FAP24

Government of the People's Republic of Bangladesh

Water Resources Planning Organization

European Commission

Delft Hydraulics

Danish Hydraulic Institute

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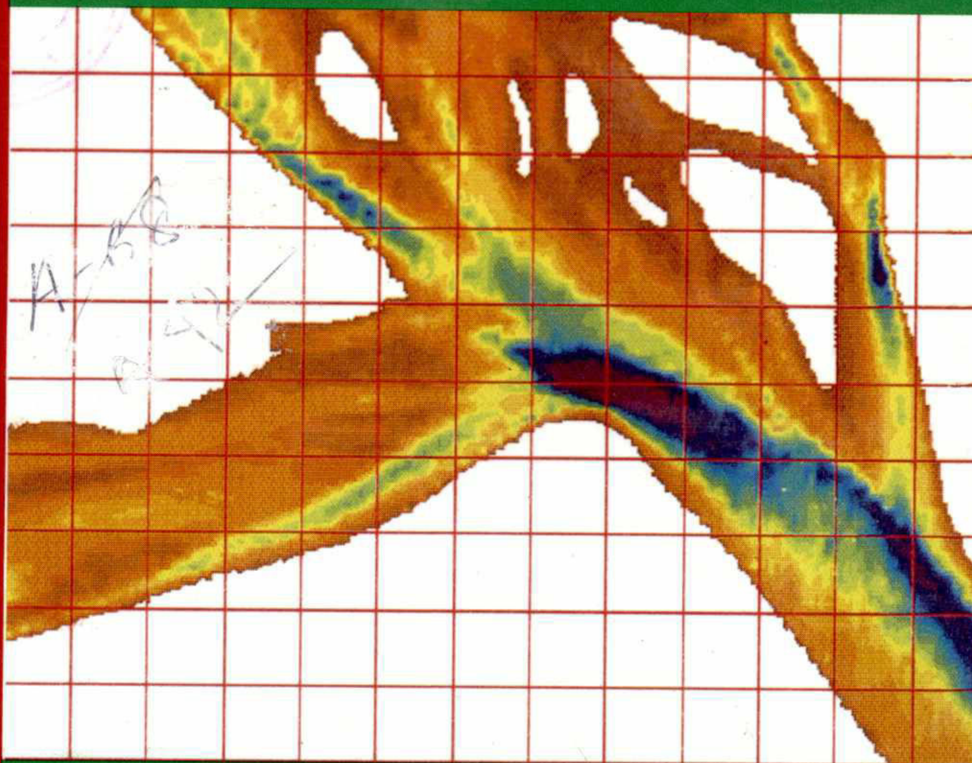
RIVER SURVEY PROJECT



Final Report – Annex 4

Sedimentology

November 1996

2

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Final Report Annex 4

Sedimentological Characteristics of the Main Rivers of Bangladesh

November 1996

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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	($m^{1/2}s^{-1}$)
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_1	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$(s_h/D^{3/2}{}^1g\Delta)$	(-)

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_O	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_2t); 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^1	Effective dimensionless shear stress	($\mu\psi$)

Indices

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

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1 General

1.1 Introduction to 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 the end of 1995, FPCO merged with the Water Resources Planning Organization (WARPO) under the same Ministry, at which time WARPO took over the project execution. Funding has been granted by the Commission of the European Communities. The Consultant is a joint venture of DELFT HYDRAULICS and the DANISH HYDRAULIC INSTITUTE (DHI), in association with Osiris, Hydroland and Approtech. Project supervision is done 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, containing a summary of the background, a brief overview of the activities within each project component, and general 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 4 specifically discusses sediment transport processes in the main rivers of Bangladesh. As (1) sediment transport is caused by water flow and (2) sediment transport is the driving agent behind morphological changes, it should be read and assessed in conjunction with Annexes 3 and 5.

1.2 Scope of this Annex

This Annex is one of the three 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. Such a study should comprise improvement of the understanding of sediment transport phenomena in these rivers, as morphological characteristics and morphological changes are mainly determined by sediment transport.

The scope of this Annex 4 is to present and discuss the current understanding of sediment transport 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 sediment transport phenomena in Bangladesh. Hence also the results of previous studies are incorporated while attempting 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 Kahn rivers, in accordance with the Terms of Reference. This network for the morphological data and characteristics is slightly different from 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.

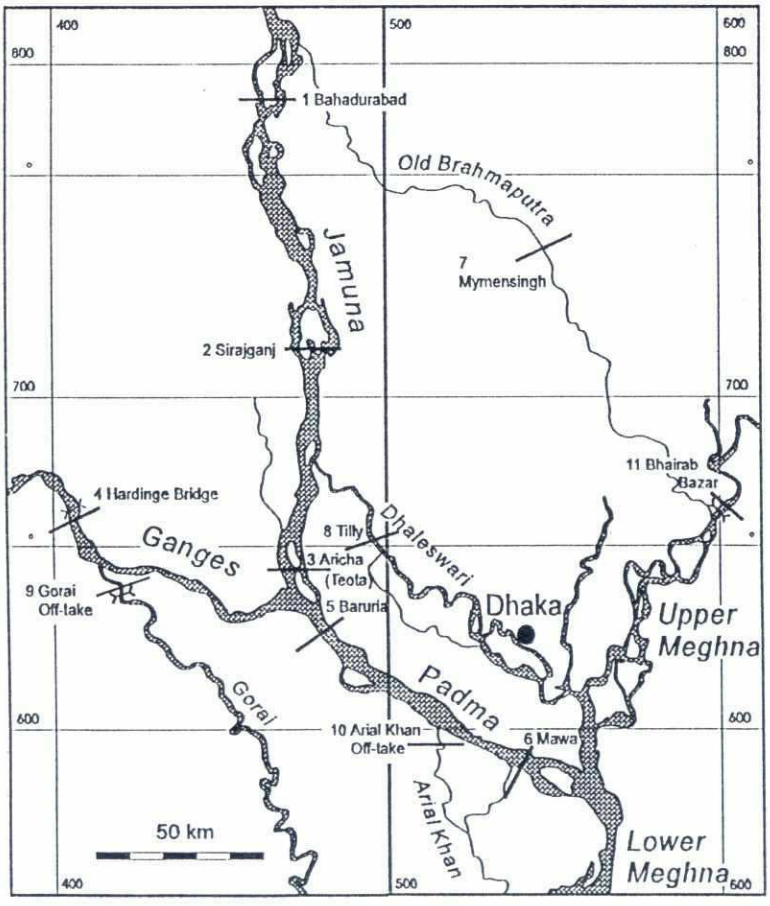

Figure 1.1
Study area showing RSP measuring locations

1.3 Previous work

The benchmark paper for the sedimentology 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 had been carried out regarding the different main river systems in Bangladesh, mostly within the framework of a consultancy study regarding the feasibility of proposed structures. During these studies use was made of the data collection programme of the BWDB. It should be emphasized that it is through these data that most of the knowledge is obtained. An overview of the available data on sediment transport and other 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 when it was attempted to study a specific aspect in more detail (Jamuna Bridge study: bedforms; FAP1: bank material and exchange processes).

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

Surveys of inland waterways and ports (NEDECO, 1967)
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 elevation of their river beds some morphological aspects like sediment transport and the planform were studied and many data on planform and some on sediment size were collected.

Jamuna Bridge Project (RPT et al, 1987; 1988 and 1990)
Available data on sediment transport, cross-section and other data were collected and analyzed, including the bed material of the Jamuna and the Padma Rivers. Historical data were analyzed, including the BWDB cross-sections and sediment transport data. A number of special field surveys were carried out in the southern part of the Jamuna River during the extreme flood of 1987, including a study of bedforms and their changes in some reaches. For the first time a systematic study into planform changes was done using satellite imagery.

Brahmaputra river training studies (FAP1) (Halcrow et al, 1992)
This 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. The sediment transport and the 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 covers the full width of the river over a 12 km long reach south of Sirajganj and contains both major confluence and bifurcation features. The second covers the western channel with a sharp bend in the vicinity of Kazipur.

Meghna River Bank Protection Short Term Study (FAP9B) (Haskoning et al., 1992)
A detailed bathymetric survey of the Lower Meghna River from Haimchar to Mawa along the Padma River was carried out during March and August 1991. Bed samples were collected from the Meghna and the Padma Rivers. The analysis of the morphological data yields an insight into the morphological characteristics of the Padma, the Upper and Lower Meghna Rivers. Also results from mathematical model studies of the flow field are available for studying e.g. local slopes and their variation.

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 Resources Management Study, FAP4
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 training project on the brahmaputra river, China-Bangladesh Joint Expert Team
	1993	FAP1, Brahmaputra River Training Studies, Halcrow, DHI
	1992	FAP3.1, Charland Study, Sogreah, Halcrow, Lahmeyer
	1993	FAP21/22, 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	FAP9B, Meghna river bank protection short term study, Haskoning/DELFT
Padma River	1967	Surveys of inland waterways and ports, NEDECO
	1992	FAP9B, 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	FAP3, North central Regional study, BCEOM, Euroconsult
	ongoing	FAP6, 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 Mitigation Study
Gorai River	1967	Surveys of inland waterways and ports, NEDECO
	1993	FAP4, South West Area Water Resources Management Study, Halcrow, DHI
Arial Khan/Dubaldia Rivers	1967	Surveys of inland waterways and ports, NEDECO
	1993	FAP4, 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

Bank protection & Active Flood Plain Management pilot project (FAP21/22)(RRI et al, 1993)
After a feasibility phase in which mostly data collected in the past were collected and processed, amongst others soil-mechanical investigations (mainly drillings) were done near Kamarjani and Bahadurabad. Interesting information was obtained into the composition of the floodplain.

Environmental Impact and GIS study (FAP16/FAP19) (ISPAN, 1993; 1995)
Several char land studies were carried out by the combination of FAP16 and FAP19. FAP19 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 fellow workers (Klaassen et al, 1988), Bristow (1987), Goswami (1985) and Thorne et al (1993). These papers were mostly derived from consultancy studies or reports. Other papers include also studies by Hossain (1992).

1.4 Summary of relevant activities carried out by the RSP

The activities carried out by the RSP in relation to the sedimentology of the main rivers of Bangladesh can be divided into:

a Collection and storage of data previously collected;

b Routine sediment gauging;

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 Routine sediment gauging

In principle sediment transport was measured on a routine basis in all stations indicated in Figure 1.1. In addition, bed samples were taken regularly.

Re c Special surveys

The following special surveys were carried out that are relevant for the sedimentology of the main rivers in Bangladesh:

- local slopes measurements;
- bed material sampling of the Ganges River and the Old Brahmaputra River;
- sampling of bed material for determination of mineralogical and physical properties;
- survey of bedforms along longitudinal profiles (mostly thalweg)
- internal structure of bars;
- bedforms and sediment transport under tidal conditions;
- joint sediment transport measurements together with BWDB;
- sediment plumes measurements;
- near-bed sediment transport measurements;
- floodplain sedimentation measurements.

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Re d Studies

The following special studies were carried out in relation to the sedimentology of the main rivers in Bangladesh, mainly during Phase 2 of the project:

- local slopes variations;
- deposition of fine sediments in the riverbed;
- spatial sorting in the Jamuna River;
- composition of bed material of the Ganges River and changes in longitudinal direction;
- composition of bed material of the Old Brahmaputra River and changes in longitudinal direction;
- mineralogical and physical properties and changes in longitudinal direction;
- occurrence and dimensions of bedforms, including lee side slopes;
- bedforms under tidal conditions;
- internal structure of bars;
- resistance to flow;
- different contributions to resistance to flow;
- contribution of bedforms to resistance to flow and effect of slope of lee-side of bedforms;
- sediment transport predictors;
- sediment rating curves;
- sediment balances;
- sediment distribution and selective sorting at offtakes;
- continuity of sediment volumes, particle sizes and mineralogy at confluences;
- applicability of ADCP back-scatter for sediment transport measurements;
- sediment transport under tidal conditions;
- changes in sediment transport concentrations in sediment plumes;
- contribution of near-bed sediment transport to the total bed material transport;
- joint sediment transport measurements together with BWDB;
- spatial variation and rates of floodplain sedimentation.

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

1.5 Structure of present Annex

It is not an easy task to discuss sediment transport phenomena in the main rivers in Bangladesh without at the same time giving due attention to the complicated morphology of the main rivers. The morphology of these rivers 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 an interpretation of the sediment transport phenomena so difficult.

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. Sediment transport in these rivers, caused by these currents, shows the same variability. In interpreting sediment transport patterns the linkage between river morphology on the one hand and flow and sediment transport on the other hand should always be kept in mind.

However, it is still advantageous to schematize and simplify, as it is not always required to take this very complicated 3-d flow patterns and river morphology into account when discussing river processes. In a first and tentative approach it is possible to consider the main rivers as sediment conveying conduits linked in a network. This is in fact the approach taken in this Annex. As will be shown in the later Chapters this approach is versatile when trying to establish a first insight into annual flows and sediment transport loads. Hence, changes in flows and loads as proposed under FAP can be assessed in regard to their consequences on slopes and levels.

Consequently, the structure of this Annex is particularly directed at providing a simplified approach to the river network, including the linkages at offtakes and at confluences. It starts with an overview of bed material characteristics for the various rivers. Both particle sizes and mineralogical characteristics of the main rivers are discussed (in Chapter 2). Sediment transport is strongly affected by bedforms. Bedforms observed in the different rivers are discussed in Chapter 4. Bedforms may have a substantial contribution to resistance to flow, but there are also other contributions.

Chapter 5 is an important one within the context of simplifying the sediment transport in these complex rivers. It provides a qualitative discussion of sediment transport phenomena and its complexity. Using many examples encountered during the many surveys during the project, this complexity is illustrated, sometimes complementing it with phenomena observed on satellite imagery. These illustrations serve to better comprehend the possibilities and limitations of a schematized approach.

Chapters 6, 7 and 8 deal with sediment transport proper. In Chapter 6 an overview is given of the available data on sediment transport in the main rivers. Also a discussion on their quality is presented, in combination with some results of joint measurements with the BWDB. In Chapter 7 the BWDB data previously collected are used to develop a sediment transport predictor applicable in the main rivers of Bangladesh. The sediment transport predictor is developed on the basis of BWDB data collected in the past and subsequently adjusted because of probable measuring errors. The predictor is verified against RSP data, partly as such and partly in an integrated way using the results of 2-D mathematical modelling of the river morphology near the Jamuna Bridge now under construction. Sediment rating curves are required for obtaining a better insight into the annual sediment loads. In Chapter 8 sediment rating curves are developed and explanations for the large scatter in the sediment rating curves for Hardinge Bridge on the Ganges and Baruria on the Padma River are studied and found.

Chapters 9, 10 and 11 deal with the overall sediment transport characteristics of the main rivers considering the system as a network. In Chapter 9 balances are made to check the quality and the consistency of the sediment rating curves developed in Chapter 8. Because part of the fine sediments is being deposited on the floodplains during floods, the floodplain sedimentation rates are taken into account as well. A possible explanation for the high floodplain sedimentation rates (about 1 cm/year) is subsidence. Chapter 10 studies the consistency of the data by considering the overall slopes of the rivers, as these are linked to the flows, sediment loads and sediment calibers. Also the conditions at the offtakes and confluences are assessed in more detail, in particular via continuity checks on particle sizes and mineralogy. A fairly consistent image emerges from this Chapter. The improved insight obtained is used for a first qualitative assessment of the impact of proposed scenario's for FAP implementation. Although in the short term the stages may rise slightly due to the construction of some embankments, in due course the conditions will even improve over the present conditions. More study is needed however.

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 4 therefore concludes with a Chapter in which suggestions are made for further studies. These will certainly increase the understanding of the sediment transport 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 in the longer run, "taming" the main rivers of Bangladesh in the greater interest of the country and the people of Bangladesh.

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2 Bed and bank material of the main rivers in Bangladesh

2.1 Introduction

Together with discharges and sediment loads, the characteristics of the bed and the bank material is one of the most important parameters of an alluvial river (see also Annex 5, Chapter 2). Many properties of the rivers are ultimately determined by the size and other characteristics of this bed material. The sediment transport load is e.g. inversely related to the size of the material: the coarser the bed material, the smaller the sediment transport. Also deposition of sediment is dependent on its size: the smaller the particles, the smaller their settling velocities, and the slower the particles settle. Also the bar deposits, the composition of the banks and floodplains, and even the channel geometry and the planform of the rivers are ultimately influenced by the bed material characteristics. Hence a good knowledge of the bed material of the main rivers in Bangladesh is imperative for a better understanding of the sedimentological and morphological processes in the main rivers of Bangladesh.

The bed material is a reflection of the types of sediment that are transported in the river. This again is ultimately a function of the sediment produced in the catchment, and hence is determined by the geological conditions and the climate. Information on the origin of the sediments in the Brahmaputra-Ganges delta is provided by Monsur (1995). Of course a delay in the response of the bed material characteristics will occur when the composition of the sediment coming from upstream is changing (in aparticular because there is a lot of storage of sediment in river bed, chars and floodplain, but ultimately one would expect that an equilibrium stage is reached whereby the bed material characterisitcis remaoin do not change in time. This may be different in Bangladesh which is geologically fairly active, as can be derived from many indicators (to start with the major avulsion of the Brahmaputra to its present Jamuna course around 1800).

Traditionally, the transported sediment is distinguished in bed material load and wash load, where the wash load is supposed to be the finer sediment (smaller than some 50 μm). The wash load is supposed not be found in the bed of the river, as the wash load is supposed to originate from sources upstream, either in the catchment or from bank erosion. The classification of Figure 2.1 is applicable in many rivers.

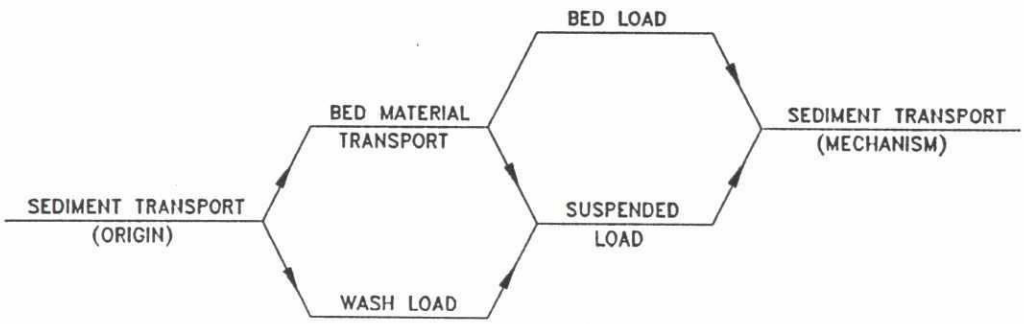


Figure 2.1 Origin and mode of transport of sediment (Jansen, 1979)

As will be discussed in Section 5.6 of this Annex the role played by the finer sediment is much more complicated in braided rivers like the Brahmaputra when compared with rivers in e.g. Europe. Although fine sediment are found in the river bed as well this fine sediment is probably not so important for short-term morphological processes. Hence the fine wash load is not so important for deposition in the channels of the rivers. It does play a significant role however in the floodplain building.

Already quite some knowledge on the bank and bed material of the main rivers in Bangladesh was available at the start of FAP24, owing to a number of studies that have been carried out since the 60ies, when the benchmark study of Bangladesh's rivers (NEDECO,1967) was published. These were mainly Consultancy reports (see Section 1.2 for an overview of these studies). Under FAP24 this material was collected and summarized in SR3 (River Survey Project, 1993b). At the same time some additional were carried out into the bed and bank material characteristics of some rivers for which no systematic data were available, and some studies were carried out into the occurrence of fine sediments in bed samples. Furthermore an exploring study into the physical characteristics of the bed material and the material in transport was carried out. The main results of these additional studies together with the summarized previous material is presented in this Chapter, together with a summary of other information on bed and bank material.

Hence in this Chapter the following information can be found: composition of the bed material in most of the main rivers in Bangladesh, some discussion on the donwstream fining of the bed material, some results form the preliminary results into the physical properties of the sediments, information on the composition of the bars in the Jamuna River and a summary of some studies into the composition of the floodplain of the rivers. More detailed information can be found in Study Reports 3 (Morphological characteristics), 8 (Bed material sampling) and 14 (Physical properties).

2.2 Composition of the bed material of the main rivers

The bed material of the main rivers in Bangladesh is fine fairly uniform sand. Figure 2.2 summarizes the presently available information on the size of the bed material of most of the main rivers in Bangladesh. The information presented is the characteristic particle size D_{50} and geometric standard deviation σ_g of the main rivers in Bangladesh along the following reaches:

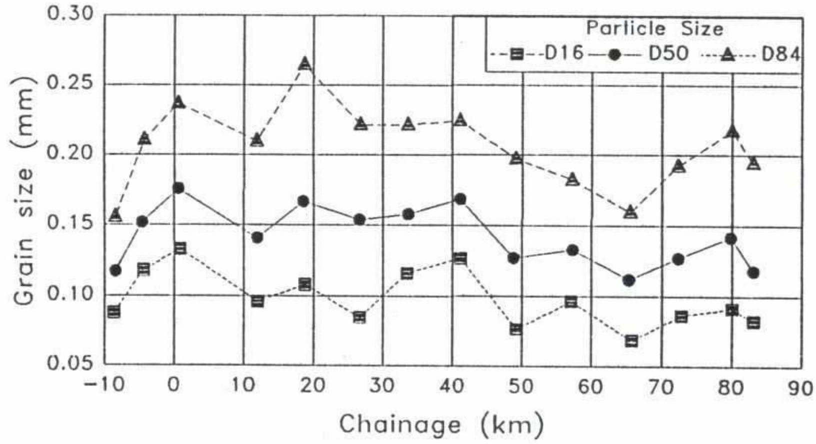
(a) Brahmaputra-Jamuna-Padma-Lower Meghna Rivers
(b) Brahmaputra-Old Brahmaputra-Upper Meghna-Lower Meghna Rivers
(c) Ganges-Padma-Lower Meghna Rivers

These two diameters are defined as:

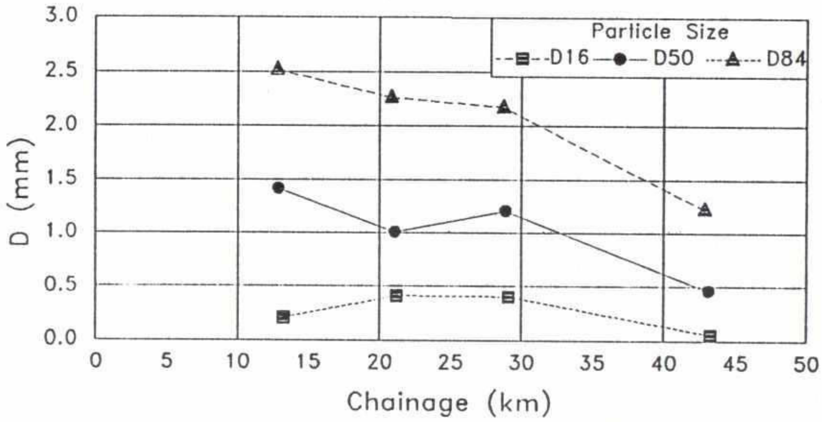
D_x = diameter not exceeded by x % (by weight) of the sample
σ_g = geometric standard deviation, defined via:

$$\sigma_g = \frac{1}{2}\left(\frac{D_{84}}{D_{50}} + \frac{D_{50}}{D_{16}}\right)$$

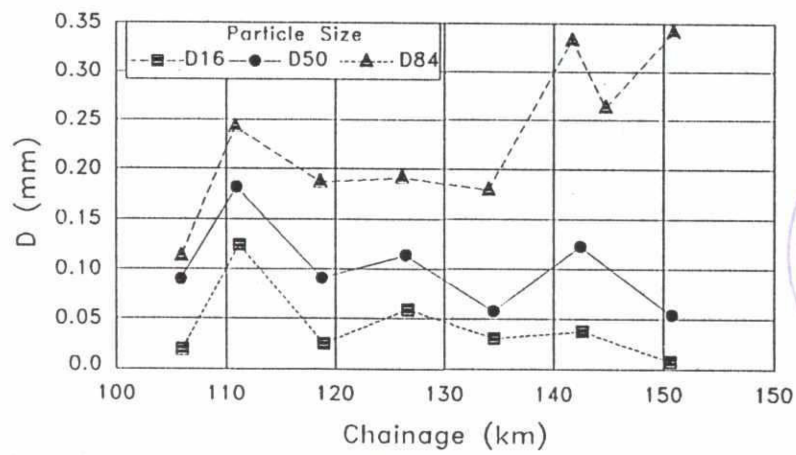
The information provided in Figure 2.2 is based on the following sources: Jamuna Bridge Study, Phase 1 (RPT et al, 1987) for the Brahmaputra, Jamuna and Padma Rivers, (Haskoning et al 1992) for the lower reach of the Padma River, and for the Upper and Lower Meghna Rivers, and special surveys under FAP24 for the Ganges and the Old Brahmaputra River (see SPR-08, Bed Material Sampling)



(a) Along Brahmaputra-Jamuna-Padma-Lower Meghna Rivers



(b) Along Brahmaputra-Old Brahmaputra-Upper Meghna-Lower Meghna Rivers



(c) Along Ganges-Padma-Lower Meghna Rivers

Figure 2.2 Characteristic particle size D_{50} and geometric standard deviation σ_g along the main rivers in Bangladesh

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The data for the Jamuna River are based on large numbers of samples at some specific stations available at the former River Research Station and they were processed under the Jamuna Bridge Study, Phase 1. The other data are mostly based on systematic sampling of the different reaches. This sampling was done along the river at mutual distances of usually 5 km, while samples were collected in the midlle of the river and along the left and right bank. The data presented are the average for each section. Still however there is a considerable scatter due to sorting processes (see also Annex 5).

Compared to the NEDECO (1967) study the information presented here is much more complete, and it may be stated that probably further studies for the reaches included would only marginally improve over Figure 2.2. It should be stressed however that of some of the main rivers data are still missing, notably the Dhaleswari, Gorai and Arial Khan Rivers. For these rivers additional studies are still needed.

A number of the samples that were collected during the special surveys under FAP24 contained very high percentages of fine sediments in the silt range. Also the data presented in NEDECO (1967) and data from Goswami (1985) for the Brahmaputra in India indicate that at some locations the bed samples can be very fine. Inclusion of these samples when determining the composition of the bed material would have resulted in much lower values for the D_{50} and higher values for σ_g.

A separate study was done into the occurrence and relevance of these fine sediments. First of all it was assessed where samples with large percentages of silt were found. This was done for the samples in the Ganges River. Roughly speaking it can be stated that silts were found near eroding banks where the flow velocity is high, and in areas with low velocities the silts can form deposits, for example at the downstream ends of bars. In the Old Brahmaputra River many silt samples were found in the downstream reach, which is under the influence of the backwater from the Upper Meghna River. Deposition of fine sediments is only possible in water with very low velocities or in stagnant water. Hence, in second instance, the results from sampling in the routine survey transects were used to link the occurrence of fine sediments with velocities. It was found that silt is only present when the velocities fall below 0.4 m/s. These velocities are only met in areas in the wake of bars, near banks and in stagnant areas (upon the recession of the flood in old channels etcetera.). As will be discussed in Section 5.6 in more detail, it is felt that these silts are only "opportunists" (settle where the velocities are low enough) but are not important for morphological changes at short and medium term. Hence it was decided to eliminate their effect on the bed material. Hence Figure 2.2 is to be understood and interpreted as the bed material that is important for morphological changes.

For more details on the bed material sampling under FAP24, and the occurrence of silts and the relation to the water velocity reference is made to Study Report 8.

2.3 Mineralogical properties of the bed material

Under the project two special surveys were done to determine the "physical characteristics" of the bed and transported material of some of the main rivers in Bangladesh. Here the physical properties are to be undertsood as mainly the mineralogical characteristics. This study was done upon the specific request of the Project Advisor. In this Chapter only bed material data are presented and discussed. The results of the analysis of the transported sediments are

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presented in Chapter 5. The ultimate aim of this study is to assess the possible effect of the density and shape of the sediment on its transport and depositional behaviour. In this Section only the main results of the study will be provided. For more details reference is made to SRP 14, while the implications of the findings presented here is discussed in Chapter 5.

During the two surveys samples were collected from the river bed of the Teesta, Brahmaputra, Jamuna, Ganges and Padma rivers. These samples were split up in the three fractions sand, silt and clay. Analysis was done primarily to determine the mineralogical characteristics (via light microscope, and for the finer sediments x-ray diffraction), but also shape (via fall velocity and microscope), density (pycnometer) and grain size (sieving or settling tube) were determined. An example of the mineralogical composition in a sample taken from the riverbed can be seen in Figure 2.1, and more examples can be found in SPR 14, "Mineralogical and physical properties".

Group		Type of mineral	Origin	Density (10^3 kg-/m^3)	Hardness
1	Mica	Muscovite	Igneous rocks	2.8-2.9	2.5
		Biotite	Igneous and meta-morphic rocks	2.8-3.4	2.5
		Chlorite	Igneous rocks	2.6-3.3	?
2	Carbonates	Calcite	Sedimentary and meta-morphic rocks	2.7	?
		Dolomite	Sedimentary rocks	2.85-3.0	?
3	Quartz etc	Quartz	Igneous and meta-morphic rocks	2.65	7
		Feldspar	Igneous rocks	2.56-2.76	6
		Rock fragments	Igneous, sedimentary and metamorphic rocks		
4	Heavy minerals	Non-opague	Igneous and meta-morphic rocks	3.0-4.6	5-7.5
		Opaque	Igneous rocks	?	?
		Ampholites	Metamorphic rocks	3.0-3.6	?
		Pyroxene	Igneous and meta-morphic rocks	3.25-3.55	6
5	Clay minerals	Kaolinite		2.6	2
		Illite		2.0-2.7	2-2.5
		Chlorite	Igneous rocks	2.6-3.3	2.5
		Montulorillonite			

Table 2.1 Most important minerals found in the bed samples of the main rivers of Bangladesh

The minerals that were found in the different samples are listed in Table 2.1 together with some of their main properties. These main properties include the density of the particles, their shape and the hardness of the sediments. The latter is provided on a scale from 1 to 10 where 10 stands for diamonds. It is obvious that the minerals present in the bed is a reflection of the sediments produced in the catchment. More information on the rocks in the catchment is found in SPR 14.

