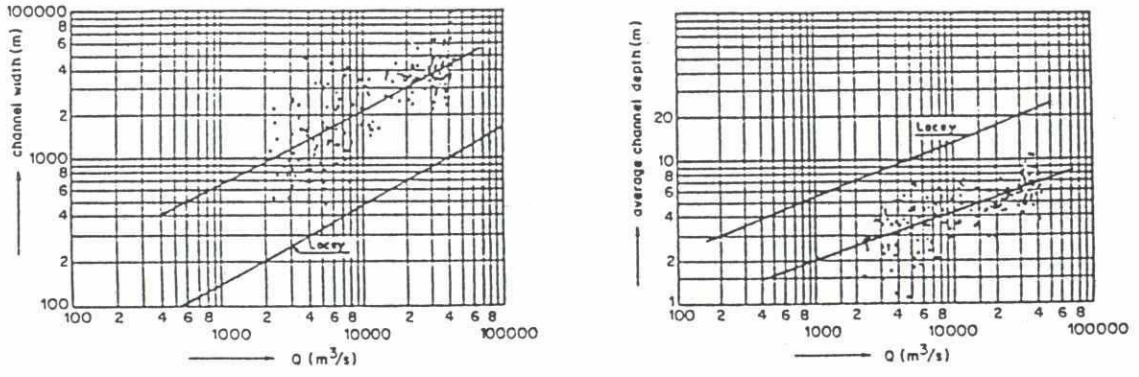


Figure 5.23 Cross section J13-1 in the year 1985-86 and the relative conveyance as function of distance from the left bank



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

Figure 5.24 Width and depth of Jamuna River channels at bankfull discharge (44,000 m^3/s)

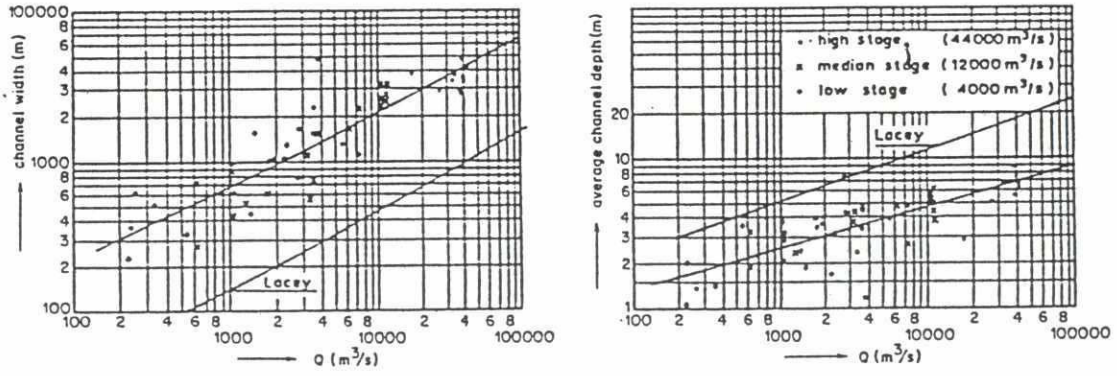


Figure 5.25 Channel width and depth at cross section J6-1 at three defined stages

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6 Offtakes

6.1 Introduction

Offtakes are bifurcations where the one branch is clearly minor compared to the other. The minor branch is the offtake from the main branch. Bifurcations may again join further downstream, which means the conditions at the bifurcation may be affected by a common downstream boundary. This is not the case for the offtakes which do not join the main branch and conditions upstream at the offtake are unaffected by the main branch from its downstream end. The term 'Offtake' may mean the entire distributary, but it would usually be a smaller part of the minor river where it is 'taking off ' from the main branch.

Main distributaries (or offtakes) from the Ganges and the Jamuna rivers are:

- Old Brahmaputra
- Dhaleswari
- Arial Khan
- Gorai

The offtakes from the main rivers of Bangladesh with their numerous branches distribute part of the discharge of these mighty rivers over a large area where it is useful for many purposes, such as irrigation, fishery, recharge of the ground water reservoir, etc. In addition the offtakes are river transport routes, connecting different regions of the country. Thus, the offtakes are important elements in the river network.

Three of the four main offtakes show clear signs of deterioration. The Old Brahmaputra and the Dhaleswari convey a decreasing fraction of the discharge of the Jamuna and may be dying within a not too distant future, see RSP SR3. The Gorai has for the last decade been disconnected from the Ganges every year during the dry season, which it did not use to be, see RSP SR10. The visual signs of deterioration both for the Gorai and the Old Brahmaputra appear as heavy deposition of sediments near the mouth of the offtakes.

The distribution of discharge and sediment transport at river offtakes is a key factor for the long term morphological development of the distributaries of the main rivers. The distribution of water would be governed by the geometry (conveyance) of the offtake, and the gradient down the distributary. The distribution of the sediment transport to the two branches is more complex. The sediment transport distribution is influenced by flow conditions locally at the offtake and is therefore much dependent on the local planform and bathymetry at the offtake. These conditions, in turn, may depend on flow conditions in the entire distributary and in the main river. This complex interaction between different mechanisms has at present not been fully comprehended and quantified.

6.2 Offtake of the Gorai River from the Ganges River

The offtake of the Gorai was selected for a detailed study during Phase 2 of the RSP. It was selected partly because of the importance of this distributary for the fresh water inflow to the Southwest region reducing salinity intrusion, but also because the Gorai is a well defined single channel without any tidal influence and therefore, in these respects, is less complex.

The RSP study has three main elements:

- Analysis of historical data in order to understand how the hydraulic conditions at Gorai offtake have changed over the last 30 years.
- Collection and analysis of detailed data in special surveys of the RSP. The data have been used to set up and calibrate a two-dimensional morphological model of the area.
- Two-dimensional morphological modelling to improve the understanding of which processes are important for the development of the dry season flow to the Gorai.

6.2.1 Historical changes of hydraulic conditions

There is only little direct information about the bathymetry of the Gorai mouth from the past, and only from the most recent years. FAP4 (1993) carried out surveys of Gorai mouth in 1992, and BWDB carried out cross section surveys in the 1990'es in relation with dredging of the offtake channel. Instead, water level and discharge data have been analysed to provide information on the threshold bed level at Gorai mouth.

- The minimum water level of the Ganges has clearly fallen since 1964 by more than 2 metres. The drop has been particularly sharp after 1987, but seems to have been going on gradually over the entire period. The maximum water level does not show any decreasing or increasing trends.
- The time it takes for the Ganges water level to fall from 11 m to 7 m PWD has reduced to approximately half over the last 20 years (Figure 6.1). This may be critical for the erosion of a dry season offtake channel.
- The bed levels at the controlling cross section at Gorai mouth have increased in the last decade by on average 1-1.5 metre (Figure 6.2). The high flood of 1987 initiated this increase. The increasing bed level after 1987 seem to have caused reduced conveyance for the flow to Gorai for all stages. Repeated dredging seems to provide only a short-term solution.
- There is a tendency of narrowing of the lower part of the controlling cross section at Gorai mouth since 1982 and increasingly from 1989 (may be due to the dredging of narrow channels). The intermediate part of the cross section, and to some extent also the upper part, shows a tendency to widen since 1987.

6.2.2 Analysis of RSP data

- The development of the curvature of the bend upstream of Gorai offtake which may be important for the performance of the offtake is cyclic in time (period of the order of 40-50 years). Presently, the development is towards a sharper bend and it is likely this development will continue some years ahead (Figure 6.3).

- The total volume of erosion upstream of Gorai offtake has been estimated to be in the order of 10 mill. m^3/year (deposited volume), corresponding to an average contribution to the sediment transport balance of this area of approximately 0.2 m^3/s (grain volume).

- Typical grain diameters are:
  Ganges: d_{50} = 0.15 mm
  Gorai mouth: d_{50} = 0.17 mm

- The main features and developments of the bathymetry locally at and near Gorai mouth over a monsoon period are as follows:
  — the deepest channel becomes more shallow and wider at the peak of the monsoon as it was before the monsoon; after the monsoon it again becomes deeper and more narrow (Figure 6.10)
  — the changes in position and direction of the deepest channel seem to be minor, although there seem to be a tendency that the main offtake channel moves towards the left bank of Gorai (Figure 6.10)
  — the large scour hole in the Ganges near Talbaria was there also in 1992 and has not moved significantly since
  — the 1992 bathymetry shows the presence of two offtake channels. The tendency of formation of a two-channel system was also observed from the 1995 bathymetries.

- Water level slopes in the upper Gorai (down to Gorai Railway Bridge) indicate that the controlling cross section shifts during the monsoon: At the lower stages in the Ganges the Gorai mouth is clearly a controlling section, but as the discharge to the Gorai increases at higher stages of the Ganges, this control vanishes; it may have been replaced by a control further downstream.

The set of data collected by the RSP from within the study area is very extensive and detailed. It has only been partly utilised in the present study. This data set will be very useful in any future studies of the Gorai offtake.

6.2.3 Morphological modelling

Mathematical modelling was introduced as a tool to interpret the information provided by the field data in an integrated way. The mathematical model makes it possible to explore the governing river processes in detail and to investigate the effects of various measures to improve the conditions for flow into the Gorai river. The two-dimensional morphological modelling system MIKE21C, developed by Danish Hydraulic Institute, was used. A short description of MIKE21C is given in Appendix 4 of RSP SPR 10. MIKE21C has already been applied extensively in relation with model studies in Bangladesh: The Brahmaputra River Training Studies in 1991-92, see FAP1 (1993), Enggrob et al (1994); the Jamuna Multipurpose

Bridge Project for morphological forecast simulations in 1995-96, DHI/SWMC (1996), and for several minor studies of Bangladeshi rivers, see e.g. DHI/SWMC (1996a) and SWMC (1996). MIKE21C comprises computational modules to describe flow hydrodynamics including helical flows (secondary currents), sediment transport on plane and sloping bed including the effect of time/space lag on suspended sediment load. The model is fully morphological with feedback from calculated changes of bed levels and bank lines to the hydrodynamic simulation. One-dimensional (1D) modelling of the Gorai has also been carried out at SWMC in connection with another project (SWMC/DHI,1996). A 1D model cannot automatically simulate bifurcations and offtakes as it requires explicit specification of the sediment distribution. This distribution is conveniently provided by a two-dimensional model.

The 2D model simulations carried out for the 1995 monsoon period addressed the following aspects:

- the development of the offtake channel
- the development of the bar in front of the offtake and effects of changes of it
- the effect of the flow distribution in the Ganges
- the effect of the flow resistance of the Gorai
- the effect of narrowing the Gorai mouth
- the effect of a different angle of the offtake channel near the mouth

The model area, model bathymetry and some examples of results are shown in Figures 6.4 to 6.14. For a more extensive presentation of results including animations on a diskette, see RSP SPR 10.

In summary, the following was learnt or confirmed from the 2D modelling:

- the flood dynamics (rate of water level changes) is important for the development of the offtake:
  - during rising stage, the bed level at the offtake raises and the channel becomes wider;
  - during falling stage, the bed level drops and the channel becomes more narrow;

- development of the bar in front of the offtake is quite sensitive to the flow resistance in the downstream reach of the Gorai

- to simulate the planform development of the offtake channel additional resistance had to be added; only in this way it was possible to reproduce the shape of the offtake channel which is decisive for the sediment distribution at the offtake, and which may have an important effect on the river development further downstream

- where this increased resistance has to be added is a matter of further investigations

- a sudden increase in bed levels at the offtake (due to for instance one year of severe flood) would remain in the following year after a normal flood event

- the 2D model provided valuable information about the distribution of sediment at an offtake, which can be used in a 1D model for long-term predictions

- the chosen modelling area was too small to allow for accurate model predictions as the boundary conditions had significant effect on the results. Thus, the same flood event (1995) had to be used for calibration and application of the present model

For rough estimates of the long-term morphological state of equilibrium of a river, the simple expression by Lane (1955) may be used:

$$S \cdot D \sim Q \cdot i$$

where S is sediment transport (m^3/s), D is grain size (mm), Q is discharge (m^3/s), I is energy slope of the river (m/m) and $\sim$ means 'proportional to'. Klaassen (1995) investigated Lanes balance further and used it to assess the state of equilibrium of the main rivers in Bangladesh. He improved the balance relation by combining a flow formula (Chezy formula $u = C \cdot h^{0.5} \cdot I^{0.5}$) and a sediment transport formula ($s = D^{-p} \cdot m \cdot u^{n}$). With p, m, n and the Chézy number, C, being constants, the modified Lane's relation he obtained written in terms of Gorai/Ganges ratios read:

$$\frac{S_{Gorai}}{S_{Ganges}} = k \cdot \left[\frac{i_{Gorai}}{i_{Ganges}}\right]^{\frac{n}{3}} \cdot \left[\frac{Q_{Gorai}}{Q_{Ganges}}\right]^{\frac{n+3}{6}}$$

If the Chezy number is not a constant but is depth-dependent, as it is in the model simulations ($C \sim h^{1/2}$) or if a constant Manning number had been applied ($C \sim h^{1/6}$), the powers of the two ratios of the above formula are somewhat different. The powers in the three cases are shown in the table below.

CASE	Q-power		i-power	
	General	n=5	General	n=5
Constant Chezy number	(n+3)/6	1.33	n/3	1.67
Constant Manning number ($C \sim h^{1/6}$)	(5+2n)/10	1.50	3n/10	1.50
Depth-dependent Chezy as in simulations ($C \sim h^{1/2}$)	(n+1)/3	2.00	n/4	1.25

The modified Lane relation is presented together with the average sediment transport and discharge ratios in Figure 6.14 assuming a constant slope, constant Chezy number, n=5 and with k selected in such a way that the modified Lane matches with the results of the base run. Points on the line representing the modified Lanes equation would correspond to conditions of long term equilibrium, because the sediment supply matches the transport capacity. Roughly interpreted, points above the Lane line may represent a situation where the river is overloaded with sediment, and it will therefore try to increase its slope, i. Similarly, points below may represent an underloading situation, where the river would respond by developing towards a more gentle slope. The large seasonal variations predicted by the 2D model including the upper Gorai where for instance the slope is highly variable, see Figures 6.11 to 6.13, gives an impression of the simplifications inherent in the modified Lane's expression, which should therefore only be used for long-term predictions. The various scenarios

simulated with the 2D model are also depicted together with the Lane line in Figure 6.14. According to the above interpretations, the scenarios apparently have long-term effects which are opposite to their short-term effects: with higher resistance in the Gorai, the river becomes underloaded with sediment. With lower flow resistance in Gorai, it becomes overloaded with sediment. With lowering of the downstream water level in Gorai, the river becomes overloaded with sediment. These comparisons show the importance of assessing both long-term and short-term developments.

The modified Lanes balance was here used with a number of inherent simplifications: A rectangular cross section was assumed and also a simple empirical relation between width and discharge. A one-dimensional morphological model will be able to provide similar evaluations but with better quantifications, because less simplifications are required. Furthermore, the 1D model can be used to investigate the time scale of long term developments.

The pilot morphological model of the Gorai offtake has provided valuable information about the morphological nature of offtakes and it shows the possibilities and limitations of the use of 2-D models for the study of offtake behaviour. It has contributed to an explanation for the closure of the Gorai river, and it has highlighted the complexity of the morphological developments of offtakes. Some indications regarding measures to change the ongoing development have been obtained from the model applications and the potential of using 2D modelling for this kind of investigations has been demonstrated although it is stressed that 2D modelling cannot stand alone; other study tools are required to study long-term effects. The importance of distinguishing between long-term and short-term effects has been discussed and comparison between 2D model results and a simple analytical long-term predictor was done.

6.3 Offtake channel development Dhaleswari river

The Dhaleswari river is the most important offtake from the Jamuna river and it has a northern and a southern offtake channel. The northern offtake transports flood water to the area around Tangail during the monsoon. Due to the construction activities for the Jamuna Bridge this northern offtake was closed off. During the monsoon of 1995 a new spill channel developed. During the monsoon this unique development of this spill channel was monitored regularly. The surveys were analyzed with a mathematical model SOBEK (DELFT) and the results are summarized here. The closing off was done by the raising of a construction site as part of the eastern bridge approach of the Jamuna bridge, with a 3 to 5 m thick sand layer. This site closed off the northern offtake of the Dhaleswari River in autumn 1994, see Figure 6.15. During the major monsoon flood of 1995 a small existing spill channel just south of this construction site developed into a major channel. The existing meandering spill channel had a length of nearly 2 km, an average width of 30 m, a maximum depth varying between 1 and 3 m and a bankfull discharge of about 50 m^3/s. The exisitng northern entrance had a width of about 80 m, a depth of 3 m and a bankfull discharge of about 165 m^3/s, see Figure 6.16. The combined bankfull discharge of these two channels was about 215 m^3/s. After a breach on July 6th the small spill channel started to erode. In total 650,000 m^3 soil, mostly fine sand with traces of silt, was eroded in the spill channel from July to the beginning of September. At some locations the width increased from 50 to 150 m and the bed level was lowered by 4 m. Figure 6.17 provides some details of the time-wise development of the channel.

The development of the meander bends in this spill channel can be characterized by mainly a deepening in July, followed by a gradual widening and about 2 m siltation of the channel bed in September. In the longest bend of the spill channel the bed eroded during the second peak flow in July. This erosion reduced the average width/depth ratio from 30 to 20. After this peak flow the width/depth ratio increased slowly from 20 to again 30. The relative radius of curvature (radius/width) of the bends varied between 1.5 and 13 in the beginning of the monsoon. Gradually this range has been reduced to 2 to 5.5, which is closer to the equilibrium range found in other meandering rivers: 1.5 to 4.3.

In the most downstream meander bend a cross-section averaged flow velocity of 1.45 m/s was measured in a survey on 14 August 1995. With this velocity a maximum discharge of 310 m^3/s was calculated. At that date the water level was rising toward the third peak flow.

After the monsoon the width had increased to 110 m, the depth to 3.4 m and the bankfull discharge from 50 to 325 m^3/s. In an average hydraulic year the discharge into the Dhaleswari river system will start to flow about two weeks earlier than before the closure of the northern intake. If a similar flood like the one of 1995 occurs in 1996 the discharges will be significantly higher. In 1995 the peak discharge is estimated at about 400 m^3/s and in 1996 it can be 700 m^3/s if the 1995 flood repeats. This means that the discharge capacity is more than in the situation before the closure of the entrance channel.

The sediment distribution in the mouth of the spill channel can change this prediction dramatically though. Simulations with a 1-D morphological model have shown the sensitivity for this distribution. The geometry of the offtake in 1995 favours future siltation of the channel, because of the large deviation angles in the three small offtake channels. Therefore the mouth was reshaped in spring 1996, to improve the sediment/discharge ratio of the flow entering the channel. Also the bar in the Jamuna River in front of the offtake can have an importance influence on the future development of the spil channel. At this moment this bar migrates slowly in downstream direction. The Jamuna channel between this char and the floodplain tends to silt up; this was already seen from a morphological survey in September 1995. This can result in major changes in the functioning of the spill channel in the 1996 monsoon, depending also on the bridge construction activities. It might require again some human intervention to maintain a good functioning spill channel.

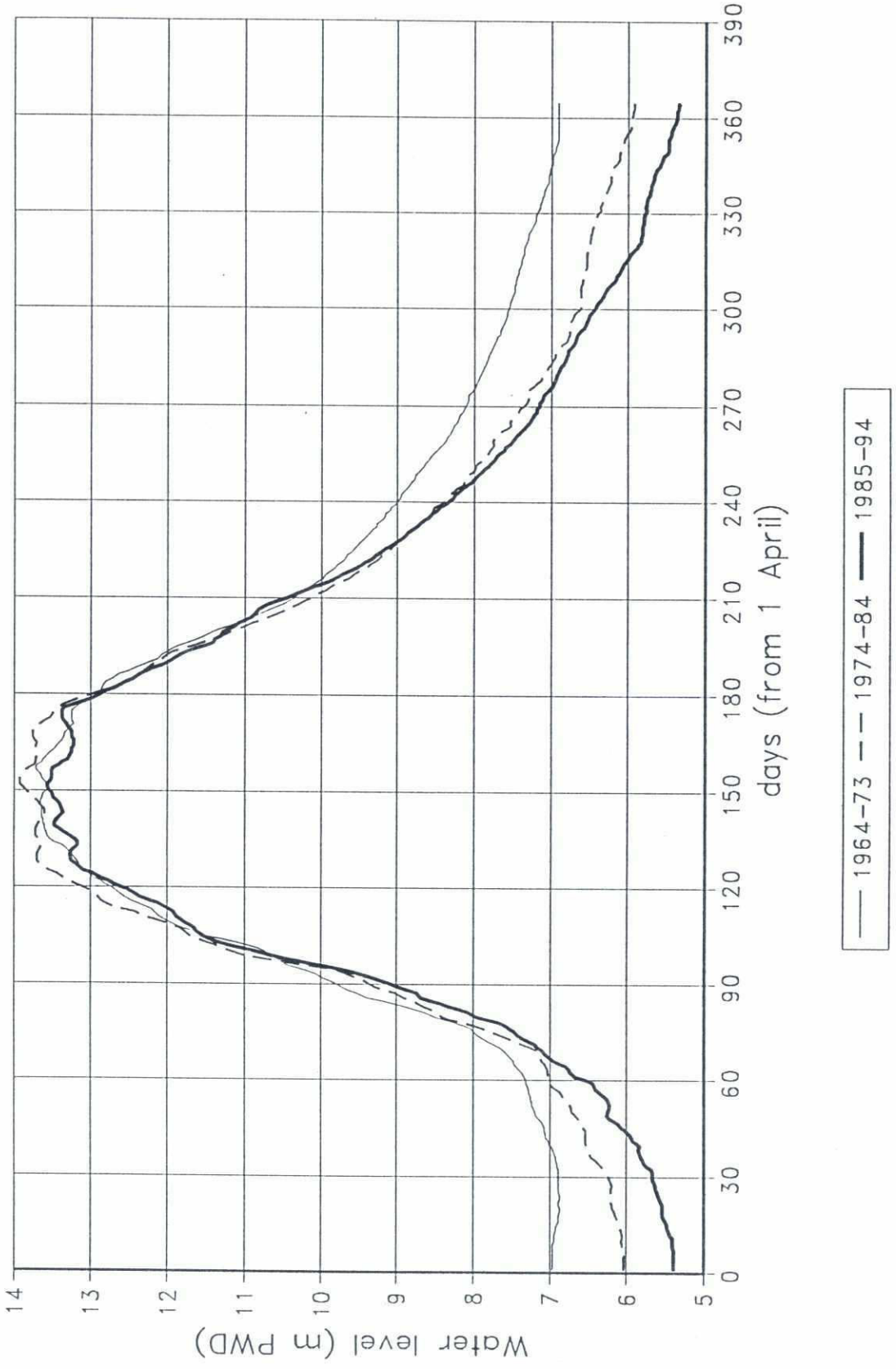


Figure 6.1 Comparison of three 10-year average water level hydrographs (Hardinge Bridge)

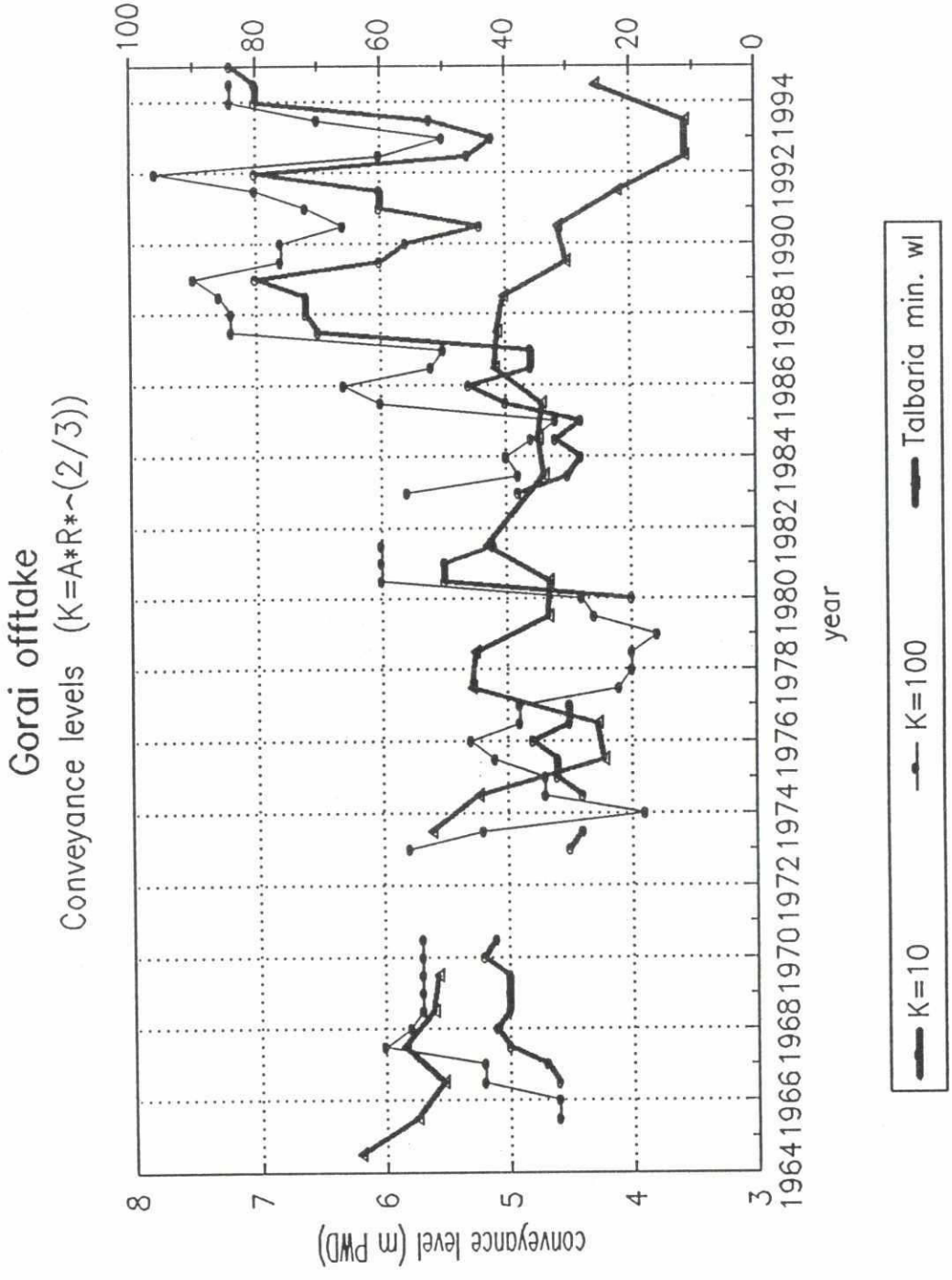


Figure 6.2 Changes in bed levels at the offtake and in lowest water level of the Ganges

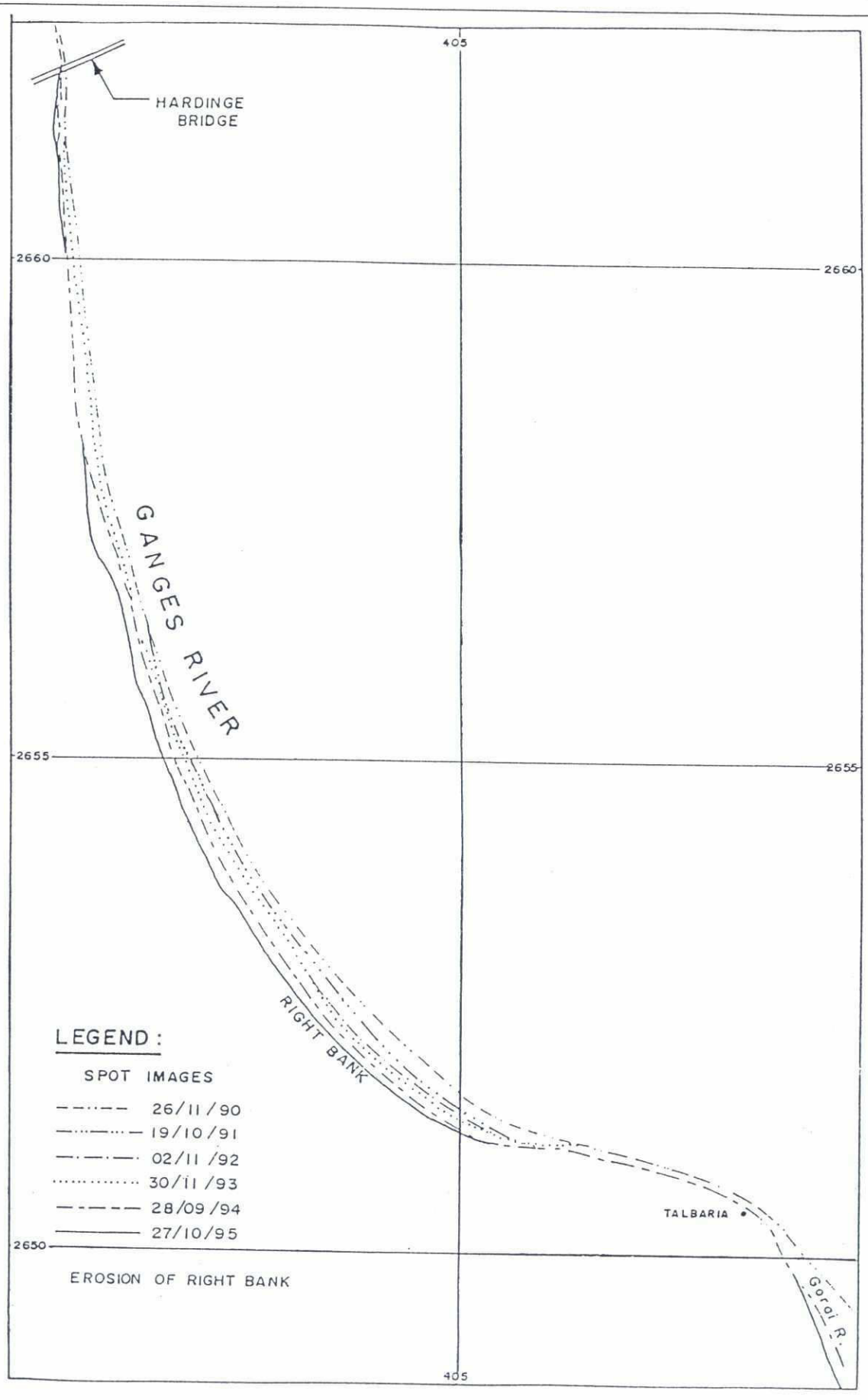


Figure 6.3 Right bank erosion in the Ganges between Hardinge Bridge and Talbaria

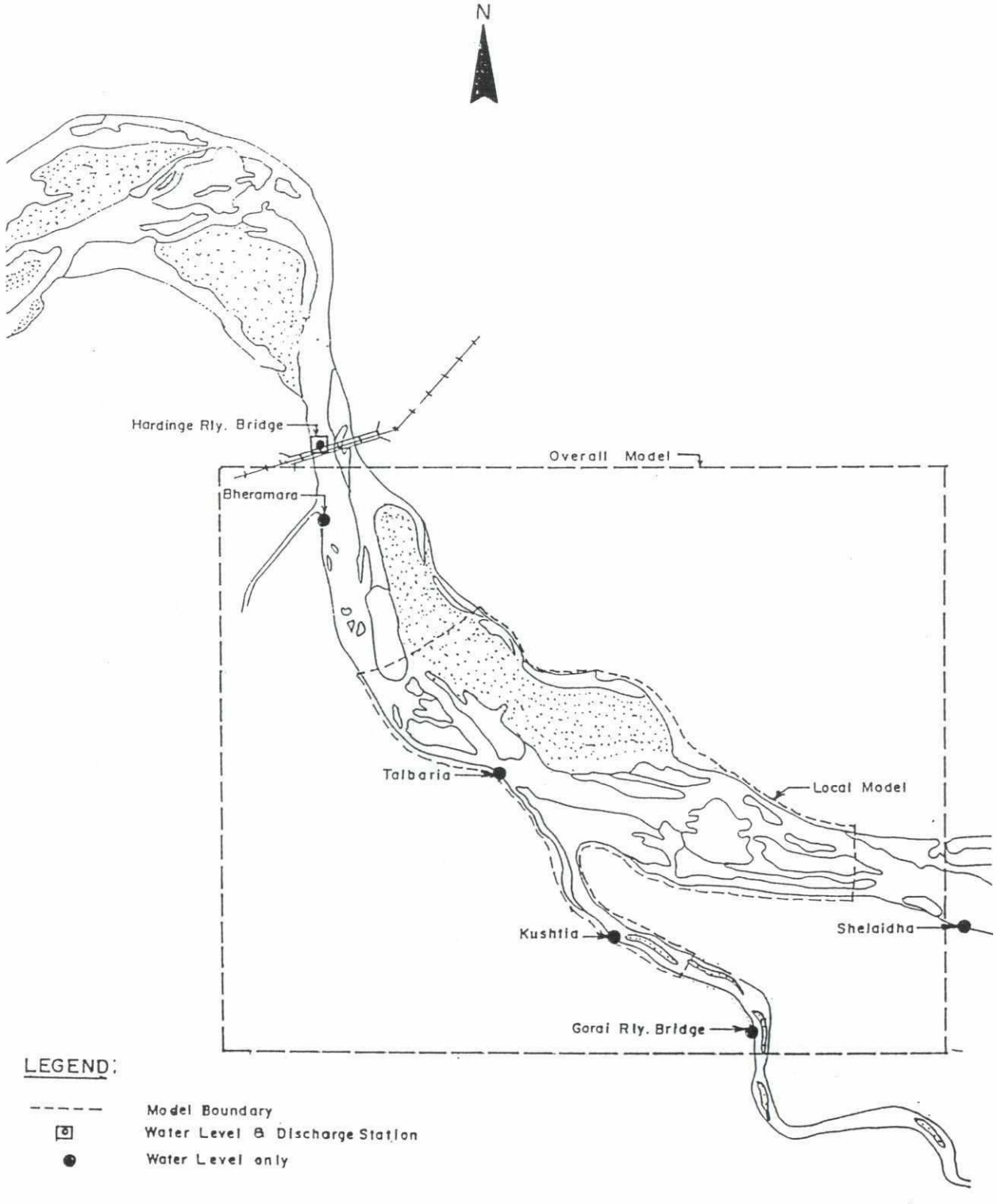


Figure 6.4 Extent of modelling areas: Overall model, local model, schematical model

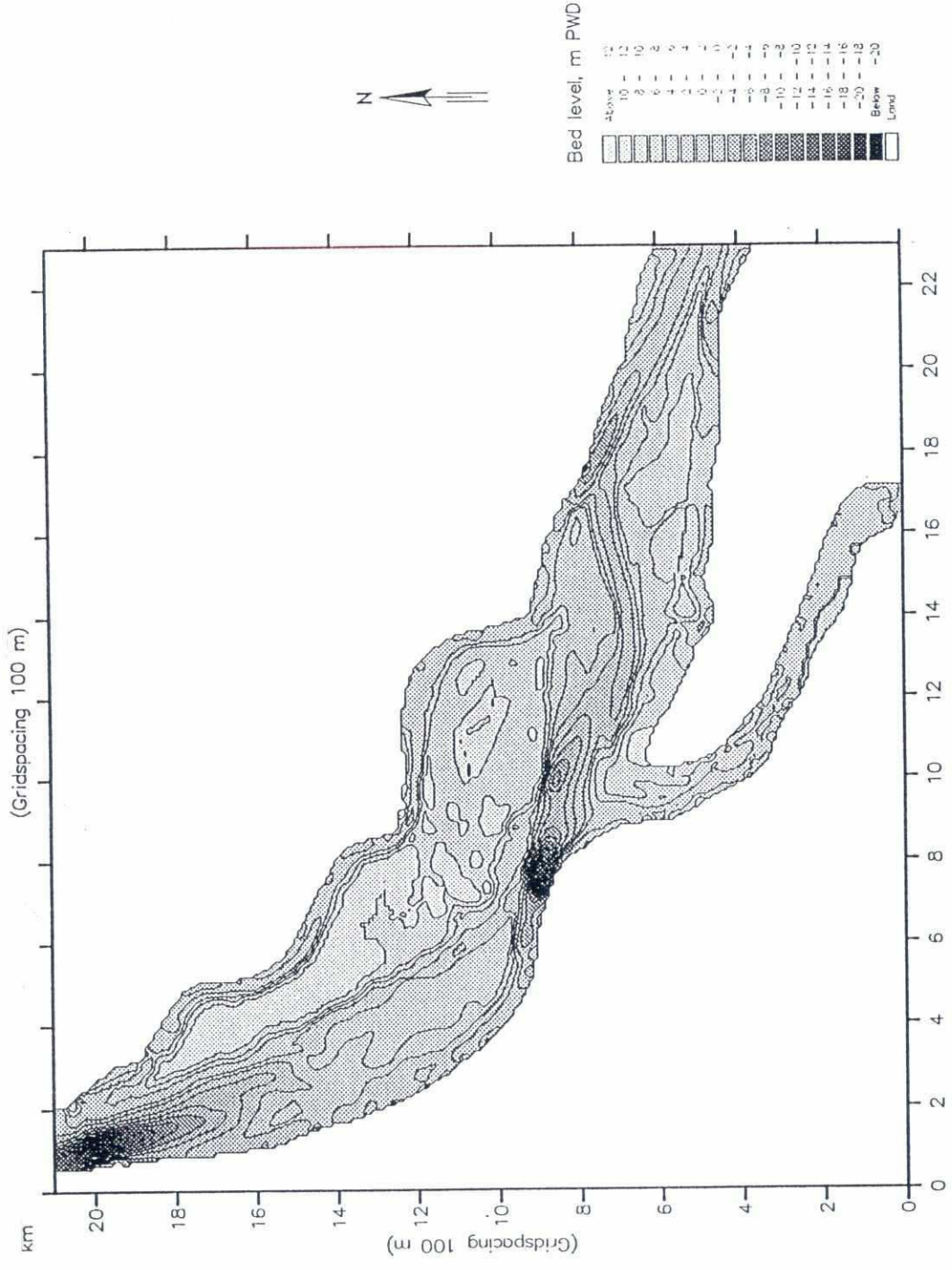


Figure 6.5 Model Bathymetry, overall model

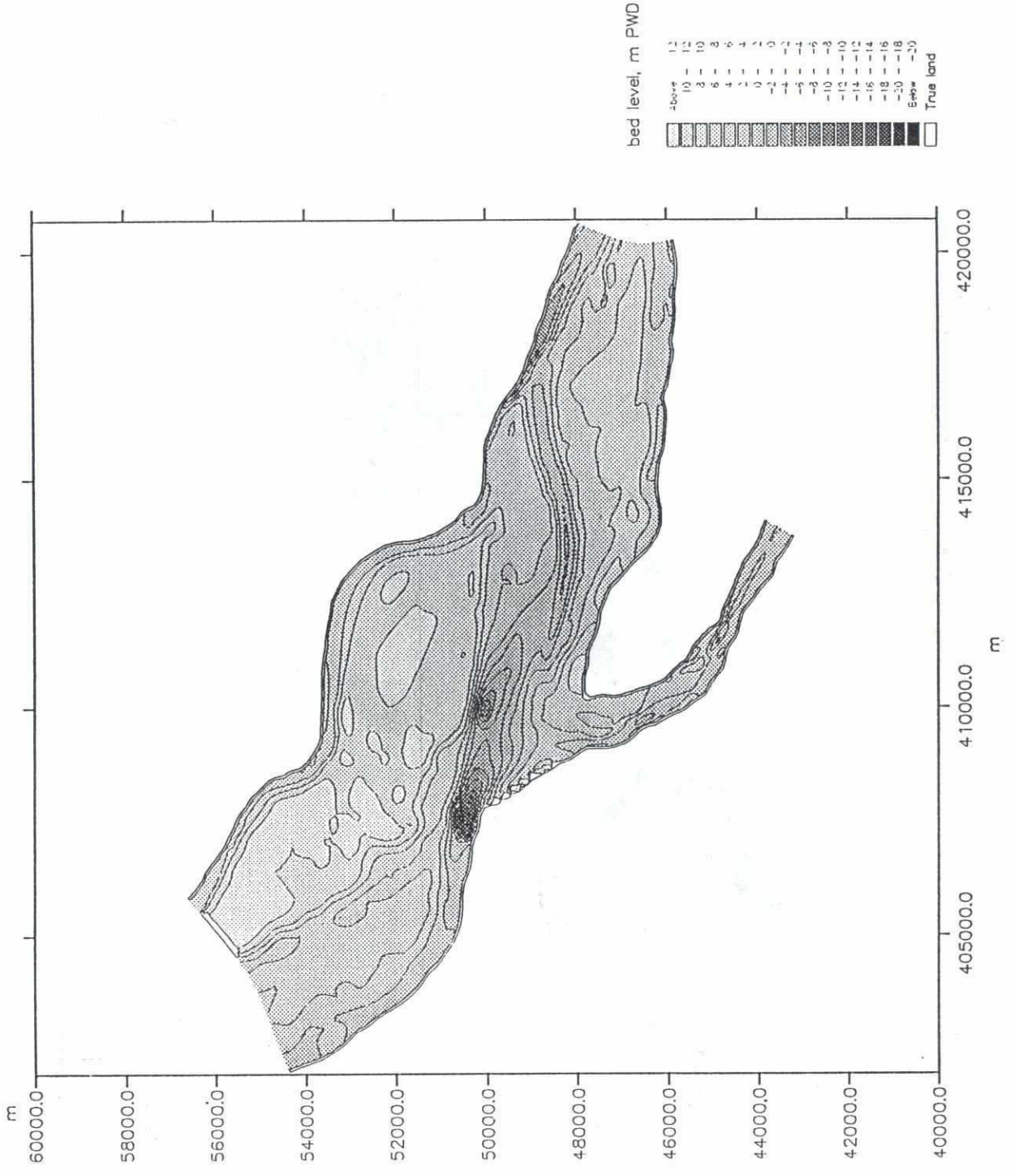


Figure 6.6 Model bathymetry, local model, based on May 1995

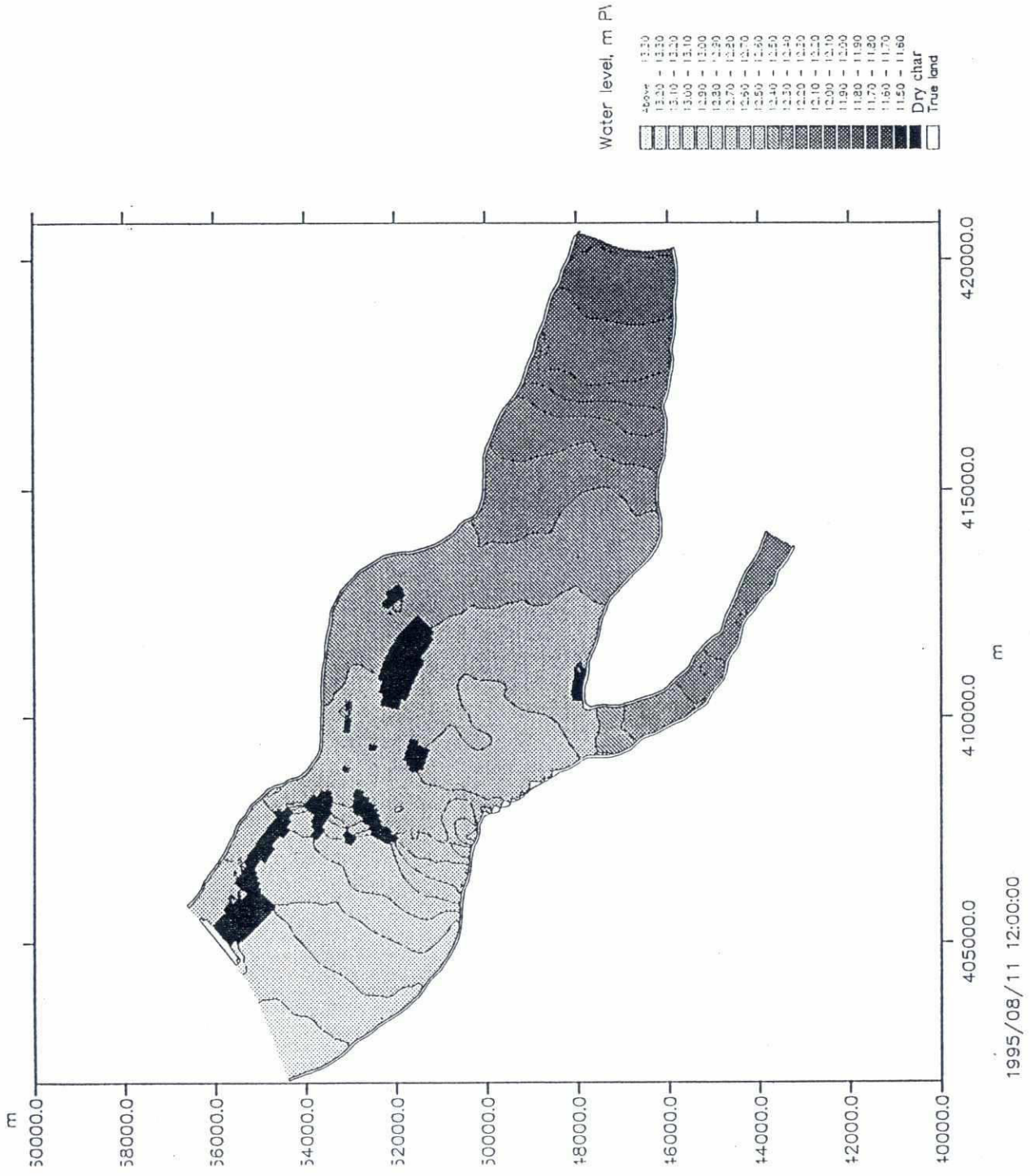


Figure 6.7 Local model, Simulated water level, horizontal contour plot, August

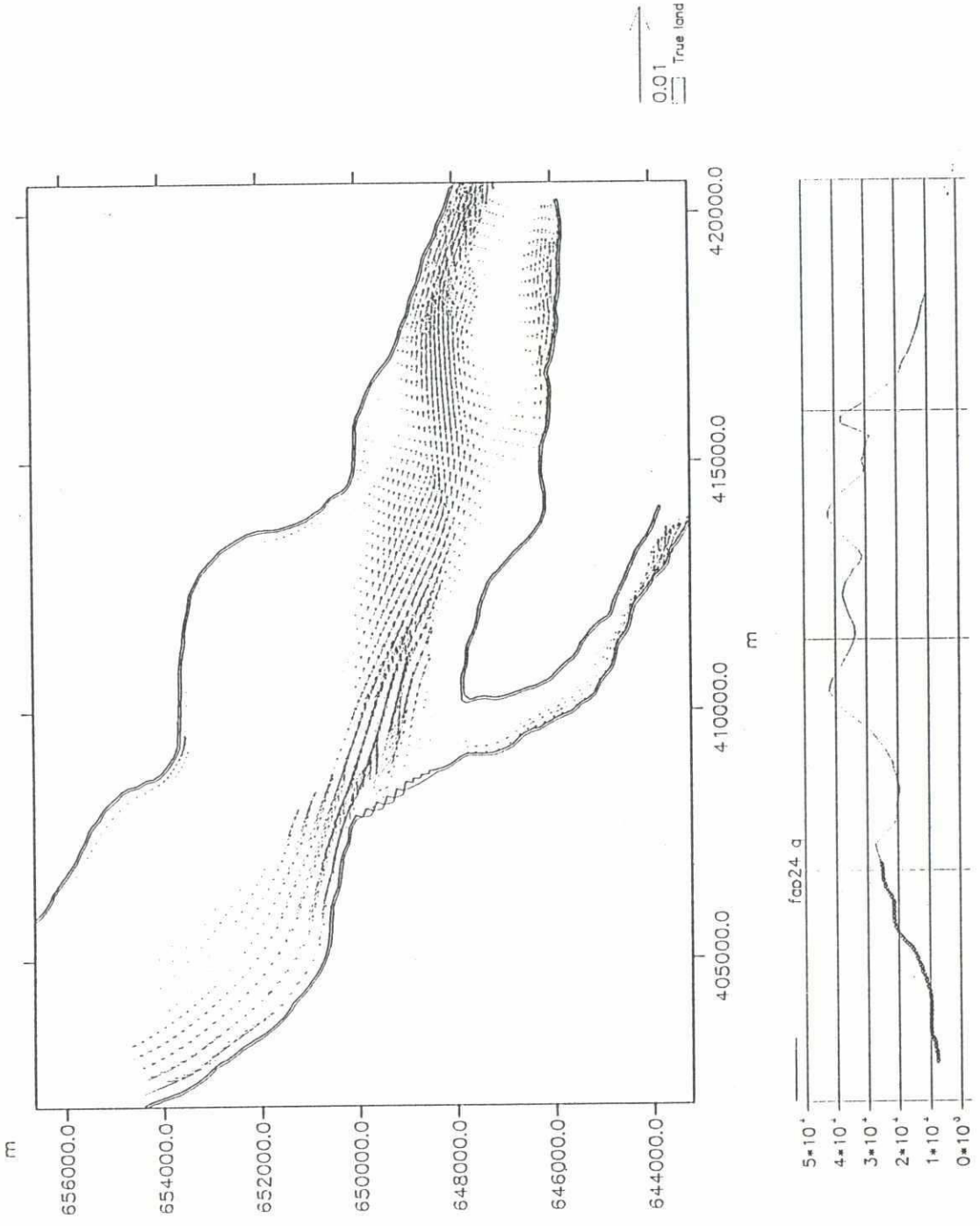


Figure 6.8 Simulated suspended load field, movable bed model.

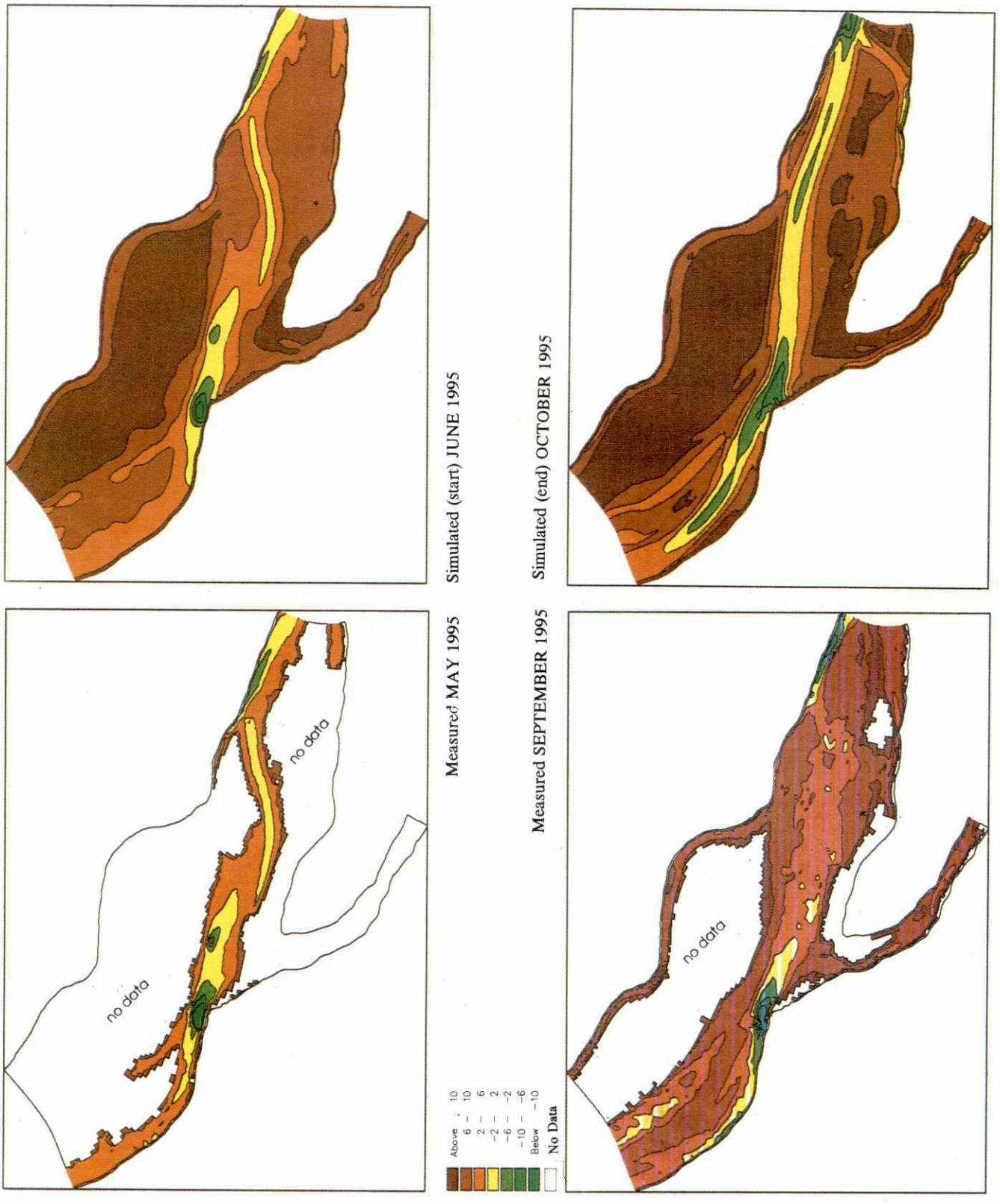


Fig. 6.9 Simulated and observed bathymetry. May/June 1995 and September/October 1995

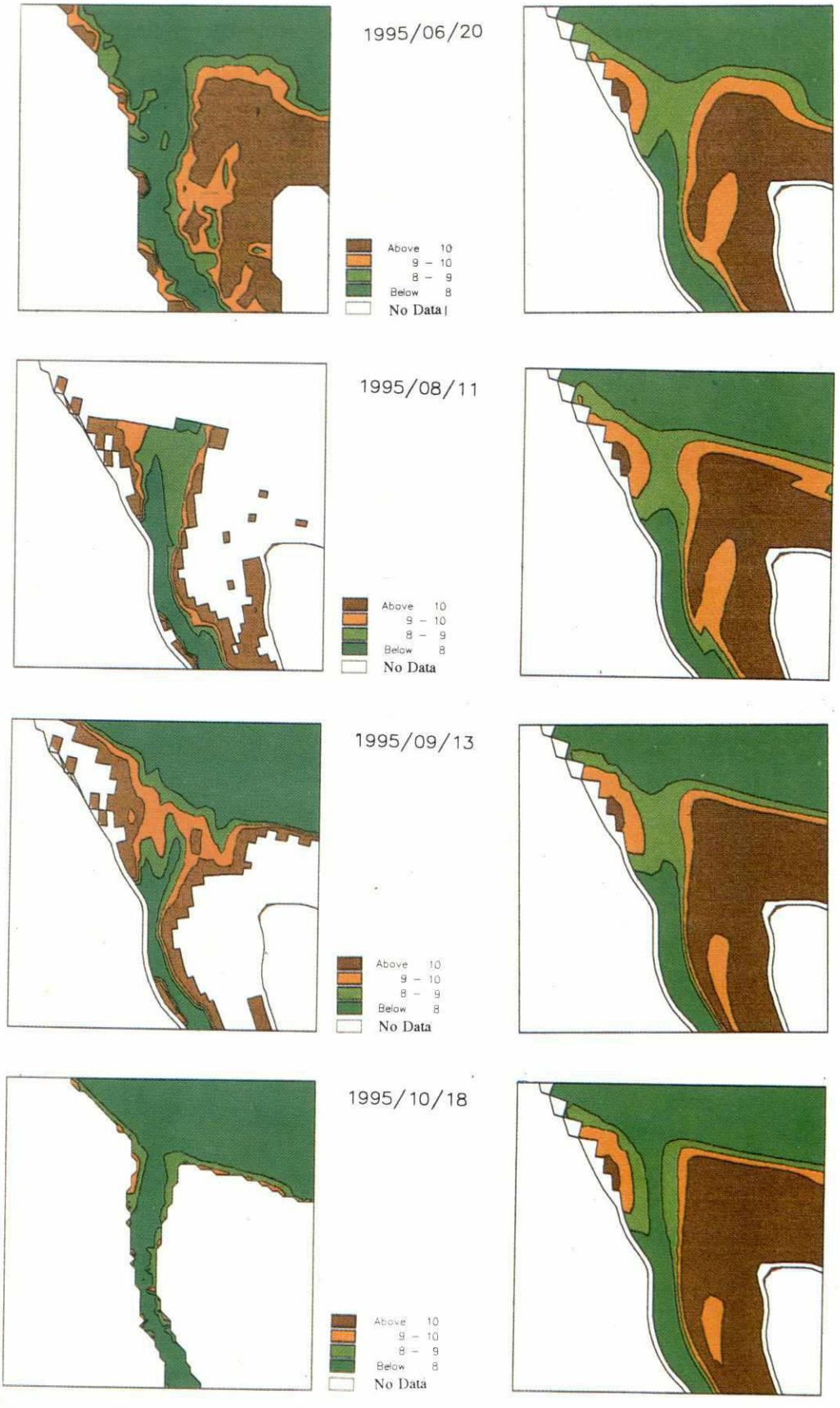


Figure 6.10 Measured (left) and simulated (right) bed levels at offtake at different times of the monsoon.

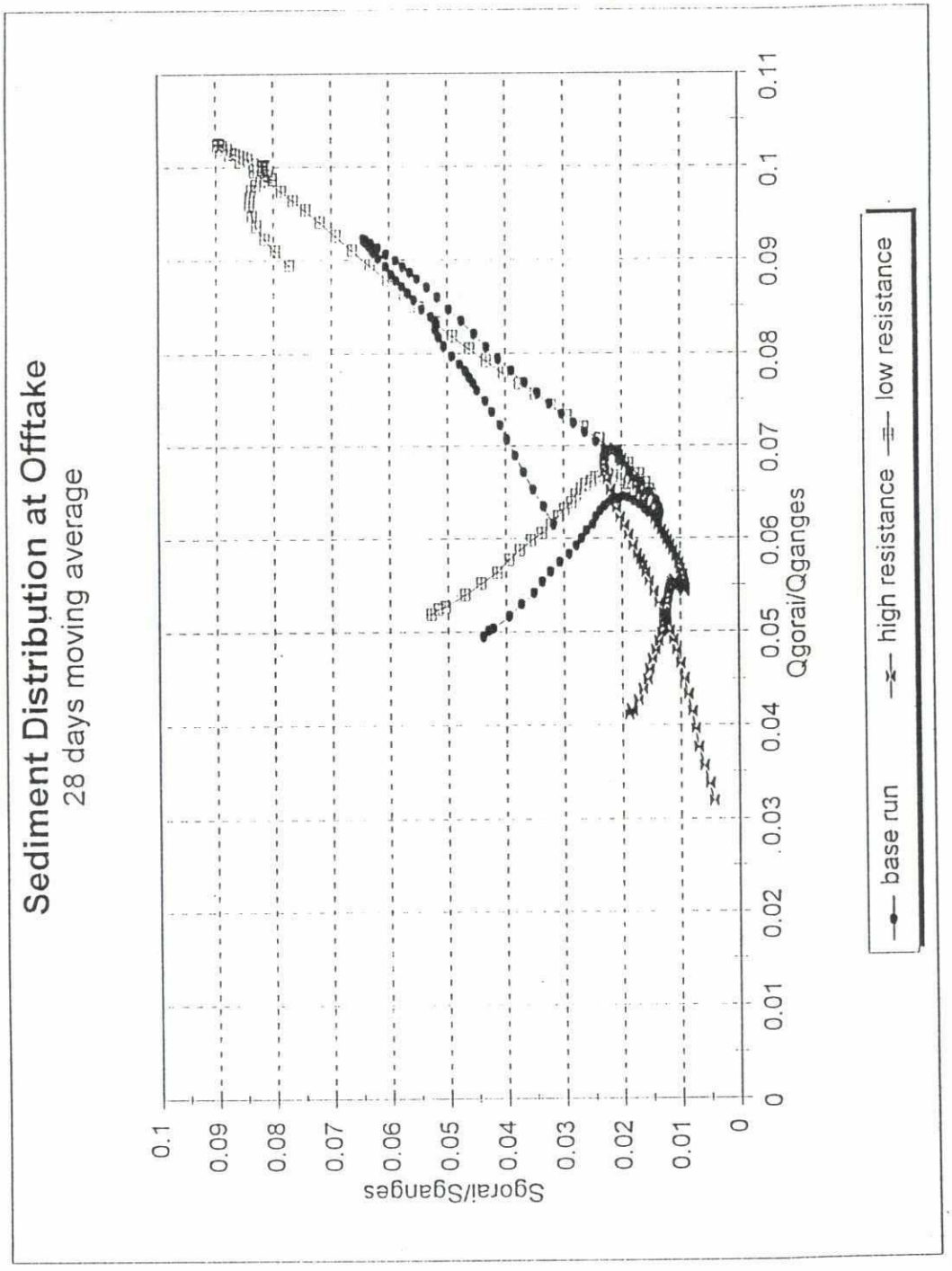


Figure 6.11 Sediment transport ratio against Discharge ratio. Running average for calibration runs.

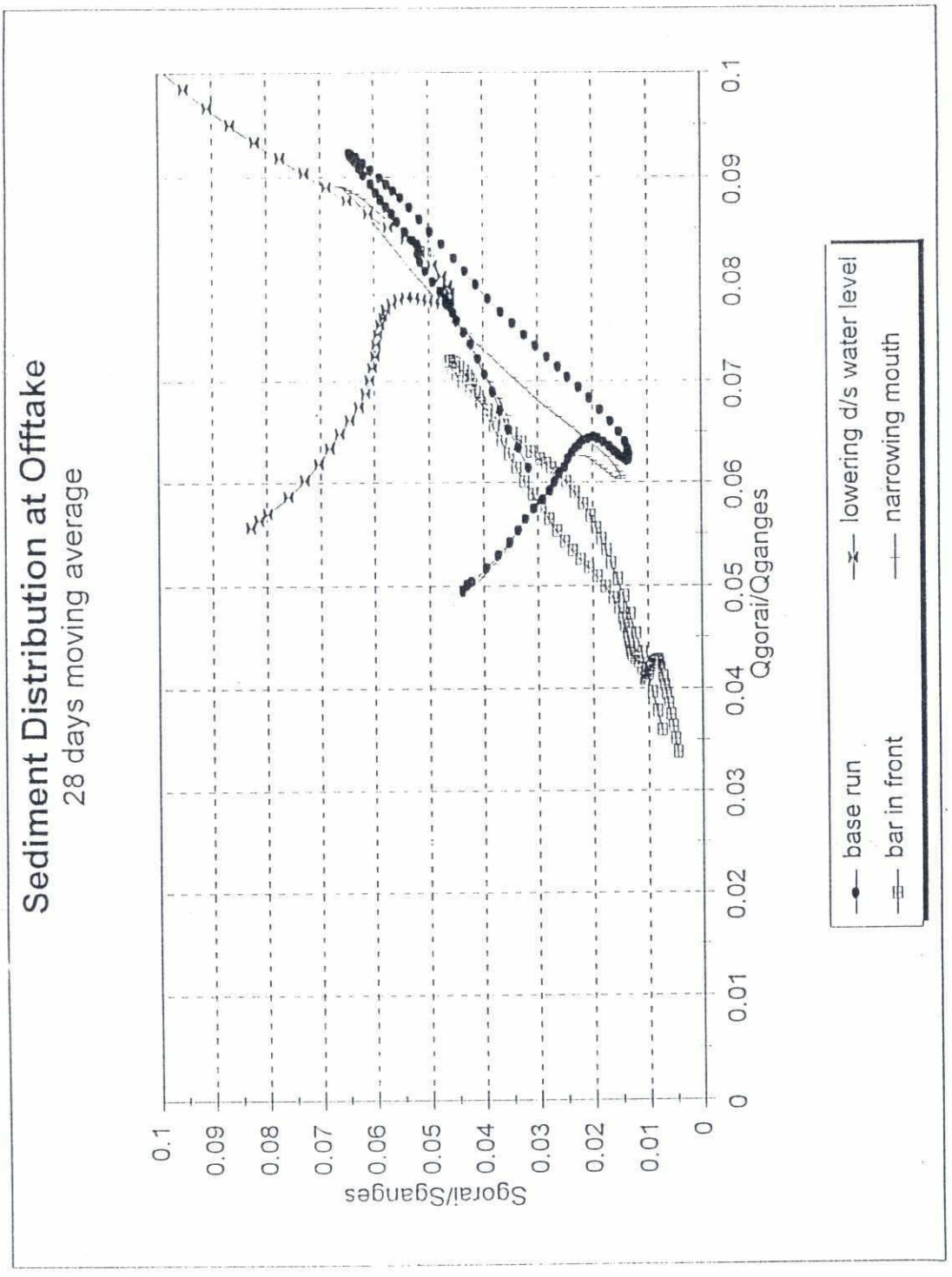


Figure 6.12 Sediment transport ratio against Discharge ratio. Running average for different scenario runs.

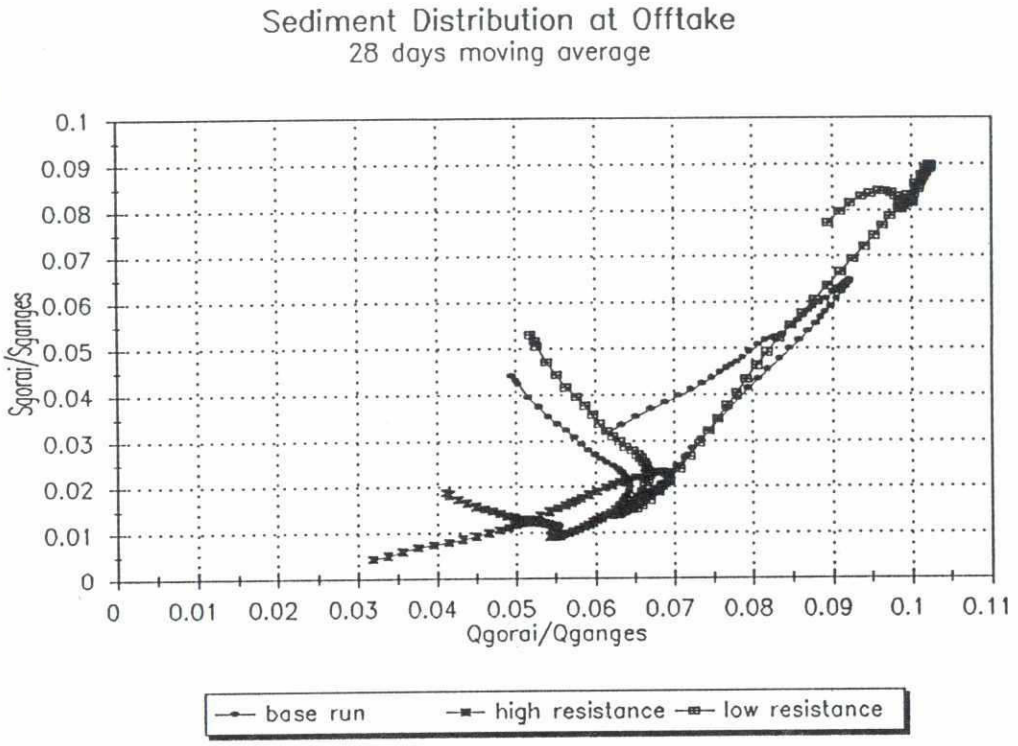


Figure 6.13 Sediment transport ratio against Discharge ratio. Running average for non-equilibrium runs.

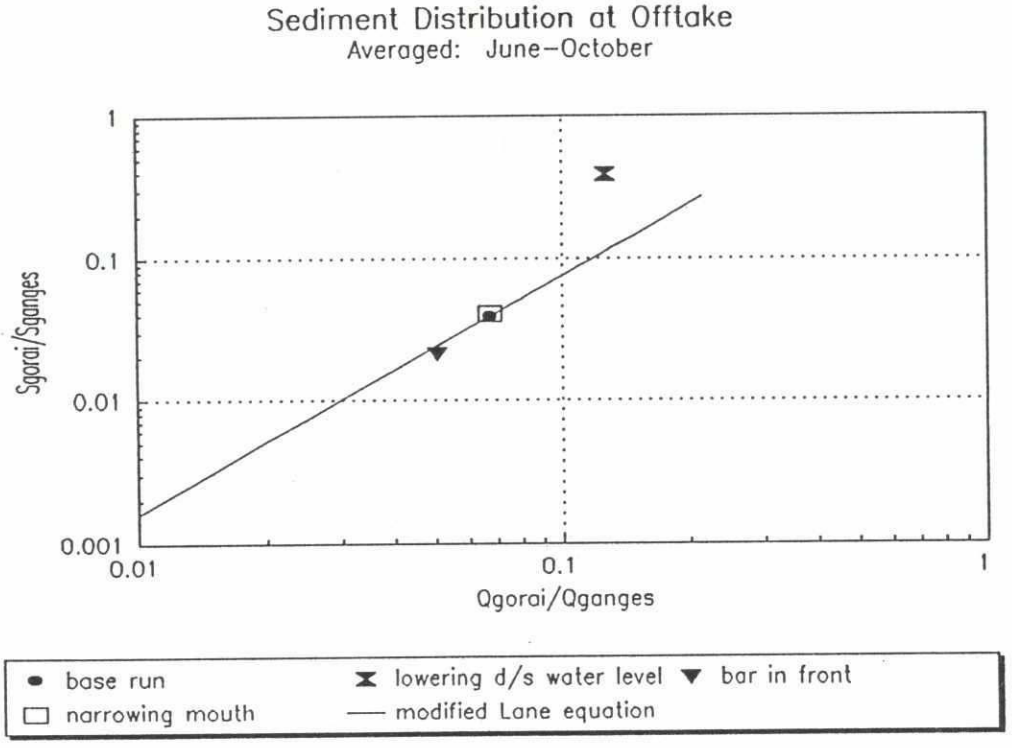


Figure 6.14 Sediment transport ratio against Discharge ratio. Mean value for different scenario runs.

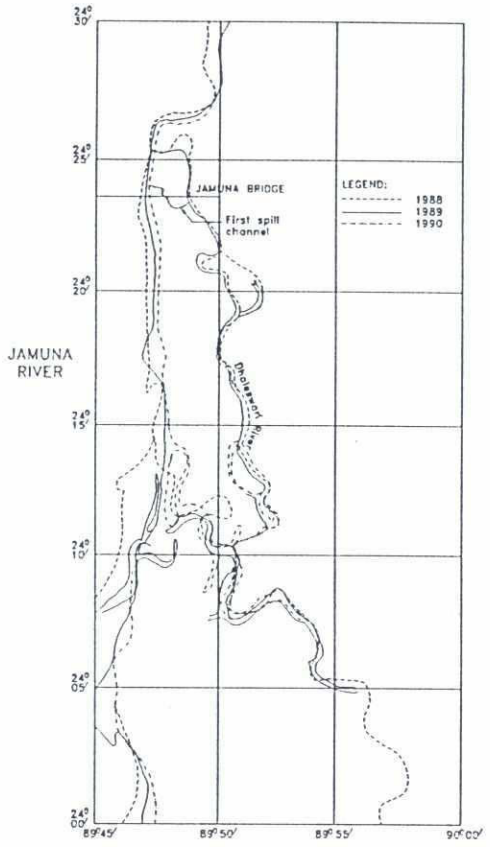


Figure 6.15 Map of the mouth of the Dhaleswari River

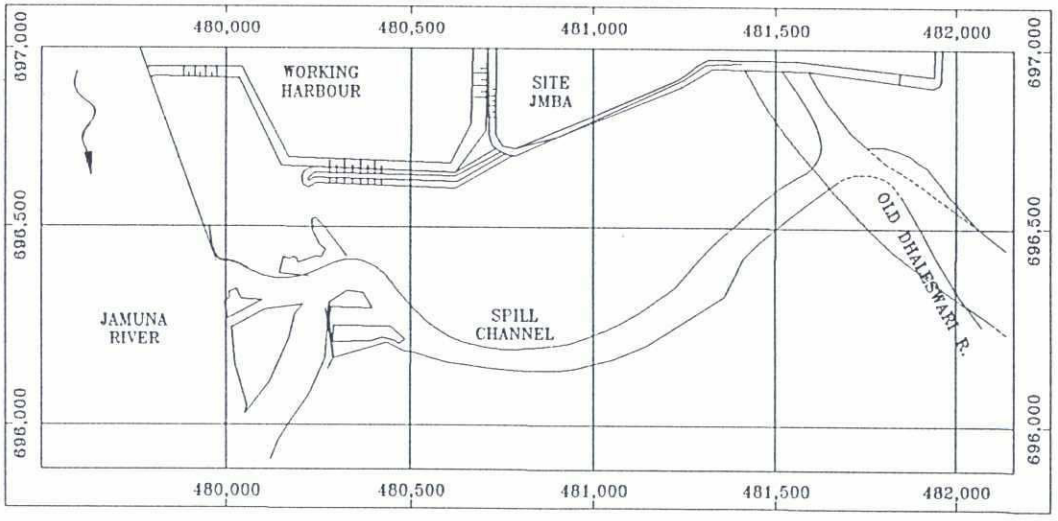


Figure 6.16 Map of the spill channel in autumn 1995

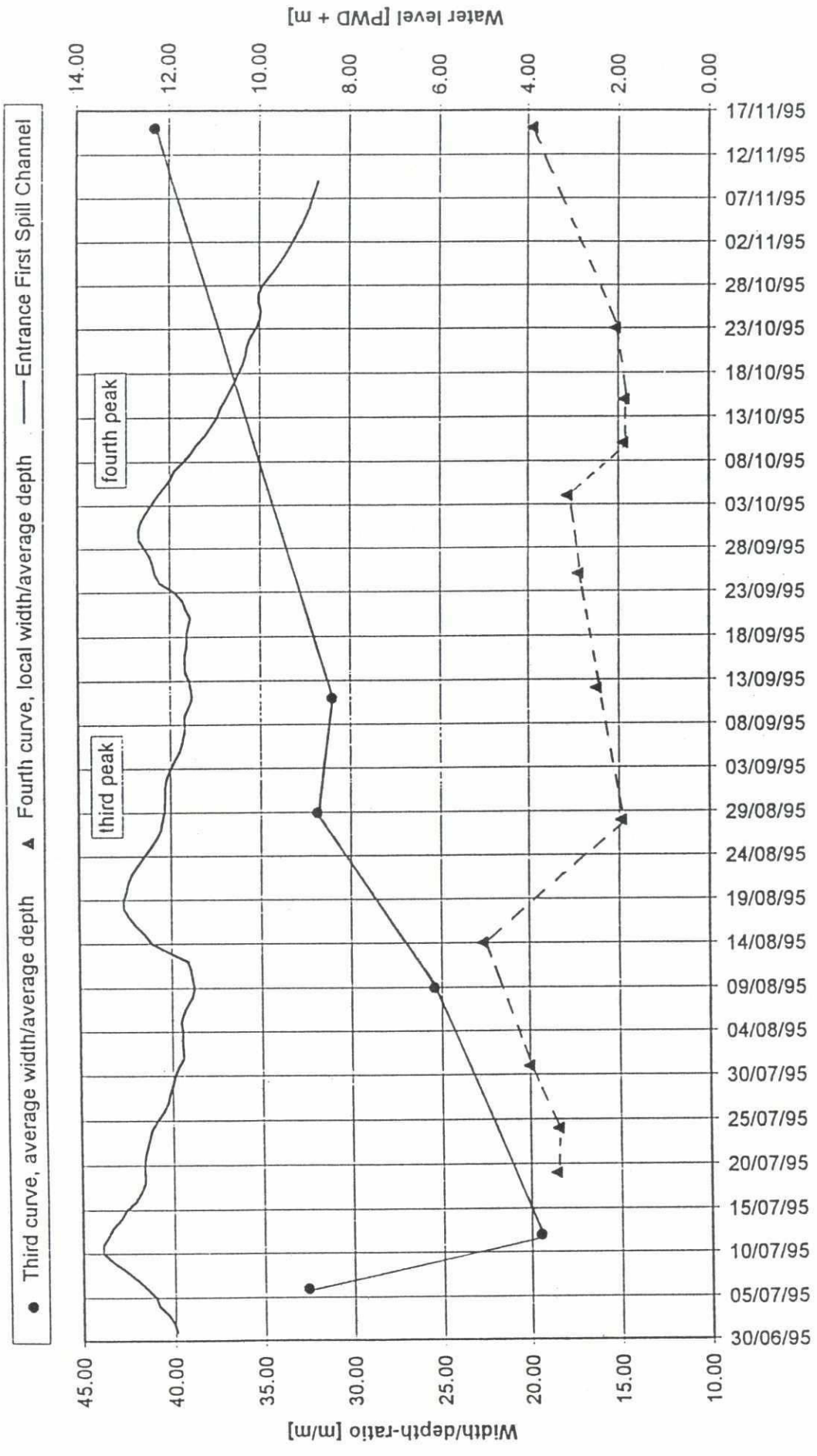


Figure 6.17 Width/depth ratios spill channel

6.4 Other offtakes

Although the main distributaries have similarities, there are also many differences. The findings regarding sediment transport distribution and morphological developments for the Gorai offtake do therefore not apply for the other offtakes.