M = muscovite,
B = biotite,
F = feldspar,
Q = quartz

Plate 2.1 Example of mineralogical composition of bed material of the Jamuna River near Sirajganj

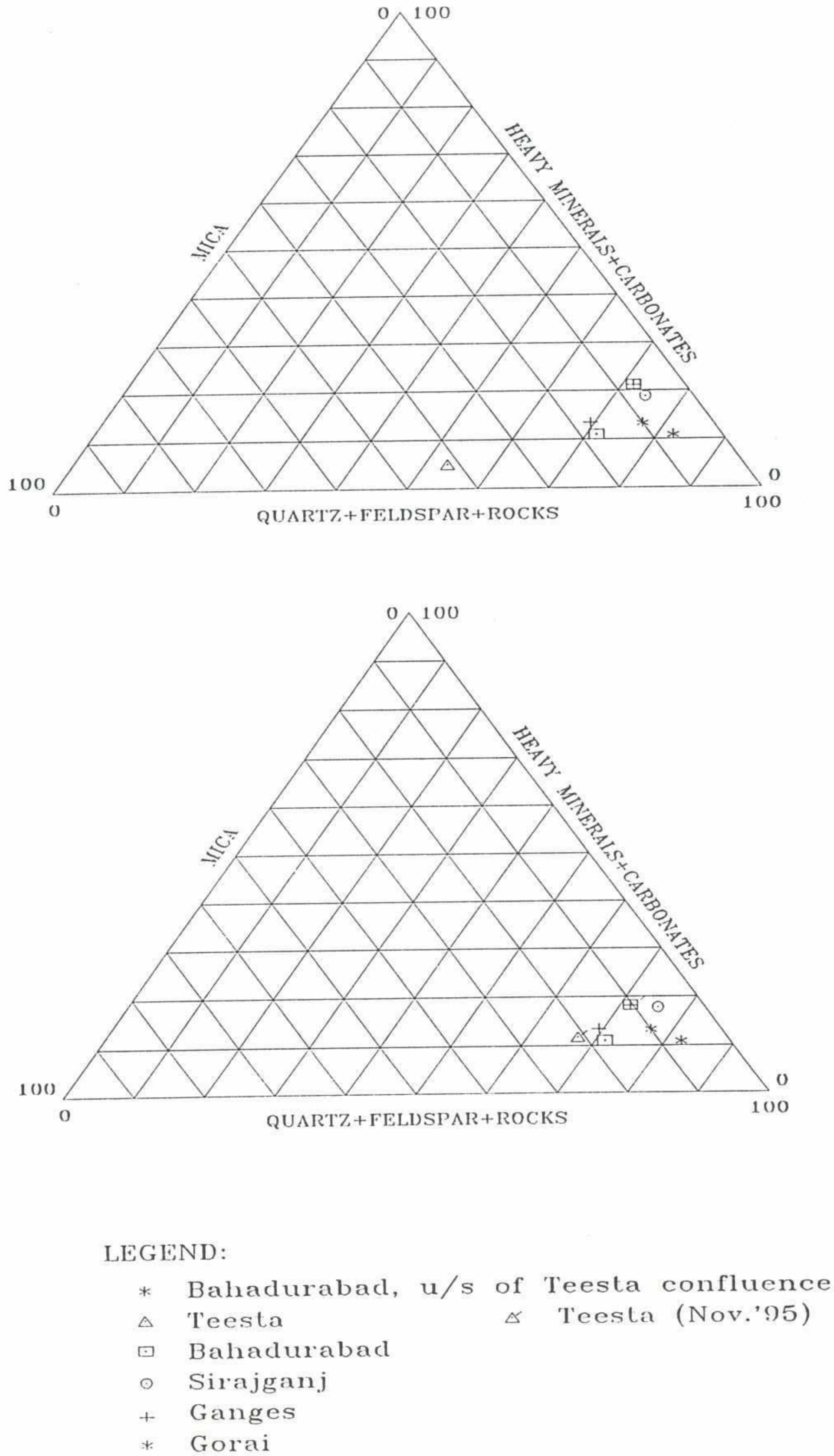

Figure 2.3 Mineralogical composition of the bed material of the main rivers (preliminary)

Location	Quartz %	Feldspar %	Rock Fragment %	Mica %	Heavy Minerals			Carbonates %	Grain Size		
					Amphiboles Pyroxene %	Non-opaque %	Opaque %		<63> Micron %	>63 micron %	D_{50} mm
Teesta	40 ± 17	5 ± 3	10 ± 8	41 ± 28	2 ± 1	2 ± 1	traces	traces	43.82 ± 27	56.18 ± 27	0.077 ± .033
Jamuna (upstream)	47 ± 5	8 ± 3	22 ± 3	10 ± 3	6 ± 2	5 ± 2	2 ± 2	traces	1.93 ± 3	98.07 ± 3	0.187 ± .066
Jamuna (Bahadurabad	42 ± 9	7 ± 3	16 ± 7	26 ± 19	4 ± 3	4 ± 3	1 ± 2	traces	26.24 ± 34	73.76 ± 34	0.135 ± .088
Jamuna (Sirajganj	41 ± 11	9 ± 3	16 ± 5	20 ± 23	6 ± 2	6 ± 3	2 ± 3	traces	19.22 ± 35	80.78 ± 35	0.152 ± .069
Padma (Mawa)	46 ± 8	8 ± 3	17 ± 5	7 ± 6	8 ± 4	7 ± 4	7 ± 9	traces	3.25 ± 3	96.75 ± 3	0.132 ± .035
Ganges	44 ± 9	8 ± 3	17 ± 5	18 ± 15	3 ± 2	4 ± 2	1	5	20.00 ± 33	80.00 ± 33	0.132 ± .064
Gorai Offtake	53 ± 4	11 ± 1	19 ± 1	11 ± 3	2 ± 1	2 ± 1	traces	2	0.25 ± .044	99.75 ± .044	0.176 ± .007
Meghna (Bhairab)	48 ± 4	10 ± 3	20 ± 3	9 ± 5	6 ± 2	5 ± 2	2 ± 2	traces	26.56 ± 23	73.44 ± 23	0.130 ± .066

Table 2.2 Mineralogical and physical properties of sand for bed material samples

Location	Quartz + Feldspar	Rock Fragment %	Mica %	Heavy minerals		Carbonates %	Grain Size		
				Non-opaque %	Black Opaque		<63 micron %	>63 micron %	D_{50} mm
Teesta (upstream)	50 ± 8	2 ± 1	15 ± 10	26 ± 10	6 ± 6	1 ± 1	24.49 ± 24	75.51 ± 24	0.093 ± .034
Teesta (confluence)	53 ± 6	2 ± 1	9 ± 2	30 ± 5	6 ± 3	trace	3.85 ± 3	96.15 ± 3	0.137 ± .029
Padma (Mawa)	55 ± 6	5 ± 1	10 ± 6	24 ± 8	4 ± 3	2 ± 1	6.63 ± 5	93.37 ± 5	0.134 ± .041
Padma (Kamargaon) On charland	53 ± 3	9 ± 1	10 ± 3	25 ± 1	2 ± 1	1	32.90 ± 9	60.80 ± 9	0.072 ± .006
Padma (Kamargaon On riverbed	45 ± 7	9 ± 3	18 ± 10	21 ± 11	5 ± 5	2 ± 2	14.18 ± 20	85.82 ± 20	0.119 ± .042
Jim's bar (head)	56 ± 2	6 ± 1	17 ± 2	19 ± 1	1	1	2.29 ± 1	97.71 ± 1	0.337 ± .006
Jim's bar (middle)	54 ± 6	7 ± 2	9 ± 4	27 ± 3	3 ± 1	trace	8.41 ± 11	91.59 ± 11	0.295 ± .032
Jim's bar (tail)	59 ± 7	10 ± 1	11 ± 2	18 ± 4	1 ± 1	1	12.91 ± 12	87.09 ± 12	0.227 ± .049
Roy's bar (head)	58 ± 3	8 ± 2	6 ± 2	24 ± 4	2 ± 1	trace	35.72 ± 19	64.28 ± 19	0.116 ± .056
Roy's bar (middle)	51 ± 6	7 ± 1	9 ± 2	30 ± 7	2 ± 2	1	13.59 ± 8	86.41 ± 8	0.120 ± .030
Roy's bar (tail)	47 ± 9	6 ± 2	5 ± 1	35 ± 9	7 ± 3	traces	18.27 ± 21	81.73 ± 21	0.100 ± .028

Table 2.3 Mineralogical and physical properties of silt for bed material samples

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Location	Illite (%)	Kaolinite + chlorite (%)	Montmorillonite (%)
Teesta	73	27	nil
Jamuna (Upstream)	72	28	nil
Jamuna (Bahadurabad)	70	30	nil
Jamuna (Sirajganj)	71	29	nil
Padma (Mawa)	73	27	nil
Ganges	74	24	2
Gorai	72	28	nil
Meghna (Bhairab Bazar)	69	31	nil

Table 2.4 Mineralogical and physical properties of clay for bed material samples

The most important findings of the study in the mineralogical properties are summarized per River in Table 2.2, where among others the composition of the bed material is given for the three different fractions (sand, silt and clay). Note that in Tables 2.2 .. 2.4 also the standard deviation is given, which in some cases is quite substantial. This suggest that the variation of the mineralogical properties is quite large, and this is an indication for spatial sorting being important. Spatial sorting is discussed in more detail in Section 5.3. The accuracy of the mean can be evaluated by dividing the standard deviation by $n^{1/2}$, where n is the number of samples. For most rivers the number of bed material samples was in the order of 5; only for the Jamuna River at Bahadurabad downstream of the Teesta it was about 30.
The same information on the mineralogical composition is also presented graphically in Figure 2.3, from which it can be observed that the mineralogical composition of the Teesta riverbed material at least according to the information presented here is quite different from the other rivers.

The following interesting points were arrived at upon study of the results presented in Tables 2.2 .. 2.4 and Figure 2.3 (see also SPR 14):

- Apart from quartz and feldspar (which constitute about half of the bed material), also substantial percentages of mica and heavy minerals are present. This will have important consequences for the transport and sedimentation behaviour: mica's are flaky and hence have a low settling velocity, while heavy minerals will settle more quickly due to their higher densities.
- The Teesta and to a lesser extent the Jamuna River are characterised by relatively high percentage of mica.
- According to the data presented the Padma contains a very high percentage of heavy minerals. In view of the lower percentages in both Ganges and Jamuna Rivers, it seems that this value should be verified.

More general it should be realised that these results are only preliminary as they are based on a limited number of samples from a few locations only. Definitely a more detailed study is needed to draw more firm conclusions.

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2.4 Changes in downstream direction

The size and composition of sediments in a river change in downstream direction. Rreduction in size is also occurring in the main rivers in Bangladesh, as can be observed in the data presented in Figure 2.2. Over the length of the Brahmaputra/Jamuna River in Bangladesh D_{50} diminishes from about 0.25 mm at Chilmari to about 0.16 near the confluence with the Ganges River. The Ganges River is already finer where the Ganges enters Bangladesh (notably a D_{50} of 0.16 mm) and D_{50} reduces to about 0.14 mm near the confluence with the Jamuna River. Downstream of the confluence the D_{50} of the Padma reduces to about 0.09 mm, a value that also holds for the Lower Meghna River near Chandpur. The sediments are known to be finer when the Lower Meghna enters into the Bay of Bengal.
According to an analysis of Sternberg (see Leliavski, 1955) the reduction in particle size may be approximated by the following equation:

$$D(x) = D_0 \, e^{-\frac{x}{L}}$$

where D(x) = particle size at location x, D_0 = initial particle size at x = 0, x = longitudinal coordinate, and L = characteristic length. For the Brahmaputra/Jamuna, the Ganges and the Padma Rivers the value of L is about 500, 1000 and 400 km, respectively. A specific reason for these differences in characteristic length is not available. The effect of the sediment transported by the tributaries of the main rivers on this formula is small. In principle, also changes in the braiding index or the hydraulic conveyance can cause changes in the reduction in particle size. Here this formula has been applied to show an overall tendency only.

The reduction in size is usually attributed to two processes, notably (1) abrasion and (2) longitudinal sorting. Abrasion is the reduction of size of particles during the transport process. It is caused by intercollision of particles during transport. Most of the minerals are fairly hard, and hence will be affected only to a minor extent by abrasion. Only the micas are fairly soft minerals, hence it may be assumed that these are quickly reducing in size. Micas are only a minor fraction of the bed sediment, and hence the reduction in size can probably not fully be attributed to abrasion.

Longitudinal sorting is only effective when the river is aggrading (Parker, 1990). Due to this aggradation coarser sediments, that are more abundantly present at the level of the troughs of the dunes (Ribberink, 1987; Klaassen, 1991), are stored in the river bed. Only a relative minor aggradation rate (order of 0.1 mm/year) is already effective in causing a substantial reduction in sediment size in downstream direction. In the Jamuna River there is no evidence of a net rising of the river bed (Klaassen & Vermeer, 1988), but still a decrease in particle sizes is quite apparent. A possible explanation is that the aggradation is compensated by subsidence. See for a more extensive discussion on these matters Section 9.5 of this Annex.

In the Old Brahmaputra a slightly different behaviour can be observed. Near the offtake from the Brahmaputra River D_{50} is about 0.15 mm, but between about 100 km and 150 km downstream the bed material size has increased to a D_{50} of about 0.25 mm. More downstream the bed material of the Old Brahmaputra River becomes finer again. Possibly this can be explained by the region, through which the river is flowing, being of slightly different geological character, and the possibility that ancient deposited (outwash) sediments from the Madhipu area affect the size distribution (Alam, 1988). This different geological makeup might be a reason for the change in the planform from a very wide river near the offtake to a meandering river with a single channel more downstream.

It is relevant to discuss the change in mineralogical composition in downstream direction. As an example the composition of the sand fraction along the Brahmaputra-Jamuna-Padma is presented in Figure 2.4. Even when the relative inaccuracy is taken into account, it can be observed that due to the input from the Teesta the mica percentage increases substantially. More downstream the percentage of mica decreases quickly (a reduction of 50 % in some 100 km), while there is a slight increase in the quartz and heavy mineral content. The decrease in mica content may be explained by the softness of the mica, which makes mica very sensitive to abrasion. The increase in quartz and feldpar and in heavy minerals is explained by the quick reduction of the contribution of mica.

It is of interest to note that the decrease of mica content in the sand farction is apparently not compensated by an increase in the mica content of the silt. For more details see SPR 14.

2.5 Spatial sorting

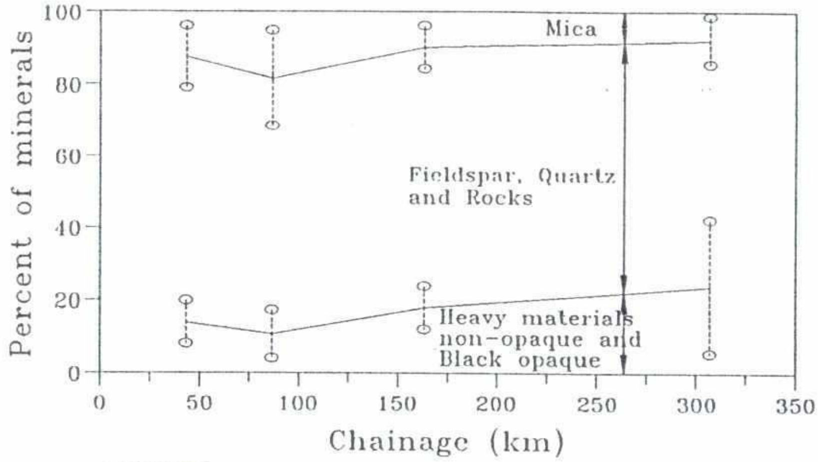
Because the bed material of the river is not uniform and because it consists of a variety of minerals with different densities and shapes, it may be expected that there is also local sorting taking place. The main reason for this spatial sorting is the differential transport behaviour of the different sediments in transport. In the rivers reworking is playing an important role. In fact probably during all stages the river is trying to adjust to the changing discharge conditions.

2.6 Composition of bars

Relatively sandy bed-material samples have been found at the head and both sides of a mid-channel bar, and silty samples at its tail. The tendency to such developments has also been found around point-bars. These silty samples contain > 40 % silt and clay and they have a slightly larger geometric standard deviation than the rather uniform sandy samples. However, in the active riverbed part of a cross-section perpendicular to the main flow direction no distinct grain sorting process has been found, see SPR-8 on bed material sampling. On a smaller scale spatial sorting occurs in dunes on the river bed. The relatively coarse grains are found in the trough and the finer grains on the crest.

Apart from in the riverbed, also much sediment is stored in the bars in the rivers, at least temporarily. In Bangladesh, bars in the rivers are usually referred to as chars. In Annex 5, much attention is paid to these bedform features. In this Section the emphasis is on their composition. This composition, however, is very much linked to their genesis, and hence for a better understanding of the composition of a char it is important to discuss the development of chars in some detail.

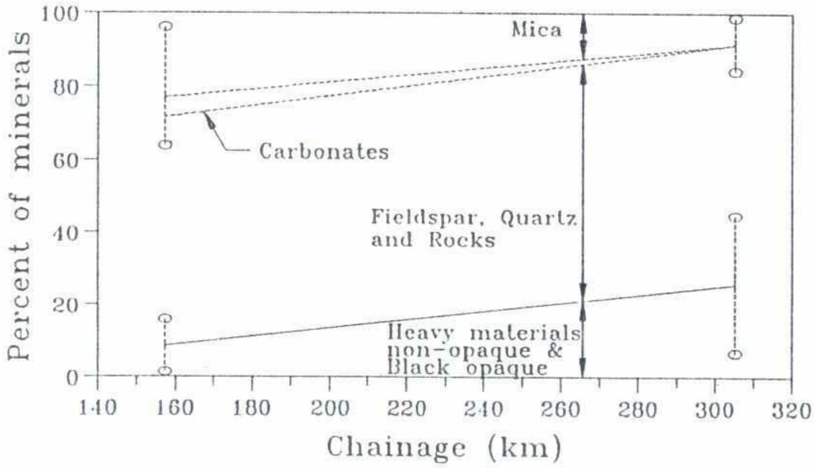
Ultimately, chars are phenomena which are caused by an instability between riverbed and overflowing water. There is an important positive feedback mechanism involved: initial bar formation leads to curved flow lines and these result in secondary flows, which enhance the bar formation. In a certain stage of the bar formation non-linear effects start to play an increasingly important role, resulting in a slowing down of the increase in amplitude (read height) and possibly a further widening of the char.



LEGEND:

Samples at chainage:
Bahadurabad u/s Teesta 44 km
Bahadurabad 85 km
Sirajgong 162 km
Mawa 305 km
0----0 2 * Standard Deviation

a. Brahmaputra–Jamuna–Padma system



LEGEND:

Samples at chainage:
Ganges 157 km
Mawa 305 km
0----0 2 * Standard Deviation

b. Ganges–Padma system

Figure 2.4 Downstream change in mineralogical composition along the Brahmaputra/Jamuna/Padma Rivers

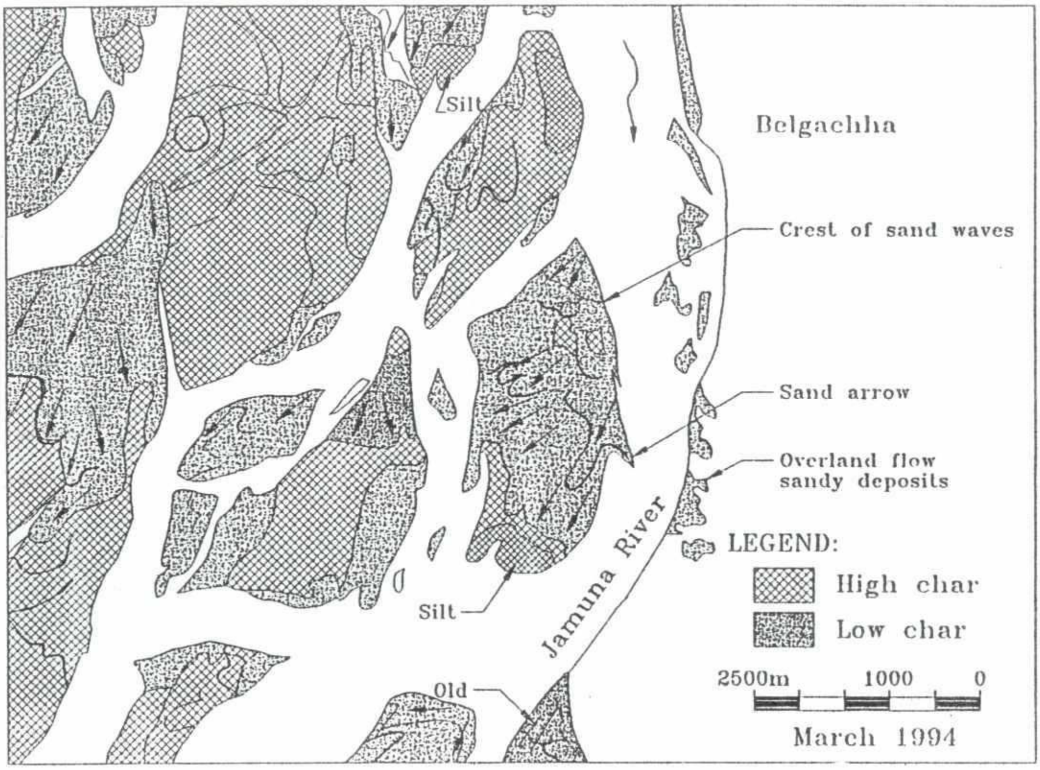


Figure 2.5 Formation of a bar in the Jamuna River plus opportunities for fine sediment deposition

Essentially bars are bed features and hence their composition is very much connected to the bed material of the river. Some sorting is involved however, as can be seen in Figure 2.6 which shows the different layers in the subsoil of a bar (see SPR Bars and bedforms in the Jamuna River). At a certain stage of their development, however, the bars are characterised by a certain horse-shoe type of form (see Figure 2.5, which presents a bar that has been surveyed over some years.

An important issue is the deposition of fine sediment due to the bars. There are two types of deposition. One is deposition in the lee of the developing bar (see Figure 2.5).

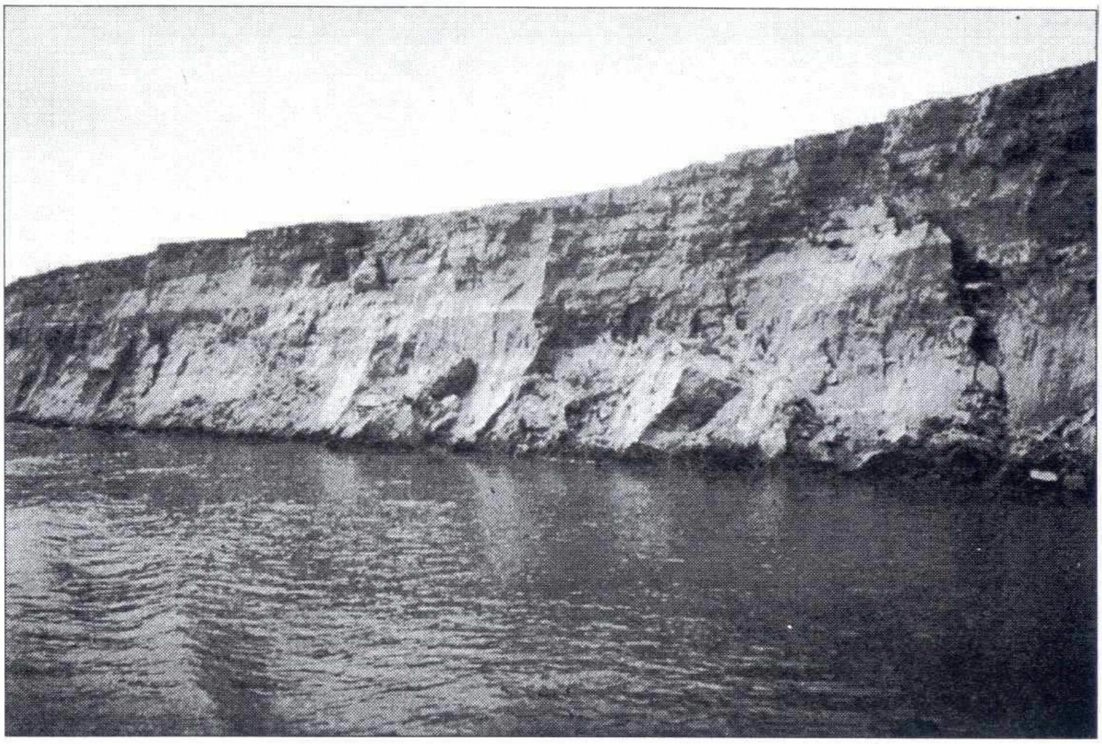


Plate 2.2 Eroding char edge

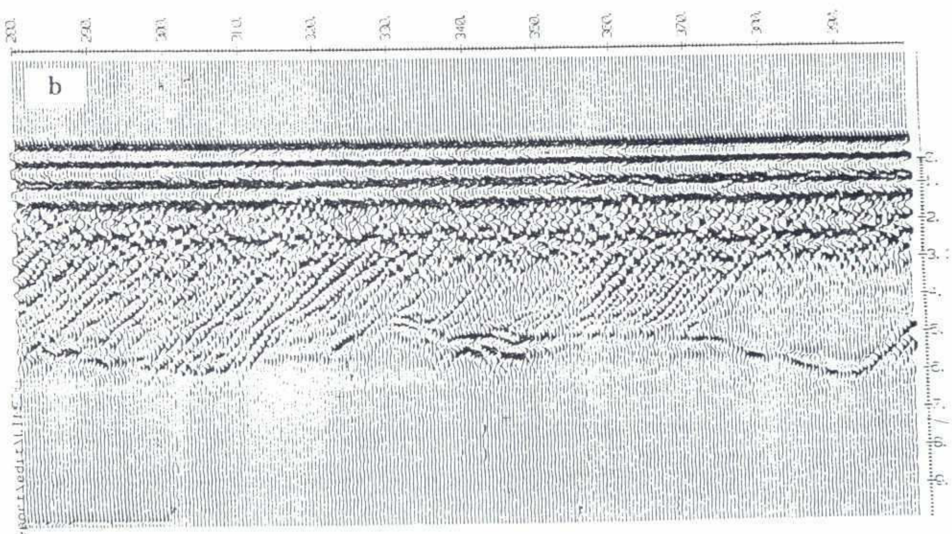


Figure 2.6 Silt deposits as shown in a cross-section of a bar as obtained by a ground-penetrating radar

This is shown nicely on an image of a ground-penetrating radar that was used during one of the special surveys. This particular image is of interest for the topic under discussion because it probably shows silt deposition a few meters buried below the present char level. It demonstrates that in the chars apart from sand also silt and possibly even clays are buried. As in due time these chars will be eroded again they act as a temporary sink for silt, but would upon erosion in due time act as source again. This may have to be taken into account when making sediment balances.

2.7 Bank material and floodplain composition

Finally the composition of the banks and the floodplains is discussed. A conceptual model of floodplain deposits was proposed as long ago as 1937 (Mackin, 1937). Floodplains are depositional features that mainly consist of point-bar deposits (which are often relatively coarse and deposited under slight angle) and (finer) deposits from overland flows, mainly in fairly horizontal layers. Oxbow lakes complicate this simple picture, as these lakes (in Bangladesh often referred to as beels) are subject to siltation with fine sediments, but often forming thicker and in later stages more consolidated deposits. This may lead to areas which are less easily erodible.

In Bangladesh the conditions are much more complicated than for many other major rives in the world, because in the past both main and smaller rivers have "wandered" over Bangladesh's delta (see e.g. Morgan & McIntyre, 1959 or Coleman, 1969). As a consequence some of the rivers are flowing in deposits which are not their own. This holds for instance for both the Jamuna River where it erodes its left bank and the Padma River, e.g. near Mawa. Other examples (for the Arial Khan) are given by Winkley et al (1994). This may cause that the deposits eroded due to bank erosion might have a different composition than the bed material and transported sediments. Generally it can be stated however that all rivers that have been flowing over the delta of Bangladesh originated from the Himalayas, so as first approximation it may be assumed that the sediments in the past will not deviate too much from the composition of the present sediment. This would imply that also the floodplains deposited in the past will to some degree comparable to a "real" floodplain of an alluvial river.

To substantiate this statement information on the bank material and the floodplain composition will be used. Unluckily there is not much known about the bank materials of Bangladesh's main rivers. However, under FAP1 the banks of the Jamuna River were sampled. Results are presented in Halcrow (1992), see also Thorne et al (1993). From this study it was concluded that the composition of the banks is not essentially different from the composition of the floodplain, and that no more resistant reaches could be identified.

Recently more information on the composition of some floodplains was obtained, notably form the Jamuna River. For some proposed bank protection projects under FAP21 borings were made and the results of these can be used. Table 2.3 presents some results of borings near Kamarjani on the left and near Bahadurabad on the right bank of the Jamuna River. In Bahadurabad the floodplain is a fairly recent floodplain deposits, probably deposited over the last 100 years, while the Kamarjani floodplain is probably much older.

For in total four borings per location the percentage sand, silt and clay is given for different depths down to 25 m. Some borings go as deep as 40 m without a substantial change in composition.

	Location borehole																							
Depth below ground level (m)	Kamarjani (old deposits)												Bahadurabad (recent Jamuna deposits)											
	1			2			3			4			1			2			3			4		
	Sa	Si	Cl	Sa	Si	Cl	Sa	Si	Cl	Sa	Si	Cl	Sa	Si	Cl	Sa	Si	Cl	Sa	Si	Cl	Sa	Si	Cl
0-1																								
1-2							72	28	–				11	89	–				27	73		42	51	7
2-3													10	56	34	79	21	–						
3-4										33	67	–	16	77	7									
4-5										8	85	7							83	17		82	18	–
5-6	87	13	-	79	21	-										9	88	3				91	9	–
6-7							85	15	–				79	21	–	88	12	–						
7-8	89	11	-				78	22	–													84	16	–
8-9										88	12	–												
9-10				85	15	-										84	16	–	80	20	–			
10-11													22	77	1							82	18	–
11-12																								
12-13																								
13-14							86	14	–	86	14	–							84	16	–	91	9	
14-15	80	20	-	91	9	-																		
15-16				89	11	-										79	21	–						
16-17																								
17-18																						86	14	–
18-19																			88	12	–			
19-20				88	12	-	92	8	–													88	12	–
20-21	89	11	-							88	12	–	88	12	–									
21-22																								
22-23																								
23-24																								
24-25																								

Legend: Sa = sand fraction (> 0.063 mm)
Si = silt fraction (between 0.063 and 0.04 mm?)
Cl = clay fraction (< 0.04 mm?)

Table 2.5 Composition of floodplain on two locations on left and right side of the Jamuna River

Although there are some traces of clay in two of the borings in Bahadurabad over the first few metwers, it can be stated that on both sides of the river the composition of the floodplain is not really different. Up to a depth of 40 m (the maximum depth of the borings) the floodplain consists of silty sand covered by a layer of a few metres of sandy silt with some clay. This is typically also the composition one would expect from present-day Jamuna River deposits.

Hence it may be concluded tentatively that the floodplain deposits bordering the Jamuna River are not varying too much. There will however be differences when weathered sediment faecies would border a river. It is usually believed that near Mawa the river is bordered by more resistent clays. These are probably also present at Sara and at other places along the Ganges River. It should be stressed that not much is known about the composition of the floodplains along the main rivers in Bangladesh. There is a clear need for more detailed studies that could start with the collection of results from borings at other locations along the main rivers.

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3 Bedforms

3.1 Introduction, definitions and objectives

An understanding of the nature of bedforms within all of the main rivers of Bangladesh is of critical importance for the estimation of bedload transport, analysis of resistance factors, prediction of local scour depths and in planning well-constrained sampling/measurement programs (Klaassen et al., 1988; Lukanda et al., 1992; Peters, 1993). Additionally, the role of bedforms in the growth of larger scale bar features, and associated bank erosion/channel incision, form key factors in assessing river channel behaviour. Past work on bedforms within the Jamuna has suggested the occurrence of a wide range of bedforms from ripples → dunes → upper-stage plane beds (Coleman, 1969; Klaassen et al., 1988), although there is uncertainty on the relative occurrence of each bedform type and their stability in relation to flow stage. For example, past work has both suggested that upper-stage plane bed conditions may become common at high flow stages and that dunes persist throughout the peak flows (Klaassen et al., 1988). Flattening of the river bed has also been recorded in other large rivers, such as the Zaire (e.g. Peters, 1977; Peters and Goldberg, 1989)

Coleman (1969) documented a range of large bedforms within the Bramahputra and reasoned that some of the largest avalanche faces, up to 15 m high, represented very large 'sand waves'. Coleman also noticed the close association between dunes and the occurrence of strong 'boils' on the water surface that carried high concentrations of suspended sediment. Julien and Klaassen (1995) compiled data from a range of very large alluvial channels, including the Jamuna, and showed that mean dune steepness and van Rijn's (1984) bedform height parameter do not always decrease at high transport stages in large rivers, and that large bedforms may exist even at high transport stages. Julien and Klaassen (1995) also demonstrated the importance of considering the Froude number in addition to the transport stage in large rivers, since the Froude number in such large channels may often be low and allow the stability of dunes at transport stages that are dominated by upper-stage plane beds in shallower flows. It is evident from past work on bedforms in the large alluvial channels that there is a need for high quality morphological data throughout the flood hydrograph (Peters, 1993) and integration of these morphological measurements with details of the flow field, especially in relation to bedload transport estimates and controls on sediment suspension. Arising from this work, and that of others (see reviews in Allen, 1982; Ashley, 1990; Yalin, 1992; van Rijn, 1993; Dalrymple and Rhodes, 1995; Kostaschuk and Ilersich, 1995), the following definitions are adopted in this study:

Ripple: a bedform with an asymmetrical with height < 0.05 m and wavelength < 0.60 m. These bedforms usually cannot be resolved on echo-sounder traces but maybe identified from some side scan sonar images and are common in bartop sections exposed at low flow.
Dune: an asymmetrical profile bedform whose maximum dimensions may scale with the flow depth such that $H \sim 0.2/0.3h$ and $\lambda \sim 5\text{-}7h$, where h and λ are bedform height and wavelength respectively and h is flow depth. However, bedform superimposition and lag effects through the flood hydrograph may result in many excursions from these relationships. Maximum dune heights of ~ 6 m and wavelengths of 340 m have been documented in this study. It should be noted the large (~ 15 m high) bedforms recorded by Coleman (1969) are not in fact dunes but more likely avalanche/leeside faces associated with bars, possibly at tributary junctions, confirming the earlier suggestions of Klaassen et al (1988).

Upper-stage plane bed: a flat bed, with minor relief (mm-several cm) associated with intense sediment transport (Allen, 1982; Best and Bridge, 1992).
Bar: a larger scale morphological feature which scales with channel width, whose height is often a significant proportion of the flow depth, and may become emergent at constant or waning flow conditions.

The descriptive classification of dunes outlined by Dalrymple and Rhodes (1995), which is based on a consensus view from many workers (e.g. Ashley, 1990), was also adopted in this study (Table 3.1). The term 'dune' encompasses the bedform previously described as megaripples by several other researchers (e.g. Coleman, 1969; Bristow, 1987; Klaassen et al., 1988) which are dynamically analogous to dunes (Ashley, 1990).

First-order descriptors					
Size:	Term	small	medium	large	very large
	Wavelength, λ, m Height, h, m	0.6-5 0.05-0.25	5-10 0.25-0.5	10-100 0.5-3	>100 >3
Shape:	**2-Dimensional** - relatively straight-crested, lacking scour pits **3-Dimensional** - sinuous to lunate, with scour pits				
Second-order descriptors					
Super-imposition:	**Simple** - lacks superimposed dunes **Compound** - bears smaller, superimposed dunes (termed secondary and tertiary dunes)				
Sediment Charac-teristics	grain size, sediment sorting				
Third-order descriptors					
Bedform profile:	bedform shape (λ/H); stoss and lee slope lengths and angles				
Orientation:	transverse, oblique, longitudinal				
Dune behaviour:	migration rate, change in form and hysteresis effects				
Occurrence:	percentage of bed covered by dunes				
Flow history:	mean flow & turbulence fields associated with dunes				

Table 3.1 Descriptive classification of dunes and terms used in this study (after Dalrymple and Rhodes, 1995)

3.1.1 Objectives

The principal objectives of this study topic are described in SPR-9 Bars and bed forms in the Jamuna River as:

- Quantify the morphology of bedforms (size, shape, three-dimensionality) and how these vary through the flood hydrograph.
- Examine the occurrence of different bedforms within the active channels and how this changes through the flood hydrograph.
- Assess the hydraulic controls on bedform stability (e.g. discharge, flow velocity, shear stress)
- Examine the flow fields associated with dunes and their influence on sediment suspension, and,
- Examine the nature of bedform-bedform and bedform-bar superimposition (see also Annex. 5, Section 6.6).

3.2 Data sources

3.2.1 Surveys

This topic used data acquired during normal routine surveys as well as more detailed special surveys conducted at Bahadurabad (SPR 9, Bars and bed forms in the Jamunua River).

1) Routine Surveys

Data from most routine gauging surveys from November 1993 - December 1995 were used for analysis of bedform longitudinal profiles. Three longitudinal profiles were normally run during each routine measurement, approximately 1 km long and oriented parallel to the main flow. All lines from both the Phulchari and Bahadurabad main sites have been used in this analysis together with data from Sirajganj and Bhairab Bazar.

2) Special Surveys

Five special surveys over dunes occurring at Bahadurabad were conducted over the period August 1994 - March 1996 (Table 3.2). During each survey, repeat lines were run in order to examine dune morphology, migration and flow structure as revealed by ADCP. Side scan sonar surveys were also run on three surveys (Table 3.2) to detail dune planform morphology. Additionally, run lines from Bahadurabad-Aricha during transit between routine surveys permit assessment of bedform occurrence within a large area of the Jamuna. Examination of dunes on exposed bartops during March 1995 and February 1996, conducted in association with the study of bars (Annex 5, Topic 6), also aided study of dune morphology.

Special Survey Date	Equipment employed	Water level*
10-14 August 1994	Standard surveying equipment - DGPS, ADCP, EMF, echo-sounder, MEX-4, suspended sediment sampler and bed grab samples	17.86
19-20 September 1994	Standard surveying equipment	17.56
7-13 March 1995	Standard surveying equipment and side-scan sonar	13.18
11-17 September 1995	Standard surveying equipment and side-scan sonar	17.86
26 February - 4 March 1996	Standard surveying equipment and side-scan sonar	13.28

Table 3.2 Special surveys at Bahadurabad concerning dune dynamics
*SLW at Bahadurabad is 12.03m + PWD

3.2.2 Techniques

Standard techniques were used in this study with data from routine surveys from vessels DHA and DHB (see Annex 1). For examination of the mean and fluctuating flow structure associated with dunes, ADCP measurements were conducted using 10 ping ensembles for each profile averaged approximately every six seconds. Side-scan sonar was deployed both at low and high flow - although excellent results were obtained in low flow conditions in the deeper talwegs, less well-defined images were obtained at high flow with high suspended sediment concentrations causing signal attenuation and loss of bottom tracking.