The discharge of the Old Brahmaputra has gradually reduced by more than 30 percent during the last 20 years. This may be seen as a development which has been going on for the last 200 years, since the abandonment of the river as the main course of the Brahmaputra in favour of the Jamuna. The Old Brahmaputra has been stable in its present course for over 20 years.

The Dhaleswari, like the Old Brahmaputra, are linking the Jamuna and the Meghna rivers. Also Dhaleswari shows a decreasing trend in discharge, but with apparently no correllation with the decrease of the Old Brahmaputra. Unlike the Old Brahmaputra, the Dhaleswari is a relatively 'young' river, which has not recently been stable in it course. The river has not only a single offtake from the Jamuna and the offtake channels change with time and shift in location.

The Arial Khan apparently has doubled its discharge over a 20 year period, i.e. its development has been opposite to the other offtakes. This in itself makes it interesting to compare this offtake with the others. The conditions of the Arial Khan offtake are influenced by tidal flow.

A study of historical water level, discharge and cross-section data would be able to clarify in more details the developments of these three offtakes. It is therefore recommended to carry out analyses of the historical development of these offtakes in line with the analyses carried out for the Gorai, if availability of data allows. Such analyses should be carried out prior to or in connection with modelling.

7 Confluences

7.1 Introduction

The conditions in the river system, both in the main rivers and in the distributaries, are influenced by the interaction between the different river reaches. This interactions takes place where the reaches are linked. Typically these links are at offtakes and at confluences. Offtakes were considered in the previous Chapter 6. In this Chapter confluences are dealt with.

Although no special surveys were done within the RSP on confluences, the contractual bathymetric surveys of the confluence of the Ganges and Jamuna Rivers made it possible to analyze this major confluence. In total five bathymetric surveys have been executed, notably October 1993, April 1994, December 1994, April 1995 and January 1996. In addition some studies were done with a 1-D morphological model which elucidated the phenomena occurring at confluences, in particular the interaction between the different reaches during one hydrological year. In Section 7.2 of this Chapter first some considerations for a simplified confluence are given. The results of this analysis are supported by the results of the 1-d mathematical model and by the field measurements. In particular the field evidence for the phenomena discussed in Section 7.2 which appear to support these consideration, are discussed in Section 7.3. For the results of the mathematical model the reader is referred to *RSP Special Report 18.*

In addition and supported by the project a limited study was carried out by a student of the University of Leeds into planform evolution of the Ganges-Brahmaputra confluence on the basis of available satellite imagery covering the period 1973 - 1994. Some results are presented in Section 7.4. For more detailed results reference is made to Steel (1995).

The comparison of the contour maps and making difference maps study on the shape (planform, channels, scour holes, etc.) of the confluences and their change over time is possible. Results are presented in Section 7.5. Here no analysis is made of the scour depth at the confluence. These scour depths were analyzed in combination with the confluence scour depths observed at Bahadurabad, and the results are discussed in Chapter 9 (the comparison with predictors is given in Section 9.7).

In this chapter the interactions at the confluences are discussed on the basis of the bathymetric maps. It is obvious that the conditions at the confluence determine the development of the upstream river reaches, as the conditions at the confluence provide the downstream boundary conditions of the joining rivers. This is not discussed here. The emphasis of the present study is on the changes taking place during a hydrological year.

7.2 Hydraulic and morphological phenomena at confluences - some considerations

Consider a simple confluence of two rivers, numbered 1 and 2. See Figure 7.1. Downstream of the confluence only one channel remains, channel 3. Consider first also steady flow and hence steady sediment transport conditions. Furthermore 1-dimensional conditions are assumed. This means that the differences in lateral direction are assumed to be minor, and width-averaged parameters can be used.

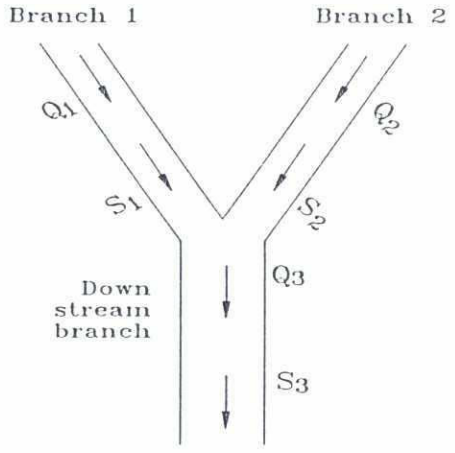


Figure 7.1

Schematized confluence with used nomenclature

For the internal boundary conditions at the confluence it holds that the continuity of flow and sediment transport has to be fulfilled. This means that:

$$Q_1 + Q_2 = Q_3$$

where Q_i = discharge in river i, and furthermore:

$$S_1 + S_2 = S_3$$

where S_i = sediment transport in river i. Hence the discharge in the downstream river 3 are given. This means that given the width of river 3 (the width probably given by a regime equation), and based on the imposed discharge and sediment transport, the slope and depth of the downstream river are determined. For these steady conditions in all three rivers uniform conditions will be present. The water depth in the downstream river will usually be larger than in anyone of the upstream rivers, hence in addition to a difference in slope there will be also a "step" in bed level.

Turning now to the unsteady conditions (e.g. with a yearly hydrograph in each of the upstream rivers), it holds also here that at any time:

$$Q_1 + Q_2 = Q_3$$

For the sediment transport it holds that on the average all the sediment that is supplied at the upstream side has to be transported in the downstream reach. Hence for the sediment transport it holds that:

$$\int S_1 dt + \int S_2 dt = \int S_3 dt$$

where the integration is carried out over e.g. the whole year. Also in this case the slope of the downstream river will be adjusted in such a way that on the average the flow but in particular the sediment that is supplied at the confluence can be transported.

The water-level in the downstream river will hardly ever be such that in the upstream reaches uniform flow exists. More common the typical flow profile will either be a drawdown curve or a backwater curve, depending on whether it is low flow or flood, but more importantly on the discharge in the other confluencing channel. In alluvial rivers such deviations from

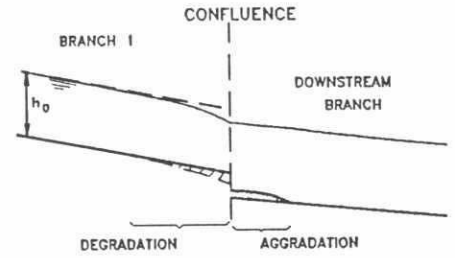
uniform flow will give rise to either degradation (drawdown curve) or aggradation (backwater curve). Hence in reality the reaches upstream of a confluence are all the time adjusting but at the same time fluctuating around an average bed level. Hence it is truly a dynamic equilibrium. The ratio between the two confluencing rivers is an important parameter for the morphological behaviour at confluences. The more the flood hydrographs are out of phase, the more pronounced morphological changes become.

Similarly it can be shown that downstream of the confluence alternatingly aggradation and degradation does occur. This gives rise to the generation of sand waves which travel through the downstream river. Hence the picture that emerges of a confluence of rivers with realistic hydrographs is a system in which all the time adjustments are taking place, and where sand waves are generated which are travelling through the downstream reach. This dynamic system is schematically indicated in Figure 7.2.

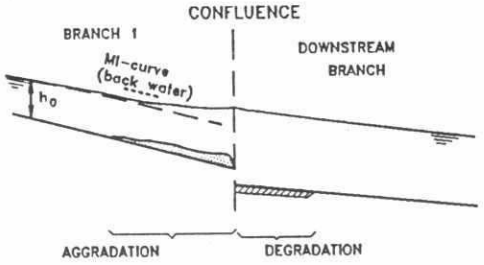
The 2-D bed topography and the 3-D flow pattern make the conditions even more complicated. Due to the chars travelling through the system, the actual location of the confluence varies over the years. The degradation of the upstream reaches during the occurrence of drawdown curves takes place in existing channels rather than on chars (see also Germanonski & Schumm (1993) for a recent experimental study into this phenomenon).

This means that during the whole year a re-distribution of the sediment has to take place in lateral direction too, otherwise there is no dynamic equilibrium.

Summarizing, the following statements can be made regarding the phenomena occurring at confluences:



(a) HIGH FLOW IN BRANCH 1, LOW FLOW IN BRANCH 2



(b) LOW FLOW IN BRANCH 1, HIGH FLOW IN BRANCH 2

Figure 7.2 Dynamic equilibrium around a confluence

- Confluences give rise to the so-called dynamic equilibrium behaviour (see in the two upstream rivers)
- This dynamic effect is most pronounced immediately upstream of the confluence, but reduced in upstream direction (after some tens of kms the effect is hardly noticeable
- In the downstream channel sand "waves" are generated which travel in downstream direction and are dampening while doing this
- The specific conditions, and hence the river characteristics, of the confluencing rivers and also of the downstream river are not really affected by the presence of the confluence
- Some more 2-dimensional complicated phenomena occur near the confluence but on a larger scale the interaction at confluences is not of major importance for the development of the upstream and downstream rivers.

7.3 Aggradation and degradation upstream of the Jamuna-Ganges confluence

In the previous Section the hydraulic and morphological phenomena occurring at confluences were discussed for a general case. In this Section the observed changes upstream of the Jamuna-Ganges confluence are reviewed on the basis of the bathymetric surveys of the confluence made during the project.

In total five surveys were carried out, notably in October 1993, April 1994, December 1994, April 1995 and January 1996. As discussed in the previous Section the dynamic behaviour upstream of the confluence is triggered by discharge differences between the two confluencing rivers. The discharges in the Jamuna and in the Ganges River for the period April 1993 - October 1995 are plotted in Figure 7.3(a). The discharge ratio Q_r, defined as the ratio between the discharges of the Ganges and of the Jamuna, respectively, is plotted in Figure 7.3(b). Upon inspection of these two figures the following observations can be made:

- The Jamuna rises earlier than the Ganges River. The fall of the Ganges is usually also earlier, though in the fall of 1995 the discharges in the Ganges River remained high for a longer period.
- Only when the Ganges River is in flood the discharge ratio Q_r approaches 1; during the rise and the recession part of the hydrograph and in particular during the low flow period, the flow in the Ganges is much smaller than in the Jamuna.
- The surveys were all made during the periods when the discharge ratio Q_r was low: between 0.4 and about 0.05. Between the first and the second surveys in the low flow seasons only the Jamuna River was still carrying still conveying a substantial flow.

The implication is that during low flow the Jamuna River is by far dominant and hence the confluence almost vanishes.

The bathymetric data were processed in a GIS by EGIS (see *RSP Special Report 17*) to obtain maps with the water depths relative to SLW and to determine in a next step changes in bed topography (erosion and deposition) in the periods between the different surveys. The results are presented as a series of seven figures, notably the Figures 7.4(a) through (g). The index to these figures is as follows:

- Figure 7.4(a) Bed topography October 1993
- Figure 7.4(b) Differences between October 1993 and April 1994
- Figure 7.4(c) Bed topography April 1994
- Figure 7.4(d) Differences between April 1994 and December 1994
- Figure 7.4(e) Bed topography December 1994
- Figure 7.4(f) Differences between December 1994 and April 1995
- Figure 7.4(g) Bed topography April 1995

The results of the processing by EGIS of the January 1996 were not available during the analysis discussed hereafter.

In this Section in particular the differences are discussed, hence the Figures 7.4 (b), (d) and (f). The Figures 7.4 (b) and (f) relate to the changes occurring during and after the recession of the flood, while Figure 7.4 (d) shows changes that take place during over a whole flood.

First the changes during the recession (Figures 7.4 (b) and (f)) are discussed. Although a detailed analysis was out of the scope of the project, the following tentative observations are made:

- During the recession of the flood deposition dominates in the Ganges River upstream of the confluence.
- In the Jamuna the picture is more complex: both deposition and scour occurs, and there is no real dominance of either of the two. Apparently there is some dominance of deposition in the later part of the low flow season (see Figure 7.4(f)).
- This would lead to the tentative conclusion that the influence of the Jamuna on the Ganges is much larger than the influence of the Ganges on the Jamuna River. This is in line with the observations made on the basis of the discharge hydrographs. The ratio Q_r is hardly ever larger than 1.
- The confluence scour holes are filled in during the low flow season. During the early part of the recession this filling in seems much more effective than in the later part (compare the changes in the confluence between
- During the recession existing channels are scouring into the river bed. From inspection of the Figures 7.4 (b) and (f) it is clear that within the braided Jamuna River a system of meandering channels is developing. This phenomena is often referred to as retarded scour. This scour is in many places in the order of 5 m, hence fairly pronounced.

Figure 7.4(d) relates to changes taking place over a flood. The following observations can be made:

- In the Ganges River scour is dominating in the Southern channel; in a Northern channel there is some deposition. Overall however scour appears dominant.
- In the Jamuna River both scour and deposition are occurring. The changes are rather due to 2-d processes (bank erosion, shifting of channels, etcetera) rather than due to the type of 1-d phenomena discussed in Section 7.2.

All in all a tentative conclusion can be that the bathymetric surveys seem to confirm the somewhat theoretical 1-D analysis presented in Section 7.2, though in the Jamuna River the 2-D character of the processes obscures the 1-D phenomena to some extent. A more detailed analysis is appropriate. In principle this can be done using a GIS. Such an analysis can be supported by a 1-D mathematical model study of the morphological changes near a confluence in a similar way as the model used in *RSP Special Report 18*.

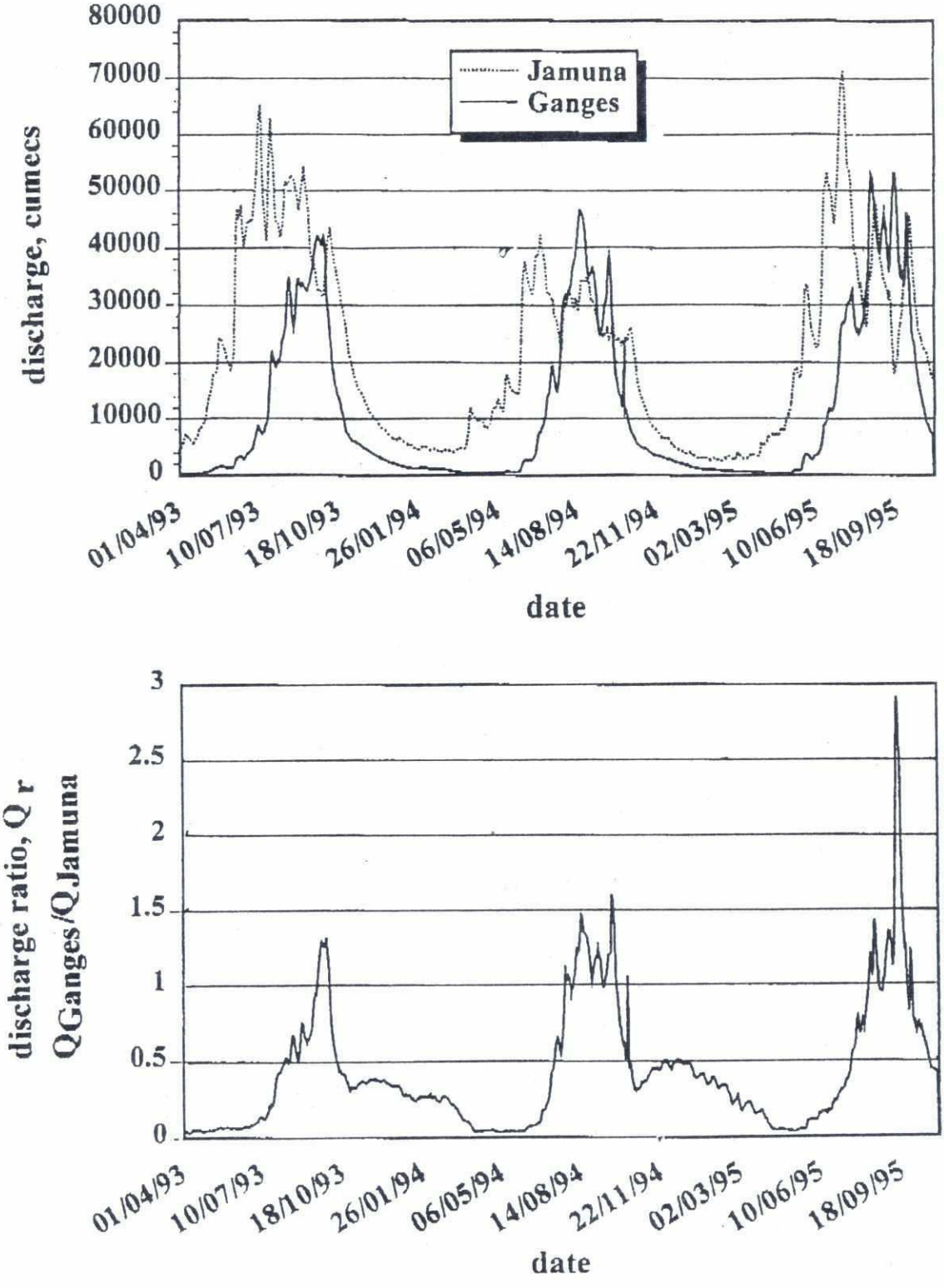


Figure 7.3 a) Hydrographs of the Jamuna and Ganges near their confluence. Ganges data from Hardinge Bridge gauge; Jamuna data derived from difference between discharge estimated at Baruria and at Hardinge Bridge.

b) Simple discharge ratio (Q_r) between the Ganges and Jamuna at their confluence through the study period. Note the non-coincident hydrographs and wide range of discharge ratios. Note also the large discharge ratio as the Ganges peaks after the Jamuna.

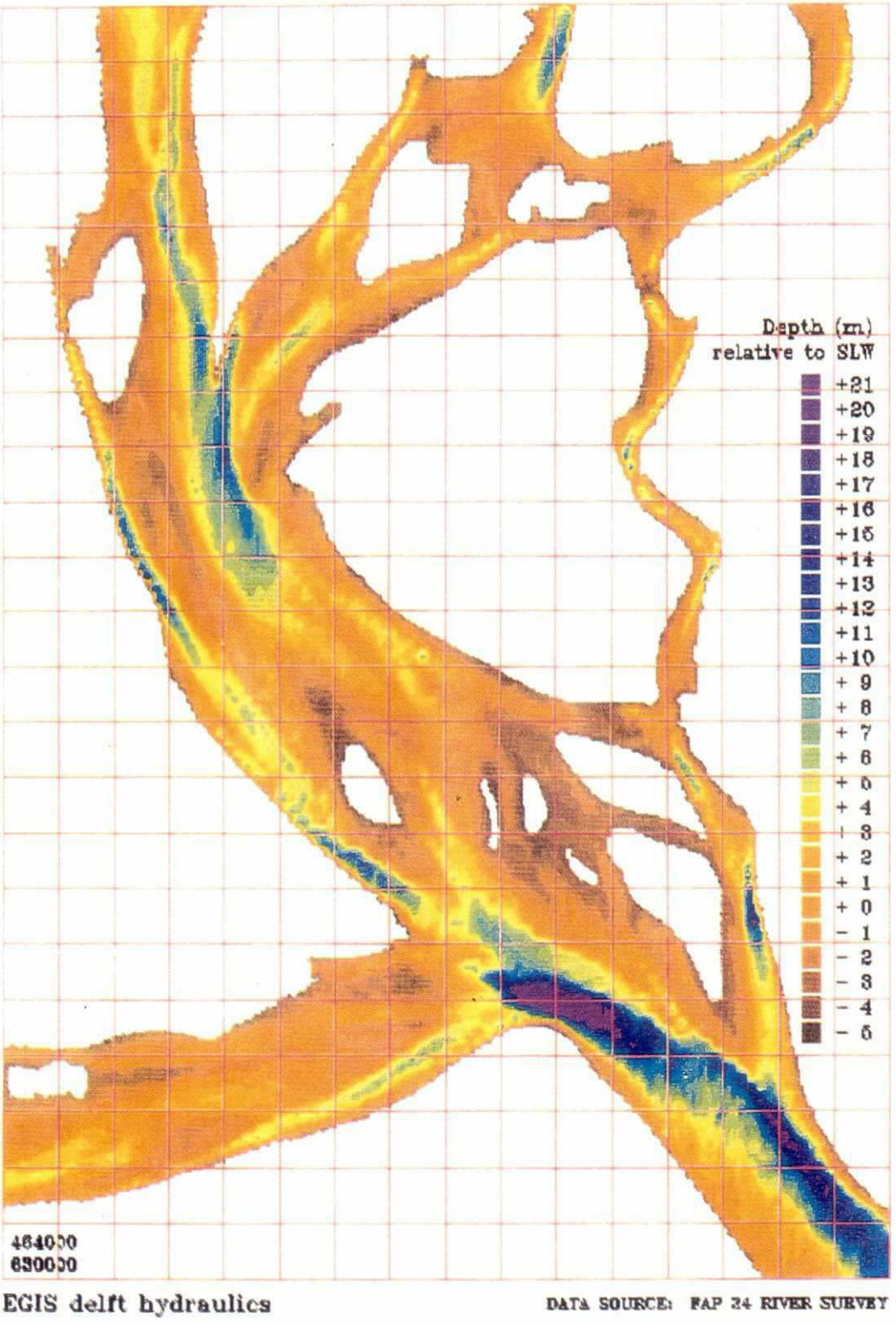


Figure 7.4 The results of the first four bathymetric surveys and the difference maps between the successive surveys are presented as follows:

a) Contour map of the confluence October 1993

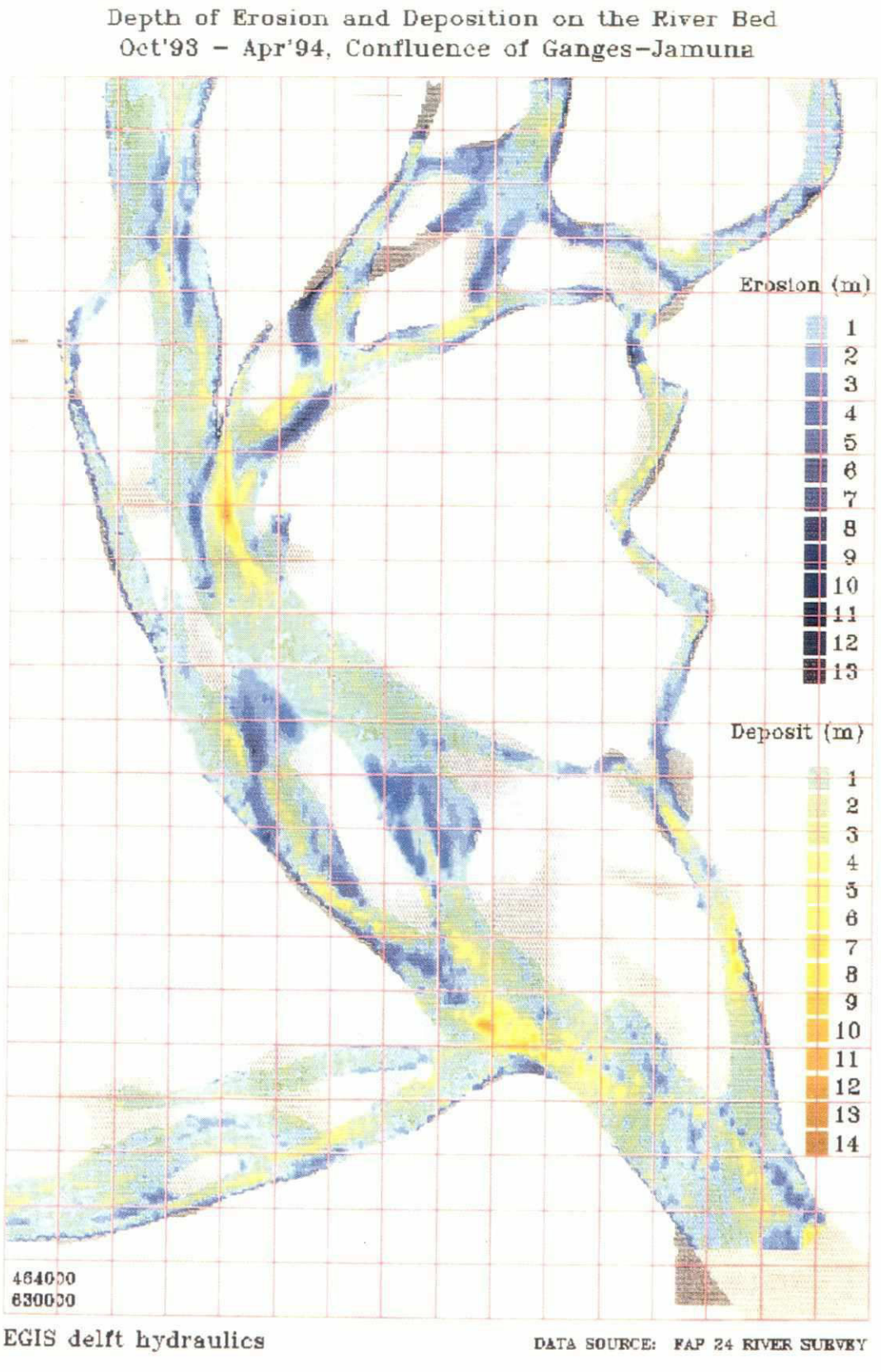


Figure 7.4 The results of the first four bathymetric surveys and the difference maps between the successive surveys are presented as follows:

b) Erosion/deposition October 1993 - April 1994

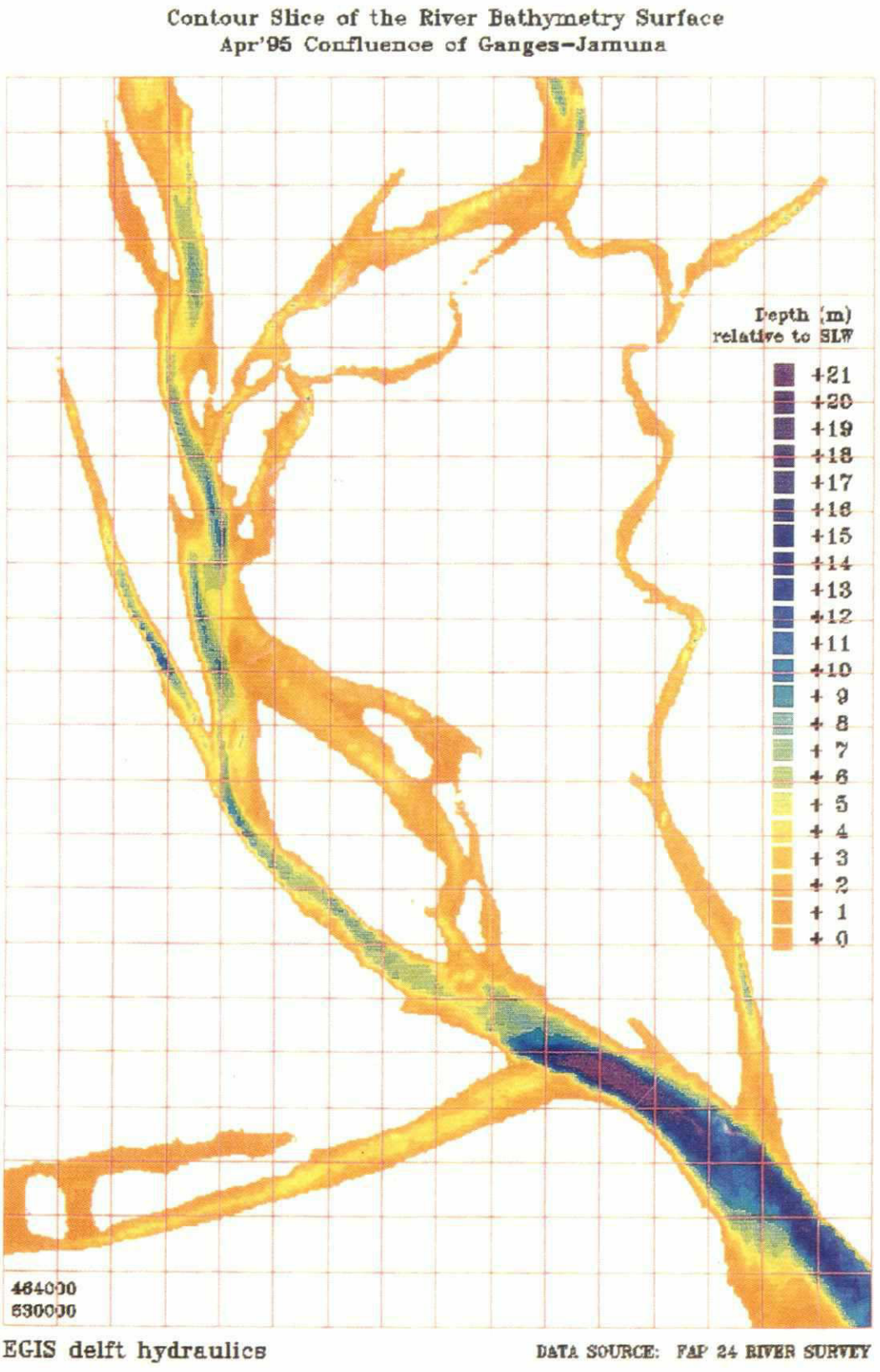


Figure 7.4 The results of the first four bathymetric surveys and the difference maps between the successive surveys are presented as follows:

c) Contour map of the confluence April 1994

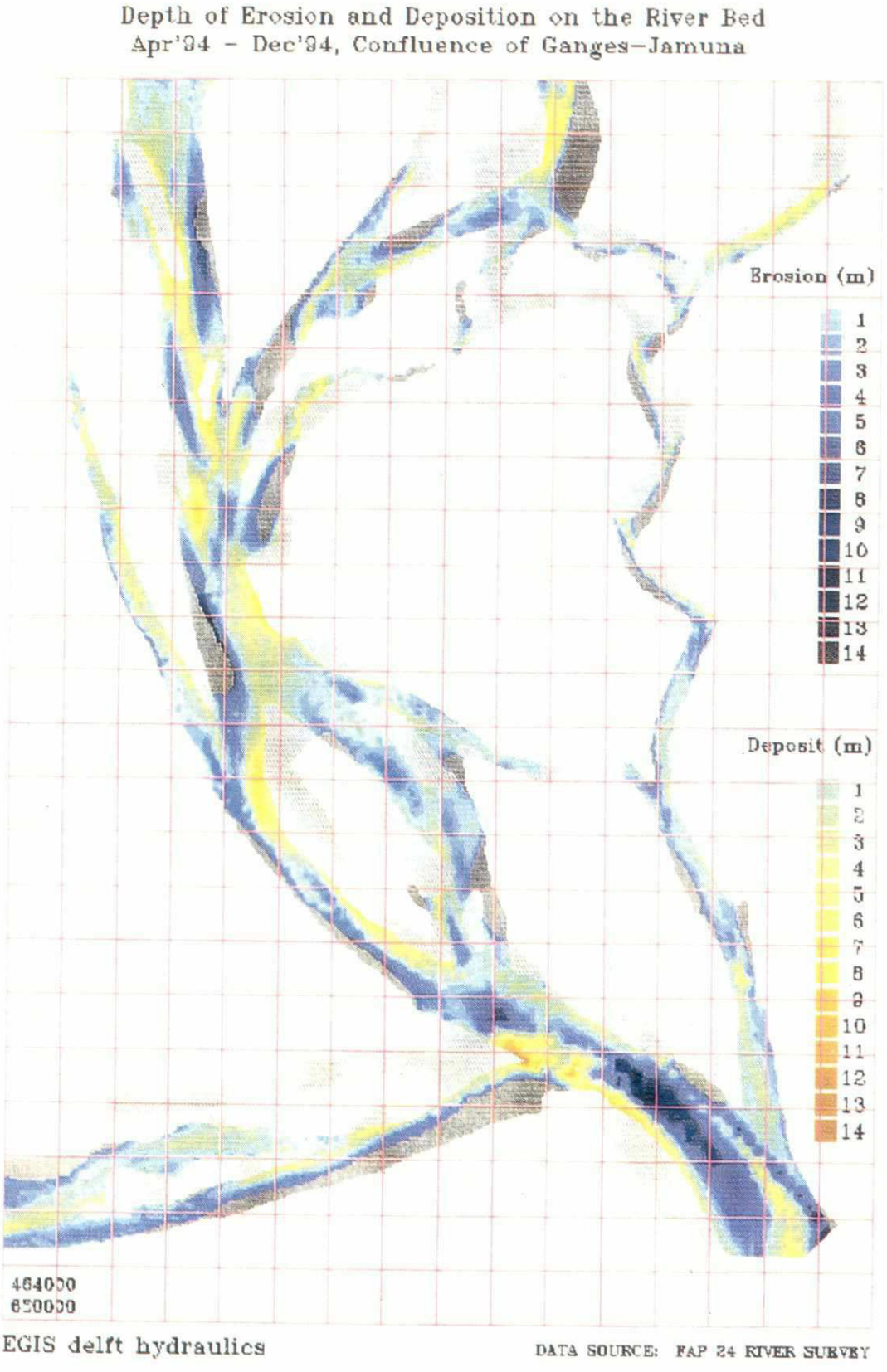


Figure 7.4 The results of the first four bathymetric surveys and the difference maps between the successive surveys are presented as follows:

d) Erosion/deposition April 1994 - December 1994

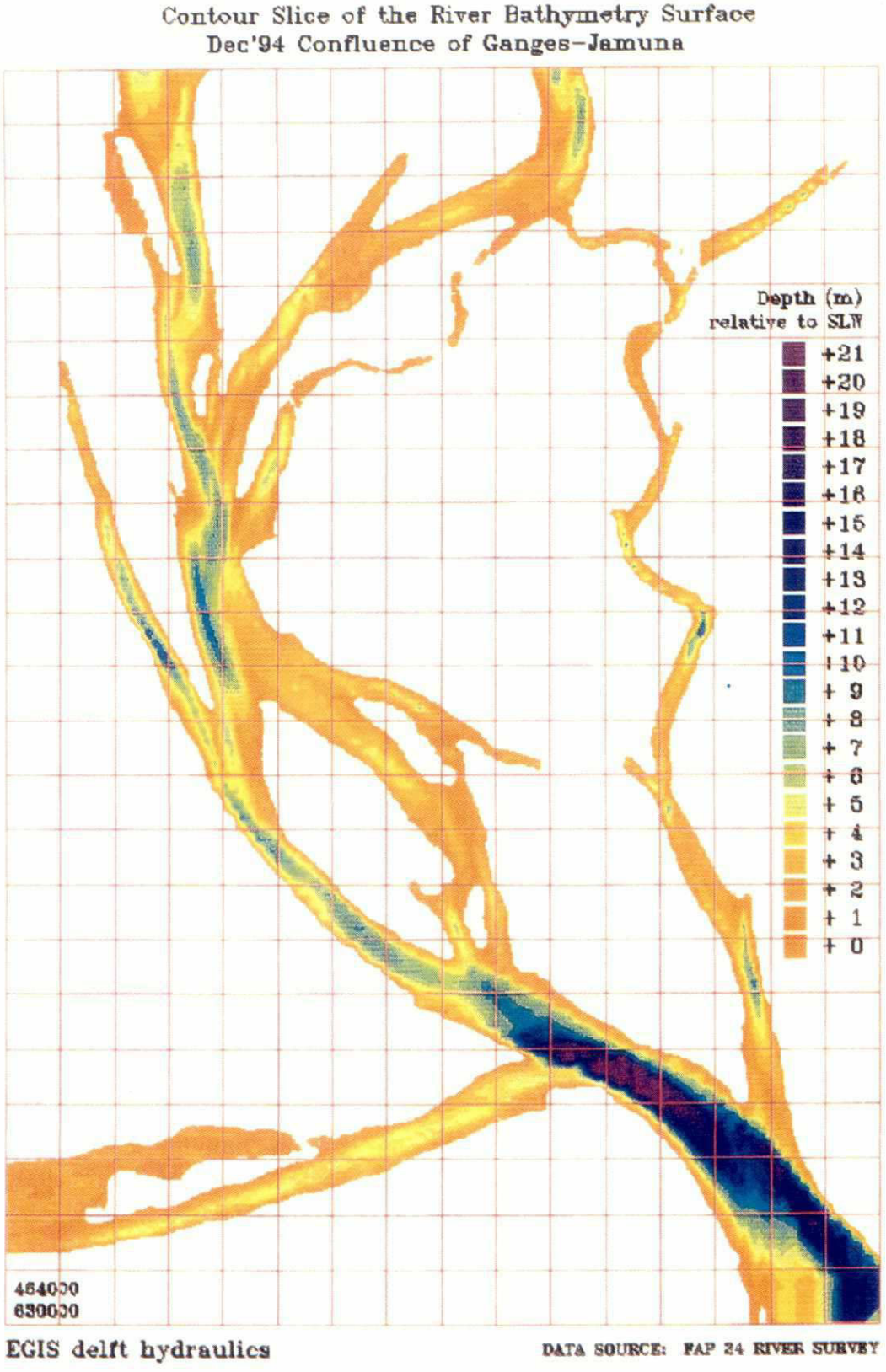


Figure 7.4 The results of the first four bathymetric surveys and the difference maps between the successive surveys are presented as follows:

e) Contour map of the confluence December 1994

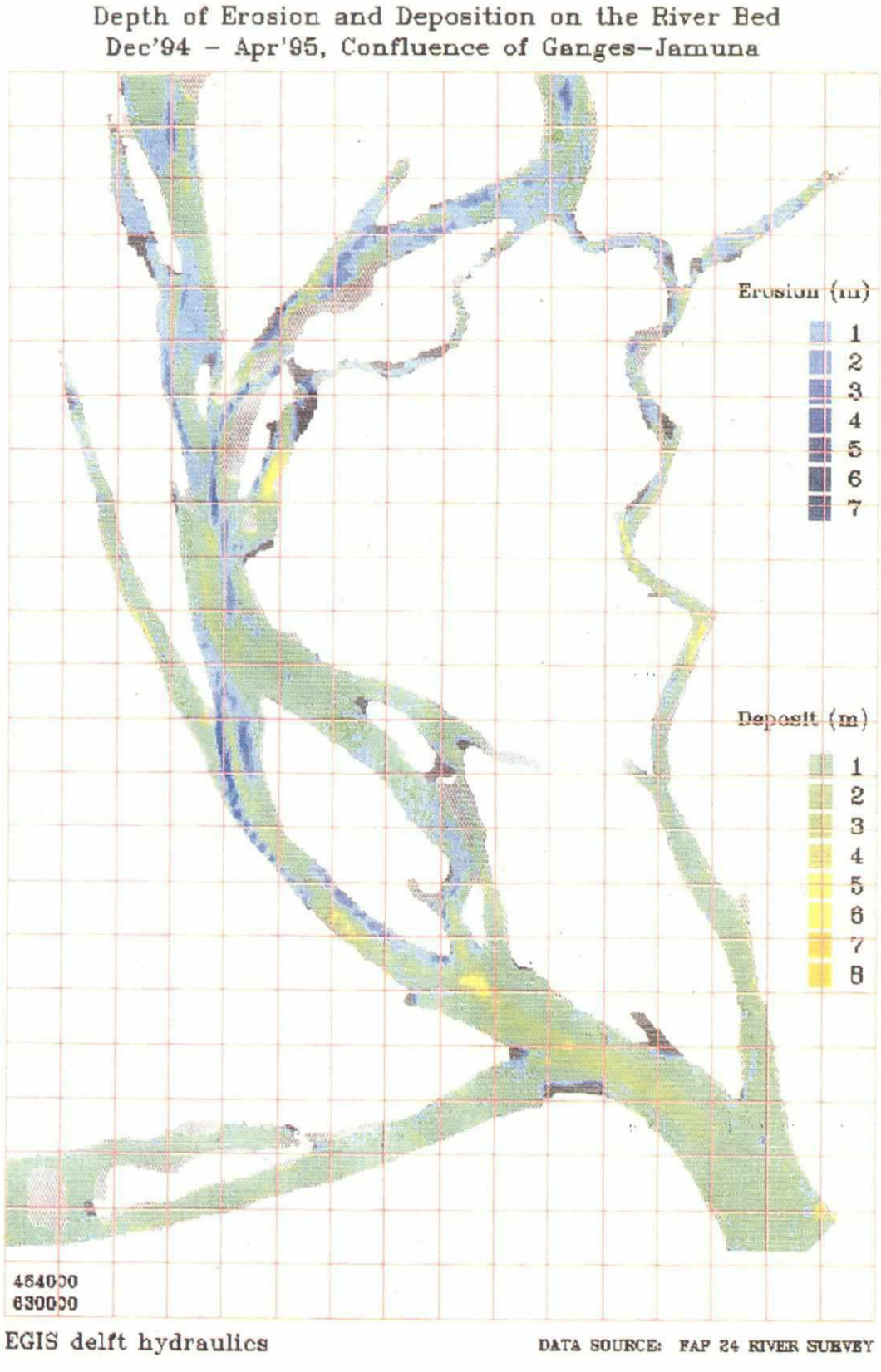


Figure 7.4 The results of the first four bathymetric surveys and the difference maps between the successive surveys are presented as follows:

f) Erosion/deposition December 1994 - April 1995

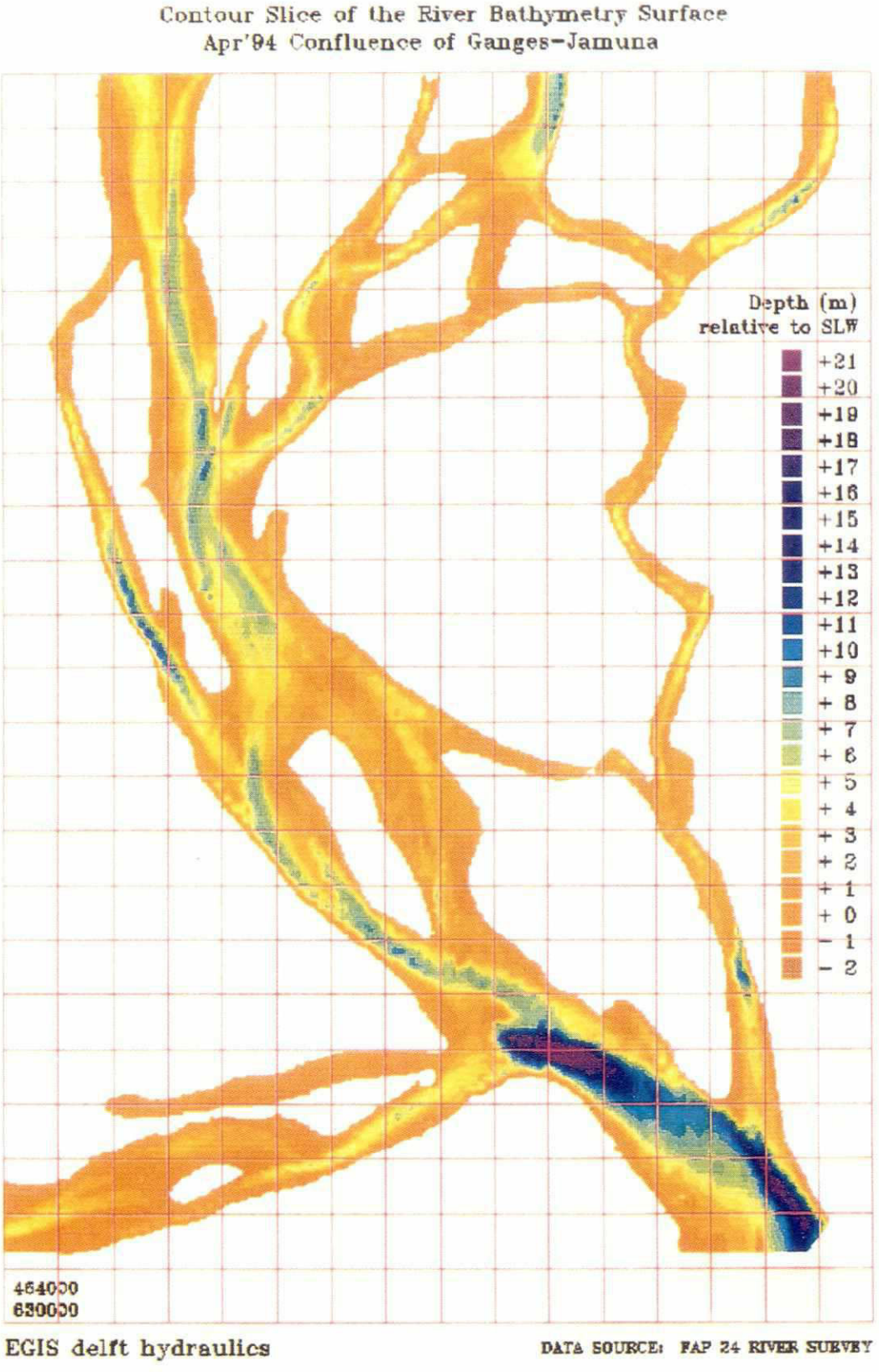


Figure 7.4 The results of the first four bathymetric surveys and the difference maps between the successive surveys are presented as follows:

g) Contour map of the confluence April 1995

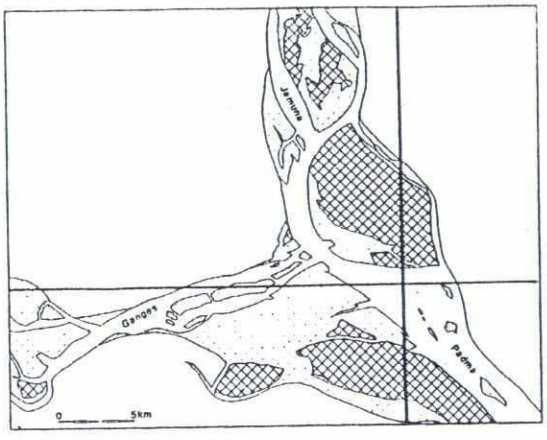
7.4 Planform evolution of the Jamuna-Ganges confluence

Parallel to the RSP project (and with some assistance from the project via the providing of satellite imagery) a brief study was carried of the planform evolution of the Jamuna-Ganges confluence. Here the results of this analysis are summarized. For more details reference is made to Steel (1995).

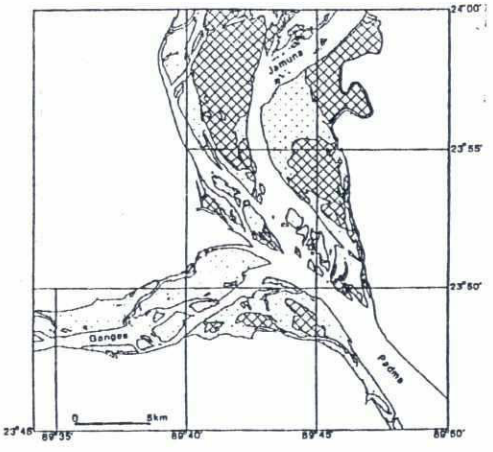
The confluence of the Ganges and the Brahmaputra exists at its present location only for about 200 years (Coleman, 1969). Some information is available from the period before 1973 via topographic maps. Since 1973 satellite imagery is available for almost every year and this is the basis for the analysis carried out by Steel (1995). Use was made of the classified imagery prepared under the Jamuna Bridge project and later FAP21 (see Klaassen & Masselink, 1992) supplemented by more recent SPOT imagery. Figure 7.5 shows the planform of the Jamuna-Ganges River in four different years during the period 1973-1995. In addition to the confluence and its location itself also the planform of the upstream river reaches were considered.

From the analysis of the maps prepared on the basis of these satellite images the following tentative observations can be listed (Steel, 1995):

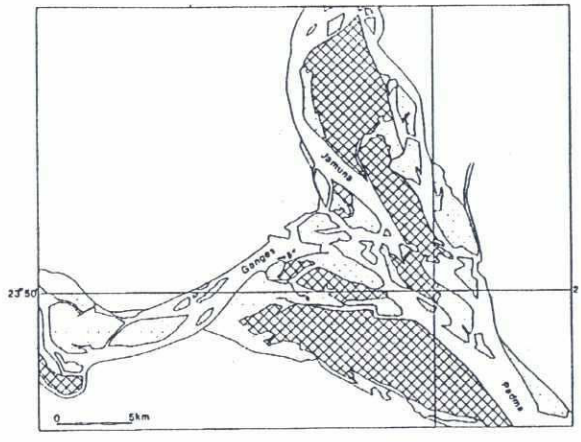
- The Ganges has maintained a slightly braided form through the whole period considered. The Jamuna appears to have increased its braiding intensity (in line with the observations of Klaassen & Vermeer, 1988) and complexity, and possibly as a result, chars have become more common at the meeting point of the rivers.
- Due to the increased braiding the braid belt of the Jamuna River has increased, whereas the width of the Ganges River in terms of unstable and low chars seems to have decreased.
- The Padma immediately downstream of the confluence provides an excellent example of a consistent nodal point. The Ganges node is clearest in 1973 (see Figure 7.5), when the river had more of a node/island reach form, but remains a recognisable feature in later years.
- Several years (especially 1973 and 1989) display a large area of unstable/low char on the Ganges -Padma corner, whose position and nature suggest formation of flood waters occurring across this corner. The boundary of the confluence becomes more stable after a number of years, but often retains one or more overflow channels.
- The movement of the Ganges' entrance to the confluence on a NW-SE axis, and likewise the Jamuna's entrance on an E-W axis and the results of these motions could be considered the most interesting confluence variables. See Figure 7.6. The Ganges' entrance occupied a northern position from 1973-1980, then shifted to a more southern position from 1983-1987, then moved further south for the period 1989-1994. The Jamuna only had one main channel in 1973, then for the period 1978-1986 had two large anabranches separated by a permanent char. From 1987 onwards the growth of a large bend in the eastern channel has dominated the planform. Apart from moving the channel meeting point of the rivers, these changing conditions have also influenced its form: for example the growth of a large char opposite the Ganges entrance is strongly associated with the growth of the meander to its north. Interpretation of the most recent data appears to suggest a possible future reversion of form to a state similar to the early 1980s.



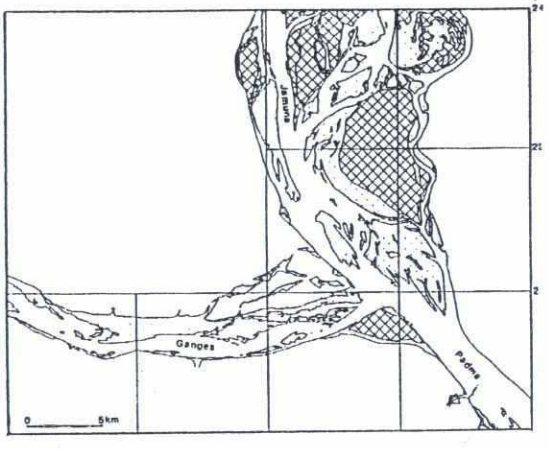
(a) 1973



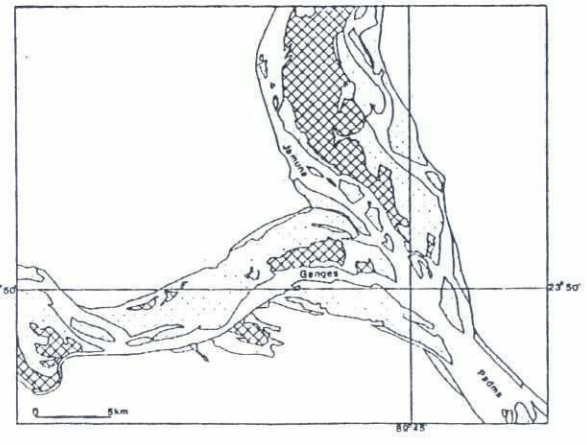
(d) 1989



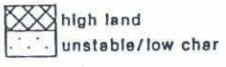
(b) 1978



(e) 1994



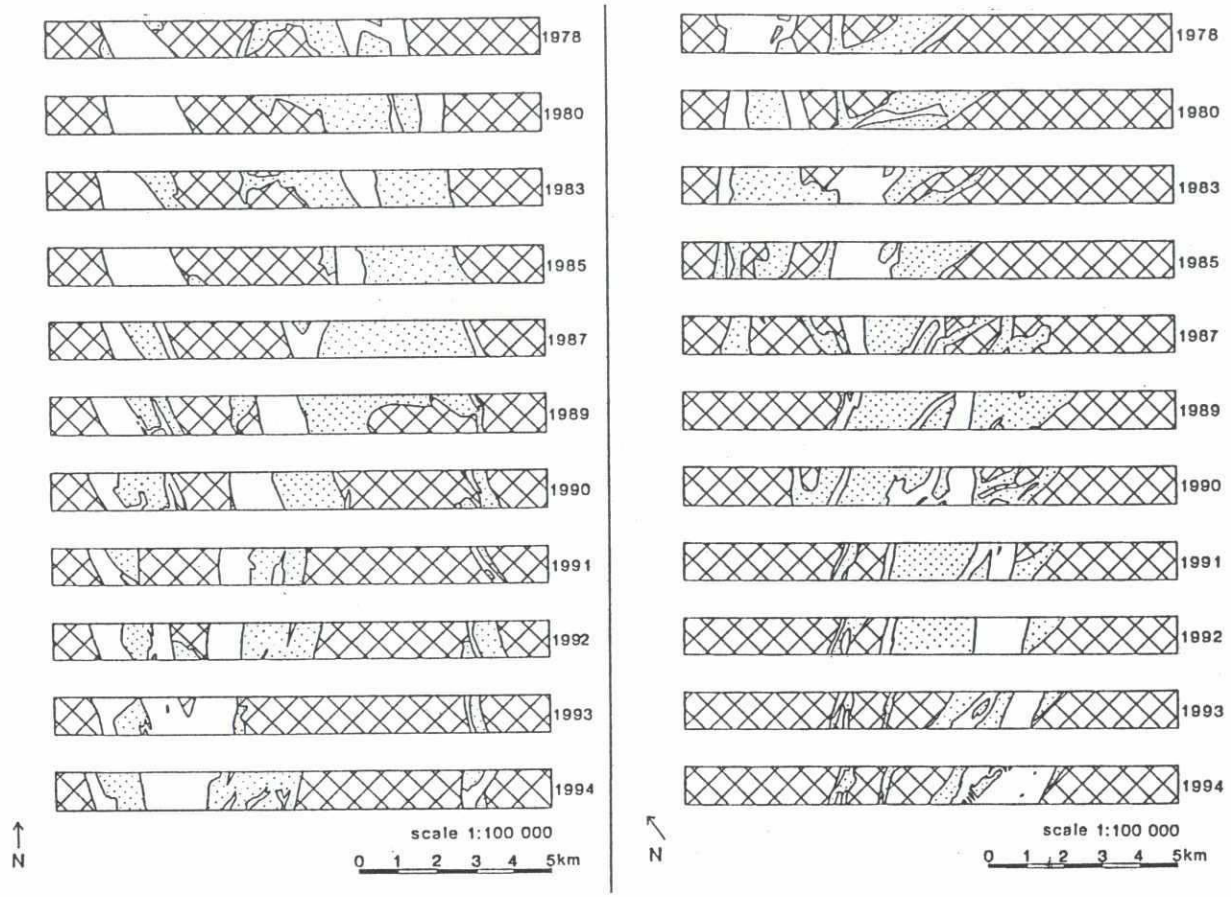
(c) 1983



Source: FAP24 Landsat & SPOT imagery

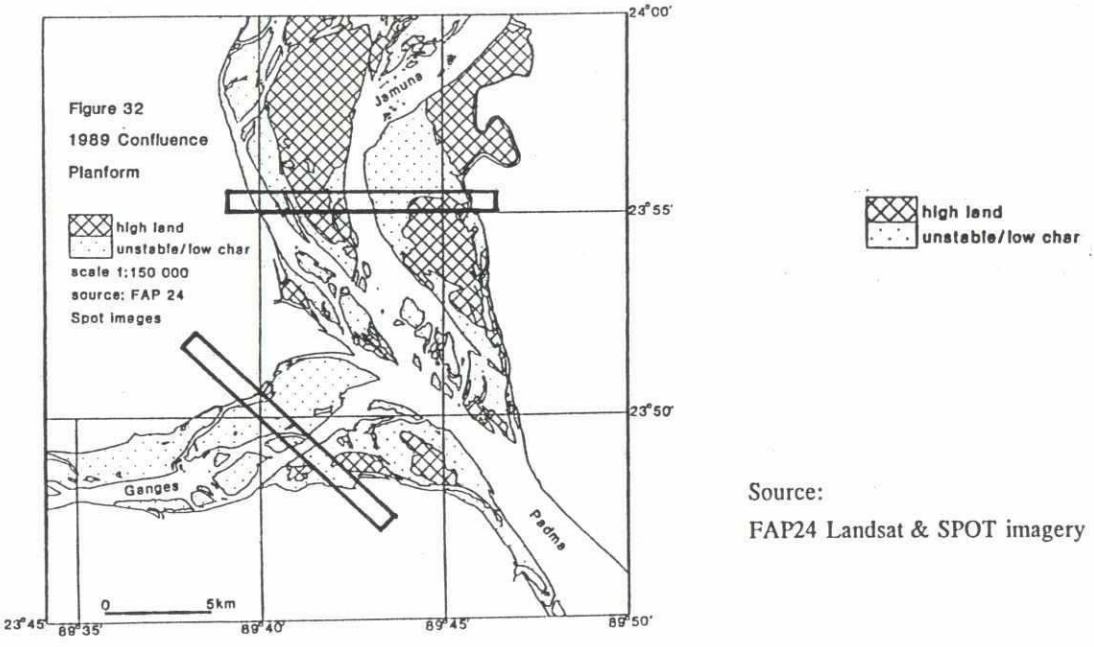
Figure 7.5

Planform evolution of Jamuna-Ganges Confluence (after Steel, 1995).



(a) Jamuna upstream of confluence

(b) Ganges upstream of confluence



(c) Location of reference cross-sections

Figure 7.6 Evolution of river reaches upstream of Jamuna-Ganges confluence (after Steel, 1995)

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7.5 Shape of the Jamuna - Ganges Confluence

7.5.1 Introduction

The confluence between the Jamuna and Ganges has been detailed in five bathymetric surveys between October 1993 and January 1996. This section presents a more detailed interpretation and observations on the junction morphology and its changes through this period, and in particular concentrate on the similarity of this morphology to past laboratory flume studies and research on river junctions of smaller size. The discussion is presented, for clarity and brevity, as a series of bullet points in two sections:

1) broad points concerning general patterns and changes over the entire survey period (see Figures 7.4(a) through 7.4(9), and
2) some discussion points specific to each survey period (see Figures 7.7 and 7.8).

7.5.2 General patterns and changes

- The general morphology of the confluence scour is similar to much past work conducted on both smaller river channels and in laboratory flumes (Mosley, 1976; Ashmore and Parker, 1983; Best, 1987, 1988; Klaassen and Vermeer, 1988; Bridge, 1993; Bristow et al., 1993; Biron et al., 1993; M^{c}Lelland et al, 1996). The bed morphology at all flow stages is dominated by: 1) a central junction scour (up to 21m below SLW) whose orientation approximately bisects the junction angle. Marked changes in depth occur at the junction entrance although the steepest angle of these slopes is approximately 4-5 degrees, unlike the angle-of-repose avalanche faces documented at channel junctions in previous studies (Best, 1988; Bridge, 1993; M^{c}Lelland et al., 1996), 2) a bar is present on the Ganges side of the post-confluence channel (see October 1993 survey especially) and may be related to both the curvature in the southern bank at the Ganges entrance and possible flow separation which has been found in these regions at smaller channel junctions (Best and Reid, 1984), 3) a region of higher elevation is also present at the junction apex (especially April 1995) and may be related to a flow 'stagnation zone' often present at these sites
- Although the confluence morphology is *broadly* similar to past work, it is far more complex than both previous model and field studies conducted on smaller rivers. Several features illustrate this morphological complexity:

1) the occurrence of a central scour, which has two 'centres' of deepest erosion (October 1993), probably related to the two distinct Jamuna channels which enter the junction (October 1993-December 1994). It can be seen that the scour hole becomes less bipartite and forms a longer linear scour in the later survey periods (April 1995 and January 1996) as the eastern Jamuna channel entering the confluence begins to infill, becomes shallower and presumably conveys a smaller discharge. More flow is concentrated into the main western Jamuna channel and the junction scour both becomes slightly deeper and simpler in its form. It can also be seen in some plots (e.g. April and December 1994, Figures 7.3, (c) and (e) that the scour extends upstream into the Jamuna. This is most likely a function of both the scour associated with the bend in the western channel of the Jamuna at the junction and the scour generated around a bar in the Jamuna just upstream from the junction,

2) the lack of distinct 'avalanche' faces at the junction entrance; this may be a function of the fine sand size and amount of sediment transported in suspension which may tend to lower these tributary mouth bar 'slipface' angles. Although past studies at smaller junctions in the Jamuna have documented leeside angles of up to 17 degrees (Bristow et al., 1993), this is not the case in any survey at the Jamuna-Ganges junction and it may be expected that the bed slopes into the Jamuna-Ganges confluence scour will be covered with a range of dune bedforms. Lower leeside angles than the angle-of-repose are also common to many dunes in the main rivers of Bangladesh,
3) the higher relative scour depth as compared to past studies (see Section 7.9), and,
4) the marked seasonal variation in scour and deposition which may be controlled largely by the non-coincident flood hydrographs and changing discharge ratio (see Figure 7.3 and discussion below).

- The bed scour responds to changes in discharge ratio in several distinct ways:

1) bed scour occurs in the flood season with deposition during low flow; this can be witnessed by the increased scour during the 1994 and 1995 flood hydrographs.
2) some surveys (especially December 1994 and January 1996) show clear deposition at the mouth of the Ganges channel as a wedge of sediment has prograded into the junction scour - by January 1996 (Figures 7.7 and 7.8) this has possibly aided migration of the scour downstream by approximately 1 km (the scour hole migration may also be related to the dominance of the Jamuna earlier in the year at the very high 1995 discharges); it appears this progradation of sediment from the Ganges is related to the non-coincident flood hydrographs between the two channels which results in marked changes in discharge ratio through the flood season. In particular, the Ganges flow becomes dominant after that of the Jamuna and the discharge ratio (expressed as the ratio of the Ganges:Jamuna discharge) becomes very high late in the flood season (Figure 7.3). It is suggested that this generates progradation of the Ganges sediment, or tributary mouth bar, into the junction, a feature noted in past work on smaller rivers (Reid et al., 1989) and in the laboratory (Best, 1988). This sediment may be deposited in a scour hole that has radically changed in position and depth in the previous stages of the flood hydrograph (see Figures 7.7 and 7.8 for changes between April 1995 and January 1996).

- The scour originating at the junction apex is displaced towards the Ganges side of the channel in October 1993, April 1994 and January 1996. This again may be related to the dominance of the Jamuna flow which is more influential both in the earlier parts of the flood season and for a greater percentage of the high flow period (Figure 7.3). This may generate scour displaced to the south of the junction when the discharge ratio is low (Jamuna dominant) followed by some infill of the scour as the Ganges rises (high discharge ratio) and possible enhanced scour to the north side of the confluence. The alignment of the scour is also mirrored by the position of the mixing layer between the two rivers evident in the SPOT images of November 1994.
- Although past work has shown the reliance of scour depth upon discharge ratio (in addition to other factors such as junction angle, channel geometry, sediment load etc.), the changing discharge ratio at the junction, combined with the spacing between surveys, results in there being little justification for examining the depth of scour as a function of discharge ratio, especially at the time of the survey. The formative flows for erosion and major infill of the scour lie during the flood hydrograph. These rapid changes in discharge ratio result in a more complex bed topography and temporal response to changing relative discharges than representation by one simple discharge ratio during the period between surveys.

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7.5.3 Observations per survey:

October 1993

- scour bifurcation at junction apex - possibly due to either non-coincident flows during last flood season or channel curvature in Jamuna and scour downstream of mid-channel bar in Jamuna upstream from confluence
- scour shallows in middle of channel and then re-establishes at the northern edge of junction downstream - the bipartite bed scour is associated with major and minor Jamuna channels
- scour on west of main Jamuna due to sinuosity in Jamuna - flow, and sediment transport, is therefore asymmetrical at the junction entrance (the same feature occurs to a lesser extent in the in Ganges to south)
- large positive elevation on Ganges bank in post-confluence channel - bar possibly linked to channel curvature or flow separation

April 1994

- distinct scour still present with two deep centres linked to two Jamuna channels
- infill at head of Ganges main channel (progradation of Ganges sediment)
- infill at centre of junction during low flow
- infill of stagnation zone area together with deepening of western Jamuna channel - thalwegs in western Jamuna channel and scour become more connected as the stage falls
- infill of eastern Jamuna channel

December 1994

- significant erosion of deepest scour and erosion/extension of the scour up into the Jamuna on the western side
- marked progradation of the Ganges sediment into the scour and deposition at southern side of Ganges mouth
- significant erosion on the south side of the scour - erosion into 'separation zone' bar
- some infilling of scour to east of main scour (scour associated with eastern Jamuna channel)
- scour continues upstream from main scour but is connected to flow around upstream bar, especially deepening of thalweg/convergence around upstream mid-channel bar

April 1995

- infill at scour apex (may be related also to infill at downstream end of upstream mid-channel bar)
- continued narrowing of eastern Jamuna channel

January 1996

- significant deposition (10m) in scour and erosion (16m) as scour shifts both down-stream and to the south
- deposition at mouth of Ganges (4m) on south side of river due to progradation of Ganges sediment into junction (associated with late Ganges flood peak)
- significant scour (~6m) on west side of Jamuna at junction
- continued infill of eastern Jamuna channel with scour hole continuing to become less bipartite in shape

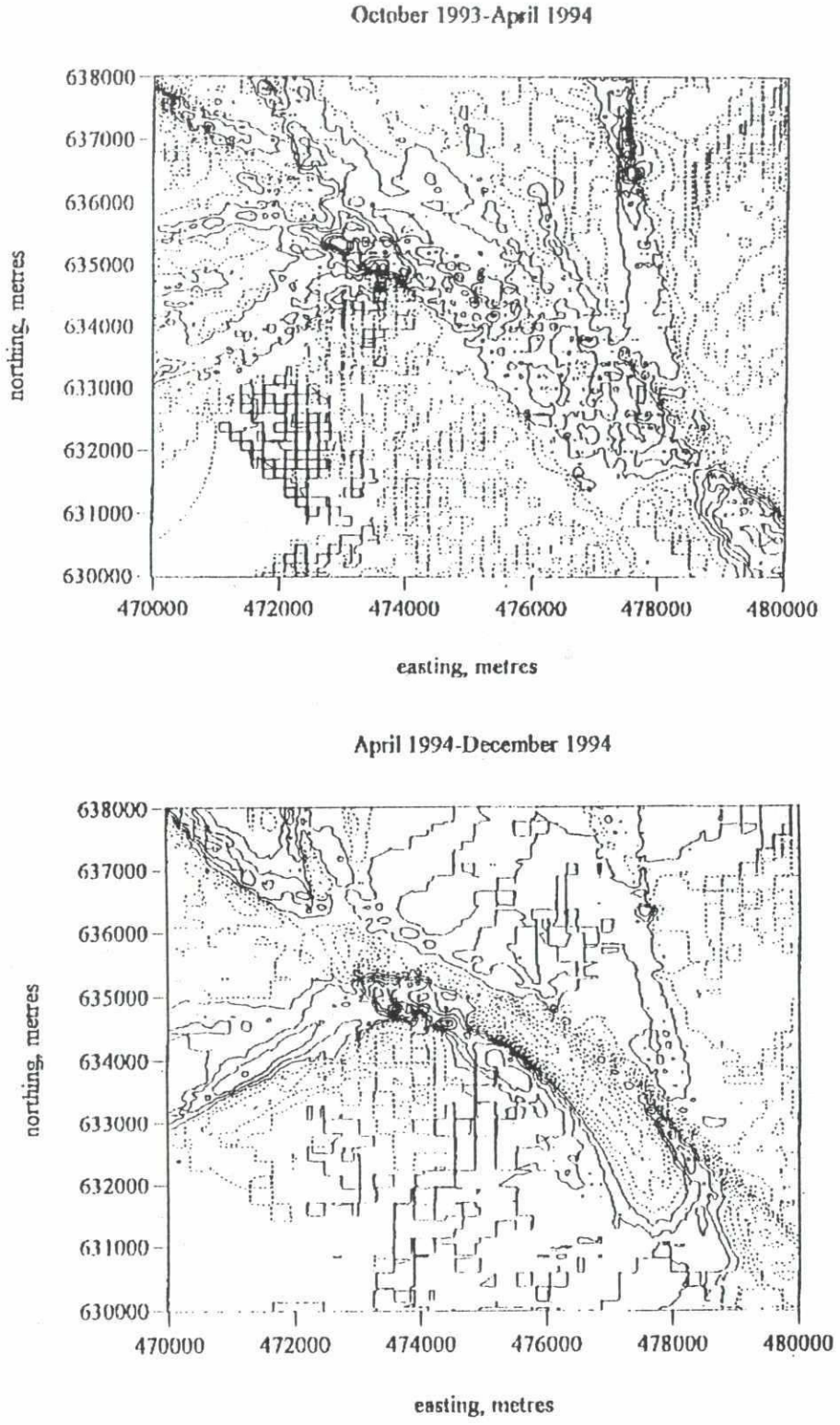


Figure 7.7: Morphological change maps of the Ganges-Jamuna junction between the five bathymetric surveys for an area including the junction (630000-638000N; 470000-480000E). On each map the relative height difference between each survey is expressed as contours at 2 metre intervals. The dashed lines represent values below zero (i.e. erosion) whilst the solid lines represent deposition. The first solid line (0 metres) represents no change in bed elevation. Maps were produced through kriging of original dataset based on a 25m sampling grid and a spherical interpolation routine.

a) October 1993 - April 1994

b) April 1994 - December 1994

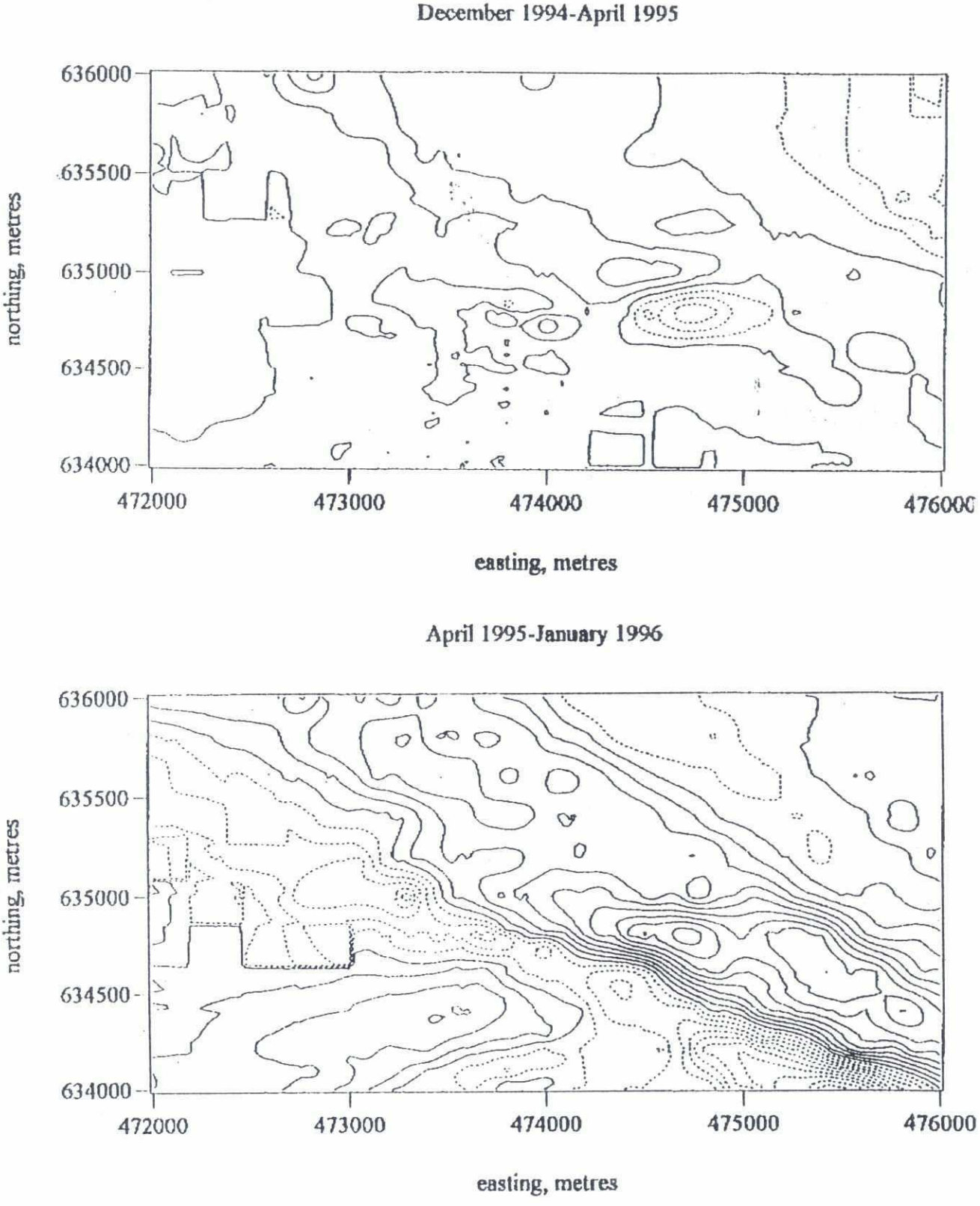


Figure 7.7: Morphological change maps of the Ganges-Jamuna junction between the five bathymetric surveys for an area including the junction (630000-638000N; 470000-480000E). On each map the relative height difference between each survey is expressed as contours at 2 metre intervals. The dashed lines represent values below zero (i.e. erosion) whilst the solid lines represent deposition. The first solid line (0 metres) represents no change in bed elevation. Maps were produced through kriging of original dataset based on a 25m sampling grid and a spherical interpolation routine.

c) December 1994 - April 1995

d) April 1995 - January 1996

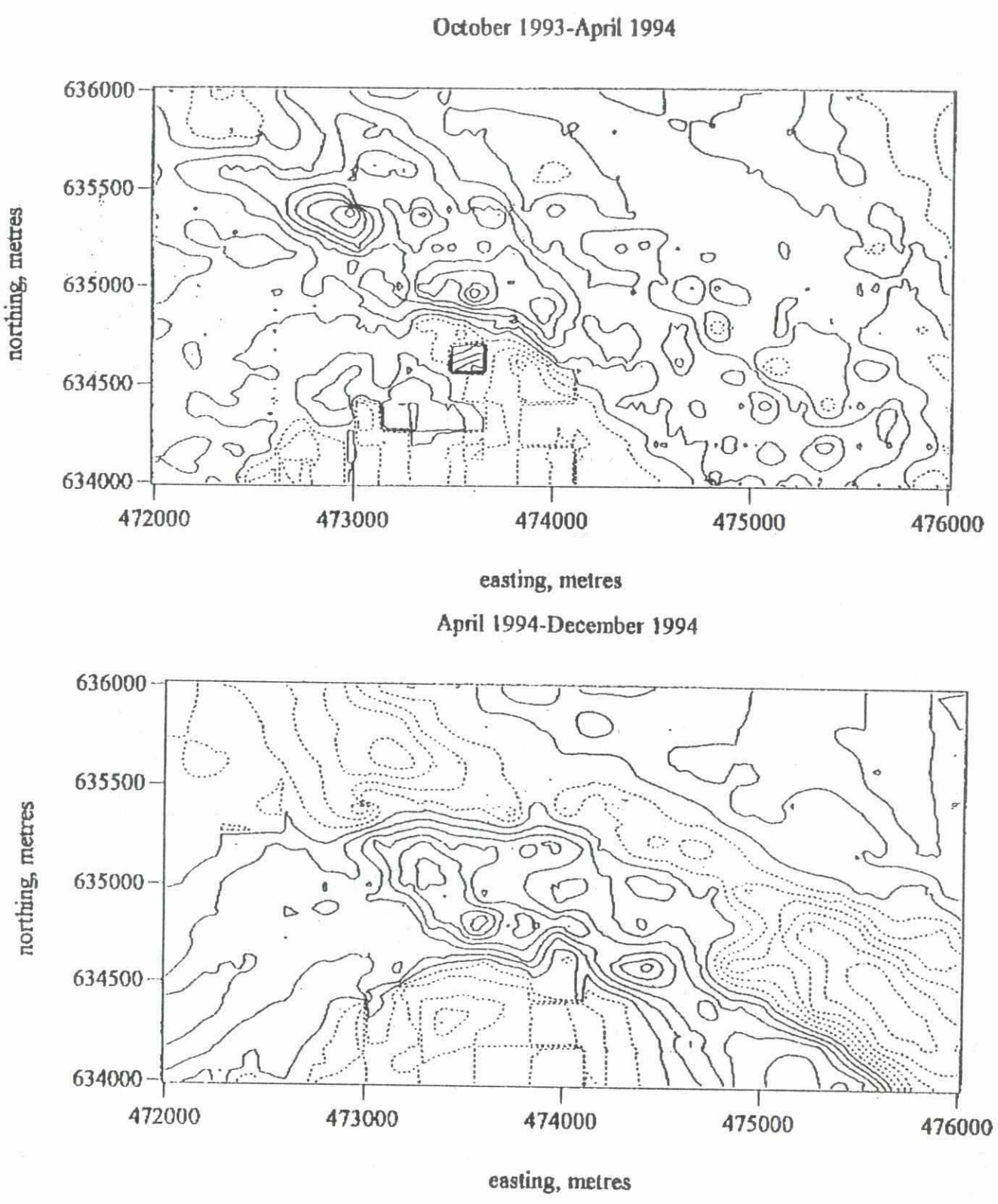


Figure 7.8 Morphological change maps of the Ganges-Jamuna junction between the five bathymetric surveys for a detailed area of the main junction scour (634000-636000N; 472000-476000E). On each map the relative height difference between each survey is expressed as contours at 2 metre intervals. The dashed lines represent values below zero (i.e. erosion) whilst the solid lines represent deposition. The first solid line (0 metres) represents no change in bed elevation. Maps were produced through kriging of original dataset based on a 25m sampling grid and a spherical interpolation routine.

a) October 1993 - April 1994
b) April 1994 - December 1994

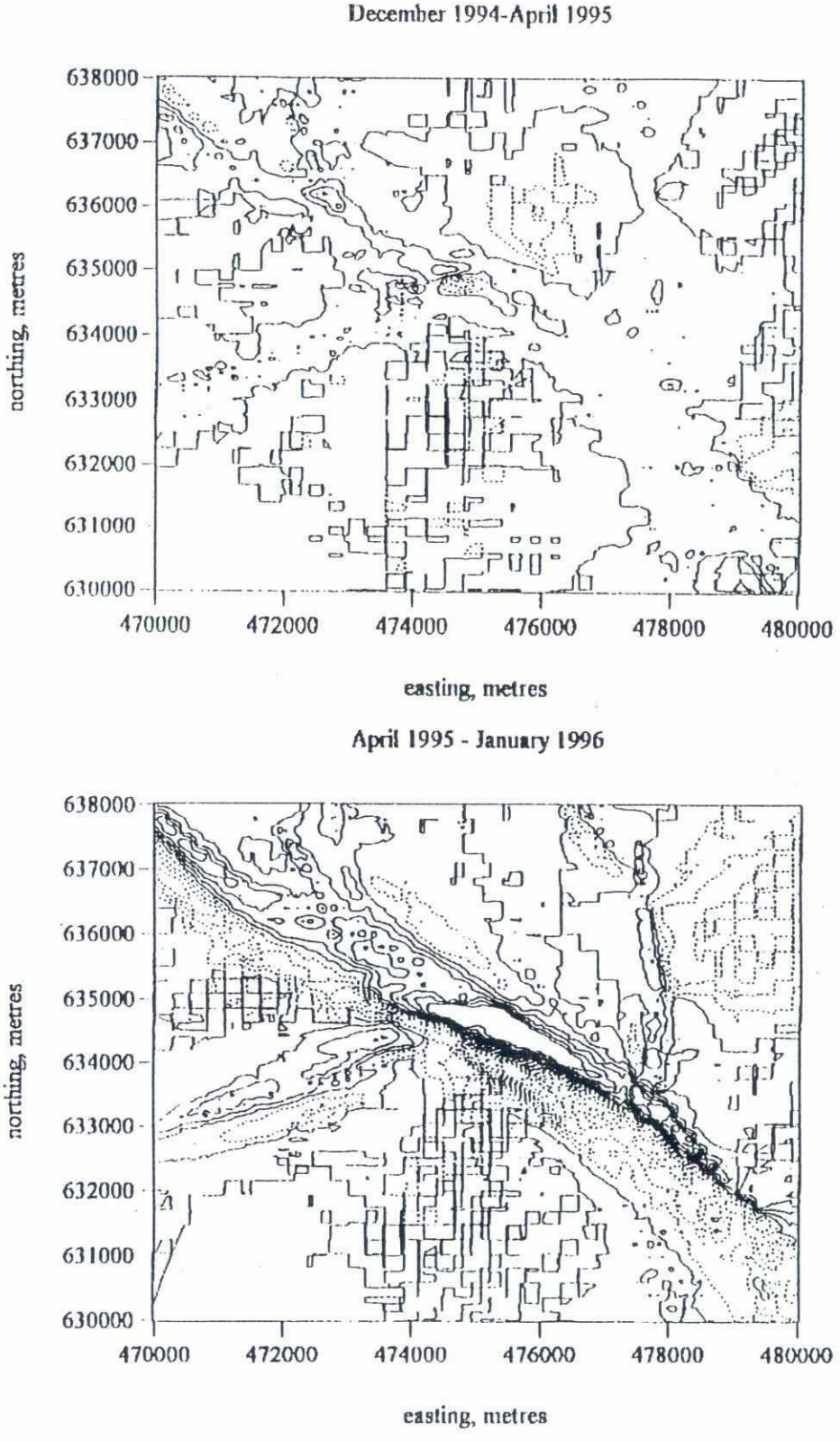


Figure 7.8 Morphological change maps of the Ganges-Jamuna junction between the five bathymetric surveys for a detailed area of the main junction scour (634000-636000N; 472000-476000E). On each map the relative height difference between each survey is expressed as contours at 2 metre intervals. The dashed lines represent values below zero (i.e. erosion) whilst the solid lines represent deposition. The first solid line (0 metres) represents no change in bed elevation. Maps were produced through kriging of original dataset based on a 25m sampling grid and a spherical interpolation routine.

c) December 1994 - April 1995

d) April 1995 - January 1996

8 Bars and bifurcations

8.1 Introduction, definitions and objectives

Braided reaches of the main rivers of Bangladesh contain many different types and size of bar (Coleman, 1969; Bristow, 1987; Klaassen and Masselink, 1992; Klaassen et al., 1993; Peters, 1993; Thorne et al., 1993), one of the most common being the mid-channel bar which is associated with flow divergence immediately downstream of a confluence or node of flow convergence (Klaassen et al., 1993; Thorne et al., 1993; Mosselman et al., 1995). A mid-channel bar may be defined as an accumulation of sediment which is unattached from the cut banks. Bar width scales with wetted channel width (Parker, 1976; Tubino, 1991; Yalin, 1992) but bar height is independent of local water depth (unlike dunes - see Annex 4, Chapter 3) and bars often become emergent via anabranch incision without a change in flow stage or discharge (Leopold and Wolman, 1957; Ashmore, 1982).