3.3 Factors controlling bedform stability

The stability and morphology of alluvial bedforms is governed by several factors:

1) Applied bed shear stress
2) Flow depth
3) Grain size
4) Froude number
5) Occurrence of suspended sediment
6) Available generation time (*cf.* duration/intensity of sediment transport)
7) Flow unsteadiness and bedform response to changing flow conditions through a flood hydrograph (Wijbenga and Klaassen, 1981)

These topics are reviewed in Allen (1982), Southard and Boguchwal (1990) and Best (1996). In relation to the main rivers in Bangladesh, whose bedload is predominantly fine sand (FAP24 SPR-14) and whose suspended sediment concentrations are insufficient to affect flow turbulence and bedform generation (Wan, 1993), bedform stability is largely a function of factors 1, 2, 4, 6 and 7 above. These parameters are discussed below when examining bedform morphology.

3.4 Bedform occurrence and distribution

Dunes are the predominant bedform occurring at *all* flow stages and in all parts of the active channels. Figure 3.1a illustrates examples from Bahadurabad, Sirajganj and Bhairab Bazar which demonstrate the percentage of channel talweg covered by dunes during the study period. Over 40% of the bed is *always* occupied by dunes at any one flow stage, with this figure often being in excess of 70%. Additionally, Figure 3.1b plots the percentage occurrence of dunes on a long profile taken between Sirajganj and Aricha (encompassing both talweg and bar margins) and demonstrates once again that between 40 and 95% of the bed is covered by dunes. Ripples may also be expected to be superimposed on many of these dunes but are smaller than the echo-sounder resolution. Dunes are also very commonly superimposed on bars (Annex 5, Figure 7a) and confirm that dunes are ubiquitous in both the deep channel talwegs and bar margins. Flat beds can also occur on steep bar margins and bar tops but the bar top plane beds are usually associated with regions of lower flow velocity (Annex 5, Section 6.5) and are probably rippled surfaces where bed shear stresses are too low to generate dunes. Additional evidence concerning the widespread occurrence of dunes within the main channels and superimposed on the larger barforms also comes from ground-penetrating radar studies of the subsurface bar structure (Annex 5, Section 6.5, Figure 7b) which show that dunes comprise the majority of the preserved sediments both near surface and to depths of ~5 m. Together with the pattern of dune superimposition on bars (Annex 5, Figure 7a), this confirms that dunes are the predominant bedform within all the active channels, both in the talwegs and bar margins.

3.5 Bedform geometry - height, wavelength, shape and planform morphology

Dune height and wavelength plotted for all data at Bahadurabad, Sirajganj and Bhairab Bazar (Figure 3.2a,b; Table 3.3) demonstrate that dune height ranges from 0.15 - 6.3 metres and wavelength from 4.6 - 342 metres. Both distributions have a log-normal form. The form index (wavelength/height) of such dunes (Figure 3.2c) shows a range of values from 3.6 - 132. Besides the form index of dunes, which is important for bedload transport estimates using dune tracking (see 3.1.1), the leeside angle of bedforms is of considerable importance in relation to energy expenditure and flow resistance over bedforms. A composite histogram of leeside angle from the three study sites (Figure 3.2d) shows a range of values from 2 - 58° (greater than the static angle of repose), with a mean dune slipface angle of 8.6° (Table 3.3), providing confirmation of the mean value reported by Klaassen et al. (1988). Flow separation in the leeside of bedforms may be expected to occur when the change in slope exceeds approximately 12°, and hence energy losses associated with the bedform increase (Klaassen et al., 1986, 1988; Ogink, 1988; van Rijn, 1993). The range of leeside angles present on dunes in the Jamuna span this critical leeside angle and suggest that leeside angle, as well as bedform shape, should be quantified when deriving bedform dimensions for use in resistance calculations.

Plots of dune height and wavelength as a function of flow depth (Figure 3.3a, b) show a wide scatter but clearly illustrate that maximum dune height approximates 0.25-0.33 of the flow depth (see Bennett and Best, 1995) and that dune wavelength is generally less than ~ 7 H (see Julien and Klaassen, 1995).

	Mean	Standard Deviation
Height, H, m	1.02	0.97
Wavelength, λ, m	36.7	40.4
Form index, λ/h	39.7	29.3
Leeside angle, degrees	8.6	7.9

Table 3.3 Summary of mean dune morphology for all data at Bahadurabad, Sirajganj and Bhairab Bazar

Side-scan sonar images of dunes collected at low flow (Figure 3.4a) show both two-and three dimensional dunes with heights of 0.6 - 1.75 metres, wavelengths of 5 - 30 metres and crest-line sinuosity ranging from 1.12 - 1.54. Composite tracings of these images allows the three-dimensionality of the dune crestlines to be measured (Figure 3.4b). Records of dune planform shape at high flow show that the bedforms are also three-dimensional, with scour troughs and spurs between adjacent crestlines. These morphologies are also present in both small (H ~ 0.4m) and larger (H ~ 2m) dunes exposed on bar tops at low flow (Figure 3.5). Bedform three-dimensionality has been proposed to reflect the strength of the flow (e.g. Allen, 1982), although recent work has suggested that bedform three-dimensionality more properly reflects the length of time available for bedform development, or the amount of bedload transport and its spanwise variation (Baas, 1994). Given that bedform migration occurs both throughout high and low flow, it is likely that all bedforms will display some degree of three-dimensionality and few dunes will remain two-dimensional. This is borne out by both side-scan sonar records and examination of exposed dunes in bartop sediments at low flow.

3.6 Bedform superimposition

Bedform superimposition is common within all the rivers of Bangladesh with smaller dunes generated in evolving internal boundary layers upon the stoss sides of the larger bedforms. Ripples will also be developed on the backs of dunes although these cannot be resolved with the echo-sounder. Plots of the relationship between the height and wavelength of the primary and secondary/tertiary dunes (Figures 3.6a,b) demonstrate that the height and wavelength of secondary/tertiary dunes generally becomes larger as the size of the primary dunes increases, although there is much scatter in this relationship. Dalrymple and Rhodes (1995) suggested that secondary/tertiary dunes only form on primary dunes with wavelength of approximately 8-10 m, this length being required in order to develop a new boundary layer in which the secondary/tertiary dunes may grow. Since most of the dunes studied in the rivers of Bangladesh have wavelengths greater than 10 m, dune superimposition may be expected to be common and supports the contention of Dalrymple and Rhodes (1995). It should also be noted that secondary dunes may be both superimposed on any part of the primary dune (stoss, shoulder or leeside) and occur on the leeside of low-angle leeside primary dunes, again highlighting the need for consideration of bedform superimposition in resistance calculations (Klaassen et al., 1986)

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3.7 Time-dependent behaviour of bedforms

3.7.1 Migration rates and short-term change in form

Estimates of bedform migration rates for dunes documented at high stage at Bahadurabad range from 1.11-16.8 m hr^{-1} (Figure 3.7 and also SPR-9, Bars and bedforms in the Jamuna River). These migration rates are much higher than for example measured in the Zaire River: 0.1 to 0.3 m hr^{-1}. (Peters, verbal communication). Dunes of smaller height superimposed on the stoss sides of larger, primary dunes generally possess greater migration rates, although there is much scatter in this relationship.

The migration rates and dune form indices recorded at Bahadurabad may be used to calculate estimates of transport rates, Q_b (in kg s^{-1} m^{-1}) from:

$$Q_b = (1-p)\rho_s m_g H \tag{3.1}$$

where α is a shape factor (often taken as ~0.55, van Rijn, 1993), p is a porosity factor (~0.4), ρ_s is the density of the sediment (~2650 kg m^{-3}), m_g is the mean migration rate (m s^{-1}) and h is the average dune height. This sediment transport rate includes bedload as well a part of the suspended sediment transport, therefore it is also called 'near-bed transport' (Peters, verbal communication). However, this relationship should only be applied with two important caveats: 1) this method of bedload transport estimation ignores partially or fully suspended material that may become deposited in the dune leeside and contribute to bedform migration (e.g. van Rijn, 1993; Kostaschuk and Ilersich, 1995). Some past studies in large rivers have suggested that as little as 5% of dune migration may be accounted for by bedload transport (see Kostaschuk and Ilersich, 1995), and, 2) these estimates assume a two-dimensional bedform.

Use of Eq. 3.1 with the migration rates, dune heights and shape given in Figure 3.2 produce a range of bedload transport rates from 0.45-10.0 kg s^{-1} m^{-1}.

3.7.2 Stage dependency of bedforms, lag times and hysteresis

Analysis of dune behaviour at Bahadurabad during the flood hydrograph for 1994 and 1995 shows that the dune height and wavelength respond rapidly to changes in flow velocity. Hysteresis plots of dune height and wavelength at Bahadurabad (Figure 3.8) illustrate that dunes respond rapidly to increases in flow velocity. Hysteresis in dune height (Figure 3.8a) displays both broad clockwise and anticlockwise rotation for the 1994 and 1995 hydrographs respectively, suggesting that the bedforms and hydraulic parameters may be either indirectly or directly related (Dalrymple and Rhodes, 1995). Dune wavelength hysteresis loops show an anticlockwise pattern (Figure 3.8b) with dune form index showing some flattening of dunes during the falling stage of 1994 but with little variation through the flood hydrograph in 1995. However, these plots also illustrate that there is little tendency for dunes to decrease in height as flow velocity increases, with dune height and wavelength increasing through the hydrograph. This demonstrates that the majority of hydraulic conditions generate bedforms within the dune stability field and not in the transitional regime to upper-stage plane beds.

3.8 Flow associated with dunes

3.8.1 Mean flow field

Figure 3.9 demonstrates the pattern of mean flow over i) dunes with a steep leeside slope (leeside angle ~ 35°; h = 4.7m, $\lambda\_$ = 163m; λ/H = 35), and ii) over a lower angled, flatter dune (leeside angle ~8°; H = 3.0 m, $\lambda\_$ = 80 m; λ/H = 27). Both bedforms show a pattern of flow common to many dunes including:

a) region of slower downstream flow, with possibly flow reversals, in the dune leeside associated with flow expansion
b) a zone of downward flow over the dune crest,
c) upwards directed flow, of lower than mean downstream velocity, over the stoss side of the dune, and,
d) flow acceleration over the dune crest

These patterns of mean flow match well with previous experimental and field work concerning flow over dunes (e.g. Raudkivi, 1966; van Mierlo and de Ruiter, 1988; Lyn, 1993; Nelson et al., 1993; McLean et al., 1994; Bennett and Best, 1995). It is evident from these plots that the mean flow patterns associated with these very large alluvial dunes, of both high and low leeside angle, bear many similarities to many past studies of smaller scale dunes; upwards directed flow in the lee of the dune may reach the flow surface, as witnessed by the many common 'boils' on the flow surface associated with dune fields (Coleman, 1969; Jackson, 1976; Best, 1996). This also suggests that the local leeside angle, which may largely determine the intensity and duration of flow separation and may be controlled by possible short lived oversteepening of the leeside (possibly through the migration of secondary dunes over the primary dune crest), may be important in the generation of turbulence, energy losses and sediment suspension.

3.8.2 Turbulence and dunes

Many past studies have noted the strong association between the occurrence of dunes and presence of large scale 'macroturbulence' within alluvial channels (Coleman, 1969), with several studies proposing that dune growth and stability are linked in some manner to this large-scale turbulence (e.g. Jackson, 1976; Yalin, 1992; Bennett and Best, 1995). At-a-point time series records obtained over very large dunes at Bahadurabad (~4m high, Figure 3.10) illustrate the occurrence of frequent upwellings of fluid over the dune trough. These upwellings, with positive vertical velocities and lower than average downstream velocity, have a periodicity ranging from 10-50 seconds. Records of the periodicity of these upwellings as they reach the surface (Figure 3.11a) and spectral analysis of the time series records (Figure 3.11b) show a mean periodicity of ~20 seconds. Use of a mean flow depth h of 13.1 m and depth averaged flow velocity u of1.32 m s^{-1}, allows comparison of the dimensionless recurrence period of the 'boils', T_b, with that proposed by past workers (Jackson, 1976; Yalin, 1992; Best, 1993), where

$$T_b = \frac{T \cdot u}{h} \tag{3.2}$$

which produces values between 0.58 and 5.1 with a mean of 2.1, in broad agreement with past work. However, the wide spread in values may be anticipated both due to vortex amalgamation in this complex flow field as well as eddy shedding form dunes of different size (primary and secondary dunes for instance) in the same mean flow conditions.

It is likely the origin of this large-scale turbulence lies in i) eddy shedding of Kelvin-Helmholtz instabilities generated along the separation zone free shear layer present over steep dunes, and ii) temporal shear layer development associated with flow expansion downstream from lower angle dunes or local oversteepening of the leeside angle through secondary dune migration over the crest of primary dunes.

Figure 3.9 also illustrates the common pattern of high backscatter intensity, and hence suspended sediment concentration, associated with the leeside and lower stoss side of dunes. These higher backscatter values are associated with the regions of lower than average downstream velocity and positive vertical velocities generated by eddy shedding in the lee of the dune. It is evident this pattern is present both for low and higher angle dunes. Significant sediment suspension within the Jamuna River is therefore often associated with large dune fields, a pattern also evident from backscatter records associated with bars (see Annex 5).

3.9 Summary

- Dunes are the dominant bedform within all active channels and on bar margins/edges at all flow stages
- Dune height and wavelength range from 0.15-6.3 m and 4-350 m respectively
- Dune leeside angle ranges from 3-50^{o} with a mean of 9^{o}
- Dune superimposition is common although there are no clear morphological relationships between the size of primary and secondary dunes. Secondary dunes may be superimposed on the stoss and leeside of primary dunes and may contribute to temporal oversteepening of the leeside angle of lower angle dunes
- Bedform response to flow stage is rapid with little lag effect but the variability in dune height and wavelength increase at higher flow stages
- Dunes create individual flow fields which control the local suspension of sediment, both over low and high angle leeside dunes

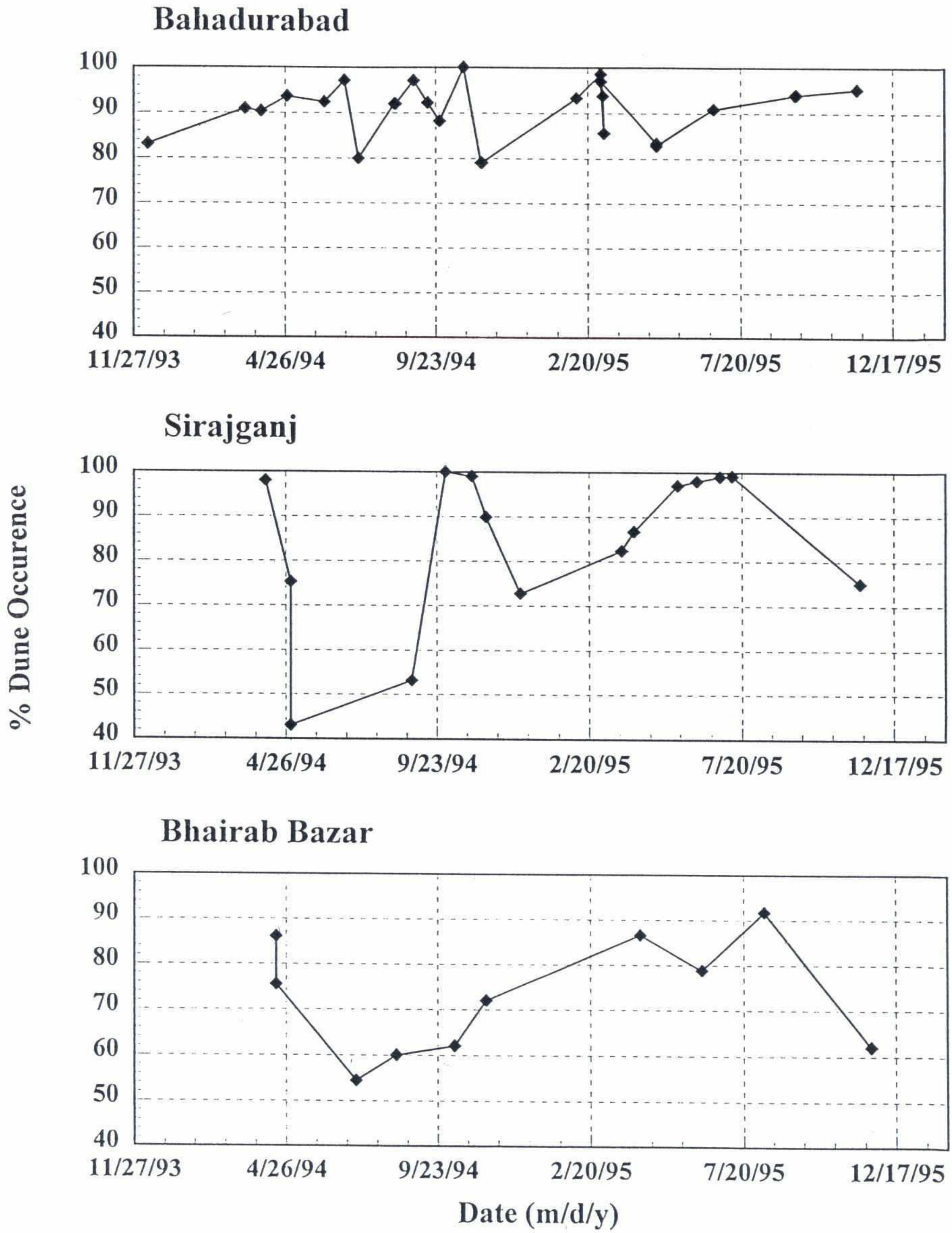


Figure 3.1 (a) The percentage occurrence of dunes at Bahadurabad, Sirajganj and Bhairab Bazar for entire study period

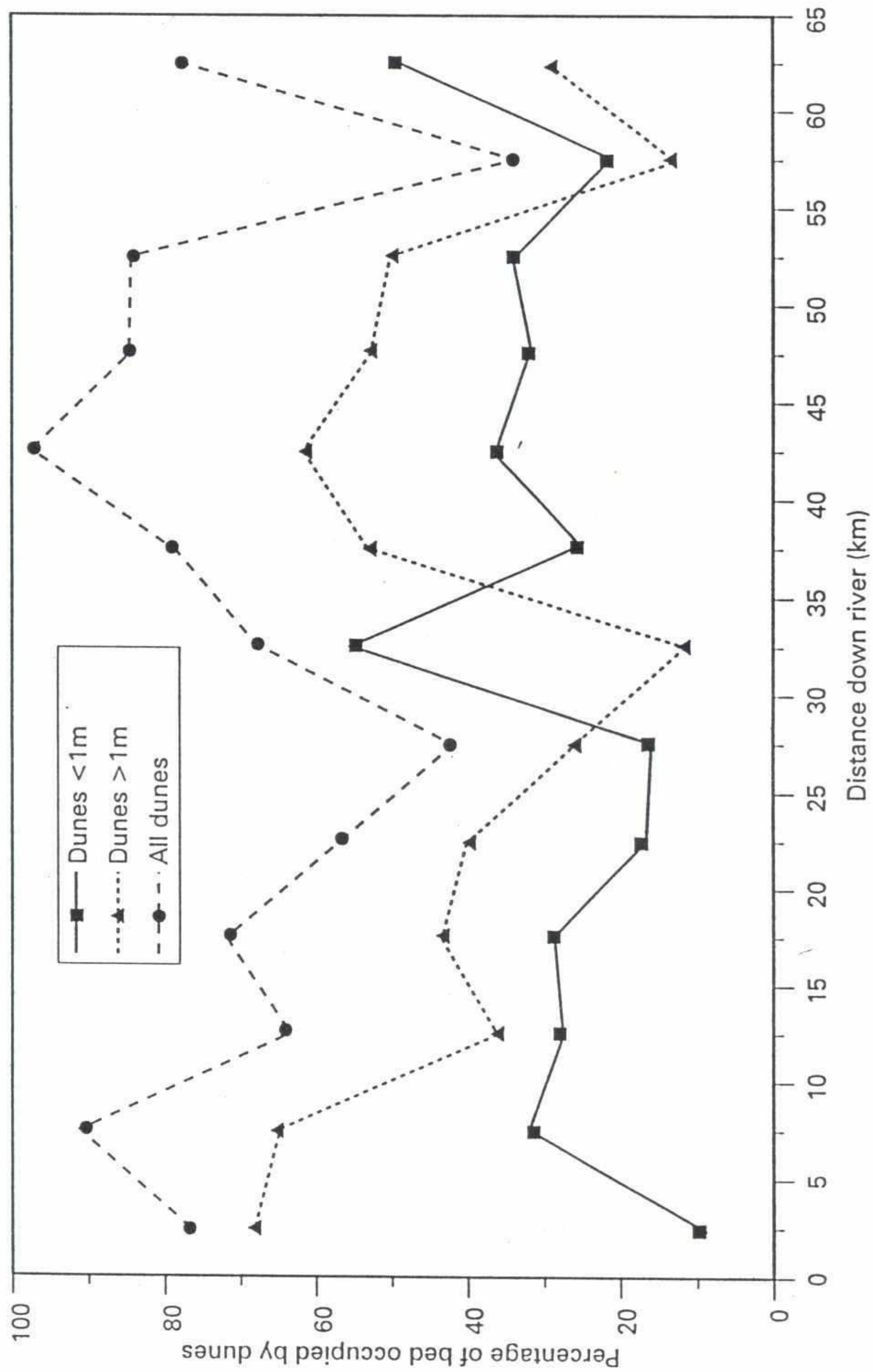


Figure 3.1 (b) The percentage occurrence of dunes along a downstream transect from Sirajganj-Aricha

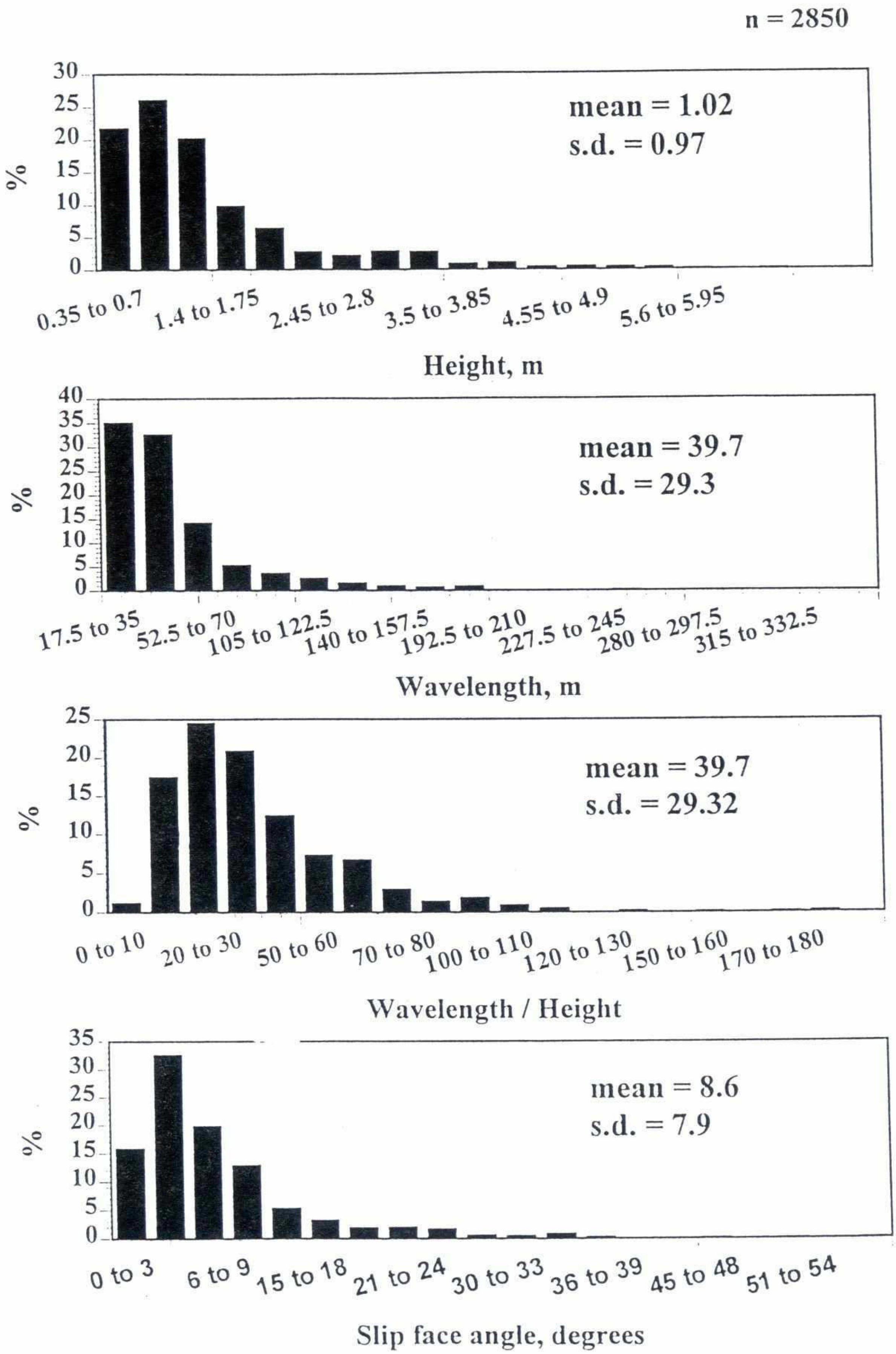


Figure 3.2 Histograms of: (a) dune height (b) dune wavelength (c) dune form index (wavelength/height) and (d) leeside angle, for all three sites for all study periods

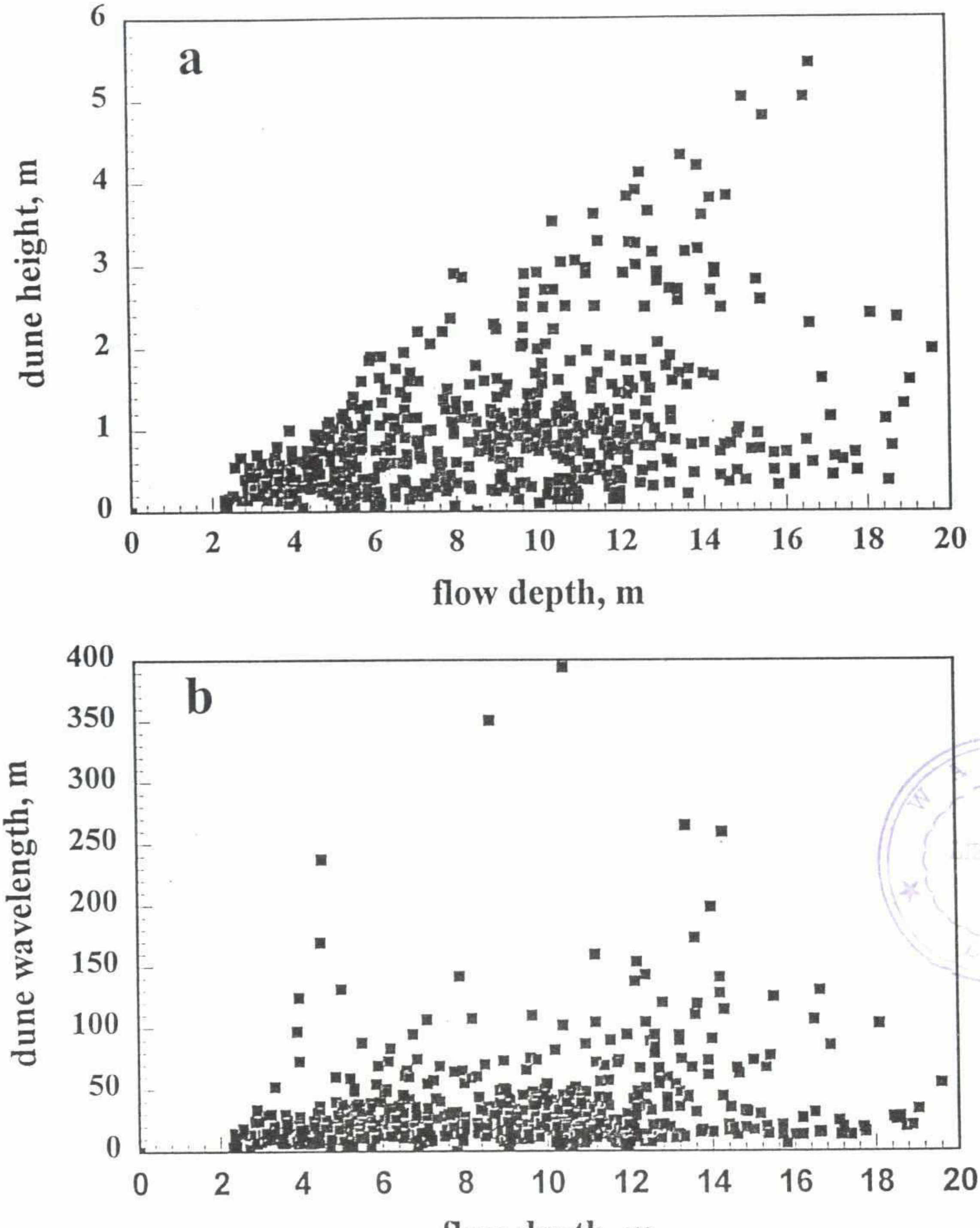


Figure 3.3 Plots of (a) dune height and (b) dune wavelength as a function of flow depth for all three study sites throughout the study period.

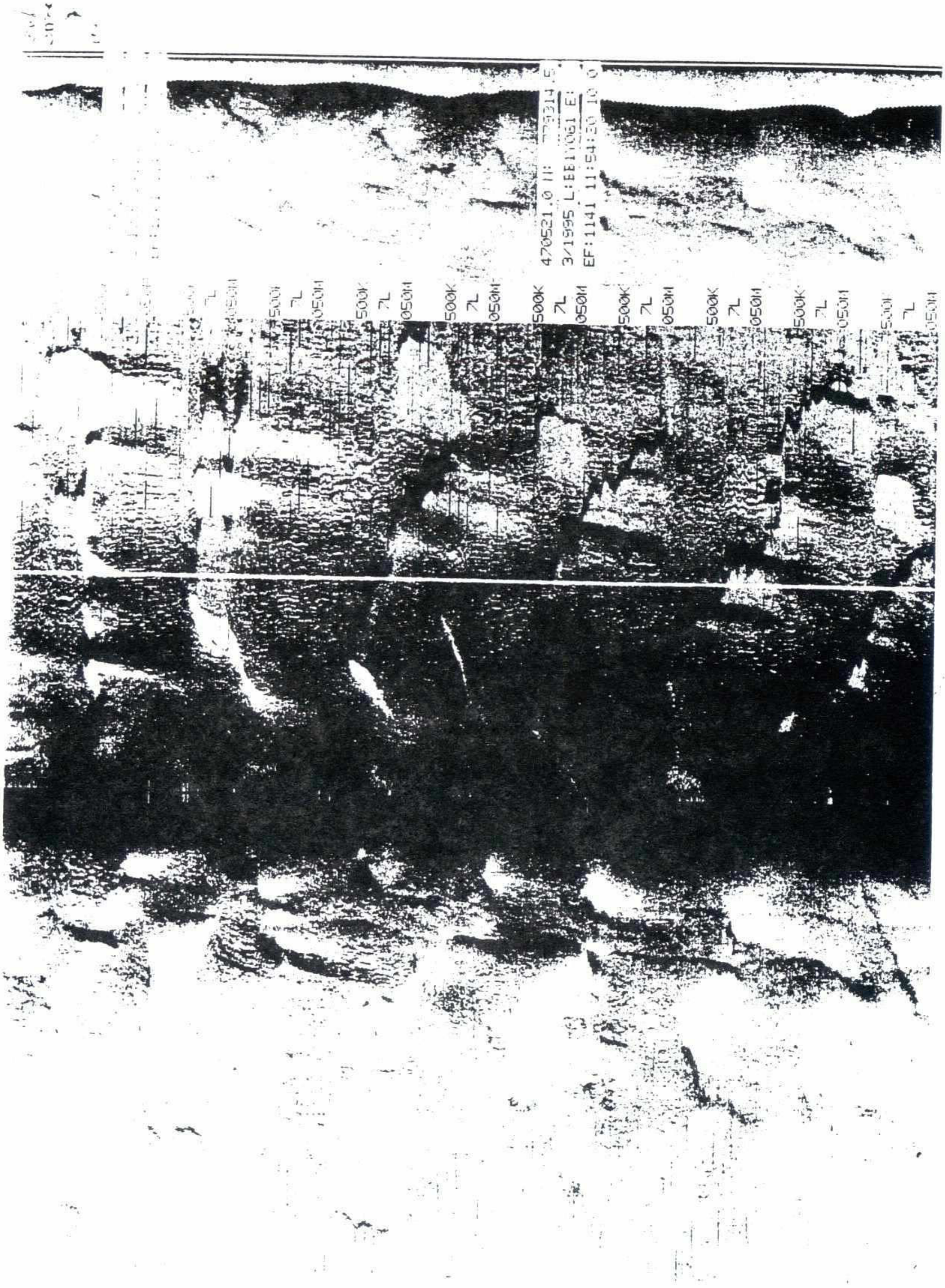


Figure 3.4 (a) Side scan sonar image obtained at low flow (March 1995) at Bahadurabad illustrating clear dune crestlines

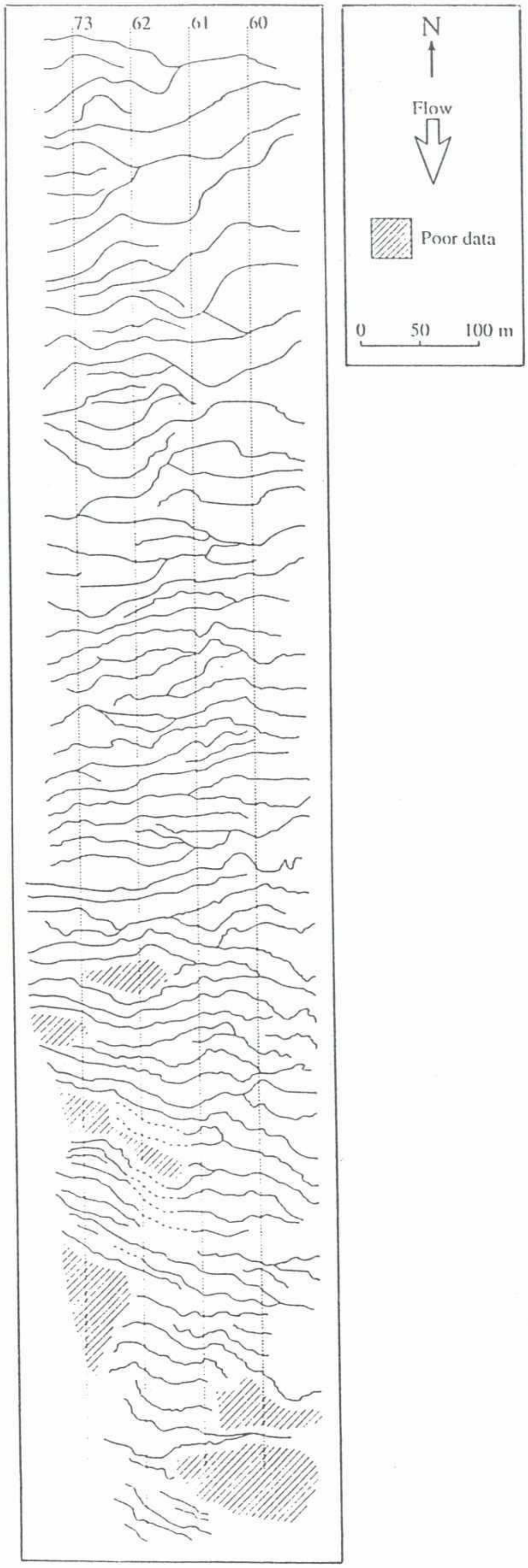


Figure 3.4 (b) Composite tracing of dune crestline morphology derived from side scan image (March 1995) showing an area approximately 1km in length and 200m wide.
Note the sinuosity of both the larger and smaller wavelength dunes

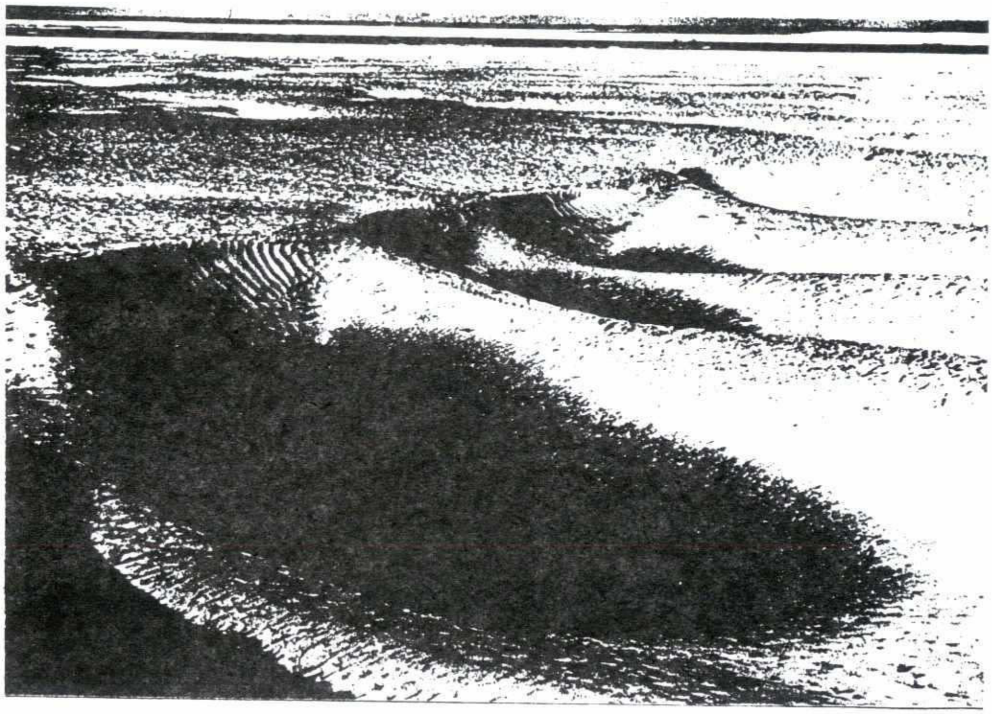


Figure 3.5 Photograph of large (h ~ 2m) dunes exposed on bar top at low flow in March 1995 illustrating a sinuous crestline with distinct spurs and troughs in the dune morphology. Bartop dunes such as these are common and illustrate that dunes are common both in the talwegs and on bar margins and tops.