Recent work in sand and gravel-bed rivers across a range of scales has shown that mid-channel bars are one of the fundamental building blocks of braided rivers (Church and Jones, 1982; Ferguson, 1993; Ashworth, 1996) because they control local flow structure (M^{c}Lelland et al., 1996; Richardson et al., 1996), sediment transport distributions (Laronne and Duncan, 1992; Lane et al., 1995), channel scour and deposition (Goff and Ashmore, 1994), bank erosion (Mosselman, 1995; Parker, 1996), channel avulsion (Cheetham, 1979; Ashworth and Ferguson, 1986; Leddy et al., 1993) and, ultimately, the evolution of channel pattern (Carson and Griffiths, 1987; Murray and Paola, 1994). These diagnostic features all apply to mid-channel bars in the main Bangladeshi rivers (Peters, 1993) and therefore quantification of the rate, form and flow processes responsible for bar growth and emergence is a prerequisite for successful prediction of bed scour, bank retreat and channel evolution.

The study of bars was performed through two FAP24 projects. The first, concentrating on bar initiation and early stage growth, was undertaken by the University of Leeds. The second, concentrating on late stage bar evolution, was undertaken by the University of Nottingham.

8.2 Bar Initiation, early stage growth and associated flow patterns

8.2.1 Objectives

The main objective of this study topic is to improve understanding of the role of braid bars in the morphological behaviour of the Bangladeshi rivers. Specific objectives are to quantify:

- morphology and dynamics of bars;
- time and stage dependency of bar growth and its impact on local and downstream channel change;
- flow structure associated with mid-channel bar growth;
- role of dune bedforms in the process of bar growth.

This study is closely linked to studies on bedform dynamics carried out together with the University of Leeds in the same study area (see Annex 4, Chapter 3).

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8.2.2 Data sources

A special study site was identified in November 1993 for monitoring bar growth and changes in channel morphology. The site is approximately 6 km north-west of Bahadurabad, bounded by BTM co-ordinates N780000→N788000, E467000→E472000 (Figure 8.1a). The site was selected because (1) it was a zone of potential mid-channel bar growth since the main channel was downstream of a significant flow convergence (Figure 8.1a), (2) it possessed a relatively 'simple' channel configuration with a parabolic cross-section and no other actively aggrading bars nearby, (3) it lies within the zone of the Bahadurabad bathymetric survey, and (4) it is of strategic importance being adjacent to the navigation cross-channel to Phulchari and immediately upstream of both Bahadurabad ghat and the new FAP21 embankment scheme.

Data on bed morphology were obtained from a combination of bathymetric and special surveys using conventional echo-sounding and DGPS techniques (see Annex 1). Bathymetric lines run West→East at 100 m spacing and cover a 20 km^2 area (see Chapter 13). For the special surveys, a series of transect lines was established perpendicular to the local flow direction (58°) and spaced 250 m apart (Figure 8.1b). These lines were usually supplemented by three lines parallel to flow (148°) over the study bar and in the left and right anabranches. The number of special survey transects was progressively increased during the study period to cover the downstream migration of the study bar and associated channel changes (Table 8.1). Bed surveys were undertaken at different times of the flood hydrograph (i.e. rising, peak and falling limbs, Figure 8.1c) to quantify the temporal variability in channel change and bar aggradation during the monsoon season (see Sections 8.3 and 8.4). Ship surveys were supplemented by EDM land surveys over emergent parts of the study bar in March 1995 and February 1996. All special surveys were undertaken by the DHA vessel.

Survey period	Survey type	Water Level* m	Number of survey lines
10-18 November 1993	Bathymetric	15.48	90+
10-14 August 1994	Special Survey	17.86	19
19-20 September 1994	Special Survey	17.56	11
1-10 November 1994	Bathymetric	15.18	90
24-27 February 1995	Bathymetric	13.03	90
7-8, 13 March 1995	Special Survey	13.18	21
25-26 June 1995	Special Survey	19.25	19
4-25 July 1995	Bathymetric	19.65	90
31 July, 1 August 1995	Special Survey	18.52	20
12-16 September 1995	Special Survey	17.86	27
11-25 November 1995	Bathymetric	15.52	90
24-26 February 1996	Special Survey	13.22	38
X-X? March 1996	Bathymetric	X?	90

* SLW at Bahadurabad is 12.03 m + PWD
\+ Only bathymetric lines between N779000 and N788000 are used to produce the bed topographic maps

Table 8.1 Source of data for monitoring bar growth and morphology, Bahadurabad, 1993-1996.

Flow velocity data were obtained from ADCP (300 kHz) profiles taken along special survey lines (see Annex 1 for a detailed description of these techniques). Velocities from each 0.5 m vertical bin were reduced to produce the resolved primary velocity vector and relative backscatter intensity. Secondary flows were not computed because of the difficulty in defining a common plane of reference in strongly non-uniform flow (though see McLelland et al., 1994 and Richardson and Thorne, SPR-16).

Topographic and velocity data were contoured using the Spyglass® visualisation package with a 25 m grid and kriging parameters that used a spherical distribution model, a variance of unity and 150 samples per kriging pass. The interpolation used between 11,672 (September 1995, Special Survey) and 346,000 (July 1995, Bathymetric Survey) individual bed survey points. The mean water level for each survey period was used to define the bank edges for each topographic map. Rates of erosion and deposition were digitised from superimposed cross-sections adjusted to a common 'Start of Line' (SOL) position. The minimum pixel size was 2.01 m^2.

Likely sources of error in the data collection and analysis are: (1) standard measurement error associated with the survey instruments (see discussion in Annex 1), (2) underestimation of erosion and deposition rates because of short-term scour and fill events (i.e. between survey periods), and (3) smoothing of abrupt changes in topography by the contouring package. The consistency of channel change at the special survey site suggests that the frequency of surveys was adequate, but, because the sediment transport rate is so high in the Jamuna, some minor channel scour and fill events will undoubtedly be missed (see discussion in Peters, (1993)). The implication of this for the morphological estimate of sediment transport rates is elaborated in Section 8.4.

8.2.3 Bar types and permanency

Bar and bank edges were traced from successive, bi-annual SPOT images (sheet 78, G11 and G12) for low (March) and high (September) flow for the period March 1991-March 1995 (see Figures and discussion in SPR-09). Bar types are predominantly 'unit' or 'longitudinal' bars (Smith, 1974; Church and Jones, 1982; Rundle, 1985) with a rhomboidal planform. Isolated mid-channel bars are less common in the Jamuna than bars associated with lower channel hierarchies (Bristow, 1987) which tend to accumulate into 'compound' or 'mosaic' bar complexes (Bluck, 1979) with a central portion of higher, vegetated, 'permanent' char surrounded by more mobile 'temporary' chars (Thorne et al., 1993). Sinuous anabranches often develop an inner point bar, which may become a mid-channel bar through chute-cutoff at high flow (Ashmore, 1991; Welford, 1994, Richardson and Thorne, SPR-16). Bar migration and reworking occurs predominantly through erosion of the barhead and deposition at the bartail (Figure 8.2) although upstream accretion onto the barhead is also common (Bristow, 1987; Lisle et al., 1991). Major bar complexes are rarely destroyed entirely as shown in Figure 8.2. Migration rates of mid-channel bars are typically < 500 m yr^{-1}. The close correlation between areas of erosion and deposition for individual bars in the 55 km long G11-12 reach implies there is little short-term *net* aggradation in the braid belt. There is a suggestion that smaller, isolated, mid-channel bars (< 2 km long, see bars labelled A in Figure 8.2) move at faster rates than the larger (> 5 km long) bar complexes. Analysis of successive SPOT images (see SPR-09) indicates that bars may be completely reworked as they pass through major nodes of flow convergence or channel confluences (see also Annex 5, Chapter 7.8). New bars are commonly created by lateral accretion onto existing attached bars

(Bluck, 1979, see bars labelled B in Figure 8.2), by mid-channel deposition downstream of zones of significant bank erosion (Mosselman, 1995) or through rapid deposition downstream of a major flow constriction (Rundle, 1985; Macklin and Lewin, 1989 - see Mawa River example).

8.2.4 Morphological development of mid-channel bars

Figures 8.3a-i illustrate the sequence of channel change at the special study site for selected periods between November 1993 and March 1996. All topographic data are reduced to SLW. The five transect lines that cover the zone of bar aggradation, together with two frequently surveyed lines immediately downstream, are plotted in Figures 8.4a-e for successive special surveys.

The study site is downstream of a major zone of flow convergence (see Figure 8.2) and in November 1993 the main channel thalweg was ~1 km wide with a low sinuosity and a simple parabolic cross-section (Figure 8.3a). Analysis of SPOT images from 1991 onwards (see SPR-09) suggests that this channel configuration has been stable for a number of years. During the peak flows of 1994 (Figure 8.1c) the main channel widened to ~2 km and deposited a symmetrical, narrow, mid-channel bar ~ 1.5 km long at a maximum height of +2.9 m SLW (Figures 8.3b and 8.4a). The reach established a marked pool-bar-pool morphology as is characteristic of the initial stages of braiding (Ferguson and Werritty, 1983; Ashmore, 1991). Figure 8.3b suggests that the mid-channel bar initially developed as a central bar core and then grew by downstream accretion, as described by Leopold and Wolman (1957). This downstream growth occurred through migration of accretionary dune fronts across the bar top/margin (Figure 8.7a), possibly in response to fluctuations in the hydrograph (Figure 8.1c). The flow structure associated with this period of bar growth is described in Section 8.2.5.

During the recession limb of the 1994 hydrograph the study bar deposited around its central core to create a broad bartop platform ~1 km wide. This was accompanied by incision of both anabranches by up to 7 m (Figures 8.3c and 8.4a). This pattern of bar growth is again consistent with the classic description of braiding by Leopold and Wolman (1957), who observed that bar emergence is usually aided by anabranch incision after initial central bar deposition. The broadening of the bar morphology is associated with development of strong secondary flows in the well-defined anabranches on either side of the bar which are responsible for lateral sediment transport and accretion at the bar margins (see Section 8.2.5 and descriptions in Bristow, (1987); Ashworth et al., (1992); Bridge, (1993) and Richardson and Thorne, (SPR-16)). These secondary flows also cause formation of two bartail limbs (cf. Cant and Walker, 1978) which extend downstream from the main bar nucleus (Figures 8.3c and 8.5a), creating a sheltered, low velocity zone where significant volumes of fine sediment can accumulate. Peters (1993) suggests that deposition in such backwater areas may lead to formation of highly cohesive "clay plugs". Grain size analysis of two volumetric bed samples taken in the bartail of the study bar reveals 7.8 and 11.0% clay and 84.4 and 87.7% silt, respectively, both with a median grain size, (D_{50}) of 0.011 mm (see SPR-09). This indicates that the sediment trapped in zones of low velocity are dominantly fine silts which represent the finer fractions of the wash load (D_{50} = 0.042 mm, SPR-14, Table 1c) but with sufficient quantity of clay to impart some cohesivity to the sediment. Inspection of Jamuna SPOT images reveals this mid-channel bar morphology is extremely common (the fine-grained sediments trapped in the bar tails often being used for intensive rice production (cf. Peters, 1993)) and

the high preservation potential of this cohesive plug may be responsible for the long-term storage (depending on bar residence time) of the finest fractions of the sediment load.

The immobility of these cohesive sediments increases their preservation potential when the barhead migrates downstream. This feature is supported by results from a programme of 100 MHz ground penetrating radar surveys on the bartop in February 1996 which revealed the preservation of a 0.5-0.75 m thick fine-grained layer (i.e. a strong radar reflectance) at approximately 6 m depth at the original site of bartail accretion (transect BT5X026, see Figures 8.1b and 8.5a) which had subsequently been overridden by the downstream migrating barhead (Figure 8.5b).

During the dry season of 1994-95 (Figure 8.3d) there was negligible channel change and only minor aeolian reworking of the exposed bar surface. The full cycle of bar creation, aggradation, accretion and emergence therefore took place during a single monsoon season and did not involve any downstream migration, as also observed by Leopold and Wolman (1957).

Land survey in March 1995 showed the bar surface morphology to be dominated by two dune fields that terminated in an abrupt accretionary front up to 3 m high (Figure 8.5a) and which were bordered by 0.5 high dunes wrapping around the bar margin. This accretionary front, with an avalanche face at the angle of repose, was also observed as it migrated over the bartop during the August 1994 survey (see Section 8.2.6 and Figure 8.7a). The start of the 1995-96 monsoon runoff initiated a period of progressive lowering of the bartop (by up to 6m) and infilling of the eastern anabranch (Figures 8.3e and 8.4b). This is a common mode of development whereby the bartop flow reactivates the previous year's waning flow dune deposits (up to 4 m thick – see Section 8.2,6) and one anabranch eventually takes over as the dominant channel for bed material transport (Hoey and Sutherland, 1991; Ashmore, 1993). The special survey conducted a month later (Figure 8.3f) shows that this pattern of rapid east anabranch aggradation is reversed and the channel re-scours to its former level (Figure 8.4c). Such a rapid switch between local scour and deposition has been observed in other braided rivers (e.g. Ashworth and Ferguson, 1986; Hoey and Sutherland, 1991; Goff and Ashmore, 1994) and is associated with the downstream migration of major bar complexes through the channel network (such as the attached bar centred on E470000, N785000, Figure 8.3e). Mobilisation of this attached bar complex may have been aided by the very high July peak discharge (see SPR-XX) which also caused up to 400 m of bank erosion of the 'permanent' char that borders the west anabranch (see Figures 8.3e and 8.3f and the cross-sectional changes at sections 30 and 28 in Figure 8.4c). Even during this period of significant channel change the study bar maintained its basic symmetrical morphology and remained fixed in its original position (although the bartail aggraded and extended downstream).

The 1995 monsoon hydrograph remained at a high level into late September (Figure 8.1c) and continued to cause significant channel change. The bed scour associated with the reactivation of the eastern anabranch propagated from section 25 (Figure 8.4c) down to beyond section 26 (Figure 8.4d). The downstream scouring of the eastern anabranch supplied sediment to promote bartail growth (~ 800m) and lateral accretion (~ 200m) into the western anabranch (Figure 8.4d). This deposition occurred as the thalweg of the main channel developed a sinuous planform with flow in the eastern anabranch crossing over to the west via a shallow depositional zone at the tail of the study bar. The morphology of this cross-over point is highlighted by the ground penetrating radar survey in February 1996 which showed 3 m

high prograding slip faces, dipping east to west, superimposed by low amplitude dunes (see Figures 8.5b and 8.7b). The concentration of flow into the west anabranch after passing over this depositional front led to bed scour (~2m) and more right bank retreat (~200m) immediately downstream (Figure 8.4d). The general pattern of channel change is similar to the model described by Ferguson and Werritty (1983, Figure 3, p. 185) for the braided River Feshie with scour pool enlargement and extension, oblique riffle growth and progradation and the overall development of a sinuous thalweg planform. The study bar remains in its original position during this channel evolution but grows at the bartail through deposition at the cross-over point between the east and west anabranches.

During the falling limb of the hydrograph, the eastern anabranch continued to incise at its southern end and initiated new bar growth immediately downstream (Figure 8.3h). The study bar widened by ~200m (as also observed on the hydrograph falling limb in 1994) but shortened by ~800m as the east anabranch straightened and preferentially supplied sediment to the new mid-channel bar downstream.

The final bathymetric survey in March 1996 (Figure 8.3i) shows a deepening and narrowing of the scour hole that supplies sediment to the study reach and further downstream extension of the east anabranch (Figure 8.4e) to a point where it begins to divide again into two separate anabranches around the new mid-channel bar just upstream of Bahadurabad ghat. The study bar is still in the same position as the first stage of bar growth in August 1994 (Figure 8.3b) but it is difficult to quantify the change in bar height because land surveys are not available (hence the lower interpolated height in Figure 8.3i). Both the west anabranch around the study bar and the Phulchari cross-channel have infilled (Figure 8.3i) and the morphology of the study reach resembles a point bar and chute cut-off channel pattern (see Richardson and Thorne, SPR-16). The west anabranch downstream of the study bar continues to scour and propagate downstream aided by the flow divergence around the new mid-channel bar. This has ramifications for the downstream Bahadurabad ghat which is now a focus of major bank retreat.

Table 8.2 summarises the temporal change in erosion and deposition rate for the seven transects shown in Figures 8.4a-e (the spatial pattern is elaborated in SPR-09). Although periods of rapid, short-term scour and fill may have been missed by the surveys (Peters, 1993) the consistency of the mode and magnitude of channel change between successive transects suggests this may only be a minor source of error. It should be noted that because the transect lines are of different lengths within and between each Special Survey, the rates of erosion and deposition are also expressed as per unit length of transect line. This enables quantification of the temporal change in erosion and deposition and the approximate sediment budget for the study reach. Table 8.2 clearly highlights two features: (1) channel change in the zone of bar growth and evolution is strongly stage dependent with no apparent lag in erosion or deposition rates and a 'background' falling and low stage erosion and deposition rate of ~0.12 $m^2\ m^{-1}\ yr^{-1}$, and (2) there is no net aggradation or degradation of the study reach with a very close match (r^2 = 95.3%) between the rates of erosion and deposition. This suggests positive feedback between bar growth and local anabranch scour and widening (cf. Ashworth and Ferguson, 1986; Laronne and Duncan, 1992).

Special survey period	Erosion rate $m^2\ yr^{-1}$	Transect line erosion rate $m^2\ m^{-1}\ yr^{-1}$	Deposition rate $m^2\ yr^{-1}$	Transect line deposition rate $m^2\ m^{-1}\ yr^{-1}$
August 1994 - March 1995	83	0.11	80	0.12
March - June 1995	121	0.25	194	0.23
June - July 1995	670	0.49	402	0.65
July - September 1995	429	0.33	396	0.33
Sept. 1995 - February 1996	103	0.12	48	0.17

Table 8.2 Mean rate of erosion and deposition for transects BT5X024, 34, 25, 33, 26, 30 and 28 over and immediately downstream of the study bar site (see Figure 8.1b).

Note: The length of each transect line varies within and between surveys so the rates of erosion and deposition are also expressed per unit length of line. The February 1996 lines do not include land surveys (see Figure 8.4e). A more detailed analysis is provided in SPR-09.

The consistency in the temporal and spatial pattern of channel change in the study bar area (see discussion in SPR-09) suggests it may be possible to estimate aggregate and local sediment transport rates using either the 'morphological' or 'sediment continuity' method described in Ferguson and Ashworth (1992) and recently applied in braided rivers by Goff and Ashmore (1994), Martin and Church (1995), Lane et al., (1996) and Ashmore and Church (in press). However, these methods were developed for gravel-bed rivers, where it was possible to either directly measure the total sediment transport rate at the head of the study reach, or, to define a position in the reach where sediment transport rate tends to zero. In the case of the Jamuna, there are two difficulties with these conditions: (1) a high proportion of the bedload is associated with migrating dune bedforms which represents sediment throughput (Peters, 1993), and (2) it is difficult to estimate the proportion of suspended load incorporated within the migrating dune bedform (cf. van Rijn, 1993; Kostaschuk and Ilersich, 1995). Nonetheless, both the 'morphological' and 'sediment continuity' methods may be used to compute a lower bound on the estimate of sediment transport rates in the Jamuna, particularly if the bedload transport rates associated with dune migration can be quantified from measurements of dune height, morphology and celerity (see Annex 4, Chapter 3.7.1). This proposal is elaborated in SPR-09.

The observations of bar dynamics and channel change permit erection of a six stage model for mid-channel bar growth and channel evolution which may be more widely applicable in the Jamuna. The sequence is:

1 Development of straight, parabolic, main channel downstream of a major node of flow convergence (a 'Y' shaped planform, *cf.* Carson and Griffiths, (1987)).
2 Flow divergence (initiated by either bank widening or activation of a distributary offtake) and deposition of a symmetrical mid-channel bar caused by either (1) exceedance of the local transport capacity (Ashmore, 1991; Ashworth, 1996) and the progressive stacking of dunes, or (2) growth of a local flow instability (Parker, 1976; Tubino, 1991).

3 Broadening of the initial bar nucleus and bartail extension through lateral accretion (Bristow, 1987; Ashworth et al., 1992), aggradation of the bartop by the downstream migration of dune accretionary fronts, and anabranch incision leading to bar emergence (Leopold and Wolman, 1957).
4 Preferential scour and propagation of one anabranch (Cheetham, 1979; Hoey and Sutherland, 1991), probably determined by the asymmetry of the upstream scour hole (Mosley, 1976), the morphology and degree of emergence of the barhead (Ashworth, 1996) and the direction of local transport pathways (Hoey and Sutherland, 1991).
5 Development of planform sinuosity of the thalweg with the dominant anabranch crossing over to the minor anabranch via a submerged transverse bar (Ferguson and Werritty, 1983). Attachment of the transverse bar to the original bartail and progradation towards the bank edge causing anabranch scour and bank erosion (Lewin, 1976).
6 Further propagation of the dominant anabranch leading to abandonment of the minor anabranch upstream and its incorporation into the 'floodplain' (Richardson and Thorne, SPR-16). Possible channel bifurcation at the terminus of the anabranch scour front and development of a new mid-channel bar. Positive feedback and repetition of stages 1-6.

It should be noted that no downstream migration of the mid-channel bar is necessary for this sequence of channel evolution although the main morphological units will move if the node of flow convergence translates downstream (*cf.* Ashmore, 1993).

8.2.5 Flow structure associated with early stage bar growth

A number of linear (Engelund and Skovgaard, 1973; Parker, 1976; Fredsøe, 1978) and non-linear (Colombini et al., 1987; Tubino, 1991) stability analyses have been developed to predict the criteria for bar initiation, but few studies have been able to verify the flow structure in the field (Ashworth, 1996). Use of ADCP along all transect lines during the special survey of August 1994 permits quantification of the 3-D flow field at the stage of early bar growth in the study area (see Figure 8.3b). Changes in the flow field as the bar emerges are discussed in SPR-09.

Figures 8.6a-d show the magnitude and direction of the downstream velocity vector (U-W) and backscatter intensity for four transects that cover the area of the single feeder channel (BT5X036, 750 m upstream of the barhead), the barhead (BT5X036), the mid-bar (BT5X021, 250 m downstream) and the bartail (BT5X034, a further 500 m downstream). Figure 8.6a shows a central core of high velocity (up to 2.3 m s^{-1}) in the single channel approaching the barhead, with strongly convergent flow into the thalweg where backscatter intensity is also the highest. As flow approaches the barhead (Figure 8.6b) it divides into two filaments of equal velocity (maximum $\sim$2 m s^{-1}), with flow becoming strongly divergent ($\sim 60^{\circ}$) throughout the water depth. Backscatter intensity is high in the thalweg and bar margin of each anabranch, with local peaks associated with dunes (see Annex 4, Chapter 3.8.3). Further down the bar, the flow accelerates down the east anabranch (up to 2.4 m s^{-1}) with a compensating deceleration (maximum 1.8 m s^{-1}) in the west anabranch (Figure 8.6c). The 'topographic forcing' of flow (Dietrich and Smith, 1983; Nelson and Smith, 1989) which causes flow divergence at the barhead is weakened by funnelling of the flow down the two anabranches and the introduction of streamline curvature effects (Prandtl, 1952) from the sinuous anabranch planform. This promotes production of secondary flows (Fujita and Komura, 1988; Weerakoon et al., 1991;

Rhoads and Kenworthy, 1995) which are initially evident only in the west anabranch (Figure 8.6c), but become fully developed in both anabranches 500 m downstream at the bartail (Figure 8.6d). The inward near-bed secondary flow is likely to be responsible for lateral accretion and growth of the bartail limbs described in Section 8.2.4. The zone of low flow velocity (0.4 m s^{-1}) at the bartail is associated with low suspended sediment concentrations (Figure 8.6d), consistent with the accumulation of substantial fine-grained sediment (Section 8.2.4).

The overall pattern of flow structure at the early stages of bar growth is consistent with descriptions in the literature (Ashworth, 1996; M^{c}Lelland et al., 1996; Richardson et al., 1996), with topographic forcing of flow at the barhead causing flow divergence and anabranch curvature producing significant secondary flows (see models in Ashworth et al., 1992, Figure 25.3 and Richardson and Thorne SPR-16, Figure 1.5). The zone of flow divergence and deceleration most likely promotes dune stalling and stacking (see Section 8.6) with secondary flows in the anabranches causing lateral accretion and bartail growth.

N.B. To come (currently reducing data): Influence of different degrees of bar emergence on the flow structure (contour maps of surface and bed velocity vectors for 5 transects over bar – BT5X024, 34, 25, 33, 26, July and September 1995).

8.2.6 Relationship between bedforms and bar growth

Annex 4, Chapter 3.4, demonstrates that dunes are ubiquitous in the Jamuna at all flow stages and their morphology is stage dependent. Since dunes are the dominant mode of bedload transport, they are intimately linked to bar creation and growth. Figure 8.7a shows a downstream survey line over the study bartop in August 1994 (which corresponds to the period of rapid bar aggradation – see Figures 8.3b and 8.6a-d). Dune height decreases as the flow shallows from the upstream thalweg onto the barhead. The 3 m high accretionary front (labelled DF in Figure 8.7a) was exposed at low flow in March 1995 (see Figure 8.5c) and represents the stacking of successive dunes as they migrate onto the barhead. Formation and migration of the accretionary front may be associated with short-term (days) fluctuations in discharge (stage changes of $\pm$1m, see Figure 8.1c) at the hydrograph peak which provide the necessary flow depth and velocity to promote dune migration on the bartop platform.

As discussed in Section 8.2.3, after deposition of an initial bar core, growth is promoted by a combination of lateral accretion and stacking of successive dune fields which migrate both onto the barhead (Figure 8.7a) but also wrap around the bar margin during waning flows. Lateral accretion can produce foresets up to 3 m high (Figure 8.7b) which may subsequently be superimposed by a series of 0.5-1 m high dunes (Figure 8.7c) to produce a characteristic two-stage profile of subsurface alluvial architecture (Figure 8.7b).

8.2.7 Summary

A number of conclusions may be proposed from this study of bar dynamics:

- Mid-channel bars are the most common bar type in the Jamuna and exert considerable influence on the local flow structure, channel change and bank erosion;

- Sand bars often form downstream of a zone of flow convergence and are initially deposited as a central symmetrical bar core, aligned sub-parallel to the primary flow direction;
- The basic planform morphology of a mid-channel bar is rhomboidal with two protruding bartail limbs. This morphology is characteristic of all scales of mid-channel bars;
- The bartail may be an important storage zone for fine sediment and can form highly cohesive and resistant 'plugs' which may be difficult to erode. Downstream migration of the barhead may preserve this plug and temporarily 'remove' the finest fractions from the channel and floodplain transport system;
- Mid-channel bars grow through (1) flow divergence at the barhead and deposition at the bar margins, (2) lateral accretion induced by secondary flows in the anabranches, (3) vertical aggradation by successive stacking of dunes, and (4) downbar migration of an accretionary dune field front. This front may only form during short-lived (days) fluctuations in discharge at the hydrograph peak;
- Bar growth and channel change is not always accompanied by downstream migration of the bar nucleus. The basic bar morphology may thin and lengthen at high flow and broaden at low flow;
- Channel change and the rate of sediment erosion and deposition is strongly stage dependent with no lag behind the hydrograph peak. The mean erosion and deposition rates are in balance throughout the hydrograph suggesting no net aggradation or degradation of the braid belt;
- There is a close relationship between bedform development, morphology and migration and the mechanics of bar growth. This is evidenced in both bed surveys and preserved subsurface alluvial architecture;
- A six-stage model for mid-channel bar growth and morphological change in the study area is proposed which is consistent with observations in the literature and may be applied more widely in the Jamuna.

8.3 Flow patterns and late stage bar evolution

8.3.1 Objectives

The objectives of this study are:

- to define the primary and secondary flow patterns responsible for coherent flow structures around a mature bifurcation-bar-confluence feature in the braided Jamuna River;
- to establish the effects of secondary currents on the concentration of suspended sediment;
- to examine the influence of changing stage on coherent flow structures; and,
- to relate the flow pattern to late stage evolution of bar and channel morphology observed over a monsoon runoff season.

8.3.2 Data sources

Field measurements were made using the DHA vessel, with ADCP (300kHz) used to measure velocities and differential GPS for position fixing. Measurements were made along 16 transects around an established, emergent bar in the left (east) anabranch of the Jamuna River, south of the Bahadurabad Ghat (Figures 8.8 and 8.9). Data were collected on the rising (May), peak (August) and falling (September) limbs of the monsoon hydrograph for 1994 (Figure 8.10). The draft of the DHA vessel meant that it was not possible to survey all lines on all occasions. All data recorded may be found in Study Report 16.

8.3.3 Historical bar evolution

Short-term measurements of flow velocities, sediment dynamics and associated morphological changes must be interpreted within the context of longer-term and larger-scale evolution of the channel. In Study Topic 16, historical satellite images dating from 1973 were used to establish trends of channel change in the reach containing the study bar. The results indicated that:

- The division of Jamuna flow between its two main anabranches is variable. When flow is predominantly in the left bank anabranch it adopts a braided pattern while the lesser right bank anabranch meanders. When flow is equally split, both anabranches are in transition between braiding and meandering.
- The planform morphology for the left bank anabranch in the reach displays an "hour glass" shape, with a relatively narrow neck (or node) west of Bahadurabad Ghat (Figure 8.8).
- Depending on the proportion of Jamuna flow following the left anabranch, bar assemblages predominantly form either braid bars or point bar type features.
- In 1994 the study bar was part of a heavily dissected point bar complex in the left anabranch.
- Due to abandonment of a loop in the channel north of Bahadurabad in 1993, the flow alignment approaching the study bar changed from southeast to almost due south. In 1994, this approach orientation favoured flow to the right (west) anabranch at the study bar, at the expense of flow to the left (east) anabranch.

8.3.4 Patterns of primary and secondary flow

Figure 8.11 shows example measurements for line 08. These are typical of the data for all the other transects. The data are considered in detail, transect by transect in Study Report 16 and only a brief overview is presented here.

The field measurements were processed to produce plots of primary and secondary velocity. The primary direction was determined using a computer program that maximized a secondary flow function for each individual core of maximum velocity at a section. The basis for this program is explained fully in Study Report 16.

The results showed a strong and consistent relationship between secondary patterns and suspended load concentration (represented by the strength of ADCP backscatter). Generally, zones of near-bed convergence and upwelling produced high concentrations, while zones of surface convergence and downwelling produced low concentrations.

The salient features of the flow pattern around the study bar may be summarized as:

- May measurements in the left anabranch show that immediately downstream of the point of bifurcation topographic forcing of the flow around the bar nose drives clockwise helical flow that produces deep scour next to the bar at section 4 (Figure 8.12a). The main flow crosses to the outer bank at section 5, and curvature induces strong counter-clockwise helical flow at sections 6 and 7. The main flow crosses back to the inner bank at sections 8 and 9, with some evidence of clockwise helical flow.
- August measurements present a broadly similar picture in the left channel, but the pattern is shifted downstream by about one section (Figure 12b). Also, a new medial bar appears, extending between sections 4 and 5 and leading to a new flow bifurcation in the left channel. In the right channel sections 13 and 12 show strong clockwise helical flow midway along the bar, while sections 10 and 9 indicate counter-clockwise secondary circulation in the right anabranch at the bar tail.
- September results indicate preservation and continued downstream migration of the patterns and features present in August (Figure 8.12c).

8.3.5 Bar evolution

Comparison on the satellite images for November,1993 (Figure 8.8) and November,1994 (Figure 8.13), allows assessment of planform evolution of the bar during the study period. Detailed bathymetric surveys were also performed and these yield information on changes of bed topography throughout the study reach. These results are presented in Study Report 16.

The main features of bar evolution evident from Figures 8.8 and 8.13 in relation to the flow pattern are:

- Erosion around nose of the study bar, leading to downstream migration of the bar head – this is a product of the measured clockwise helical flow in the left anabranch downstream of the bifurcation which promotes bed scour and bank erosion at the inner bank along the upstream third of the bar. (It is inferred that counter-clockwise helical flow occurred in the right anabranch at this location).
- Accretion on both flanks, leading to broadening of the bar in along the middle third of its length, coupled with retreat of the outer banks on either side – this is a product of the strong helical flow measured in both anabranches and observed to concentrate erosion at the outer margins of the anabranches and sedimentation at the inner margins.
- Accretion and sculpting of the bar tail, especially on the right side, leading to downstream extension – this a product of deceleration in the lee of the bar coupled with helical flows that tend to cut into the bar to give it a characteristically rhomboidal planform. Note: The study bar becomes asymmetrical during the 1994 because macro-form clockwise planform curvature of the left bank anabranch evident in the satellite image overrides the local counter-clockwise curvature along the left side of the study bar.

- Enlargement of the right anabranch and generation of bifurcated flow in the upstream half of the left anabranch through growth of a medial bar – this is a product of switching of flow from left to right anabranches due to re-alignment of the approach flow from southeast to due south. This development cannot be explained in terms of local flow pattern and demonstrates the importance of larger-scale channel evolution in driving local morphological changes.

8.3.6 Conclusions

- The field measurements indicate that ADCP is a powerful tool in morphological studies, capable of yielding comprehensive information on 3-dimensional flow patterns and relative distribution of suspended sediment.
- The study of historical channel planform demonstrates that short-term, local bar development is driven by changes in approach flow orientation that in turn occur in response to longer-term, larger-scale planform changes.
- Close association between zones of upwelling or downwelling and variations in suspended load concentration indicate the importance of secondary currents in affecting sediment transport pathways.
- The pattern of helical flow around a bar is more complicated than was previously thought. Measurements suggest that in the left anabranch clockwise secondary circulation just downstream of the point of bifurcation leads to scour and bank erosion at the bar head. About one third of the way along the bar the main flow crosses to the outer bank and counter-clockwise secondaries generate scour at the outer bank scour and sedimentation on the flank of the bar at the inner bank. The main flow crosses back to the inner bank about two thirds of the way along the bar, generating clockwise secondary circulation and tending to sculpt into a rhomboidal shape. Flow patterns in the right anabranch are broadly a mirror image of those in the left channel.
- These flow patterns can explain most of the observed trends of planform change for the study bar during the period of observation. However, other features can only be understood when viewed in the wider context of large-scale, longer-term planform evolution.

Figure captions

Figure 8.1: (a) close-up of study reach morphology traced from G12 SPOT on 24/3/95, (b) Special Survey lines over and around the study bar between 7-13 March 1995, (c) flood hydrographs from November 1993 to February 1996 highlighting the water level during survey periods. Only the mean date of each survey period is shown (see Table 8.1c).

Figure 8.2: Channel change and bar migration 3/3/94-24/3/95. Bar positions are traced from G11 and G12 1:50000 SPOT images. The bars labelled A show the characteristic barhead erosion and bartail deposition, the bars labelled B migrate upstream by accretion of secondary lobes onto the barhead and margin.

Figure 8.3: Spyglass® contour maps of bed topography for (a) 10-18 November 1993, (b) 10-14 August 1994, (c) 1-10 November 1994, (d) 7-8, 13 March 1995, (e) 25-26 June 1995, (f) 31 July/1 August 1995, (g) 12-16 September 1995, (h) 11-25 November 1995, (1) X-X March 1996. The area of bed survey is different for special and bathymetric surveys (but all the figures are plotted at the same scale, see Table 8.1c). All heights are reduced to SLW to enable comparison between dates. The position of the water edge for each bathymetric survey period is digitised from the bed contour at the relevant SLW level (emergent bar shown as black). These water edges are also used to defined the approximate water margin for special surveys (emergent bar highlighted with dotted fill). The land survey over the study bar in February 1996 is incomplete so the bartop contours are unrealistically low.

Figure 8.4: Superimposed cross-sections for the five bar transects (BT5X024, 34, 25, 33, and 26) and BT5X030 and 28, 750 and 1250 m downstream of BT5X026 respectively (see Figure 8.1b). The periods of special survey are (a) 10-14 August 1994-7-8, 13 March 1995, (b) 7-8, 13 March 1995-25-26 June 1995, (c) 25-26 June 1995-31 July/1 August 1995, (d) 31 July/1 August 1995-12-16 September 1995, and (e) 12-16 September 1995-24-26 February 1996. The area of each block of erosion and deposition is given in SPR-09 and summarised in Table 8.2. Note that the February 1996 land survey is incomplete.

Figure 8.5: (a) planform morphology of the emergent study bar as land surveyed in March 1995. The two dunes fields terminate in a 3 m high, steep, accretionary front (see text). Measurements of dune orientation indicate the flow was strongly divergent over the bartop. (b) 100MHz ground penetrating radar trace for transect BT5X026. The trace is west to east (left to right) with the lateral distance from the water edge shown on the top scale (280-400 m). The trace shows steeply dipping (note the vertical exaggeration), bar slip faces, prograding east to west, superimposed by a 1 m layer of low-amplitude dunes. An impermeable layer at 330 m and 5-6 m depth (strong radar reflectance), represents the 'old' bartail area where substantial amounts of fine-grained sediment accumulate (see text and Figure 8.5a).

Figure 8.6: Spyglass® contoured ADCP records of the resolved (U-W) downstream velocity and direction and backscatter intensity for transects (a) BT5X023, (b) BT5X036, (c) BT5X021, (d) BT5X034 (see text and Figure 8.1b). Flow directions must be considered relative to the bearing of the bar's long-axis which is 148°.

Figure 8.7: (a) downstream bed profile of the newly emergent bar in August 1994 (line BB1Y038). Note the accretionary dune front migrating onto the barhead (labelled DF) and the changing dune size over the bar with large dunes in the deeper flows around the bar flanks and progressively smaller dunes as flow shallows on the stoss side of the bar. The flat bartop area (labelled BT) has few dunes and is not characterised by upper-stage plane beds, thus it must be an area of lower sediment transport rates, (b) 100MHz ground penetrating radar trace for transect BT5X033 (250 m upstream of BT5X026 shown in Figure 8.5b). The trace is west to east (left to right) with the lateral distance from the water edge shown on the top scale (280-400 m). The trace shows bar slipface accretion, with several sharp erosion surfaces, superimposed by a 3m layer of stacked, low-amplitude, dunes. The dunes are typically 0.5 and 1 m high, with well defined crests and troughs, (c) 2m trench section taken on GPR line BT5X026 showing the preservation of stacked, low-amplitude dunes with trough cross-stratification (note penknife for scale). Mean D_{50} grain size of the preserved dunes is 0.23 mm.

Figure 8.8a: Satellite image showing study bar location in November 1992. Scale 1:120.000 (image supplied by FAP19)

Figure 8.8b: Satellite image showing study bar location in November 1993. Scale 1:50,000 (image supplied by FAP-19)

Figure 8.9: Study site showing position of survey lines

Figure 8.10: Monsoon hydrograph for 1994 with survey dates

Figure 8.11: Plots of primary and secondary velocity and backscatter intensity. Line 08 from May to September 1994

Figure 8.12: Discharge distribution maps of study area in: a) May, b) August, c) September 1994.

Figure 8.13: Satellite image showing study bar in November 1994. Scale 1:120,000 (image supplied by FAP-19)

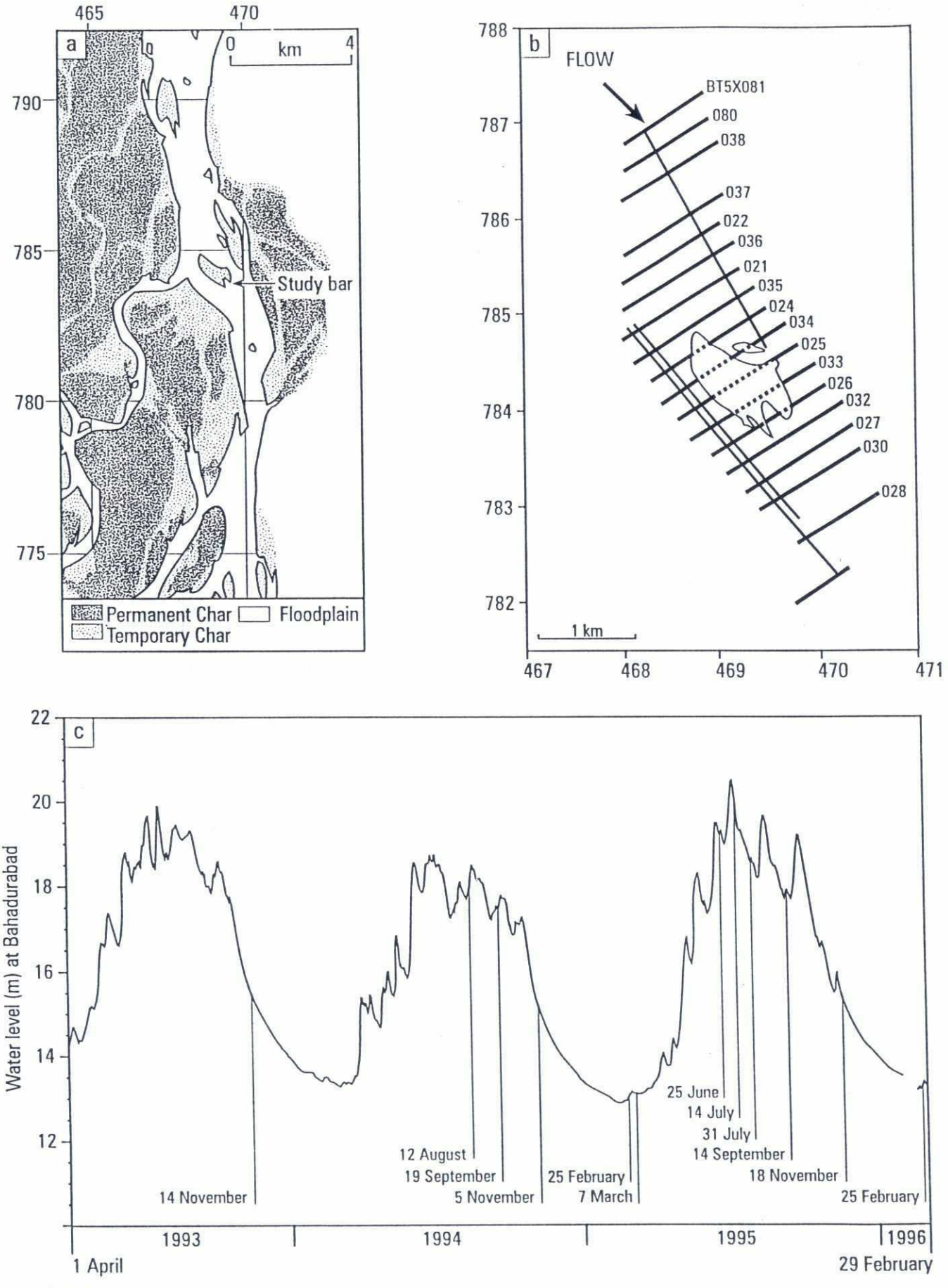

a
465
470
0
km
4
790
785
780
775
Study bar
Permanent Char
Floodplain
Temporary Char
b
FLOW
788
787
786
785
784
783
782
BT5X081
080
038
037
022
036
021
035
024
034
025
033
026
032
027
030
028
1 km
467
468
469
470
471
c
Water level (m) at Bahadurabad
22
20
18
16
14
12
14 November
12 August
19 September
5 November
25 February
7 March
25 June
14 July
31 July
14 September
18 November
25 February
1993
1994
1995
1996
1 April
29 February

Figure 8.1

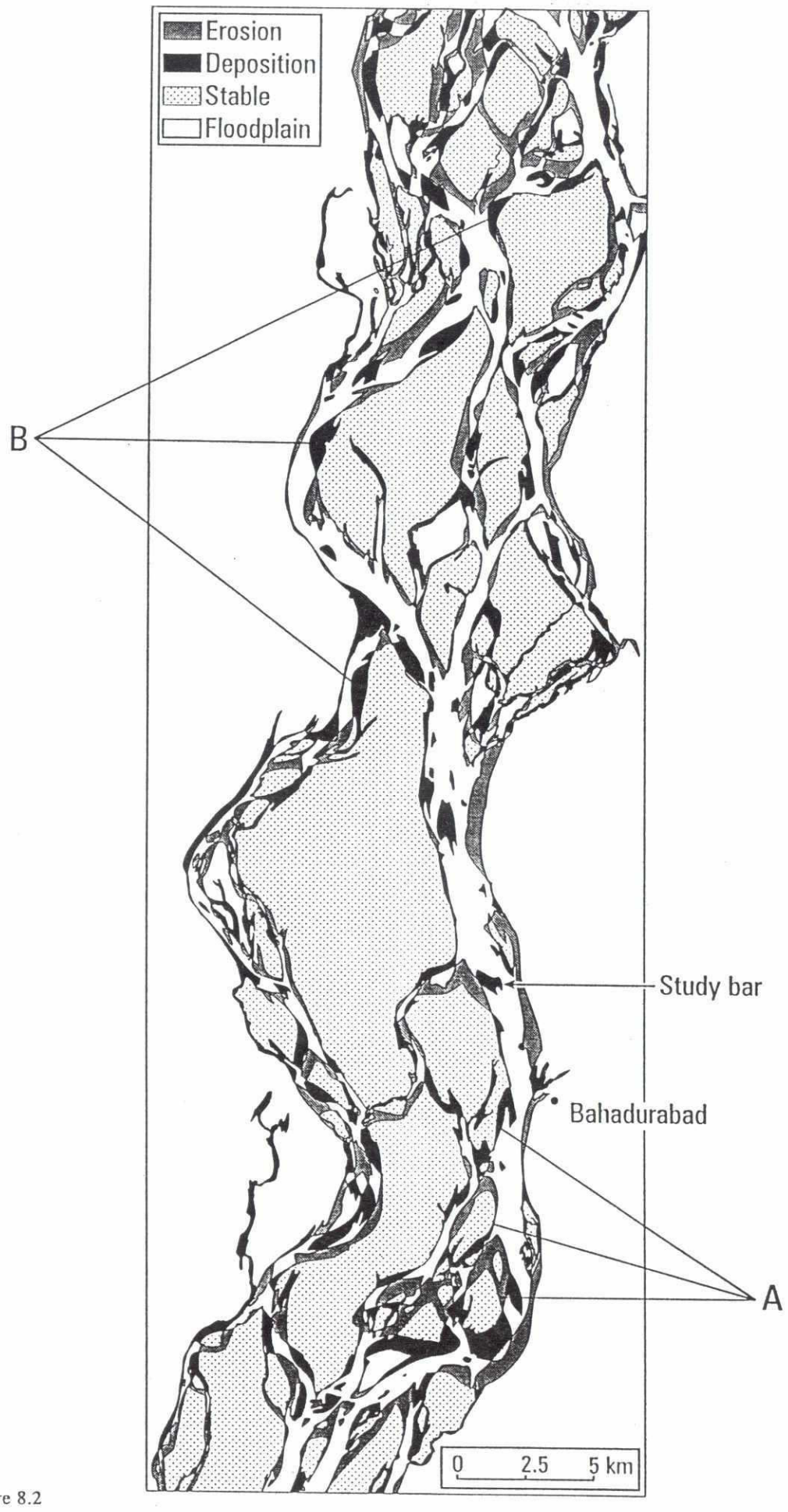

Erosion
Deposition
Stable
Floodplain
B
Study bar
Bahadurabad
A
0 2.5 5 km

Figure 8.2

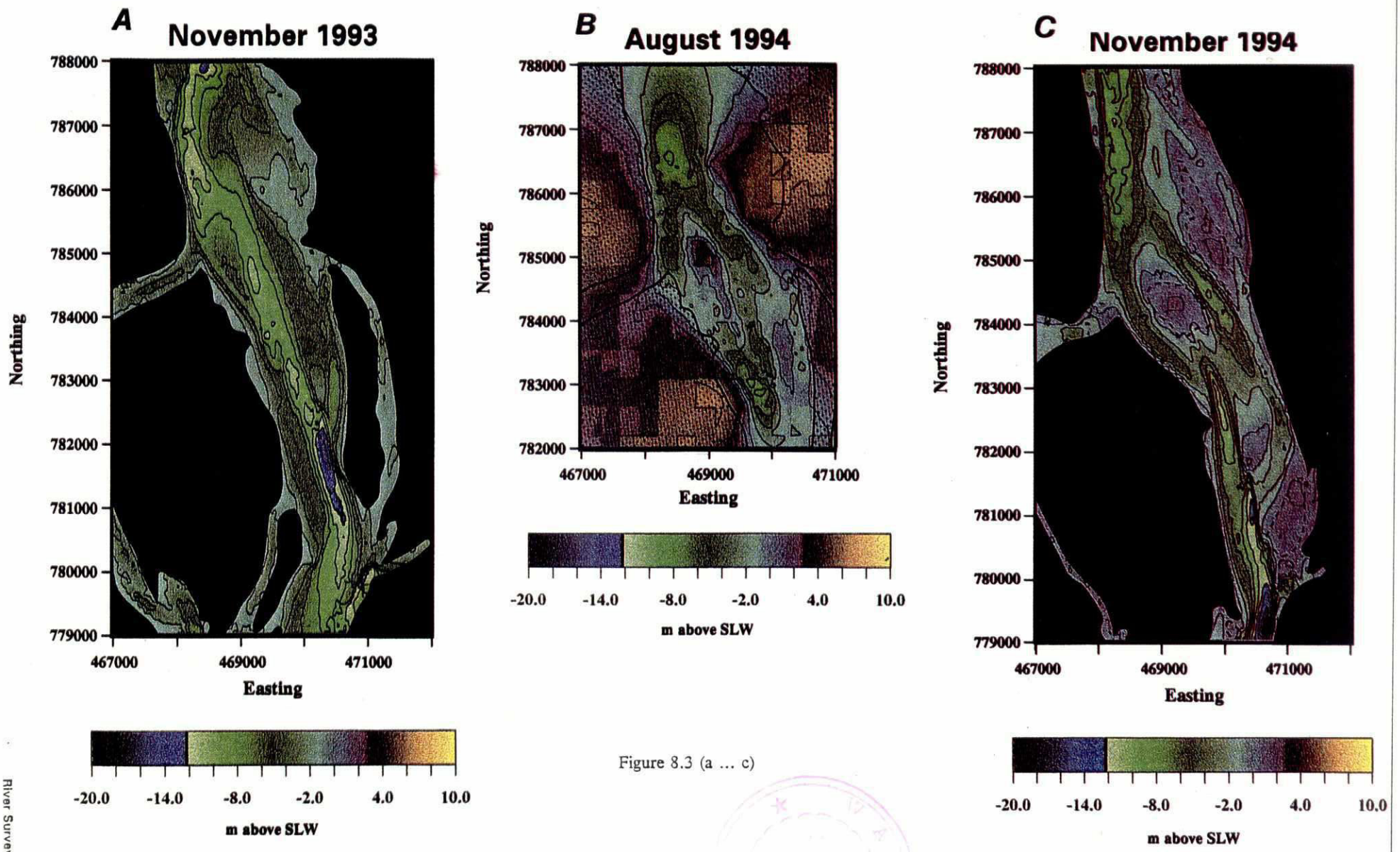

A
November 1993
B
August 1994
C
November 1994
Northing
Easting
788000
787000
786000
785000
784000
783000
782000
781000
780000
779000
467000
469000
471000
-20.0
-14.0
-8.0
-2.0
4.0
10.0
m above SLW

Figure 8.3 (a ... c)

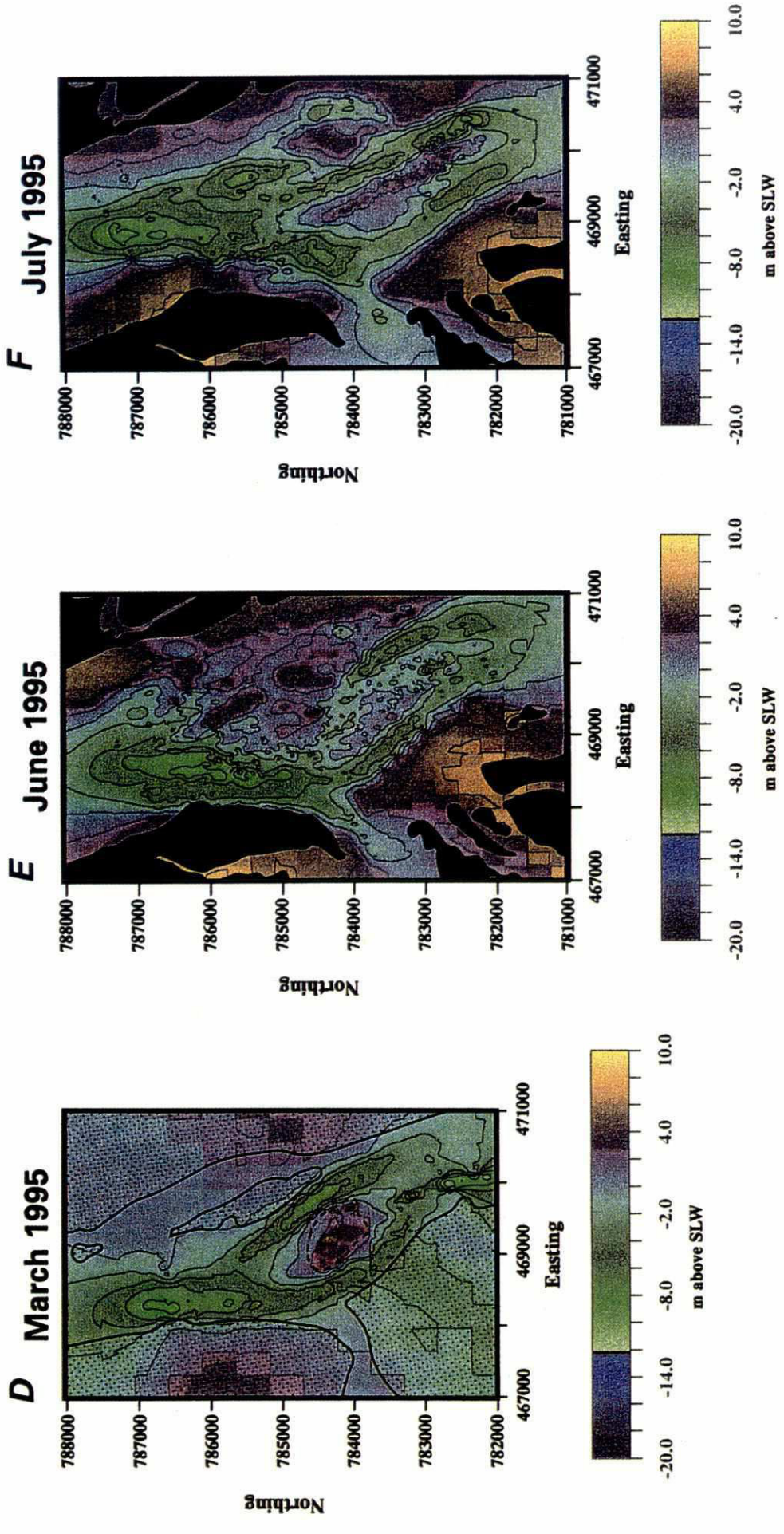

F July 1995
E June 1995
D March 1995
Northing
Easting
m above SLW
788000
787000
786000
785000
784000
783000
782000
781000
467000
469000
471000
-20.0
-14.0
-8.0
-2.0
4.0
10.0

Figure 8.3 (d ... f)

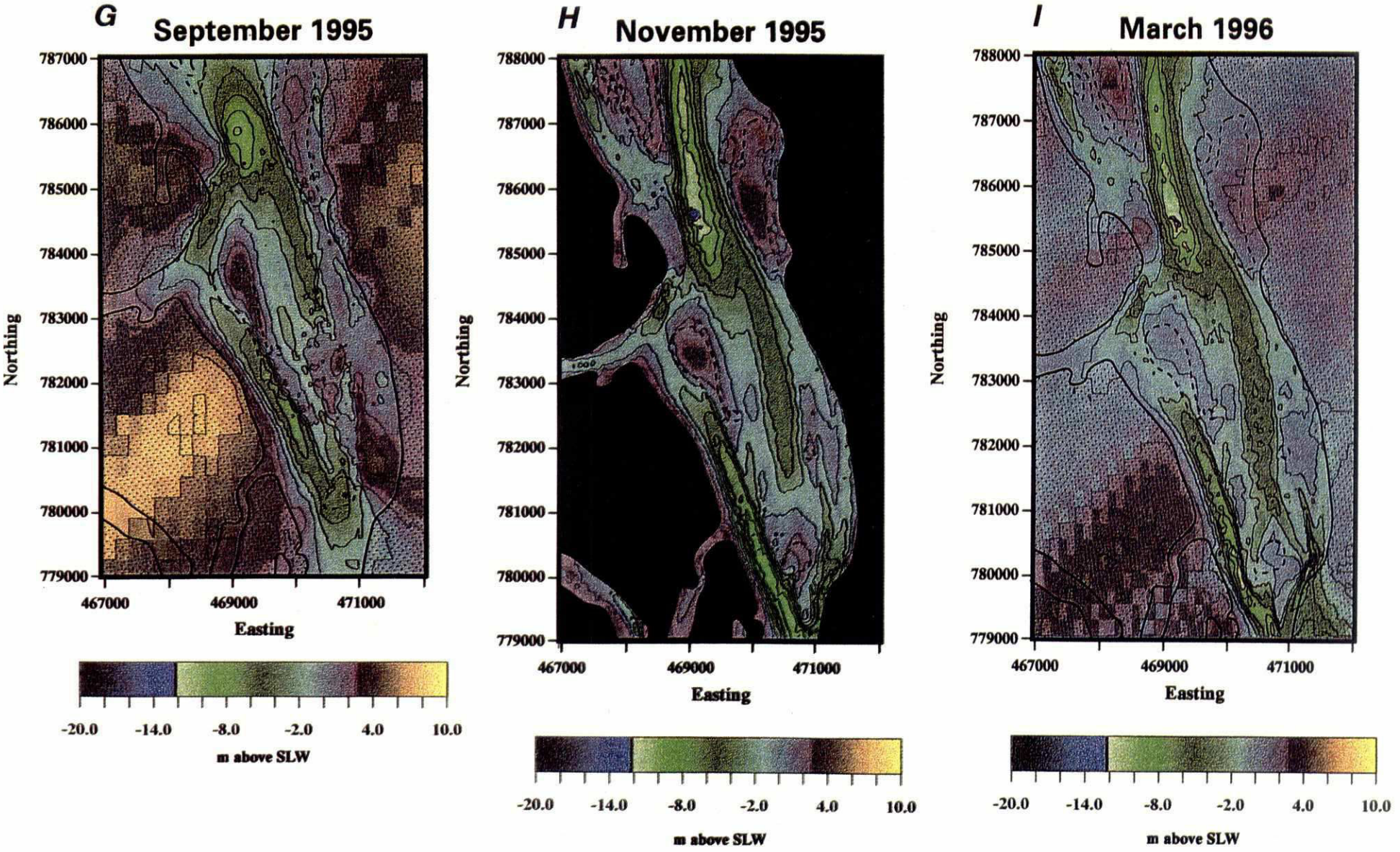

G
September 1995
787000
786000
785000
784000
783000
782000
781000
780000
779000
Northing
467000
469000
471000
Easting
-20.0
-14.0
-8.0
-2.0
4.0
10.0
m above SLW
H
November 1995
788000
787000
786000
785000
784000
783000
782000
781000
780000
779000
Northing
467000
469000
471000
Easting
-20.0
-14.0
-8.0
-2.0
4.0
10.0
m above SLW
I
March 1996
788000
787000
786000
785000
784000
783000
782000
781000
780000
779000
Northing
467000
469000
471000
Easting
-20.0
-14.0
-8.0
-2.0
4.0
10.0
m above SLW

Figure 8.3 (g ... i)

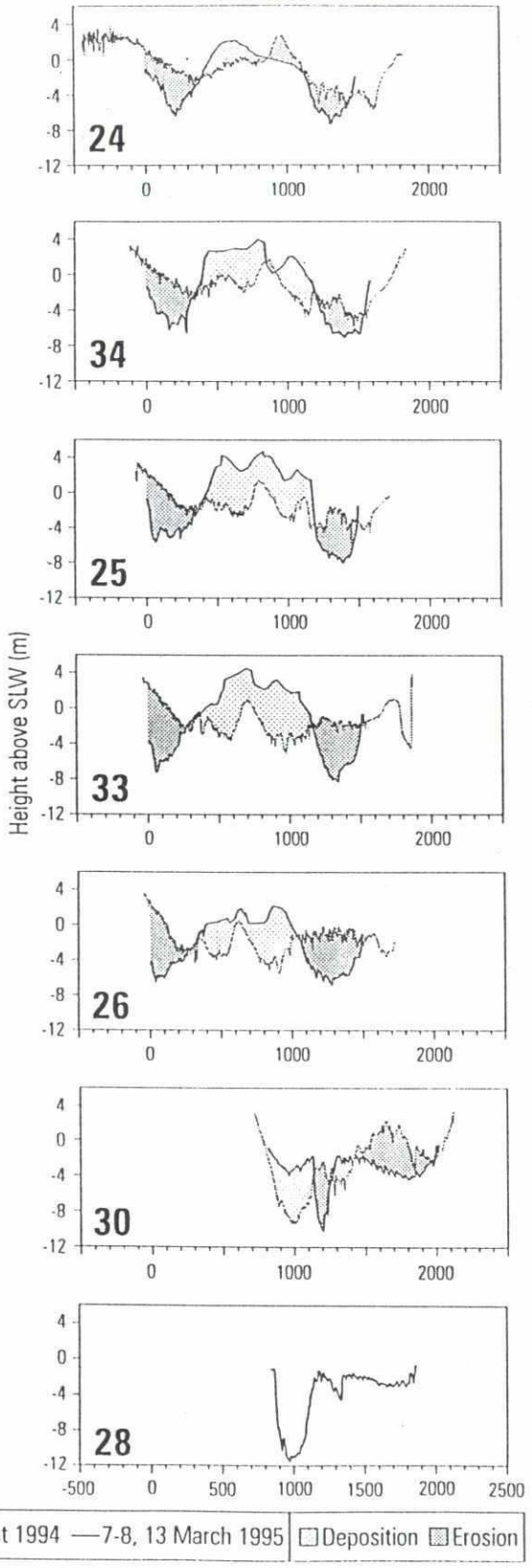

24
34
25
33
26
30
28
Height above SLW (m)
4
0
-4
-8
-12
0
1000
2000
-500
500
1500
2500
10-14 August 1994
7-8, 13 March 1995
Deposition
Erosion

Figure 8.4a

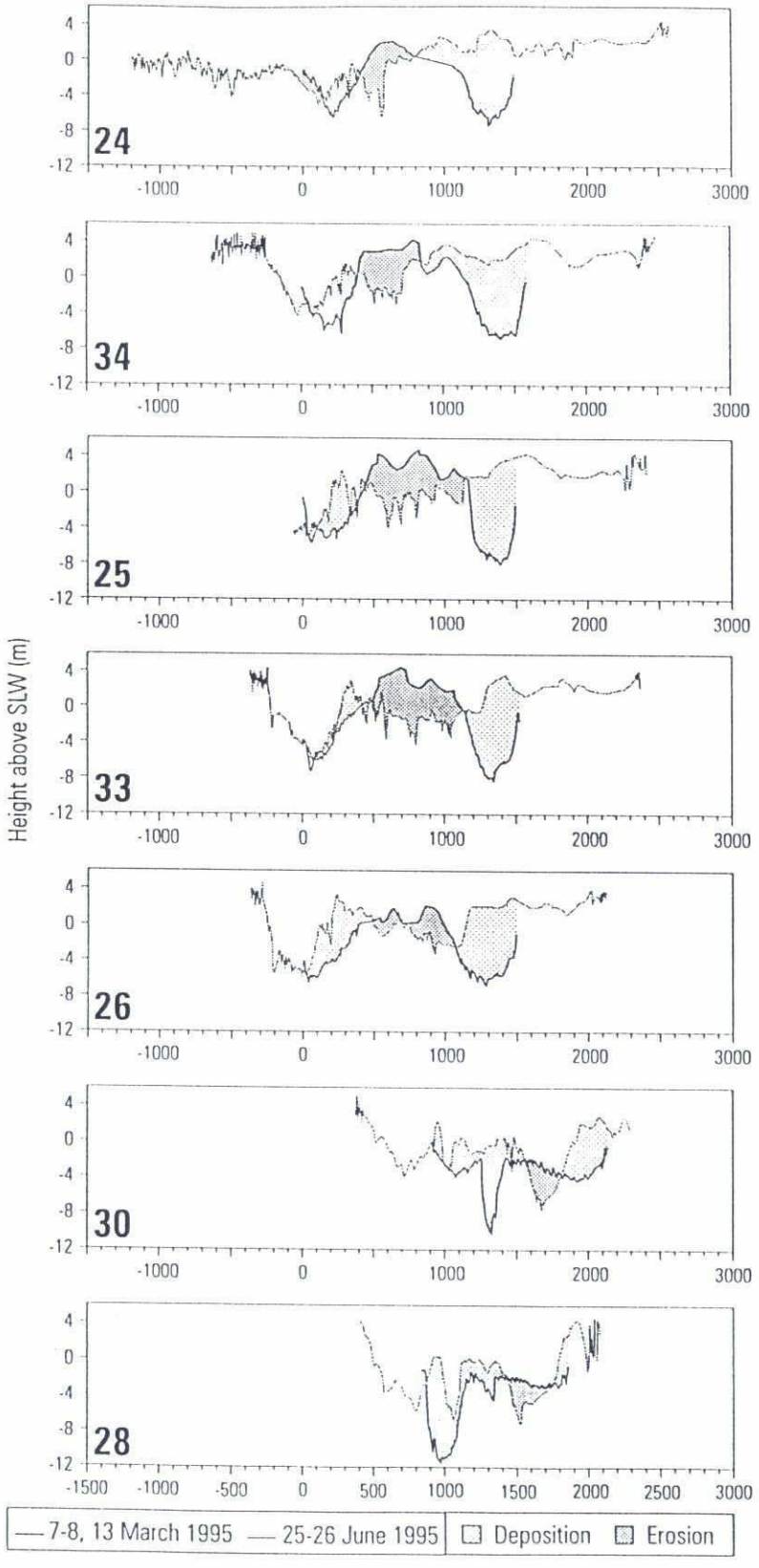

Height above SLW (m)
24
34
25
33
26
30
28
4
0
-4
-8
-12
-1000
0
1000
2000
3000
-1500
-500
500
1500
2500
7-8, 13 March 1995
25-26 June 1995
Deposition
Erosion

Figure 8.4b

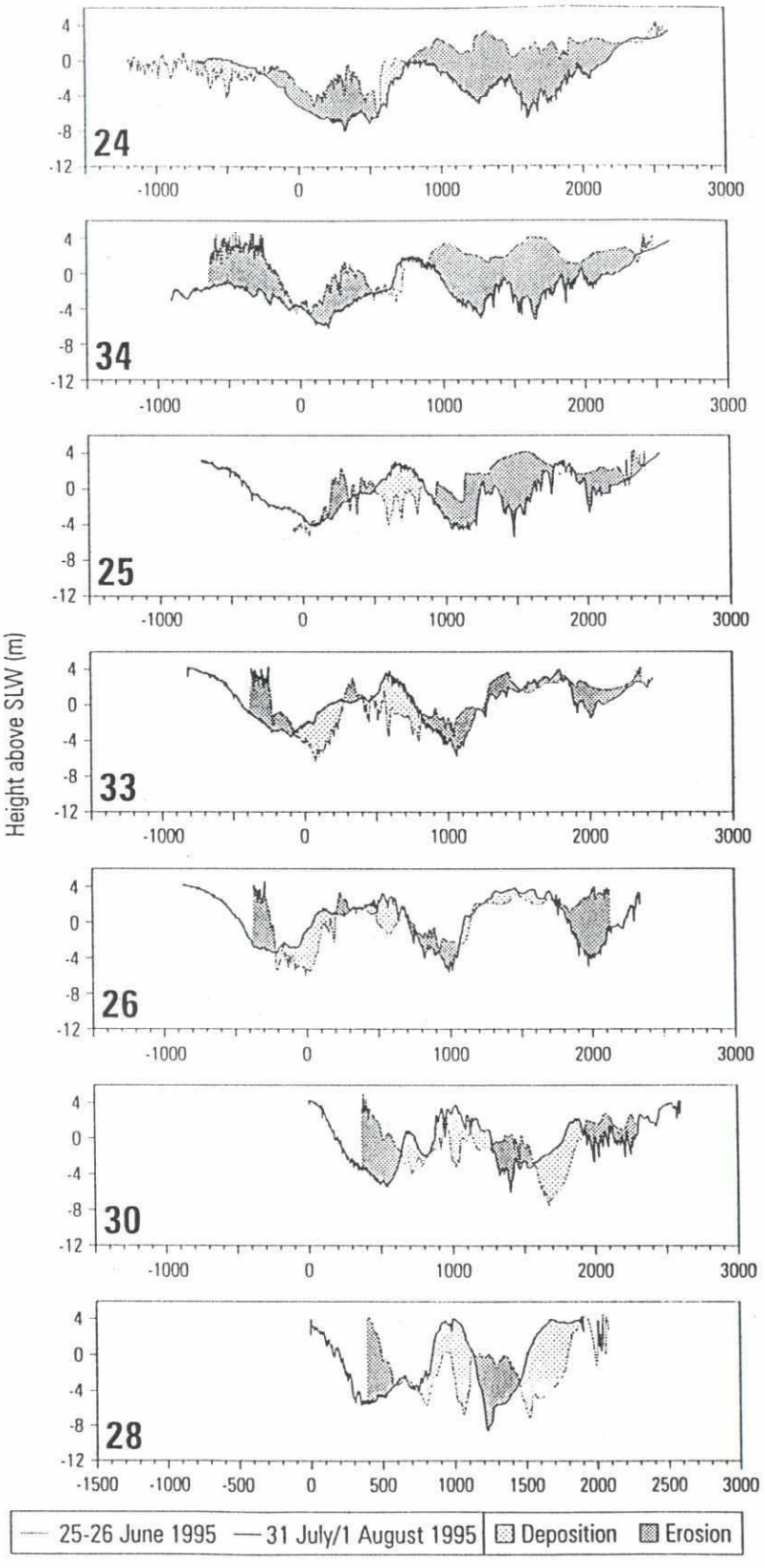

Height above SLW (m)
24
34
25
33
26
30
28
-1500 -1000 -500 0 500 1000 1500 2000 2500 3000
25-26 June 1995
31 July/1 August 1995
Deposition
Erosion

Figure 8.4c

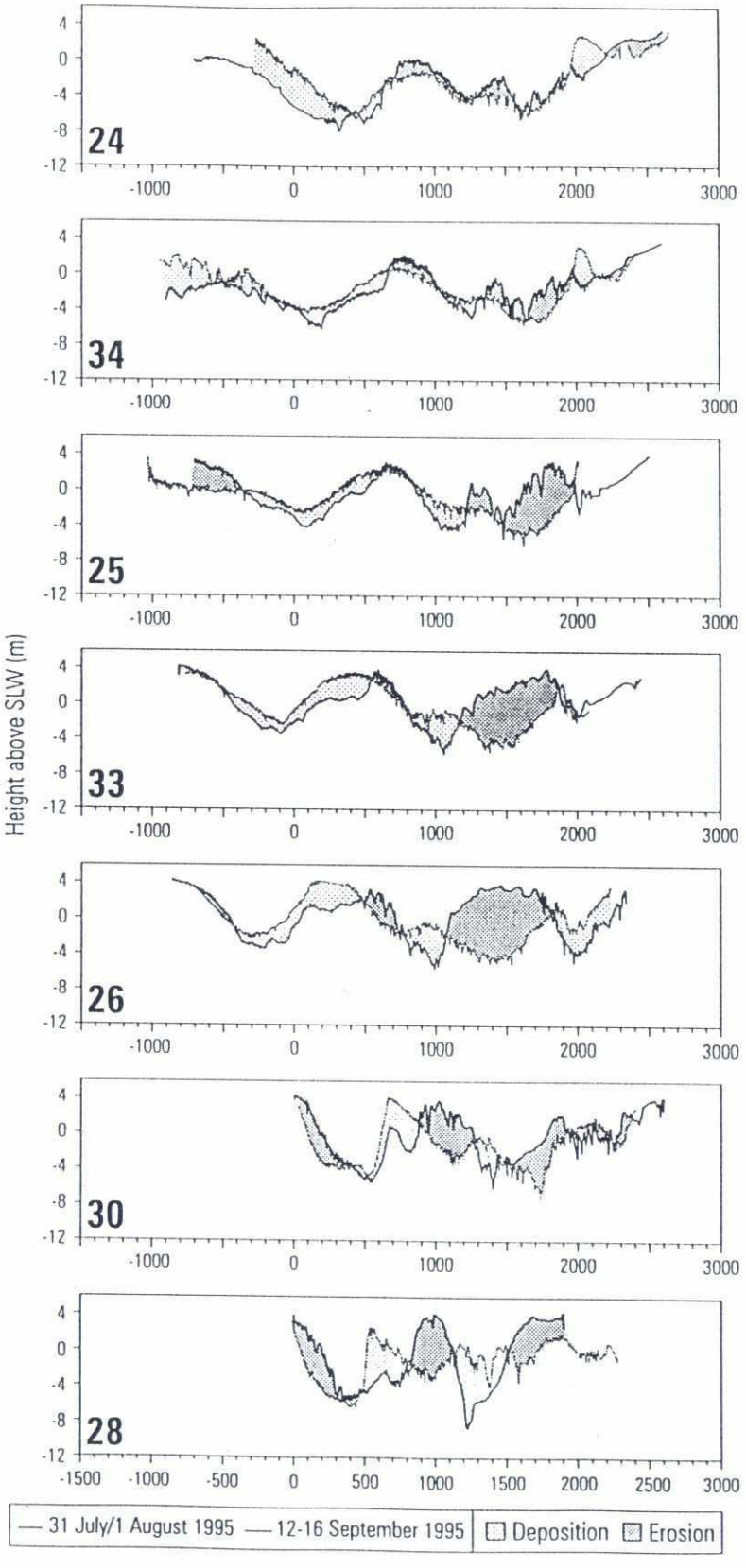
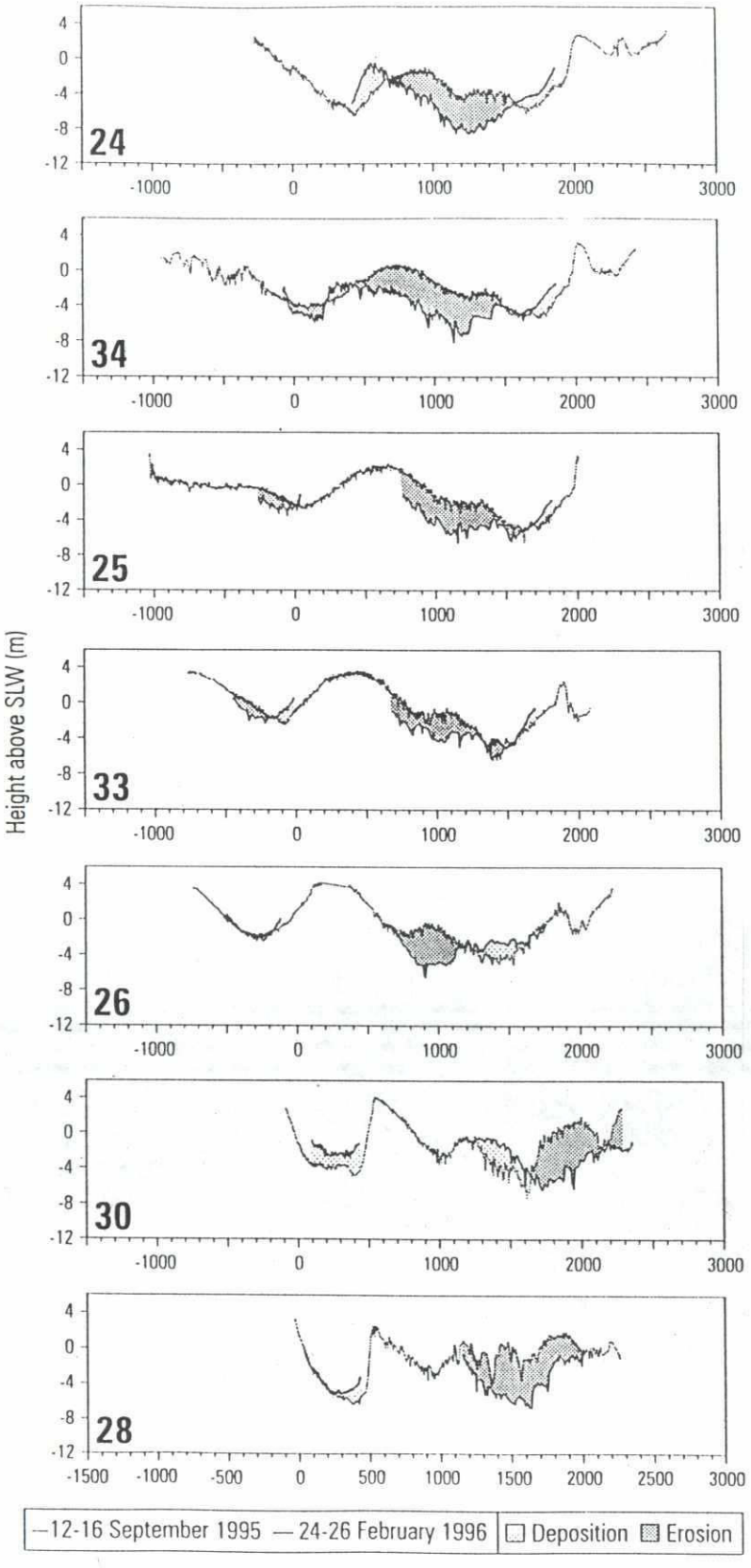
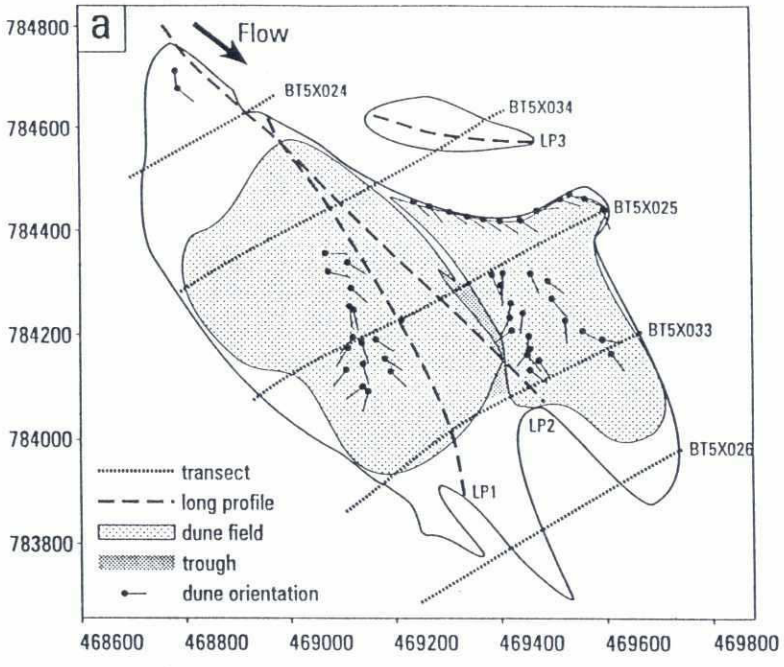

Height above SLW (m)
24
34
25
33
26
30
28
4
0
-4
-8
-12
-1000
0
1000
2000
3000
-1500
-500
500
1500
2500
— 31 July/1 August 1995
— 12-16 September 1995
Deposition
Erosion

Figure 8.4d



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Figure 8.4e


a
Flow
BT5X024
BT5X034
LP3
BT5X025
BT5X033
LP2
BT5X026
LP1
transect
long profile
dune field
trough
dune orientation
784800
784600
784400
784200
784000
783800
468600
468800
469000
469200
469400
469600
469800

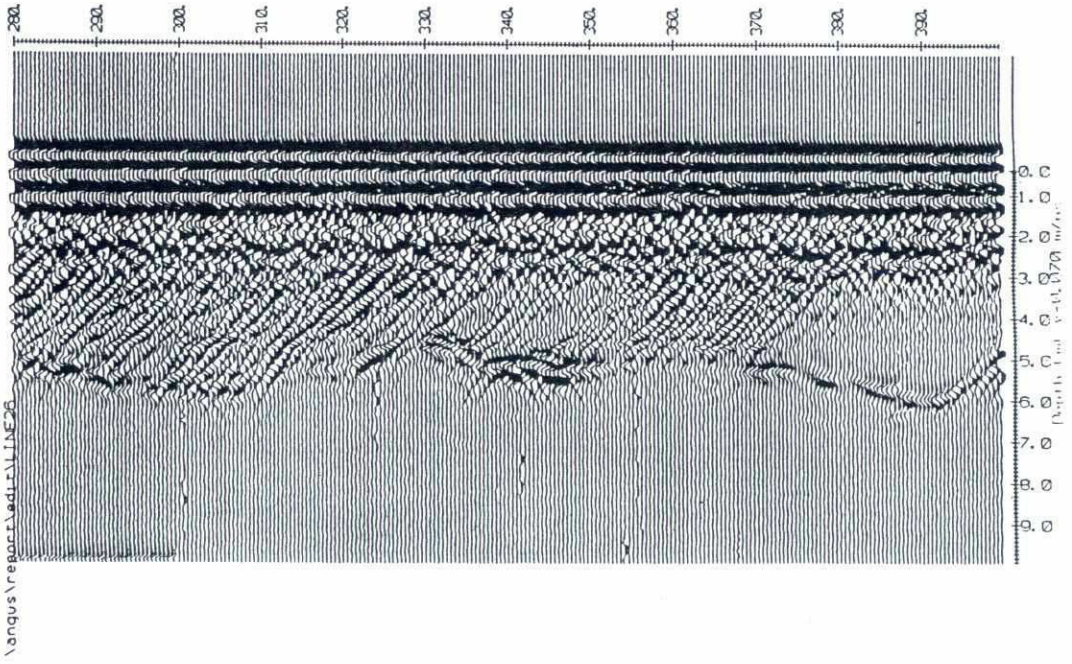
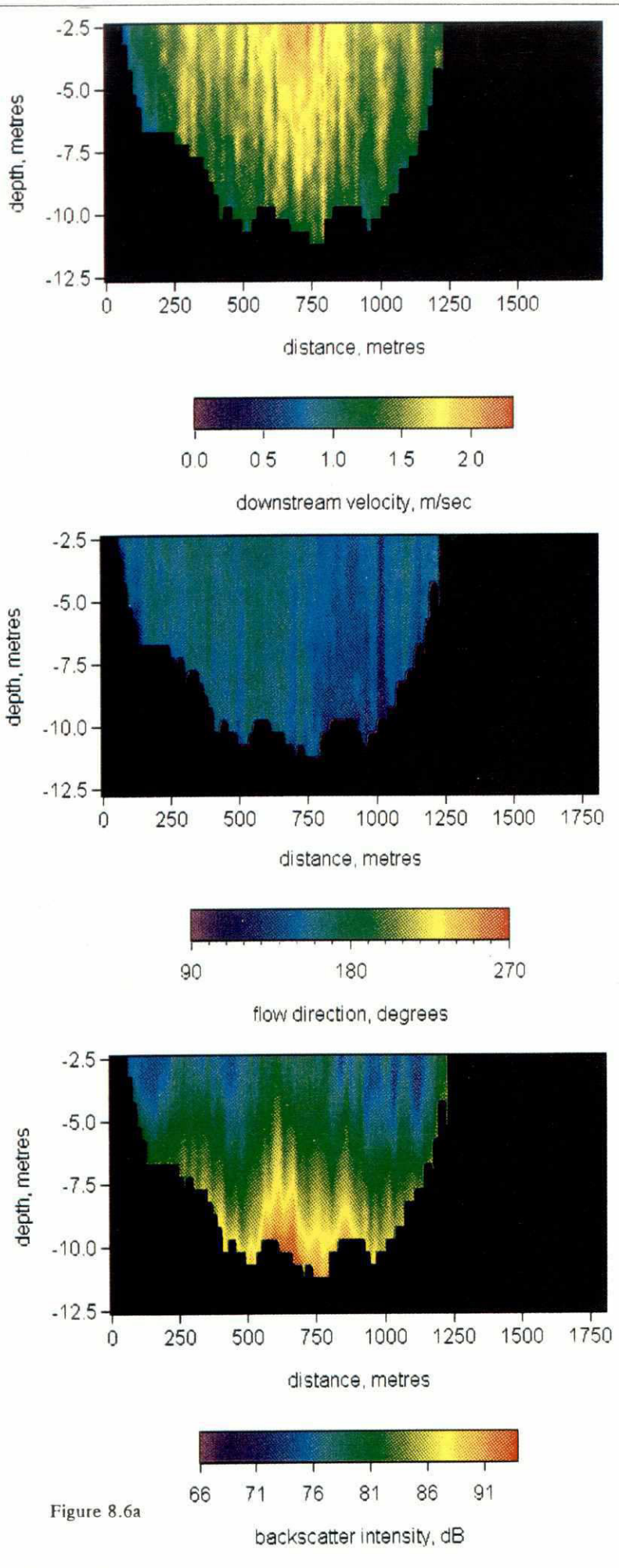

280.
290.
300.
310.
320.
330.
340.
350.
360.
370.
380.
390.
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0

Figure 8.5



BT5X023

A

Figure 8.6a

B
BT5X036
distance, metres
0 250 500 750 1000 1250 1500 1750
depth, metres
4 6 8 10 12
downstream velocity, m/sec
0.00 0.50 1.00 1.50 2.00
distance, metres
0 250 500 750 1000 1250 1500 1750
depth, metres
4 6 8 10 12
flow direction, degrees
90 180 270
distance, metres
0 250 500 750 1000 1250 1500 1750
depth, metres
4 6 8 10 12
backscatter intensity, dB
66.0 71.0 76.0 81.0 86.0 91.0

Figure 8.6b

29

C BT5X021

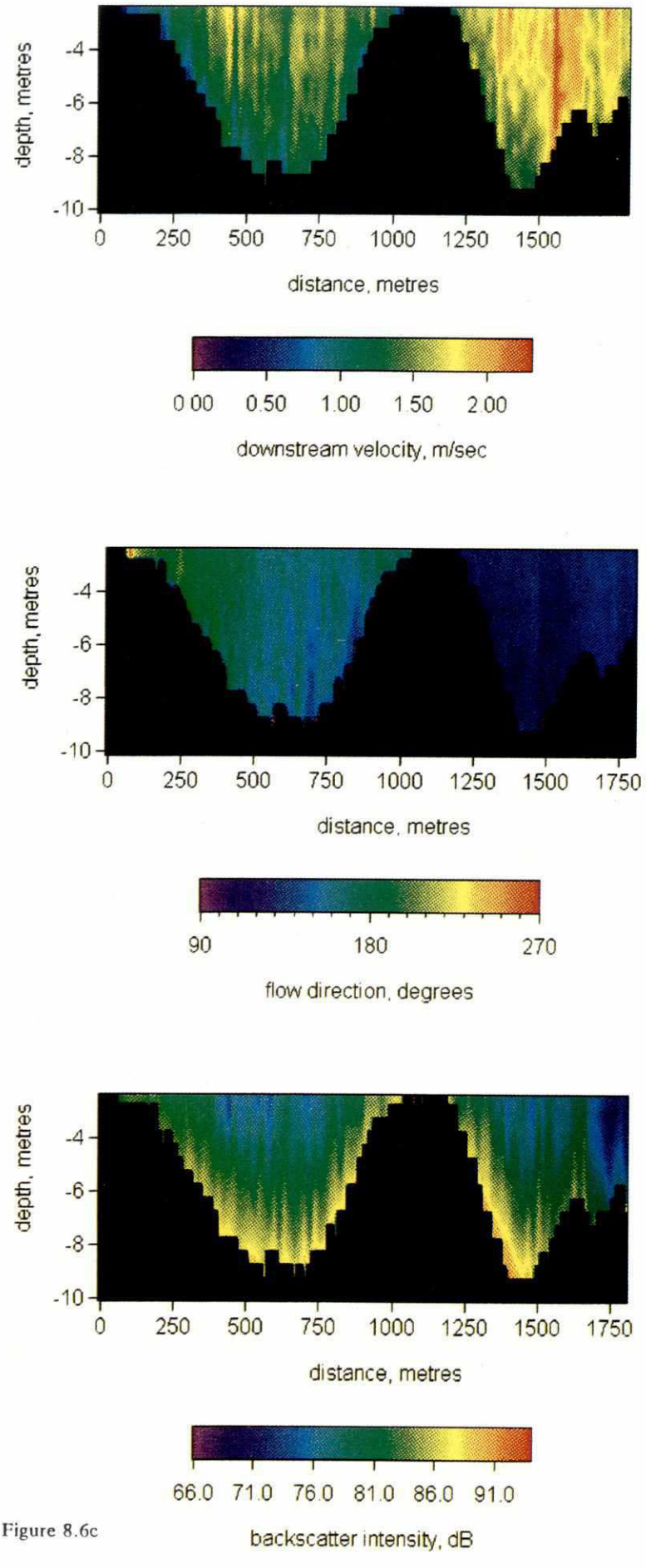


Figure 8.6c

D BT5X034

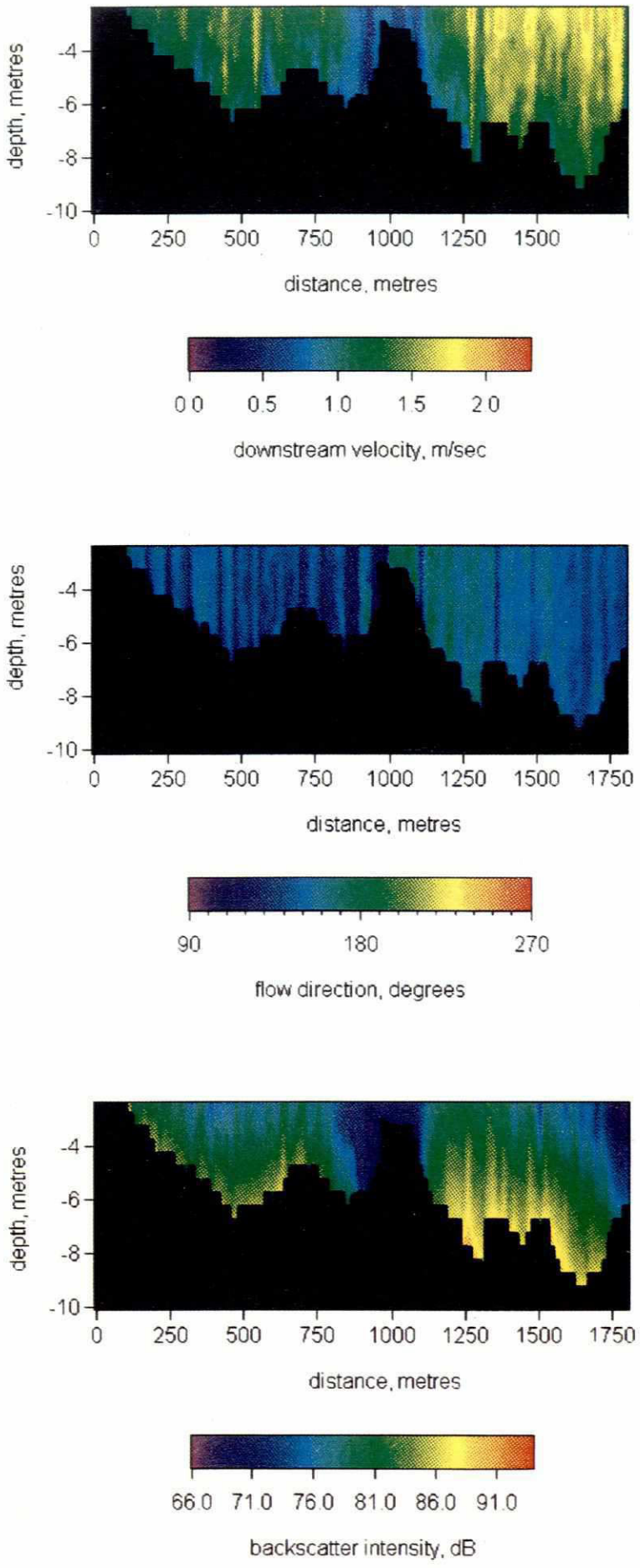


Figure 8.6d

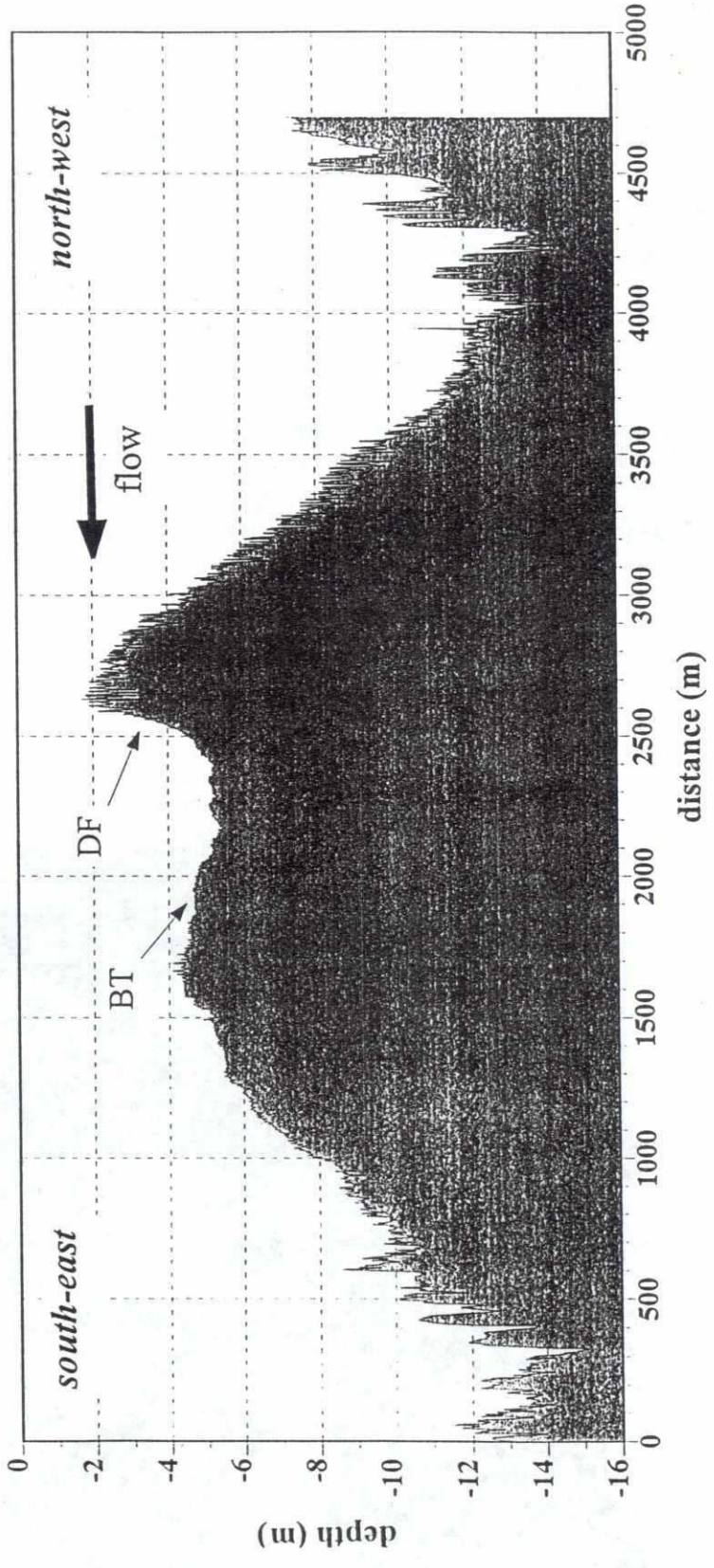
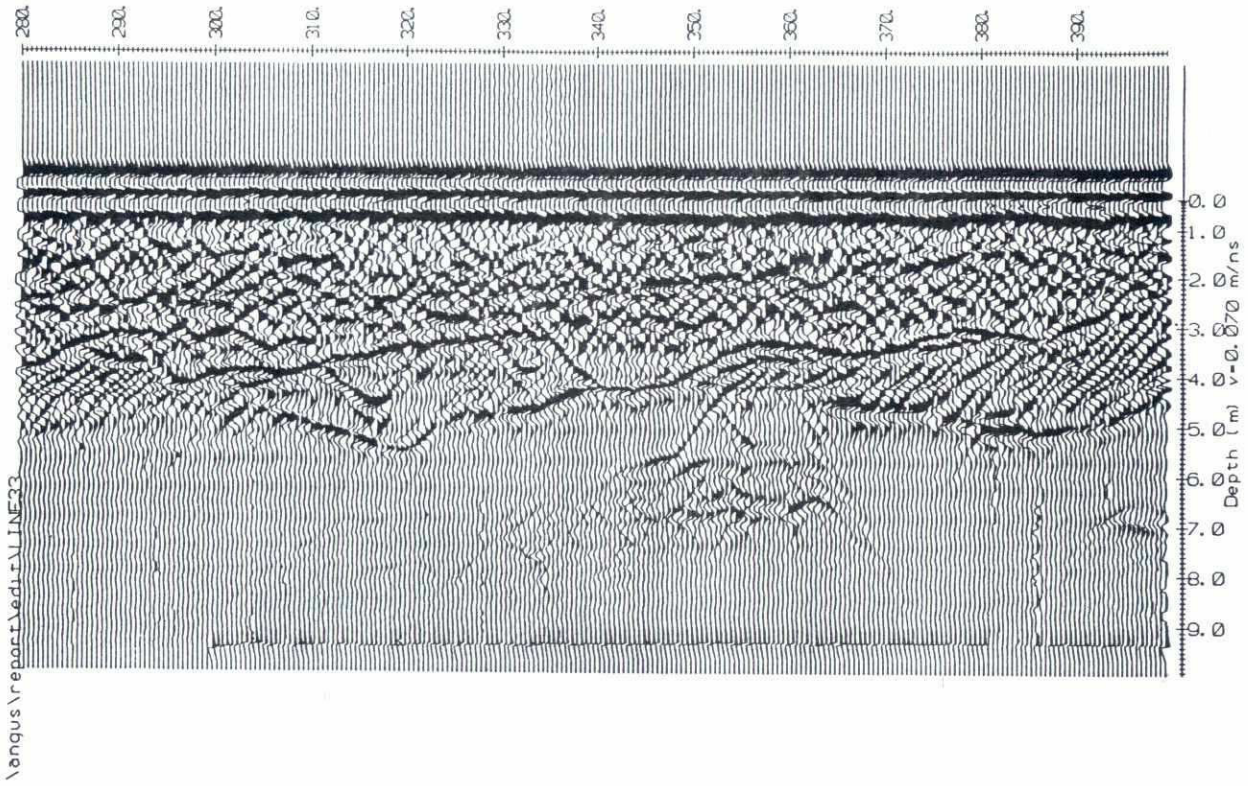

north-west
south-east
flow
DF
BT
depth (m)
distance (m)
0
-2
-4
-6
-8
-10
-12
-14
-16
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000

Figure 8.7a


280.
290.
300.
310.
320.
330.
340.
350.
360.
370.
380.
390.
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
Depth (m)
v=0.070 m/ns
\angus\report\edit\LINE33

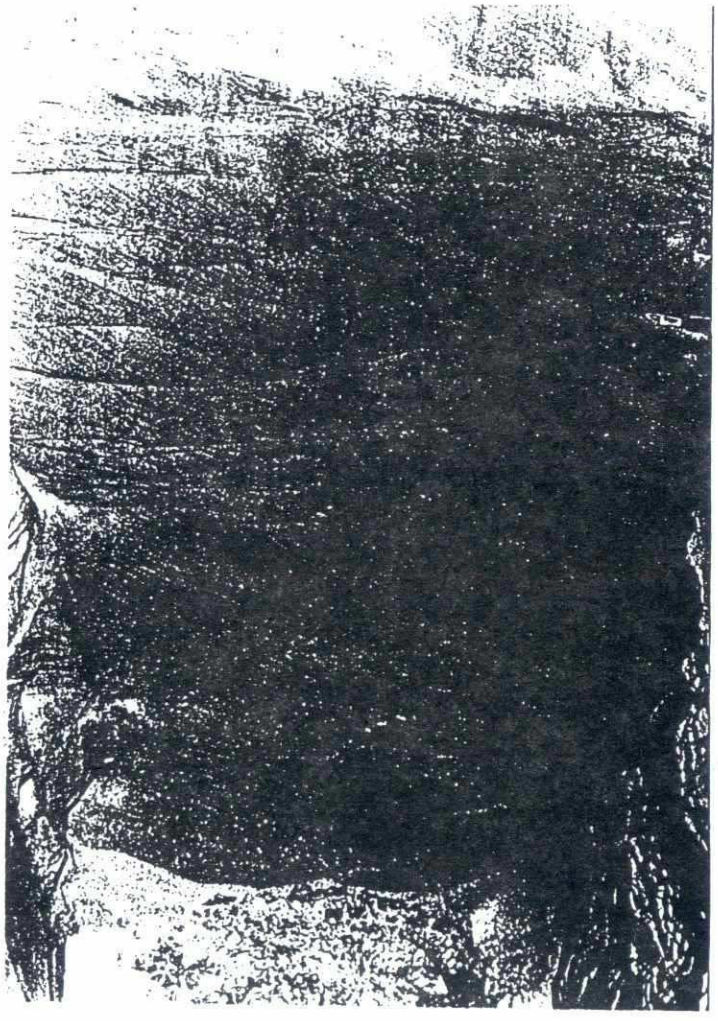


Figure 8.7b/c



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Figure 8.8a

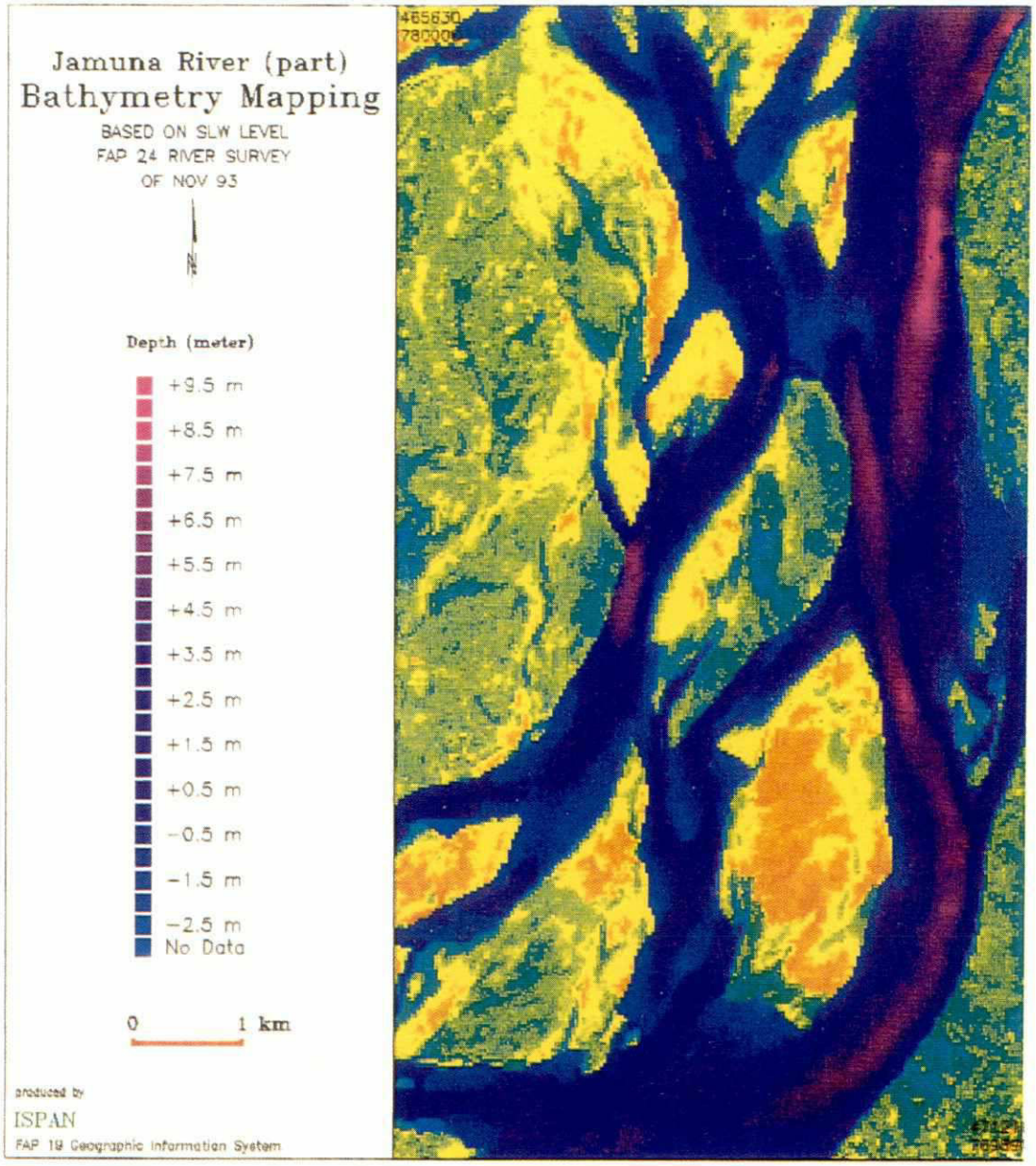

Jamuna River (part)
Bathymetry Mapping
BASED ON SLW LEVEL
FAP 24 RIVER SURVEY
OF NOV 93
N
Depth (meter)
+9.5 m
+8.5 m
+7.5 m
+6.5 m
+5.5 m
+4.5 m
+3.5 m
+2.5 m
+1.5 m
+0.5 m
-0.5 m
-1.5 m
-2.5 m
No Data
0 1 km
produced by
ISPAN
FAP 19 Geographic Information System

Figure 8.8b

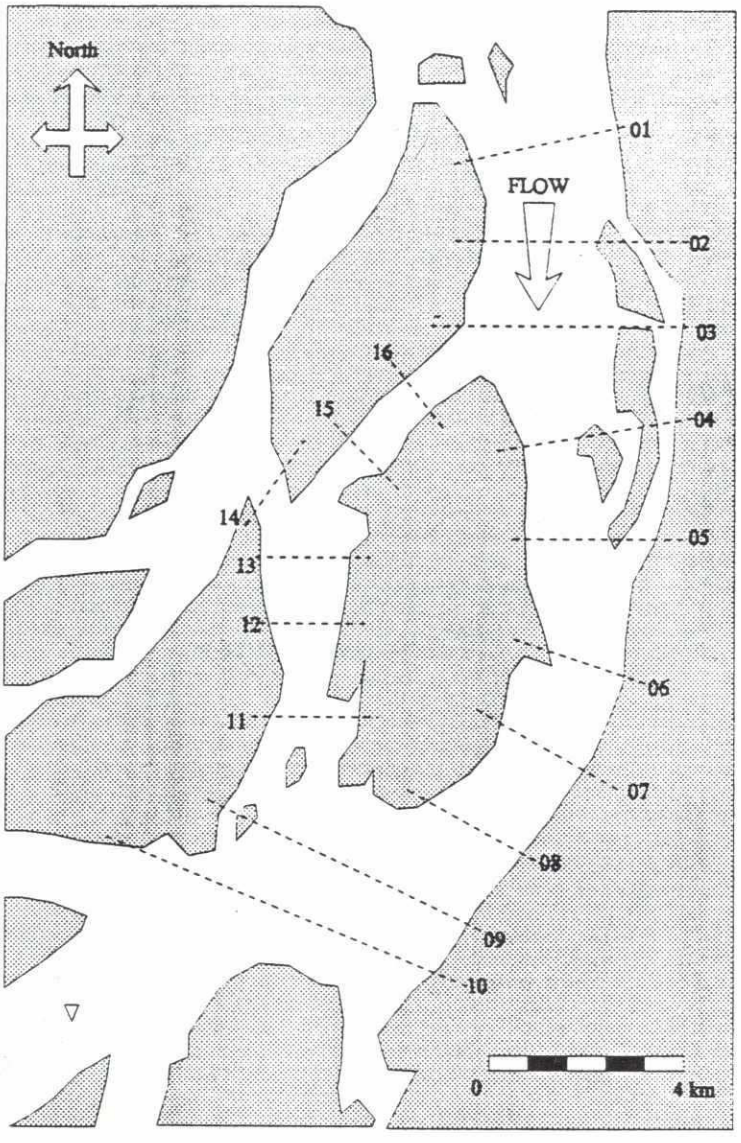


Figure 8.9

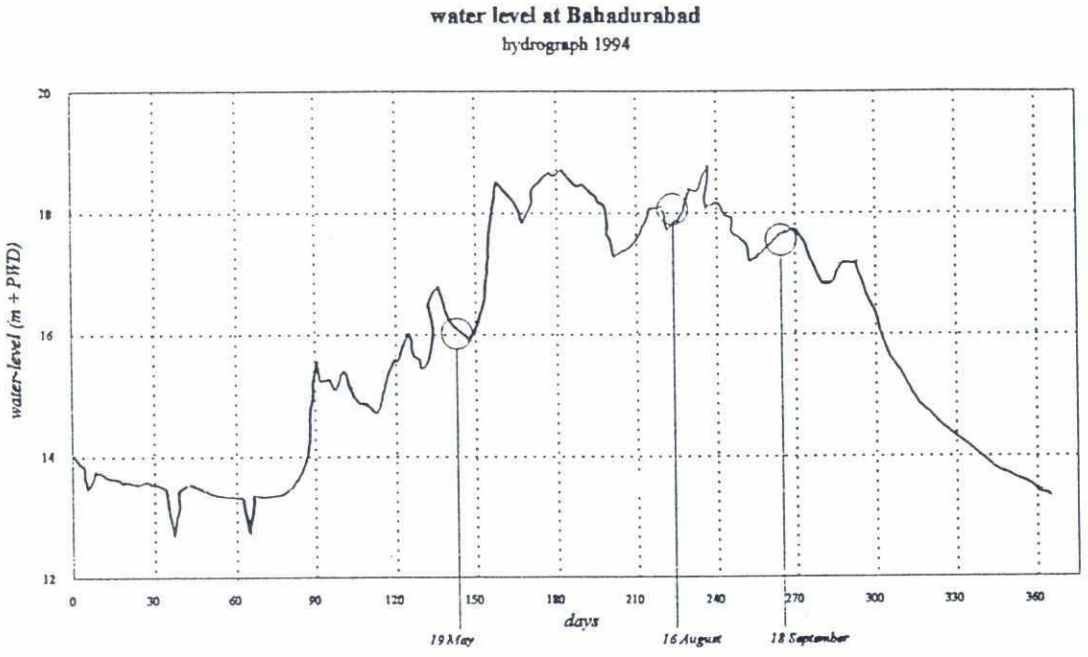

water level at Bahadurabad
hydrograph 1994
water-level (m + PWD)
20
18
16
14
12
0
30
60
90
120
150
180
210
240
270
300
330
360
days
19 May
16 August
18 September

Figure 8.10

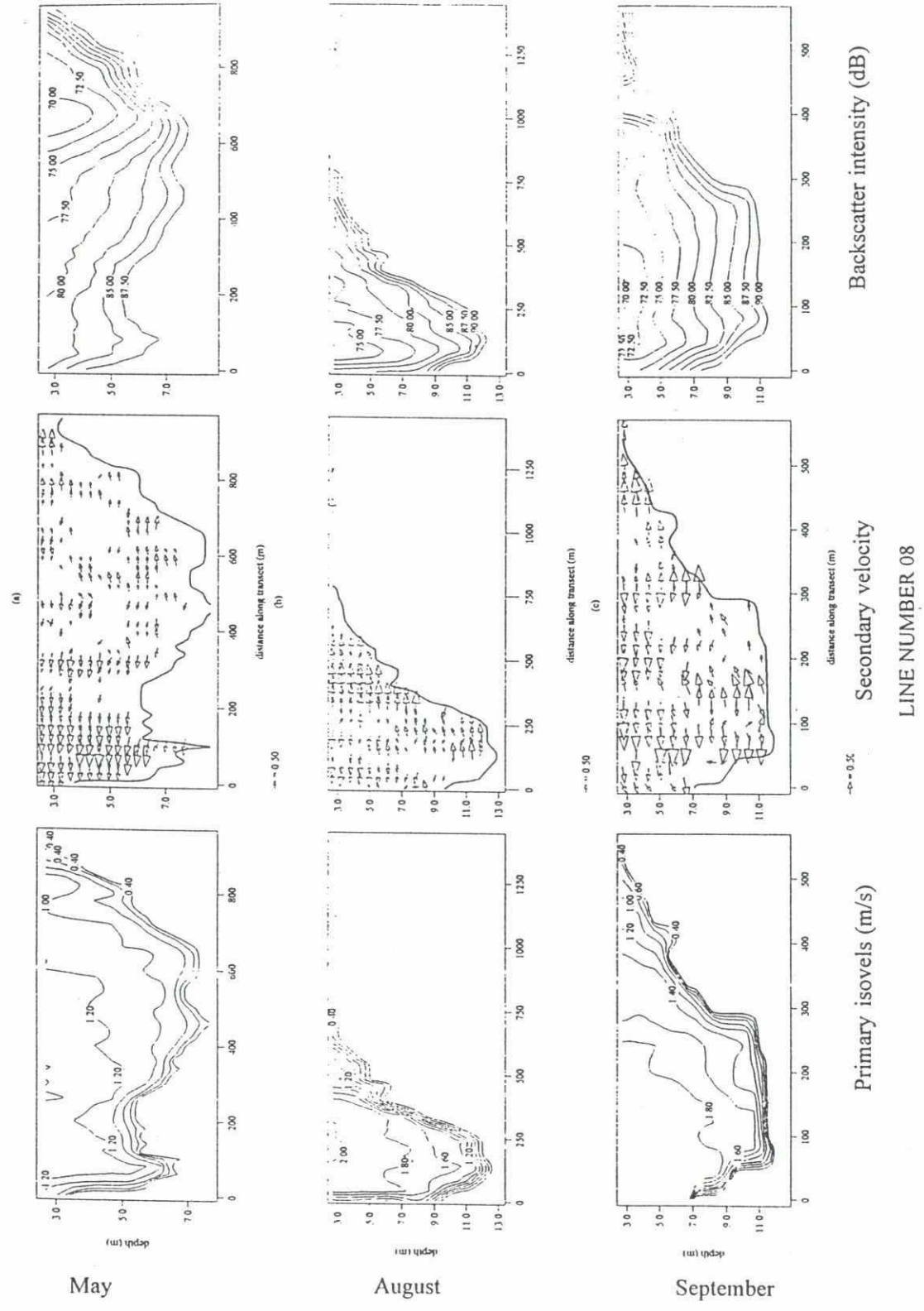

Backscatter intensity (dB)
Secondary velocity
LINE NUMBER 08
Primary isovels (m/s)
May
August
September
distance along transect (m)
depth (m)

Figure 8.11

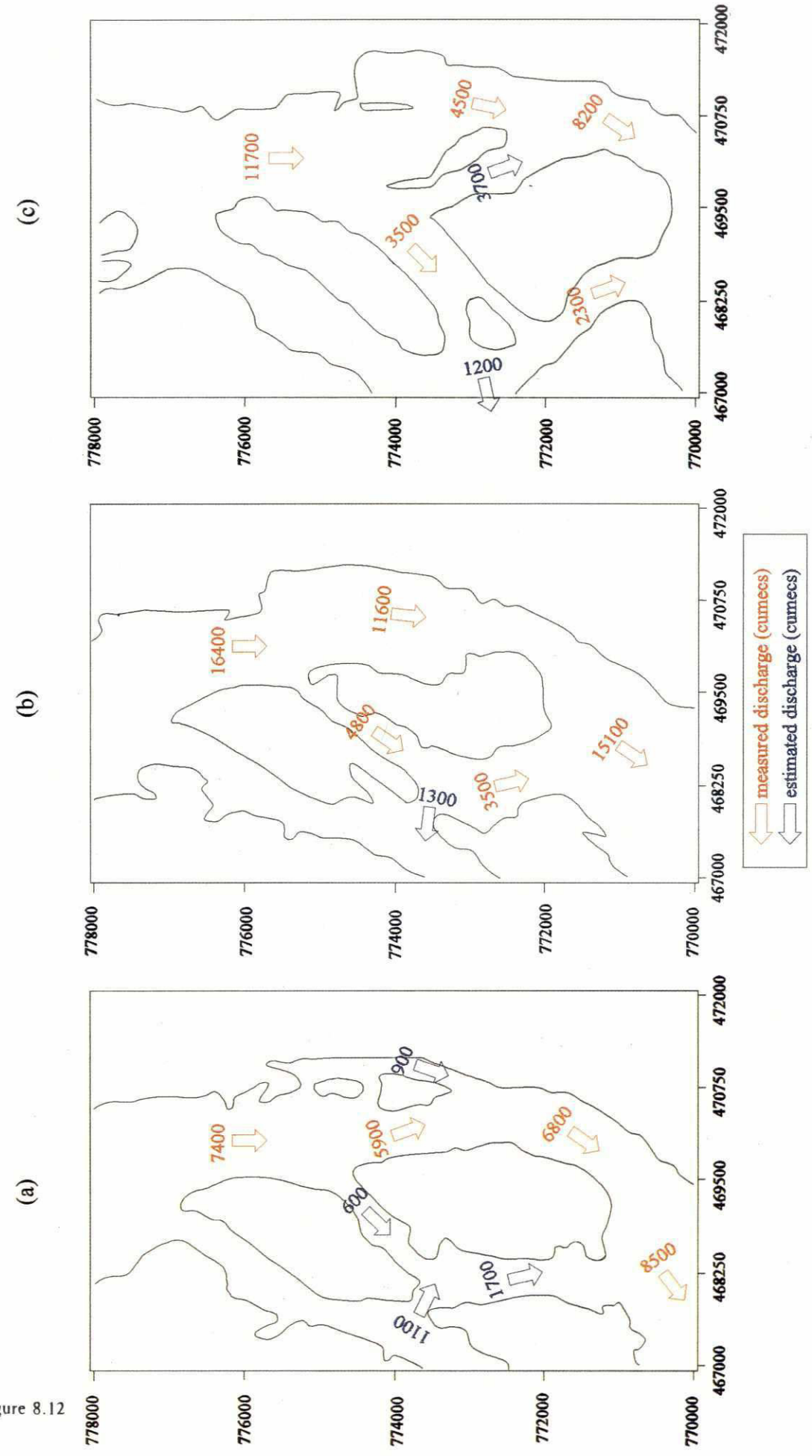

(a)
(b)
(c)
7400
5900
900
600
6800
1700
1100
8500
16400
11600
4800
1300
3500
15100
11700
4500
8200
3700
3500
2300
1200
778000
776000
774000
772000
770000
467000
468250
469500
470750
472000
measured discharge (cumecs)
estimated discharge (cumecs)

Figure 8.12

289

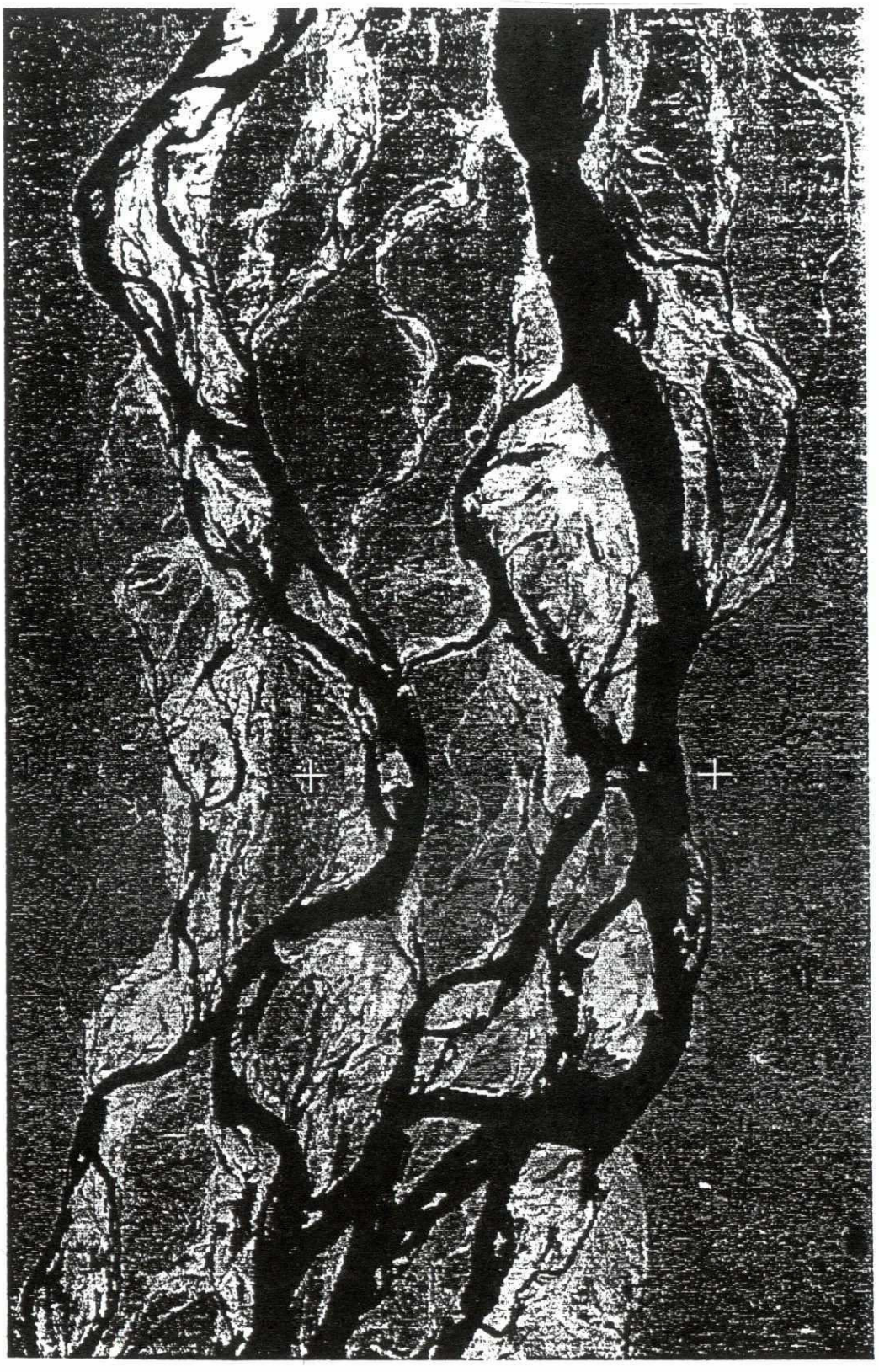


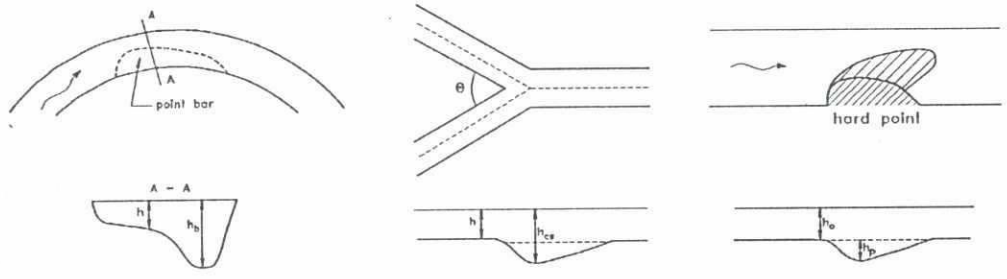
Figure 8.13

9 Scour holes

9.1 General

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

The reasons for the occurrence of scour holes are manifold: local flow condition or secondary flow locally, may generate larger (than average) shear stresses on the riverbed, causing bed scour or bed degradation. Also increased turbulence levels may cause deeper sections locally. Scour holes are often differentiated in constriction scour, bend scour, confluence scour, protrusion scour, bedform scour and local scour (occurring near hydraulic structures). In addition, general scour is often mentioned, but as this corresponds to long-term aggradation and degradation, it is not relevant here. In the Bahadurabad and Aricha area there are no hydraulic structures and neither any types of natural constriction were observed during floods. From the RSP bathymetric survey, it is not possible to identify bedform scour due to the large interspacing of the transect lines (100 m) during bathymetric surveys. Therefore, the emphasis of this study is on bend scour, confluence scour and protrusion scour (see also Figure 9.1).



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

Figure 9.1 Different types of scour holes

In this Chapter (in Section 9.2) first the causes of scour holes mentioned above and the prediction methods of different types of scour holes are discussed next to identifying the different types. The data used for studying the confluence scour holes in the Jamuna River is presented in Section 9.3. The development and the movement of the scour holes from the bathymetric maps is dealt with in Section 9.4. Dimensions and slopes of scour holes are discussed in Sections 9.5 and 9.6, respectively. The observed scour holes are compared using different predictors, in Section 9.7. Finally, a summary of the main findings of this study is presented in Section 9.8.

9.2 Causes of scour hole and prediction method

9.2.1 Introduction

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

9.2.2 Bend-scour

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

$$\left(\frac{1}{h_y} - \frac{1}{h_c}\right) = \left(\frac{1}{R_y} - \frac{1}{R_c}\right) \frac{1.5\ \alpha\ R_c\ i_c}{\Delta\ D} \qquad (9.1)$$

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

Struiksma (1988) presented a graph (Figure 9.2) to estimate the maximum scour depth at the outer bend of curved channels in terms of cross-sectional average parameters. In the figure the relevant parameter h_{bs}/h is the ratio of the maximum scour depth and the average depth, B/R is the ratio of width and radius of curvature, θ is dimensionless Shield parameter and A is secondary flow coefficient which depends on the Chézy coefficient as expressed via:

$$A = 2\ \kappa^{-2}\left(1 - \frac{\sqrt{g}}{\kappa\ C}\right) * 0.85 \qquad (9.2)$$

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

$$\frac{\partial h}{\partial n} = A\sqrt{\theta}\,\frac{h}{R} \tag{9.3}$$

where δh/δn represents transverse slope.

This graph is based on the same limitations as mentioned in the case of Equation (9.1). During the 'Meghna River bank protection short-term study' (FAP 9B), Haskoning et al (1990) found that the prediction of the depth of the maximum scour hole by Struiksma is about three times higher than the actual value. Similar observations were made for the Jamuna River in the Jamuna Bridge Study, Phase 2 (RPT et al, 1989). One explanation for this difference can be the influence of suspended load. According to Ikeda and Nishimura (1986) suspended load increases the lateral slope for the axi-symmetric conditions. See also Ikeda and Nishimura (1985) and Talman (1992). In addition, due to the assumption of fixed banks, the influence of the bank erosion products on the bed level is neglected. In a natural river, where the bank erosion rate might be significant, it considerably reduces the maximum scour depth. Moreover, the parameters involved in the prediction method are not so well defined in a natural river compared to a curved channel in laboratory flume. Mosselman (1989) provided an expression for the influence of bank erosion product on the transverse bed slope in an axi-symmetric case and modified expression of his equation is (Mesbahi, 1992):

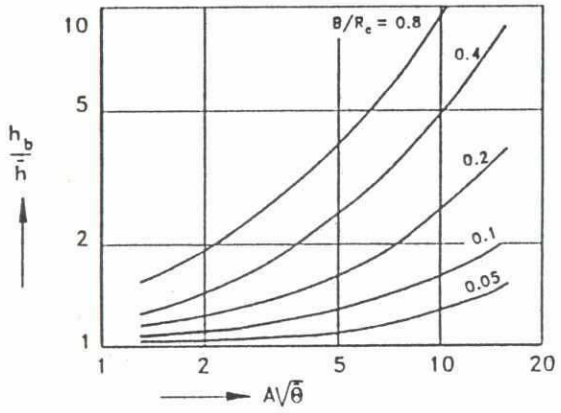


Figure 9.2 Method for finding the maximum bend scour depth (Struiksma, 1988)

$$\pi\,\frac{h'}{B} = f(\theta)\left(A\,\frac{h}{R_c} - \frac{1}{\pi}\,\frac{\eta h_b}{s_x}\,\frac{\partial n}{\partial t}\right) \tag{9.4}$$

where h' is first-order perturbation of h, varying with average flow direction only. It can be considered as: $h' = h_b - h_{avg}$, θ, A, h and R_c are similar as defined earlier, η = wash load factor, s_x = sediment transport in longitudinal direction and δn/δt = bank erosion rate. The first part of this equation is similar to Equation 9.3. Input of bank erosion products (second part of the equation) reduces the scour depth and the reduction is very significant when the bank erosion rate is high. The effect of bank erosion products was studied recently by Shishikura (1996). He found that the effect of these products on the transverse slope is substantial in sand-bed rivers like the Jamuna River.

9.2.3 Confluence scour

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

$$\frac{h_{cs}}{\bar{h}} = f\left(F_o, \bar{i}, \theta, \varepsilon\right) \tag{9.5}$$

where

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

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

$$\frac{h_{cs}}{\bar{h}} = 2.235 + 0.0308\,\theta \tag{9.6}$$

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

$$\frac{h_{cs}}{\bar{h}} = 1.292 + 0.037\,\theta \tag{9.6}$$

It was observed that the maximum scour depth in the Jamuna River is slightly smaller than the Ashmore and Parker (1983) predictor. This may be the influence of part of the bed material being carried in suspension as well. Other predictors for confluence scour were proposed by Best (1988), where the relative scour depth is proposed to be linearly proportional with ln θ. Furthermore a difference is made as to the value of Q_r (which is of course closely linked to ε.

9.2.4 Protrusion scour

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

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

$$\frac{h_p}{\bar{h}} = 4\ Fr^{0.33} \tag{9.7}$$

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

9.3 Data used

Mainly the RSP bathymetric surveys at Bahadurabad location are used to study the scour hole processes in the Jamuna River. In addition four bathymetric surveys at Aricha location are used, especially to study the confluence scour at the confluence of the Ganges and the Jamuna River. Four monthly monitoring bathymetric surveys of FAP 21/22 at Kamarzani location for the period of August to November 1995 are also used mainly to analyses the bend scour hole. In Figures 9.3, 9.4 and 9.5 the scour holes are shown bathymetric maps. All the scour holes observed at the Bahadurabad location are marked with letters to recognise those in the bathymetric surveys performed in different period. Hereafter, the scour holes at Bahadurabad will be mentioned together with marked letter and the period of bathymetric surveys.

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

Scour hole is generally defined as an area in a channel reach which is comparatively deeper than other areas of that reach. From the seven bathymetric surveys at Bahadurabad the identified scour holes are shown in Figure 9.3. Two types of scour holes are indicated in the figure, notably shallow scour holes, minimum bed level of which is above +6 m SLW and deep scour holes, minimum bed level of which is below +6 m SLW. In considering the channel geometry, three main types of scour hole can be identified: confluence scour, bend scour and protrusion scour. There are some other types of scour holes. The reason for their existence is not clearly known. Some of these scour holes moved through the system after their formation. These are named 'wandering scour holes'. However, the identification of the types, development and movement of the scour holes at Bahadurabad location are presented below. It is mentioned earlier that only confluence scour holes observed at Aricha (Figure 9.4) and bend scour holes at Kamarjani location (Figure 9.5) are studied only. Therefore, identification of those scour holes are not evident.

9.4.1 Bend scour

Scour hole I in the outer bend can be classified as a bend scour (Figure 9.3). Although in June-July 1993 three separate scour holes I_1, I_2 and I_3 were present, probably these scour holes were the remnant of a scour hole that had developed before the upstream cutoff. During the survey in June-July 1993 the direction of the flow was in transition due to the changing flow direction resulting from the cutoff process. After the further development of the cutoff through the New Main Channel an attached bar developed at the location of previous scour holes and the flow attacked the left bank farther downstream. This shifted the scour hole I about 1.5 km in downstream direction, increasing its scour depth from 8 m +SLW to about 16 m +SLW as can be seen from the August 1993 bathymetric survey. Bank erosion during the period of August to November caused the scour hole to move in an outward direction. Reduction of the flow in November resulted in an increase of the curvature of the scour hole (induced by changes in the flow lines) and a decrease in depth (Figures 9.6 and 9.7). The later survey in November 1994, showed that scour hole I had moved farther outward, following the bank erosion. The division of flow due of formation of bars over two channels approaching towards the bank, shaped the scour holes I_1 and I_2 to a combined scour hole.

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

The bend scour hole at Kamarjani is just downstream of the bank protection work of FAP 21/22, see Figure 9.5. The bank was eroding continuously and consequently the scour hole had been following the bank line migration in 1995.

9.4.2 Confluence scour hole

A confluence scour hole G exists in June 1993 as a result of the confluence of the Old Main Channel and the smaller channels bisecting the low char area north of Bahadurabad. Due to

the development of the New Main Channel after the cutoff processes and the consequent reduced discharge in the Old Main Channel, the direction as well as the maximum depth of the scour hole reduced from 13.5 m +SLW to 10.5 m +SLW in August 1993, see Figures 9.4 and 9.5. Further deterioration of the Old Main Channel resulted in a further reduction of the scour depth to 8.5 m +SLW and the upstream part of the scour hole shifted about 1.5 km in downstream direction with considerable reduction in size.

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

Confluence scour at Aricha shifted its position in relation with the planform development of the Ganges and Jamuna rivers at the upstream reach of the confluence (Figure 9.6).

9.4.3 Protrusion Scour

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

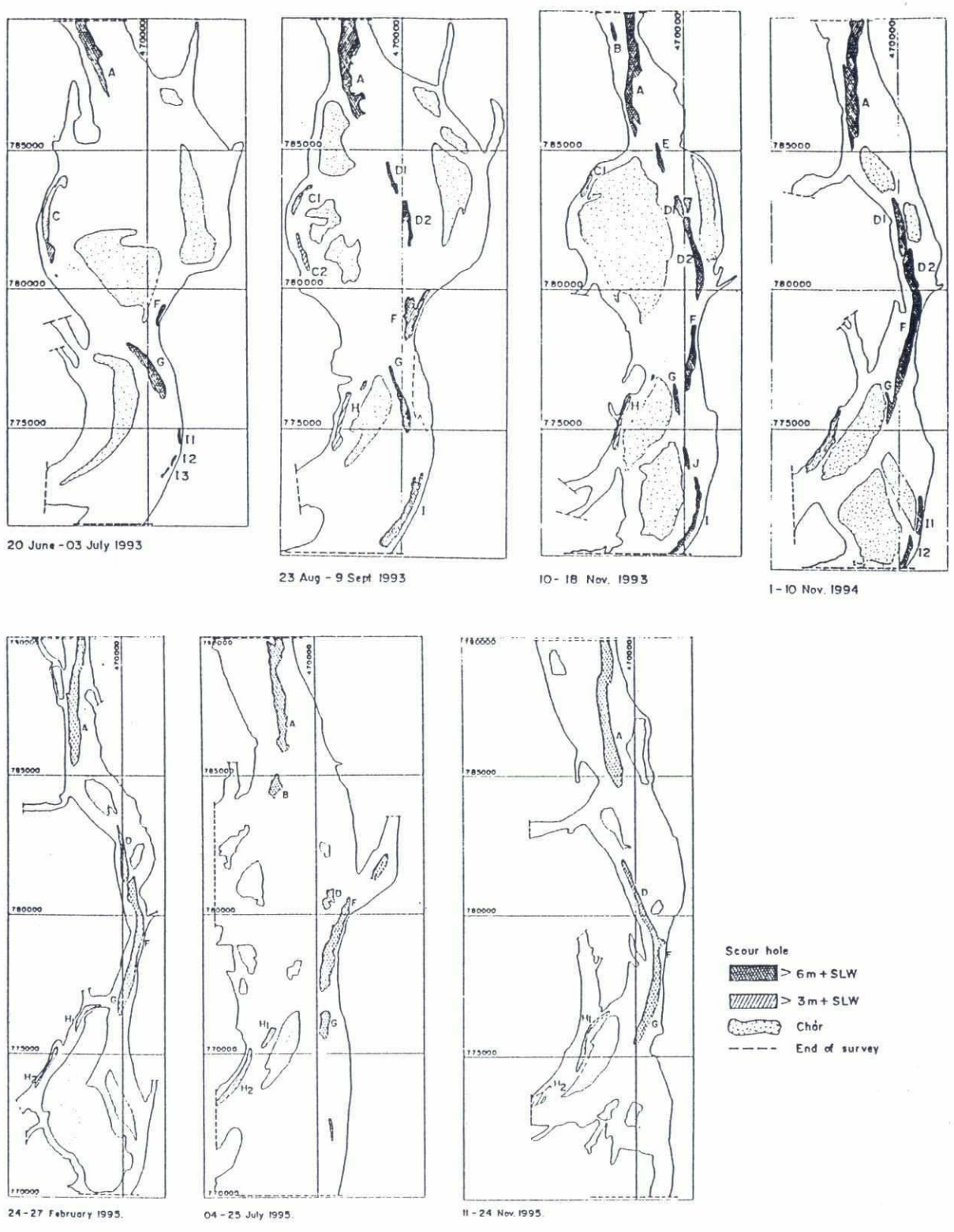


Figure 9.3 Scour holes at Bahadurabad identified in different bathymetric surveys



Figure 9.4 Location of the scour hole at the confluence of the Ganges and Jamuna Rivers (bathymetric survey October 1993).

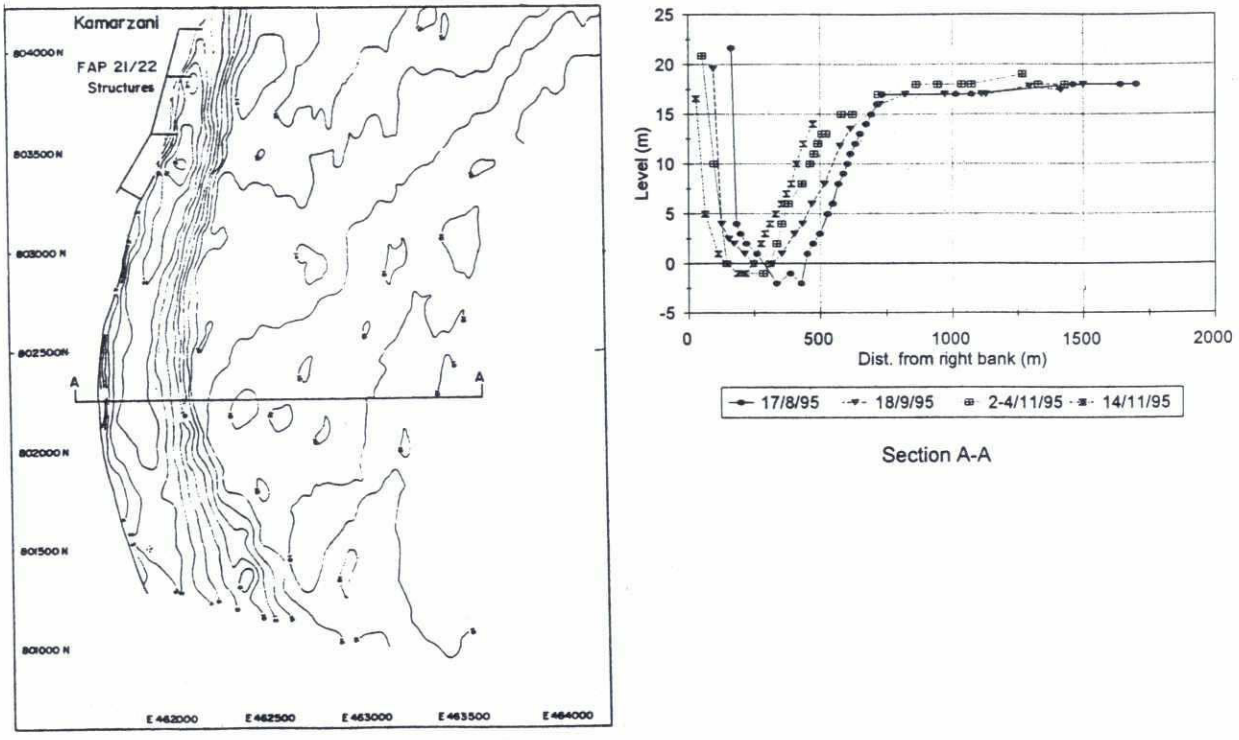
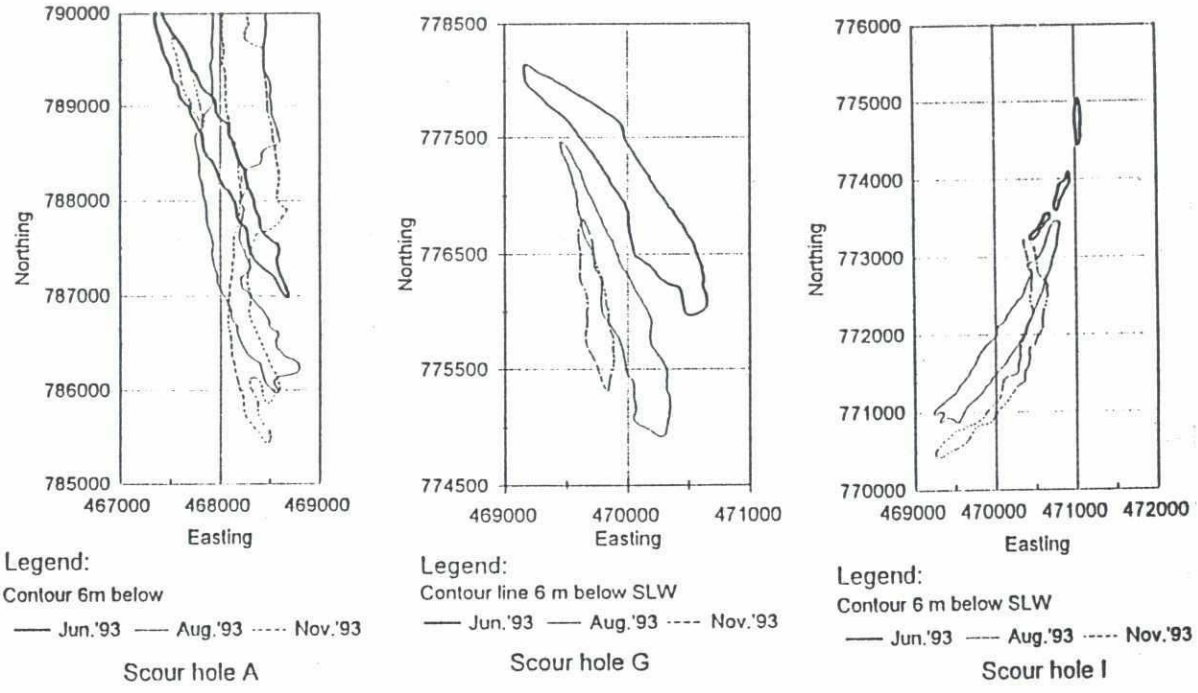


Figure 9.5 The bend scour hole at Kamarjani (FAP 21/22 bathymetric survey, August 1995)

9.4.4 Wandering of scour holes

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

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



(a) Scour holes at Bahadurabad

Figure 9.6 Shifting of the scour holes in time

9.4.5 Other scour holes

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

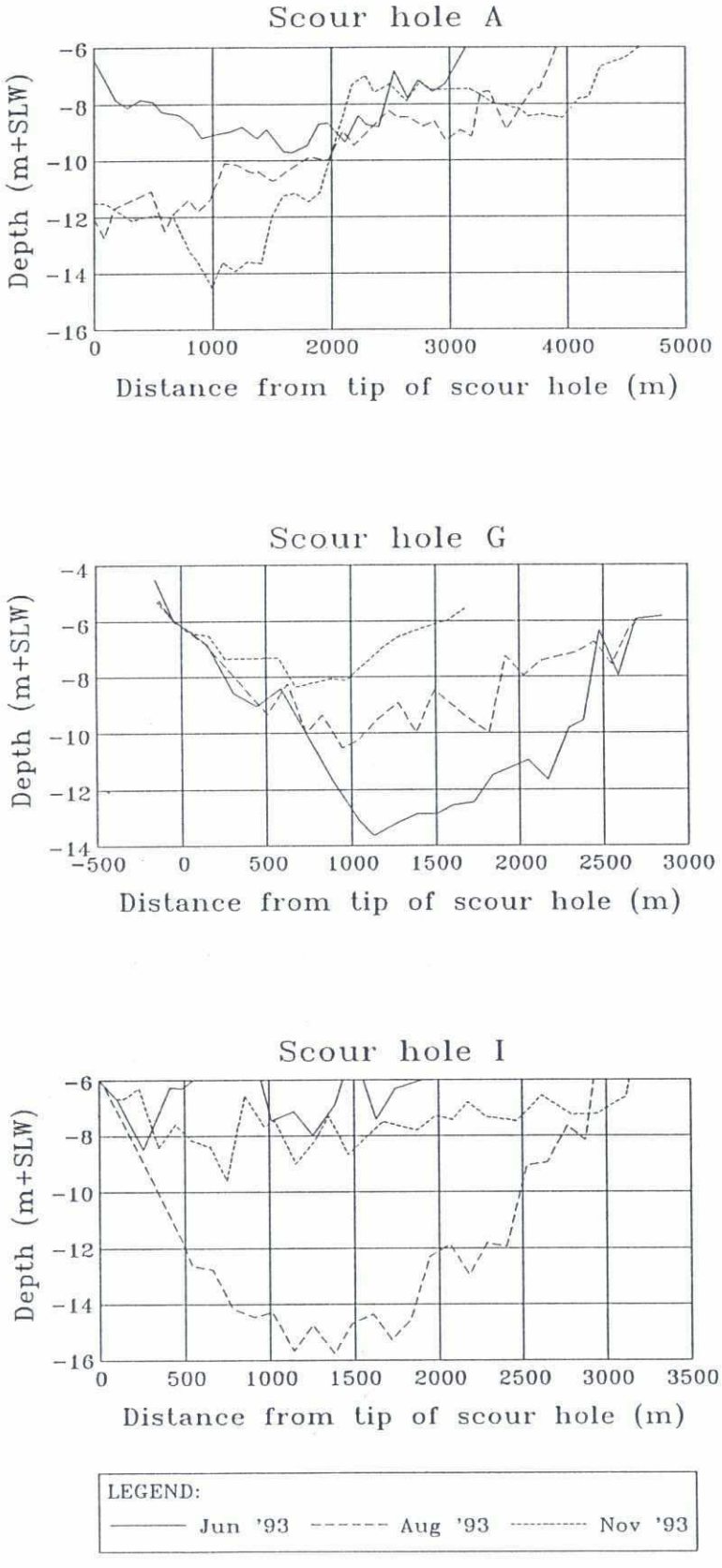


Figure 9.7 Changing of the long profiles of the scour holes in time

9.5 Dimensions of the scour holes

As indicator for the typical dimensions of the scour holes the maximum depth, area and volume below certain levels are analyzed here. The maximum depth is considered as a depth below SLW level; the area and volume are estimated below the +6 m SLW. These parameters for the scour hole at Bahadurabad location are presented in Table 9.1. The maximum depth presented in the table is not the maximum depth of the scour holes, rather it indicates the relative lowest bed levels of the holes. The maximum scour depth observed at the Bahadurabad location is 17 m +SLW of the scour hole F during the lean season survey, the maximum observed area and volume are found for the scour hole A in November 1995, notably 2.6 Mm^2 and 8 Mm^3 respectively. The shift of the scour hole A from June to August 1993 involved about 6 Mm^3 of riverbed erosion, which is about 25% of the total transported volume of sediment through the left channel at Bahadurabad during that period (see RSP SPR 24). The maximum scour depth at Aricha is about 26 m +SLW and the variation of the confluence scour depth with time is small within a range of 23 to 26 m +SLW only. The area of this confluence scour is about 5 Mm^2 and volume is about 30 Mm^3 below 6m + SLW. A partial shift of this scour hole involved a huge volume of sediment erosion and deposition in the riverbed, furthermore a reduction of average 1 m depth of this scour hole require almost 5 Mm^3 sediment supply from upstream which is nearly 45 % of the total sediment transport in the Jamuna River during the dry season. This estimation based on consideration of average during dry season discharge as 6000 m^3/s, then from the sediment rating curves (Annex 4) the average estimated sediment transport volume from November to March is about 11 Mm^3. Therefore, it can be concluded that the shifting of scour holes, which takes place continuously, involves huge amounts of sediment via deposition and erosion of the riverbed and probably has a significant contribution to the changing of the planform of the river.