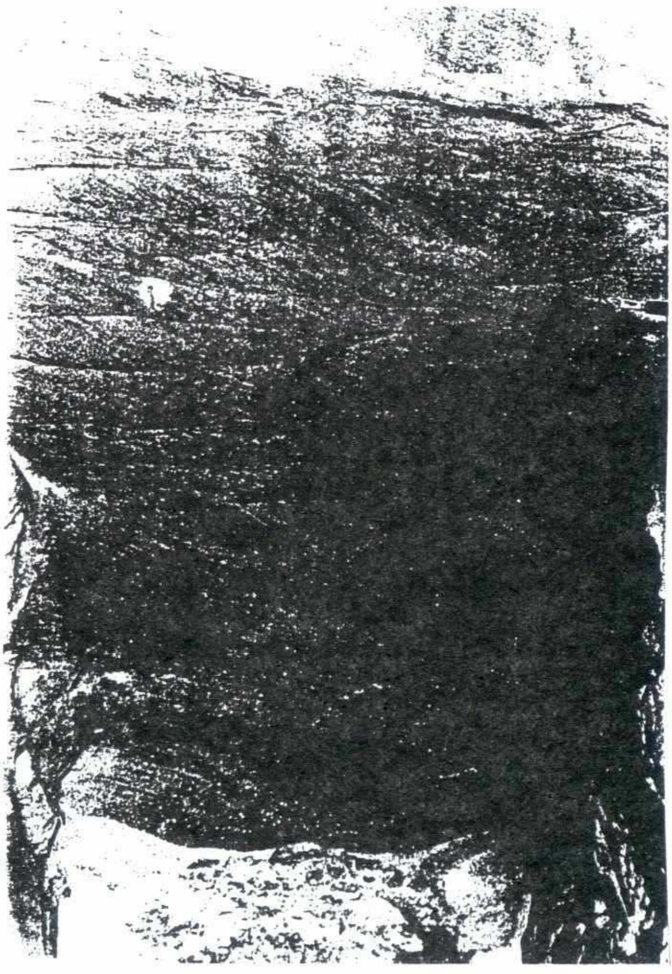
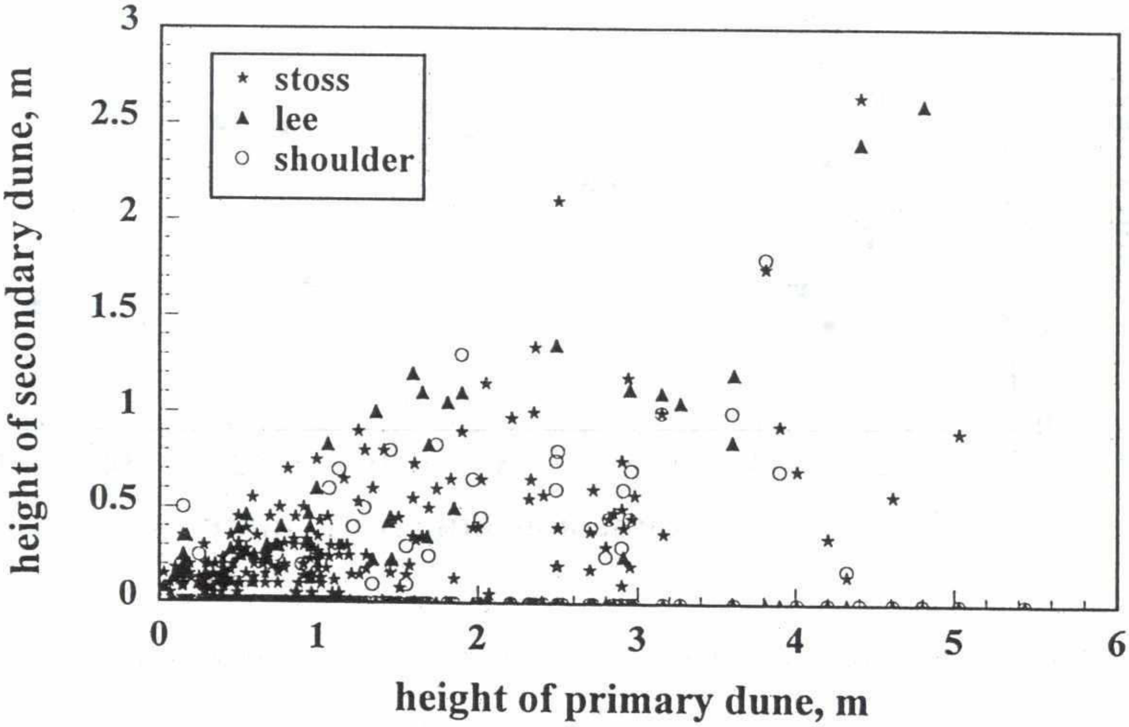


Plate 3.1 Example of the sedimentation pattern in the subsoil of the bar



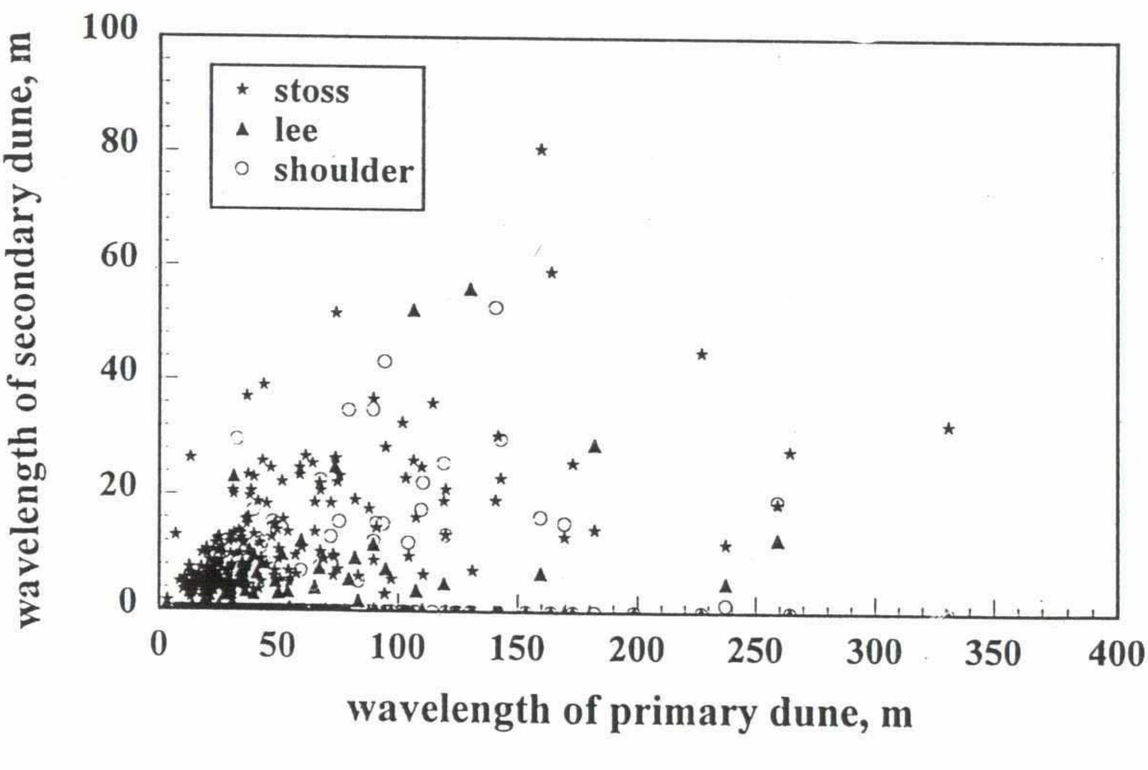


Figure 3.6 Scatterplots of (a) height of primary dunes -vs- height of secondary dunes and (b) wavelength of primary dunes -vs- wavelength of secondary dunes, subdivided according to position on the primary dune (leeside, stoss side or crestal shoulder)

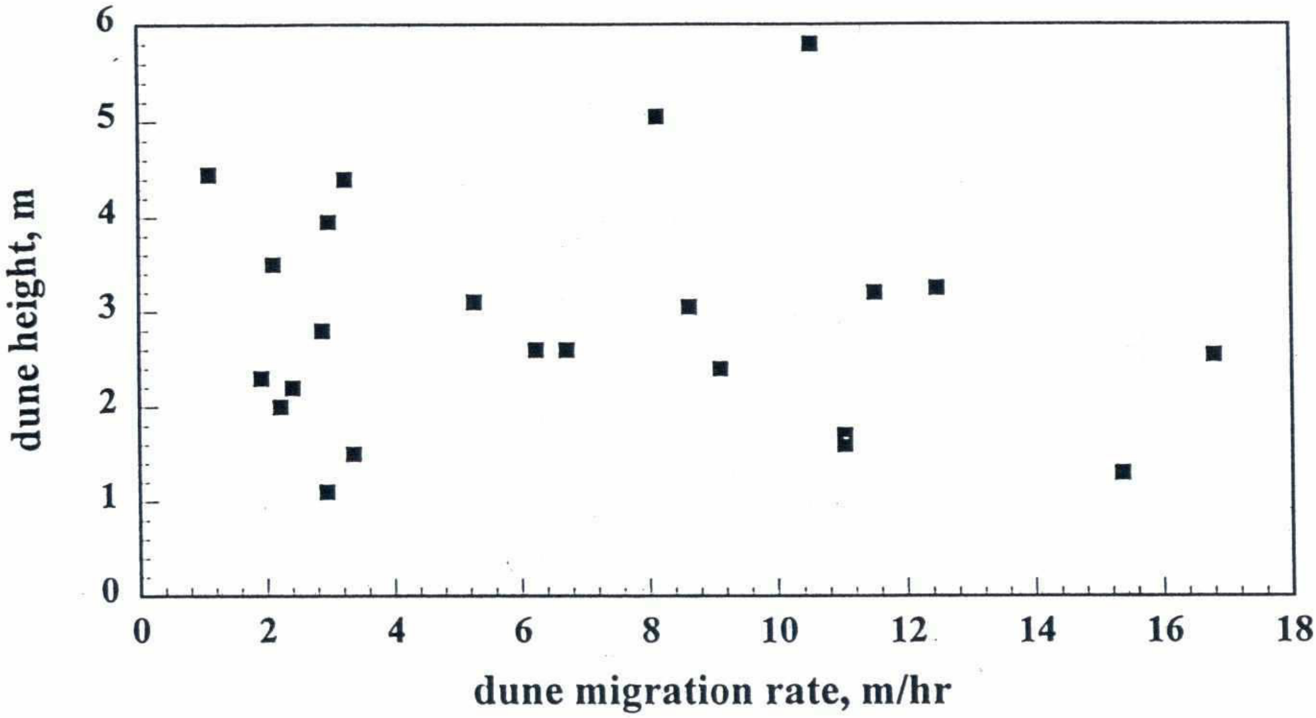
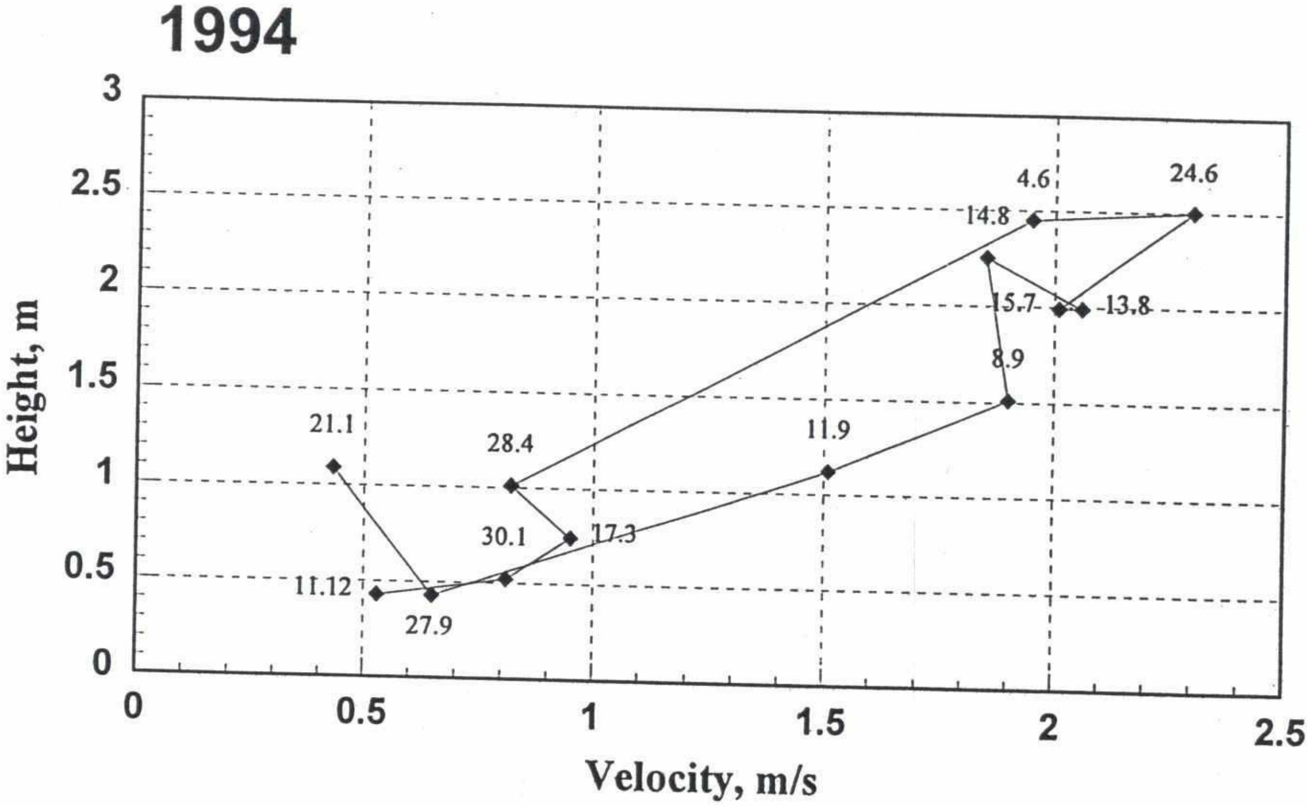


Figure 3.7 Scatterplot of dune migration rate -vs- dune height at Bahadurabad for high flow stage



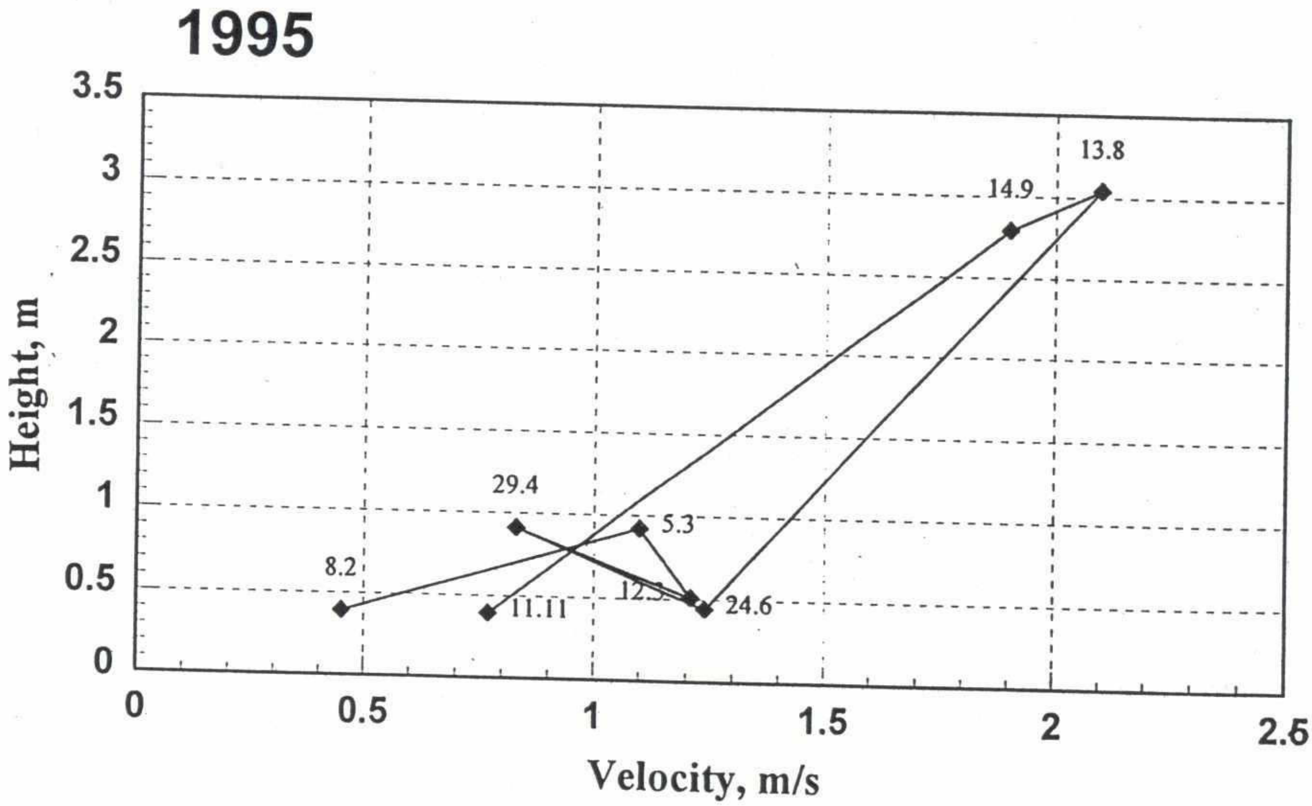
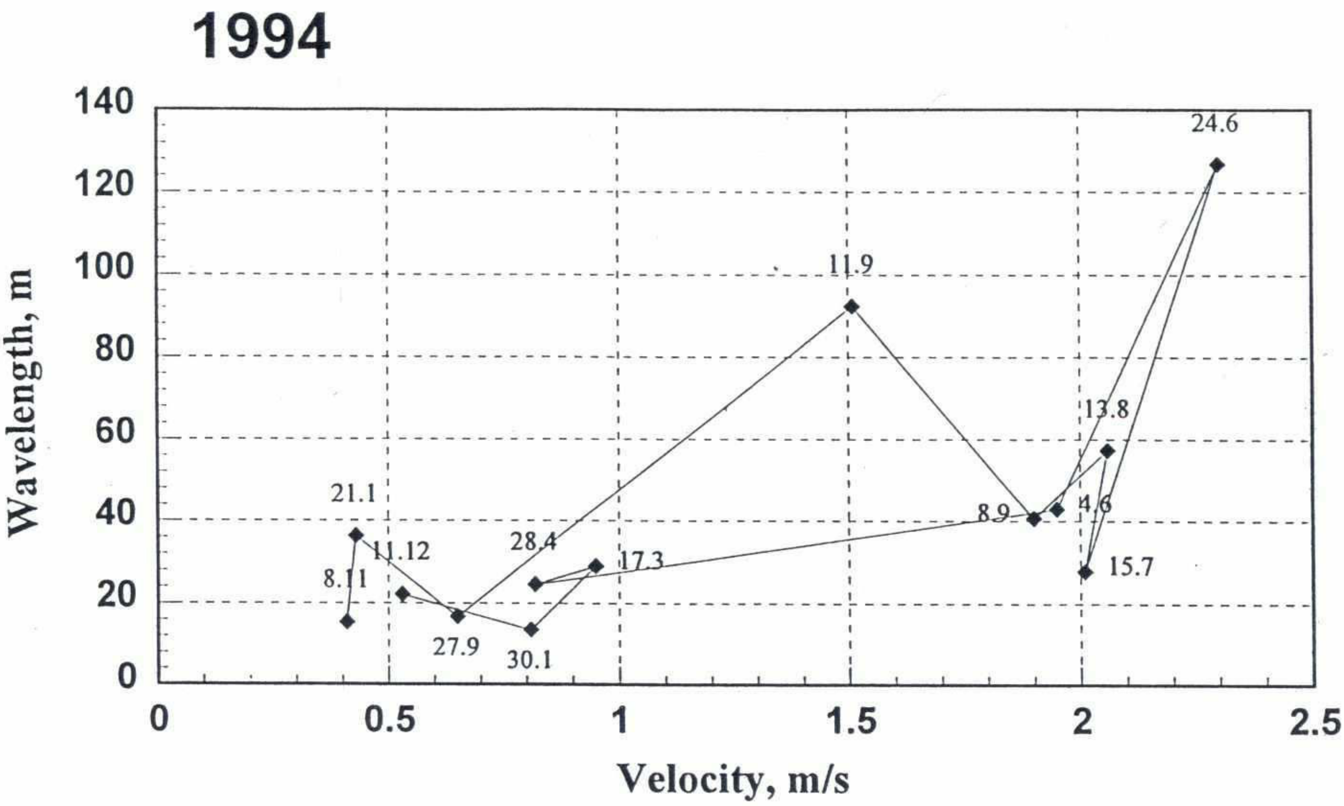


Figure 3.8 (a) Hysteresis plots for 1994 and 1995 hydrographs at Bahadurabad for dune height



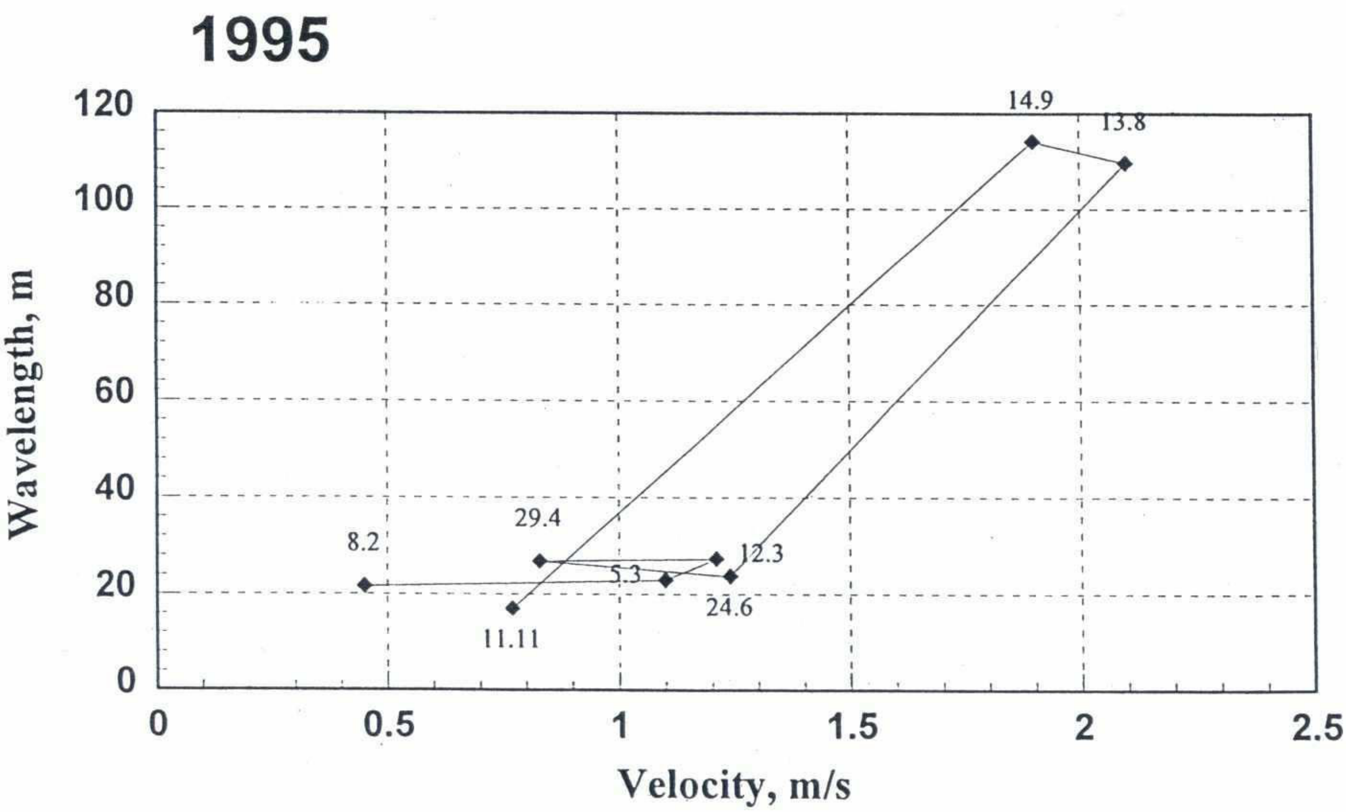
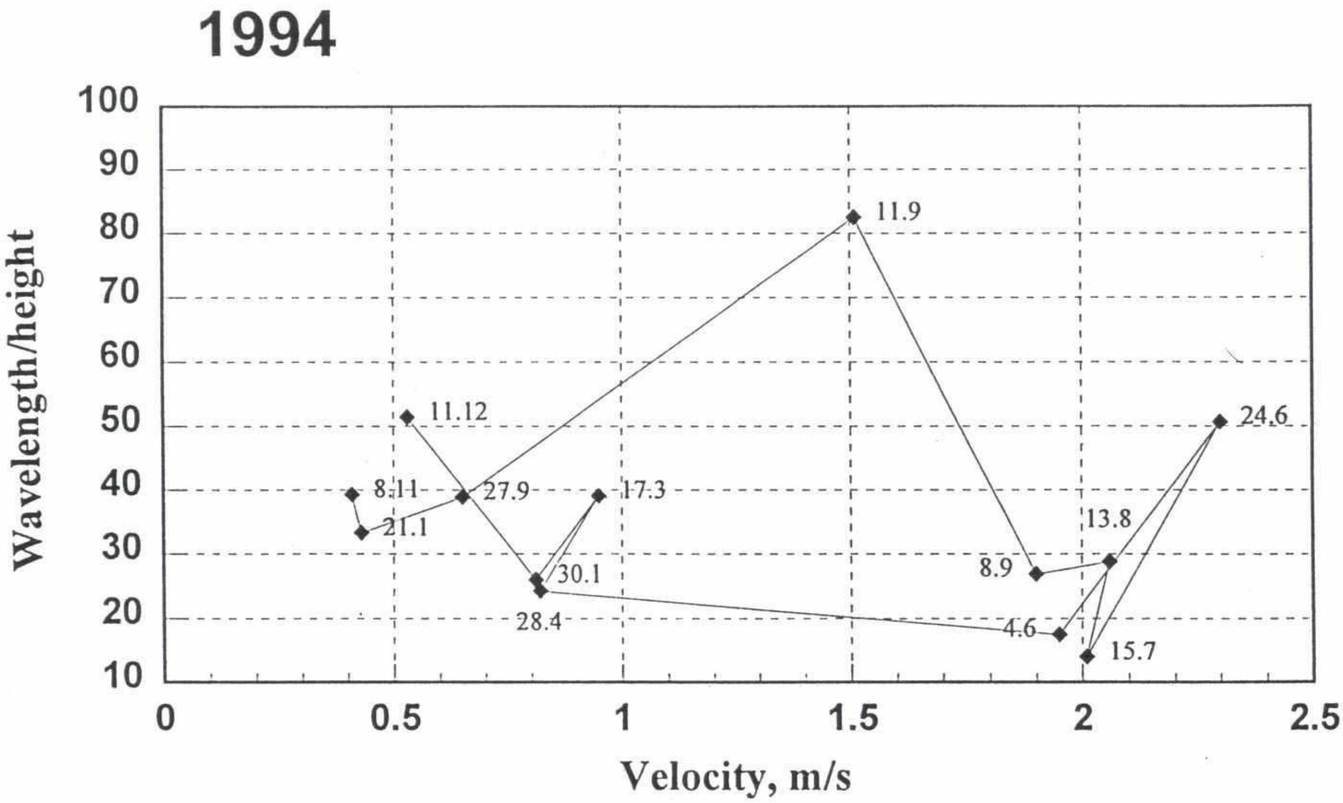


Figure 3.8 (b) Hysteresis plots for 1994 and 1995 hydrographs at Bahadurabad for dune wavelength



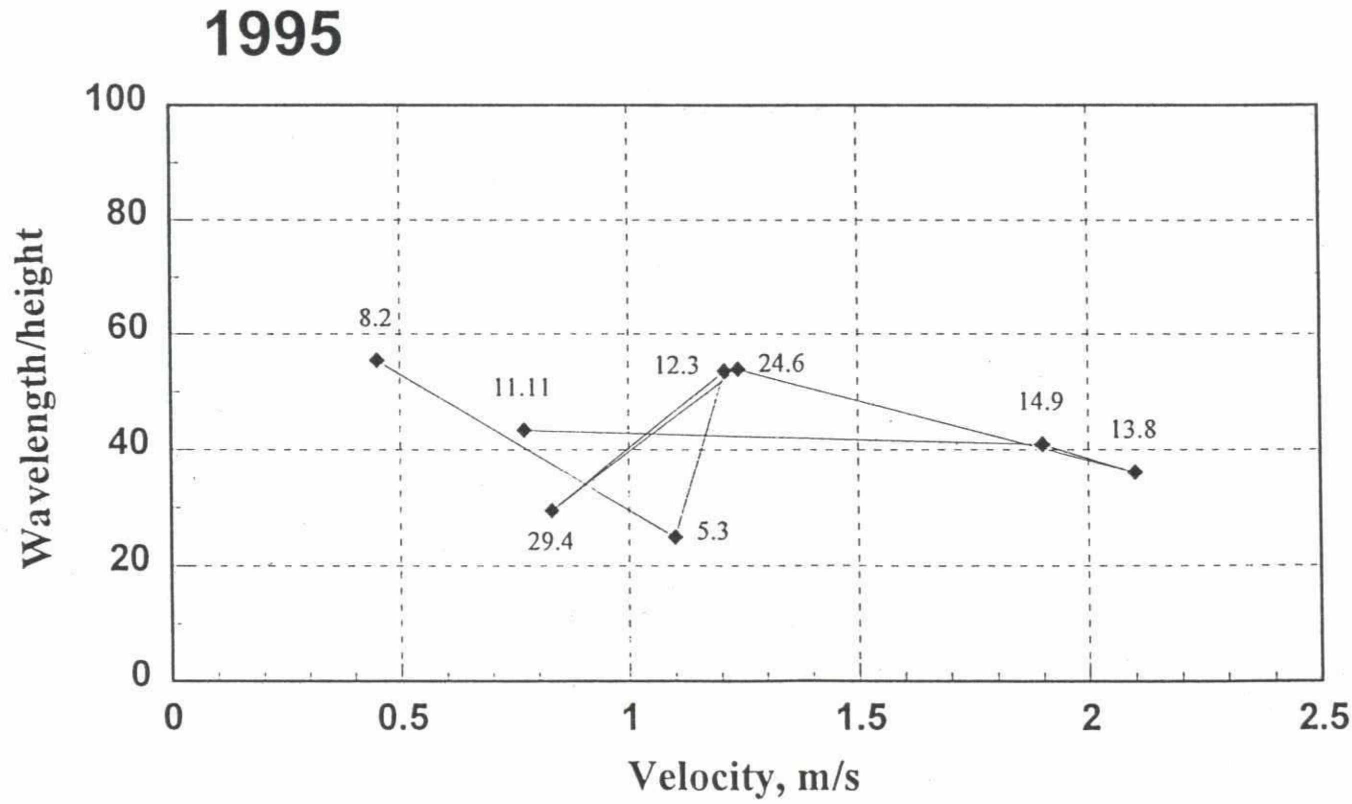


Figure 3.8 (c) Hysteresis plots for 1994 and 1995 hydrographs at Bahadurabad for dune form index plotted as a function of mean flow velocity derived from ADCP records.