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

Unlike to what is suggested in Breusers (1991a) the monsoon surveys do not show an increase in scour depth during the passage of floods. On the average the maximum scour depth, area and volume of scour holes at Bahadurabad location do not change with the season, see Figure 9.8. Due to the disappearing of a few scour holes, for example scour hole D during the monsoon, on the average comparatively overall deeper channels exist during the lean season.

9.6 Slopes of the scour holes

A brief analysis was carried out of the slopes of the scour holes as well. Both the longitudinal slopes of some scour holes and the lateral slopes were studied.

During the shifting and also during the development or diminishing of a scour hole, it appears to maintain an almost constant longitudinal slope, both at the upstream and the downstream side, see Figure 9.7. The upstream slopes are ranging from 1 to 100 to 1 in 200, while the downstream slope is varying from 1 in 250 to 1 in 400. These values indicate very mild slopes at both ends of the scour holes. They are also much milder than the scour hole slope found by Breusers (1991b) for scour holes downstream of hydraulic structures. The mild longitudinal slope is probably due to the large contribution of the suspended sediment transport to the total bed material transport.

The lateral slopes of the inner bend of scour hole I derived from the three bathymetric surveys of 1993 are shown in Table 9.2 (see also Figure 9.9). The radius of curvature (R_c) is estimated from a line draw through approximate 50% conveyance line of the reach of the river bend. The maximum slope occurred in August 1993 and varied through the bend. The highest scour depth occurred, where the transverse slope is highest (see Figure 9.9). The slopes of scour hole I in June and November 1993 have much lesser value. The magnitude of the inner bend slope is to the interaction between the transverse bed-shear stress due to the secondary current profile and the gravity forces of the grains. However, the outer bend slope varies from 1:2 to 6, probably depending on the bank erosion intensity of the bend and the characteristics of the bank materials.

Lateral slopes of the confluence scour holes were not studied extensively. First estimates on the basis of the bathymetric surveys (e.g. the Figures 7.4 and Figures 13.6 and 13.7) suggest slopes in the order of magnitude of 1 over 50. Hence the lateral slopes of the confluence scour holes are steeper than the longitudinal slopes. This can also be deduced form the shape of the confluence scour holes: the are clearly elongated.

Scour holes

Scour hole	Jun.1993				Aug. 1993				Nov. 1993				Nov. 1994				Feb. 1995			
	Max. depth		Area	Volum	Max. Depth		Area	Volume	Max. Depth		Area	Volume	Max. Depth		Area	Volume	Max. Depth		Area	Volume
	Below SLW		Below 6 m SLW		Below SLW		Below 6 m SLW		Below SLW		Below 6 m SLW		Below SLW		Below 6 m SLW		Below SLW		Below 6 m SLW	
		(m)	(Mm²)	(Mm³)		(m)	(Mm²)	(Mm³)		(m)	(Mm²)	(Mm³)		(m)	(Mm²)	(Mm³)		(m)	(Mm²)	(Mm³)
A		10	1.2	2.2		12	2.6	6.6		14	1.6	5.1		11	2.2	5.7		10	1.8	4
B										7	0.06	0.05								
C		5			*C1*	6			*C1*	4										
					C2	6				3										
D					*D1*	7	0.3	0.2		7	0.2	0.3		10	0.5	0.3		10	0.5	1.6
					D2	9	0.4	0.9		10	0.8	1.3		12	0.5	0.6		11	0.3	0.8
F		8	0.06	0.1		10	0.8	1.6		10	0.6	1.3		17	1.6	6.6		17	1.5	6.3
G		13	0.9	2.5		8	0.6	1.3		8	0.2	0.2		7	0.2	0.2		8	0.2	0.2
E										7	0.3	0.4								
H					*H1*	5				7				8	0.1	0.2		6		
					H2	8	0.05	0.1		8	0.05	0.1		8	0.2	0.4		8	0.1	0.2
I		7	0.1	0.1		15	0.9	3.6		9	0.5	0.6	*I1*	8	0.2	0.3		8	0.1	0.2
													I2	8	0.3	0.6				
J										8	0.2	0.3								

Jul. 1995				Nov. 1995			
Max. Depth		Area	Volume	Max. Depth		Area	Volume
Below SLW		Below 6 m SLW		Below SLW		Below 6 m SLW	
	(m)	(Mm²)	(Mm³)		(m)	(Mm²)	(Mm³)
	10	1.6	3.4		13	2.6	8
					9	0.8	1.7
	13	1.8	5.2		14	1.4	4.8
	10	0.5	0.9				
	7	0.3	0.6				
	9	0.1	0.2		8	0.1	0.2
	6						

Table 9.1 Maximum scour depth, area and volume (below SLW +6m) of the scour holes at Bahadurabad location in the period June 1993 - November 1995

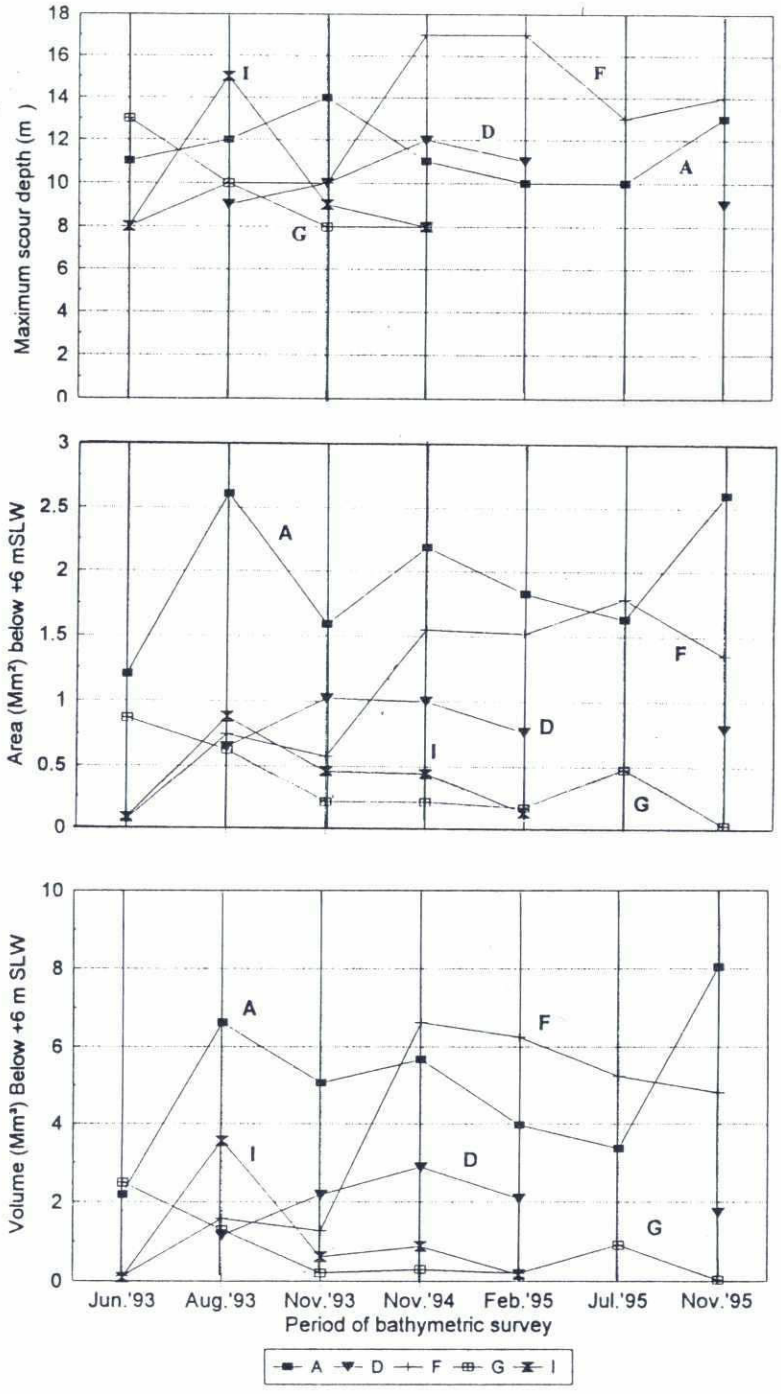


Figure 9.8 Variation of maximum depth, area and volume of different scour hole at Bahadurabad location in time

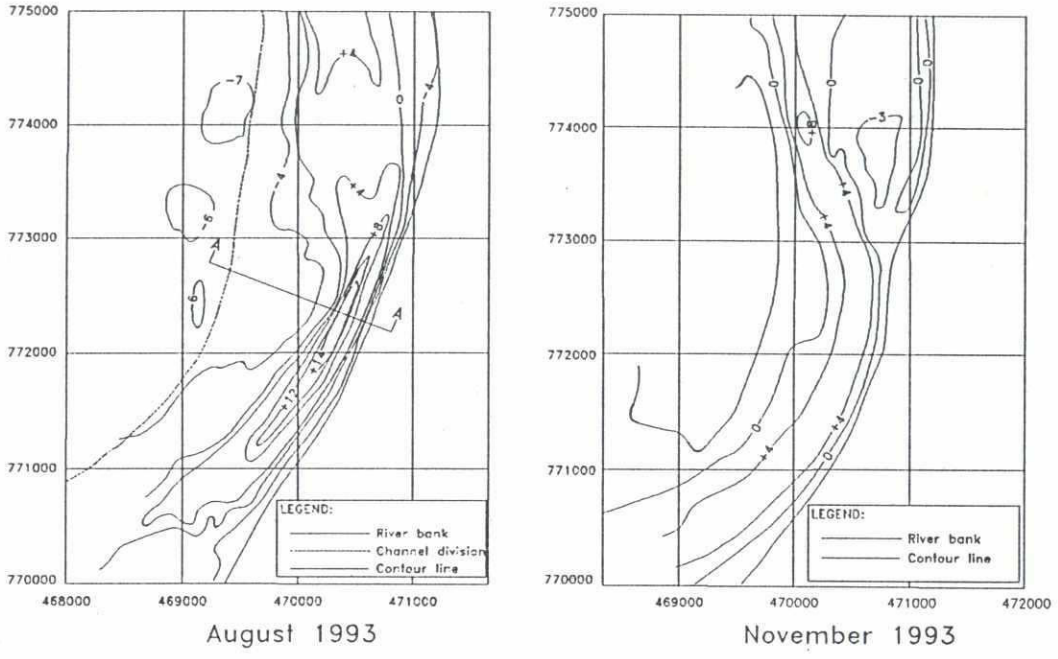


Figure 9.9 Scour hole I in August and November 1993 bathymetric surveys

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

Table 9.2 Average width, depth, radius of curvature and inner bend slope of the bend scour hole I, 1993 at Bahadurabad location

9.7 Comparison with different predictors

There are a number of predictors available for predicting the maximum scour depth. Here the predictors are limited to those which were previously used in the main rivers of Bangladesh under earlier studies. The different predictors for estimating the maximum scour depth mentioned in Section 9.2 are compared with the observed scour hole data. Here the main difficulty encountered is in estimating the parameters related to the prediction methods. Unlike a flume, in a natural river no parameters like B, h, R, i, u etc. are well defined, and they vary in space and time. Moreover, in the Jamuna River the range of variation of these parameters is quite high. In this study, B and h are estimated by averaging relevant stretches of a river, average radius of curvature is considered a representative of R, for i the average slope of the river at Bahadurabad is used and for the cross-sectional velocity u is derived from the measured discharge. In estimating B, h and R subjective judgement influences the derived parameters. In addition, the possible time lag of the riverbed with respect to flow increases the range of uncertainty in the prediction method.

9.7.1 Bend scour

According to the Struiksma method the relative bend scour depth (h_{bs}/h) increases with the increasing of the product of the secondary flow parameter and the square root of the Shield parameter ($A\sqrt{\theta}$), and with the increasing of the ratio of the width and radius of curvature (B/Rc). The secondary flow parameter A of Equation (9.3) was estimated here by assuming a constant Chézy's C value 70 $m^{1/2}/s$. This value was suggested by Klaassen et al (1988b) for the Jamuna River during monsoon flow. For the average slope (i) a value of $7*10^{-5}$ is used.

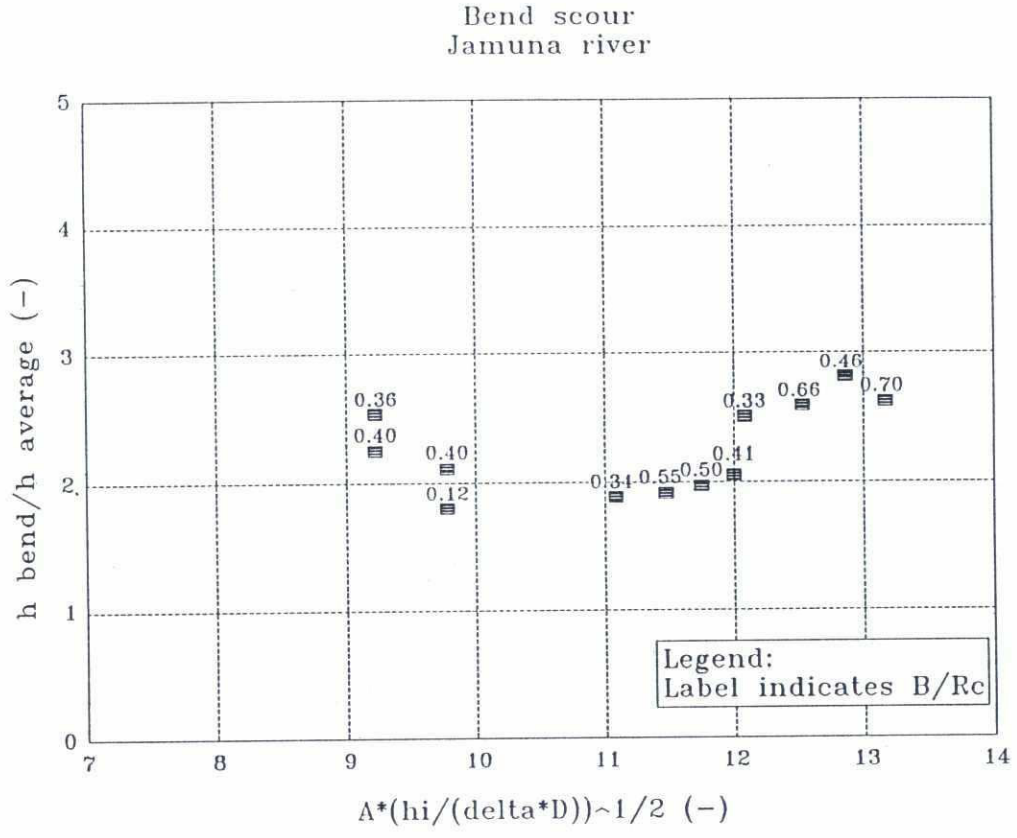


Figure 9.10 Maximum relative bend scour depth plotted according to the Struiksma (1988) design graph

Although there are some uncertainties in estimating the parameters related to the prediction method, it can be observed in Figure 9.10 that relative scour depth hardly shows any variation with the parameter B/Rc and ($A\sqrt{\theta}$). Like the observation of Haskoning (1990) in the Meghna River, the maximum bend scour depth is almost 3 to 4 times smaller than the predicted depth by Struiksma (see Figure 9.11). The average relative bend scour hole h_{bs}/h is about 2.4, which is higher than the Meghna River. This significant difference between the observed and the predicted depth can be seen via Figure 9.12, where cross-section A-A (see Figure 9.7) is compared with a cross-section derived using Equation (9.3), based on the parameters of the section A-A (Table 9.2). There are a number of reasons for these high differences, notably, (1) the estimated river width used here may be higher than a width where an axi-symmetric flow condition prevails and (2) the Struiksma method was developed for bed load transport, suspended sediment may have some effect in reducing transverse bed slope, (3) the Struiksma method is strictly speaking only appropriate for axi-symmetric conditions (but

considering the conditions at the beginning of a bend would lead to an increase rather than a decrease of scour depth), (4) the bank erosion product is not considered in Struiksma's method. Moreover, a number of other factors like the time-scale of the development of the scour hole as indicated by Klaassen (1988), the erodibility of the bank near the bend, intensity of the flow, the variation of width and radius of curvature along the bend might cause that the scour depth is fairly insensitive to the parameter B/Rc. More studies are needed to better identify possible causes of this discrepancies. Clearly the prediction of the scour depth in bends of rapidly eroding sand-bed rivers still has to be improved considerably.

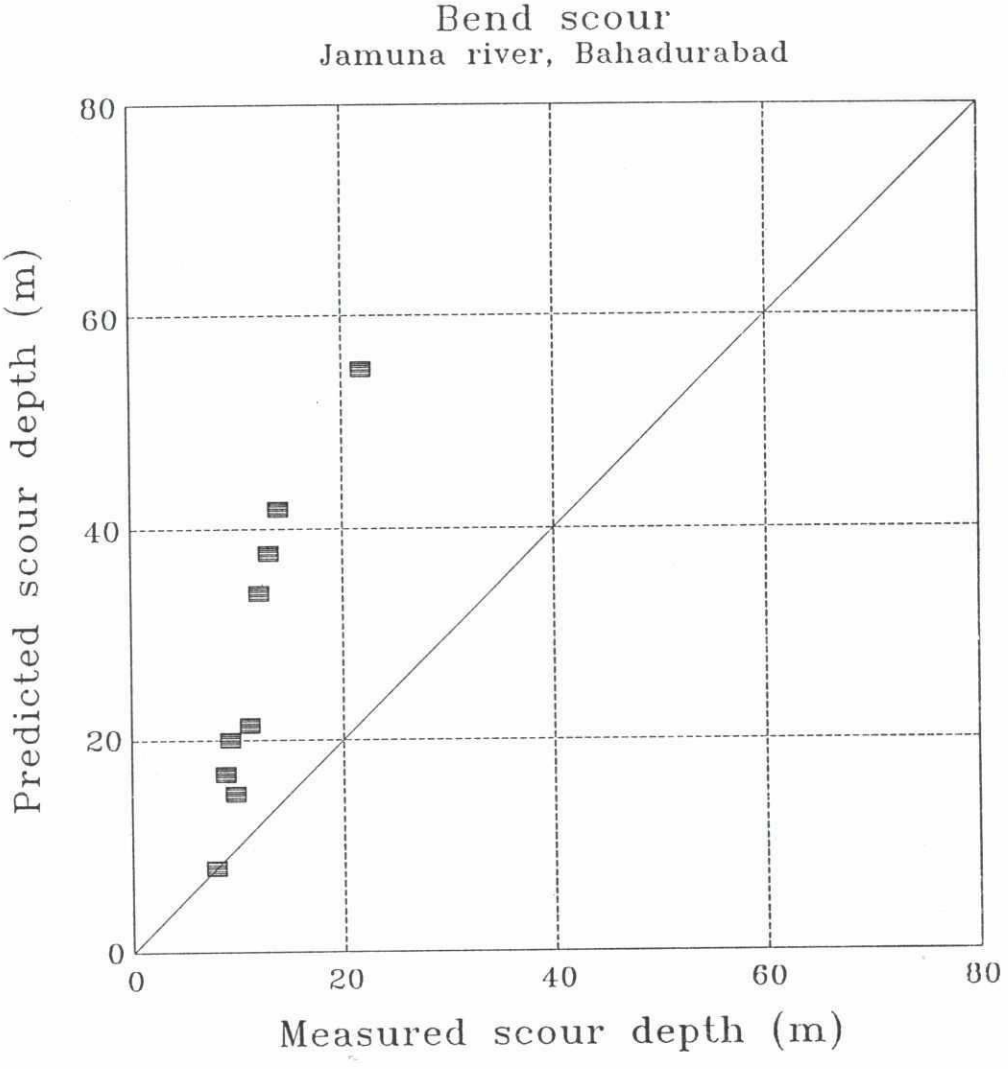


Figure 9.11 Comparison between observed and predicted (Struiksma, 1988) bend scour depth

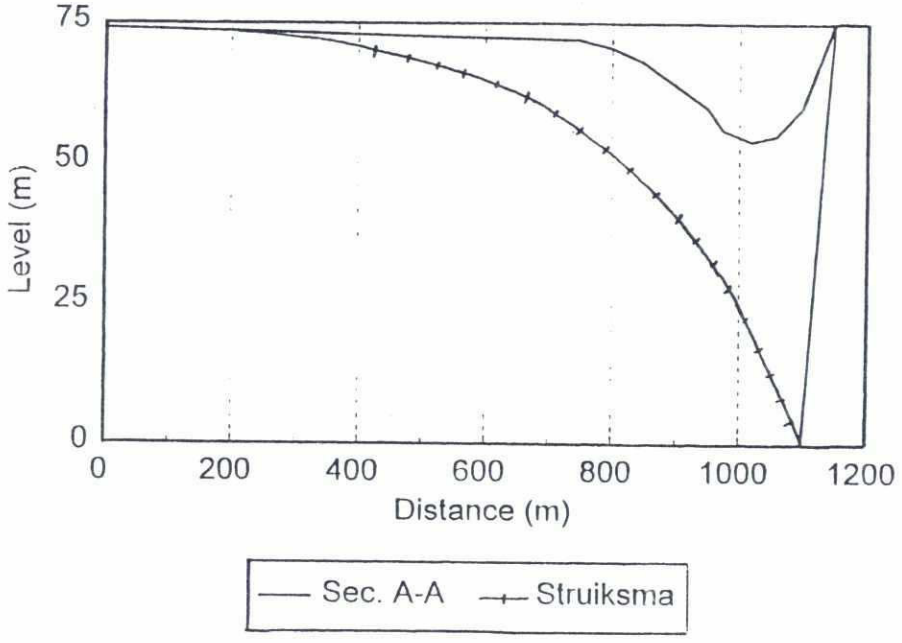


Figure 9.12 Comparison cross-section A-A (see Figure 10.7) and the predicted cross-section based on Struiksma (1988)

However, for the Jamuna River to predict the bend-scour depth an average value of relative scour depth can be considered. In Figure 9.10, it is observed that the relative bend-scour depth varied within a range of 2 to 2.8, the average value can be selected as 2.4.

9.7.2 Confluence scour

The relative scour depth (h_c) of the confluence scour increases with the angle of incidence (Θ) of the confluencing channel (see Equation 9.7). To apply the Klaassen and Vermeer (1988) prediction method for confluence scour, the average depth of the upstream channels has to be estimated, and this can only be done with limited accuracy. To estimate the value of ε the discharge of the confluencing channels are estimated from the RSP measured discharges and discharges obtained from rating curves. Initially the conditions during the survey were used: hence the average depths and discharges during the survey were introduced in the analysis. Klaassen and Vermeer (1988) used at-a-station relations for estimating the discharge, thus linking the depths of the channels surveyed by BIWTA to the width during the survey.

Confluence scour depths (see Figure 9.13) are broadly in-line with relationships proposed in past experimental and field studies. The scour documented at Bahadurabad fall within the range of mean values recorded in past work. During the derivation of Equation (9.5) Klaassen and Vermeer (1988b) excluded scour holes for which $\varepsilon > 0.75$, because they observed that for the higher values of ε, no relation existed between h_{cs}/h and Θ, probably due to the diminishing of the confluencing effect. However, the Bahadurabad data suggest that the confluencing effect is probably also significant beyond the mentioned range of ε.

The confluence scour between the Jamuna and Ganges plots above these trend lines, revealing a larger scour depth than predicted in past studies. Bearing in mind the likely errors associated with this plot (i.e. estimation of mean flow depth in the upstream channels, exact determination of scour depth, errors in estimating junction angle), several other factors may serve to make scour depth relationships at this junction more complex than those at Bahadurabad:

1) the wide range of discharge ratios experienced within the junction, especially due to the non-coincidence of the Jamuna and Ganges peak flows (Figure 7.3);

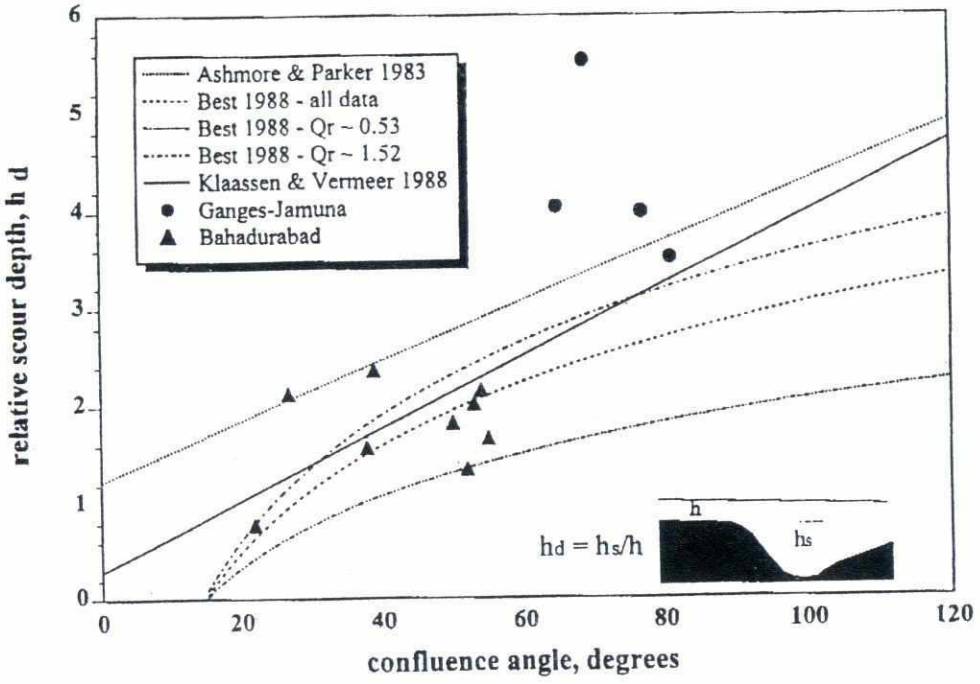
2) the presence of multiple channel inputs to the junction. This is especially clear for the Jamuna in the October 1993 - December 1994 surveys which show a distinct channel to the east side of the Jamuna junction entrance which is associated with the second scour at the junction;

3) curvature in the upstream confluent channels which most likely produces markedly non-uniform flow velocities and sediment transport pathways across the width of each channel at the junction, and

4) non-coincident bed heights in each confluent channel at the junction, which may induce both different flow mixing processes and sediment dispersal at the junction, with clear implications for the bed topography (Best and Roy, 1991; Gaudet & Roy, 1995; Biron et al, 1996).

5) the confluence scour that is produced during the monsoon, almost maintained its lowest bed level (due to lack of sediment supply to fill the scour from upstream) after ceasing the confluence effect due to very low flow through the Ganges in the lean season. In consideration the above, if the lean season surveyed data are excluded from Figure 9.13, only one data of October 1993 remain, which is close to Klaassen and Vermeer (1988) prediction method (Equation 9.7).

An alternative way of approaching this is to assume that the maximum depth of the confluence scour is not changing anymore during the recession of the flood, and hence is linked to the conditions during the flood season. The rationale for such an approach is that according to the comparison of the bathymetric surveys there is filling in from the upstream part of the scour hole (see Section 7.3), but the filling in is not sufficient to affect the conditions at the location with the maximum scour depth. Following this reasoning and in a first attempt it was assumed that the upstream water depth can be determined by assuming that the "dominant" water level in both upstream branches is 7.00 m above SLW (which is about 2 m lower than the maximum flood level). In Figure 9.14 a comparison is made between an approach using the momentaneous water depth (above) and the water depth during the flood (below). As can be observed using the water depths during floods brings the observations more in line with the Klaassen & Vermeer (1988) predictor and also more in line with the Bahadurabad data. A correction as done is fairly arbitrary. More study is required, e.g. using a 2-d mathematical model to study the time dependency of confluence scour depths.



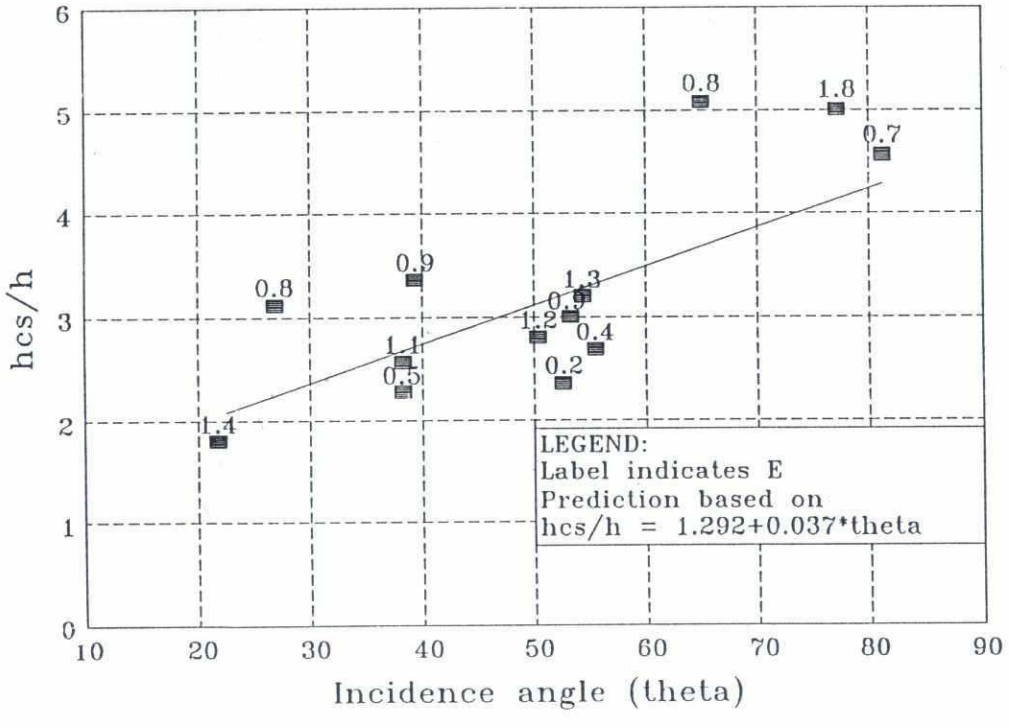
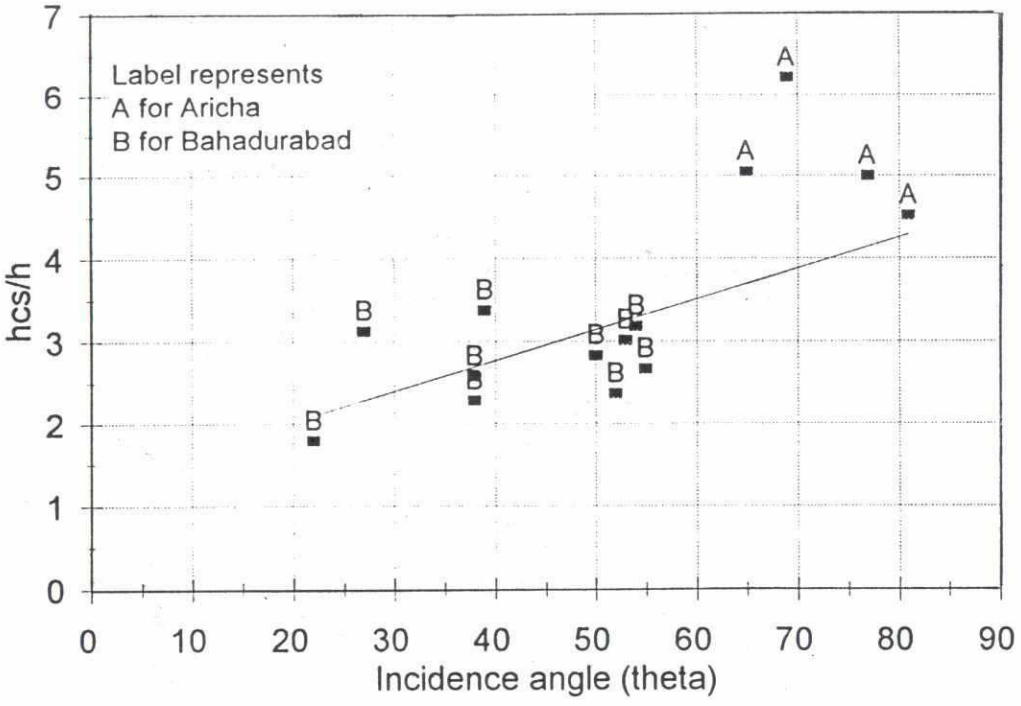
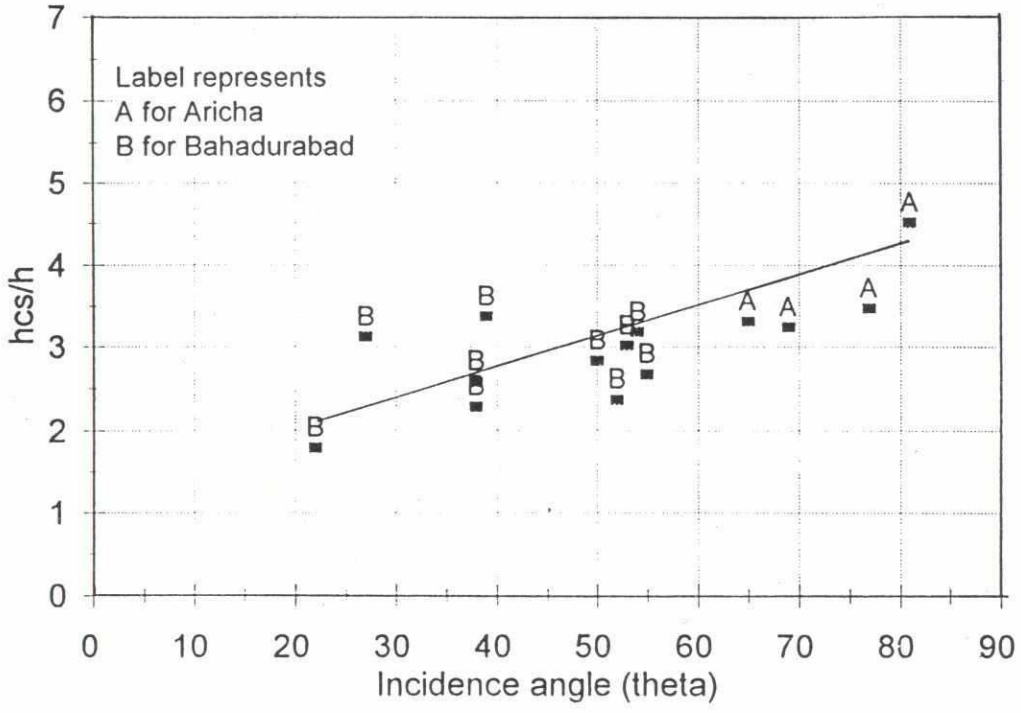


Figure 9.13 Relation between the relative confluence scour depth and the incidence angle



(a) Using water depth measured during bathymetric surveys



(b) Using "dominant" water depth during flood season

9.14 Effect of correction of relative confluence scour depth for previous conditions

9.7.3 Protrusion scour

Comparing the observed scour depth with Simons and Sentürk (1977) prediction method for abutment scour, it was found that the predicted depths are slightly higher than the actual values, (see Figure 9.15). The average observed value of $4*Fr^{0,33}$ is 2.1, where as the average h_p/h is about 1.8. One possible explanation is that in the case of abutments the sediment supply from the bank completely ceases, while in the case of a natural protrusion as at Bahadurabad, the bank is erodible. Consequently there is sediment supply from the bank, which might reduce the scour depth. In the Meghna River the protrusion scour holes are similarly related to the Froude number, indicating that the protrusion scour holes in the main rivers of Bangladesh can be fairly well predicted by the Simons and Sentürk (1977) method.

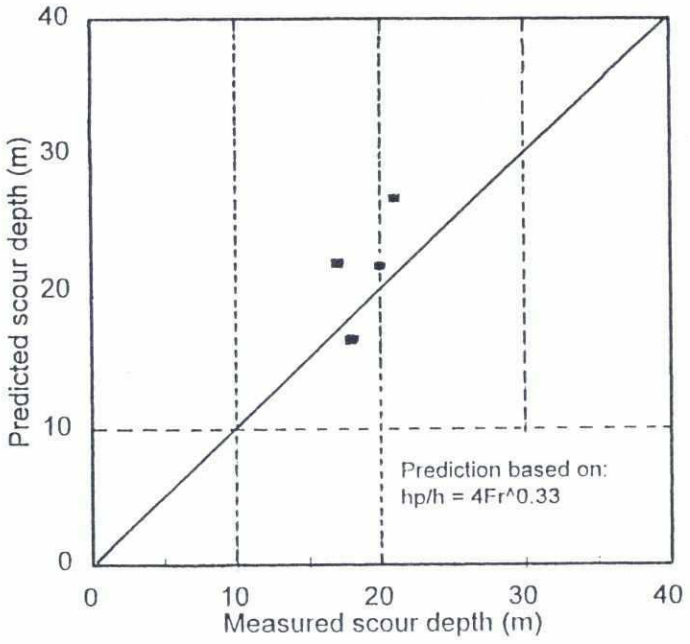


Figure 9.15 Observed and predicted (Simons and Sentürk 1977) protrusion scour depth

9.8 Summary

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

- The different types of scour holes could be studied in this study using more reliable riverbed data, flow and other parameters than in any previous study, although uncertainties remain in estimating some of the parameter used in the prediction method.

- The development and movement of the scour holes in the Jamuna river are extremely dynamical processes and they are mainly related to the rapid changes of the upstream planform. The formation, movement and diminishing processes of a few scour holes are also related to the seasonal variation of discharges.

- The shifting of the scour holes is generally associated with major aggradation and degradation of the riverbed which may involve up to 25% the total sediment transport (coarse fraction) volume.

- The upstream and downstream slopes of the scour holes are comparatively very mild, which is probably the large contribution of the suspended bed material load to the transport in the river.

- The dimensions of the scour holes i.e. the maximum scour depth, area and volume change time, but on average no seasonal variation of scour hole dimensions are observed at Bahadurabad over the observation period.

- The prediction method by Klaassen and Vermeer (1988b) can be used to estimate the confluence scour in the Jamuna River. For protrusion scour the Simons and Sentürk (1977) method can be applied for the Jamuna River. For bend scour depth an average relative scour depth (h_s/h) can be considered as 2.4 for the Jamuna River.

10 Bank erosion and cutoffs

10.1 Introduction

In this chapter bank erosion and cutoff processes in the Jamuna River are discussed mainly on the basis of RSP SPR24. These processes have an important role in planform development. Klaassen and Masselink (1992), Thorne et al (1993) studied the bank erosion processes in the Jamuna River moreover Klaassen and Masselink studied also the cutoff processes as well. Mosselman et al (1994) also studied the cutoff processes in the Jamuna River. Klaassen et al (1993) developed a stochastic planform predictive model for the Jamuna River in which bank erosion and cutoff processes are two main components. These previous studies were mainly based on satellite images. In studying the bank erosion and cutoff in the Jamuna River, River Survey Project mainly used their measured bathymetric surveys, and flow and sedimentary data. These data provide to have an more insight into the bank erosion and cutoff processes. First a brief introduction of these two processes are presented below:

10.1.1 Bank erosion

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

The flow in a river bend attacks the toe of the river bank, removing the sediment from the toe, resulting in an over-steepening of the river bank and causing the bank failure by slumping. Although bank erosion is quite a complicated process, over the recent years a number of methods were developed to predict the bank erosion rates along a river. These methods can be distinguished into two types: the first one is related to a 2-D mathematical model and developed to compute bank erosion on the basis of local channel geometry, flow and/or sedimentary processes (Mosselman, 1992 and DHI 1996). The other type of prediction method estimates the yearly bank erosion rate on the basis (1) overall channel parameters such as discharge and characteristics of bank materials, and (2) local channel geometry (Hickin and Nanson, 1984). Theses prediction methods for predicting the bank erosion rate will be compared later with the observed bank erosion rate.

10.1.2 Cutoff

Cutoffs of curved channels are often observed in meandering rivers and cutoff processes play an important role in planform development. Although being a braided river, in the Jamuna similar cutoff processes are often observed in river bends (Klaassen & Masselink, 1992). Here the river bend is mostly formed by an outflanking anabranch and after a few years the anabranch is abandoned, often by a cutoff process. This type of cutoff process markedly

changes the downstream planform of the river. Therefore, a better understanding of the cutoff process is quite relevant to better predict the morphological development of the river. During the RSP bathymetric surveys at Bahadurabad, a cutoff took place and later surveys show the channel and planform development in that reach. Here the development of the cutoff and the later development of the channel is discussed using the RSP bathymetric surveys.

The data used for studying the bank erosion and cutoff processes are presented in Section 10.2. The flow around eroding river bank, location of bank erosion and bank erosion rates are presented in Sections 10.3, 10.4 and 10.5 respectively. Finally the occurrence of cutoffs and Morphological changes due to cutoff are presented in Section 10.6 and 10.7 respectively.

10.2 Data sources

As indicated that the bathymetric surveys of RSP are the main sources of the study. RSP preformed eight bathymetric surveys at Bahadurabad location from June 1993 to February 1996. Among these seven bathymetric surveys are used in studying the bank erosion. In addition FAP 21/22 bathymetric surveys in 1995 are also used in studying the bank erosion at Kamarjani location. Special surveys for the RSP/UoN Joint Study (see SRR 16) are also used to asses the flow in outer bends. In addition RSP flow and sediment data also used as well in studying the bank erosion and cutoff processes. In studying the cutoff processes SPOT images of 1992 to 1994 are utilized.

10.3 Flow field near the eroding bank

In a meandering river, bank erosion generally occurs along outer bends due to the presence of secondary flow currents, which makes surface layer and bottom layer flow in a different direction, see Figure 10.1. As the maximum sediment concentration is in the bottom layer, in a river bend the direction of the average flow follows the bend axis, while the average sediment transport directed towards the inner bend, thus liable for the formation of point bar. In a meandering river the river bend is generally well defined. In a braided river, however, the bend is formed as a part of one of the anabranches. In such a river there is a continuous change in distribution of the water and sediment in between the different anabranches, which makes a river bend more unstable and less defined than in the case of a meandering river. Also the flow structure in such a bend is more complicated. Here data from the RSP/UoN special study are analyzed to demonstrate the complexity of the flow pattern.

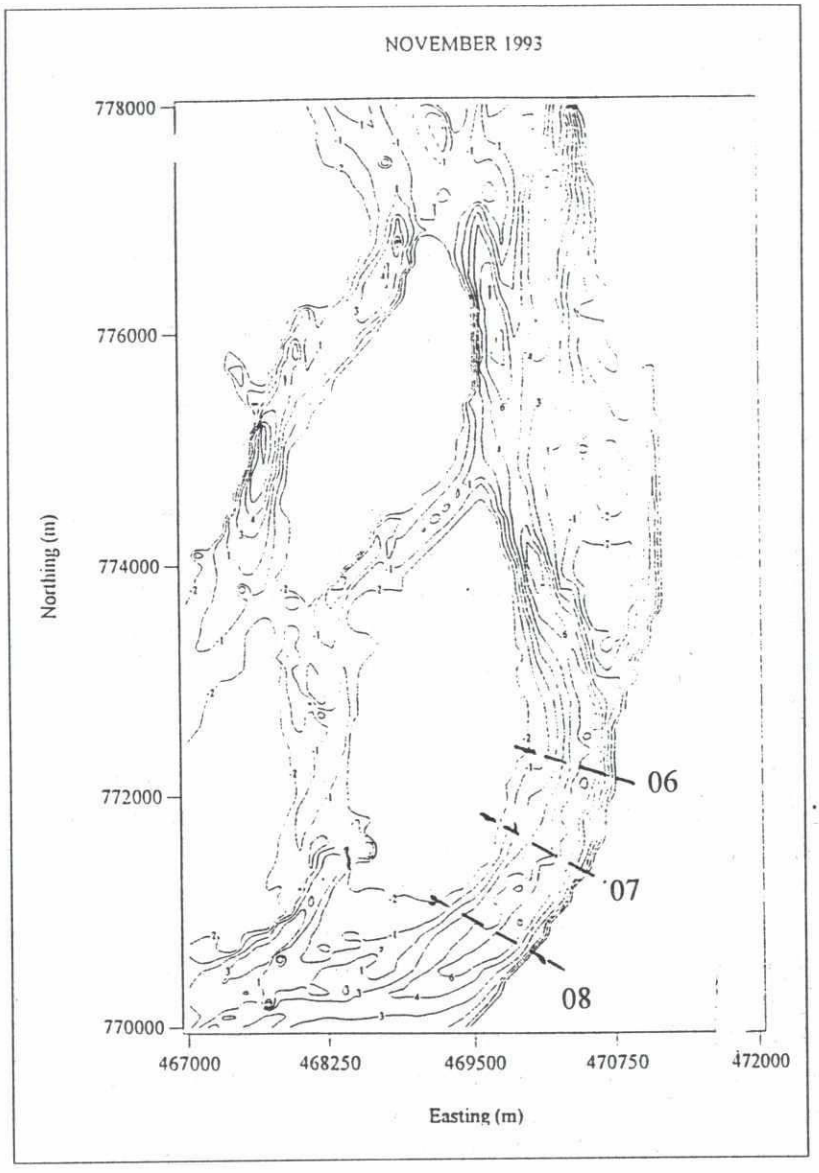


Figure 10-1a

Bathymetry map of study reach in November 1993

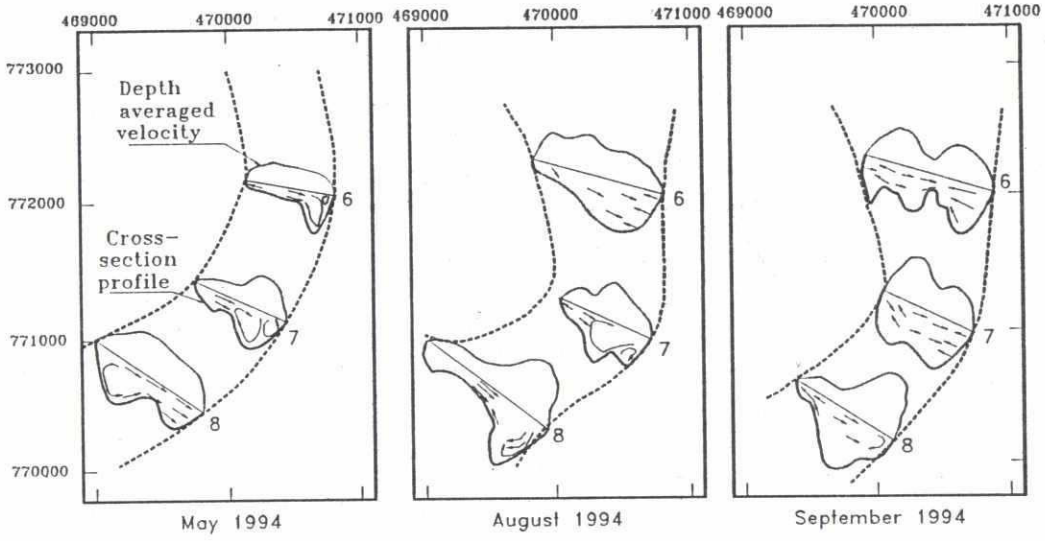


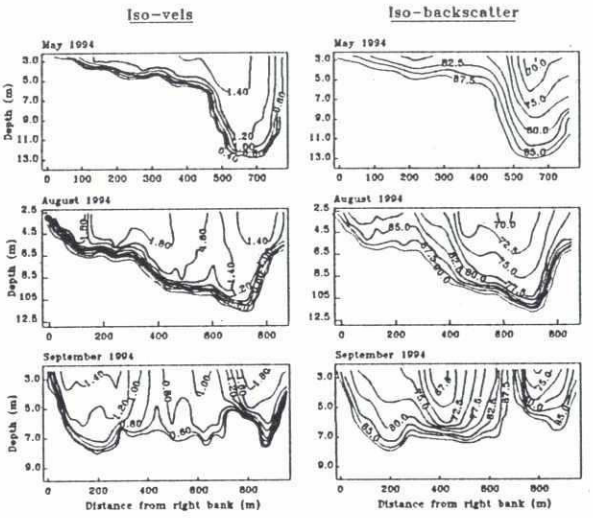
Figure 10.1-b

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

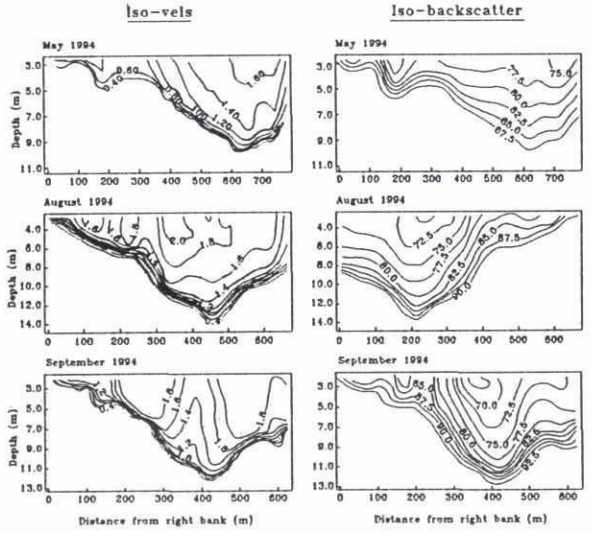
To study the flow structure near an eroding bank of a river bend in the Jamuna River, data from three surveys carried out 1994 are used (see Figures 10.1 and 10.2). From the surveys three cross-sections were selected (notably the sections 6, 7 and 8) where bank erosion was taking place. For easy reference the cross-section numbers are kept the same as in RSP SPR-16. At the other sections the left bank shifted due to the overtopping of a low level bar by rising of the water level in the river (Figure 10.3), say for instance in the sections 5 and 9, and not due to bank erosion. The secondary flow structure presented in Figure 10.1 is also based on RSP SPR-16. The flow structure and the river response in connection to bank erosion are discussed below as an example of the complexity of these processes in these braided rivers.

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

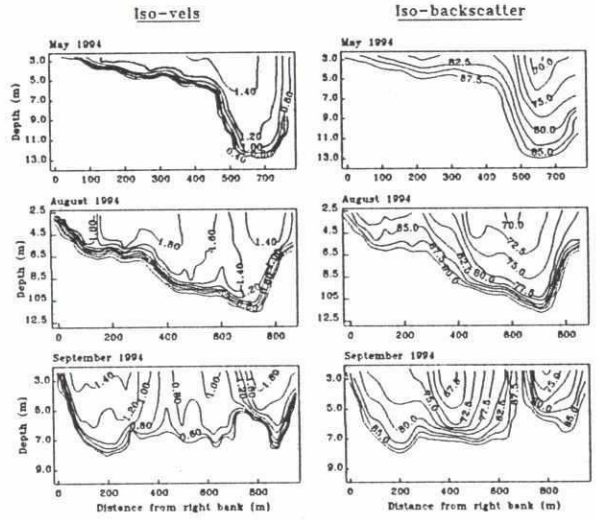
The shape of Section 7 in May is not showing a perfect bend section as Section 6. The convergence of iso-vels and iso-backscatter, however, indicate the presence of secondary currents near the bank and the depth-averaged velocities are also higher near the outer bend. This caused bank erosion of about 340 m in the May-August period. After this marked large bank erosion rate, conditions changed and the flow structure in the August survey was already different: the high flow shifted toward the inner bank, resulting in almost no bank erosion in the August-September period.
The shape of Section 8 in May 1994 was a typical cross-section in a river crossing. Minor bank erosion occurred in the May-August period. In the August survey the section appeared as a typical river bend section with respect to its shape, the convergence of iso-vels and iso-backscatter at the outer bend and the maximum velocity near the outer bend. As a result a rapid bank erosion occurred at this section in the period of August-September. The survey of September also indicates that the bank erosion was probably continuing.



Line No. 6



Line NO. 7



Line No. 6

Figure 10.2

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

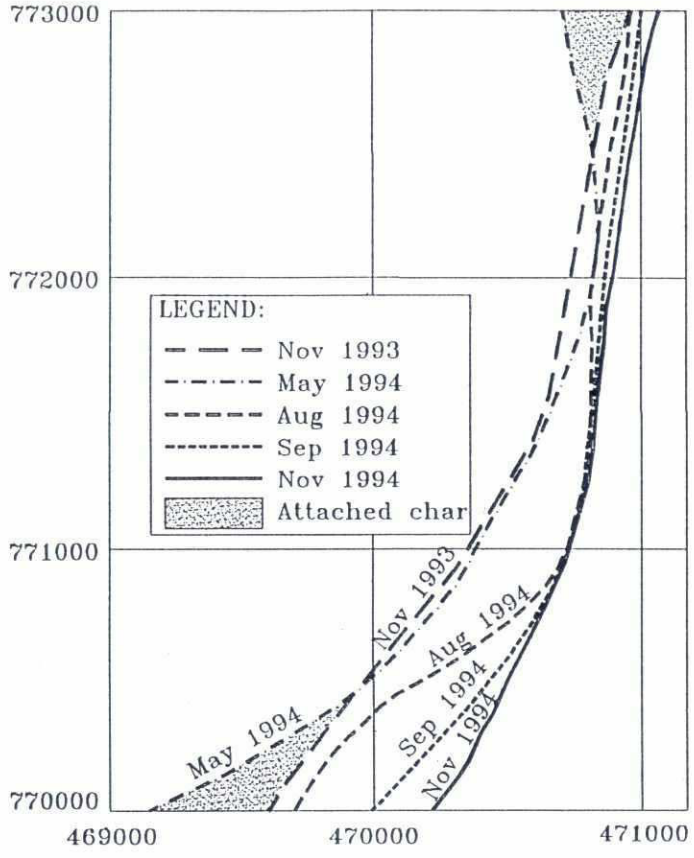


Figure 10.3

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

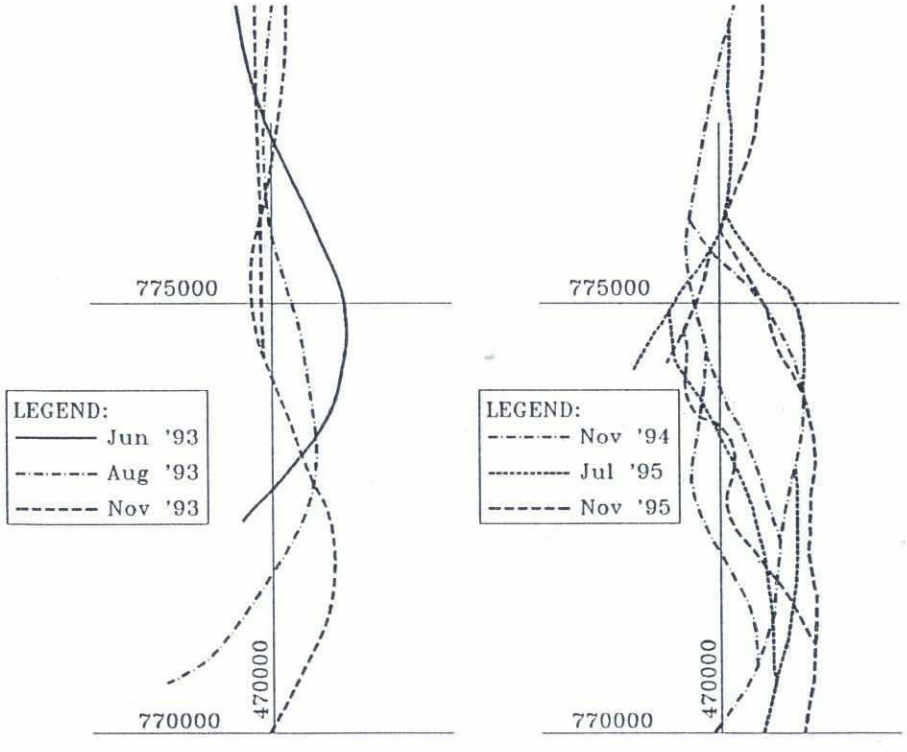


Figure 10.4 Changes of the curvature and shifting of the eroding bend in time downstream of Bahadurabad

In this example of a river bend downstream of Bahadurabad, the bank erosion rapidly shifted in downstream direction associated with the changing of the cross-sectional profiles and probably also with the changing of the planform of the river bend. This can be illustrated by Figure 10.4, where the changes of the thalweg downstream of Bahadurabad with time are shown. The curvature of the bend downstream of Bahadurabad migrated in downstream direction from June to August 1993 due to the occurrence of a cutoff upstream. The migration continued in the following period. In 1994, the curvature of the bend had moved in downstream direction; at the same time an outflanking channel upstream of Bahadurabad became more prominent and continued to erode the bank, though to a lesser extent. After 1993 the eroding river bend was not a single channel; rather, it was a combination of two or more smaller anabranches. In 1995 these anabranches were almost at the same location as they were in 1994, although there was some variation in the curvature depending on the importance of those channels. It appeared that a channel bend may migrate in downstream direction, but another outflanking channel may begins to develop and result in continued bank erosion upstream. The development of the outer bend channel during the period indicates that this bend was losing its importance and in the near future the bank erosion will stop, unless another marked planform change would occur upstream, which could change the conditions again seriously.

The type of bank erosion often encountered in meandering rivers is also present in the Jamuna River. As an example, here the bend at Kamarjani is shown in Figure 10.5. In this bend bank erosion was quite uniform along the whole length of river bend downstream of the FAP 21/22 test structures in the period from August to November 1995, as can be observed from the bank line locations for August, September, October and November 1995 (see Figure 10.5).

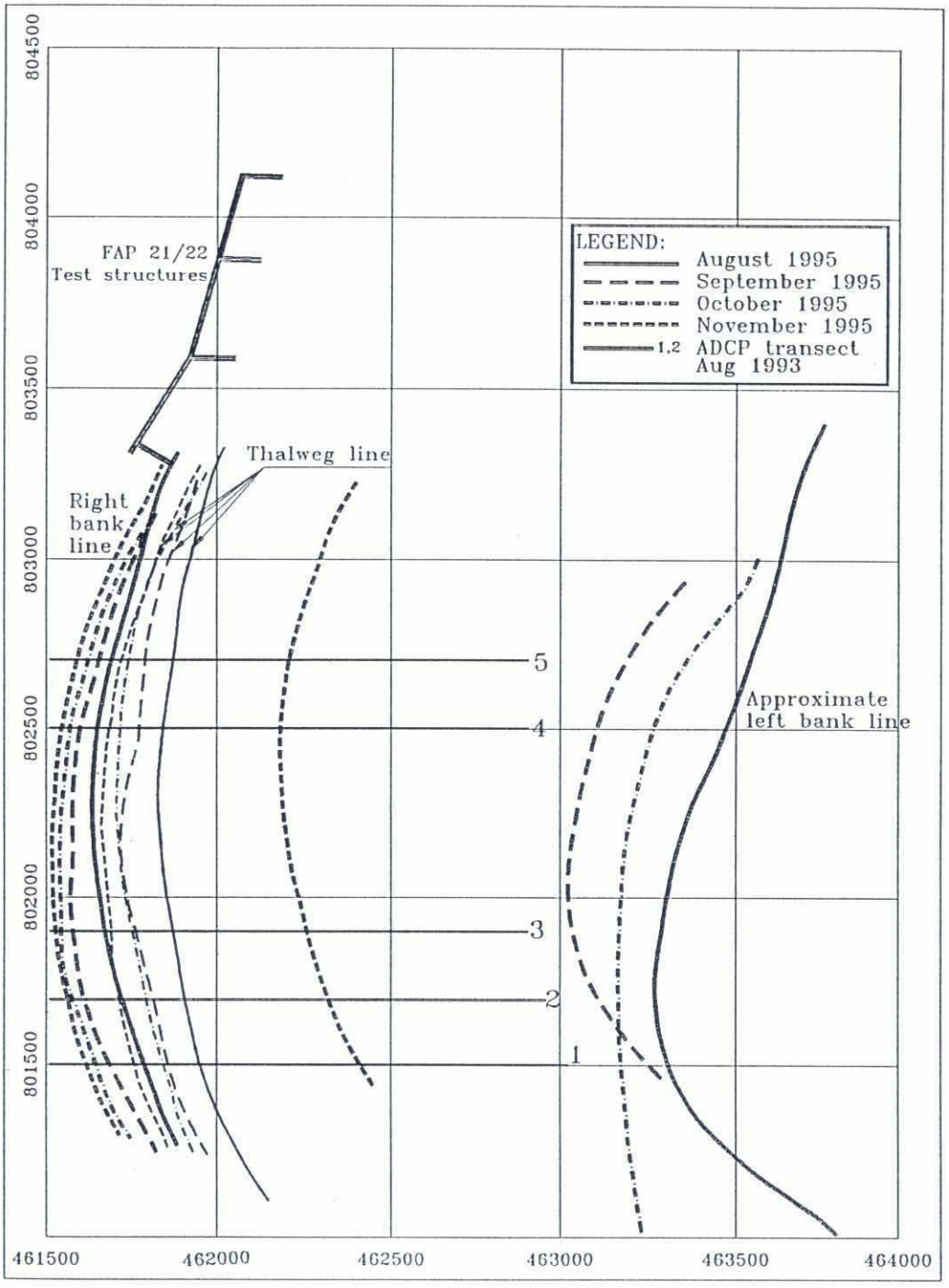


Figure 10.5 Bank erosion in the river bend at Kamarjani (FAP 21/22 bathymetric survey 1995)

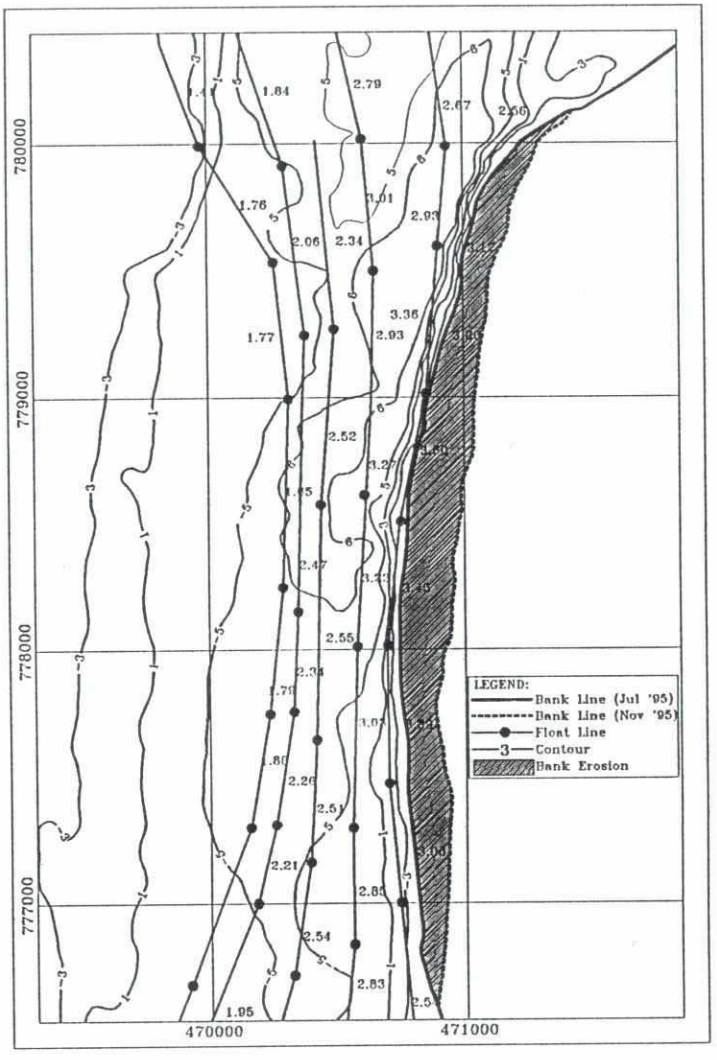


Figure 10.6

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

In the Jamuna River, bank erosion may occur at places other than along the outer bends. The flow convergence due to impedance of flow by a comparatively harder river bank, or by a bank that has not yet sufficiently eroded, may cause comparatively high flows to occur very close to a river bank. Such high velocities near the river bank may cause bank erosion as well. As an example, the conditions near Bahadurabad in July 1995 may serve. The velocities measured via float tracking (see Figure 10.6) showed that a higher flow velocity (more than 3 m/s) occurred very close to the river bank due to flow impedance by Bahadurabad Ghat area. Due to these high velocities, substantial bank erosion occurred in the period of July-November 1995, see Figure 10.6. Evidently, such type of bank erosion occurs during the monsoon only.

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

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

10.4 Location of Bank erosion

Back erosion is an important process in the planform development of the river. The location (this section) and the transport rates (next section) are essential parameters in the analysis of erosion. Often one splits the process in far-field and near-field erosion patterns and in short-term, mid-term and long-term developments.
The far-field aspects, such as locations of bank erosion along an important river stretch are mostly studies on the basis of satellite images and part of the analyses of planform developments, see Chapter 13.
The near-field erosion can sometimes be studied on the basis of special bathymetric/topographic survey results as was the case in the RSP near the Gorai offtake, near Bahadurabad and near the Jamuna-Ganges confluence, where series of bathymetric surveys were executed. From the differences in time the erosion of banks can be selected, see for instance (for the Gorai offtake) Section 6.2, (for the Jamuna near Bahadurabad), see section 10.6, and (for the Jamuna-Ganges confluence, see Section 7.3.

10.5 Bank erosion rates

In this section observed bank erosion rates from bathymetric surveys and SPOT images, and comparison with prediction methods are presented. In addition the area and volume of bank erosion near Bahadurabad are presented and the volume of bank erosion are compared with the sediment transport volumes to have an idea about the contribution of the bank erosion product in changing the planform of the river.

10.5.1 Bank erosion rate

The bank line migration of the left bank downstream of Bahadurabad during the period of June 1993 to November 1995 could be derived from RSP bathymetric surveys (see Figure 10.7). Bank erosion was also derived from SPOT images during the period 1991-1995 and these are shown in Figure 10.8 as well. The corresponding estimated bank erosion rates are presented in Tables 10.1 and 10.2. Due to differences in the positioning systems used by RSP and SPOT images, about 500 m needs to be added to the Northing of RSP surveys to have the bank erosion rates estimated from bathymetric surveys correspond to that from SPOT images at same location. The estimated erosion rates may still differ with some tenths of metres, due to errors in the grid system of the SPOT images, errors in locating the bank line on the SPOT images and the limited resolution of the satellite imagery.

The figures and tables indicate that the bank erosion rates vary along the bend and the maximum bank erosion occurred at the downstream end of the bend. As a result, the maximum erosion rate migrated 1.5 km in downstream direction from August 1993 to November 1995 (see Tables 10.1 and 10.2). The maximum yearly bank erosion rate at the river bend downstream of Bahadurabad (Northing 770000 to 776000) is about 800 m, which can be classified as an extreme event of bank erosion (Klaassen and Masselink, 1992). Within less than three years the maximum bank retreat was about 2 km. The maximum bank erosion rate along the inner bend near Bahadurabad (Northing 777000 to 780000) is about 400 m/year in 1995, which is almost half of the downstream river bend. The channel geometry, the structure of flow and probably the characteristics of the bank material are different at both locations. Probably due to different characteristics of the bank material the maximum bank erosion at Kamarjani is less, although it is a well developed river bend.

The observed bank erosion rates in the river bend were compared with the different predictive methods (see RSP SPR 24). Klaassen and Masselink (1992) observed that bank erosion along a river bend in the Jamuna River varies in a wide range from 0-1000 m/year. They also noticed that applying the method of Hickin and Nanson (1983) for predicting the bank erosion rate in the Jamuna River yields very less bank erosion rate than the observed erosion rate. In RSP SPR 24, the method of computing bank erosion rate using near bank flow and sediment transport by Mosselman (1992) and DHI (1996) for simulating 2-D mathematical model are compared with the observed bank erosion rate. For comparing their methods, bank erosion rates of both methods are transformed as a function of near bank velocity (see RSP SRP 24). The bank erosion rates increases linearly with the near bank velocity as per Mosselman (1992), while bank erosion rates related with power relation (?) of near bank velocity as per DHI (1996), see Figure 10.8. It appeared that DHI (1996) can probably predict the bank erosion rate, where the rate is moderate like Kamarjani location. But where the bank erosion rate is very high like downstream of Bahadurabad, apparently DHI (1996) is unable to predict the rate. For this type of bank erosion, probably the flow structure in the bend and the effect of bank erosion product in changing the planform is very important.

10.5.2 Bank erosion area and volume

The eroded areas and the eroded volumes during the period in-between the subsequent bathymetric surveys are shown in Table 10.3. To estimate the volume, the difference between the highest bank level and the average bed level along the eroding river bend was multiplied with the eroding area. The highest bank level is considered to be -7m SLW and the average bed level was estimated from the bathymetric surveys. The maximum eroded area downstream of Bahadurabad was 2.6 Mm^2 and the corresponding eroded volume was 24 Mm^3 in the period from November 1994 to November 1995, in which year the duration and magnitude of flood were comparatively higher than in the other periods. In contrast, the eroded area and volume were 1.1 Mm^2 and 10 Mm^3 respectively, in the period between November 1993 and November 1994, which was a relatively dry year. These guidings support the probable relation between the eroded area and the overall discharge through the river during the same period in the Jamuna River (Mosselman et al, 1993). The estimated total area yearly eroded along the whole Jamuna River varies according to Mosselman et al. between 2 to 5.5 Mm^2, which seems to be very low in view of the yearly eroded area found for the left bank at Bahadurabad location only.