a

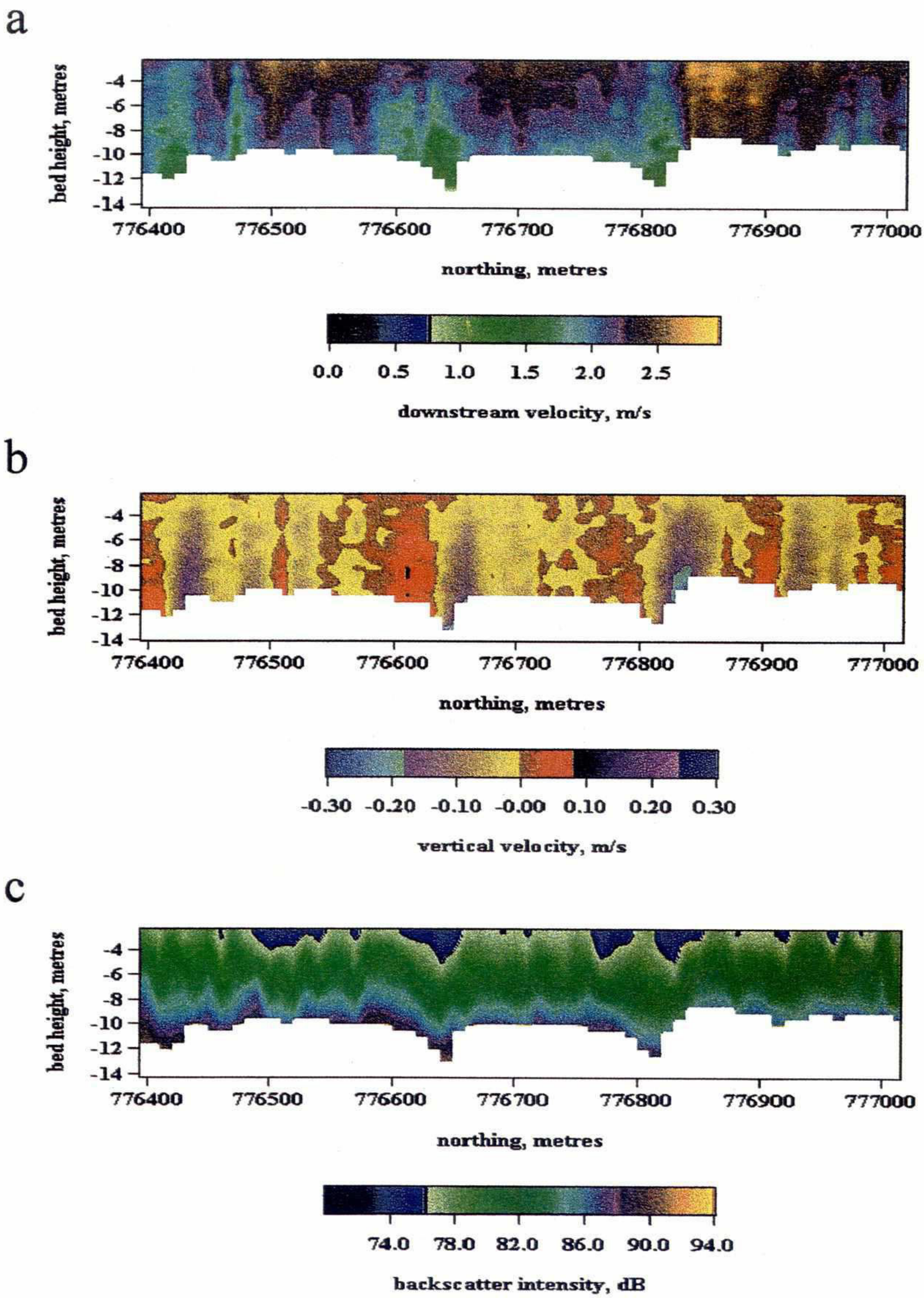


Figure 3.9 (a) Plots of downstream and vertical flow velocities and backscatter intensities over a) steep and b) low-angle leeside dunes at Bahadurabad

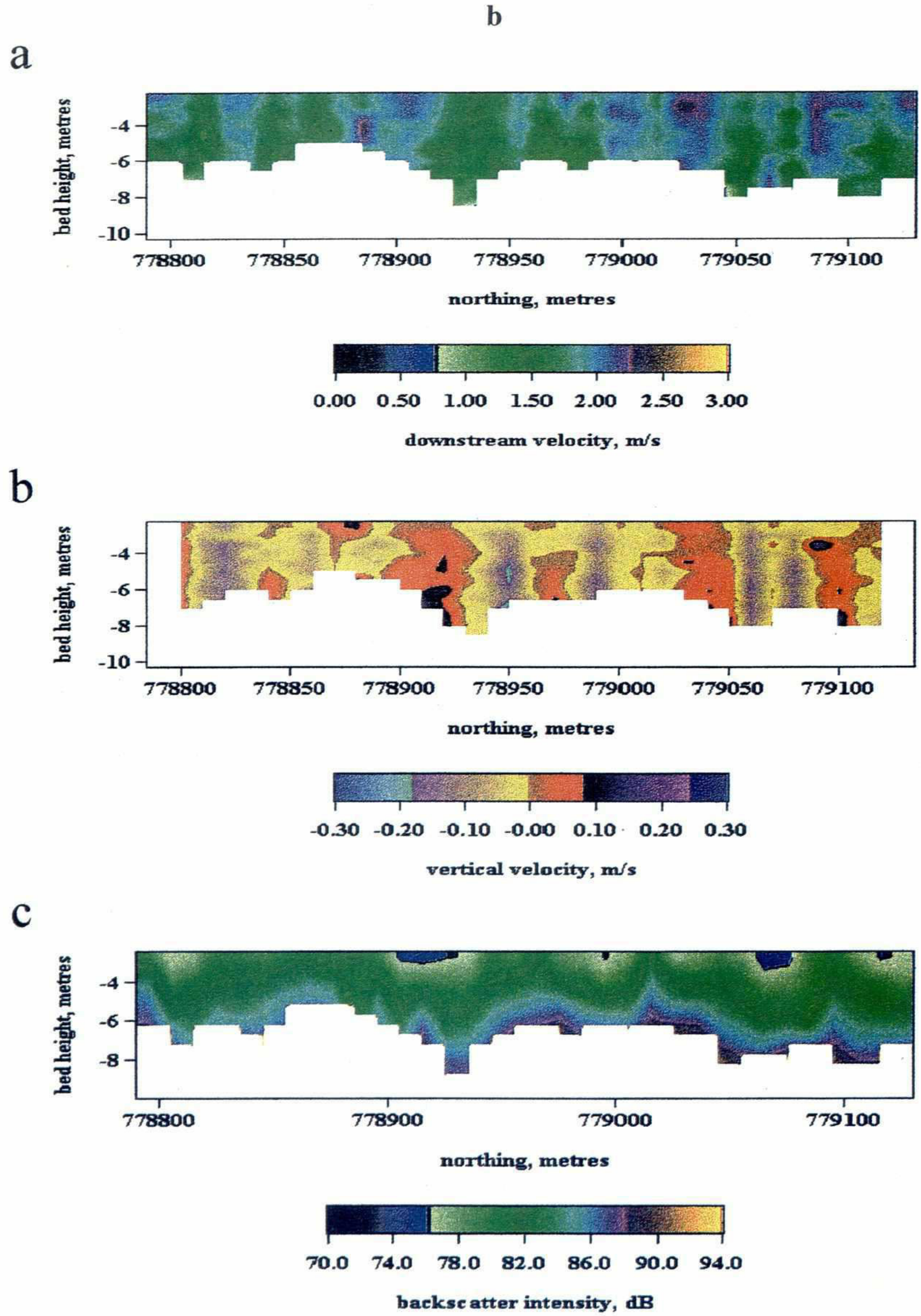


Figure 3.9 (b) Plots of downstream and vertical flow velocities and backscatter intensities over a) steep and b) low-angle leeside dunes at Bahadurabad

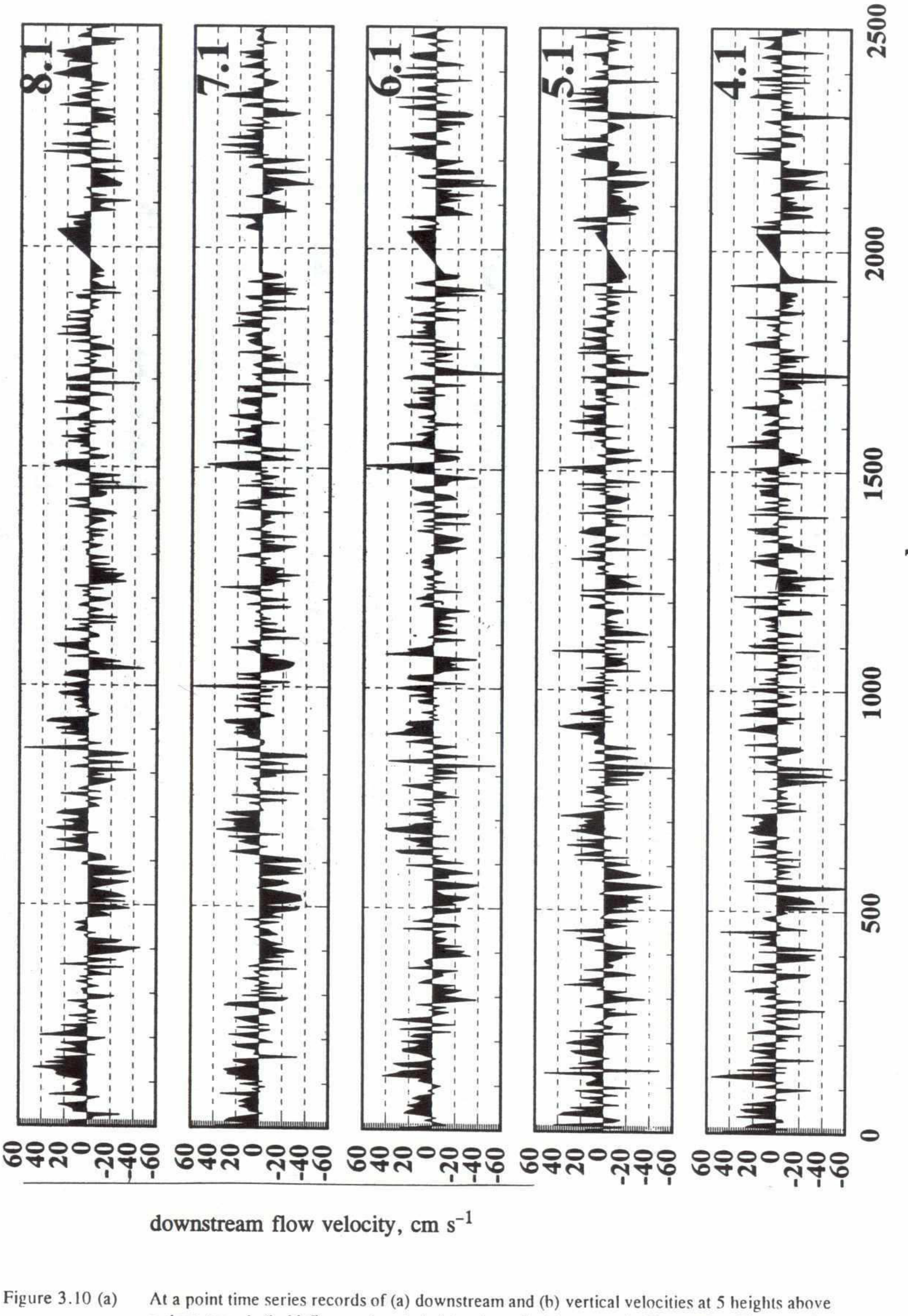


Figure 3.10 (a) At a point time series records of (a) downstream and (b) vertical velocities at 5 heights above a dune trough (bold figures denote height above bed in metres). These plots illustrate the occurrence of low downstream velocity upwellings associated with the dune leeside. Both velocities are expressed as deviations from the mean at-a-point temporal average velocity; absolute velocities are shown in Figure 3.9(a).

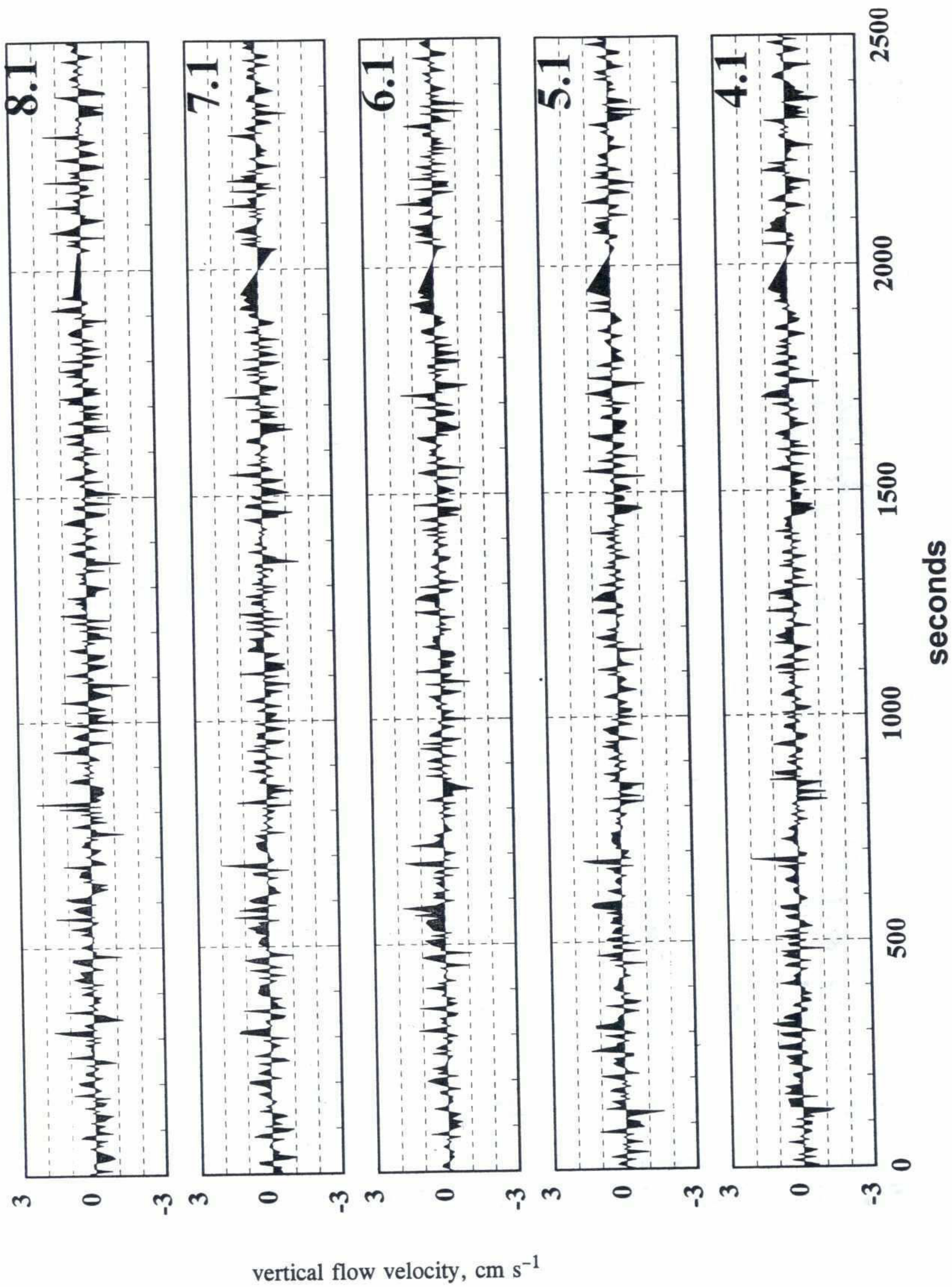


Figure 3.10 (b) At a point time series records of (a) downstream and (b) vertical velocities at 5 heights above a dune trough (bold figures denote height above bed in metres). These plots illustrate the occurrence of low downstream velocity upwellings associated with the dune leeside. Both velocities are expressed as deviations from the mean at-a-point temporal average velocity; absolute velocities are shown in Figure 3.9(a).

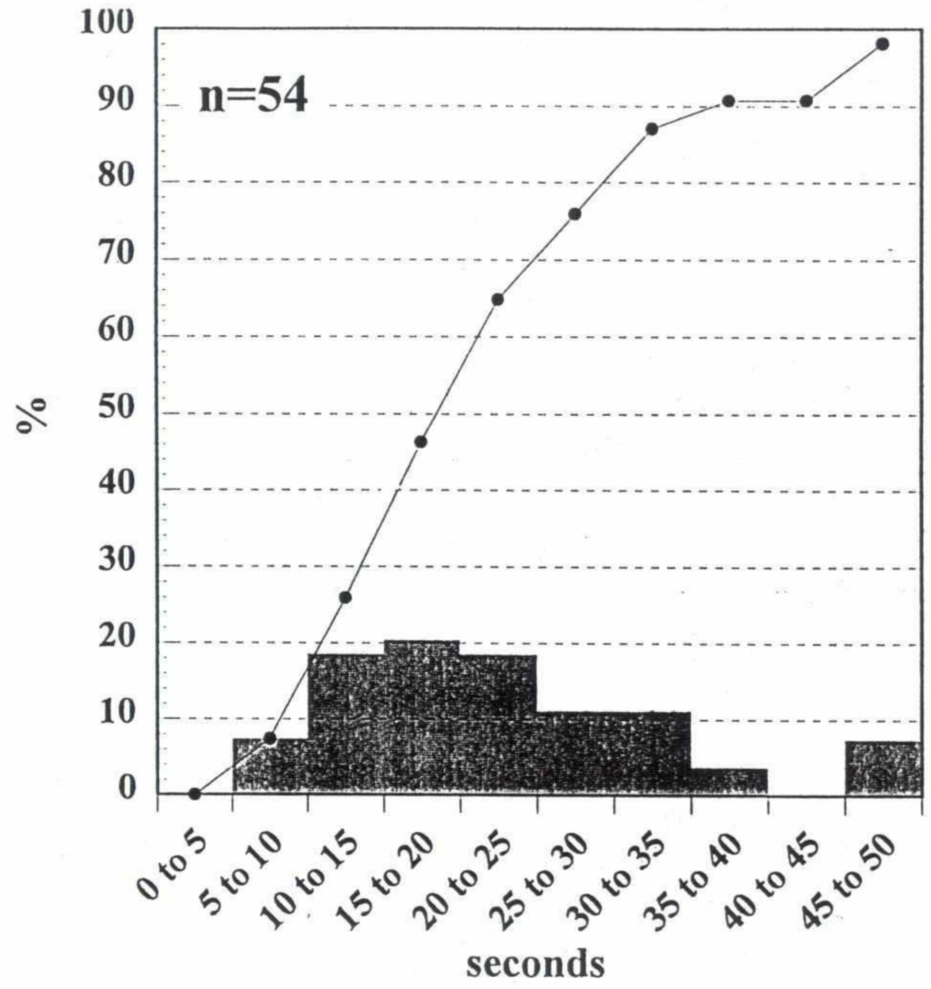


Figure 3.11 (a) Temporal occurrence of 'boils' associated with dunes at Bahadurabad, August 1994 estimated from: a) visual records of 'boil' surface upwellings and b) spectral analysis of ADCP downstream and vertical velocity records over a dune crest and trough.

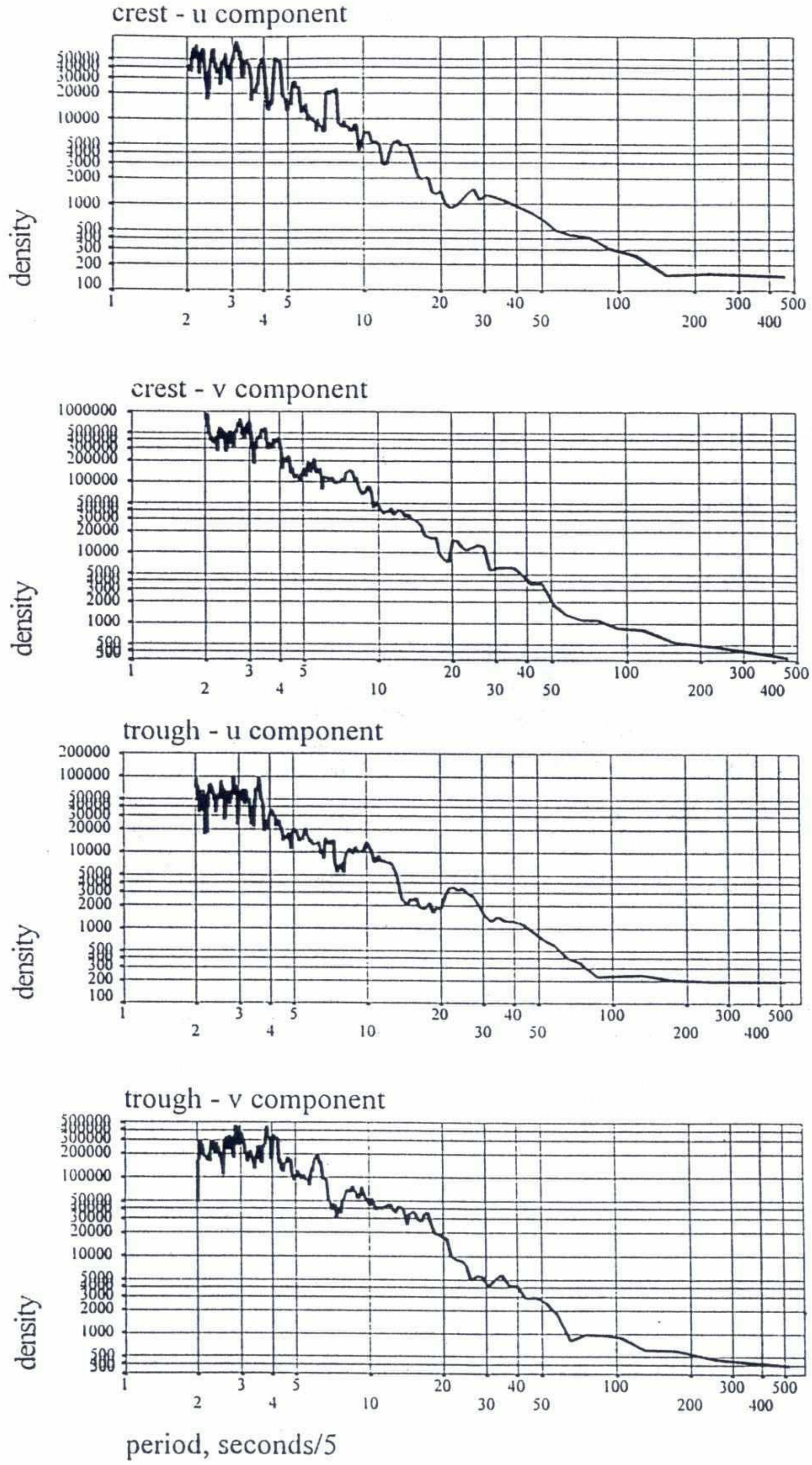


Figure 3.11 (b) Temporal occurrence of 'boils' associated with dunes at Bahadurabad, August 1994 estimated from: a) visual records of 'boil' surface upwellings and b) spectral analysis of ADCP downstream and vertical velocity records over a dune crest and trough.

4 Resistance to flow

4.1 Introduction

This Chapter deals with resistance to flow. The resistance to flow is often expressed by a roughness coefficient, either the Chézy coefficient or the Manning coefficient. As was discussed in Study Report 1 (RSP, 1993?), there were some important questions regarding the resistance to flow of the main rivers in Bangladesh to tackle under the River Survey Project. Firstly, very low values for the resistance to flow of the main rivers in Bangladesh had to be used during various studies in the past (FAP1, FAP9B, FAP21/22), notably Chézy C-values in the order of 80 to 100 $m^{1/2}/s$ and more. Otherwise it was not possible to reproduce observed or extrapolated stages with known discharges. An explanation for this is needed. Secondly, for low flow conditions a much larger resistance to flow (C-values in the order 50 $m^{1/2}/s$) is observed (see Klaassen et al, 1988). Also this should be explained.

Before discussing some results of the project, first the roughness coefficients normally used will be discussed here. This will only be done in a summarized form. More extensive introductions into flow resistance can be found in Jansen et al (1979), Chang (1988) and van Rijn (1990). The flow in an alluvial river is a free surface flow in channels with typically large width/depth ratios. Along a single flow line the one-dimensional equation of the depth averaged motion reads (Jansen et al, 1979):

$$\frac{\delta u}{\delta t} + u\,\frac{\delta u}{\delta s} + g\frac{\delta h}{\delta s} + g\frac{\delta z_b}{\delta s} + g\frac{u|u|}{C^2.h} = 0 \qquad (4.1)$$

in which

- u = depth-averaged flow velocity (m/s)
- s = distance along flow line (m)
- t = time (s)
- z_b = bed level (m)
- g = acceleration by gravity (m/s^2)
- h = water depth (m)
- C = Chézy coefficient ($m^{0.5}/s$)

The last term of Equation (4.1) is the resistance term which can be written as a function of the shear stress τ:

$$\frac{\tau_b}{\rho.g.h} = \frac{u^2}{C^2.R} \qquad (4.2)$$

in which:

- R = hydraulic radius (m); often in wide alluvial rivers it is assumed that R = h
- u = cross-section averaged flow velocity (m/s)
- ρ = density (kg/m^3)

The Chézy coefficient is a flow resistance coefficient in Equation (4.3) which follows from (4.2) after substituting $\tau_b = \rho$.g.h.i:

$$\bar{u} = C\ .\ \sqrt{R\ .\ i} \qquad (4.3)$$

In a similar way the Manning coefficient, n, is defined as:

$$\bar{u} = \frac{1}{n} \cdot R^{2/3} \cdot i^{1/2} \tag{4.4}$$

The Manning coefficient can be expressed in the C coefficient:

$$n = \frac{\phi}{C} \cdot R^{1/6} \tag{4.5}$$

in which:

ϕ = 1.49 for English units, 1.00 for SI units.

The use of a Manning coefficient has some advantage over the Chézy coefficient as it varies less with changing stage.

In the simple case of a wide flume with a movable bed the Chézy coefficient is mainly determined by the hydraulic roughness induced by bed forms and the grain surface. In flumes also the roughness of the smooth walls of a flume also contributes to the measured Chézy coefficient, but in wide rivers the influence of the bank erosion is usually less. In a river the total flow resistance is determined not only by bed forms and grain roughness. In this chapter some aspects of the total resistance to flow are described and the influence of the other components is estimated.

4.2 Contributions to resistance to flow

Traditionally resistance to flow in alluvial flow is ascribed to a combination of particle roughness and form roughness. This is not necessarily applicable for wide untrained rivers. The overall flow resistance in a river can be studied in a stretch between two water-level gauges. In large rivers such a stretch has often a length of more than ten kilometres. From such studies in the Zaire River, it was concluded that the bedforms are only part of the flow resistance and that bars or other large-scale riverbed features (even islands) contribute to it (Peters, 1993 and 1994). The local flow resistance can be studied from detailed flow velocity verticals along a flow line. The local flow resistance is often dominated by the presence of bedforms. The overall flow resistance, however, is also influenced by additional contributions, such as:

- lateral exchange of momentum,
- decelerating flow, and
- (secondary) flow patterns in bends.

These contributions are due to irregularities of the river bed and banks, in particular pronounced in braided rivers both during floods and during lower flow stages. In smaller rivers, in particular the distributaries being used for agriculture during the low-flow season, energy losses due to vegetation might also be considerable in some periods. No separate study was done into the latter contribution. Some studies were done however to assess the contribution of the other components to the overall resistance to flow. These studies were either field investigations or theoretical assessments of the possible magnitude of some contributions. In this Chapter some results are presented.

Particle roughness and bedform roughness

Different methods for assessment of the resistance to flow due to particle and form roughness are available. Here the frame-work proposed by van Rijn (1990) is used. The Chézy coefficient is expressed as a function of the water depth h and a roughness value (height) k_s, according to the following equation:

$$C = 18 \log (12\,h / k_s) \qquad (4.6)$$

The roughness height k_s is a function of the particle size and the dune dimensions:

$$k_s = 3\,D_{90} + 1.1\,\gamma_d\,H\,(1 - e^{-25\,H/L})$$

where γ_d = form factor (-)
H = dune height (m)
L = dune length (m)

The form factor γ_d expresses the influence of the dune form on the roughness height. Ogink (1988) performed flume experiments to study the influence of the dune form on the resistance to flow. A considerable reduction of roughness height occurs for gentle leeside slopes because flow separation (the main cause of energy losses downstream of dunes) is less pronounced or even absent. Figure 4.1 shows the value of gamma_d as a function of the leeside slope characteristics according to Ogink (1988).

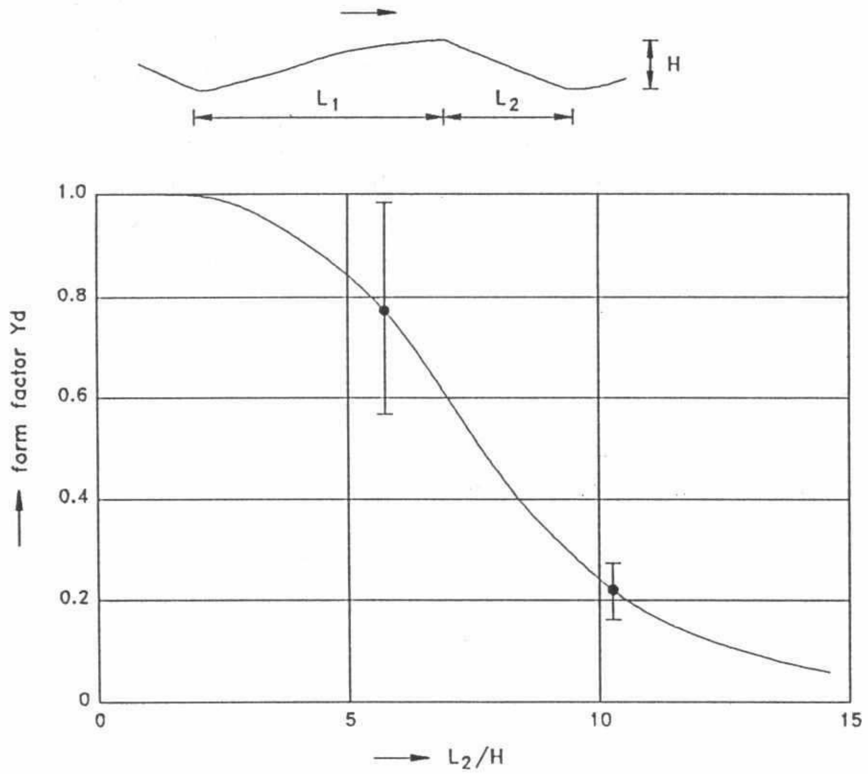


Figure 4.1 Form factor of dunes as function of the leeside slope (Ogink, 1988)

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For the interpretation of this Figure in relation to the conditions in the Jamuna River it is of interest to relate the available data on leeside slopes (Figure 3.2) to the parameter of the horizontal axis (cotangent of the leeside slope angle). According to Figure 3.2 about 35% of the leeside slopes are between 3 and 6 degrees. For an average value of 4.5 degrees the cotangent corresponds to about 13. According to the above results of Ogink (1988) the contribution of the form roughness would decrease to about 10% only. Hence in the Jamuna River the contribution of the form roughness to the overall roughness might be much smaller than one would estimate on the basis of the dune dimensions only. This conclusion was reached earlier by Klaassen et al (1988).

Dunes in large, wandering alluvial rivers with mild slope and in a natural state exhibit shapes and sizes that do not fit traditional approaches or theories and bed-form predictors fail (Delft Hydraulics, 1986 M2130/Q232). It means that the slope of the leeside of the dune is so gentle that no flow separation occurs (see Section 3.8 and SPR 19 Bars and bed forms in the Jamuna River). The riverbed is hydraulically smooth and rather high Chézy values are found as function of the height and the length of the dunes. These rounded dunes have also been found in the Jamuna River.

To study resistance to flow in detailed slope measurements were carried out in a relatively straight river reach downstream of Bahadurabad during the years 1993, 1994 and 1995 (See *Annex 3)* and *RSP Special Report 4.* In particular the surveys in 1995 were important when in addition to bathymetric soundings and discharge measurements, also float tracking was done. Form the bathymetry in 1995 it was concluded that the effect of contributions to resistance to flow other than particle and bedform roughness was minor. A detailed analysis was carried out of the measurements for which also float tracking results were available, from which it was concluded that the Chézy-values were in the order of 70 $m^{1/2}/s$. These could be explained fully from grain roughness and bedform roughness corrected for the gentle leeside of the bedforms, making the contribution of the bedform roughness almost negligible. Tentatively it may be stated that during high stages there may still be bedforms (see Chapter 3 of this Annex or Julien & Klaassen, 1995), but due to their gentle lee-sides they have a minor contribution to the resistance to flow.

Lateral momentum exchange

The possible effect of lateral momentum transfer was assessed analytically. The lateral exchange of momentum reaches maximum values near strong transverse velocity gradients in the bathymetry of a river. A typical situation occurs in a meandering river with a floodplain. On the transition of the main riverbed to the floodplain often a strong transverse gradient in the bed occurs during floods when the floodplain is inundated. For this situation Ogink (1985) compared different approaches to estimate the reduction in the discharge in the main river.

Using the approach of Evers the effect of transverse exchange of momentum can be estimated by a balance of forces in a stream tube. For the situation sketched in Figure 4.1 this balance reads:

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$$B_1 \cdot \tau_1 - h_1 \cdot \tau_{s,1-2} + h_3 \cdot \tau_{s,3-1} = \rho \cdot g \cdot A_1 \cdot i \tag{4.7}$$

in which:

A	= cross-sectional area of stream tube	(m^2)
B	= width of streamtube	(m)
h	= water depth	(m)
i	= water-level slope	(-)
τ	= shear stress	(N/m^2)

The shear stress is a function of u^2 and the Chézy coefficient:

$$\tau_1 = \rho \cdot g \cdot \frac{u_1^2}{C_1^2} \tag{4.8}$$

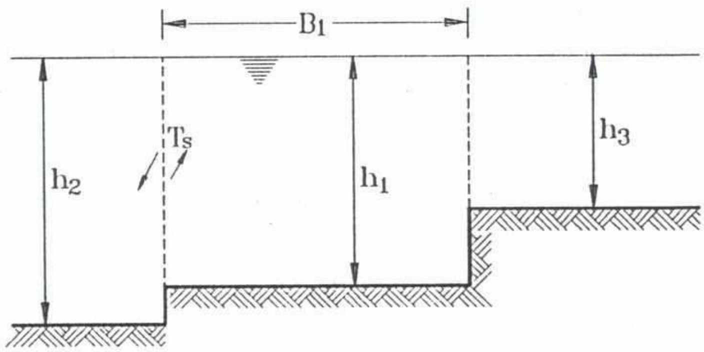
The lateral shear stress is calculated with:

$$\tau_{s,1-2} = c_s \cdot \rho \, (u_2 - u_1)^2 \tag{4.9}$$

in which:

c_s = coefficient (-), its value is assumed at 0.02.

In the same way $\tau_{s,3-1}$ is defined.



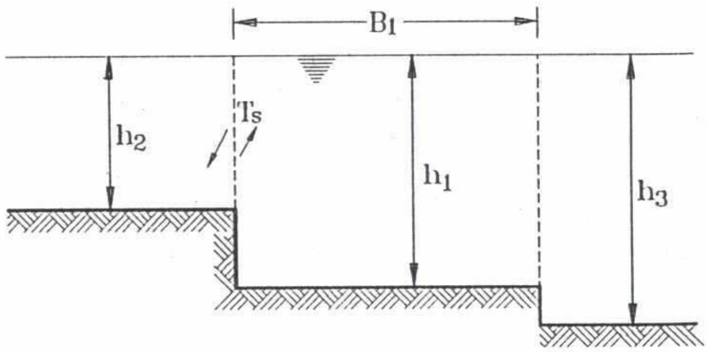


Figure 4.2
Schematization to estimate lateral momentum transfer

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For another situation as sketched in Figure 4.2 the minus and plus signs in Equation (4.8) can be different. In general, the contribution of the lateral shear stresses is only a few percent

of the bed-shear stress. This contribution is often negligible. But locally, for example near a steep (eroding) bank of an inundated char, the lateral shear stresses can contribute 10 to 20% of the bed-shear stress.

A bathymetric survey of a channel north of Bahadurabad showed that bedform heights vary considerably in a channel cross-section. The analysis of the water-level gauges near North Harindhara and Resposu showed that the overall resistance can be attributed almost completely to the rounded dunes. The contribution by lateral momentum transfer can be neglected in that area under moderate flow conditions. In the survey area the flow bifurcated around a bar. This bifurcation did not induce significant additional flow resistance.

Flow deceleration

In a river the flow decelerates often very gradually and such a deceleration does not contribute to the flow resistance. But a sudden deceleration as can occur in the flow mixing downstream of a confluence creates additional energy dissipation and increases the flow resistance in a rather small area of the total river cross-section.

An analysis of measured flow velocity verticals in the transect near Bahadurabad showed the influence of accelerations and decelerations on the flow-velocity distribution in a vertical. In a decelerating flow the shear stress on the riverbed will be less than the shear stress in a uniform, steady flow. However, the overall effect of decelerations on the flow resistance will often be small in the main rivers of Bangladesh.

Bend flow

In a river bend more energy is dissipated than in a straight channel with the same hydraulic conditions (depth, flow velocity and hydraulic roughness). This increased resistance reduces the flow velocities in the bend and this increases the water level at the upstream side of the bend. This induces a backwater effect, which represents an extra storage of potential energy which supplies the excess energy dissipation through the bend. This increase in energy expenditure in a bend can be attributed to internal fluid friction due to secondary currents and increased transverse shear stresses, specially near the outer boundary. In Chang (1988) these additional energy losses are discussed and a calculation method is proposed to estimate these effects: this method can be used in further studies. In Section 4.3 an overall method for the assessment of bends is discussed, which suggests that especially during lower flow conditions (when the flow of the water becomes more turtuous) bend losses might not be negligible. They can possibly explain the increase in roughness when the stage falls. Another aspect that plays a role during low flow conditions is the increased sinuosity of the flow. Bars that have emerged in the second order channel force the flow in a more curved pattern, and this increase in length is translated into an (apparent) increase in resistance to flow, which may partly explain the observed behaviour.

The above exploring computations show that the effect of lateral diffusion and flow deceleration on the overall resistance to flow is probably negligible for these wide rivers. During low flow, when the resistance to flow increases the effect of the non-uniformity of the cross-sections, the effect of bars and the form roughness (steeper lee-sides?) may be larger. The influence of lateral momentum transfer remains very small. Estimates of the other contributions could not be assessed fully, but in view of the measured C-value of about 70 $m^{1/2}/s$ (to be compared with 80 to 100 mentioned before) their contribution can only be significant in exceptional cases (depending on the bathymetry).

To summarise the foregoing, it seems that the bedform roughness is the main component to the hydraulic resistance in the Jamuna River and that in moderate flow conditions the contribution by lateral momentum transfer and by bars or other components can be neglected.

4.3 Overall hydraulic resistance

In the recent past expressions for the resistance to flow of some of the main rivers have been proposed. Klaassen et al (1988) used at-a-station-relations (relations between the average depth and the width versus the discharge) to derive an expression for the overall resistance in terms of the Chézy coefficient in the Jamuna River.

Furthermore an expression for the resistance to flow in the Jamuna River was tested recently in the 2-D morphological modelling for the Jamuna Bridge (DHI, 1996). To reproduce the overall resistance to flow correctly and to prevent a too smooth bathymetry over the chars, the following expression was introduced. This expression consists of two parts, notably the "average" value of C (which is required to simulate the correct slope) and the relationship between C and the local water depth. Here mainly overall resistance to flow is discussed, but the approach used by Klaassen et al (1988) can be applied to provide some support for the expression used by DHI (1996) as well. See later in this Section.

In an overall analysis the Chézy coefficient can be estimated from the Chézy equation for each channel of the braided river, which reads as:

$$Q = B \cdot C \cdot h^{1.5} \cdot i^{0.5} \tag{4.10}$$

In this equation the at-the-station relations for the channel width, B, and the channel depth, h, are substituted. Coefficients in the at-the-station relations for the Jamuna River which are slightly different from the ones proposed by Klaassen & Vermeer (1988), have been determined in *SPR 7, Geomorphology and channel dimensions*. These relations read:

$$B = c_1 \cdot Q^{0.54} \tag{4.11}$$

and

$$h = 0.84 \cdot Q^{0.21} \tag{4.12}$$

Here a coefficient $c_1 = 11.5$ is used in the relation between B and Q instead of the value of 10.46 which has been published in SPR 7, because the latter was determined from regression analysis on log values and a regression analysis on the linear values provides an more appropriate value, notably 11.5.

The equation resulting after introducing the at-a-station-relations reads:

$$C = 0.137 \cdot Q^{0.145} \cdot i^{-0.5} \tag{4.13}$$

9Q

The overall water-level slope in the Jamuna River between Bahadurabad and Sirajganj varied in 1993 between 7.10^{-5} and 8.10^{-5}. The flow does not follow a straight line between those places: therefore the actual water slope after correction for this minor sinuosity is slightly less, notably between 6.10^{-5} and 7.10^{-5}. Using these values for the slopes a relation between the overall C and Q can be determined, which is shown in Figure 4.3. The overall resistance to flow apparently increases with the discharge in a channel.
Equation (4.13) is valid if the discharge is below bankfull discharge. Furthermore Equation (4.13) calculates the C-value per channel and this value can deviate from the overall C-value. This can be seen in Figure 4.3.

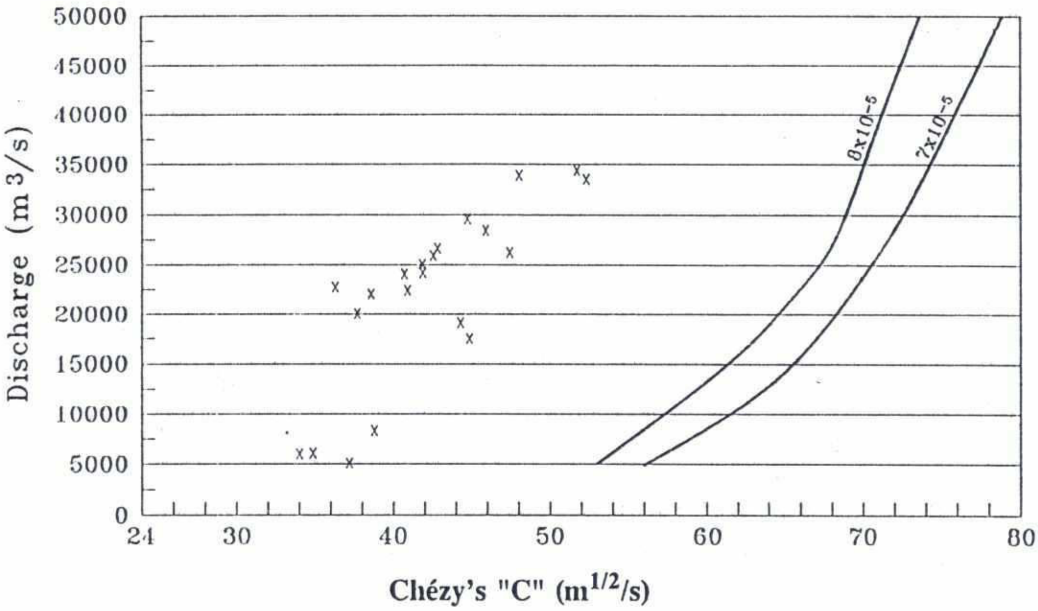

Figure 4.3 Chézy coefficient as function of the discharge in the Jamuna River in 1994

This difference depends on the number and the size of the channels in a cross-section. An expression for the overall C-value when the cross-section consist of n channels is presented hereafter:

$$C_0 = \sum_{j=1}^{j=n} C_j \cdot \frac{A_j \cdot \sqrt{R_j \cdot i_j}}{A_0 \cdot \sqrt{R_0 \cdot i_0}} \qquad (4.14)$$

in which A = cross-sectional area (m^2), R = hydraulic radius (m) and n = number of channels in a cross-section. Especially if a cross-section contains many small channels than the difference between the C-value per channel and the overall C_0 can be considerable. For example the standard BWDB cross-section near Bahadurabad in 1995 had in total eight channels of which three main channels and five minor channels, which leads to major differences.

The overall C-values as a function of the total discharge in 1994 in Figure 4.3 is similar to a figure presented in Klaassen et al (1988). The overall Chézy coefficient varies between 20 and 100 $m^{0.5}/s$ in the main rivers, if the overall water-level slopes are used. This example of the difference between overall C-values and the C-value per channel shows the importance of a clear definition how C-values have been calculated.

In the study of the rating curves in Jamuna River at Bahadurabad the Chézy coefficients for the left and the right channel separately were determined from the local water-level slope in the 1993 to 1995, see Figure 4.4. It was found that the Chézy coefficient does not differ much between both channels. Therefore it was not recommended to make this distinction.

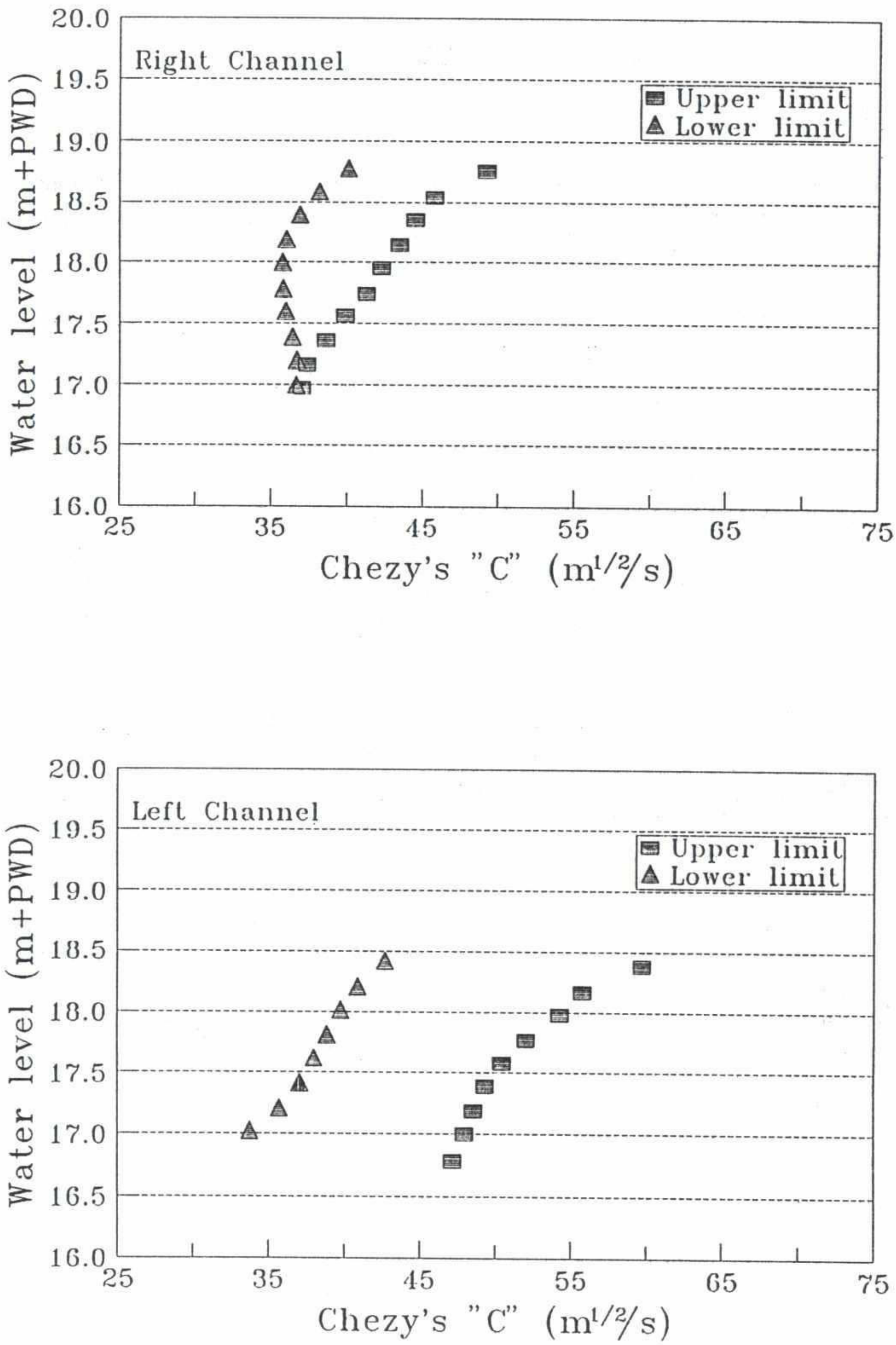

Figure 4.4 Chézy coefficient in the right and the left channel near Bahadurabad

As indicated above, some support for the relation used by DHI (1996) can be found by using the at-a-station relations for the Jamuna River (Klaassen & Vermeer, 1988). The DHI (1996) proposal reads:

$$C = 60 \cdot \left(\frac{h}{h_{mean}}\right)^{0.50}$$

which by using h_{mean} = 5.8 m can be transformed to:

$$C = 24.8 \; h^{0.50}$$

Using the same approach discussed above, notably combining the at-a-station-relations with the continuity equation and the Chézy equation and at the same time assuming that the slope corresponds to 7 cm/km, it can be shown for any h

$$\overline{C} = 22 \; \overline{h}^{\,0.61} \simeq 27.\overline{h}^{\,0.5}$$

As can be observed, this has a clear resemblance with the relation proposed by DHI (1996).

In the literature a number of methods for the prediction of the resistance to flow have been proposed. See e.g. Graf (1971), Vanoni (1976), van Rijn (1990), for overviews. Most methods are related only to the effect of the particle roughness in combination with the bedform roughness. One method, known as the SCS method (French, 1986), is attractive to consider here as it takes the effect of bends explicitly (though in an overall way) into account. Hence it is possible to assess the effect of the increasing sinuosity of the flow during falling stage.

The SCS method (developed by the Soil Conservation Service, USA) for estimating the Manning coefficient of natural streams involves the selection of a basic n value for a uniform, straight and regular channel in natural material and then modifying this value by adding correction factors. The natural streams for which the method was developed are smaller than the Jamuna River and therefore the validity of parts of this method for the Jamuna River still to be investigated. The basic n value for an alluvial channel is 0.02. Correction factors are applied for vegetation, changes in channel cross-sections and the channel alignment. In natural rivers the changes in channel cross-sections are gradual and therefore the correction factor for this aspect is rather small in rivers like the Jamuna River, typically in the order of 0.000 to 0.005. The channel alignment is characterized by the sinuosity, defined as the ratio l_m/l_s where l_m = meander length of the channel in the reach and l_s = straight length of the reach under consideration (French, 1986).

sinuosity (l_m/l_s)	degree of meandering	modifying factor
1.0 - 1.2	minor	0.00
1.2 - 1.5	appreciable	0.15 n'
> 1.5	severe, and high risk of a cut-off	0.30 n'

Table 4.1 Modifying factor for channel alignment according to SCS-method

In the alluvial rivers n' is the sum of the basic value of n (0.02) and the correction factors for vegetation on chars (0.005 to 0.010) and irregular cross-sections (about 0.005) should be added. However, in the Jamuna river no vegetation occurs below the level of bankfull discharge and therefore no correction factor for the roughness by vegetation is needed. If the stage and the discharge decrease then the irregularity of the cross-sections and the meandering of the channel alignment gradually increase and this will have some influence on the value of n:

- for $30,000 < Q < 48,000$ m^3/s:

  $n = 0.020 + 0.005 + 0.15\,(0.02+0.005) = 0.02 + 0.005 + 0.0038 = 0.029$

- for $20,000 < Q < 30,000$ m^3/s:

  $n = 0.020 + 0.0075 + 0.175\,(0.02+0.0075) = 0.02 + 0.0075 + 0.0048 = 0.032$

- for $Q < 20,000$ m^3/s:

  $n = 0.020 + 0.010 + 0.20\,(0.02+0.010) = 0.02 + 0.010 + 0.006 = 0.036$

In this example the meandering of the channels does increase the overall n value by 13%, 15% and 17%. This n value can be converted into a Chézy coefficient per channel by Equation (4.14) in which R is the hydraulic radius of a cross-section in a channel. In channels with a large width/depth ratio the hydraulic radius can be approximated by the average water depth. This water depth can be estimated by a regime Equation (4.12) if the discharge in a channel is known.

$$C = \frac{1.49}{n} \cdot R^{0.167} \tag{4.15}$$

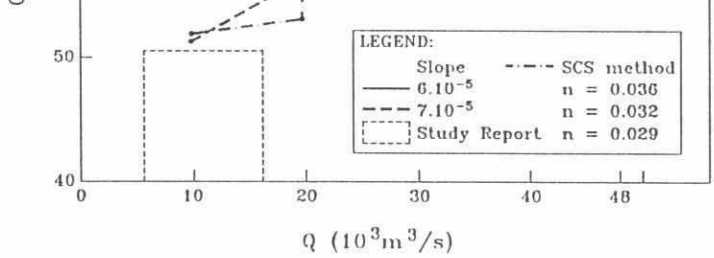

Figure 4.5
Chézy coefficient per channel by SCS method

In Figure 4.5 it can be seen that the SCS method gives a fair prediction of C-value per channel if compared with the C-values calculated by the regime Equation (4.13).

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5 Sediment transport phenomena

5.1 Introduction and definitions

The basic concepts of sediment transport were developed using the results of tests with steady uniform flow in laboratory flumes. In this chapter several complicated sediment transport phenomena in an alluvial braiding river are described briefly so as to support the rationale for the simplified approach in the following chapters.

In this study the sediment transport is defined as the transported volume of sediment per unit of time including the porosity. In some references the sediment transport has been defined as the transported sediment weight per unit of time. If a conversion from sediment weight to transported volume is made then the effect of the porosity should be properly accounted for.

5.2 Sediment transport distributions in space

The distribution of the suspended sediment concentration in the channels of the Jamuna River often deviates from the well known Rouse distribution (called standard distribution) of suspended sediment in a stationary flow through a prismatic channel. Generally, also the flow in these channels of the Jamuna River deviates from the concept of a stationary uniform flow distribution. The spatial distribution of the sediment transport in a channel can be considered as the distribution in transverse direction and in the flow direction.

In *transverse direction* this distribution is mainly governed by the upstream supply of sediment and the local conditions in the transect area. Especially the distribution in bifurcations, bends and confluences is not according to the standard distribution. In cross-sections the grain sizes and the sediment concentrations show often large variations during a flood. However, in the lean season these variations are much smaller.

In *longitudinal direction*, along a flow line the sediment concentration adapts with some delay to changes in the hydraulic parameters. For example, the flow along an eroding outer bend picks up the eroded material and, as a consequence, the sediment concentration increases. Downstream of an eroding bank often high sediment concentrations result in overloading of the flow. Downstream of such a bank part of the sediment settles and forms fresh depositions. The coarse fraction (fine sand) has a tendency to deposit at a relatively short distance from the eroding bank whereas the fine fraction settles over much larger distances. The adaptation length for this fine fraction (silt) can be a few kilometres. The grain size of the fine fraction varies less in the monsoon flood than in the lean season.

From satellite images it seems that secondary flow cells result in streaks with higher sediment concentrations along outer bends. These streaks have a length of a few hundreds metres up to about 2 kilometres.

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5.3 Effect of upstream conditions and sorting

In the study of the sediment transport measurements by RSP it was found that the upstream conditions can have a significant influence on the sediment transport measured in a transect. The non-uniform cross-sections in the river channels cause the flow to decelerate or to accelerate. The measured flow velocity vertical in a transect shows the typical deviations from the logarithmic velocity profile associated with a decelerating or accelerating flow. On the one hand, these deviations affect the sediment transport capacity. On the other hand, the supply of sediment is often not in equilibrium with the flow. In general, the riverbed in a constricted reach will erode during the flood and it will aggravate in the lean season, when the eroded bed functions as a sediment trap. Downstream of such a constriction, the sediment transport is disturbed by upstream conditions, which results in underloading and overloading of the sediment transport typically over a length of a few kilometres. A sand arrow can develop and the silt fraction will deposit much further downstream than the sand fraction. For example the sediment transport measurements in the standard transect in the left channel of the Jamuna River downstream of Bahadurabad Ghat, have been influenced by the erosion and deposition in the local scour hole in that channel just upstream of that transect.

In general, scour holes influence the sediment transport downstream of the scour holes over a length of a few kilometres. The sediment transport in a transect just downstream of a cut-off channel will change before and after the cut-off has developed.

Overall downstream fining of the grain size by abrasion and selective transport has been found in the Ganges River and in the Jamuna and Padma Rivers. The effect of sorting on grain sizes in the Ganges River is not negligible.

5.4 Special features

During the study several features, which are associated with the sediment transport in the main rivers, drew the attention. Some of them are described briefly to outline the special character of sediment transport in large alluvial rivers.

Upwellings on the water surface

Upwellings or boils which are seen at the water surface (Coleman 1969), are caused by macro-turbulence which starts at and originates from the flow separation point at the dune crests, see also Section 3.8 of this Annex. Coleman showed in aerial photographs some examples of areas with upwellings in the Jamuna river. The SPOT satellite image 79 I/12 of 13 October 1994 shows some white lines which indicate most probably upwellings in the Lower Meghna River south of Chandpur, see Figure 5.1.

In general, these upwellings have a diameter of 10 to 25 m at the water surface, whereas they were separated roughly 50 to 150 m from one an other. The pixel size on a SPOT image is about 20 m which is about the size of an individual upwelling. In the image a bright white stripe can be seen of the area with the relatively high sediment concentrations. The white colour indicates that the upwelling transports sediment to the surface. This sediment from the river bed has a higher concentration than the surrounding water at the surface. In the image it can be seen that the distance between these areas with upwellings is about 100 m in the flow direction. And also that these upwellings, which indicate dunes on the riverbed,

are found in a rather small and specific area of the riverbed. Probably the dunes in these areas are associated with higher sediment transport rates compared with the neighbouring areas of the riverbed.
In the Upper Meghna River, covered by sheet 79 I/11, a similar pattern of white stripes can be seen. In that river the sediment transport originates from the Lahkya and Old Brahmaputra Rivers and it is much less compared to the Lower Meghna river. The average distance there between the white stripes is 230 m, which is rather large for the length of bedforms. In that case these upwellings cover only a small part of the riverbed.
These upwellings are relevant for sediment transport phenomena in the rivers because relatively high sediment concentrations can be expected in areas with upwellings and because the riverbed is only partially covered by these areas (three-dimensional effects).

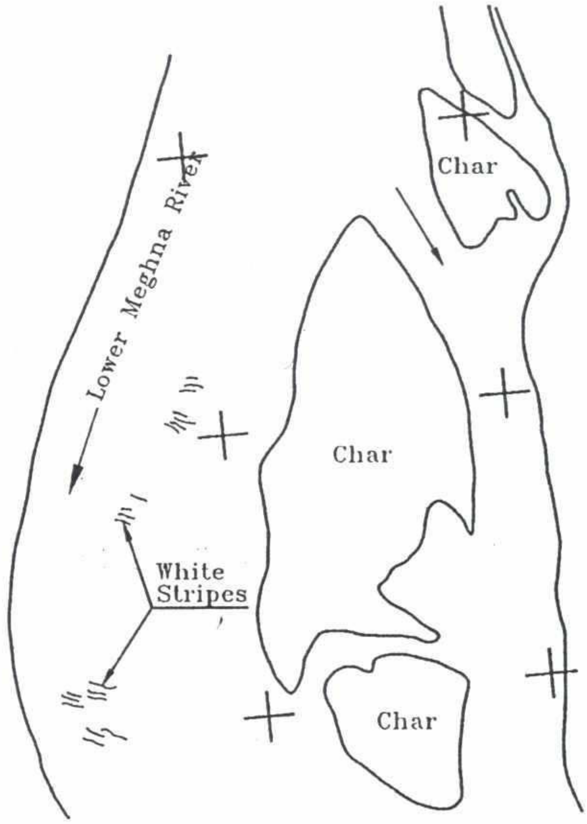

Figure 5.1 Assumed upwellings in the Lower Meghna river, seen in a SPOT image, October 1994.

Mixing downstream of a confluence the two flows mix very gradually
The confluence of the Upper Meghna River with a low discharge, low flow velocities and a low sediment concentration with the Padma River with a high discharge as well as, high flow velocities and a high sediment concentration, can be seen in Figure 5.2. The mixing of the two flows takes many kilometres, and the various flow velocities create large "von Karman"-type eddies. In this confluence only a small scour hole is present. This mixing is influenced by tidal fluctuations in the flow.

The confluence of the Jamuna river with the Ganges River shows no strong eddies because both rivers carry a medium discharge, medium flow velocities and medium sediment concentrations in September/October 1994. In this confluence a large scour hole is present and it has a significant influence on the flow. The tidal action in that reach is very small.
In some confluences downstream of a large bar in the Upper and Lower Meghna River the drainage and rain water discharge in the river at the tail of the bar where the two flows meet. This results in a large dark stripe in the satellite sheet, indicating that the rain water does not mix quickly with the sediment-laden flow. The difference in flow velocities in these coalescing flows is probably small.

This gradual mixing has some relevance for the overland flow returning to the main river. The returning flow has a relatively low concentration of sediments, because a part of the sediments in the overland flow were deposited in the floodplain. The returning flow mixes slowly with the river water and picks up gradually sediment from the riverbed and the river bank over a length of some kilometres.

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Figure 5.2 The confluence of the Upper Meghna with the Padma river in SPOT sheet 79 I/11 of 13 October 1994

Streaks of high sediment concentrations

The flow along the eroding bank in a well developed meander bend is overloaded with bank material. The fine sand and silt are transported by the river as suspended bank material. Along a flow line the sediment concentration will decrease in downstream direction, because part of the sediment settles. In a SPOT image this can be seen as a white or light-grey streak.

An example of such a streak can be seen along the eroding bend in the right bank of the Ganges River downstream of Hardinge Bridge, see Figure 5.3. Upstream of the bend this stripe touches the bank and its width is about 50 m. In downstream direction this streak becomes gradually wider, up to 125 m, and it becomes separated from the bank by a darker area with a width of 50 to 100 m. The lower sediment concentration in this darker area can be caused by a secondary flow cell near the water surface, as has been found in many smaller rivers (C. Thorne 1993, and SPR16). This gradual widening is a measure for the rate of development of this secondary eddy. This pattern is seen only in a few bends with a steep bank, not in every bend.

An other interesting example is a white grey streak in the Ganges River just downstream of the offtake of the Gorai River (see Figure 5.3). This streak indicates erosion along the side slope of the main channel, because this streak follows the relatively steep gradient along the main channel. It is well known that in the flow over a parallel slope vertical vortices are generated near the riverbed. These vortices cause additional sediment transport, seen as a white/grey streak. In this way a streak is an indication of the alignment of the main channel.

These examples show that streaks on the SPOT images indicate local sediment concentrations which are important for the short-term morphological developments.

Figure 5.3 The Ganges River in a SPOT image September 1994

High sediment transport rates.
In a braided alluvial river the sediment concentration varies in time and in space because of the dynamic character of the river. A sediment transport formula is valid for a uniform and stationary flow. A straightforward application of a sediment transport formula to predict the sediment transport in the Jamuna River often results in an under-estimation or an over-estimation of the sediment transport.
Under-estimation is called underloading as the flow starts to pick up the sediment from the river bed or from the bank. An over-estimation is called overloading, which means that the flow carries more sediment than predicted. This occurs for example near an eroding which bank supplies large amounts of sediment to the flow.

This is illustrated with the measurements in a special survey between Bahadurabad and Kamarjani. Just upstream of the confluence of a main branch with the Kamarjani branch a shallow area had developed. During the rising stage in the pre-monsoon of 1995, this area was eroded. The local water-level slopes had been measured along the right bank of that main branch starting at 0.02 m/km, indicating a backwater effect because of this shallow area, to a maximum local slope of 0.19 m/km. Along a flow line the flow velocities and the sediment concentration increase in this shallow area. The sediment transport predicted with the Engelund-Hansen formula using the overall water-level slope of 0.07 m/km underestimated the measured sediment transport in the verticals. The same comparison improves considerably if, instead of the overall water level slope, the local slope is substituted in the formula. This means that overloading and underloading can be calculated if the local water slope is used instead of an overall water-level slope. It is expected that within a few years the measurement of the local water-level slope in wide river branches will be become accurate and low-cost using new types of instruments.

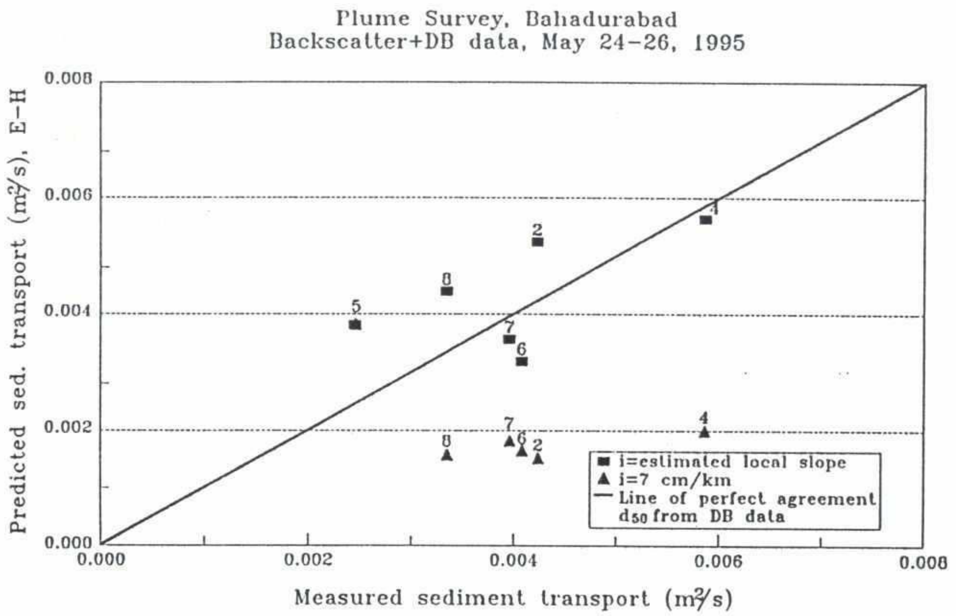

Figure 5.4 Measured and predicted sediment transport using the overall- and the local water level slope

5.6 Suspended load and near-bed transport

A major objective of the RSP has been to measure the transport of bed material in the main rivers and to study the way this transport is related to flow conditions etc. Both 1D and 2D mathematical modelling of sediment transport and morphology rely on sediment transport measurements for calibration and verification. Especially for 2D-modelling it is important to distinguish between the transport with only little contact with the bed and the transport with frequent bed contact. The present section reviews the measurement results in terms of their representation of actual transport rates, with a view to the different modes of transport. The separation in near-bed transport and suspended load is discussed and quantified.

The total transport of sediment is composed of bed material load and wash load. The wash load, which is usually taken to be the silt fraction and finer, depends mainly on the availability of fine materials rather than the transport capacity of the flow. For the bed material load, erodible sediment is readily available and the transport rate depends on the transport capacity of the flow. Only the bed material load is considered in the following.

There are two modes of transport for bed material:

- Bed load, where the sediment moves in more or less continuous contact with the bed (rolling, sliding, and saltation).
- Suspended load, where the sediment grains only occasionally would have contact with the bed. The individual grains are kept in suspension by the turbulence of the flow.

In addition to these two modes it is useful to determine the near-bed sediment transport which comprises the bed load and the coarse fraction of the suspended load. This near-bed sediment transport concept has ben applied to analyze the morphological changes in the bathymetry of the Jamuna River (Peters, Annexure IV of his seventh mission report, 1994).

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For the main rivers of Bangladesh, with their relatively fine bed sediments, the suspended sediment transport is clearly dominant. The bed load may, however, even though it is a minor part of the total transport, play an important role in certain morphological developments. The reason is that it behaves differently from the suspended load. The bed load is affected by gravity on sloping beds (the suspended load is not) and helical flows move the near-bed transport component (part of the suspended load plus bed load) towards the opposite bank as the suspended load higher above the bed. In addition, the bed load depends (almost) entirely on local flow conditions, whereas the suspended load has a time/space lag due to the time it takes to adjust concentration profiles to flow conditions, which change with time and place. These effects on the transport magnitude and direction may be important for the morphology of the river and are incorporated in 2D models. It is, therefore, important to be able to distinguish between the part of the transport which has frequent contact with the bed and the part which has not.
The suspended load and bed load have been measured by RSP using a number of different instruments:

- pump bottle samplers (bottle sampler, collapsible bag) to measure point concentrations;
- depth-integrating samplers to measure the average concentration over depth;
- ADCP to measure backscatter intensity profiles from which suspended sediment concentrations are derived;
- various sediment flux type samplers (Delft Bottle, Helley-Smith sampler).