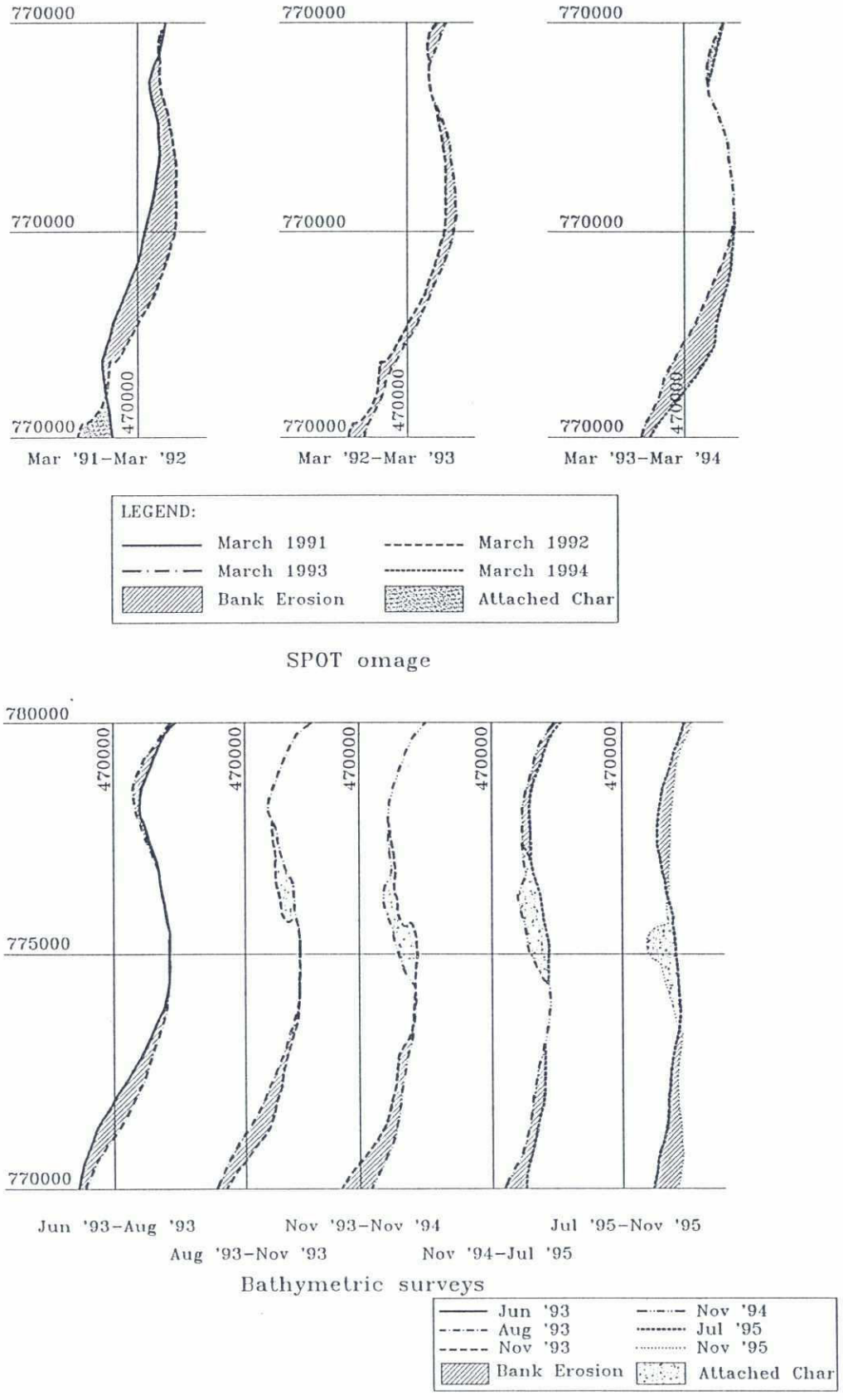


Figure 10.7 Bank erosion at Bahadurabad based on SPOT images and RSP bathymetric surveys

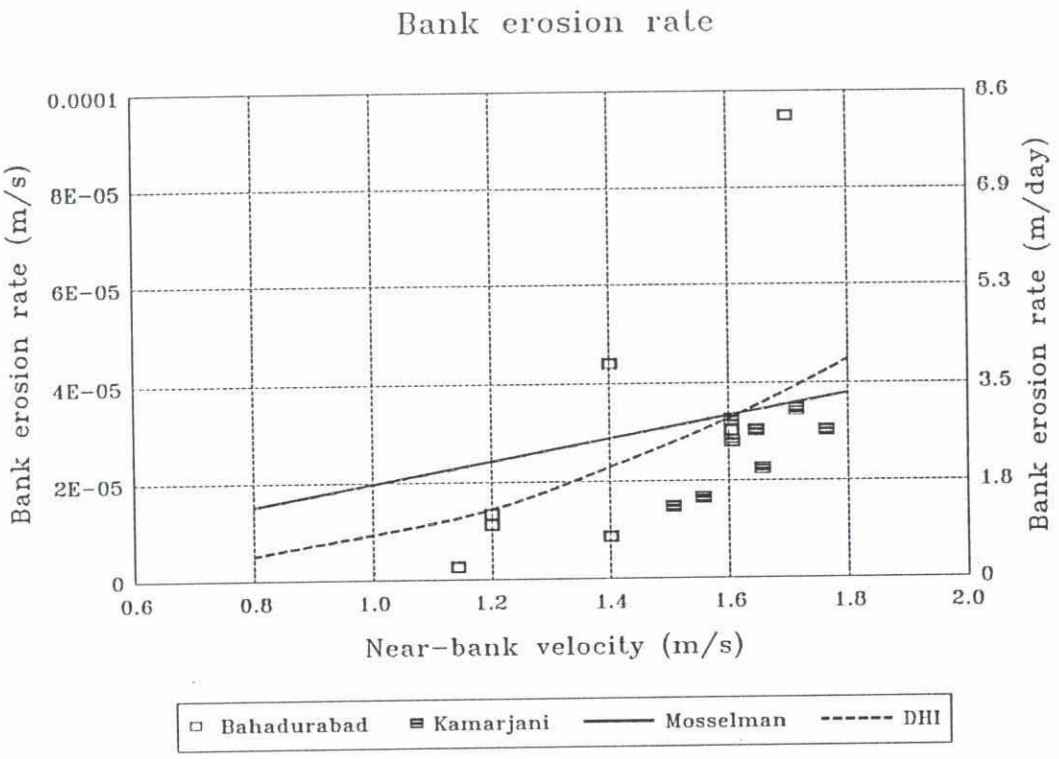


Figure 10.8 Observed bank erosion rates at Bahadurabad and Kamarjani location in relation with near bank velocity

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

Table 10.1 Bank erosion rates at Bahadurabad based on SPOT images

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

Table 10.2 Bank erosion rates at Bahadurabad based on bathymetric surveys

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

Table 10.3 Bank erosion area and eroded volume at Bahadurabad

It is interesting to compare the volume of material originating from bank erosion with the average sediment transport volume in the left channel to see the significance of the bank erosion product with possible complications for river planform changes. During the period of Jun-Aug. 1993 the bank erosion volume is about 45% of the total sediment transport in the left channel and in the Aug-Nov. 1993 period it is more than 60% (see RSP SPR24). This tremendous input of sediment from bank erosion might change the planform of the river bend within a short period (see Figure 10.4). In the period between June to August 1993 the downstream bend had shifted. After then (in 1994) instead of a single channel at the bend, division of flow occurs due to formation of an attached bar, reduces the capacity of the curved channel, further bank erosion in 1995 almost abandoned the river bend. This type of

rapid changes is in line with the observations by Klaassen and Masselink (1992) and Thorne et al (1993), when they observed that the duration of an aggressive bend is very limited. It is observed that tremendous volume of bank erosion product changes the planform of the river bend and also probably downstream, unfortunately the bathymetric survey boundary limited to see those changes.

10.6 Occurrence of cutoff

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

Some years ago Klaassen and Van Zanten (1989) studied analytically the cutoff processes in curved channels as part of a braided river system. There appears to be an essential difference between cutoffs in meandering rivers and cutoffs in braided ones. For the development of a cutoff channel in a meandering river it is sufficient that in the floodplain the critical shear stress of the floodplain soil is exceeded. Often it is required to correct for floodplains vegetation that is responsible for a part of the resistance. In braided sand-bed rivers the critical shear stress is always exceeded, and whether a potential cutoff channels develops depends on the ratio of sediment supply from the offtake into the cutoff channel (1) and the sediment transport capacity of the channel, moreover the ratio of the roughness of channel (1) and the curved channel (2), see Figure 10.9.

$$C_1 = \gamma C_2 \tag{10.1}$$

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

$$\frac{S_{1\,incoming}}{S_{2\,incoming}} = \frac{1}{\sigma}\,\frac{Q_1}{Q_2} \tag{10.2}$$

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

$$\frac{h_1}{h_2}\,\sigma\,\gamma\,(\lambda)^2 > 1 \tag{10.3}$$

where h_1 and h_2 = depth of channel (1) and (2) respectively.

According to this criterion graphs were presented by Klaassen and Van Zanten, one of them shown in Figure 10.10. Although a number of simplifications were made (see Klaassen and Van Zanten, 1989) to derive this criterion, it provides a clear idea about the contribution of the parameters involved in a cutoff processes in a braided river.

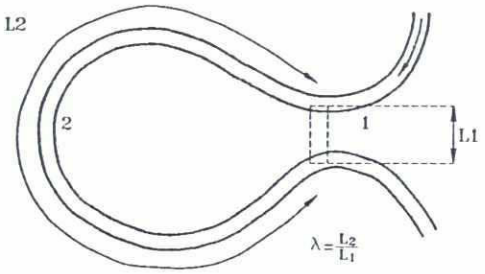


Figure 10.9

A definition diagram of cutoff ratio.

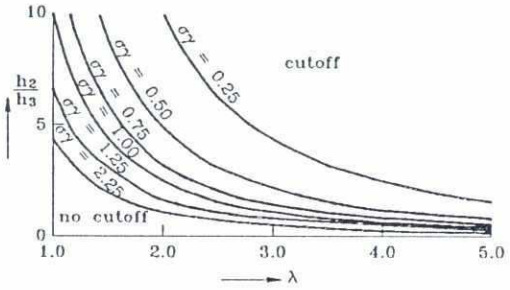


Figure 10.10

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

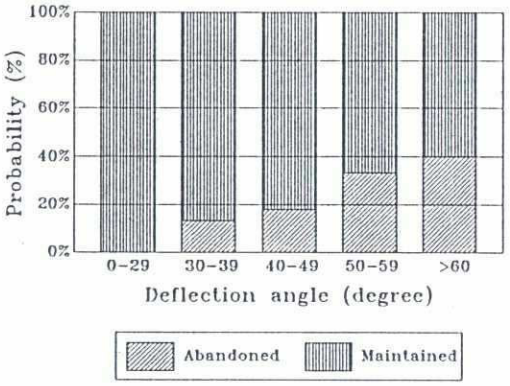


Figure 10.11

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

Klaassen and Masselink (1992) observed that the cutoff ratio is an important parameter for cutoff processes and their observed average cutoff ratio is 1.25 for the Jamuna River, which is very small compared to critical values for meandering rivers. Recently, Mosselman et al (1994) showed that the deviation angle of a channel from the upstream channel is more important in the Jamuna River and based on their observation the probability of channel abandonment as a function of deviation angle see Figure 10.11. They suggested to consider the deviation angle of the curved channel as 40^{o} as a threshold value for the development of cutoff. In the Zaire River, Peters (1986) found that cutoff process can be derived from local slope variation among two anabranches and a predictive method was developed for the river on the basis of local slope variation.

Development of a cutoff had occurred in the Left channel of the Jamuna River upstream of Bahadurabad in 1993. This cutoff development was within the bathymetric survey are of River Survey Project. An investigation of the development of this cutoff has been performed by RSP and presented in SPR 24. The development of the planform before and after the cutoff is shown in Figure 10.12 from SPOT images. The development of the planform during the cutoff process is presented in Figure 10.13 on the basis of RSP bathymetric surveys. Peters (1994) indicated likely causes of the cutoff that occurred at Bahadurabad in 1993. According to Peters, due to bank erosion along the right bank upstream of the bifurcation in the period of 1992-1993, the point bar 'A' moved in downstream direction (see 1993 imagery of Figure 10.10) and almost closes the offtake of the old main channel.

As a consequence, the flow from the upstream end had no alternative than to cut through the smaller channels in the medial bar complexes. With the development of the point bar and the opposite bank erosion, the bifurcation also moved in downstream direction over a distance of about 2 km during 1992 to 1993. Three channels flowed in downstream direction from the bifurcation including the main channel in 1992 and 1993 although the bifurcation points was not at same location. The offtake angle (α) and the cutoff ratio (λ) varied throughout time as shown in Table 10.4 The offtake angle from the upstream main channel was 36^o in 1992 and it increases up to 60^o in 1993. The latter value is greater than the average cutoff angle estimated by Mosselman et al, (1994). In June 1993 the offtake moved further downstream and at one stage the deviation angle reached almost 90^o. Instead of a gradual further development of the cutoff, it suddenly accelerated as can be seen in the August 1993 bathymetric survey. After the development of the new cutoff channel the deviation angle of the old main channel reduced to 50^o. In subsequent years this angle varied from year to year and the location of the bifurcation had shifted within a range of a few kilometres.

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

Table 10.4 Variation of deviation angle α and cutoff ratio λ with time

It is observed in Figures 10.12 and 10.13 and Table 10.4 that the deviation angle, which determines the sediment distribution among the channels from the offtake changes considerably during the process of cut-off. Although the cutoff process started during the monsoon of 1992, the fulfilment of the criterion by Klaassen and Masselink (1992) and Mosselman (1994) for cutoff was only observed in the March 1993 SPOT images and later. This is probably due to the fact that both predictive methods were based on satellite imagery. Due to the very rapid morphological processes in the river and the lagging behind of the planform with respect to the changes of flow distribution, satellite images are unable to reveal these processes.

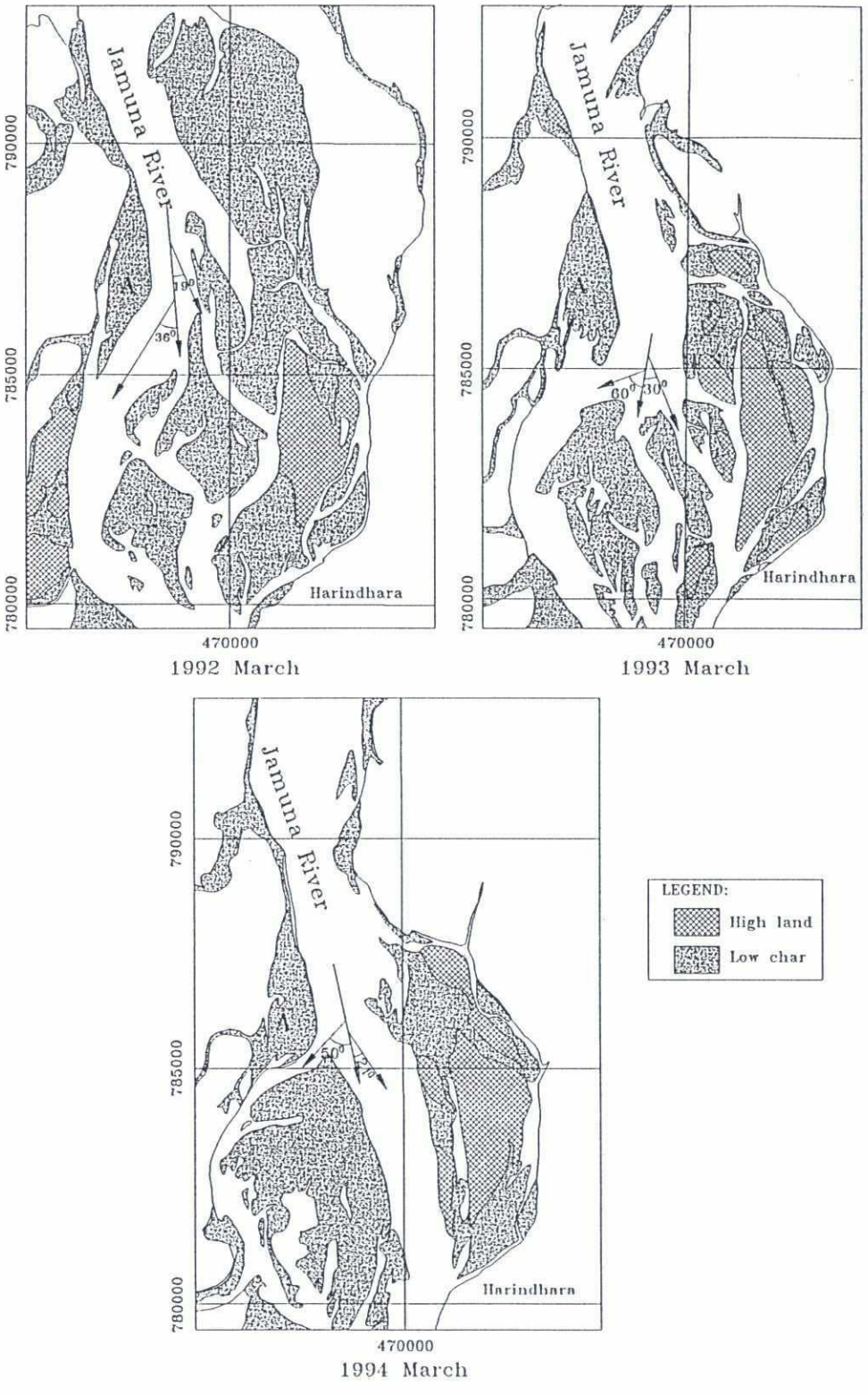


Figure 10.12 Changes of the planform of the offtake, SPOT images 1992, 1993 and 1994

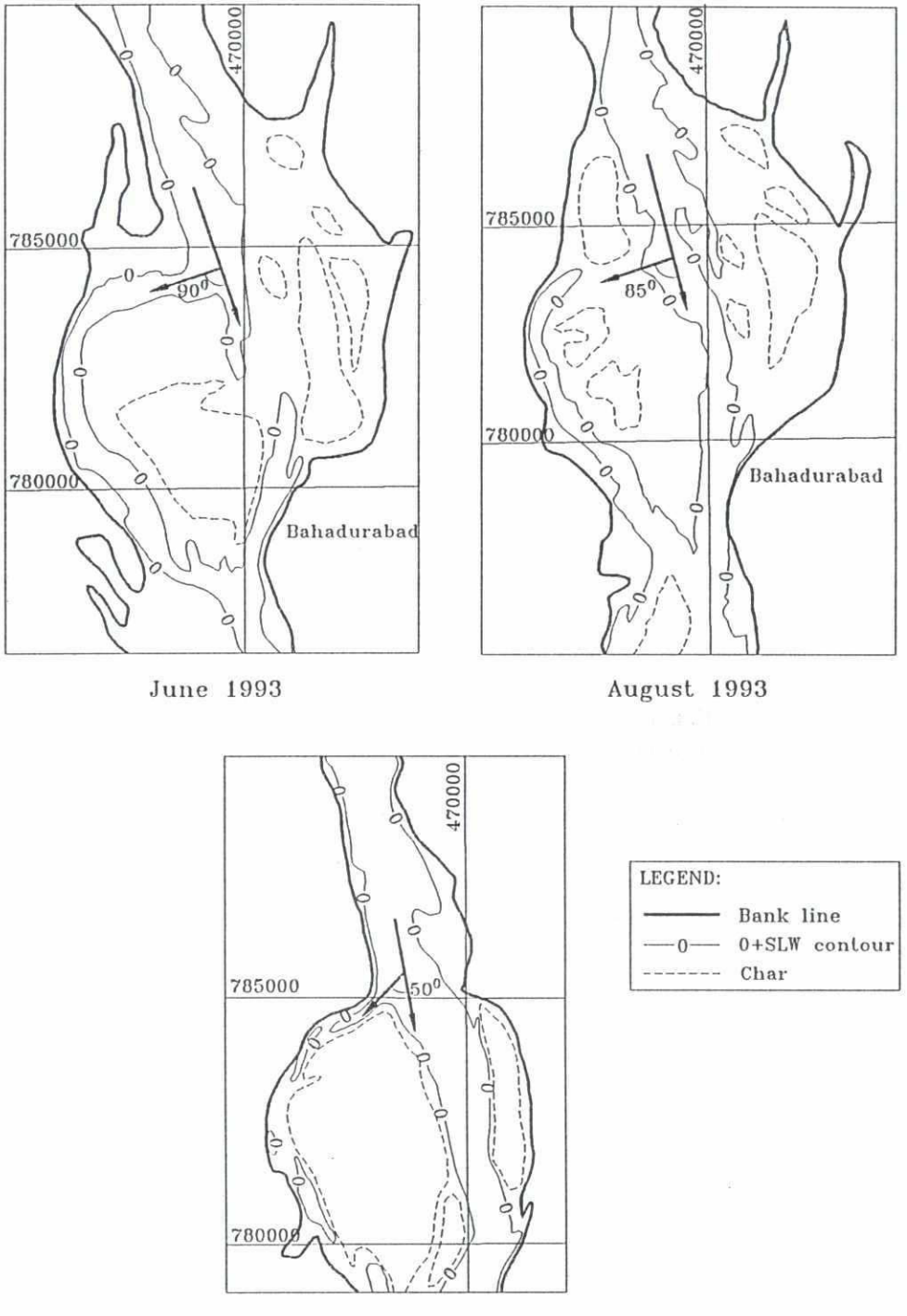


Figure 10.13 Changes of the planform of the offtake in 1993, bathymetric surveys

To better understand the cutoff process, the variation of local slopes of the channels were studied as well. In Figure 10.14 the local slopes of the reaches Khatiamari-Bahadurabad and Khatiamari-Charparul from the month of July 1993 onwards, are shown. It is observed that the local slope of the Khatiamari to Bahadurabad reach varied within a range from 9 to 11 cm/km, whereas the slope of the Khatiamari-Charparul varied from 8 to 9 cm/km in the period of July to October 1993. The local slopes here presented are not completely representative for the slope of the Old Main Channel and of the New Main Channel respectively, as Khatiamari is located about 4 km upstream of the bifurcation. However, this figure indicates that while the cutoff was taking place, the local slope of the cutoff channel was considerably higher than that of the old main channel and also higher than in the following years.

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

The sediment distribution at the offtake delivered into the curved and the cutoff channels plays an important role (Equation 10.3). The distribution of sediment depends on the deviation angle from the upstream channel. It is observed that the deviation angle was very high during the development of the cutoff upstream of Bahadurabad. An attempt was made to estimate the sediment distribution during the development of the cutoff (see RSP SPR 24). It appeared that when the deviation angle of the curved channel was high the sediment input from the upstream in comparison discharge was also high (for detail see RSP SPR 24). This supports the concept of the sediment distribution being dependent on the deviation angle from the upstream channel. Also it is possible to check the criterion proposed by Klaassen and Van Zanten (1989). As $h_1 \cong h_2$, and $\gamma = (h_1/h_2)^{0.5}$ it follows that a cutoff will occur if

$$\sigma > (1/\lambda)^2$$

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

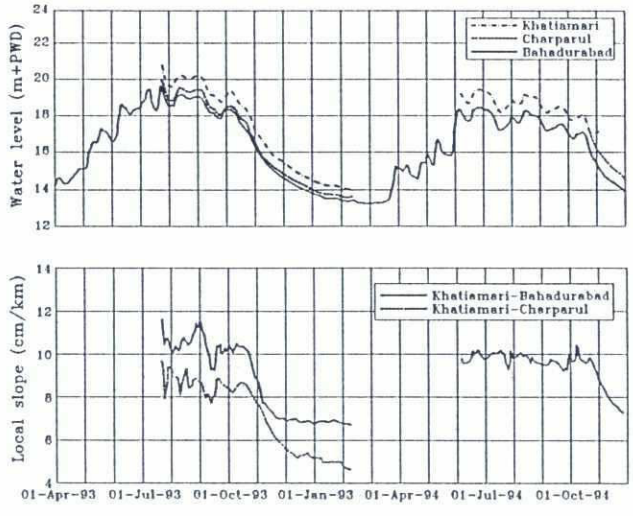


Figure 10.14

Observed water levels near Bahadurabad and local water level slopes

10.7 Morphological changes due to cutoff

A occurrence of a cutoff causes an enormous changes in the downstream. The changes that took place after the cutoff development at upstream of Bahadurabad in 1993 can be considered as an example. The development of the old channel and the new channel, and the planform changes at the downstream of the cutoff were studied by RSP and presented in SPR 24. Generally depth increases first in a cutoff channel and width adjustment occurs later.

In a meandering river this kind of channel adjustment process is obvious due to variation of erodibility of bed and bank material and variation of bed bank shear stresses. Chien (1961) also observed a similar type of depth and width adjustment in the braided reach of the Lower Yellow River. In the case of the cutoff near Bahadurabad, it was observed that after the development of cutoff in 1993 the adjustment of the depth and width in the both old and new channels are almost simultaneous see Figure 10.15. The reasons can be explained as follows: the cut of developed through pre-existing smaller channel over a recently deposited bar complex. The erodibility of the bed and bank materials are same. Moreover, due the lateral movement of the channel during the development probably liable for the simultaneous adjustment of the depth and width in the cutoff channel.

After the cutoff development in 1993 the confluence scour G shifted downstream in reducing its size and gradually lost its importance, see Figure 9.3. A new bar appeared downstream of Bahadurabad can be seen in the November 1993 bathymetric survey (Figure 9.3). In 1992 and in early 1993 an outer bend was just downstream of Bahadurabad. After the cutoff the location of bank erosion along the outer bend had shifted near about 2 km (see Figure 10.4). Moreover, the new cutoff channel was directed to the Bahadurabad ghat which later causes bank erosion at the Bahadurabad (Figure 10.6). These are in brief the description of the morphological development observed after the cutoff development near Bahadurabad (for detail please see SPR 24).

Old channel

New Channel

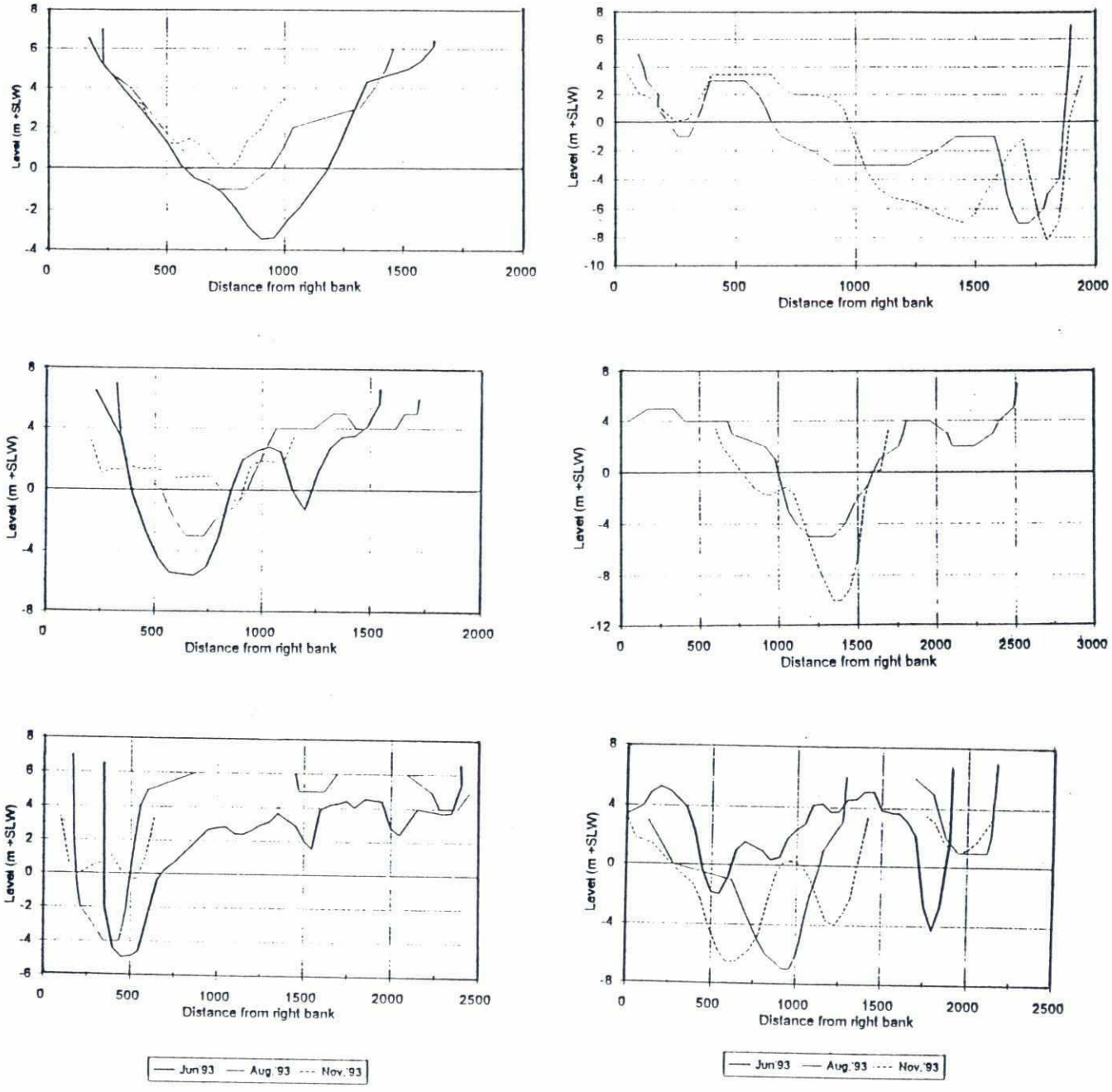


Figure 10.15 Changes of the cross-section of the old and new channel in 1993

2 27

11 Maximum flow velocities

11.1 Introduction

Information about maximum flow velocities is usually required in relation with any construction works interfering with the flow of the river. The designers will need information about the velocities in the higher range for various purposes: bank protection, flow forces on bridge piers and abutments, assessment of scour etc. Such information has in the past been extracted from one-dimensional models calibrated against measurements of water levels and discharge, see West et al. (199?) Presenting the method used in the FAP1 study. The one-dimensional model is able to provide information about velocities along the river, but only based on a limited number of cross sections and only the average velocity over the entire cross section. For design of structures it would not be sufficient to know the cross section averaged velocity. The flow may be concentrated along one bank where velocities could be considerably higher. The flow velocity pattern depends not only on one cross section but on the entire bathymetry within a larger area around the cross section considered. Thus, velocities are linked to the morphology: The morphological developments of the recent past determines the velocity distribution, but these velocities (the flow) will eventually after some time determine the morphology of the future. Therefore this chapter on maximum velocities in an Annex about morphology.

Discharge measurements involve measurements of velocities. With the traditional methods the velocities are measured in a (small) number of verticals at a cross section, whereas the measurements of the RSP using ADCP contain very detailed velocity information from a large number of cross sections. Measurements have been carried out repeatedly at a number of preselected cross sections. Since these measurements have been performed at a wide range of discharges, the data material available on velocities and their distribution at different times is quite extensive.

11.2 Analysis of RSP flow velocity data

Under the RSP a limited analysis has been performed for three selected sites: Bahadurabad on the Jamuna, Hardinge Bridge on the Ganges and Baruria downstream of their confluence on the Padma. These three sites were selected because float tracking surveys were carried in these areas. It was the intention to use the float tracking data to provide the spatial dimension to the information extracted from the transect surveys: The transect surveys provide the variation with time and the cross sectional variation of the velocities; the float trackings provide pictures of the velocity field over a larger horizontal area. The use of the float trackings in this respect proved less successful, although it did give an indication. Furthermore, at Baruria the routine transect was not within the area of the float tracking survey.

The following type of velocities have been considered in this chapter:

- the average velocity over a cross section ($u_{av}=Q/A$)
- the maximum depth averaged velocity ($u_{dep.\ av,\ max}$)
- the maximum (point) velocity (u_{max}).

The former is expected to be rather stable unless the cross section where measurements are carried out is changing considerably (or if the transect has been shifted between measurements). The maximum depth averaged velocity is of interest if comparisons are to be made with results of a 2D model. The latter, the highest velocity measured is expected to contain quite some scatter, because it could depend on local turbulence, eddies etc. This result is also the one most prone to faulty records, because it is a single value whereas the others are averages over a number of values.

The following relations have been tried out through plotting:

- u_{av} vs. stage (z) and discharge (Q)
- $u_{dep.\ av,\ max}$ vs. z and Q and u_{av}
- u_{max} vs. z and Q and u_{av}

Relating the cross sectional average velocity, u_{av}, to Q has been used, but one should be aware of the inherent correlation in this relation. Since Q is included on both axes any variability would be due to variations in the cross section area, A. The results are presented in Figures 11.1 to 11.18.

The following observations have been made from the analysis of these data:

Bahadurabad

The transect measurements include 4 channels of which the first is the main channel. The analysis focuses mainly on this channel. The locations of the survey transect in the main channel vary only little, although a few lines are about a kilometre upstream of the others. Since no difference was found in the correlations tested, all results from the main channel were included without distinction between locations. The results of surveys done 23 August 1995 and 10 November 1995 have been excluded from some comparisons; the former because a large deviation was found in the discharge rating curve, the latter because a large deviation in cross section area was found.

Figure 11.1 shows the cross section average velocity against discharge together with the relation suggested by Klaassen and Vermeer (1988):

$$u_{av} = 0.095 \cdot Q^{0.26} \qquad (u_{av} \text{ in m/s, Q in m}^3\text{/s})$$

The results from channels 1, 2 and 3 are included for comparison. Considering only the main channel it seems that the constants of the above relation would need to be adjusted slightly to provide a good fit at the RSP transect. The following relation was found:

$$u_{av} = 0.054 \cdot Q^{0.32} \qquad (u_{av} \text{ in m/s, Q in m}^3\text{/s})$$

Figures 11.2 and 11.3 show the relations between maximum velocities and discharges. Figures 11.4 and 11.5 show the same maximum velocities, now plotted against the cross section average velocity. Three cross channels are included, labels showing the channel number. Finally, Figure 11.6 shows the ratio of these maximum velocities and the cross section average velocity versus the cross section average velocity. The following is observed:

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- Focusing on the maximum velocities in the higher end of the scale it appears that
  $u_{dep.\ av,\ max} = 1.75 \cdot u_{av}$, and
  $u_{max} = 2.0 \cdot u_{av}$

- The ratios between maximum velocities and cross sectional average velocity (u_{max}/u_{av} and $u_{dep.\ av,\ max}/u_{av}$) are higher for the lower velocities than for high velocities. For the velocities in the higher end ($u_{av} > 1.5$ m/s) the range was 1.4 to 2.2 for u_{max}/u_{av} and 1.3 to 1.9 for $u_{dep.\ av,\ max}/u_{av}$.

Hardinge Bridge

All results were included in a similar set of plots as described above for Bahadurabad (Figures 11.7 to 11.12). The Ganges at Hardinge Bridge is a single channel.

In RSP SPR 7 a relation for cross section average flow velocities for braided parts of the Ganges was developed:

$$u_{av} = 0.36 \cdot Q^{0.15} \qquad (u_{av} \text{ in m/s, Q in } m^3/s)$$

Figure 11.7 shows that this relation fits poorly with the measurements at Hardinge Bridge. Within the discharge range (up to 40,000 m^3/s) and based on the relatively few points a better relation for Hardinge Bridge would be:

$$u_{av} = 6.25 \cdot 10^{-5} \cdot Q \qquad (u_{av} \text{ in m/s, Q in } m^3/s)$$

The flow of the Ganges is in general more influenced by controls than the flow of the Jamuna. There are a number of constricted cross sections near Hardinge Bridge. The cross section shapes influenced by constriction will govern the relation between u_{av} and Q. Furthermore, constricted cross sections may experience large seasonal variations in bed levels, which again affect the velocities.

The following is observed:

- Focusing on the maximum velocities in the higher end of the scale it appears that
  $u_{dep.\ av,\ max} = 0.5 + 1.2 \cdot u_{av}$, and
  $u_{max} = 0.6 + 1.4 \cdot u_{av}$

- The ratios between maximum velocities and cross sectional average velocity (u_{max}/u_{av} and $u_{dep.\ av,\ max}/u_{av}$) are higher for lower velocities than for high velocities.

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Baruria

All results were included in a similar set of plots as described above for Bahadurabad and Hardinge Bridge (Figures 11.13 to 11.18)

Within the discharge range of approximately 10,000-80,000 m^3/s a simple relation between the cross sectional average velocity and the discharge is:

$$u_{av} = 0.4 + 2.63 \cdot 10^{-5} \cdot Q \qquad (u_{av} \text{ in m/s, Q in } m^3/s)$$

The following is observed:

- Focusing on the maximum velocities in the higher end of the scale it appears that
  $u_{dep.\ av,\ max} = 1.5 \cdot u_{av}$, and
  $u_{max} = 0.3 + 1.5 \cdot u_{av}$

The scatter on maximum velocities in the higher range is somewhat higher for this site than for the others and the uncertainty is therefore correspondingly higher.

- The ratios between maximum velocities and cross-sectional average velocity (u_{max}/u_{av} and $u_{dep.\ av,\ max}/u_{av}$) are higher for lower velocities than for high velocities.

It should be noted that none of the relations given in this chapter are suited for direct use in relation to design of structures. The relations describe fitted lines through a number of points i.e. it represents an average estimate. No attempt has been made to make a statistical analysis of the data. Furthermore, they are established for particular cross sections; a different cross section only a few kilometres away may have completely different conditions in this respect.

Float trackings

By only considering the flow condition at a single cross section the spatial variation is left out. A few float trackings carried out by the RSP gives some information about the flow pattern over a larger area, but only at a few instants. A comparison at the times of float tracking surveys showed that maximum velocities within a few kilometres from the transect line could be up to 20 percent higher than at the transect line.

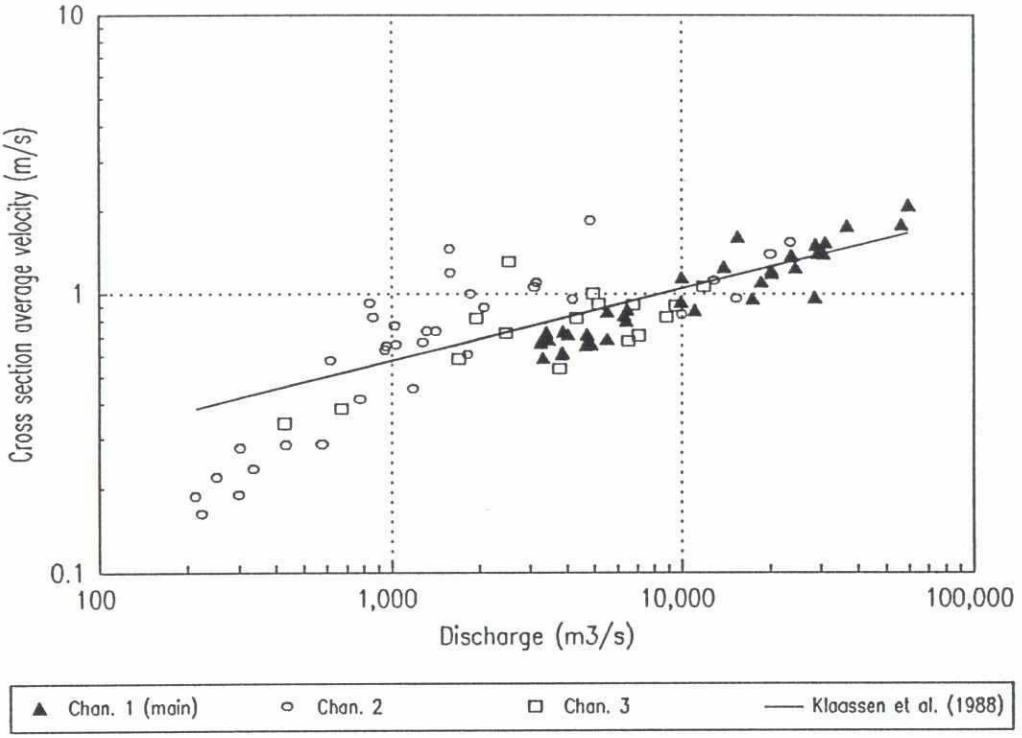


Figure 11.1: Cross section average velocity versus discharge Bahadurabad

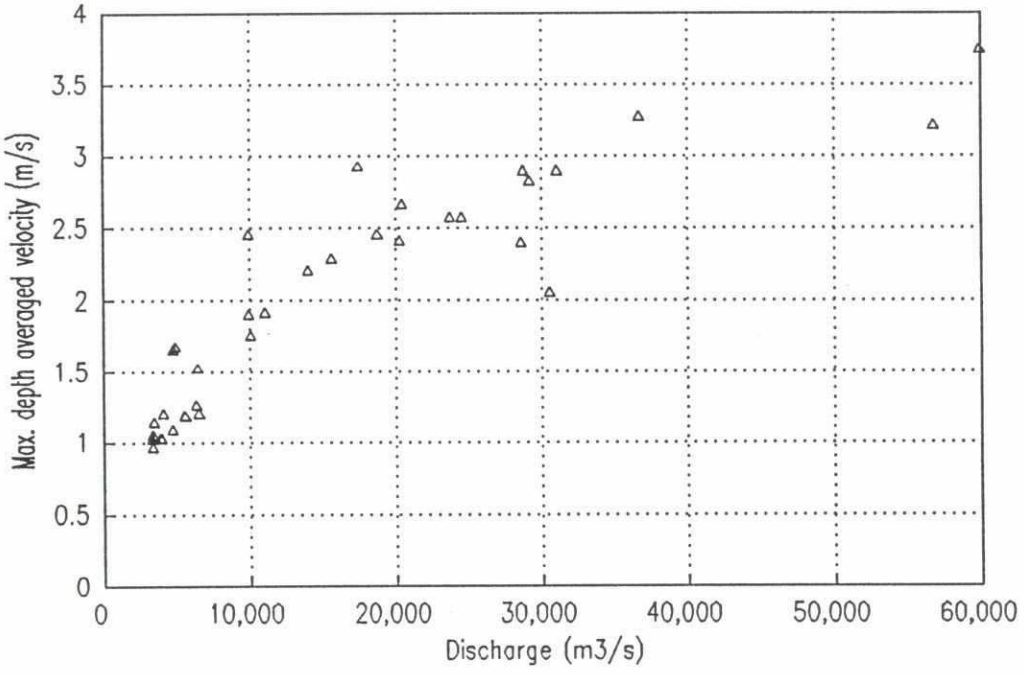


Figure 11.2: Maximum depth averaged velocity versus discharge Bahadurabad

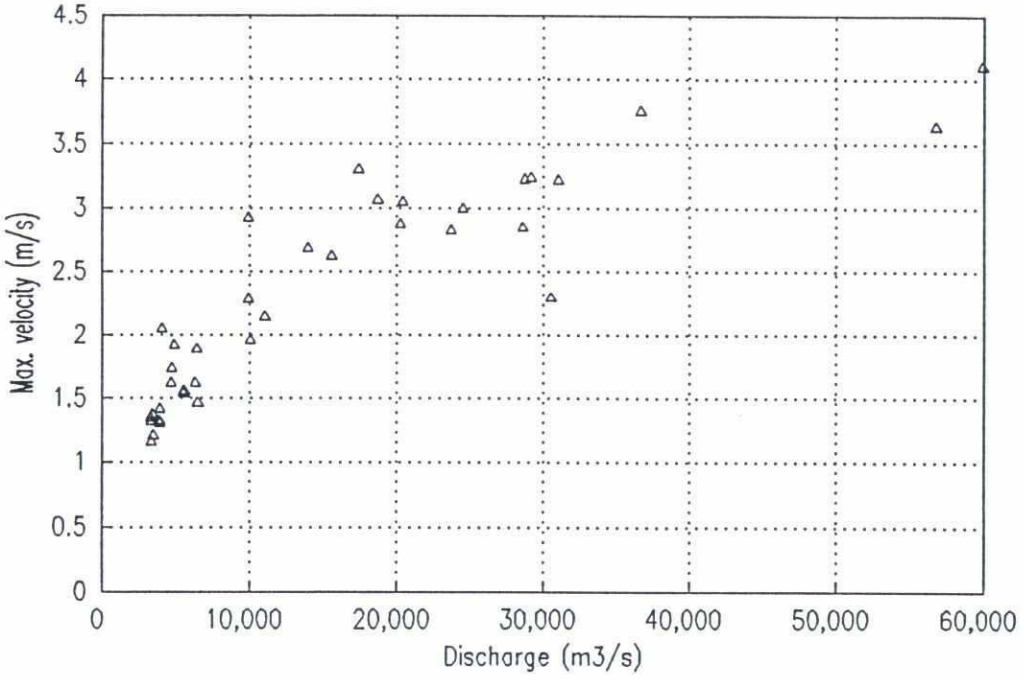


Figure 11.3: Maximum velocity versus discharge Bahadurabad

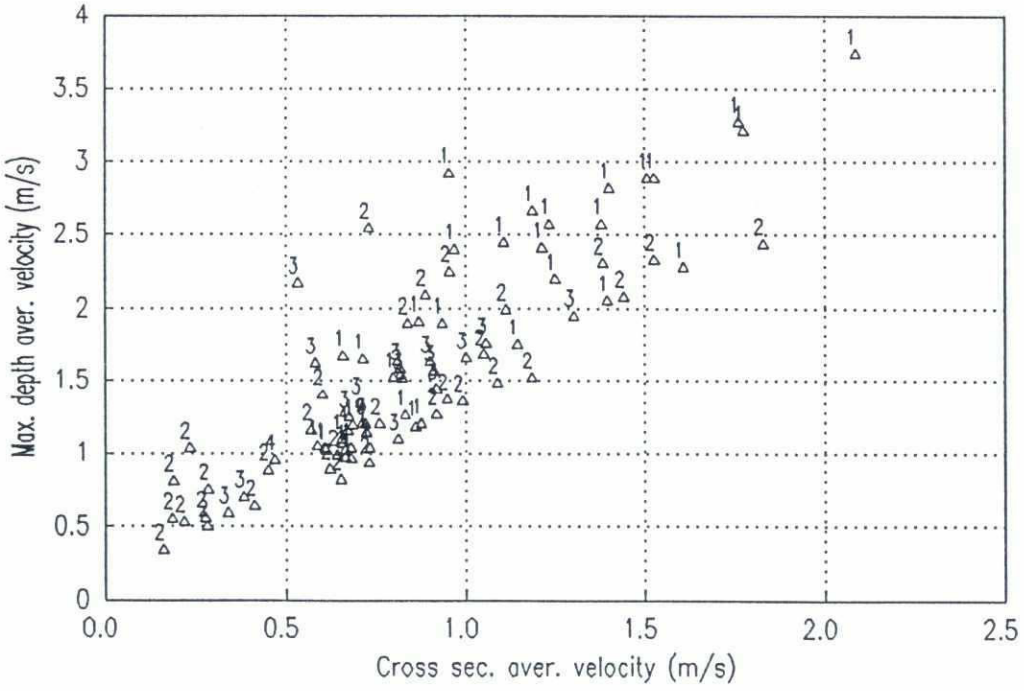


Figure 11.4: Maximum depth average velocity versus cross-section average velocity Bahadurabad

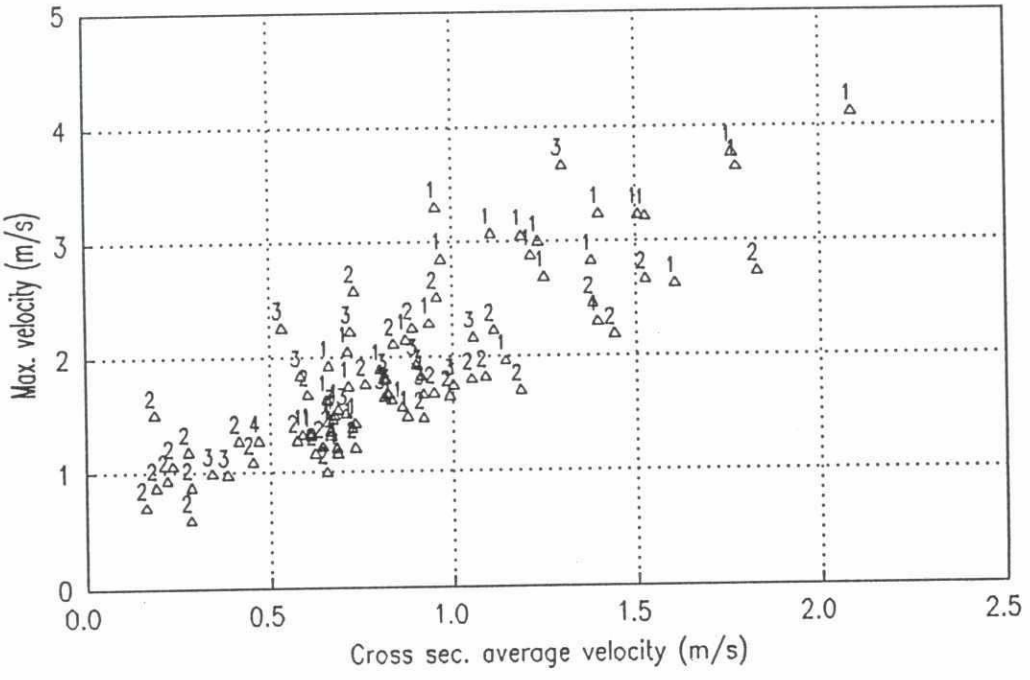


Figure 11.5: Maximum velocity versus cross section average velocity Bahadurabad

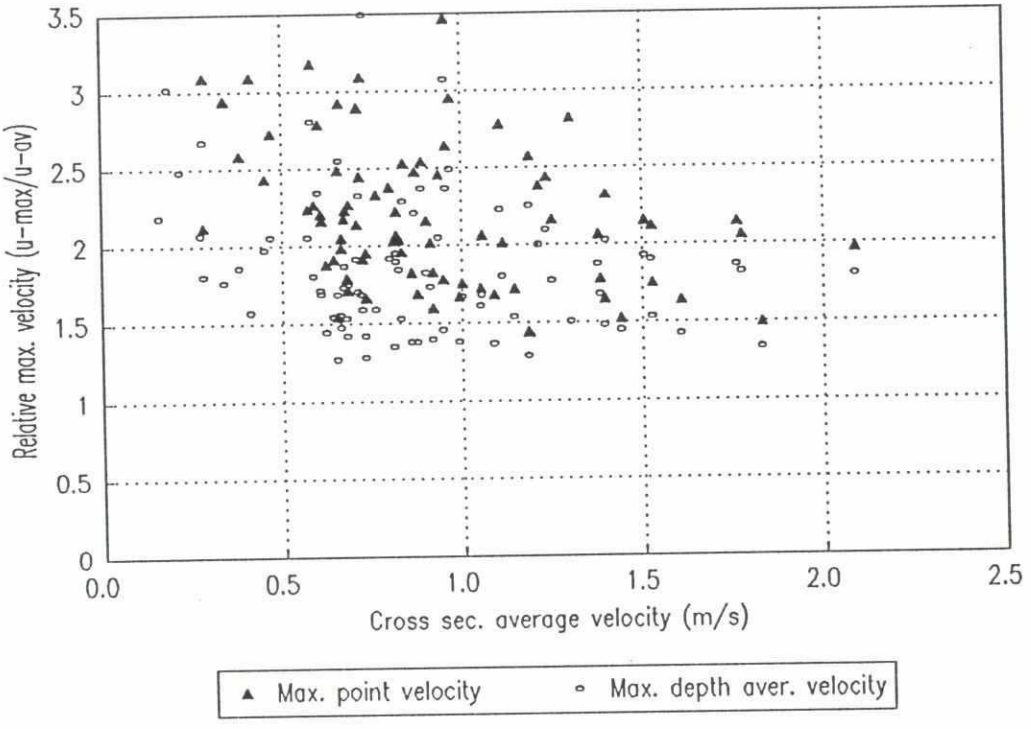


Figure 11.6: Maximum velocity ratio versus cross section average velocity Bhadurabad

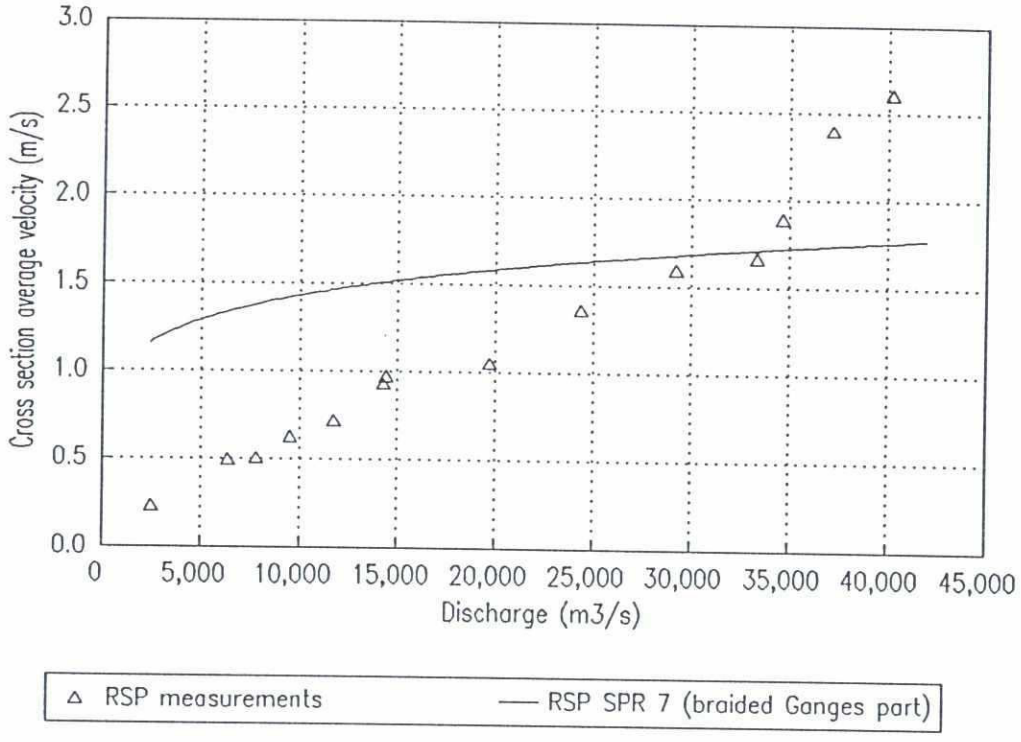


Figure 11.7: Cross section average velocity versus discharge Hardinge

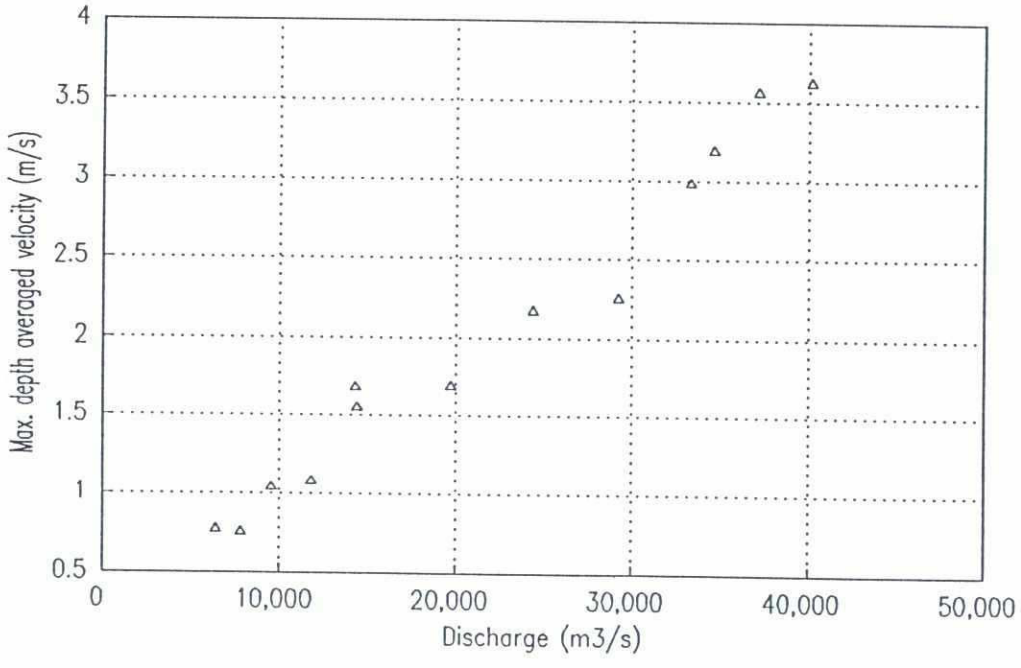


Figure 11.8: Maximum depth average velocity versus discharge Hardinge

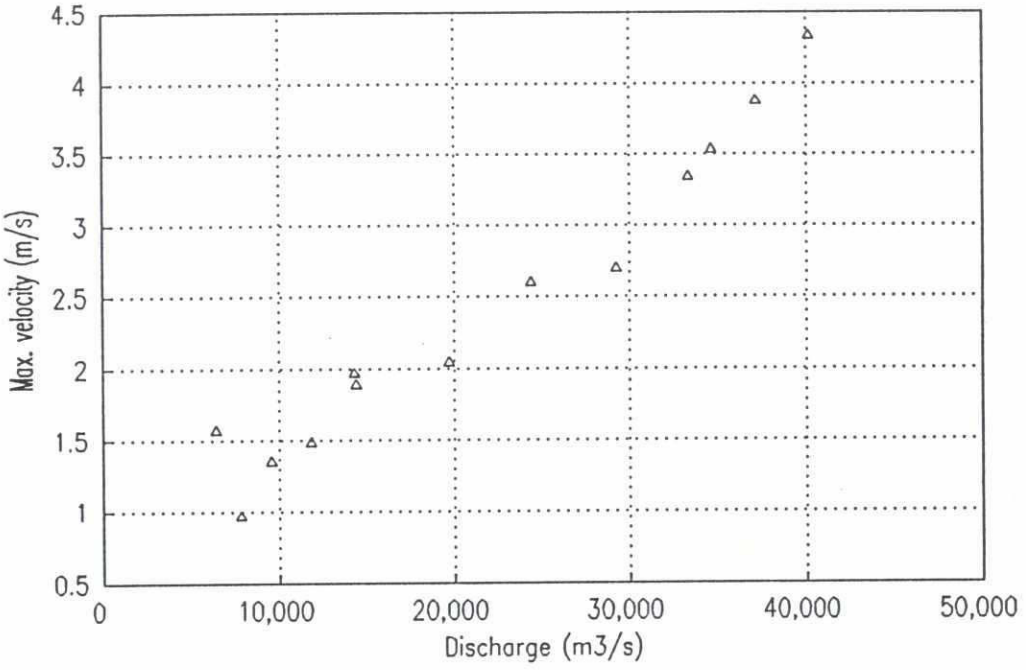


Figure 11.9: Maximum velocity versus discharge Hardinge

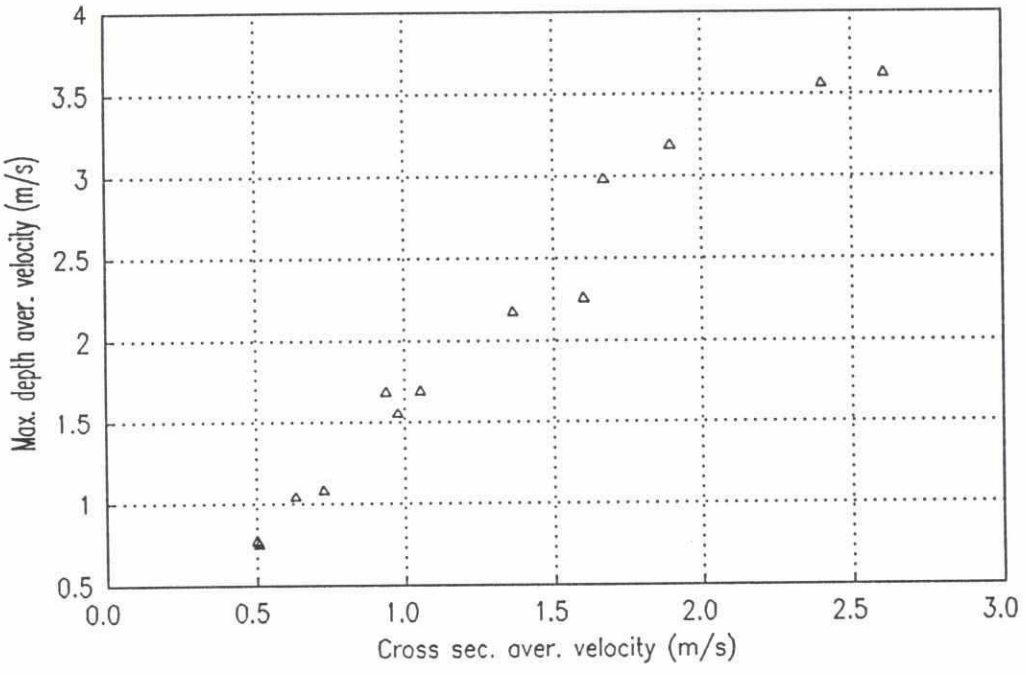


Figure 11.10: Maximum depth average velocity versus cross section average velocity Hardinge

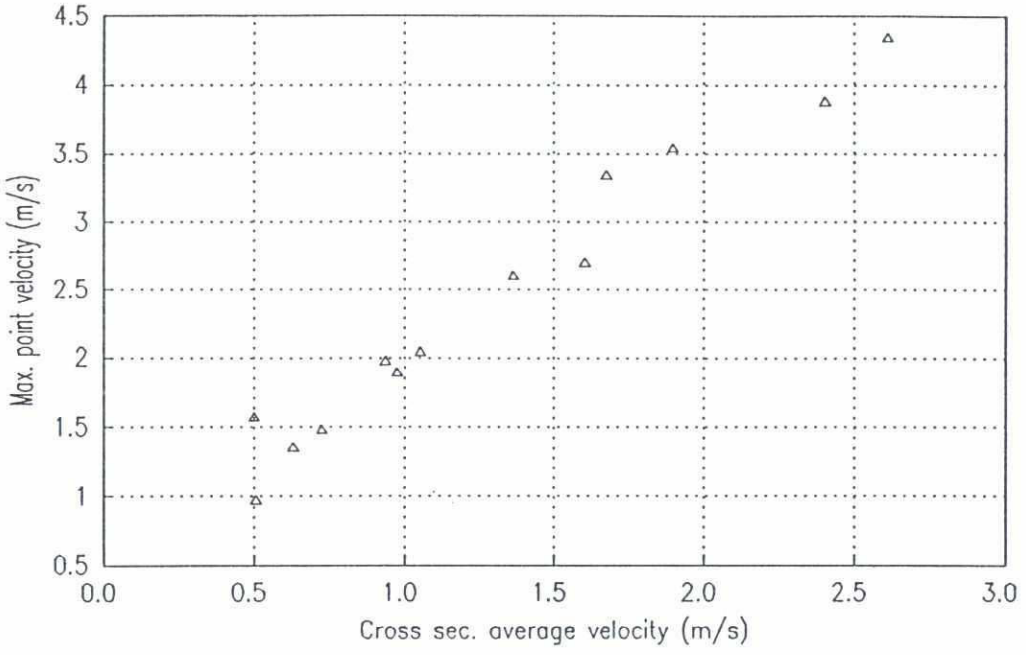


Figure 11.11: Maximum point velocity versus cross section average velocity Hardinge

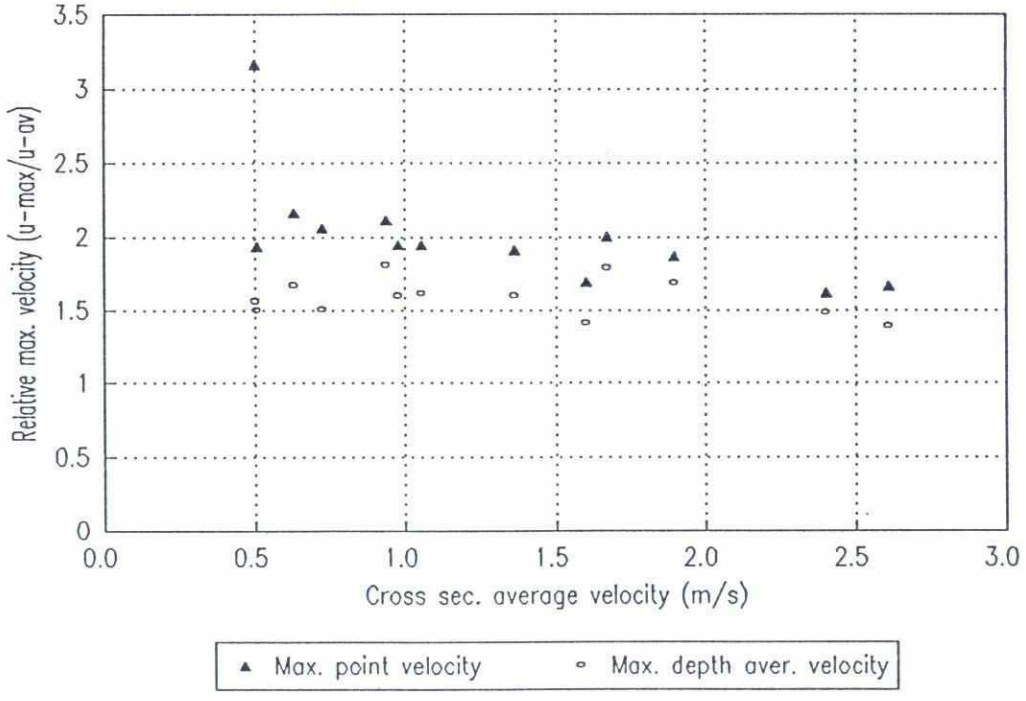


Figure 11.12: Maximum velocity ratio versus cross section average velocity Hardinge

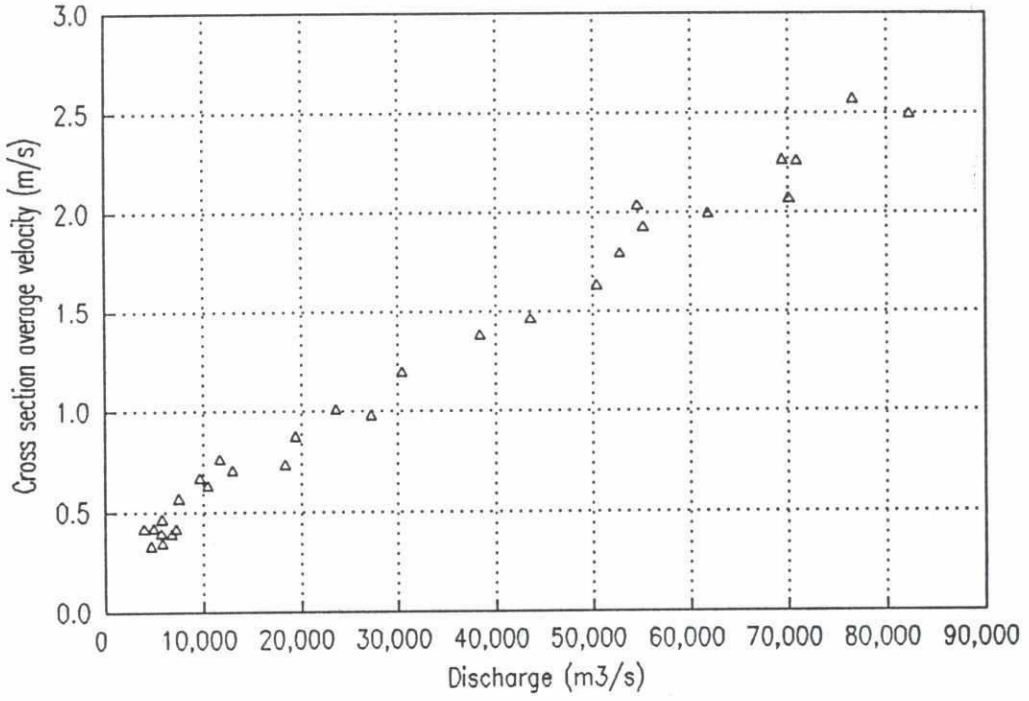


Figure 11.13: Cross section average velocity versus discharge Baruria

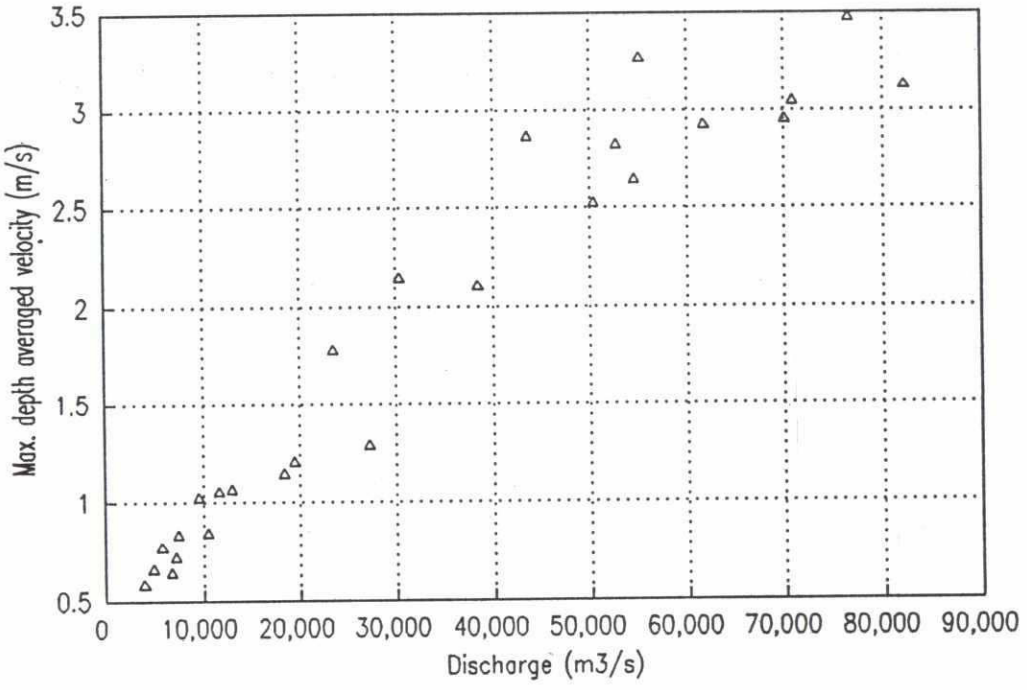


Figure 11.14: Maximum depth average velocity versus discharge Baruria

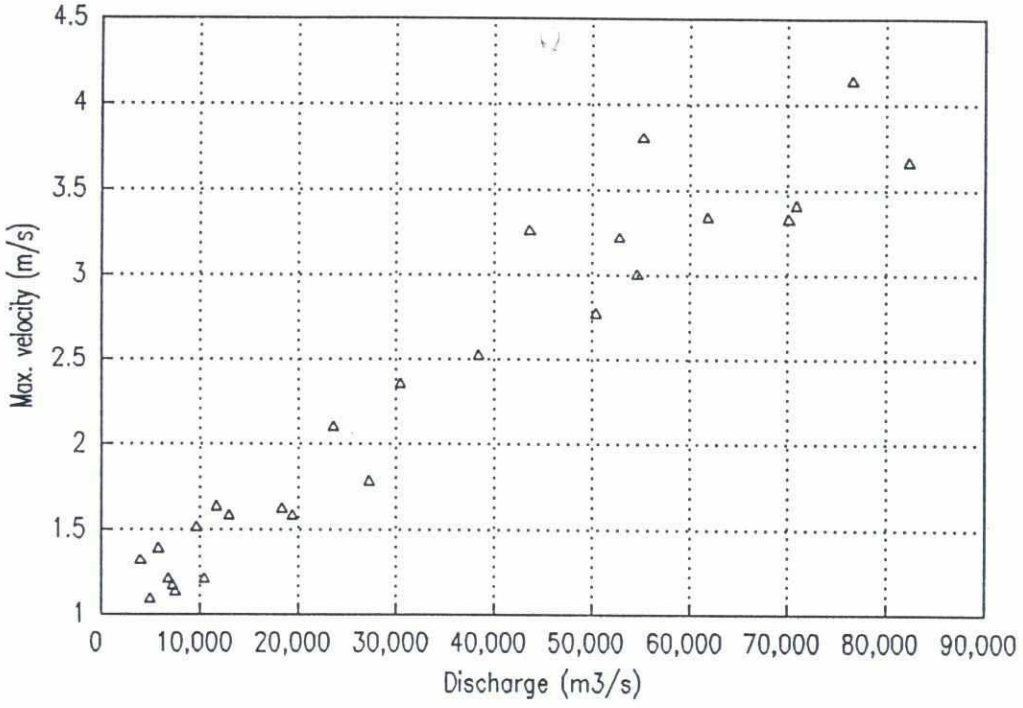


Figure 11.15: Maximum velocity versus discharge Baruria

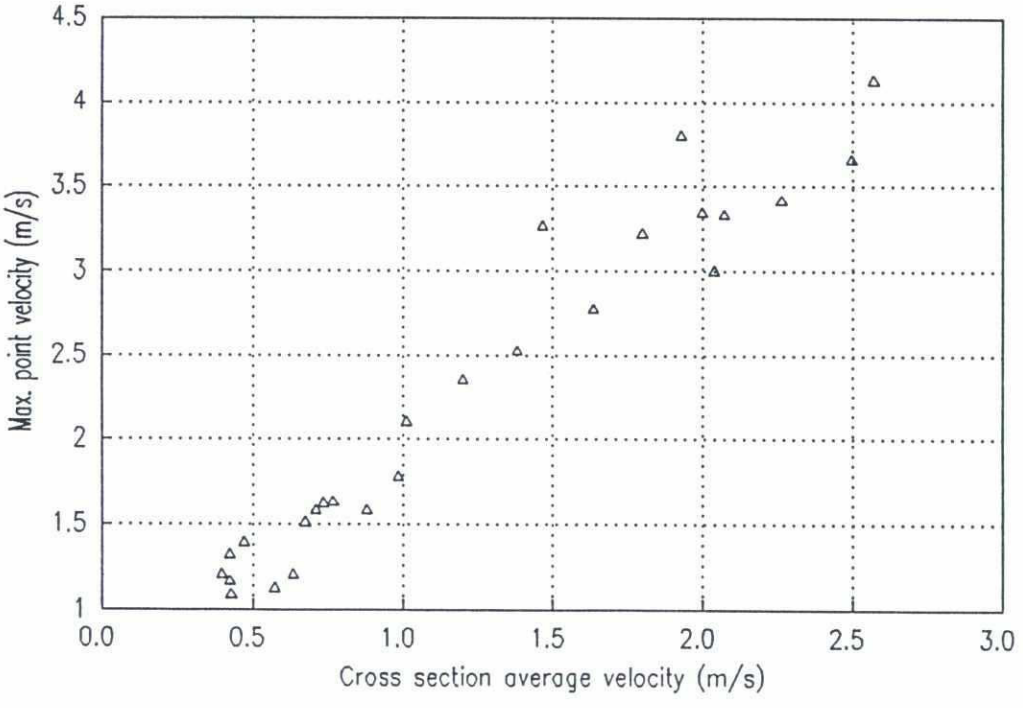


Figure 11.16: Maximum depth average velocity versus cross section average velocity Baruria

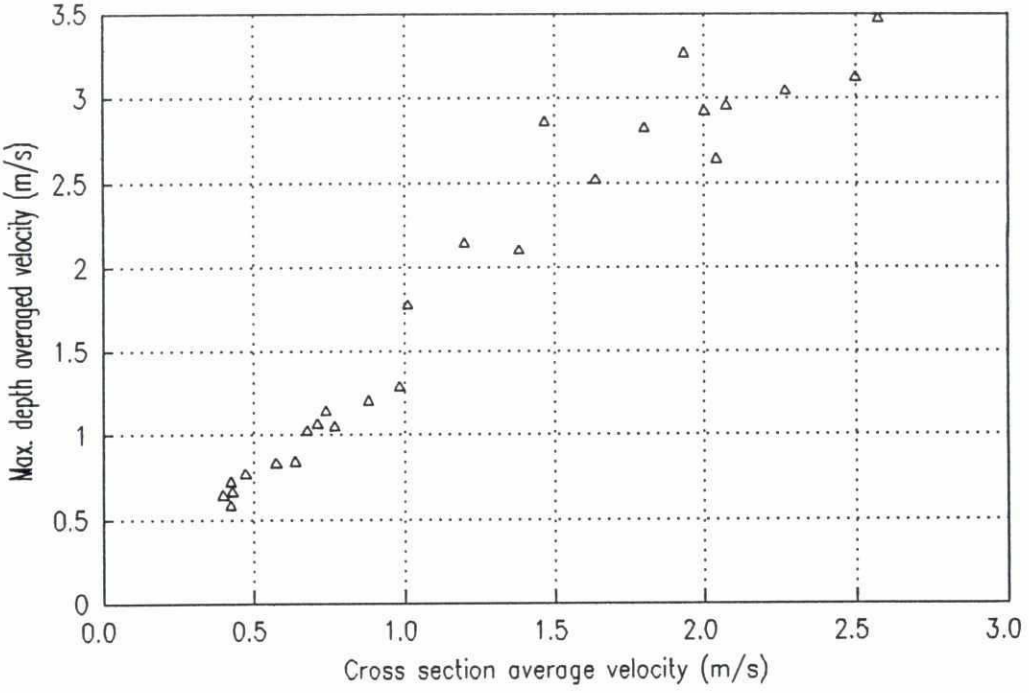


Figure 11.17: Maximum point velocity versus cross section average velocity Baruria

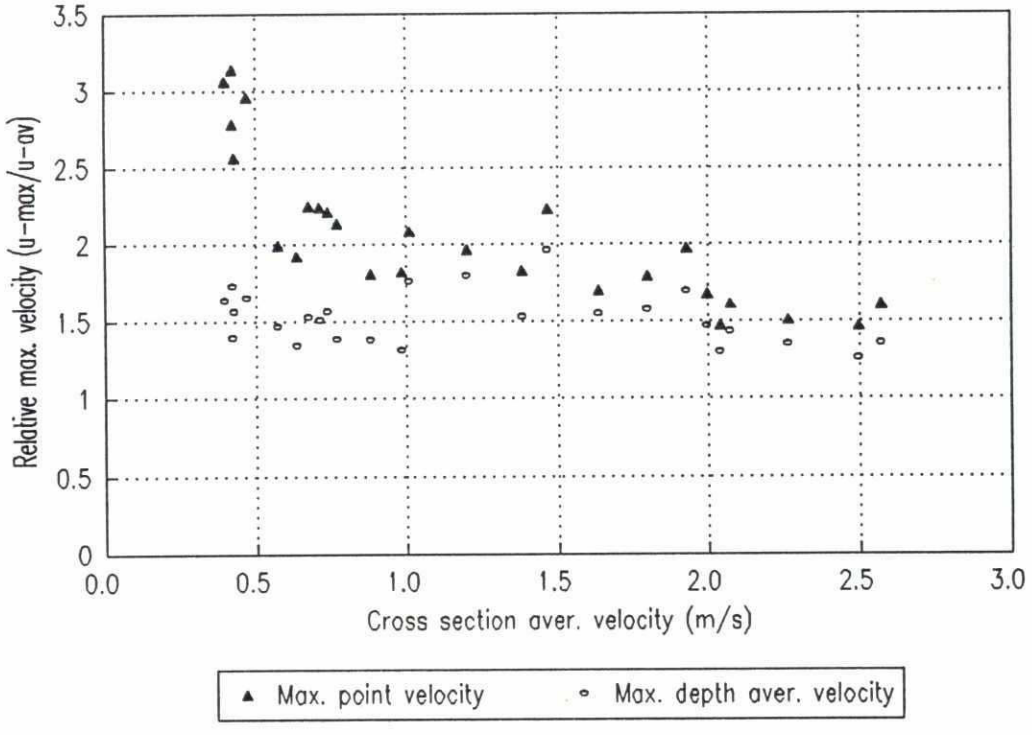


Figure 11.18: Maximum velocity ratio versus cross section average velocity Baruria



12 Exchange of sediments

12.1 Introduction

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

12.2 Causes of erosion and deposition (on the riverbed)

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

$$\frac{dz_b}{dt} + \frac{ds_x}{dx} + \frac{ds_y}{dy} = 0 \qquad (12.1)$$

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

$$\frac{L}{h} = \int \left[\frac{s}{s_e}, \frac{w_s}{u_*}, \frac{k_s}{h} \right] \qquad (12.2)$$

where L = adjustment length, h = water depth, s = actual suspended load transport, s_e = equilibrium suspended load transport, w_s = fall velocity, u_* = bed-shear velocity, k_s = effective bed roughness height. The result is presented in graphical form in Figure 12.1, where k_s/h is kept constant at a value of 0.01. The parameter s/s_e represent the ratio of incoming suspended sediment transport and the transport capacity and this parameter, have significant influence on the riverbed erosion and deposition. According to Figure 12.1, the adaptation length of suspended sediment for different grain sizes and densities of particles assuming water depth 10 and 5 m, overloading factor (s/s_e) is 3 and shape factor 0.7 are presented in Figure 12.2. Suspended bed material particle varied in the Jamuna River from 0.10 mm to 0.03 mm, and the shape factor and density can be considered as 0.7 and 2650 km/m^3. The adaptation length of suspended sediment for overload is factor 3 would be 3000 m to 600 m for 15 m water depth.

In a natural river, depth and distribution grain sizes are quite variable, making a large range of variation in adaptation length of sediment in a river.
Thus Equation 7.1 can be modified for taking into account the contribution of suspended sediment transport in erosion and deposition processes as (Van Rijn) :

$$\frac{dz_b}{dt} + \frac{d(hc)}{dt} + \frac{ds_x}{dx} + \frac{ds_y}{dy} = 0 \qquad (12.3)$$

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

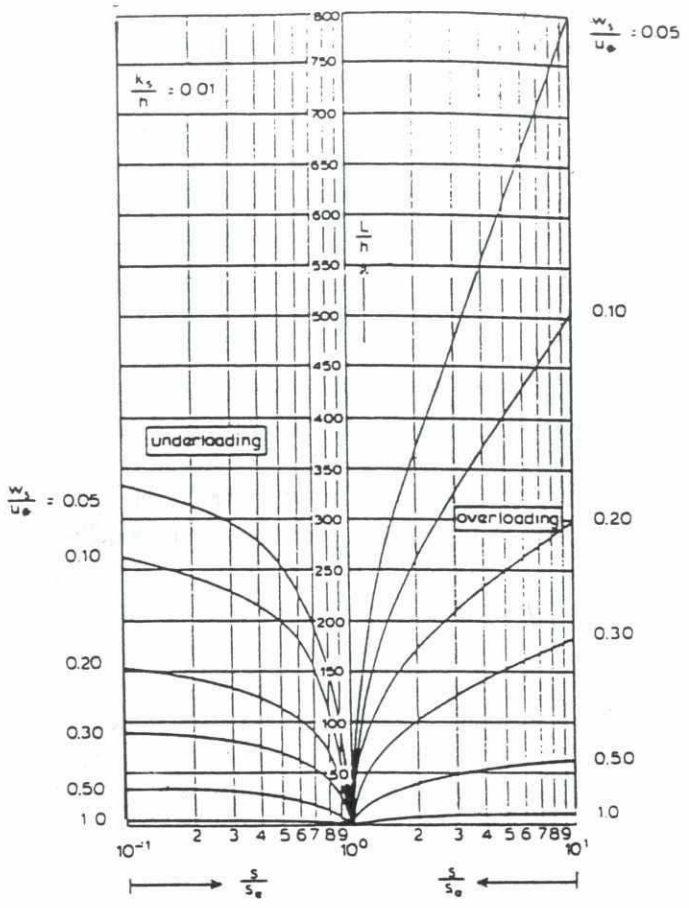


Figure 12.1

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

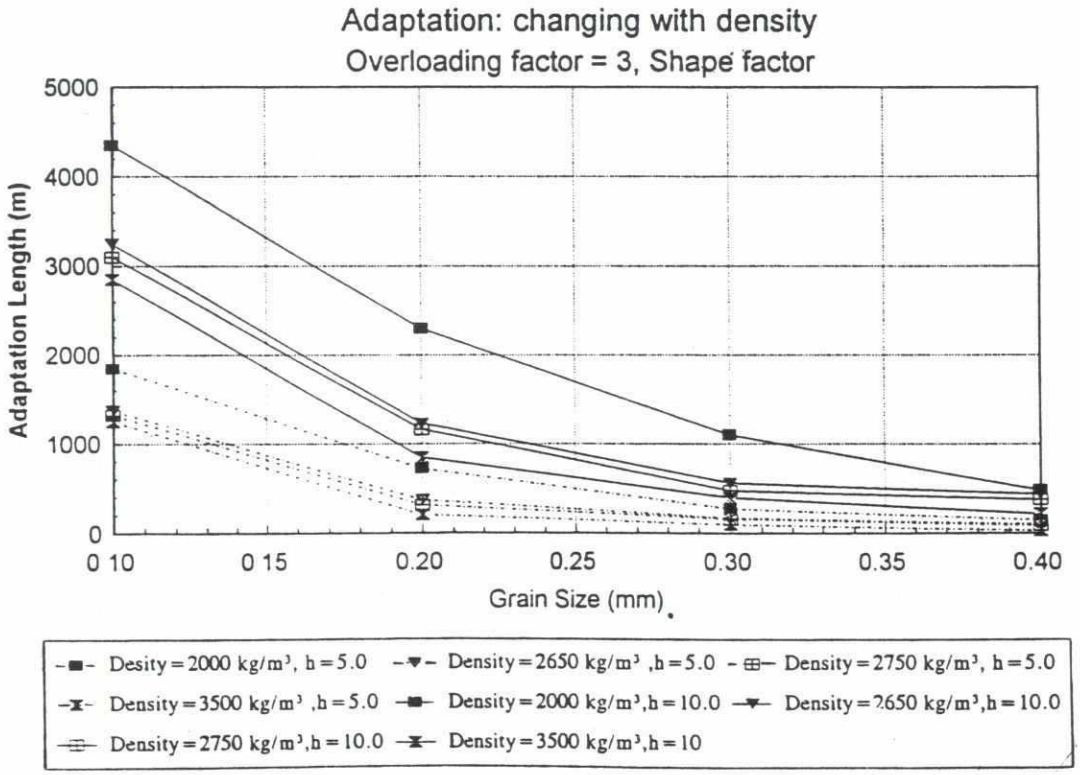


Figure 12.2 Estimated adjustment length of suspended sediment based on Van Rijn (1987) as a function of grain sizes and depth

12.3 Estimation of erosion and deposition

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

Two types of erosion and deposition can be identified, viz: erosion/deposition in lateral direction, and net erosion/deposition in downstream direction. The comparison of August 1993 and November 1993 bathymetric surveys, processed by GIS, can provide a fair impression on the magnitude of erosion and deposition in the riverbed within a time interval of less than two and a half months (see Figure 12.10). In one section of the river the simultaneous occurrence of erosion and deposition may often be in the range of 10 m or more. The two categories of erosion and deposition mentioned above are present in this difference map.

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

12.3.1 Overall balances

In a difference map the local erosion and deposition of the riverbed can be very high. It is interesting to study whether any net aggradation or degradation had occurred during the period of study or any changes of average width, area of the channel had occurred by using the overall balances. This can provide an idea about the overall processes in the Jamuna River. The bathymetric surveys at Bahadurabad were performed during different water levels prevailing at Bahadurabad, see Table 12.2. Therefore, the reach averaged width and flow area and total flow volume of the channel estimated for the different bathymetric surveys, can be compared in relation to the respective levels.

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

Using the GIS processed depth frequency data (Figure 12.3), the reach averaged sectional width and area of the river are estimated, see Figure 12.4. The wet volume of the total survey area in respect to various levels during the different surveys are presented in Figure 12.5.

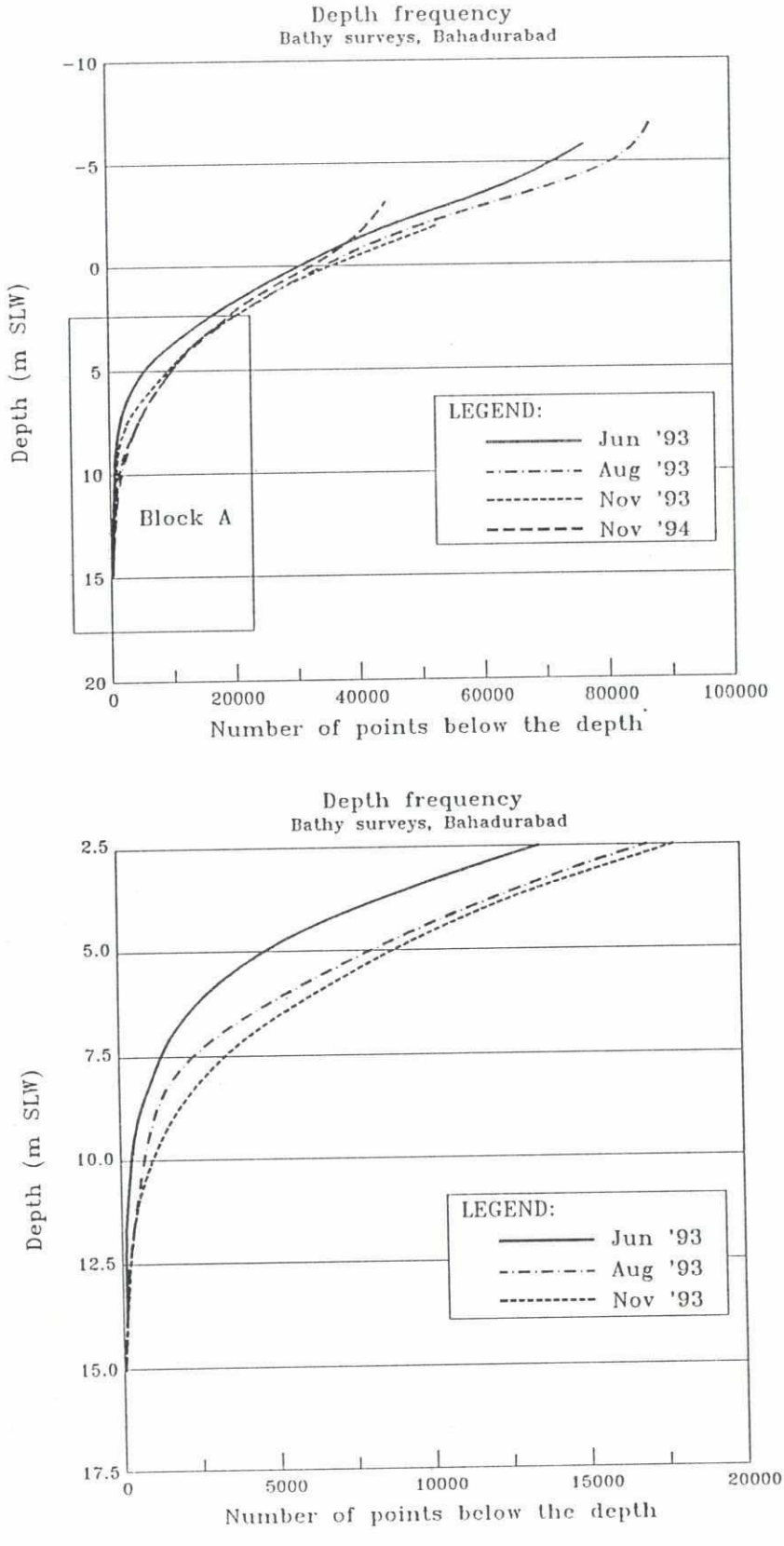


Figure 12.3 Example of depth frequency data for Bahadurabad

The June 93 survey is excluded from comparing the overall balances, the reason of which was indicated earlier. The volume below certain levels, relative to SLW, are also shown in Table 12.1. In the figures and the table the levels are sounded off to full metres although the prevailing average water levels are in fractions of metres. This adds some uncertainties in estimating the balances.

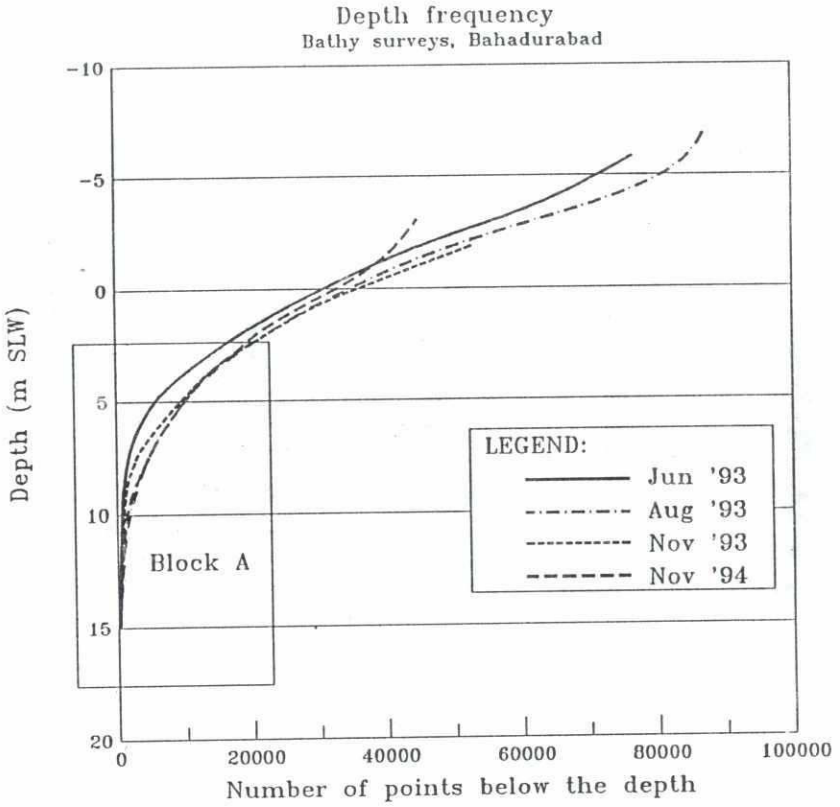
No	Reference	Period		Average water level Bahadurabad		Discharge left channel	Local water level slope (cm/km)
		Start	End	(m + PWD)	(m + SLW)	(10^3 m^3/s)	
1	Jun 93	20 Jun 93	03 Jul 93	18.51	-6.48	26.34	8.4
2	Aug 93	23 Aug 93	09 Sep 93	19.15	-7.12	28.86	8.5
3	Nov 93	10 Nov 93	18 Nov 93	15.48	-3.45	7.90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

Table 12.1 Overview of the bathymetric maps of the left channel at Bahadurabad included in this study

It is understood from Figure 12.4 that the changes of the reach averaged width of the different surveys are very little under different levels. However, the levels represent the different discharges. The figure indicating that on average the river maintains a width in relation to discharges, although the spatial variation of width of a channel is often two-fold. This implies the applicability of the at-a-station relations derived by Klaassen and Vermeer (1988a) for the Jamuna River.

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

Table 12.2 The volume of the channels under different levels



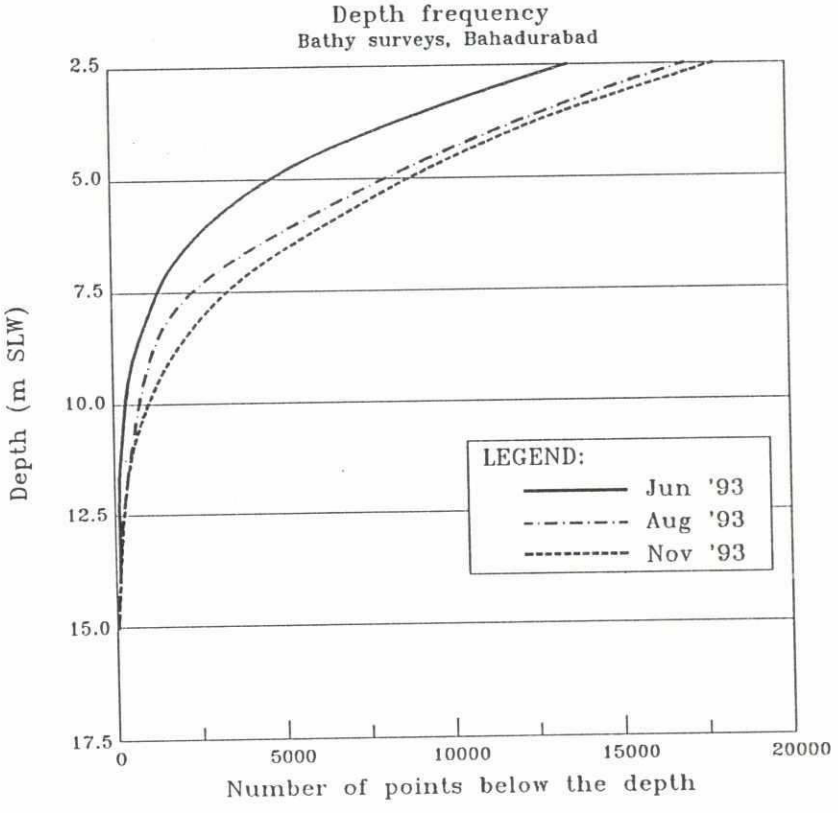


Figure 12.4 The changes of reach averaged flow width and area under different level in different bathymetric surveys at Bahadurabad

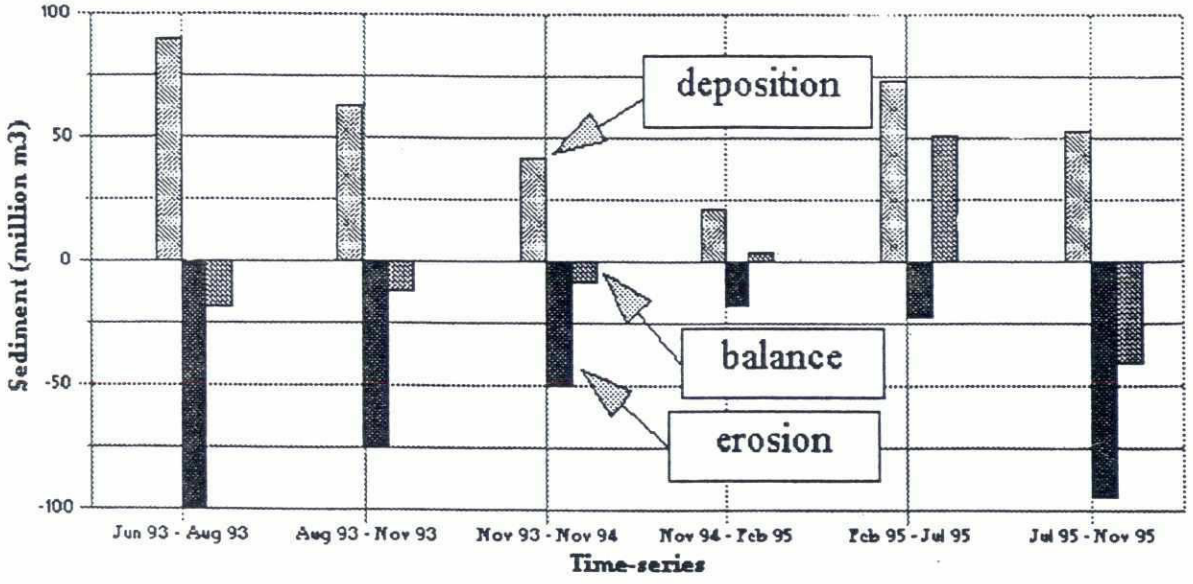


Figure 12.5 Volume of erosion and deposition on the riverbed estimated by comparing consecutive bathymetric surveys (RSP/EGIS, 1996)

Figure 12.5 also shows a little variation of the overall volume among the different surveys, but in comparison to the total sediment transport volumes in between the consecutive surveys (see Table 12.3), Table 12.3 shows often a higher change in flow volumes. This seems to be unrealistic, the reason of which is mentioned earlier. Therefore, it can be noted here that from the RSP bathymetric surveys the estimation of overall balance is not possible.

12.3.2 Local balance

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

To study the local erosion and deposition of a flood cycle, the bathymetric surveys of June 1993, August 1993 and November 1993 were selected. It should be mentioned that local balances using June 1993 surveys is subject to some uncertainties, especially in branch 2 (Figure 7.4), for reasons indicated earlier. The local erosion and deposition also compared with the bed material transport during the period of June-August 1993 and August-November 1993 (see Table 12.3). It is assumed that the estimated sediment transport volume is the total sediment input into the system during the mentioned period. As the system is fairly in balance, the input is the same as the output sediment volume. Furthermore, it is assumed that only the bed material (and not the silt and clay fraction) participated in the erosion and deposition processes. The local erosion and deposition is estimated from two consecutive surveys relative to the lowest prevailing water level of the two considered (see Table 5.2).

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

Table 12.3 Total bed material sediment transport in between the consecutive bathymetric surveys

The net erosion and deposition volumes in the different branches are shown in Table 12.2. In the period of June-August 1993 the maximum deposition in branch 5 (the Old Main Channel) is about 17 Mm^3, equalling more than 60% of the sediment transport in the left channel during this period. The maximum erosion shown in the table for the same period in branch 2, representing the New Main channel is 41 Mm^3. This value shows a higher erosion than occurred in reality for reasons indicated earlier. It can be expected though that substantial erosion did occur in this branch due to the cutoff development of the channel. In the period of August-November, the maximum deposition (4 Mm^3) occurred in the upstream part (branch 1) and in the Old Main channel (branch 2).

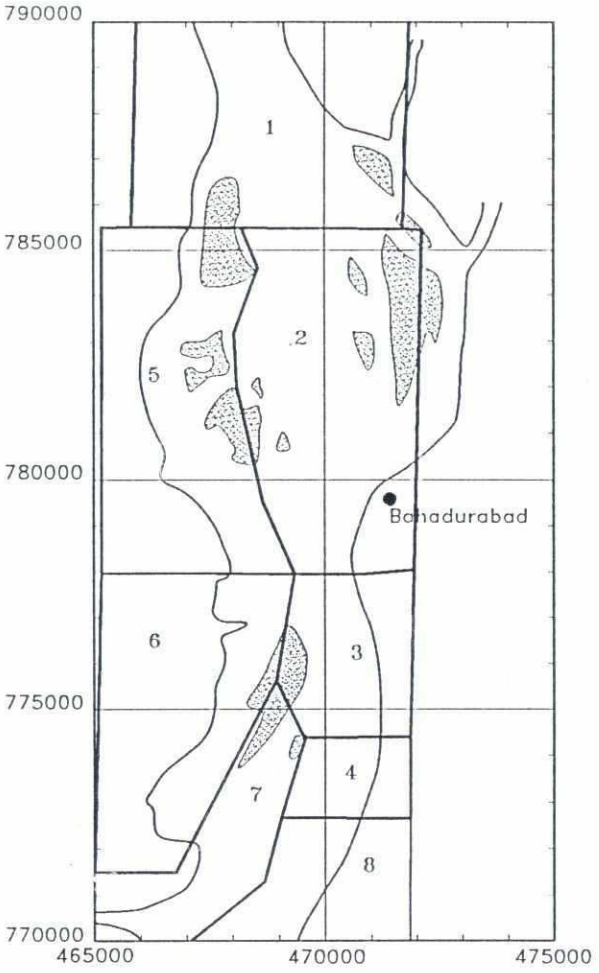


Figure 12.6

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

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

Table 12.4 Local erosion and deposition in the period of August-November 1993 in the different branches

The maximum erosion is 8 Mm^3 in the New Main channel; compared to the total bed material transport in the left channel this is more than 50%. The overall balance by adding the local balances in the left channels in the August-November 1993 period are very close to zero. It indicates that due to some inconsistencies in the survey the overall balance can be estimated by addition of the local balances.

Figure 7.7 presents the net erosion and deposition of the river from the upstream end of the bathymetric survey along branches 1 and 2 in the period of August-November 1993 as function of the chainage. It is observed that in branch 1 the net cumulative deposition increases and with chainage in branch 2 downstream of the bifurcation the net erosion processes compensate the previous deposition. The overall sediment transported volume (see Table 12.3) during the period of August-November survey can be compared with the net erosion and deposition along the chainage from the upstream, see Figure 7.6. This figure gives an impression of the relative importance of erosion and deposition processes in the total sediment transport in the river. It is interesting to observe that up to 40 to 60% of the average sediment transport participated in erosion and deposition processes, indicating that the sediment transport in the Jamuna river is not uniform in downstream direction; but it is an intermittent process. This implies that in the Jamuna River two simultaneous sediment measurement campaigns in two different locations for a period can result in a varying factor of 2.

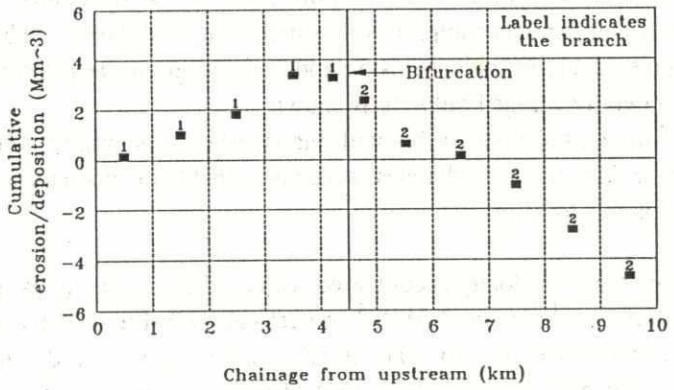


Figure 12.7

The variation of erosion and deposition in downstream direction

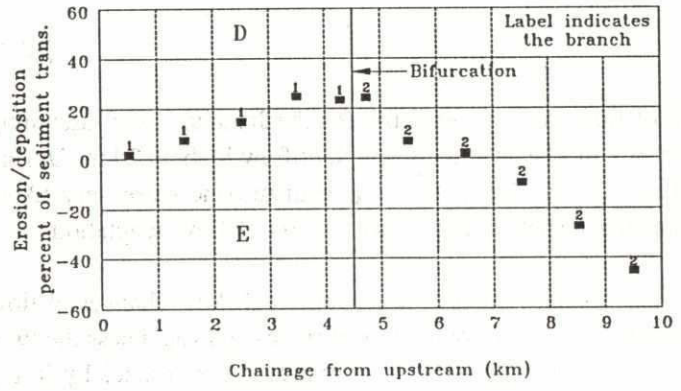


Figure 12.8

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

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12.4 Processes of erosion and deposition on the riverbed

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

12.4.1 Flow processes in the river

The case of uniform flow can be described by the Chézy's equation ($u = C\sqrt{(hi)}$, where for the same bed roughness (C) and the same energy slope (i), the depth-averaged velocity is proportional to the square root of water depth (hydraulic radius). In a natural river, especially in rivers like the Jamuna substantial deviations from this can be observed, due to the spatial variation of these parameters. Figure 7.7 shows the erosion and deposition on the riverbed during the period August-November 1993 together with cross-sectional profiles, interspaced at 400 m with an indication of the depth-averaged velocities measured during the August 1993 bathymetric survey. The depth-averaged velocities are derived from the ADCP transects measurements. It can be seen from the figure that at location (A), the depth-averaged velocity is small compared to the water depth and deposition occurred at this location. On the contrary, at another location (B) where the water depth is comparatively small, erosion did occur. This can be better illustrated by Figure 12.11, in which erosion and deposition on the riverbed in relation with water depth and depth-averaged velocity is shown.
It is observed that the flow distributions are not in line with the riverbed topography. Due to cutoff development upstream the flow direction changes, which is probably the main reason of this type or especially valid for this location.

If observed distribution of depth-averaged velocity is compared with predicted velocity using Chézy's relation, assuming C is on 70 $m^{1/2}/s$ and $7.5*10^{-5}$ respectively (see Figure 12.11), a range of variation of spatial distribution of velocity 50 to 100% can often be observed. The reason of this type of variation can be explained as follows: (1) The changes in the upstream reach, (2) adaptation process of flow, (3) local variation of roughness and slope. The adaptation of flow can be expressed as (Struiksma, 1983):

$$\lambda w = \frac{c2}{2g} h \qquad (12.4)$$

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

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

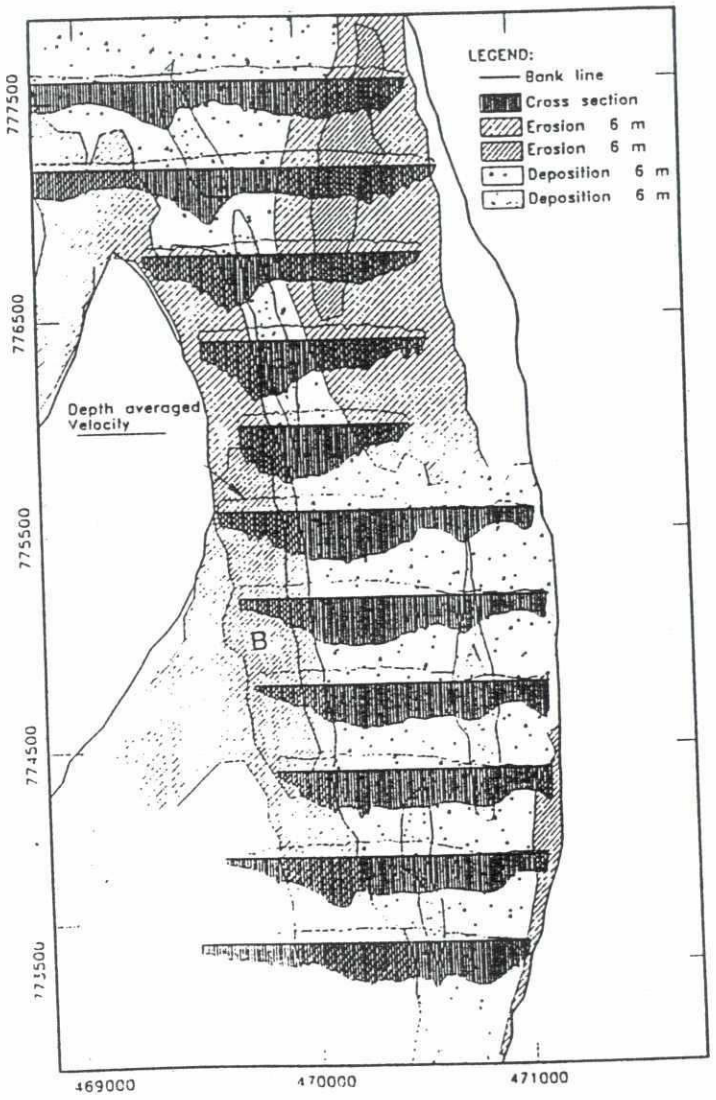


Figure 12.9

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

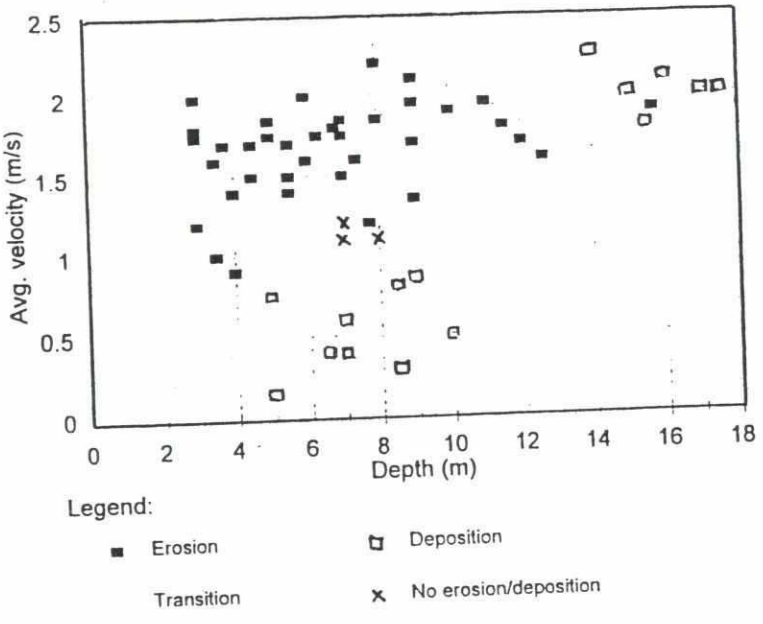


Figure 12.10
Erosion and deposition on the riverbed in relation with depth-averaged velocity and water depth

12.4.2 Sediment transport processes in the river

To better understand the sediment transport processes in the river, the upstream part of the bathymetric survey of August 1993 was selected. The reasons for this selection were that the ADCP measurement covered a comparatively large area and that the large variation of sediment concentration can provide a better idea about the underloading and overloading processes of the suspended sediment. The flow lines derived from the ADCP transect measurements can be seen in Figure 12.10. The discharge between two subsequent flow lines is 3,000 m^3/s. Along the flow lines the water depth, the sediment concentration derived from ADCP backscatter, and predicted sediment concentration are shown in Figure 12.16. The predicted concentration corresponds to the sediment transport capacity using a sediment transport predictor specially developed for the Jamuna River (Equation 3.23). In estimating the sediment concentration instead of using the parameter θ, the depth-averaged velocity is replaced by using Chézy's relation, and the modified relation reads as:

$$c = \frac{80}{1-\varepsilon} * \sqrt{\Delta g D_{50}{}^3} * \left(\frac{1}{C^2 \Delta D_{50}}\right)^{1.8} * \frac{u^{2.6}}{h} \qquad (12.5)$$

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

$$c = 1024 * \frac{u^{2.6}}{h} \qquad (12.6)$$

in which c is expressed in mg/l.

In the flow lines 1 and 2 of Figure 12.13 the sediment concentration is in fair agreement with the predicted transport capacity. In a few cases where the predicted concentration shows a sudden jump, the actual sediment concentration does not show such sudden changes. The concentration along the flow line 2 shows a clear lagging behind compared to the predicted concentration. In the flow line 1, downstream of chainage 4000 m, the predicted concentration is much higher than the actual sediment concentration, clearly showing a zone of underloading. Erosion is likely for that location, see Figures 12.12, 12.13 and 12.14.

From the flow lines 4, 5, 6 and 7 it is observed in Figure 12.13 that if the sediment transport capacity increases, a certain distance is needed for adaptation to the new transport capacity. These overloadings of sediments are prone deposition. It can be observed that most of the overloading area is deposited in the period of August-November 1993. The magnitude of over concentration and the gradual diminishing of over-concentration in downstream direction can be better illustrated in Figure 12.15. In this figure are only shown the observed suspended sediment concentration which is higher than the predicted concentrations. The estimated relative adaptation length and the overloading are presented in Table 12.3. The overloading is estimated by the ratio of sediment concentration and the predicted concentration. The estimation is done for a length where predicted concentration shows almost no variation in downstream direction, and average depth along the flow line is considered (see Figure 12.13). In natural rivers there are always some uncertainties in estimating the relevant parameters due to their variation in space. It can be seen though that the adaptation lengths derived from the field which are given in the table, is close to the predicted length estimated for the Jamuna River using average grain size based on Van Rijn (1987), see Figure 12.16.

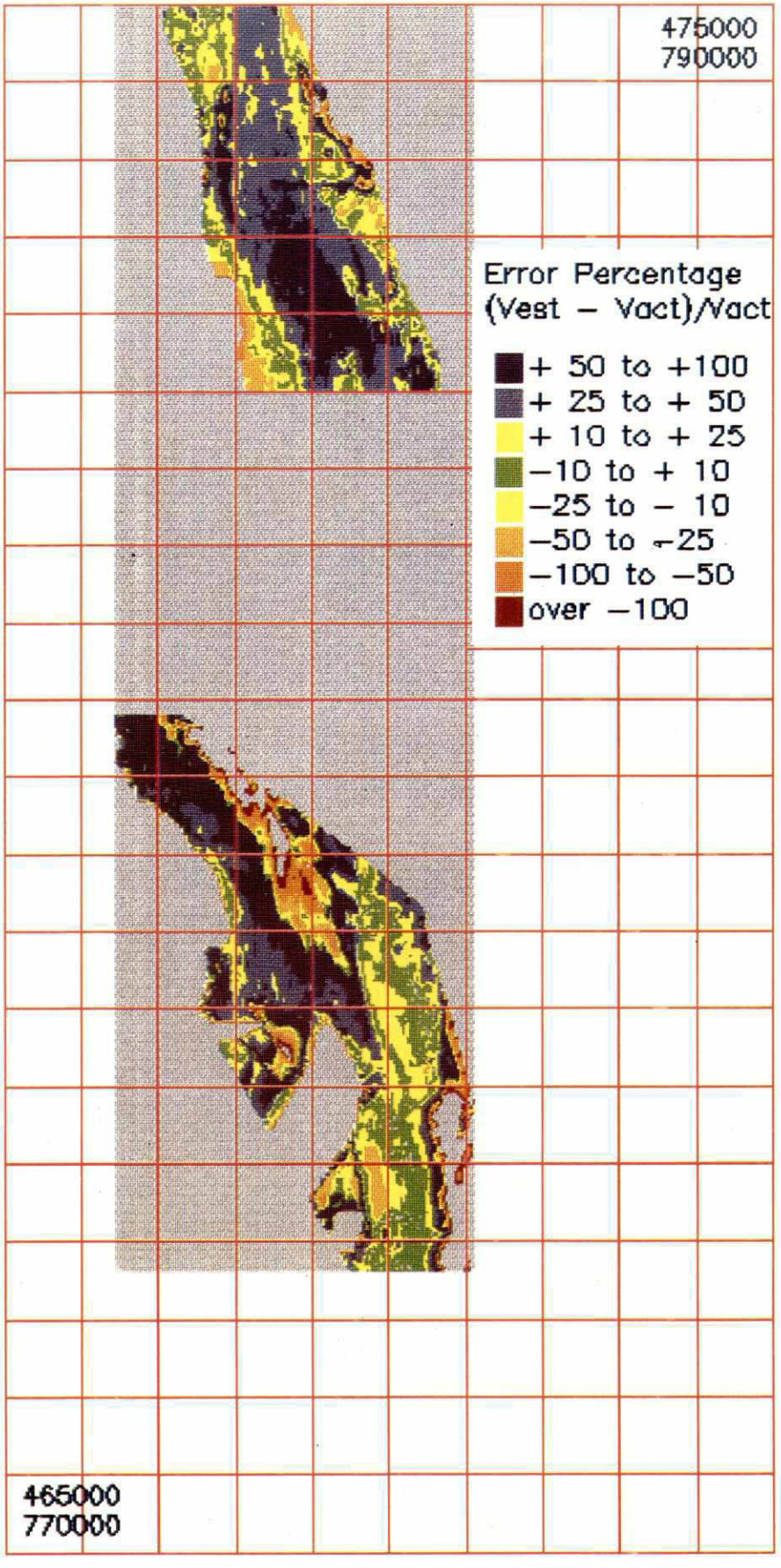


Figure 12.11 The difference between measured depth-averaged velocity and predicted velocity assuming uniform flow (C = 70 $m^{1/2}/s$, i = $7.5*10^{-5}$)

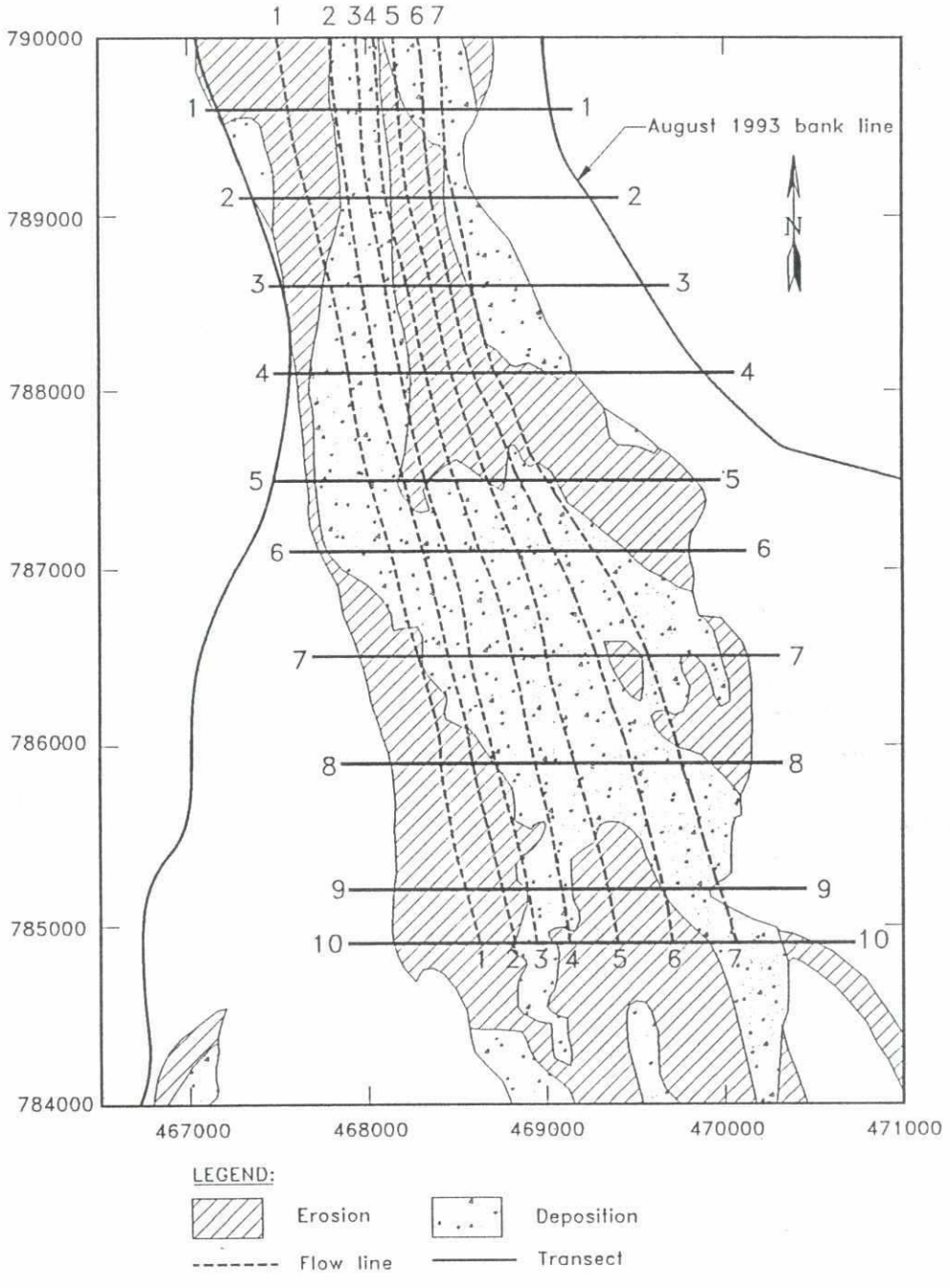


Figure 12.12 Erosion and deposition (August-November 1993) and flow lines based on August 1993 measurement

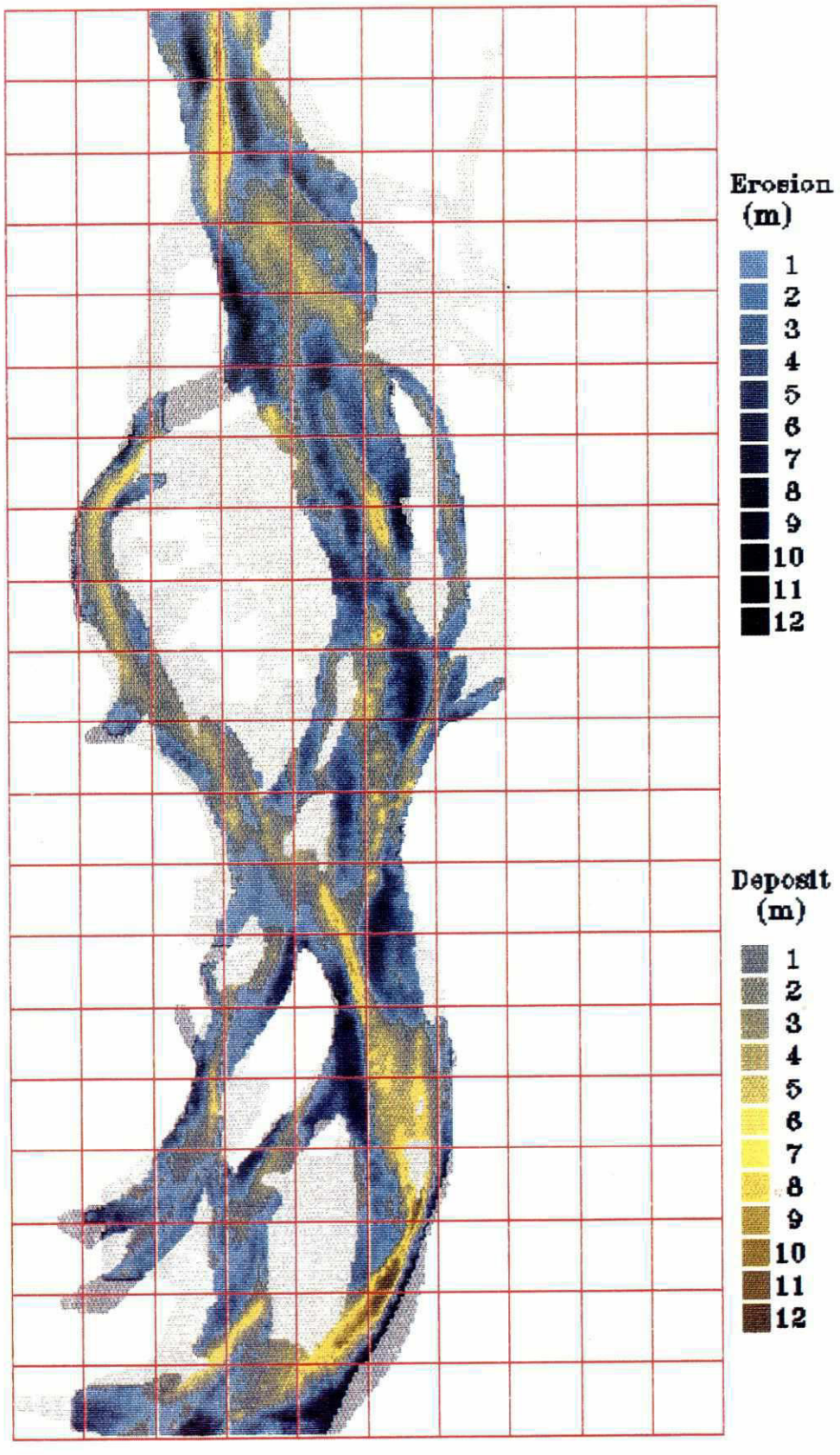


Figure 12.13 Observed erosion and deposition on the riverbed in period August-November 1993

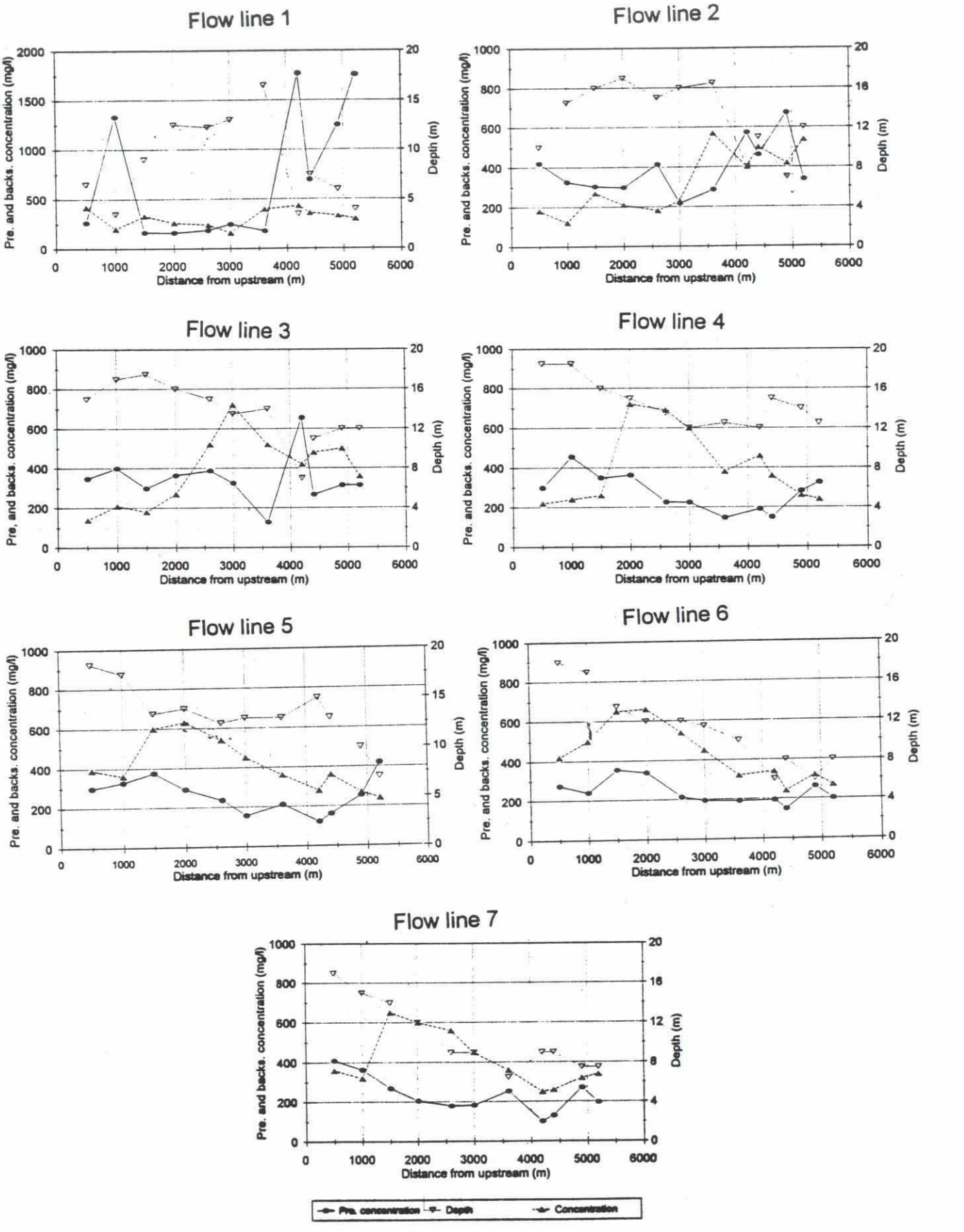


Figure 12.14 Depth, predicted concentration and actual sediment concentration along two flow lines

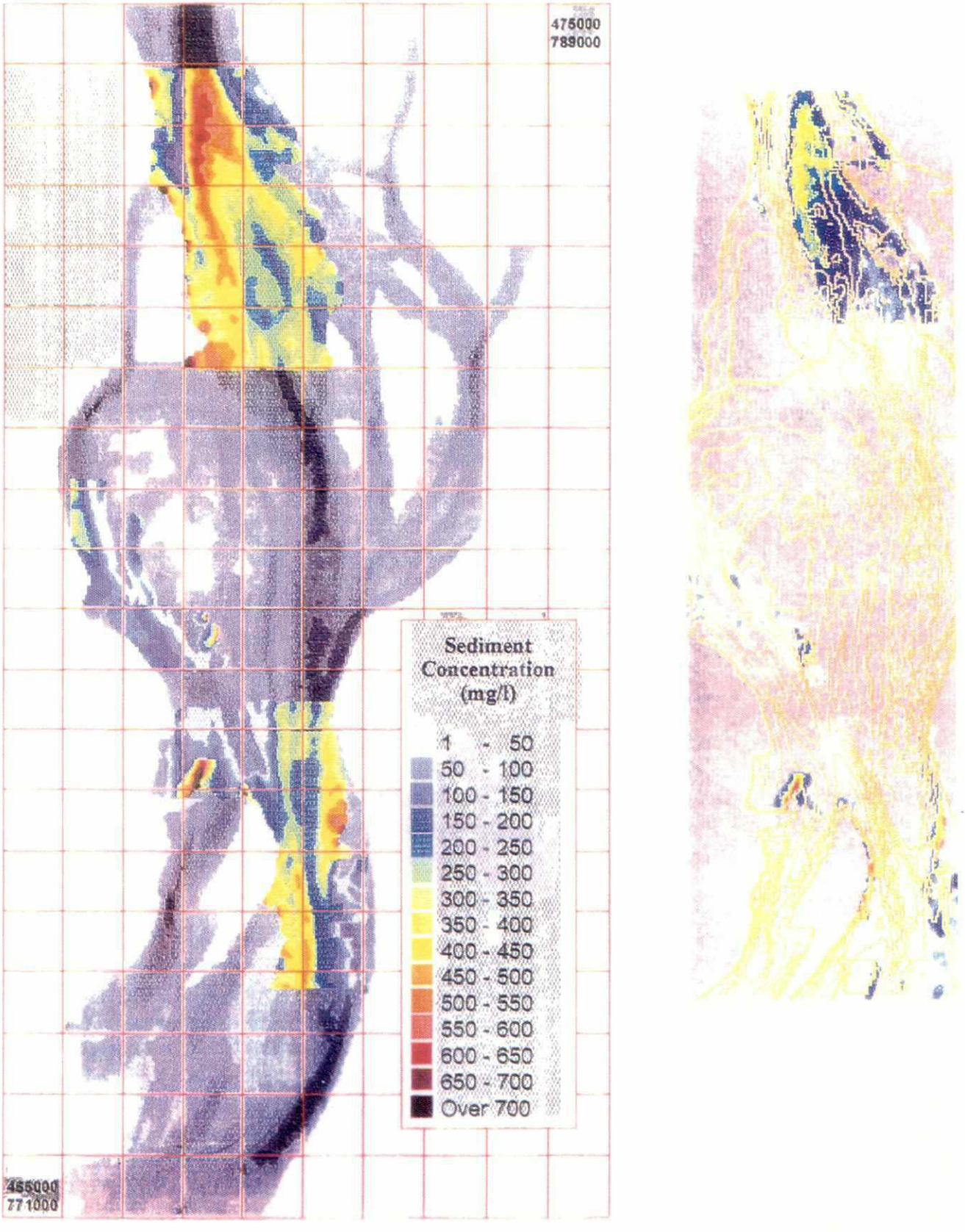


Figure 12.15 The magnitude of observed over concentration (Aug. 93)

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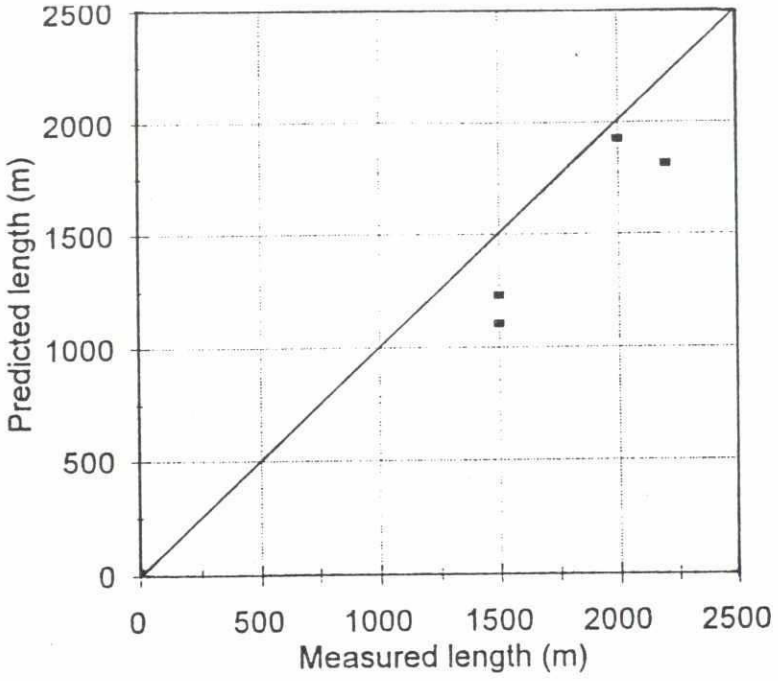


Figure 12.16 The observed and predicted (Van Rijn, 1987) suspended sediment adaptation length

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

Table 12.3 Measured and predicted adaptation length along the flow lines

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

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

12.5 Summary

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

- Two types of riverbed erosion and deposition can be identified, one is the riverbed erosion/deposition in a channel section and the other is the net erosion and deposition in downstream direction. Both processes occur simultaneously in an active river.

- Locally, quantities of erosion and deposition are quite high and depend on the flow stage in the river and may be up to 20 Mm^3 (Old main channel in June-August, 1993) in a 5 to 6 km long channel.

- The magnitude of the erosion and deposition on the riverbed can be linked to the average sediment transport capacity of the river. It is observed that more than 50% of the average sediment transport is participating in the erosion and deposition processes over a distance of some 5 to 10 km. This implies that the sediment transport in the Jamuna River is rather an intermittent processes and thus the measurement in a channel at different cross-sections can result in a high variation in measured values of up to 100% or more.

- The direction of flow often changes, mainly determined by the upstream reach and also probably the changes of momentum of flow due to discharge variation. It appeared that spatial distribution velocity in the Jamuna river is very complicated as a result of interaction processes of above two causes, continuous adaptation processes of flow and local variation of slope and roughness.

- The processes of erosion and deposition is determined by the sediment continuity relations and overloading and underloading of suspended sediment govern the processes. A sudden increase of sediment transport was observed, which may be related to the bed roughness generated by the bedform.

- It appeared that the adaptation length for the suspended sediment, especially for the overloading, is in good agreement with the predicted adaptation length based on Van Rijn (1987).
- It appeared that to better interpret the observation made on the flow and sedimentary distribution, a two-dimensional mathematical model would be helpful a tool.

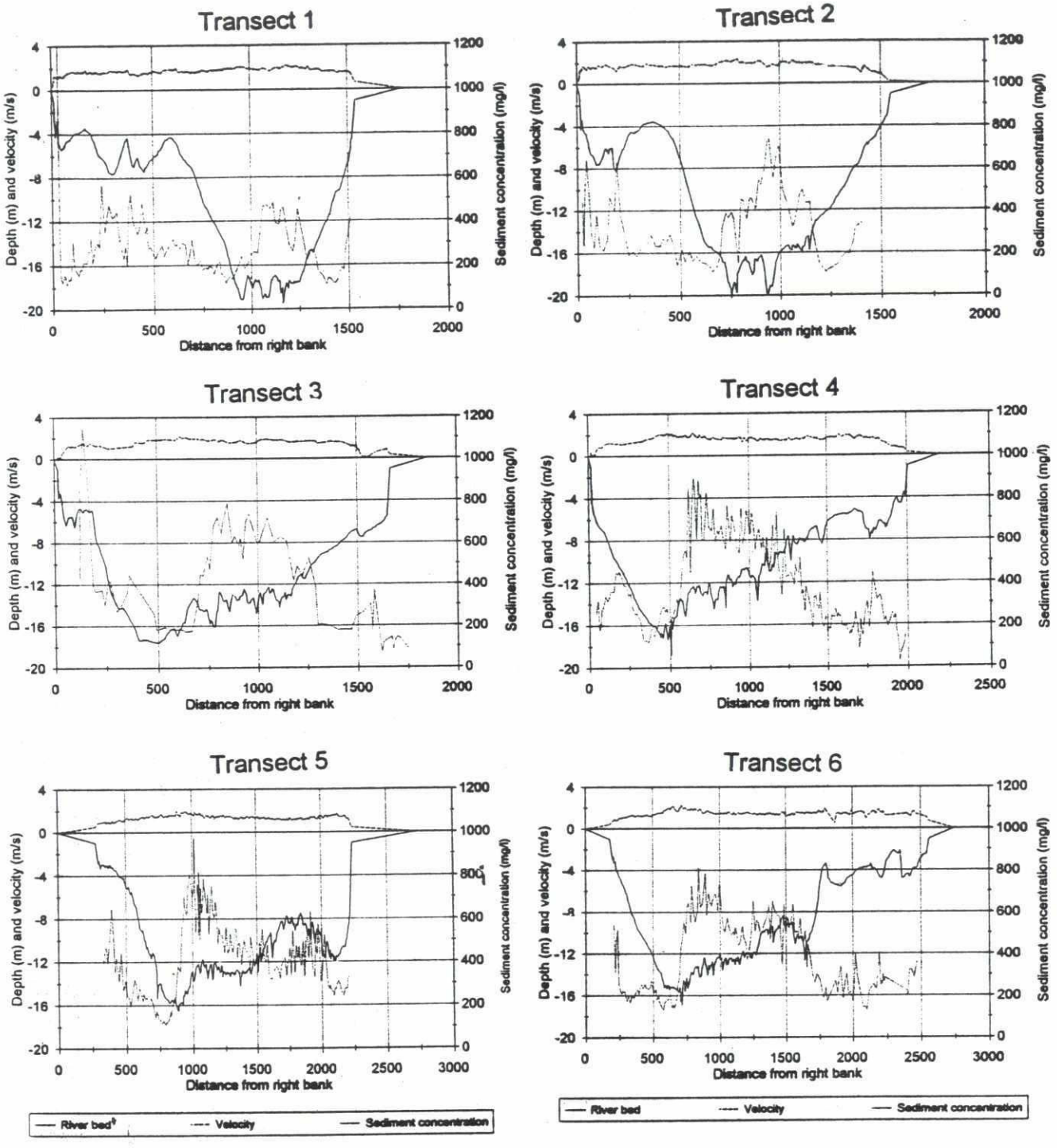


Figure 12.17 Depth-averaged velocity over cross-sectional profile and sediment concentration

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13 Planform development and predictions

13.1 Introduction

Understanding of planform changes of rivers is essential for the development (infrastructure, town planning, etc.) of the river banks and adjacent lands. By analysis of the changes in the past insight is developed to predict planform changes in the future. The time span over which the changes took place or will take place is very essential herewith. This is reflected by the structure of this chapter. Planform changes which took place over centuries (Section 13.2), years (Section 13.3) and months (Section 13.4) have been discussed, whereafter the predictability and the way the time span affects the prediction method is described.

Nowadays the understanding of meandering rivers is fair: meandering via bank erosion can be predicted to some extent (Hicking & Nanson, 1984) including the occurrence of cutoffs (Klaassen and Van Zanten, 1989), and predictive models for the development of meanders (Parker and Andrews, 1981; Crosato, 1990).
Predictive models for braided rivers are still in an initial stage. One of the problems is that the time span over which reasonable deterministic predictions can be made seems to be rather short (Klaassen et al, 1992). Present chapter is dealing with a braided river: the Jamuna River in Bangladesh and is mainly based on RSP SR24 and Klaassen et al, 1993.

13.2 Historic long-term developments

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

To describe the historic development of the river, three maps are presented in Figure 13.1. The oldest one is known as the Rennel's map, published in 1776, the second is the Wilcox map surveyed in 1821-1834 and published in 1840. The recent map is prepared by ISPAN, 1993, from satellite images (1991). To compare the bank line and migration of the river, old maps of 1914 and 1953 and maps derived from 1973 and 1992 satellite images were used as well, see Figure 13.2. The projection of satellite images, and the correction of the geo references of the old maps were done by ISPAN, 1993. They found the accuracy of the old maps to be good enough to estimate the migration of the river over time.

The Rennel's map clearly shows that in the second half of the 18th century the present Jamuna River was flowing at the Eastern side of the Madhupur tract and joined with the Upper Meghna River before meeting with the Bay of Bengal. The Wilcox map shows

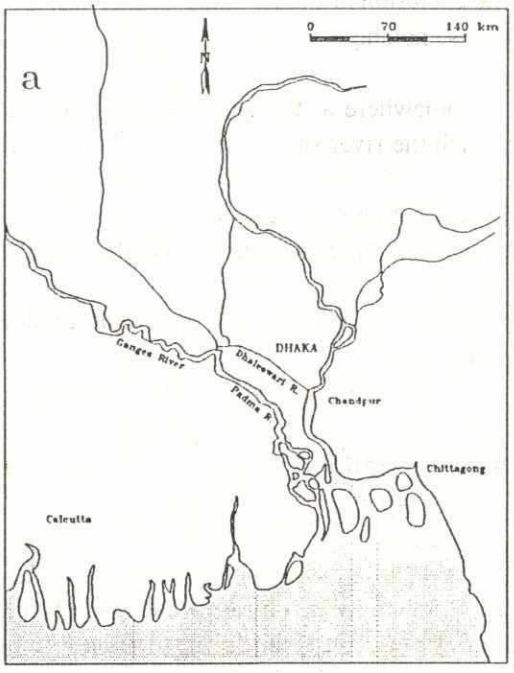
evidence that in the period between 1767 to 1830 a new channel evolved that was carrying the major part of the discharge. The Old Brahmaputra river was still important for draining off the water. The Dhaleshwari River, one of the left bank distributaries of the Jamuna River, was remarkably more prominent than in its present state. The planform of the river shown in 1830 was essentially a meandering river with very broad and low-curvature meander loops. With an increased discharge and a heavy silt load (resulting in part from the capture of the Teesta River as a tributary and the gradual loss of importance of the previous course), the stream gradually changed from meandering to a typical braided channel (Coleman, 1969). The change can be illustrated by the historic bank line position presented by ISPAN, 1993 (see Figure 13.2).

The position of the river banks were extracted from different old maps such as Wilcox's map, Survey of India (1914), Survey of East Pakistan (1953), and from the LANDSAT images of 1973 and 1992. The bank lines of these old maps and images are compared with the 1992 bank line position. In 1830 the river was farther East and the overall width was considerably less than the present state of the river. In between the period 1830-1914 the river width decreased slightly, it reduced its meander amplitude and migrated in westward direction. The increase of the width and migration westwards were very pronounced in between 1914 and 1953. Probably in this period the river evolved into its present fully grown braided form. From 1952 to 1973, although the overall river width reduced slightly, the westward migration continued. During the past two decades (1973-1992) the river had widened while continuing to migrate towards the west. The changes of average overall width and centre line migration in westward direction with respect to the 1830 centre line are summarized in Table 13.1.

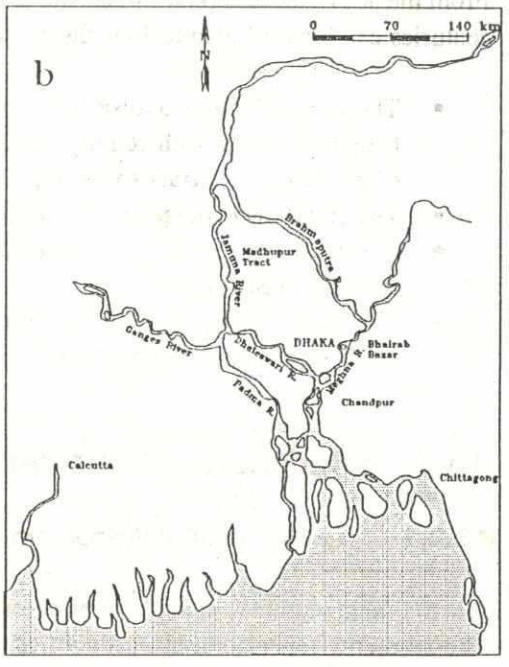
Year	Average width (km)	Westward centre line migration (10^3m), compared to 1830 location
1830	6.2	
1914	5.5	1.9
1952	9.0	3.6
1973	8.1	4.5
1992	10.6	4.6

Table 13.1 Average width of the Jamuna River and centre line migration 1830 to 1992 (ISPAN, 1993)

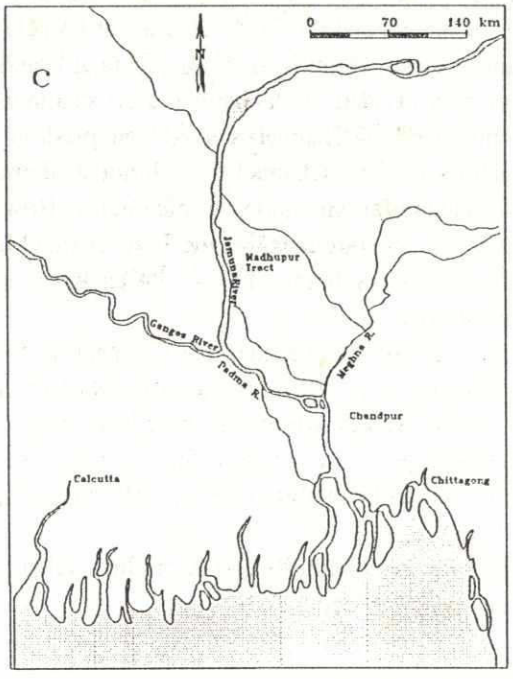
Although the accuracy of the figures on the changes of average width and the migration as shown in Table 13.1 is limited, it can be said that the average overall width of the river had increased from 6.2 km in 1830 to 10.6 km in 1992 and the westward migration of the centre line of the river has been continuing since 1830 without showing any discontinuities. There are some discontinuities in the processes of widening in 1914 and 1973. The actual bank line movement towards the west might be different from the centre line migration, because the bank line movement is the result of both the migration of the centre line and the changes of the width.



(a) End 18th Century (after Rennel's map of 1776)



(b) 1821 - 1834 (after Wilcox map, 1840)



(c) 1991 (based in satellite imagery

Figure 13.1

Historical maps of the river system of Bangladesh (ISPAN, 1993)

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

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

13.3 Recent medium term developments

13.3.1 1973 - 1994 developments

The previous section contains a brief description of the long-term development of the river. The long term trends of the river identified there, cannot be recognised during a medium-term investigation of the river behaviour as done here. In a joint study of the RSP and the University of Nottingham, the past development of the Jamuna River at the Study Area in the period 1973-1994 was studied, see RSP, SPR16. In this Special Report an analysis is given regarding the changes of planform of the anabranches together with the distribution of the discharge over them. The division of flow between the Left Channel and the Right Channel at Bahadurabad is variable. When the flow is predominant in one anabranch, then this channel braids and the smaller channel meanders. When it is equally divided, both channels have channels in the braided/meandering transition. In the seventies the Left Channel evolved from predominantly meandering to braided one and in the eighties the Left Channel flow diminished and the channel reverted to a meandering form with wide point bars and multiple chutes. However, at the beginning of the nineties a reversing process started again; the Left Channel is taking over in carrying a higher percentage of the total discharge. This is the background of our analysis of the recent development of the study area.
Other studies on the planform developments over the last two decades are for instance the Jamuna Bridge Study, (RPT, NEDECO, BLL 1987, 1989), the FAP 21/22 study (RII/L&D/CNR/DELFT HYDRAULICS, 1993), Klaassen et al, 1993, tec. These studies are mainly based on satellite images (LANDSAT). By comparison of the annual images, using often difference maps (see example of Figure 13.3) the planform developments can be analyzed on a yearly basis.

Phenomena like bank erosion, outer bend scour and channel cutoffs can be studied. Also in recent years the same techniques are applied, see next subsection.

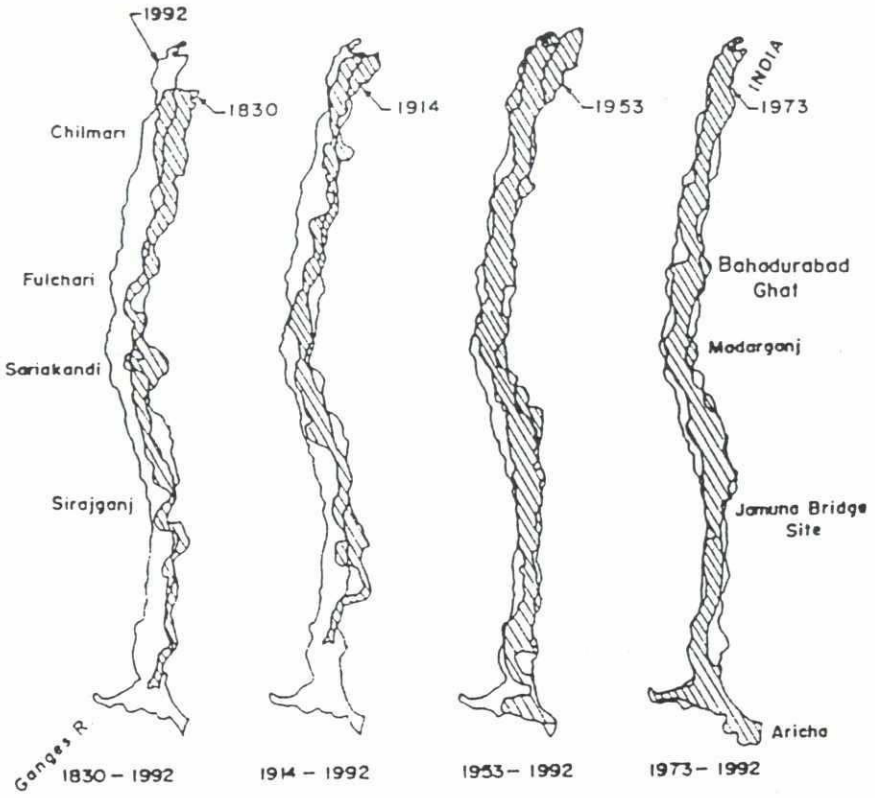


Figure 13.2 Historic bank line migration of the Jamuna River (ISPAN, 1993)

13.3.2 1990 - 1993 developments

The recent development (1990-1995) of the study reach is done on the basis of a series of satellite images over subsequent years. The series is presented in Figure 13.4. In recent studies (Klaassen and Masselink, 1992 and Mosselman et al, 1994) similar satellite imagery was used to study morphological phenomena in the same river. In principle, the same image processing was used, consisting of selection of image, geocorrecting, resampling and classification. Four classes were identified depending on the reflection characteristics, notably water (blue), sand (yellow), vegetation (green) and an intermediate class, probably wet soil with some vegetation (grey). The images included in the analysis were taken during the low flow season, because these allow the identification of the deepest and most important channels.