The concentration measurements require measured flow velocities at the same location in order that the sediment transport can be determined. The flux type measurement devices are intended to catch directly the sediment flux at a certain location and level above the riverbed. Therefore, the flux type measurements are particularly useful where it is difficult to measure the flow velocity, ie near the bed.

The Helley-Smith sampler is included in the above list although the sediment catch obtained from it initially in the project, was interpreted as 'bed load'. This is because, with a height of 7.6 cm, a large part of the Helley-Smith catch would be bed load together with 'suspended bed material load'. In fact, the Helley-Smith sampler has been the only instrument applied to attempt to measure the bed load. It is, however, very doubtful whether under high flow conditions the bed load can be assessed based on the Helley-Smith measurements. The main reasons - not including those related to imperfections of the measuring procedure - are as follows:

- The sampler will often have difficulty catching the very near-bed sediment transport (lower millimetres above the bed). The instrument is an obstruction to the flow; therefore, local scouring may quickly form a gap under the mouth of the sampler if the near bed flow velocity is high. The gap may even be there already from the beginning due to unevenness of the bed. Some of the transport will bypass the sampler and the transport very near to the bed will not be represented in the sample. Result: underestimation of the bed load transport.
- Blocking of the flow through the bag by sediment particles will reduce the flow through the mouth of the sampler and thereby the inflow of sediment. Result: underestimation of the transport. Therefore a large catch should be avoided by reducing the sampling time, which means more scatter.

- The relatively large mesh size of the sampler bag will allow a large fraction of the finer material (also including the sand fraction) to pass through without being collected. Result: underestimation of the transport. But comparative measurements with other type of samplers may provide correction coefficients.
- A large, possibly dominant, fraction of the Helley-Smith catch may be characterised as suspended sediment load, not bed load.

Starting with the 1995 monsoon, measurements by the Delft Bottle sampler at 5 and 15 cm above the river bed have replaced the Helley-Smith sampler. Furthermore, Helley-Smith samples would still be collected at the reference vertical in routine measurements, together with Delft Bottle samples. Both instruments measure the sediment flux averaged over the area of their inlet openings. The flux f, is defined as sediment concentration c, times velocity u,

$$f = c \cdot u \tag{5.1}$$

Near the bed both concentration and velocity vary strongly with the height above bed, which makes the theoretical expression for the sediment flux a rather sensitive one to work with. Therefore (5.1) is mainly used for suspended load.

Although some sediment transport formulas describe the bed load and the suspended load separately, the bed load is not a well-defined contribution to the total transport. By interpreting Helley-Smith transport as bed load it is, for instance, not taken into account that 'bed load' at low flow may be confined within millimetres from the bed and at high flow within decimeters. The Helley-Smith sampler measuring within 3 inches, i. e. up to 7.6 cm from the bed, will catch both 'bed load' and 'suspended load', but in a ratio which is dependent on the flow condition.

The Delft Bottle measures the sediment transport basically in the same way as mentioned above for the Helley-Smith sampler. The Delft Bottle catches a larger part of the finer fractions of the bed material than the Helley-Smith sampler. Furthermore, the fact that the Delft Bottle is applied at a small distance above the bed and not on the bed as the Helley-Smith sampler will make these measurements more reliable (in view of scour and variability of transport).

Another advantage of the Delft Bottle is that it covers a so-called 'unmeasured zone' of the suspended transport profile. Pump samples have been taken at a minimum distance of 0.25 m above the bed, the depth integrating bottle sampler would cover only down to approximately 0.15 m above the bed and the collapsible bag (the version with the bag above the sinker weight) was used down to 0.5 m above the riverbed.

Pump samples of suspended sediment have not been used in calculations of the suspended sediment transport in routine measurements of RSP, but only for some special measurements. However, the suspended sediment transport has been calculated using the results from the depth integrating sampler, together with near-bed measurements (Helley-Smith or Delft Bottle).

The accuracy of the depth-integrating sampler and velocity profiles is relevant for the evaluation of how large a fraction of the total transport is taking place near the bed. Sometimes the results of the depth integrating sampler have been found to deviate significantly from those obtained from the pump bottle samples - usually with the depth integrating sampler indicating a lower transport of the coarse fraction, see SPR12. The most prominent possible 'defects' of these instruments are related to the measuring procedure:

- The depth-integrating sampler may at the larger depths fill up before the sampling is completed. If a full bottle sample is obtained, the result may be incorrect. It may underestimate or overestimate the concentrations depending on where in the water column the bottle filled up.
- The pump bottle samples need to be taken with a suitable intake flow velocity. In general, a depth-averaged or a surface velocity is taken. For practical reasons the intake velocity is kept constant for the various points in a measuring vertical. This means near the riverbed too high intake velocities, which will cause underestimation of the concentration and thereby of the transport.

Prior to the decision to replace Helley-Smith measurements with Delft Bottle measurements, the Delft Bottle was tested in a number of surveys; routine surveys as well as study surveys. In a transition period from August to November 1994, both types of measurements were carried out in routine measurements at Bahadurabad. The results of these routine measurements have been further analyzed with the following objectives:

- To evaluate the importance of near bed sediment transport compared to the total transport.
- To compare the results obtained by the Helley-Smith sampler and the Delft Bottle sampler.
- To recommend a method to apply Delft Bottle measurements instead of Helley-Smith measurements in calculations of sediment transport.

Some reasons for choosing these measurements for initial analyses were:

- The number of measurements is sufficient to clearly indicate correlations, trends etc. if any.
- The measurements are all from the same transect (although from different channels), thereby reducing the number of independent variables.

The details of the analysis using the results from the depth integrating sampler to estimate the transport of suspended sediment outside the near bed zone can be found in Study Report 12. The main conclusions with respect to the importance of the near bed transport are:

1. The near-bed transport in a layer with a thickness of 0.2 m is considerable, on average 10-25 percent of the total transport dependent on the calculation method applied. For an accurate measurement of the total sediment transport in a vertical some measurements close to the riverbed are recommended, because of this relatively high percentage of the total sediment transport, transported close to the riverbed.
2. The near-bed transport as measured by both Helley-Smith sampler and Delft Bottle sampler is clearly correlated with the flow velocity. This correlation is much weaker for the suspended transport at higher levels measured by a depth-integrating sampler.
3. The near-bed transport constitutes a higher ratio of the total transport for low transport conditions.

4. It *seems* that both the average ratio and the scatter increases towards the high transport conditions.

The bed material transport in the near-bed zone as a ratio of the total bed material transport is shown in Figure 5.5.

The Helley-Smith measurements are not included in the above estimate of the ratio of near bed transport. The Helley-Smith samples on average indicate a somewhat lower sediment flux than the Delft Bottle measurements (even after correction for estimated loss of fines). If the Helley-Smith results were taken into account, the estimated ratio of near bed transport would be slightly reduced. The Helley-Smith samples were omitted because they are believed to be less reliable than the Delft Bottle and do not add to the reliability of the estimated ratio. This has been inferred also in a study on the Zaire River (Peters, personal communication).

The scatter in the plot of the near-bed transport ratio in Figure 5.5 may to a large extent be caused by the variability in measurements by depth integrating sampler rather than near-bed measurements.

It is concluded that the near-bed transport in a layer with a thickness of 0.2 m constitutes a considerable fraction of the total bed material transport at this location and time. (see SPR12, Optimization of sediment measurements).

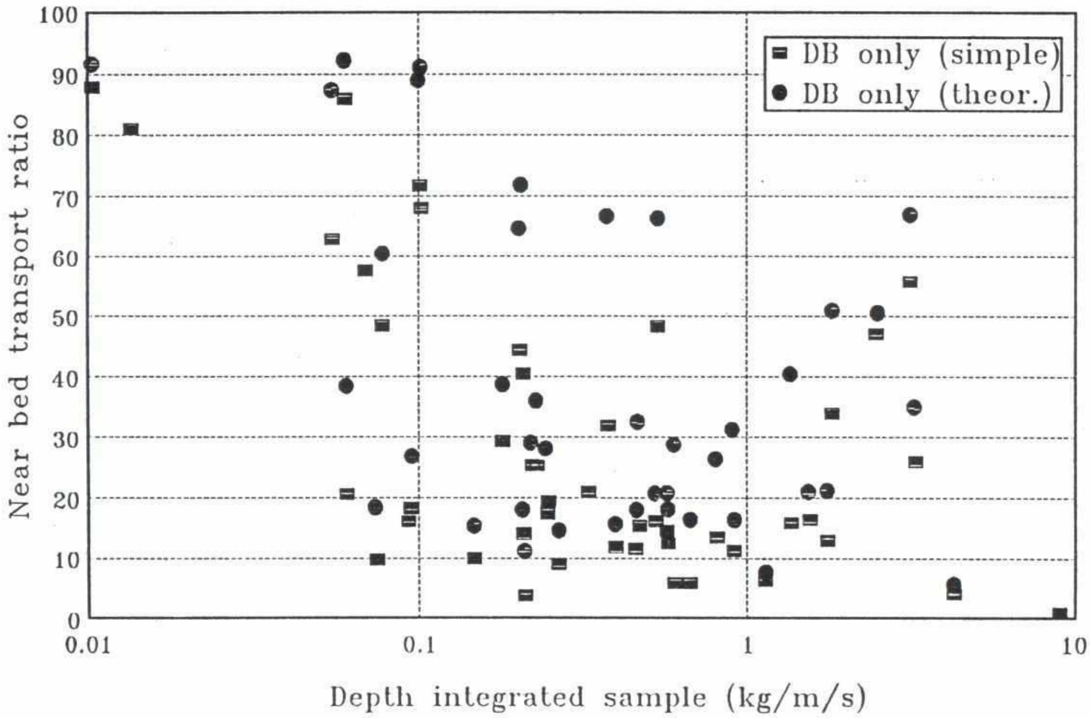

Figure 5.5 Bed material transport in the near bed zone as a ratio of the total bed material transport, estimated from Delft Bottle measurements by two different methods

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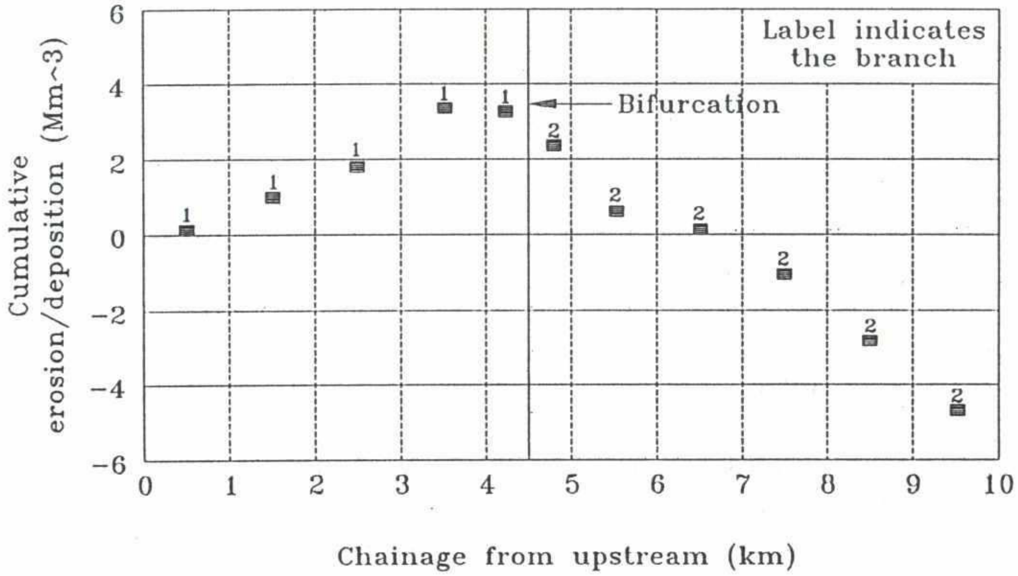
5.7 Sediment transport of fine sediments

Sediment transport of the fine or silt fraction in a braided alluvial river is not a continuous transport as in the concept of wash load in a meandering river. But fine sediment is temporarily stored in sedimentation areas with almost stagnant water. During the rising limb of the these depositions of fines may be eroded again. These deposition areas have been found, for example, in the bifurcation of the Bahadurabad left and right channel in the lean season 1994/1995. As soon as the discharge increases during the rising limb of the next flood hydrograph the deposited fine sediments in the offtake of the right channel are eroded again. The same process has been observed in scour holes, for example the local scour holes around the bridge piers of the Hardinge Bridge or the scour hole of the Jamuna-Ganges confluence. Also in the tail of a bar, fine sediments can deposit during the receding limb of the hydrograph. If the sand dunes at the head of a submerged bar migrate in downstream direction then they can cover the layer of fine sediments in the tail. After one or more floods this layer of fine sediments will be eroded when the head of the bar has been migrated to the previous location of the tail. In general longer periods (up to decades) of storage of fine sediments occur in the flood plain and in more permanent chars of the river when these areas are inundated during high floods. In the depressions of the flood plains and the high mature chars stagnant water remains after the recession of the flood. In these areas silt in the flood water has sufficient time to form thin layers of fine fertile sediments. After many years these sediments are mainly re-mobilized via bank erosion.

Thorne et al., (1993) have studied for one reach in the Jamuna River the storage of sand and silt in the chars and supply of sand to the river via bank erosion. For a reach with a length of some 100 km they propose that the silt input from the banks is only about 3% of the silt carried through that reach, but the sand yield from bank erosion is about 25% of the sand load supplied from upstream. According to their findings there is an overall widening of the river and they demonstrate that the sand eroded from the banks is closely related to the storage of sand in char growth.

Via the application of GIS on the bathymetric maps it was possible to get some insight in the variation of the sand load in longitudinal direction. It was found by comparison of bathymetric maps from Bahadurabad between August and November 1993 that the (temporal) storage of bed material in bed topography changes is in the order of 30% of the total bed material load in the river (see Figure 7.33). Hence, very substantial amounts of sediment are temporarily stored in the river and only eroded in subsequent periods. In terms of total sediment transport this figure of 30% is a substantial amount and it indicated that for making balances long-yearly averages are needed.



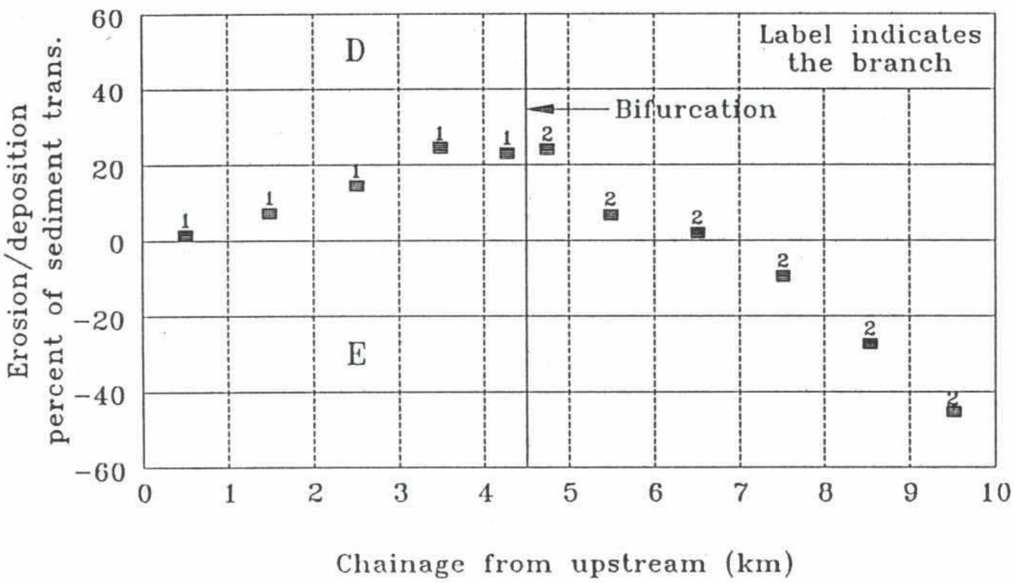


Figure 5.6 Example from analysis of balance for Bahadurabad

5.8 Sediment Transport during Tidal Flow

To establish a good set of data at a station which is strongly influenced by tidal flow requires far more extensive measurements and resources than it would at a station without tidal influence. Information about the transport of sediment as well as about the flow in a tidal or non-tidal location may be required to:

- estimate the volume of sediment 'available' in future deposition (wash load as well as bed material load),
- assess the sediment balance of part of a river system,
- assess the relation between flow and bed material transport including any phase lag
- assess the net inflow or outflow of sediment (wash load as well as bed material load)

The tidal surveys of the RSP were carried out at selected locations during the lean season when the tidal influence is highest. The results of tidal surveys are presented in the relevant survey bulletins. The surveys were carried out in three phases. In an initial phase pilot measurements were carried out at many locations. In a second phase detailed measurements were taken at only two locations selected on the basis of the initial measurements. In a third and final phase where an attempt was made to revise the survey programme, implementing findings and conclusions drawn from the detailed measurements.

The main conclusions and recommendations with respect to survey method are as follows:

1. With respect to ***flow measurements***, the half-hourly measurements over 13 or 26 hours of discharges and water levels provides a good short-term description of flow conditions. For a long-term description the detailed tidal measurements should be combined with long-term flow velocity measurements, for instance by a self-recording current meter at a fixed location 1-2 metres below surface. Long-term water-level data along the river will be required for setting up a one-dimensional mathematical model for long-term tidal flow analysis.

2. With respect to ***sediment transport measurements***, measurements in two verticals is insufficient to establish the integrated transport rates over the entire cross section in a main river. Measuring at a large number of verticals requires large resources. As a compromise it may be possible to measure regularly at few verticals and less frequently at a number of additional verticals. This method requires scaling during analysis, and has not been tested.

3. A detailed ***bathymetric survey*** covering a reach of minimum 2 times the width of the river upstream and downstream is useful for interpreting the measurements of sediment transport.

4. The use of ***dune tracking*** to determine bed load and near bed transport proved less useful. The results will be dominated by measuring inaccuracies when the transport rate is relatively low and the measuring period is short.

The following detailed conclusions can be drawn from the measurements carried out at the two locations:

Phase 2, Mawa

- The flow in the minor channel seems to be ahead of the overall flow by 10-15 minutes. It is expected that the water-level hydrographs in both channels show a lag time relative to each other.'
- The average flow is 4000-4200 m^3/s and not much different with 24.8 hours averaging compared with 12.4 hours averaging. Reversed flow occurred under this condition (approximately 1000 m^3/s).
- The median grain sizes of the Delft Bottle samples are nearly the same as for the bed sediment. There is a tendency that it is lower at high flow rate.
- The median grain sizes for the Helley-Smith samples are much higher than for the Delft Bottle samples. It tends to be highest at high flow rate/high Helley- Smith catch.
- For the suspended sediment, the grain size of only the coarsest fraction varies with the flow. The d_{90} increases with the flow velocity with a phase lag which depends on the level above bed (1 and 9 metres above bed in main channel).'
- The sediment flux measured by Helley-Smith, Delft Bottle (kg/m2/s) and from pump samples (multiplied by velocities) are generally of the same magnitude. All three methods show clear dependence on flow rate, but there are no clear phase shifts.
- It is not possible accurately to estimate the total transport over a more than two kilometres cross section based on measurements at only two verticals.
- The sand fraction makes to 20 per cent of the total sediment concentration at one metre above the bed; At higher levels this percentage reduces to 10 per cent.
- There is a clear phase lag of the concentrations compared to the discharge.
- In the secondary channel there is no distinct temporal variation of concentrations.

Phase 2, Bhairab Bazar

- Grain sizes of both bed material and near bed suspended material seem to be lower during flood flow than during ebb flow (only few data).
- The coarser fractions of suspended material tend to be coarser during ebb flow than at any other time.
- The measurements indicate that the sediment balance may be different for the wash load and for bed material load.

5.9 Implications for one- and two-dimensional modelling

The study on the river morphology has shown that major part of the erosion or deposition of the riverbed is caused by the near-bed sediment transport (SPR 12, Optimization of sediment measurements and Peters, Annexure IV of his seventh mission report, 1994).

A significant fraction of the total sediment load is moving near the bed in a layer with a thickness of several decimeters. To simulate this erosion and deposition in mathematical models it is felt necessary to develop prediction formula for the near-bed sediment transport.

At this moment only prediction formula for the bed load transport and the suspended bed material load are available for application in mathematical models. However, the RSP measurements are insufficient for a verification of the existing bed-load formula, because it is extremely difficult to perform such bed-load measurements in high flow conditions which occur during a flood. In general it can be said that for an accurate modelling of the sediment transport phenomena in the Jamuna River in mathematical models more studies and probably also more field surveys are required.

6 Available sediment transport data

6.1 Introduction

Each monsoon the BWDB has set up an extensive programme for measuring the sediment transport in the main rivers. The network of sediment gauging stations in this programme and the type and the processing of the data are reviewed in this chapter.

In the past collected sediment transport data by the BWDB and its predecessor was used to evaluate existing and to develop sediment rating curves, which are used for the calculation of sediment balances in stretches of the main rivers. In addition to these data the type of sediment transport data collected by the RSP during the last three years is briefly summarized.

6.2 Sediment measuring stations

Old reports indicate that several sediment gauging stations were established already a long time ago. For example the sediment transport measurements in a station near the Hardinge Bridge started in 1958, but the hydrological measurements started already in 1934 or probably even earlier, from the completion of the construction of the bridge in 1920. In Bahadurabad the sediment transport measurements started in 1956. And in Mymensingh the hydrological measurements started in 1940 and the sediment transport measurements in 1966. However, when RSP made an inventory of the data available, very few transport data has been found from these early periods.

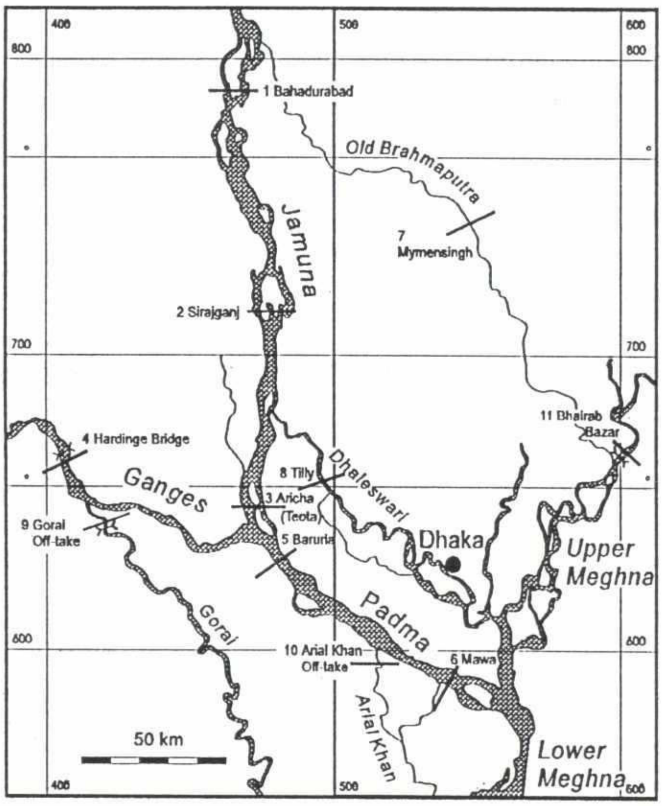


Figure 6.1

Network of sediment transport gauging stations in the main rivers

The oldest data which could be retrieved from the BWDB offices, dated from 1966 for those stations, with exception of Bhairab Bazar where the oldest available data is from 1960. Coleman (1969)) used in his article sediment data starting from 1958, showing that these old data really had been measured. Nowadays these old data could have been very useful for the determination of long term developments in sediment transport in the main rivers with a higher accuracy than possible with the available time series. Therefore the loss of these old data is regrettable and future losses of measured sediment transport data should be prevented as much as possible. It might be that part of these losses were caused by misplacement of the files when the office was shifted to a new location. This illustrates the need of a well organized archive for sediment transport data.
In the sixties the "Food and Agriculture Organisation-United Nations Special Fund" (FAO-UNSF, 1969) Hydrological Survey Team started an extensive sediment transport investigation in the main rivers of Bangladesh. In the framework of that investigation ten stations were selected within the priority area for sediment measurements, see Table 6.I and Figure 6.1. The sediment transport data in these 10 stations have been collected and analyzed by the project, with exception of a few stations. For example the station in Kamarkhali is considered to be outside the area of the River Survey Project and therefore disregarded for further study. Jagir was an unimportant station because the available data of that station covers only a period of three years: 1967 to 1970 and after 1970 this station was closed because of strong siltation in the Dhaleswari River. Since 1966 no more new BWDB sediment gauging stations were established in the area covered by the RSP.

The RSP did sediment gauging in the routine transects and, in addition, some measurements in irregular, special surveys. The RSP had added a few routine transects to the ten existing BWDB stations. For example the routine transects near Sirajganj, Aricha along the Jamuna River, in Arial Khan Offtake from the Padma River and just downstream of the railway bridge near Bhairab Bazar were added in order to make more and detailed sediment balances. 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 6.I. Again in 1972, BWDB has started sediment measurements at Bhairab Bazar gauging station on a regular basis for the period from May to November, although in the Upper Meghna River the maximum sediment discharges occur early monsoon.

The BWDB is the only organization which carries out sediment measurements on a weekly basis all over Bangladesh. According to the inventory of Surface Water Hydrology, BWDB measures the sediment transport in the main river system as well as in the smaller rivers. Recently the Surface Water Modelling Center started to collect sediment transport measurements for special purposes and projects on an irregular basis.

6.3 Historical sediment measurements

The scarce sediment transport data, which have been available from before 1966, refer to sediment samples taken by simply filling a normal bottle with a sample of the river water. All these data are related to measurements of the total sediment transport, which means that the suspended sediment sample was not separated in the wash load and the suspended bed material load.

From 1966 onwards a sample was separated in suspended bed material load (also called the coarse fraction) and wash load with the finer particles (also called the fine fraction). The wash load consists of the silt and the clay fraction. The sand fraction consists of all the sediment particles larger than 0.063 mm.

Name of Station	River	BWDB Station No	BWDB (FAO-project)	RSP
Bahadurabad	Jamuna	46.9L	x	x
Sirajganj	Jamuna			x
Aricha	Jamuna			x
Paksey	Ganges	90	x	x
Goalundo	Padma	91.9R	x	
Baruria	Padma	91.9L	x	x
Mawa	Padma	93.5L	x	x
Gorai Railway Bridge	Gorai	99	x	x
Kamarkhali	Gorai		x	
Mymensingh	Old Brahmaputra	228.3	x	x
Taraghat/Tilly	Kaliganga	137a	x	x
Jagir	Dhaleswari	68.5	x	
Bhairab Bazar	Upper Meghna	273		x
Arial Khan offtake	Arial Kahn			x

Table 6.1 BWDB and RSP sediment transport gauging locations along the main rivers

Since 1965 the Hydrological Survey Team started an extensive sediment investigation using improved techniques. A Binckley Silt Sampler made by Kelvin Hughes, was introduced to measure the suspended sediment transport (suspended bed material and wash load). In various studies it was considered to replace the Binckley Silt Sampler by a more accurate sampler, but for the purpose to built up a consistent database covering a large period it was decided to continue the Binckley Silt Sampler measurements. Therefore this instrument is still in use nowadays. It is mentioned that in the main rivers the suspended sediment transport is in general more important than the bed-load transport. During the monsoon the bed-load transport red easily in the main rivers on a regular basis.

During 1966 and 1967, the sediment data collection at the stations mentioned in Table 6.I was carried out weekly from beginning April to the end of November. These data were published in the report "FAO-UNSF Second Hydrological Survey in East Pakistan, Dhaka, April 1969 (FAO-UNSF, 1969). In 1969 at all the 10 stations suspended sediment data were collected 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".

The suspended bed material transport data, earlier also called coarse sediment transport, (expressed in tons per day) are available for the period 1966-1969.
Before 1970 the sediment concentration was expressed in parts per million (ppm) and the sediment transport in tons per month or tons per day and after that date kg/s was used as unit.

During the Liberation War of Bangladesh in 1971 no sediment transport measurements were made.

After 1972 different periods can be distinguished for each station where suspended bed material transport and/or wash load data are missing. A complete inventory is presented in SPR 18, Sediment Rating Curves and Balances (RSP, 1996). During the monsoon period from May to November sediment transport measurements were carried out at all stations and in some years, until December. In the important Bahadurabad station, sediment transport was measured during the whole year.

6.4 RSP, FAP24 routine transect surveys

In the period 1993-1996 the RSP carried out sediment transport measurements in several routine transects in the main rivers.

The locations of some routine gauging transects were selected close to the existing stations where the BWDB sediment transport measurements performs, to facilitate comparisons of the RSP data with the BWDB data, see Table 6.I. In the Jamuna River two more routine transects were determined near Sirajganj and Aricha to determine a more detailed sediment balance of the Jamuna River. The RSP did not measure near the stations in Kamarkali and Jagir because Kamarkali is outside the priority area of RSP and the Dhaleswari River near Jagir has been silted up and its function is taken over by the Kaliganga River. The Arial Kahn offtake has been included in RSP programme because that offtake is gradually gaining importance.

The routine sediment transport measurements are described in detail in Annex 2. In these surveys the sediment transport had been qualitatively measured with ADCP-backscatter. The ADCP-backscatter in the moving boat method qualitatively measured the sediment distribution in the transect. In eight to fifteen verticals the sediment transport had been quantitavely measured by a depth-integrating sampler and Delft Bottle measurements near the riverbed.

6.5 Quality checks

The network of sediment gauging stations of the BWDB had been evaluated using a set of different criteria. Several aspects related to the quality of the sediment data collected by the BWDB are described in this section.

6.5.1 Quality of the network of sediment transport gauging stations

In the main river system a limited network of sediment gauging stations have been developed in the past to meet the needs for assessing, developing and managing the rivers and the water resources. To obtain sediment data with a high quality the location of the site of a sediment gauging station should be selected carefully according to several criteria.

Easy accessability

The measurement of sediment transport in a wide river with high concentrations of suspended sediment is laborious and time consuming. Therefore an easy access to the station is an important criterion. In practise sediment gauging stations can be found near bridges, ferry ghats or townships along the river bank.

Uniform cross-section

In order to reduce the error in the estimation of the total sediment transport in a cross-section due to too few samples, cross-sections with the most uniform distribution of both the discharge and sediment transport should be selected. Usually, fairly uniform lateral distributions of the sediment concentration exist at cross-sections that are uniform in depth and are well away from obstructions or major bed-relief features. However, in natural rivers, especially braided rivers, locations with a perfect uniform cross-section are often rare. Therefore, in practice, a location with the most uniform cross-section, compared with other locations along the river, should be selected.

Uniform bed material

The subsoil in and just upstream of the transect should be preferably rather uniform at the stratum intersected by the river. This means no outcrops of rock or cohesive layers along the bank which induce local scouring of the river bed. This scouring varies as a function of the discharge and sediment transport based on measurements in a scour hole is not representative for the whole branch.

Away from an upstream confluence

Downstream of a confluence of two or more channels a confluence scour hole develops. This scouring varies also as a function of the discharge and the water depth and can disturb the sediment transport over some distance.

Beginning and end of the transect

A well defined start and end of the transect for example by embankments, facilitates accurate measurement of the sediment transport. If the transects starts and ends in a flood plain with various minor channels the sediment transport measurement may be time consuming and the result is probably inaccurate.

Not in an artificially narrowed, trained channel

Near important infra-structure along the river often the banks are protected against flooding by river training works. These river training works often narrows the river cross-section. These locations are often easy accessible and therefore attractive sites for a sediment gauging station. However, in a narrowed section contraction scour of the river bed induces yearly variations in the sediment transport. Because of these variations the measured sediment transport in the transect is less representative for a whole branch.

In the past sediment gauging sites were selected according to the criterion of an easy accessability and therefore they were often combined with the sites of the main hydrologic stations along the rivers. This selection practise has reduced the quality of the sediment data from several gauging stations. It is expected that in future the network of the sediment gauging stations should be densified and therefore the criteria which are described in this section, can be used for the selection of new gauging stations. These criteria are also useful in evaluating the quality of the sediment data of existing stations. It should be mentioned that the location of the sediment gauging station should be well defined in the chainage system of the river. In practise the selection of a location of a sediment gauging station is often a compromise of these criteria.

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In the light of the above criteria the location of some of the existing sediment gauging stations along the main river system is discussed in detail in the Special Reports and a few examples are highlighted here. The Hardinge Bridge over the Ganges River is a very convenient location for discharge measurements as the bridge is easy accessible and it has a well defined channel. But during the higher stages in the monsoon the cross-section at the upstream side of the bridge, where the measurements are carried out, is confined by bank protections on both banks over several hundred meters. This constriction had a serious influence on the sediment transport measurements. The sediment transport measurements in Baruria are affected by the effects of the confluence of the Jamuna and the Ganges Rivers. In Bahadurabad the morphological changes in the planform made it necessary to change the transect line regularly and this might have had some adverse influence on the sediment transport measurements. It is expected that the seasonal changes in the local scour hole downstream of the Gorai Railway Bridge where the sediment transport is measured, had affected those measurements. Further, this location is not optimal for measuring the sediment transport which enters the Gorai River form the Ganges River, because some spill areas are found between the mouth of the Gorai River and the railway bridge.

These examples show that a sediment transport gauging station has to be selected carefully. And the location of the existing ones is often not optimum and consequently shifting of some existing stations should be considered in future.

6.5.2 Sediment transport data

Since 1966 the BWDB uses a standard method to analyze a suspended sediment sample. The main reason for using still this method nowadays is to create a uniform database of sediment transport measurements.

The sediment samples were collected at the same time when the discharge measurements at the above stations were performed. A Binckley Silt Sampler was used for to collect a one litre sample of the river water. The samples were taken in a number of verticals in a gauging transect and from several points in each vertical. The sand and silt fractions of a sample were separated in a conical elutriator. The sand fraction was collected in a tube attached to the elutriator after 100 s. In comparative tests RSP checked this period of 100 s and found that it gives a good separation between the silt and the sand fraction. The weight of the sand fraction of a sample is determined by the weight of that tube, full of water with and without the sediment sample.

The remaining fine sediments (silt fraction) of several samples were combined together and analyzed in the Hydraulics Research Laboratory and after 1971 in the River Research Institute. But in some periods these data on the silt fraction are missing and only data on the sand fraction are available or just the other way around or both are missing, while the inventory of these data mentions they these data had been measured.

The sediment measuring and the processing methods used by the BWDB were evaluated in the joint measurements described in one of the Special Reports. In general the positioning of the Binckley Silt Sampler in a vertical, the measurement of the flow direction and the positioning system in the wider channels can be improved. In general the accuracy of the older bottle samples is low because of the short filling time of the bottle, the sample is a momentaneous sample taken in a highly turbulent flow and a large variation in the trap

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efficiency depending on the position of this bottle relative to the approach flow. Also the Binckley Silt Sampler takes momentaneous sediment samples.