The relevant characteristics of the images, such as date, origin of data, water level at Bahadurabad and discharge used here are presented in Table 13.2. For some images two dates are mentioned because Bahadurabad is at the edge of two images and sometimes images from two dates were combined. It can be noted here that the planform shown in the image of one year is the result of the flood of the preceding year; for example, the image of 1993 is related to the planform development by the flood of 1992.

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

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

Table 13.2 Characteristics of the imagery used

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

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

In 1991, the confluence at the upstream end shifted in downstream direction, the medial bar near A became a left bank attached bar which forced the water to flow along the right side of the bar. Near Bahadurabad the cluster of bars moved in downstream direction. The cluster of bars at the downstream (D) location remains as it was in 1990.

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

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

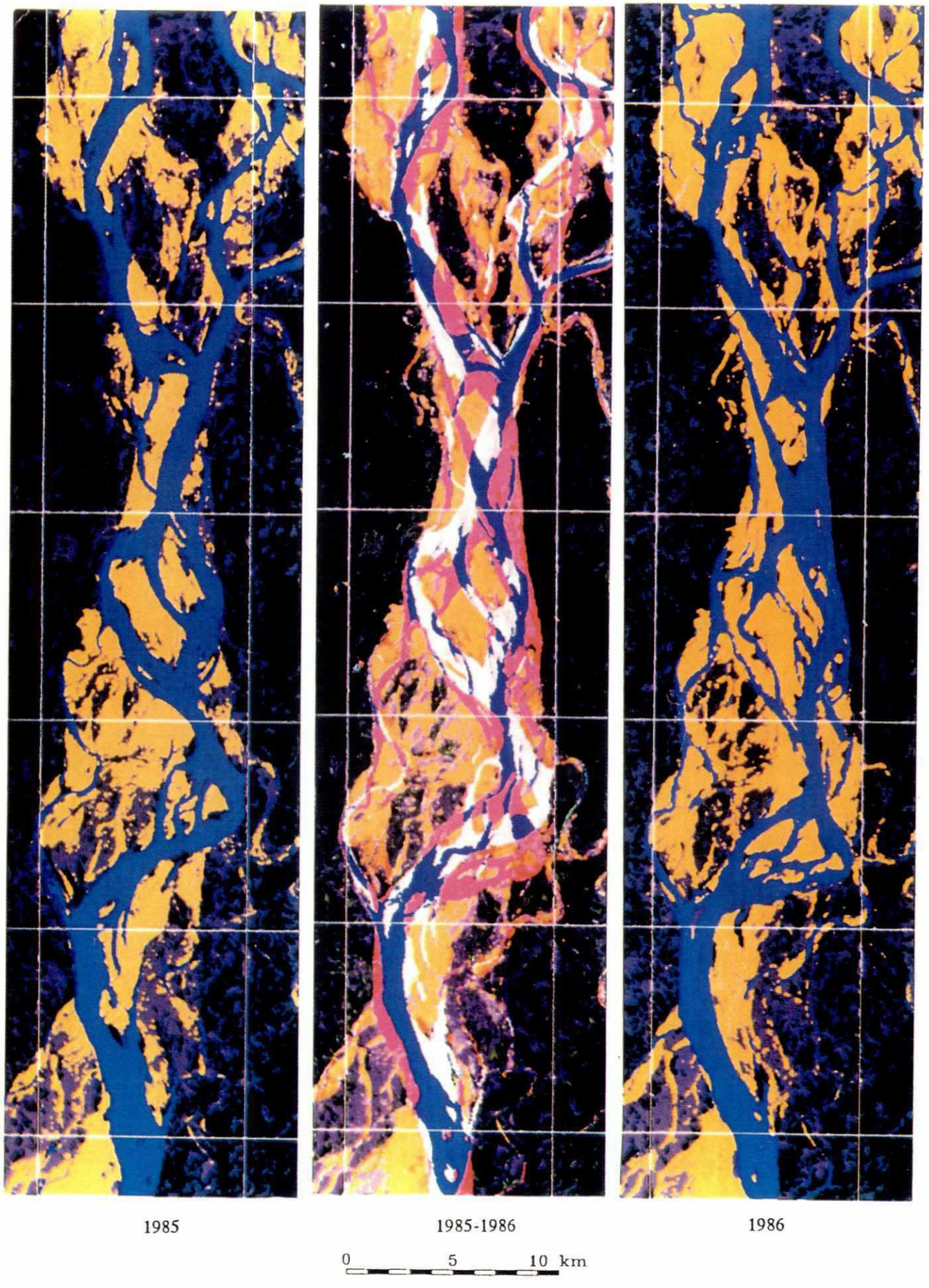


Figure 13.3 Single-year and change-detection images

13.3.3 Developments during the study period (1993 - 1995)

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

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

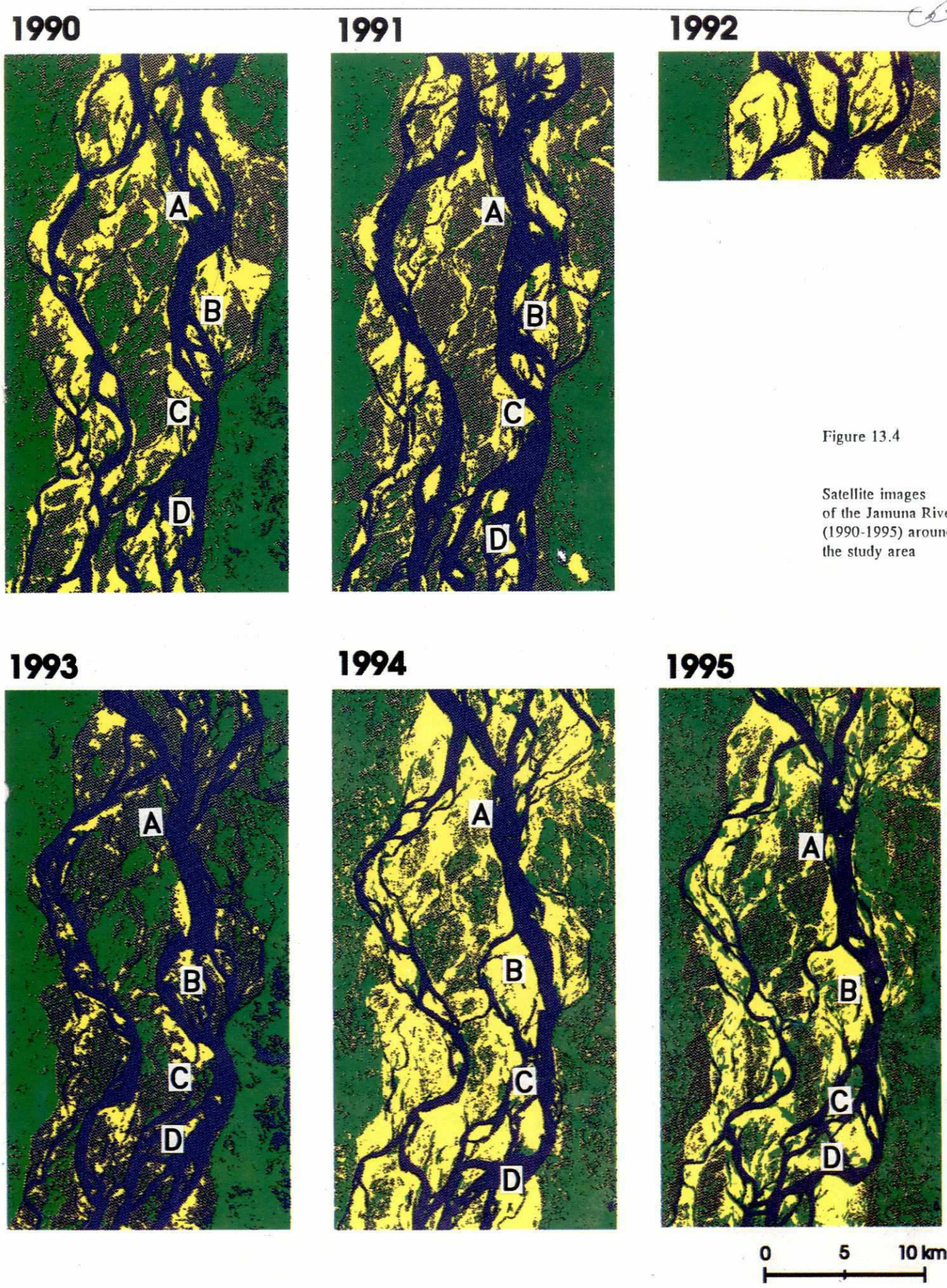


Figure 13.4

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

13.4 Recent short-term developments

Over the monsoon of 1993 three bathymetric surveys were executed by the River Survey Project in stretch of the left anabranch of the Jamuna River near Bahadurabad.

The surveys done in the beginning of the monsoon (June), just after the peak (August) and at the end of the flood season, (November) enabled to analyze in detail short-term channel and planform developments.

The bathymetric results, processed via a GIS under the EGIS project, are presented in the Figures 13.5 to 13.7.

By comparison of these figures the following changes can be observed:

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

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

The bank erosion upstream of point bar A and the changing of the direction of the deeper channel from NW-SE to almost N-S direction, probably contributed to a growing of the point bar in downstream direction. This extension of the bar increased the diversion angle of the curved channel from the upstream channel to about 90° and almost closed off the offtake of the channel. A cutoff channel developed by widening and deepening a previously shallow and narrow channel through the medial bar complexes (a dramatic event in the study period). As a result the Old Main Channel lost its importance in carrying discharges and the previous confluence scour upstream of C rotated and moved downstream while reducing its depth. The outer bend as well as the location of the bank erosion shifted more than 2 km in downstream direction. A new bar at location D became apparent. This was the bar around which special surveys were performed for the UoN/RSP joint study for, in total, three times in 1994 (see Chapter 8).

Aug.93-Nov.93
The average water level reduced about 3.7 m in the period between Aug-Nov. 1993, resulting in a less wet area shown in the bathymetric chart of Nov. 1993. The changes in this period are mainly the adjustment of the downstream channels after the development of the cutoff. The offtake of the Old Main Channel moved with an upstream reduction of the deviation angle from the upstream channel direction. The Old Main channel reduced in depth and width. The New Main Channel became wider and deeper and showed a more regular shape of the thalweg in Nov. 1993. The scour hole near Bahadurabad moved in downstream direction. The confluence of the Old and New Main channel upstream of bar C existed no

longer, although the remnant of the confluence scour hole remained visible. The size and shape of the bar C hardly changed during the period Aug.-Nov. 1993. Bar D appeared as a full grown point bar with a chute channel on the right side of the bar. Bank erosion occurred at the downstream part of the bar. The depth of the bend scour hole reduced considerably in this period, which is characterized by the recession of the flood.

The various features of the planform development during the study period are analyzed in more detail in the Chapters 5 to 10. The development of the planform near Bahadurabad as observed from the bathymetric surveys (especially in 1993 but also in the subsequent years) can be summarized as follows:

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

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

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

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

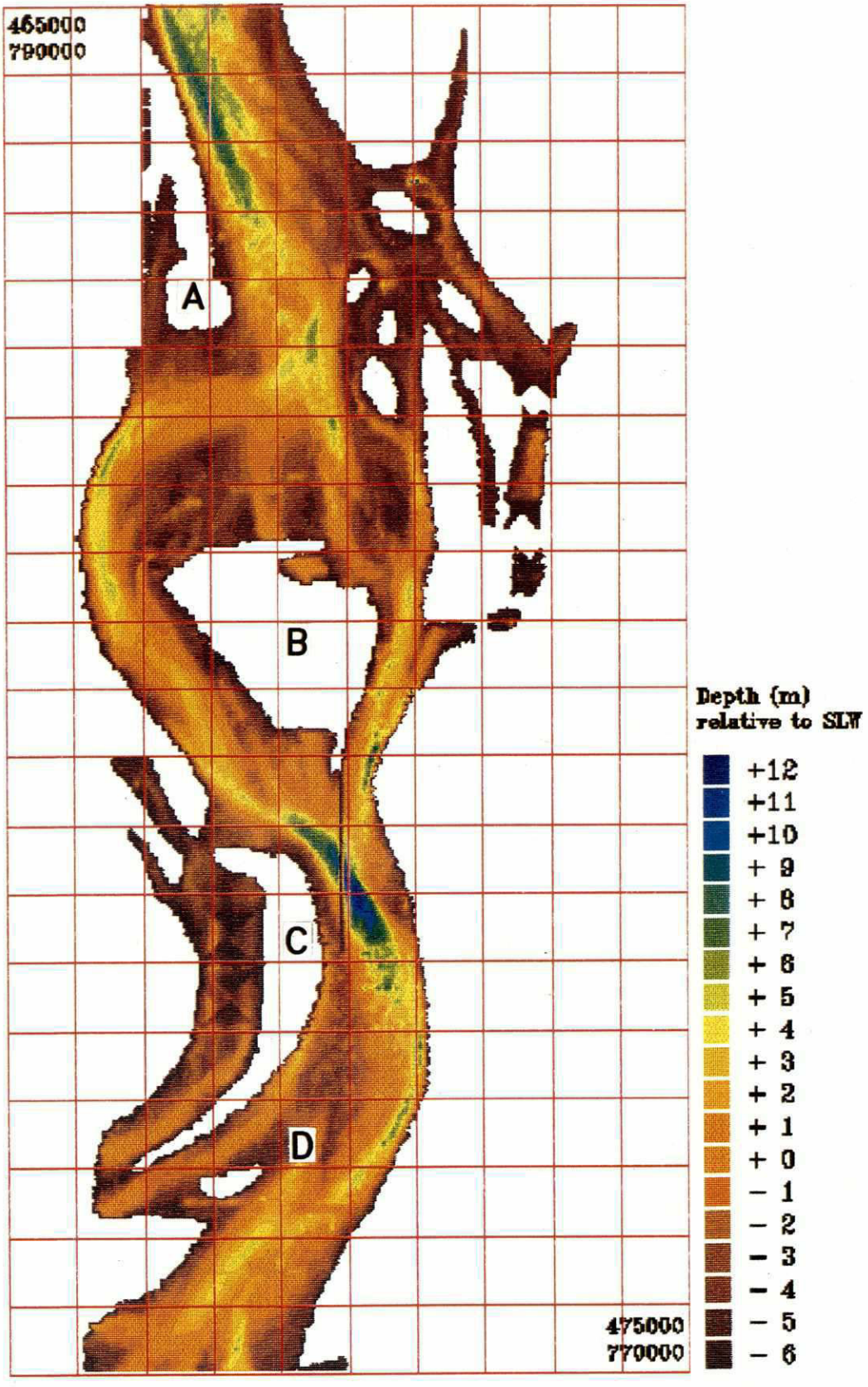


Figure 13.5 Bathymetric survey of RSP in the left channel of the Jamuna River near Bahadurabad (Jun.93)

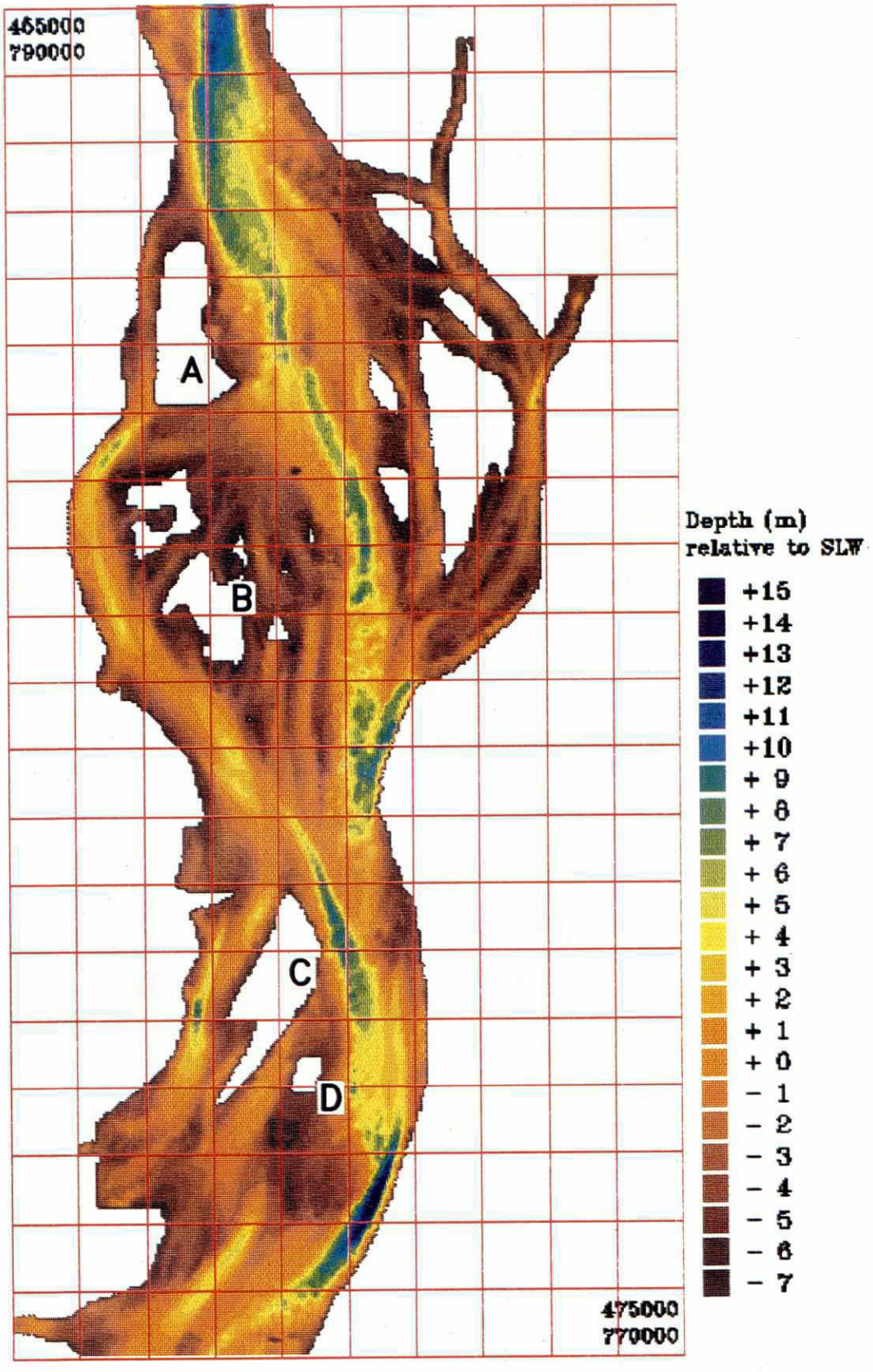


Figure 13.6 Bathymetric survey of RSP in the left channel of the Jamuna River near Bahadurabad (Aug.93)

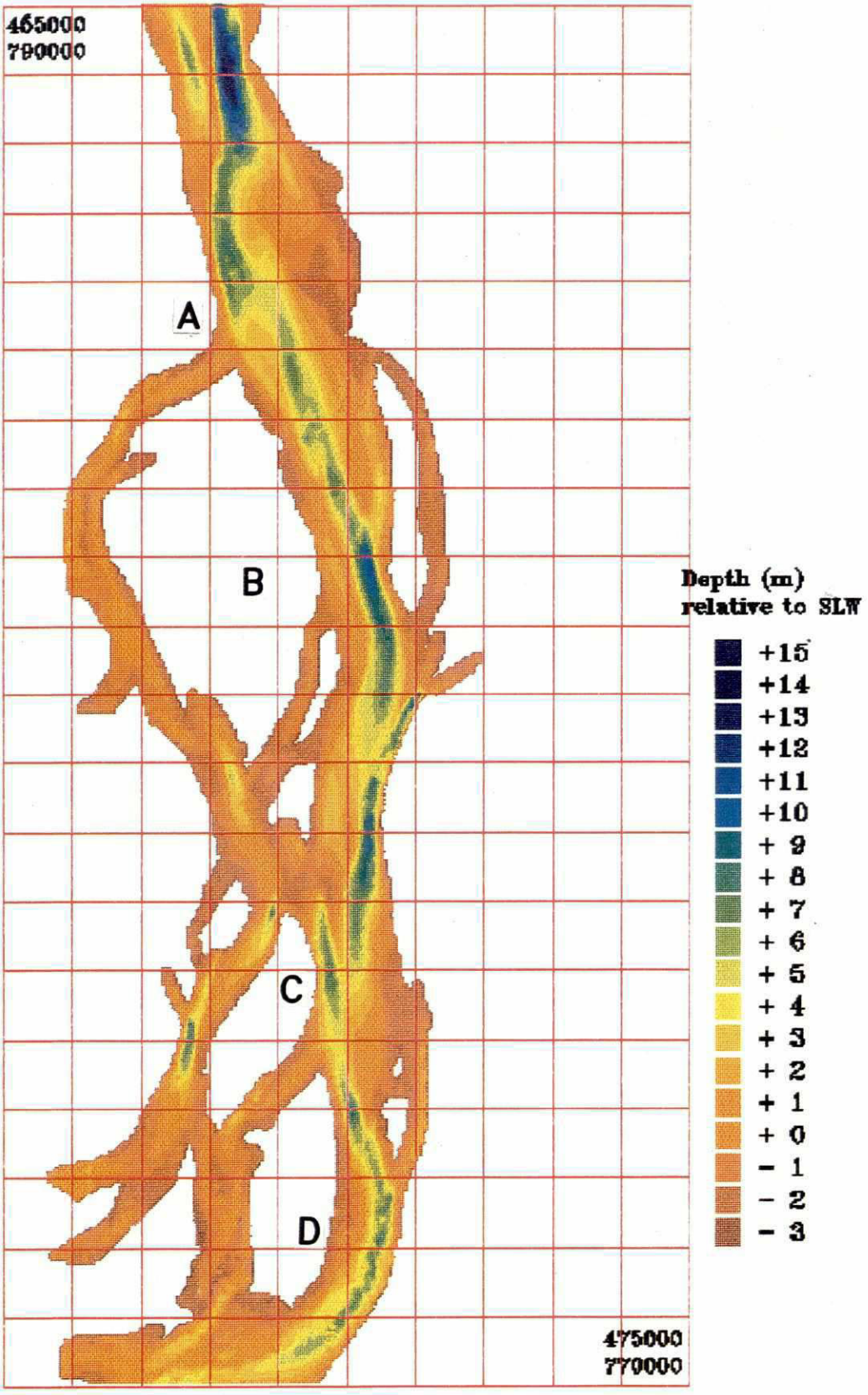


Figure 13.7 Bathymetric survey of RSP in the left channel of the Jamuna River near Bahadurabad (Nov.93)

13.5 On predictability of planforms

13.5.1 Problems of predictability

The processes in the Jamuna River are so complex, that they sometimes seem almost random. Therefore, it is important to reflect upon the predictability of these processes. The predictions are based on initial conditions, boundary conditions and the formulation of the predictive model. We discuss first how all these factors put limits to the predictability and in the next section how considerations of predictability lead to a choice of the type of model to be used.

The initial conditions are determined from observations, which usually have limited accuracy and do not provide complete information. In particular, the following problems can be mentioned:

- the resolution (pixel size) of the satellite images is on the order of 50 m;
- there are no data on the morphological changes during a flood (only the net end result can be seen on the satellite images taken in the dry season);
- cross-sections are not available for every channel;
- even when a cross-section is available for a certain channel, it is not necessarily representative because of the strong non-uniformity of the channels;
- inundated banks cannot be distinguished from eroded banks on the satellite images (hence, higher stages produce spurious bank erosion on the images).

The boundary conditions include the upstream input of water and sediment, the downstream water levels and the properties of the surrounding terrain. Here, the problems are not only related to shortcomings in observations, such as the limited information on soil inhomogeneities. Problems also arise because the boundary conditions are affected by complex dynamical systems with their own limited predictability, in particular by meteorology and geology.

The meteorological processes determine the discharges. As long-term meteorological predictions are not possible, discharges must be treated as stochastic inputs. The planform changes are very sensitive to the discharges.
Magnitude and duration of a flood determine the travel distances of wandering bars during one year, and hence whether or not such a bar arrives at a bifurcation. The arrival at a bifurcation may induce the rapid silting up of one of the bifurcated channels, which would have remained open otherwise. This represents one of the main thresholds in the system. Another influence of meteorology is that, on larger time scales, climate changes may affect the downstream boundary through sea level rise.

Bangladesh lies in one of the most active tectonic zones of the world (Coleman, 1969) and the influence of tectonics on the rivers of Bangladesh is unusually high (Baker, 1986). It is generally recognized that major avulsions are controlled by tectonic movements (e.g. Coleman, 1969), but there are indications that also the channel patterns within the present river course are influenced in this way. This might explain why channels in the river seem to have preferred courses. The influence of tectonics is currently also being studied on the basis of the satellite images.
Predictions covering a long period are also made difficult by the possible occurrence of exceptional events. A major earthquake could completely alter the present-day trends and result in a completely new orientation of the river courses (of Coleman, 1969).

Theoretically, a feasible predictive model can be derived from fundamental laws for the motion of water and sediment by a formal integration over time and space. This is not a direct integration from a small to a large scale, but a series of integration steps to ever higher levels in a cascade of scales. Due to the non-linearity of the system, each step requires the introduction of empirical closure relationships. This implies that even 'theoretical' models become to a large extent empirical, and hence inaccurate.

Another problem is that the model may be very sensitive to initial conditions, thus producing chaotic behaviour. Phillips (1992a and 1992b) discusses general arguments of why chaotic behaviour is likely to be very common in geomorphic systems. In river morphology this is still a hardly explored subject, but the sensitivity of channel abandonment to discharge as well as the non-periodicity of the meanders in the numerical simulations by Howard & Knutson (1984) and crosato (1990) do suggest chaos. Furbish (1991) explains explicitly that bend shape variations can be ascribed to the sensitive dependence of meander planforms on initial conditions and entrance conditions.

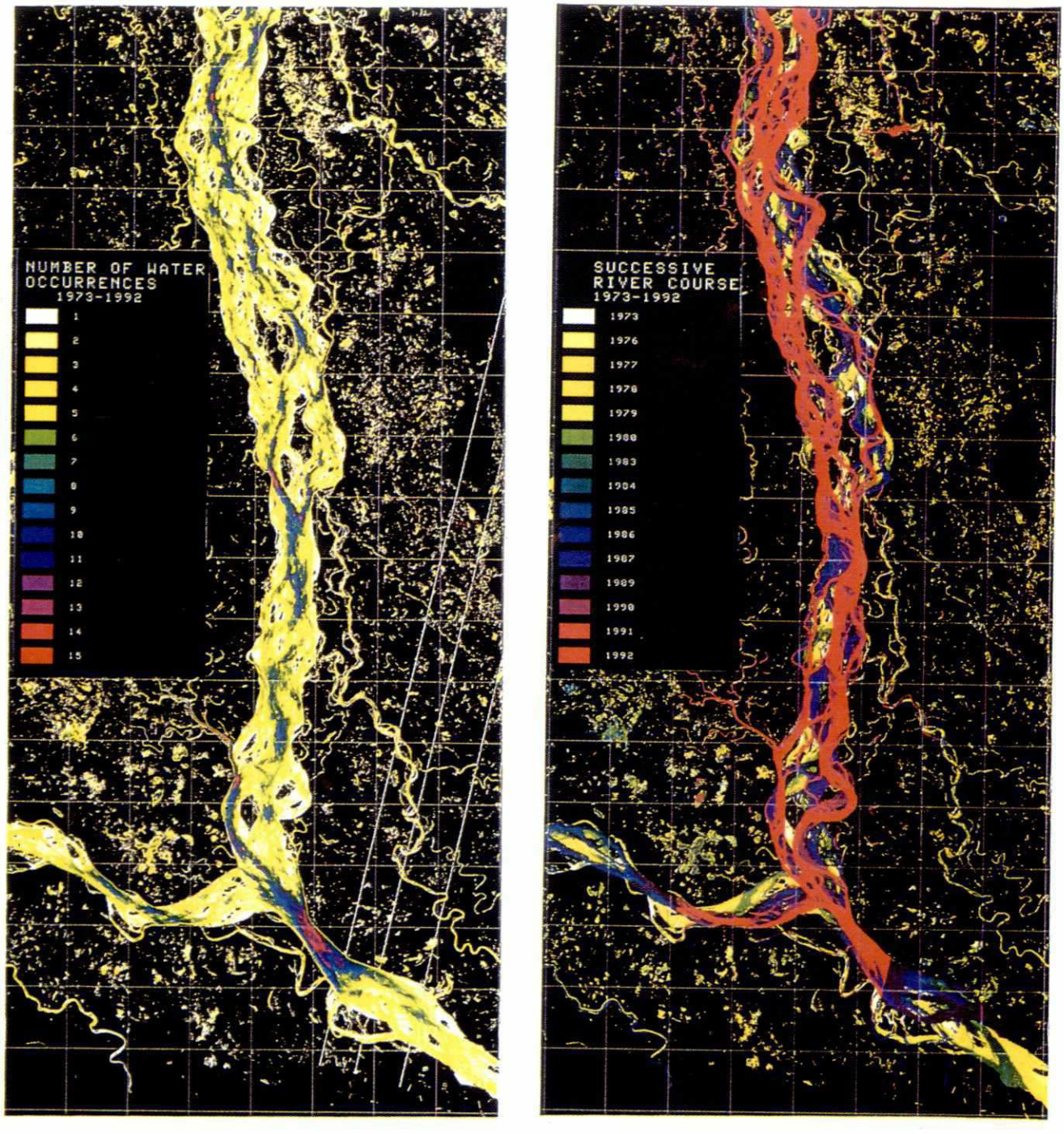
13.5.2 Deterministic, stochastic and statistical models

Considerations on predictability for the period of interest prescribe the type of model to be used. Table 13.3 gives an overview. We illustrate this by discussing models for planform changes of meandering rivers first. The boundary conditions are the discharges and the properties of the surrounding terrain. The discharge hydrograph can be more or less predictable, for instance in rivers with regular monsoon flood waves, or to a large extent irregular and unpredictable.

Planform changes are very difficult to predict if the period is short. Banks erode by mass failure during discrete events when a critical stability criterion is exceeded. This does not happen uniformly along the whole bank, but each time in small zones only, seemingly at random. This means that the surrounding terrain properties are stochastic boundary conditions and that the only modelling approach possible is a stochastic one.

For intermediate periods and relatively regular discharge hydrographs, a good prediction of river meandering is possible. The modelling can be described as deterministic. However, the sensitivity of the model to initial and boundary conditions and the possible occurrence of cut-offs make that the model should contain stochastic elements as well.

For longer periods, the question whether a certain place at a certain time is attacked is determined by the statistical distribution of water and land over a long period. Hence a statistical model can be applied, in which the spatial distribution of frequencies of water occurrence reflects patterns of soil properties, geology, terrain elevation and local human interference. This approach was used for determining the design conditions for a bridge over the Jamuna River (with an economic life time of 50 years and the river completely changing its planform in 5 to 10 years). The statistical distribution for the period 1973-1992 is shown in Figure 13.8-a, where colour intensities indicate the number of years in which locations were a part of the deep channels. Figure 13.8-b represents a superposition of the successive channel planforms from the same period.



(a)

Statistical distribution of water occurrences

(b)

Successive river courses

Figure 13.8 Multi-temporal planforms from period 1973-1992

Similar considerations hold for the choice of a model for a braided river like the Jamuna River. For intermediate simulation periods (on to three years), however, the greater complexity and the greater importance of thresholds cause the stochastic elements to be more important here than for meandering rivers.

boundary conditions	**model sensitivity to boundary conditions**	**duration of simulation period relative to characteristic time scale of morphological processes**		
		short	intermediate	long
predictable	low	deterministic	deterministic	deterministic
	high	deterministic	deterministic/ stochastic	statistical
unpredictable	low	stochastic	deterministic for time averaged	statistical
	high	stochastic	determin-istic/stochastic	statistical

Table 13.3 Selection of type of model to be used

13.5.3 Modelling concept

As the derivation of a feasible predictive model for the Jamuna River from fundamental laws would involve so many integration steps that many empirical closure relationships would have to be introduced, we believe that it is better to induce a model directly from the observations. This leads to an approach in which we (1) decompose the overall phenomena into a number of individual processes at a high level of aggregation, (2) investigate the individual processes separately, and (3) integrate the individual processes into a combined predictive tool. The high level of aggregation means the process descriptions represent the complex behaviour of large-scale river elements rather than the elementary behaviour of infinitesimal volumes of water and sediment. The individual processes at a high level of aggregation are channel migration, mid-channel bar formation, behaviour of bifurcated channels (i.e. width adjustment, channel abandonment and channel creation) and the migration of confluences and bifurcations. Some examples are shown in Figure 13.9.

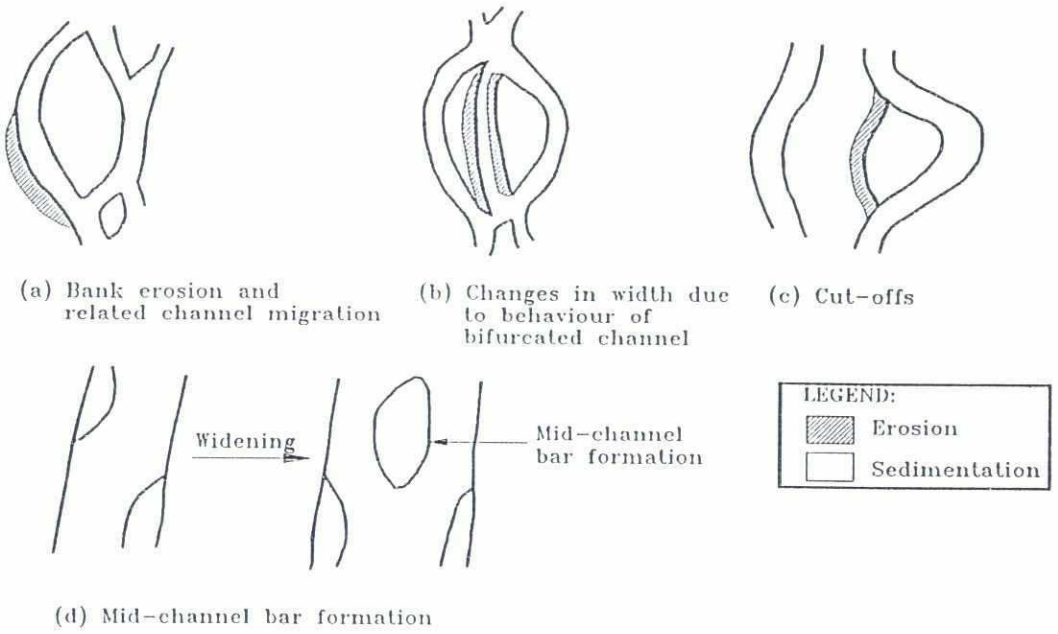


Figure 13.9 Planform changes in a braided river

This concept of modelling was also used in the River Survey Project for short-term predictions. First the predictability of some processes like erosion/deposition, cutoffs, etc. are considered which together cause the development of the planform, see next section.

13.6 Short-term prediction

13.6.1 General

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

13.6.2 Erosion and deposition

The erosion and deposition processes in the Jamuna River are discussed in Chapter 12, in relation to the flow and sedimentary processes of the river observed in the RSP data. Erosion and deposition on the riverbed can be described by the two-dimensional sediment continuity equation including changes in sediment concentration (see equation 12.3), as it was observed that the adaptation of the suspended sediment transport plays an important role in changing

the bed topography. For this type of equation the development of additional predictors for the adaptation of suspended sediment verticals for a particular river are needed, to be able to use it for modelling purposes. Besides the prediction of the river bed-level changes by modelling, simpler prediction methods can be made visual. Peters (1988) derived for the Zaire River a method for predicting the location of erosion and deposition on the riverbed on the basis of a simple graphical relation.

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

The first method on the basis of detailed information is discussed first. It was developed to predict erosion and deposition on the basis depth-averaged velocity and water depth in line with the Peters method. To predict the location of erosion and deposition on the riverbed a number of transect measurements during August 1993 survey are used for estimating the depth-averaged velocity and the water depth. During the August 1993 survey the ADCP was used for a number of river reaches and hence both parameters are available. The corresponding erosion and deposition is found by comparing the August-November 1993 surveys. The result obtained from this analysis is shown in Figure 12.8.
Instead of a linear relation between the water depth and the velocity (in conformity to Peters), for the Jamuna River the relation between the velocity and square root of the depth yields a good demarcation line between the erosion and deposition area (see Figure 13.10). It is also observed that the demarcation lines between erosion and deposition for the Zaire River are below the Jamuna River "lines" over the largest range. This is slightly amazing as the bed material of the Zaire River is coarser than the Jamuna River. The reason for this difference is discussed hereafter.

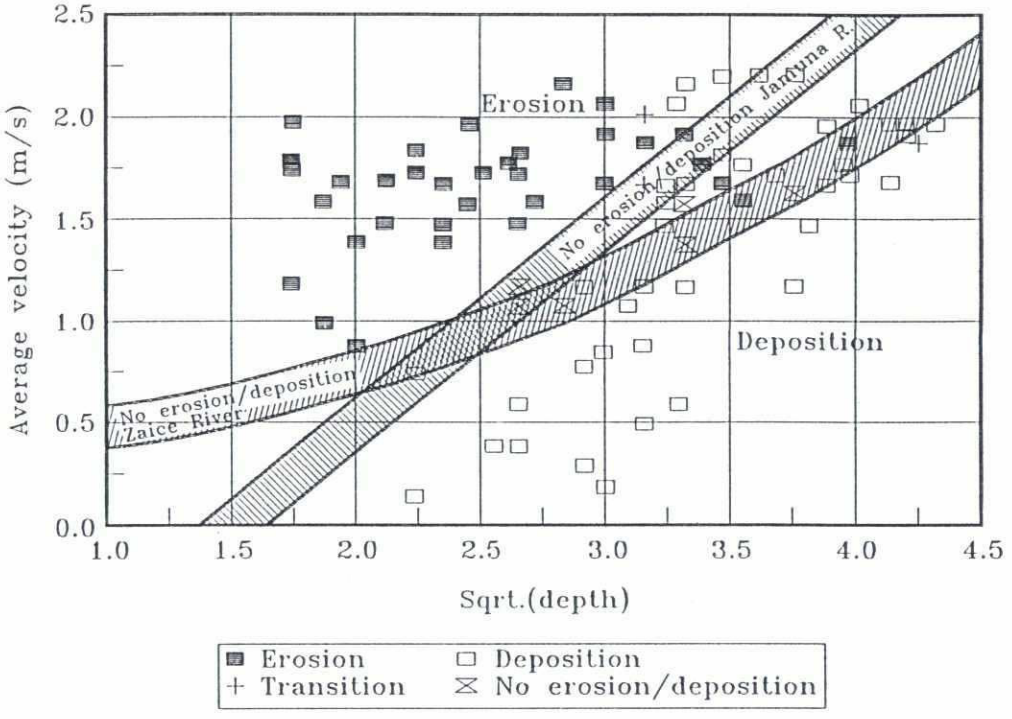


Figure 13.10 Erosion and deposition on the riverbed in relation with depth average velocity and square root of depth

The observed erosion and deposition in relation to depth and velocity is the result of a combination of different processes, and is in principle based on physical laws (Peters,1988). One probable explanation for getting this type of relation is that the involved process is an adaptation process. The bed topography (or possibly the cross-section) is lagging behind the flow pattern (see also Chapter 12). It is trying to adjust to changing conditions flow, by eroding and depositing on the riverbed. For example, the velocity measured at location "A" in August is very small compared to the water depth (see Figure 12.7). Before the August measurement the channel around area A was more active, but after the development of the cutoff the flow shifted more towards the right attacking the shallow area 'B'. Later both areas A and B react differently to the changes of the flow condition: deposition occurred in area A and erosion occurred in B. Possibly the difference of "no erosion" / "no deposition" line between the Jamuna River and Zaire river instead of reflecting the characteristics of the bed material, is rather determined by the adjustment processes of the riverbed with the flow.

The prediction method for the erosion and deposition that was derived from Figure 13.10 can be described as:

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

$$\sqrt{h} - 1.35 \le u \le \sqrt{h} - 1.65 \qquad \textit{Transition} \qquad (13.1)$$

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

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

For verifying, the above developed method data from Aug.-Nov. 1993 and July-Nov. 1995 are used.
The depth-averaged velocity obtained from ADCP and surface velocities from float tracking in Aug.93 and Jul.95 respectively and from corresponding bathymetric surveys were available in addition to water depths and areas of erosion and deposition. The results are shown in Figure 13.11 and 13.12. It is observed from the figures that the predicted transition area is comparatively covering a larger area than for the measured case. Redefining of transition for: erosion/deposition < 0.5 m rather than < 1.0 m probably can offer a better agreement between the predicted and measured transition area. There are locations where the prediction is opposite to the measured erosion/deposition and it is of interest to study these for a possible improvement of the prediction method. In both figures it is observed that the prediction method is unable to predict the shifting of scour holes (at the upstream end of the survey). It can be observed in Figures 12.10 and 12.11 that in 1993 the processes of over and underloading of sediment in this area was very high. Peters (1988) already pointed out that this type of prediction method can only be applied at areas where the actual sediment transport is near the sediment transport capacity. This implies that in addition to the velocity, sedimentary processes like overloading also have a considerable influence on the processes of erosion and deposition (as already observed in Chapter 12). Moreover, changes of flow direction can affect this prediction method as well. Nevertheless, it is observed that a good agreement exists for more than 60% for the Aug-Nov. 93 period and more than 50% for the Jul-Nov.95 period. This also indicates that the length of time over which the prediction has to be made is important. It should be noted here that the real accuracy is higher than shown in these figures and improvement can be achieved by redefining the transition for the measured case as indicated earlier. Furthermore it is noted that in principle the method can be extended to indicate also the magnitude of erosion and deposition. Finally, it is stressed that further improvements of the method can be achieved by:

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

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

The second prediction method is rather 1-D than 2-D (as the previous one is). The net erosion and net deposition in downstream direction can be related to the average velocity and average depth over the cross-section. In Figure 13.13 the average depth is estimated for one kilometre long reaches of the river and the average velocity is estimated by dividing the discharge of the channel by the average channel area of the same reach. The discharge measured in August 1993 in different channels is used in estimating the average velocity. Figure 13.13 is showing a similar type of relation of erosion and deposition as Figure 13.10 and demonstrates the potential of applying the Peters (1988) method to larger reaches as well. This type of relation can also be extended to whole branches (see Figure 13.14) and the figure shows that the relation holds also if whole branches are considered. Although this is a preliminary analysis, it nevertheless indicates that this type of relation can be developed for predicting the development of the different anabranches of the river on short-term basis.

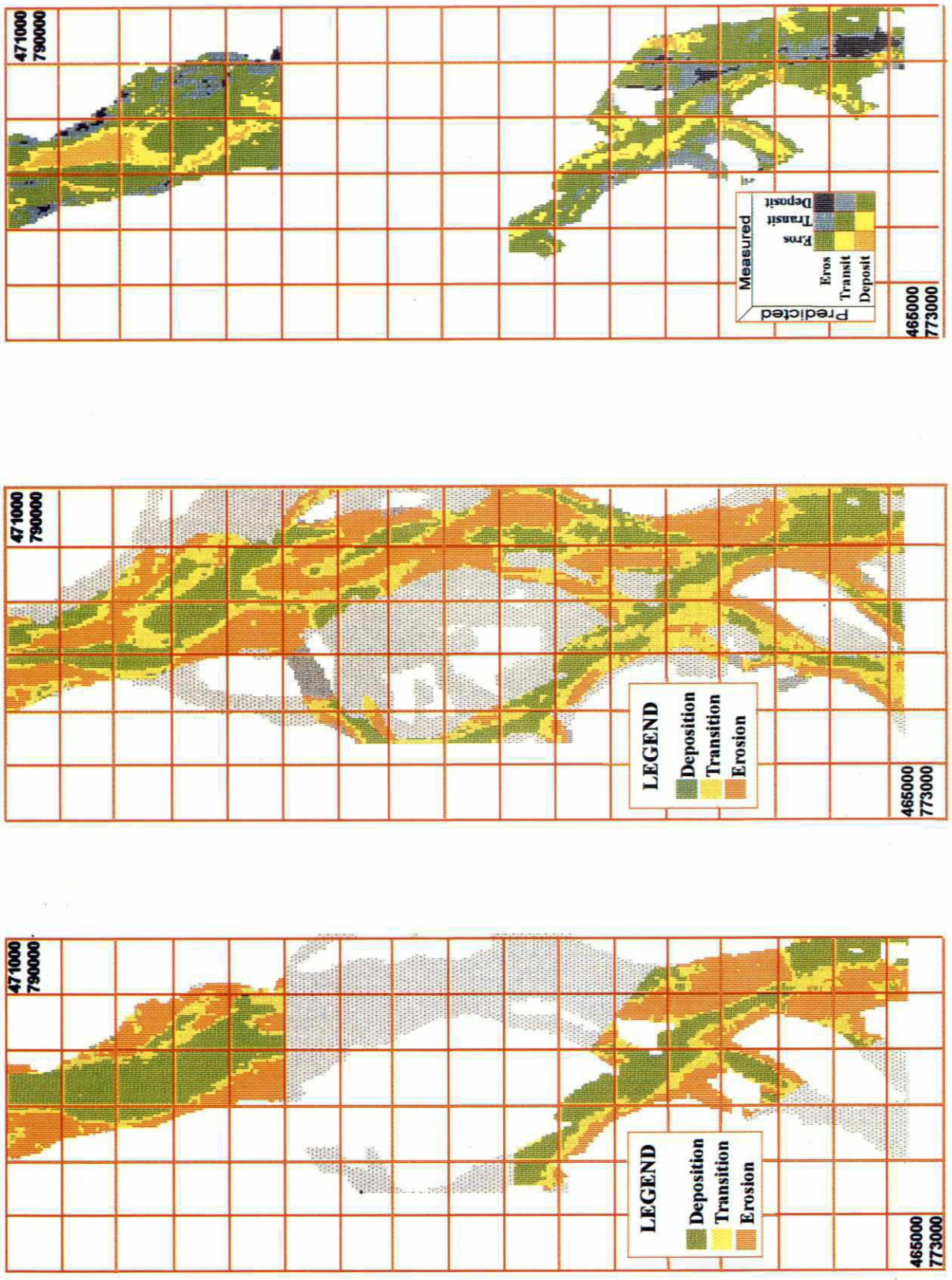


Figure 13.11 Comparison of predicted and measured erosion and deposition in the period of Aug-Nov.93

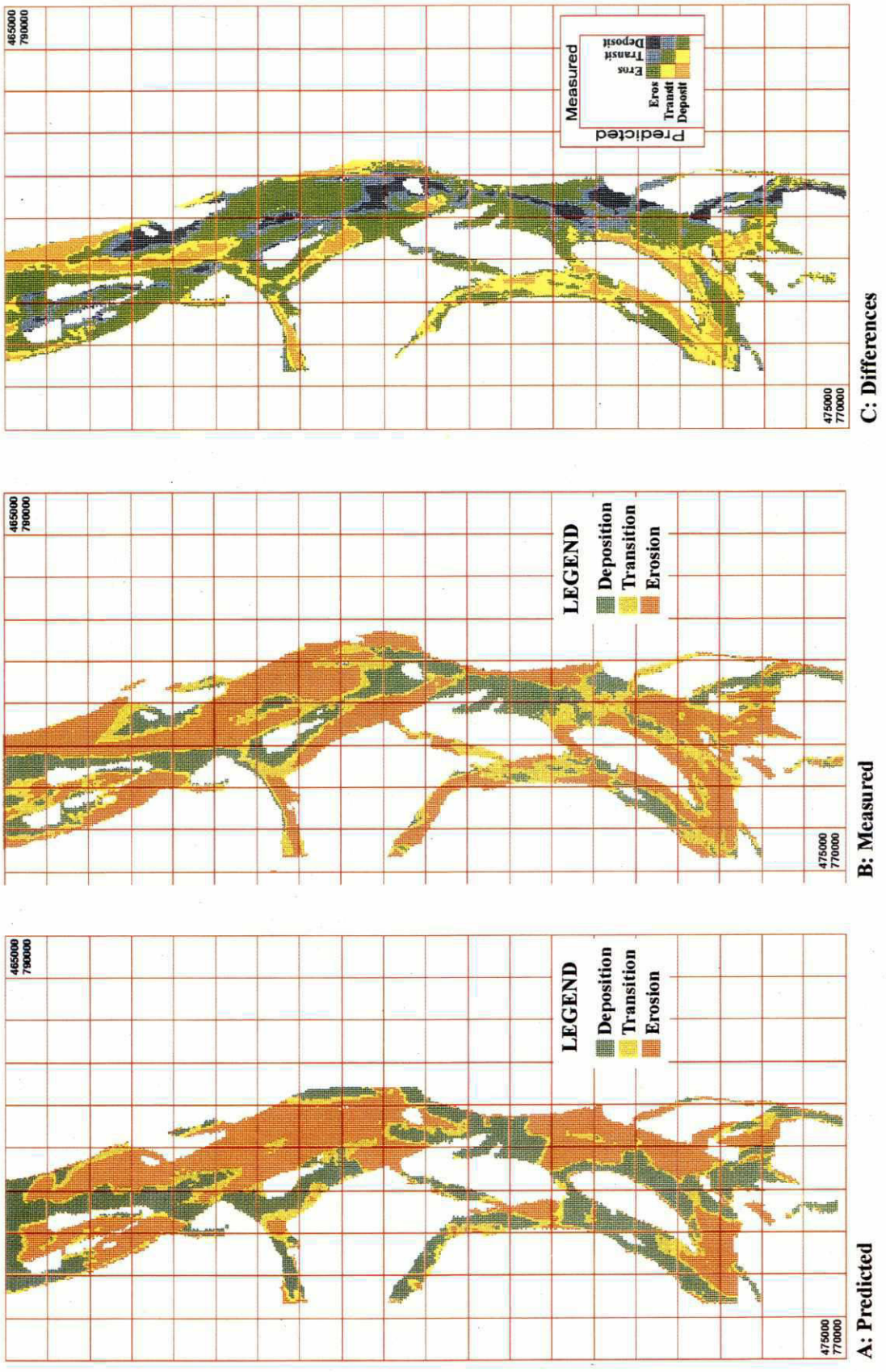
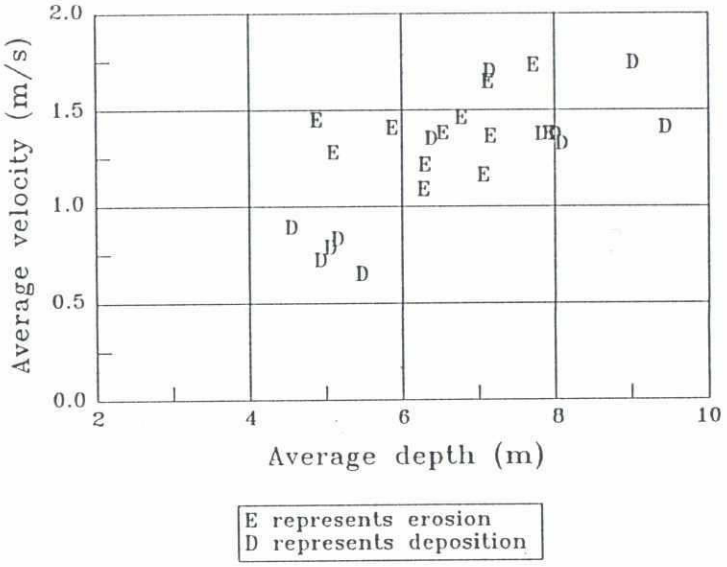


Figure 13.12 Comparison of predicted and measured erosion and deposition in the of Jul-Nov.95



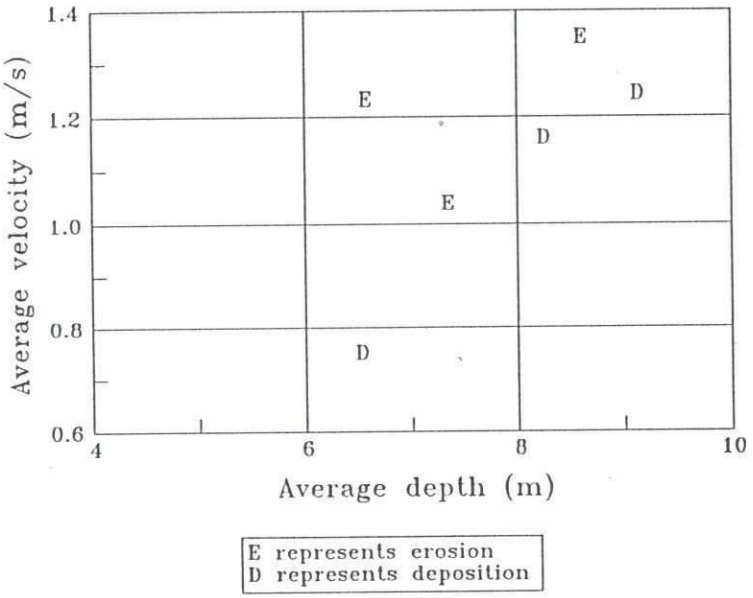


Figure 13.13 (above) Net erosion and deposition in reach of 1 km length in relation to the average depth and velocity

Figure 13.14 (below) Net erosion and deposition in different branches in relation to the average depth and velocity

13.6.3 Cutoff processes

The development of a cutoff upstream of Bahadurabad in 1993 was described in Chapter 10. The available two prediction methods for predicting the cutoff in the Jamuna River such as Klaassen and Van Zanten (1989), are here simplified to a criterion for the cutoff ratio. Klaassen and Masselink (1992), and Mosselman (1994) based on the deviation angle of the curved channel compared to the upstream channel direction. In the former prediction method the threshold value 1.25 and for the latter method the threshold value of deviation angle is 40°. During the cutoff processes in 1993, the threshold values for both predictive methods were reached. It was observed that the deviation angle varied in a wide ranges above its threshold value during the development of the cutoff processes. It appeared that Mosselman (1994) is probably a more sensitive criterion for the cutoff process and can probably better be used to make predictions.

There is much uncertainty in both methods for predicting the development of cutoff. Applying the relation shown in Figure 13.14 in association with these prediction methods can help to predict the cutoff process with better accuracy.

13.6.4 Bank erosion

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

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

13.6.5 Scour holes

Here were studied different types of scour holes as identified during the bathymetric surveys at the Bahadurabad location. The various predictors were evaluated as well and they were compared with the observed data. It was found that confluence scour can be predicted by the relation proposed by Klaassen and Vermeer (1988b). The protrusion scour depths observed at the Bahadurabad location can be predicted by a relation for abutment scour, derived by Simons and Sentürk (1977) RSP SpR24. For predicting the bend scour depth, no suitable predicting method was found. The bend scour in the Jamuna River can be estimated to be about 2.5 times of the average depth of water at the river bend. This includes a reduction of the scour depth due to the input of bank erosion products. Recent research (Shishikura, 1996) has demonstrated that the scour depth may increase considerably when bank protection works are constructed (in conformity with the experiments of Mesbahi (1992) and recent field observations by RRI et al, (1993).

13.6.6 Overall channel development

Overall planform development is related to the changes of the different morphological features discussed above. The predictability of the planform development also depends on the availability of reliable prediction methods for predicting the various morphological features of the river. Prediction methods can be differentiated to their time scale: how far ahead a method can predict changes with a certain accuracy. Accordingly, the methods can be identified as short-term, medium-term and long-term prediction methods, see Figure 13.15. Understanding of a river is a prerequisite for every type of prediction methods. For planform development a probabilistic medium-term prediction method was developed by Klaassen et al (1993) for the Jamuna River. The prediction method is based on integrating the different prediction methods for various components of the river planform, such as channel dimensions, bank erosion rate, cutoff development etc. The results of the present study can contribute to improving a few of the components of planform model. The short-term prediction method (Equation 13. 1) for the erosion/deposition on the riverbed can provide a fair idea about the lateral shifting of the channels. Probably the channel development in the lean season by retarded scour can also be predicted by this method. For the development or abandonment of a channel the relation shown in Figure 13.14 may be attractive to be included.

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

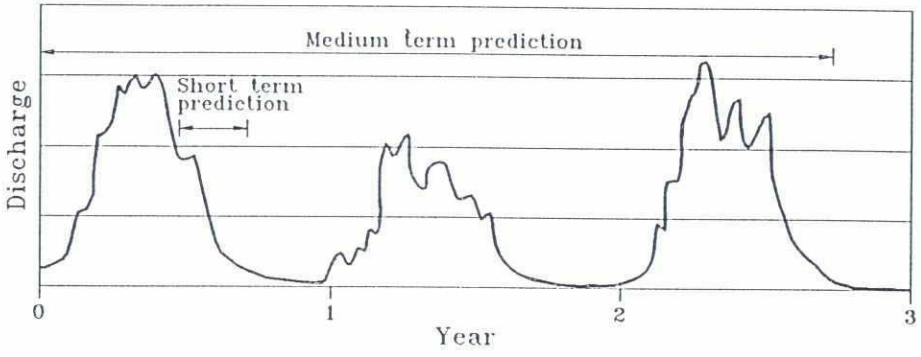


Figure 13.15 Different types of prediction methods

13.6.7 Discussion on prediction methods

One of the aims of the RSP study was to derive improved prediction methods for predicting bed topography changes and changes in the planform of the river. Based on the Peters (1988) method derived for the Zaire River, a prediction method for the changes of the riverbed was derived and verified for the Jamuna River. Via a simple relation involving local water depth and local depth-averaged velocity, it is possible to predict with fair accuracy the location of erosion and deposition on the riverbed during the recession of a flood. The dividing lines used for differentiating zones of erosion and deposition were selected on the basis of first estimates (see Figure 13.10). By trial and error, the method can be improved by changing the slope of the lines or by slightly shifting the lines. In this respect, the use of GIS can be very helpful. In some areas, especially at the upstream part of the bathymetric surveys in Aug.93, this method is unable to predict the shifting of scour holes, see Figure 13.11. It is noticed that this area was highly active with major sediment overloading and underloading. This supports the Peters (1988) observation in the Zaire River that this type of prediction method only yields good results when the sediment transport is not deviating too much from the sediment transport capacity. This also implies that, in addition to the water depth and depth-averaged velocity, inclusion of sediment transport process can improve the prediction method. On a routine basis, sediment concentration can be measured by ADCP. From the verification of the method, it is observed that the shorter the time over which the prediction is made the better prediction is. One of the limitation of this method in its present state is that only a qualitative changes of bed level can be estimated by this method, it is not possible to get a quantitative estimation from this method. It seems, however, possible to include in the method velocity gradients and this may enable more quantitative predictions.

By using a similar type of relation it is probably possible to predict the aggradation or degradation of different branches or anabranches of the river (Figure 13.15), although this type of prediction still needs formal verification, such a prediction method can help in improving the prediction method for the changes of planform. Especially for predicting the channel development or abandonment, the uncertainty inherent in prediction methods like Klaassen and Masselink (1992) and Mosselman (1994) are quite large (see Chapter 10). Applying the method as indicated in Figure 13.15 simultaneously with the above methods, it might be possible to predict the changes of planform with improved accuracy.

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

14 Proposed further studies

This Annex has presented an overview of studies carried out under the River Survey Project (FAP 24) in the field on morphological processes in the main rivers of Bangladesh. At the same time it provided a state-of-the-art of the understanding of morphological processes particularly in large alluvial rivers.

The project could only spent limited efforts however in analysing and interpreting all collected data, while a number of studies which were initially identified (see Study Report 1), could not be initiated due to the limited human resources available for the study component of the project. As a consequence many aspects of morphology of these large rivers could not or only marginally be studied. This has led to a long list of possible study topics, that potentially could be taken up in the near or further future.

It is appropriate to list the most important topics for further study at the end of this Annex. It is hoped that as part of further studies into the behaviour of the large alluvial rivers in Bangladesh these topics will be tackled. This could be as part of forthcoming projects or by a special study unit, or in either M.Sc. or Ph.D. studies of Bangladeshi students at BUET or students from abroad. For these studies the HYMOS and the PSD24 data bases are available. These will be of great help for any further studies. In addition data bases are available that could be of additional assistance, e.g. the River Morphology and Resource Information System that is presently under development within the frame-work of the EGIS project.

The morphological studies to be done in future can roughly be divided into:

- *additional measurements* aiming at completing the data base on the main rivers in Bangladesh;
- *special studies* aiming at improving the understanding of the river behaviour, using this data base and doing special studies.

Hereafter a short summary of each of the study topics proposed will be given, and for each a very short indication of topic, approach, data to be used, and results to be expected.

Additional measurements

For the time being there is hardly any for additional regular measurements. Special surveys are envisaged as part of various study topics. Only two proposals are made for data collection on a more routine basis:

(1) *Water and sediment distribution at offtakes*

In view of the importance of the offtakes for the interior of Bangladesh it is proposed to collect on a routine basis the water and sediment transport distribution at three of the four important offtakes (Old Brahmaputra, Dhaleswari and Gorai). These measurements should be done on a regular basis (weekly?) during the flood season. In view of its importance the Gorai to be measured yearly together with the sediment transport in the Ganges upstream of the offtake. For the Old Brahmaputra and the Dhaleswari is may suffice to rotate, hence concentrate on the Old Brahmaputra one year and on the Dhaleswari the next year. A plan for these measurments has to be developed, comprising in which branch of the parent river and where in the distributary has to be measured, etcetera. Satellite imagery to be used during the interpretation of the results.

Topic		Proposed studies	Ranking
Additional measure-ments	On regular basis	• Water and sediment distribution at offtakes	1
		• Scour holes	1
	Once	Various study surveys	-
Special studies	Slopes, planform and cross-sections	• Width and width adjustmnent of channels	2
		• Pointbar accretion due to bank erosion	3
		• At-a-station-relations	3
		• Meander dimensions and braiding indices	2
		• Integrated morphodynamic frame-work	2
	Offtakes	• Historical development of offtakes	1
		• Water- and sediment distribution at offtakes	1
		• Modelling of offtakes (1-d, 2-d)	1
		• Future development of offtakes	1
	Confluences	None?	-
	Bars and bifurcations	• Dimensions of bars (length, width, height)	3
		• Development of bars in time	3
		• Flow around bars and growth of bars	3
		• Water- and sediment distribution at bifurcations	2
	Scour holes	• Natural scour: types, occurrence of natural scour, depths of scour, combination of scour types	1
		• Scour near bank-protection works (Jamuna Bridge, etc.)	1
		• Wandering scour holes	2
	Bank erosion and cut-offs	• Bank erosion concepts	1
		• Development of new channels	2
		• Study of major planform changes like cutoffs and abandonment of channels	3
		• Infilling of old channels and oxbow lakes	3
	Flow pattern and maximum velocities	• Maximum flow velocities (probability of occurrence)	2
		• Location and moment of occurrence of maximum flow velocities	2
	Exchange of sediments	• Exchange of sediments (sand and silt) between main rivers and floodplain	2
		• Scour and fill in the main rivers	2
	Channel form changes and planform develop-ment	• Meandering of Dhaleswari River and other distributaries	2
		• Occurrence of hard points	2
		• Effect of neotectonics on planform	2
		• Importance of deep scour holes for planform development	2
	Prediction methods	• Prediction short-term planform changes (quick assessment)	1
		• Prediction short-term planform changes (using 2-d morphological models)	1
		• Prediction medium term bed topography changes	2
		• Probabilistic approach to mid-term planform prediction	1
	Morphological impact assessment	• Response Old Brahmaputra and Upper Meghna morphology to historical changes in flow	2
		• Impact assessment implementation FAP/NWMP implementation (including planform changes and future offtake behaviour)	2

Legend ranking:
1 = Immediately to be taken up;
2 = To be taken up in a few years (by Special Study Unit);
3 = In due time, e.g. via collaboration with Universities and institutes

Table 14.1 Proposed study topics on river morphological characteristics

(2) *Scour holes*

Near bank protection works, around bridge piers and along guide bunds scour hole depths should be measured (and probably are). This should be done on a yearly basis during the flood season including the rise and fall. Probably these data are collected for a number of structures, but they are not stored centrally. It is proposed to make an inventory of any measurements carried out, to develop a programme for future measurements and to create a data base. This data base should include satellite imagery for interpretation as scour holes near river training/defence structures are in Bangladesh very much linked to the planform of the river.

Special studies

The following special studies are proposed (see also Table 11.3, where the different proposals are grouped according to the topic they address):

(1 *Width and width adjustments of channels*

Collection of data on variation of channels in the main rivers (RSP data) and the distributaries. Study of variation over time, as a function of the water and sediment supply to the channel. Aiming at increasing insight and deriving of relations (initially empirical) for width adjustment.

(2) *Bank erosion and point bar accretion*

Study of the balance between bank erosion and point bar accretion. Very relevant for design of bank protection works. During a flood the bank erosion is measured in response to a flood and the response of the accreting bank.

(3) *At-a-station relations*

At-a-station-relations are very useful relations, as shown e.g. in Chapter 4 of Annex 4. Proposed study should in detail determine the width and the average depth versus the discharge for a number of cross-sections in straight and curved reaches to better understand these relations. Also the scatter should be explained in terms of cross-sectional variation in relation to (1) the planform of the river and (2) abandonment and development of channels.

(4) *Meander dimensions and braiding characteristics*

Inventory of meander characteristics (meander lenght, amplitude, curvatures, etc.) of main rivers and distributaries. Determine critical cutoff ratios from satellite imagery. Similar study for the braiding characteristics of the Brahmaputra/Jamuna and where relevant the Ganges and Padma River. Comparison with theoretical predictors and, if not satisfactory, derivation of empirical predictors.

(5) *Computational frame-work for river morphodynamics*

Extend the computational framework used in FAP 21/22 (see Annexure 1 of Study Report no. 1) using (1) RSP results, (2) results of some of the special studies proposed here and (3) developments elsewhere, to arrive at an integrated computational frame-work for river morphodynamics, allowing e.g. the morphological impact assessment of FAP/NWMP implementation. See also (31).

(6) *Historical development of offtakes*
Study using available data (maps, cross-sectional soundings, satellite imagery, routine gauging, RSP results and any other, if relevant) together with geomorphological analyses on offtake behaviour to assess in an integated way the historical changes of the different offtakes and to identify the possible cause of changes in offtake performance.

(7) *Water and sediment distribution at offtakes*
Field study of the water and sediment distribution at offtakes, in particular during the flood season and the subsequent fall. Concentrating on relative sediment intake. Interpretation in relation to the planform of the parent river, in particular the offtake angle and the presence of bars, and the water level differences between parent river and distributary. Interpretation using a.o. existing knowledge on bifurcations and mathematical models, see (8).

(8) *Modelling of offtakes (1-d, 2-d)*
Mathematical modelling of offtake performance, using morphological models. Purpose is identification of relevant factors for the historical development as identified under (6).

(9) *Future development of offtakes*
Based on the results of the studies under (6), (7) and (8), development of possible scenarios for the future performance of the different offtakes along the different main rivers.

(10) *Dimensions of bars (length, width, height)*
Inventory of bar dimensions from satellite imagery and bathymetric maps (RSP and BIWTA). Determination of lenght, width and height. Comparison with theoretical predictors and, if required, development of emperical ones.

(11) *Development of bars in time*
Study into initiation and movement of bars and bar complexes. Purpose is to identify the persistence of bars – either attached bars or mid-channel bars – and to study their changes over time. Also the celerity of bars should be determined, and be linked to the discharge hydrograph. The location of bank erosion of permanent bars and of floodplain land should be studied as well. Use can be made of the series of yearly satellite images available. If appropriate also 2-D morphlogical models could be used.

(12) *Flow around bars and growth of bars*
Continuation of the work carried out by the University of Leeds via special surveys and interpretation. Should result in improved insight into factors determining emergence and growth of mid-channel bars. This study should be done mainly using special surveys. Integration of surveys could be considered.

(13) *Water- and sediment distribution at bifurcations*
The water and sediment distribution at bifurcations is a key factor in the further development or the abandonment of anabranches. As the latter phenomena have been linked to a.o. the approach angle, it is of interest to measure these distributions for specific bifurcations and to interpret them in terms of this and other variables (upstream sediment distribution, overloading, etcetera).

(14) *Natural scour: types, occurrence of natural scour, depths of scour, combination of scour types*

In the main rivers of Bangladesh different types of scour have been observed: ebns scour, confluence scour, (natural) constriction scour, and protrusion scour. For each prediction methods have been proposed, but these have to be verified, and if appropriate to be improved. In particular prediction methods of scour depth in case of combinations of different types of scour still have to be developed further. This can be done by a combination of field measurements and 2-d morphological modelling. In addition the development in time of scour holes should be studied, both in the field and in mathematical models.

(15) *Scour near bank-protection works (Jamuna Bridge, etc.)*

Increasingly bank protections are being built along hte main rivers in Bangladesh. Repeated measurements should be done at locations where heavy attack is occurring to determine the related local scour. This should be tested against predicted local scour during the design. For the interpretation also satellite imagery may be needed to identify the overall flow field on the basis of the observed bed topography.

(16) *Wandering scour holes*

In the analysis of the Bhadurabad scour holes some "wandering" scour holes were identified. These may have a significant influence. Based on an analysis of their occurrence, possible locations should be identified. Repeated bathymetric surveys can be used to follow the development of such scour holes in time. Interpretation in combination with mathematical models.

(17) *Bank erosion concepts*

Study into most applicable bank erosion concepts. To be done via field surveys of bank erosion, including near-bank velocity measurements and measurement of other channel and bank features. Comparison of results with different concepts proposed. Also detailed measurements of bank line changes in time and study of failure mechanism.

(18) *Development of new channels*

An important phenomenon in planform development is the occurrrence of new channels. Regarding this phenomenon a number of questions have to be solved: to what extent are old abandonned revived, how quickly are these channels eroded and what is the type of bed material in which this erosion is taking place. To be tackled via field measurements and mathematical modelling.

(19) *Study of major planform changes like cutoffs and abandonment of channels*

In the RSP to start repeated bathymetric soundings at the Bahadurabad site in 1993 turned out to be a very lucky choice in view of the cutoff which materialized in the year. This allowed to increase the understanding of causes, development in time and effects of cutoffs considerably. Repeated soundings at other locations where major planform changes are expected, may yield comparable increased insight. Interpretation in combination with mathematical models.

(20) *Infilling of oxbow lakes and old channels* ,
The Jamuna River tends to return to old channels. Therefore relevant to get insight into the infilling rate of these old channels and lakes. This can be done via field surveys in combination with satellite imagery (for dating of abandonment). Results can be used in assessments of future planform behaviour. Also the type of material depositing in these old channels is relevant for making balances to determine temporal storage of transported sediments.

(21) *Maximum flow velocities (probability of occurrence)*
Inventory of maximum velocities during several stages of a number of floods. Maximum velocities at both "natural" locations (bends, protrusions) and near revetments and groynes. To be interpreted a.o. in terms of amplification factors and probability of occurrence. Important for design of bank protection.

(22) *Location and moment of occurrence of maximum flow velocities*
Measurements and interpretation of maximum velocities in terms of typical planforms and bed topographies. Study whether maximum velocities occur during maximum discharges, or whether more serious design conditions occur at lower (e.g. during near-bankfull stages).

(23) *Exchange of sediments (sand and silt) between floodplain and main river*
Extension of the studies under FAP1 (Throne et al, 1993) by combining data on composition of river bed, chars and floodplains with bank erosion and char erosion data. Interpretation together with analyses under topic (12) *Overall floodplain sedimentation* mentioned in Section A4.4. Study would integrate several other studies mentioned under Section A4.4 with bank and char ersion studies using satellite imagery.

(24) *Scour and fill in the main rivers*
Continuation of the studies in scour and fill in the main rivers (see Section 7.3 and Chapter 12) to get an insight into the variability of sediment transport in space and time and into time-dependent development of scour holes. Input repeated bathymetric sampling like used in the present study for Bahadurabad. Integration of results using 2-D morphological models.

(25) *Meandering of Dhaleswari River and other distributaries*
Analysis using satellite imagery of meandering of the different distributaries. Use of meander models to verify bank erosion concepts (see topic (17)) and for making predictions of future planform behaviour.

(26) *Occurrence of hard points*
Identification of possible hard points in the various main rivers and distributaries via the combination of satellite imagery and possibly maps, which allows to identify areas which have not been subject to bank erosion. This study to be carried out in combination with the proposed topic (4) *Composition of the subsoils of the rivers* mentioned in Section A4.1.

(27) *Effect of neotectonics on planform*
As possibly the planform characteristics of some of the main rivers may be affected by neotectonics (e.g. active faults) a further study of this is needed. This study should be based on further analysis of satellite imagery to identify e.g. faults. In addition an assessment study should be done regarding the sensitivity of the planform of these major rivers for neotectonics.

(28) *Importance of deep scour holes for planform development*

There appears to be a tendency for new channels in the braided Jamuna River to be directed at deep scour holes. This would explain the overall planform stability with nodes and permanent chars as observed by Coleman (1969) and Thorne et al (1993). The study should start with an analysis of satellite imagery into the formation of new channels.

(29) *Prediction short-term planform changes (quick assessment)*

There is a need for a quick assessment method to be used during the flood to predict changes that will take place during the fall. Promising attempts have been made on the basis of ADCP measurements (see e.g. Chapter 13), and there is a need for further testing and inclusion of additional parameters like slope.

(30) *Prediction short-term planform changes (using 2-d morphological models)*

Predictions of the bed topography after the next flood can be made using the bed topography measured in the beginning of the dry season. For this purpose 2-D morphological models can be used. Improvements of model performance should be based on a comparison of simulations with the models with developments in prototype, and possibly testing of the different modules to identify possibilities for improvement of the models.

(31) *Prediction medium term bed topography changes*

Medium term predictions can be done with 2-D morphological models as well, but then applied over a number of flood seasons. Also this can be done with 2-d morphological models, but the model should be run for different scenarios regarding the hydrographs in the successive years. The results to be considered and interpreted as increasingly stochastic when the simulation periods is extended.

(32) *Probabilistic approach to mid-term planform prediction*

The understanding of causes, effects and magnitude of bank erosion in braided rivers is still fairly limited. In line with existing planform models for meandering rivers, there is a need for the prediction of planform changes of braided rivers. This should be done along the lines indicated by Klaassen et al (1993), hence a probabilistic approach. Such a model will be exremely usefull in the planning of bank protection works.

(33) *Response of Old Brahmaputra and Upper Meghna morphology to historical changes in flow*

After the avulsion of the Brahmaputra to its present Jamuna course, the Old Brahmaputra and the Upper Meghna have started to adapt to the new imposed discharges and sediment loads. An impact study on the basis of historical data may yield quite interesting results which can be used in future morphological impact studies. Use can be made of (old) maps, satellite imagery, historical data in combination with mathematical models for testing of assumptions on river adjustment.

(34) *Morphological impact assessment FAP/NWMP implementation (including planform changes and future offtake behaviour)*

Extension of morphological impact assessment carried out under the RSP project and study (14) proposed in Section A4.4, but now extended to include changes in braiding and/or meandering pattern and in cross-sections. Also offtakes should be included, including their future performance as well. The latter implies that also here a stochastic approach has to be used, as different assumptions as to the development in time of the offtakes have to be included. This study will built upon many results obtained in special studies proposed above, but in particular on the topics (5) *Computational frame-work for river morphodynamics* and (9) *Future development of offtakes*, and preferably the results from (32) *Response of Old Brahmaputra and Upper Meghna morphology to historical changes in flow* as well.

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