The number of verticals in a transect measured by the BWDB is based on the criterium that not more than 10% of the total discharge should flow between two verticals. Some checks by RSP and described in SPR 3, *"Morphological Studies Phase 1, available data and characteristics"* indicated that the number of verticals is sufficient for an accurate measurement of the sediment transport, probably a small reduction of the total number of verticals will not reduce the accuracy of the sediment transport much.

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 were processed until October 1992, for a few stations they were processed until October 1993. All these processed data of BWDB were collected by the River Survey Project. The sediment transport data were used to determine the sediment rating curve, which can be determined graphically or by regression analysis. A first analysis of the sediment data showed inconsistencies in the data of the Hardinge Bridge and Bahadurabad. The sediment transport data in Hardinge Bridge shows that in the period 1966 - 1970 the sediment transport was on average about 2 times the sediment transport measured in 1976 - 1989. In a similar way the measurements in Bahadurabad suggest in the period 1966 - 1970 a 2 to 2.5 times higher sediment transport than the measurements from 1976 - 1988, probably these tendencies have been caused by changes in the measuring methodology. This means that the data from 1966-1970 is considered as the most accurate ones.

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7 Sediment transport predictors for Bangladesh's main rivers

7.1 Introduction

To predict morphological changes in rivers, increasingly mathematical models are used (De Vries et al, 1990). This trend is also noticeable for Bangladesh's main rivers: already in 1987 a simplified 1-D morphological model of the Jamuna River was used for constriction scour estimates and for general scour predictions under the Jamuna Bridge study (RPT et al, 1989). Via 1-D morphological models used by the SWMC amongst others for FAP1 and the use of a 1-D Morphological models under FAP6, presently 2-D morphological modelling is applied for the Jamuna Bridge (DHI, 1996).

Morphological models usually consist of different modules for water flow, resistance to flow, sediment transport and morphological changes. A crucial element in the sediment transport module is the prediction of the sediment transport. This is usually done using sediment transport predictors. As a full understanding of sediment transport processes is not yet available (the underlying theory still being under development), sediment transport predictors are ultimately empirical equations. Because of their empirical nature there are no generally applicable sediment transport predictors, and often predictors have to be fine-tuned versus transport data of the particular river for which simulations have to be done. For the 1-D models of the Jamuna River the Engelund-Hansen transport formula (1967) is often applied with a correction coefficient of 2 (RPT et al, 1989; Klaassen et al, 1988). The question to be addressed is, however, whether this is the most appropriate predictor, as e.g. for a similar big river like the Zaire a Bagnold (1961)-type of equation was found to be more appropriate (Lukanda et al, 1992). The latter sediment transport predictor is only slightly different in terms of the relationship between the depth-averaged velocity and the sediment transport, but this nevertheless might make a major difference in morphological behaviour. Hence the available data on sediment transport in the main rivers of Bangladesh (as discussed in the previous Chapter 6) have to be used to study sediment transport and to derive an appropriate predictor.

The sediment transport data which are available are mostly data from BWDB but in this study also the RSP data collected during the routine measurements were used. A major disadvantage of the BWDB data is that they originate from isolated transects without considering the upstream conditions. As discussed in Section 5.3 the upstream conditions are very important and can significantly affect the local sediment transport rates. Hence interpreting the local sediment transport as a function of the local conditions only, may lead to substantial scatter as one of the important parameters is not included in the analysis. Some data which are clearly yielding very high loads due to special conditions like strong 3-D phenomena have been deleted. This necessitates however to add these special phenomena in models if they are very important for the overall development of the morphology.

An additional disadvantage of the BWDB data collected in the past is that there appears to be an inconsistency between "coarse" sediment transport data collected in the period 1966-1970 and in later periods (conform Section 6.5). Hence, no matter how useful the data collected in the past are for getting an overall insight in quantities of sediment transported in the system, they might be less attractive for the development of a sediment transport predictor.

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In this respect the use of RSP data might allow for the derivation of a sediment transport predictor with better applicability.

The approach used to develop an appropriate sediment transporter is described in Section 7.2. In principle the development of a sediment transport predictor is limited to a predictor for bed material load (see Section 2.1). Prediction of wash load is by definition not really possible, because it depends mainly on the supply of clay and silt from upstream and to a lesser extent on the hydrodynamic forces.

7.2 Approach

In this Section the approach followed in developing a sediment transport predictor for Bangladesh's main rivers is outlined. The largest amount of data on sediment transport in the main rivers are the BWDB routine measurements that are collected on a regular basis. Long series are available for three stations, notably Bahadurabad (and Fulchari) on (left and right bank of) the Jamuna River, Hardinge Bridge on the Ganges River and Baruria on the Padma River. Hence initially these BWDB data were used for the derivation of a sediment transport predictor. A disadvantage of both the Hardinge Bridge and the Baruria station is that they are located in river reaches that are not uniform: Hardinge Bridge corresponds to strong constriction and Baruria is immediately downstream of the confluence.

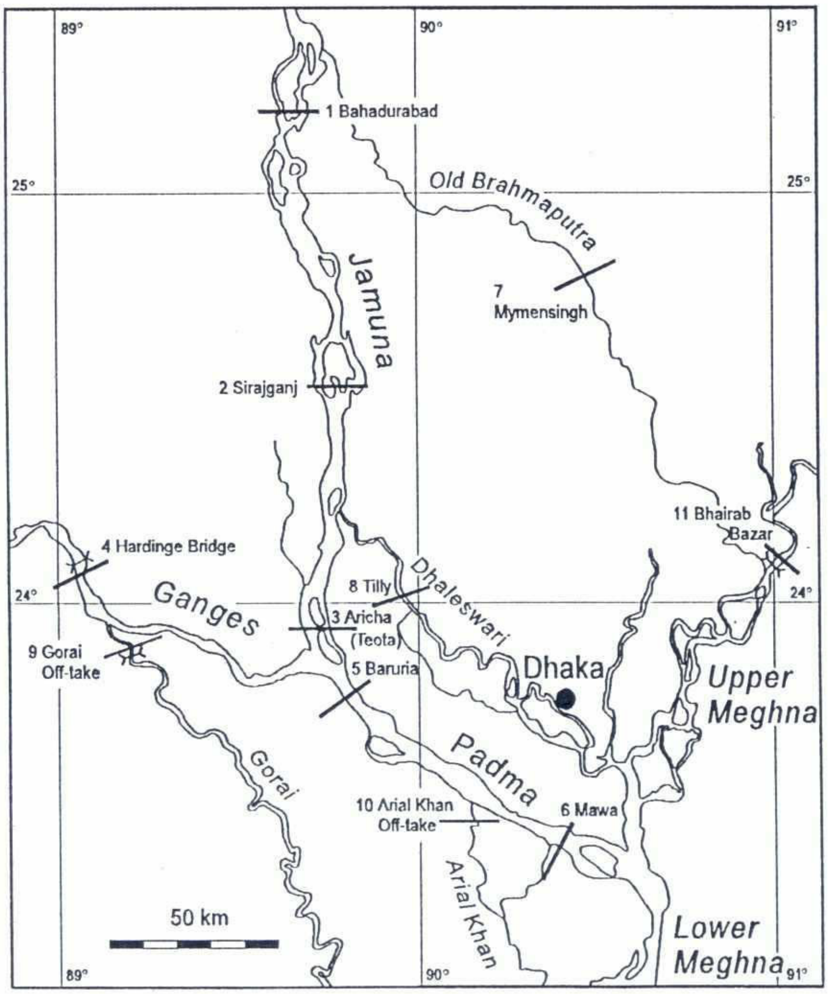

Figure 7.1 Stations from which sediment transport data were used

A constriction causes that local slopes may deviate considerably from the overall slope. This makes interpretation of the data quite difficult. This was already demonstrated by Galapatti (1993) for the effect of the constriction at Hardinge Bridge, and under the present study this was shown for the Baruria station as well. Hence it was decided to use from the BWDB data only the Bahadurabad measurements for the development of a sediment transport predictor. A second decision taken in an early stage of the project was to use detailed (Bahadurabad) data from the 1984-1987 period for the analysis. The main reason for not using data from the 1966-1970 period was that for that period detailed discharge sheets were not available. The detailed sheets were required for deriving the sediment loads in a vertical. Only in a late stage of the project it turned out that the use of 1984-1987 data was not appropriate. Hence the analysis was repeated using the sediment transport data measured by RSP during routine measurements. In particular sediment transport data from Sirajganj, from the right channel near Bahadurabad and from some distributaries were used to fit a sediment transport predictor. These locations were selected because these channel reaches were rather uniform in 1993-1995.

Once the data to be used were selected, the preferable form of the sediment transport predictor was determined. Aspects to consider are whether to include initiation of motion and/or a correction for the gradation of the bed material and how to include the resistance to flow. An important issue is the selection of a correct power in the relation between sediment transport and velocity, which is very important for a proper representation of the morphological behaviour.

Subsequently the development of the sediment predictor was done in a number of steps. First the proper relation between sediment transport and shear stress was derived. This was done in two different ways. For the BWDB data the shear stress was determined estimating the shear stress on the basis of the local depth and the overall slope. Because the local slope can deviate considerably from the overall slope, this caused substantial scatter and related inaccuracies. Hence when in a later stage the RSP data were analyzed, a different approach was used. The resistance to flow was estimated with a predictor (essentially the one developed for the 2-D morphological modelling of the Jamuna River (see DHI, 1996)) and this, in combination with the measured depth-averaged velocity, allowed for a better estimate of the local shear stress. Next a correction for the resistance to flow has to be introduced in these relations. In particular this part could only be done in a preliminary way: additional improvements are needed. Finally the contribution of the non-measured sediment transport near the river bed was studied. This can be included in any predictor, either on the basis of the BWDB data or using the RSP data.

The applicability of the derived sediment transport predictor for the Hardinge Bridge and at Baruria was tested by using a 1-D morphological model in which the specific conditions (a constricted reach and a constricted reach downstream of a confluence, respectively) were included. This model was used to study whether the trend of the data and the large scatter observed for both stations can be explained by the use of local sediment transport data with overall slope data. Results are presented in Special Report 19. Furthermore a comparison was made with the results obtained during the verification of the 2-D morphological model used for the Jamuna Bridge (DHI, 1996).

In this Chapter only a summary for the analyses carried out is presented. More details on the study on the basis of the BWDB data can be found in SPR 13. For a better understanding

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of sediment transport processes in Bangladesh's main rivers also SPR 19 can be consulted. For the time being it is however proposed to use the predictor developed on the basis of the RSP data, as this predictor was found to yield acceptable results when compared (using the 2-D model) with field data.

7.3 Preferable form of predictor

Before starting with the actual derivation of a sediment transport equation applicable for the main rivers in Bangladesh, it is important to reflect on the preferable form of such a sediment transport predictor. This will be done by assessing the conditions in the main rivers. It is assumed that the reader is familiar with the basics of sediment transport in rivers. If required handbooks like Graf (1971), Jansen (1979), Garde & Ranga Raju (1977), Raudkivi (1976) or Van Rijn (1994) should be consulted.

In its most simple form most sediment transport predictors can be written as a relation between the sediment transport and the driving force. There are two "schools" as far as the driving force is concerned: one "school" uses the power of the flow, while the other prefers the use of the shear stress. Typical examples of the two schools are Bagnold (1966) (power) and Engelund-Hansen (1967) (shear stress). For the time being the approach from the second school will be used here.

Sediment transport formulae from the second school can be written in the form:

$$\psi = f(\theta) \qquad (7\text{-}1)$$

where $\psi = \dfrac{s}{\sqrt{g \Delta D^3}}$ = *dimensionless sediment transport* (-) (7-2)

and $\theta = \dfrac{\tau}{\rho g \Delta D} = \dfrac{h.i}{\Delta . D}$ = *dimensionless shear stress* (-) (7-3)

Different phenomena can or cannot be included in a sediment transport formula (in the expression f in Equation (7-1)), notably:

(a) effect of initiation of motion (below initiation of motion there is no sediment transport although the shear stress still has a finite value);
(b) effect of gradation of the sediment (takes into account possible hiding and exposure effects);
(c) effect of resistance to flow on the sediment transport (reduces the overall shear stress for bedforms and other contributions to resistance to flow).

A general form for a sediment transport predictor is:

$$\psi = K_1 \left(\gamma_1 \, \delta_1 \, \theta - \delta_2 \, \theta_c\right)^{n/2} f_1(C) \qquad (7\text{-}4)$$

Here K_1 = proportionality coefficient, γ_1 = possible correction coefficient for the resistance to flow, δ_1 and δ_2 = possible correction coefficients for the gradation, and θ_c = critical (dimensionless) shear stress. The power n/2 refers to the power n of a simplified sediment transport relation that is often used in analytical considerations and which reads as:

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$$s = m.u^n \tag{7-5}$$

The following observations are relevant as far as the different corrections are concerned. In the main rivers of Bangladesh initiation of motion of the particles is almost always exceeded. This can be evaluated by considering the value of the Shields parameter (= dimensionless shear stress θ). For values of θ higher than say 0.06 initiation of transport is exceeded. In the rivers of Bangladesh with very fine sediments (D_{50} is about 0.2 mm as a maximum), slopes of 5.10^{-5} and depths in the order of 5 m or more, values of θ are in the order of 1. Hence there is no need to include initiation of motion into a sediment transport formula for the main rivers of Bangladesh as almost always $\delta << \delta_c$.

The gradation of the sediment becomes important when the geometric standard deviation of the bed material is large and when the conditions are near initiation of motion. In view of the flow conditions almost always by far exceeding initiation of motion, also gradation needs not to be taken into account. Hence δ_1 and δ_2 can be deleted as well.

This simplifies the preferable form of the sediment transport to:

$$\psi = K_1 \ (\theta)^{n/2} f(C) \tag{7-6}$$

This is the form which will be used as a basis for the development of an appropriate sediment transport predictor.

It is relevant to stress here the importance of a correct value of n (or n/2). As is shown in e.g. Jansen (1979) the value of n is quite fundamental in the response of a river system. Some examples are given in Special Report 13 as well. Phenomena which are quite relevant for the main rivers in Bangladesh are constrictions and the occurrence of bars, their wave lengths and damping lengths. To reproduce these correctly it is very important to use a sediment transport predictor that is using the correct value of n/2. Hence the proper order for developing a sediment transport predictor is first to decide on the value of n (e.g.by plotting s versus u or Ψ versus θ and to determine n). Only in second instance the value of K_1 should be calibrated. Hence a sediment transport predictor that yields values far away from the measurements but that demonstrates a good relation between Ψ and θ is by far preferable over a sediment transport predictor that on the average shows a good performance, but in which the value of n is not correct. Hence the approach followed here will be first to select n, then to determine the correction for the resistance to flow and finally to determine K_1.

To illustrate the above point it is of interest to see the variation of n for different sediment transport formula. This was studied in the project and some results of this study are summarized in Figure 7.2, presenting the variation of n for typical Jamuna particle size and slope for some often used bed material load predictors (Ackers & White, 1971; Bagnold, 1966; Engelund & Hansen, 1967; van Rijn, 1984; and Yang, 1993).

Figure 7.2 relates to typical Jamuna particle size and slope, as it was found that depending on the type of predictor the value of n is affected not only by the Shields parameter θ, but also by the particle size and the slope. It can be observed that for typical Jamuna flood conditions with the Shields parameter varying between 1 and 3, the value of n can vary between 3 and 5. For low Shields number there is usually an increase of n due to the effect of initiation of motion. It can be noticed that the Engelund-Hansen formula corresponds to

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n = 5, whereas for Bagnold n is about 4. This may result in essentially different morphological behaviour. For more information and details see *Study Report 13*.

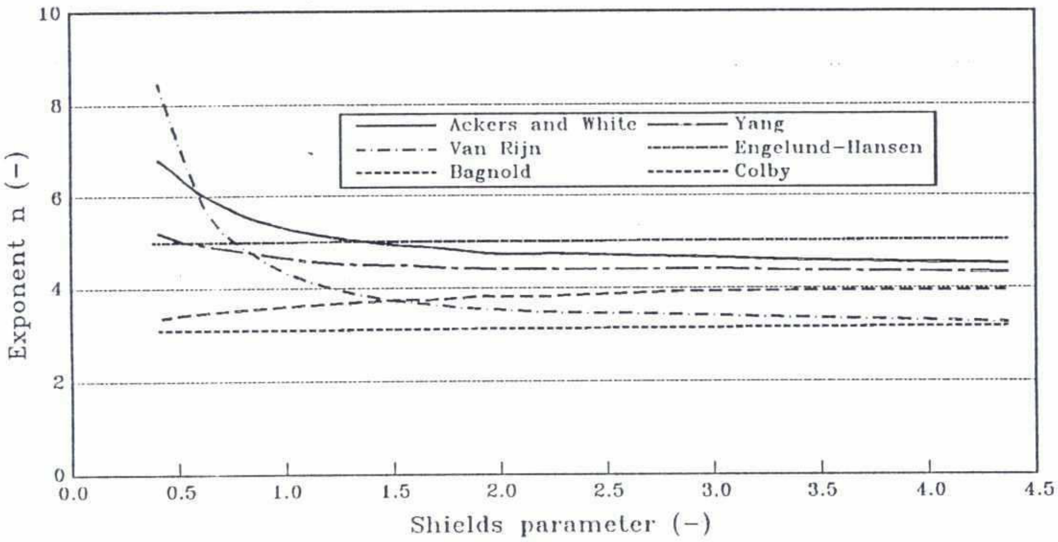


Figure 7.2 Variation of n for some bed material load predictors for typical Jamuna conditions

7.4 Data used and their accuracy

This study uses field data from the Jamuna, the Ganges and the Padma Rivers and from some tributaries. Data from two different sources were used here: (1) field data collected by BWDB during routine surveys of flow and sediment plus water level data to determine the overall slope, (2) data collected by the River Survey Project (RSP). The hydraulic and sediment data used in the analysis are described below. The locations of the stations from which data were used are shown in Figure 7.1.

BWDB data

Extensive flow and suspended bed material transport data have been measured by BWDB at the Bahadurabad, Hardinge Bridge and Baruria stations since the sixties. Because not the total flow and sediment transport were of interest but rather the conditions in any vertical, it was required to collect the BWDB field sheets with detailed data on sediment measurements and flow velocities. These field sheets were collected for the periods 1983-1987 for Bahadurabad, 1990-1994 for Hardinge Bridge, and 1986-1994 for Baruria. An inventory of the applied data is given in Table 7.1.

River	Station	Period from which sediment transport data were used	Number of vertical for which data are available
Jamuna River	Bahadurabad	1984-1987	582
Ganges River	Hardinge Bridge	1990-1994	196
Padma River	Baruria	1986-1987, 1987-1992, 1994	541

Table 7.1 Sediment transport data measured by BWDB and used in this study

In total, 582 sets of data for Jamuna River at Bahadurabad, 196 sets of data for Ganges River at Hardinge Bridge, and 541 sets of data for Padma River at Baruria were used in the analysis. Each set of data represents the sediment transport in a vertical of a measuring transect.For the derivation of a sediment transport formula also information on the bed material size and on the slopes are required. The available data are shown in Table 7.2. This table lists bed material samples collected for size analysis by the River Survey Project, and the calculated overall water surface slopes for the major rivers.

River	Gauging station	Grain size of bed material River Survey Project							Overall water level slope (1993-1994) (10^{-5})
		Number of samples	Collection period	D_{16} mm	D_{35} mm	D_{50} mm	D_{84} mm	D_{90} mm	
Jamuna River	Bahadurabad	56	1993-1994	0.13	0.16	0.22	0.29	0.34	7.5
Ganges River	Hardinge Bridge	50	1993-1994	0.10	0.12	0.15	0.18	0.21	5.5
Padma River	Baruria	30	1993-1994	0.10	0.12	0.14	0.18	0.22	4.0

Table 7.2 Grain sizes and overall slopes used in the analysis of sediment transport prediction formula

The available data were quality checked. This was done amongst others by plotting the dimensionless sediment transport rate ψ versus the dimensionless shear stress θ (for definitions see Equations (7.2) and (7.3). A typical result is shown in Figure 7.3, presenting the sediment transport from Bahadurabad for the monsoon periods of 1983-1987. As can be observed there is a substantial scatter. Part of this scatter is caused by the use of the overall slope in the determination of θ, as is explained in Section 7.6. Other contributions to the scatter are related to the non-uniformity of the cross-sections and hence the influence of upstream features like scour holes and eroding bars. In addition to this there are very clear outliers.

From the figure it can be seen that the samples 195, 196, 200, 202 and 203 are outliers, i.e. behaving differently from the cloud of the sediment samples. An examination of the position of these outliers shows that the sampling verticals were located on high eroding chars (Figure 7.4). It was decided to remove these data from the data base. As it was perceived that here strong 3-dimensional effects could cause this abnormal results.

The implication is however that the sediment transport to be derived is only valid for "normal" conditions. When modelling is done, in particular 2-dimensional morphological modelling, it may be required to add the mechanism responsible for this abnormal result, for example to measure the local water level slope instead of the overall slope.

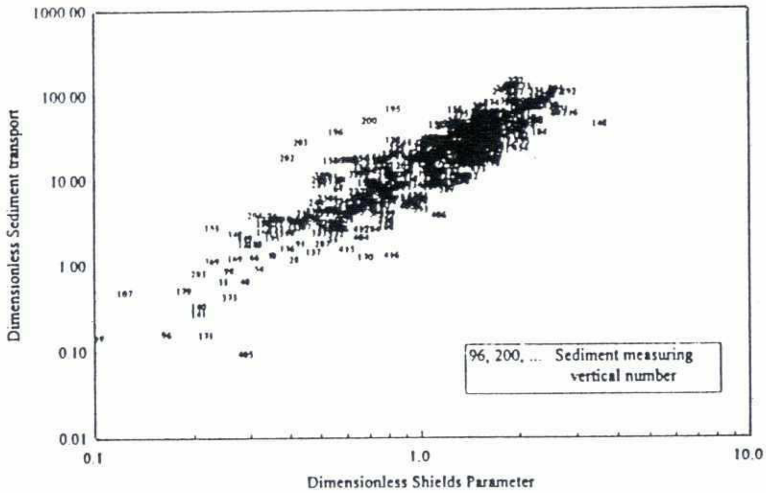


Figure 7.3 Quality check of Bahadurabad flood season data

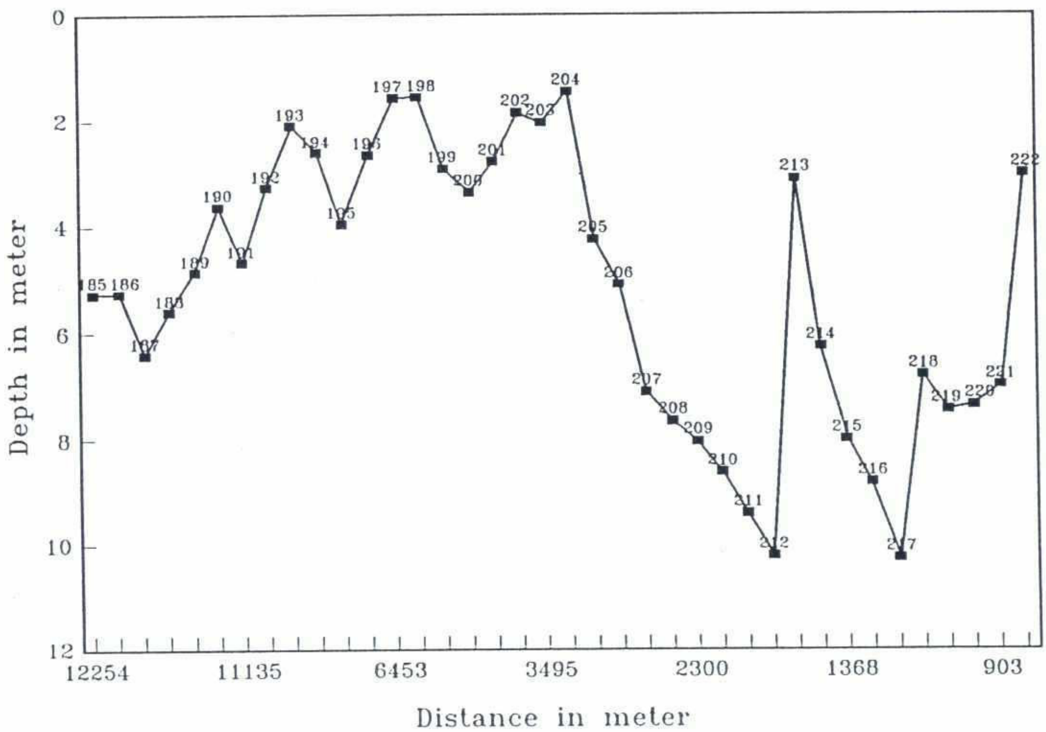
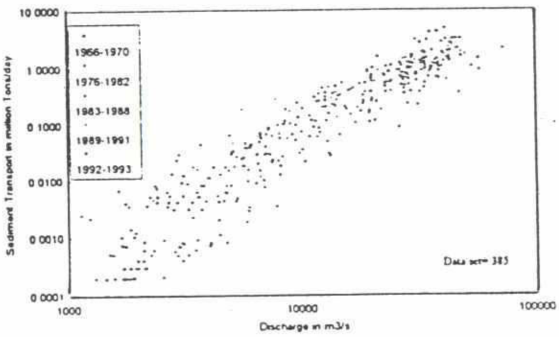


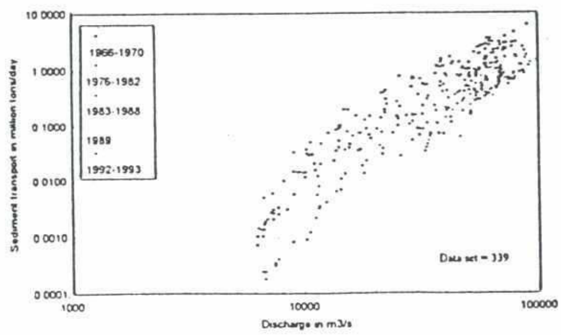
Figure 7.4 Location of verticals with outlying results

Similar plots of the dimensionless sediment transport rate ψ versus the dimensionless shear stress θ were made for Hardinge Bridge and Baruria as well. These are shown in the Figures 7.5 a and b. It can be observed that in these graphs the scatter is much larger. This large scatter is due to two causes:

1 scatter due to the same reasons as the scatter in Bahadurabad;
2 the specific conditions of Hardinge Bridge being a constriction and the Baruria measuring site being located downstream of the confluence.



(a) Ganges River at Hardinge Bridge



(b) Padma River at Baruria

Figure 7.5 Dimensionless sediment transport rate ψ versus the dimensionless shear stress θ for two other stations

As will be discussed later, the latter cause is due to the non-uniform conditions, for which the overall slope is not representative for the slope of the energy gradient near the measuring site. This introduces systematic errors, which are reflected in the Figures 5(a) and 5(c) as a large scatter. For this reason it is not possible to use the Hardinge Bridge and Baruria data for the derivation of a sediment transport formula as can be done for Bahadurabad.

For the Bahadurabad station it can be assumed that fairly uniform conditions are present in the years without a pronounced local scour hole in the left channel near Bahadurabad Railway Ghat. Hence the approach adopted initially was to use only the Bahadurabad data for the development of a sediment transport predictor for bed material load. The Hardinge Bridge and Baruria data can only be used in combination with a 1-dimensional model that allows to estimate the local slope (as discussed RSP Special Report 19).

RSP data

In a later stage of the project, when the sediment transport data collected by the project became available, these were used as well. These data were collected on a routine basis in the period 1993-1996. Details on the measuring campaign under which they were collected is given in Annex 1. Two types of data on suspended sediment transport were collected, notably depth-averaged sampling and point-integrated sampling. In the present analysis the data from the point-integrating method were preferred. These data were processed to get the suspended bed material transport per unit width. In 1993 no distinction was made between wash load and bed material load; in the subsequent years also the suspended bed material was determined. This is comparable to the "coarse" sediment load determined by the BWDB.

Table 7.3 provides an overview of the data used in the further analysis. The data base consists of data from the Jamuna River (Bahadurabad right channel and Sirajganj), from the Old Brahmaputra River at Mymensingh and from the Dhaleswari River at Tilly. These data series were collected because they appeared to be affected only marginally by constrictions.

River	Station	Period from which sediment transport data were used	Number of verticals for which data are available
Jamuna River	Bahadurabad (left channel)	June 1994 - September 1995	35
Jamuna River	Sirajganj	June 1994 - September 1995	63
Old Brahmaputra River	Mymensingh	June 1994 - September 1995	57
Dhaleswari River	Tilly	June 1994 - September 1995	66

Table 7.3 Sediment transport data measured by RSP and used in this study

River	Gauging station	Grain size of bed material River Survey Project			
		Collection period	D_{16} mm	D_{50} mm	D_{84} mm
Jamuna River	Bahadurabad (left channel)	1993-1995	0.13	0.20	0.29
Jamuna River	Sirajganj	1993-1995	0.13	0.19	0.29
Old Brahmaputra River	Mymensingh	1993-1995	0.11	0.20	0.35
Dhaleswari River	Tilly	1993-1995	0.11	0.16	0.26

Table 7.4 Grain sizes used in the analysis of RSP sediment transport data

Also information on the bed material size at the different routine gauging sites is required. The available data are shown in Table 7.2. This table lists the results of bed material sampling collected for size analysis by the River Survey Project for the different stations.

In principle more data from RSP routine measurements are available for other stations. These have not been used as they did not satisfy the criterion that the cross-section would remain fairly uniform also during the recession of the flood. In those cases it was observed that the sediment transport became negligible for lower stages.

7.5 Initial attempts to derive a sediment transport predictor

As discussed above initially a sediment predictor was developed on the basis of the BWDB data from the period 1984-1987. This analysis and its result is summarized hereafter. Essentially this is a summary of *RSP Special Report 13*. Hence for more details reference is made to this report.

Once the BWDB Bahadurabad 1984-1987 data were quality checked and clear outliers had been removed, they were used for the development of a sediment transport predictor. The selection of a certain period from which data are to be used is quite important as it was observed (see Special Report 19) that over the decades the sediment rating curves have changed. As this is probably caused by other than natural causes, it requires a judgement as to the quality of the data in the different periods. For a number of reasons (as discussed in more detail in Study Report 13), the main being the possibility to get access to the detailed discharge measuring forms, data from the period 1984-1987 were preferred.

In a next step a graph was produced of the dimensionless sediment transport rate ψ versus the dimensionless shear stress θ. For the computation of θ the measured depth h and the overall slope i was used. For the characteristic particle size D here D_{50} (see Table 7.2) was used. As no data are available on the bed load and the BWDB data relate only to the suspended load, the dimensionless sediment transport rate ψ relates only to suspended load. Hence it would be preferable to refer to this parameter as to ψ_s, where the index s refers to suspended load. For convenience the index s is dropped hereafter.

In the graph of the dimensionless sediment transport rate ψ versus the dimensionless shear stress θ a number of existing sediment transport predictors were plotted to check whether anyone of these did fit to the data. The sediment transport predictors were used for checking tare predictors for bed material load, comprising both bed load and suspended bed material load, notably Bagnold (1966), Engelund & Hansen (1967), Yang (1971), Ackers and White (1973) and Van Rijn (1984). This graph is presented here as Figure 7.6. In this Figure also a regression line has been added on the basis of all the accepted Bahadurabad data. It can be observed that none of the existing sediment transport predictors coincides with the empirical data from the Jamuna River.

As discussed in Section 7.3 in particular the value of the power n is important. This is indicated by the slope of the lines. It can be observed that the Ackers & White, Engelund & Hansen and Yang predictors are substantially steeper than the regression line. As far as this slope is concerned the Van Rijn and the Bagnold predictors score better although not good. As can be seen from Figure 7.2 these two equations have fairly low values of n. Apart from that, the Yang equation also yields too low predictions almost over the full range of θ.

Based on the above observations it was concluded that none of the existing sediment transport predictors is applicable to the conditions in the Jamuna River, although both the Bagnold (1966) and the Van Rijn (1984) are fair choices, both in terms of slope and in overall performance. It was decided to develop a dedicated sediment transport formula. In doing this the approach as outlined earlier was adopted. Hence first the relation between the dimensionless sediment transport rate ψ versus the dimensionless shear stress θ was determined and in a second and third step a correction for the resistance to flow and the inclusion of the sediment transport near the river bed were tackled.

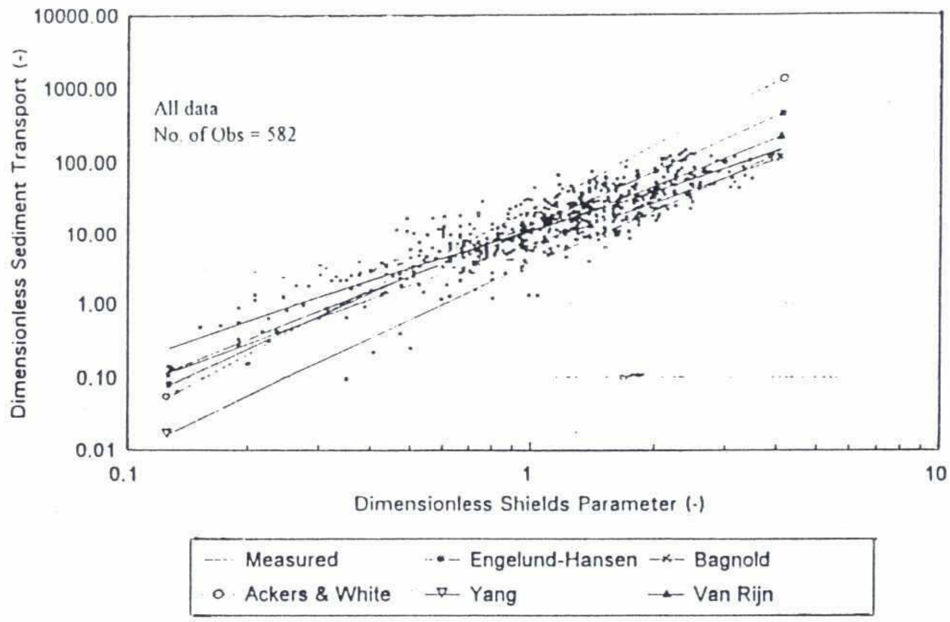


Figure 7.6 Different predictors compared with BWDB measurements from Bahadurabad 1983-1987

The relation between the dimensionless sediment transport rate ψ versus the dimensionless shear stress θ was determined using the regression line in Figure 7.6. The regression line corresponds to the following equation:

$$\psi = 11\ \theta^{1.83} \tag{7-7}$$

This relation can be written in a generalized form as:

$$\psi = K_1\ \theta^{\frac{n}{2}} \tag{7-8}$$

Here, the coefficient K_1 is 11. The power 'n/2', which is the exponent of the Shields parameter (θ), is 1.83, and 'n' is equal to 3.66. As can be seen from Figure 7.2 this value of n is fairly low. This can also be written as:

$$\psi :: \theta^{1.83} \tag{7-9}$$

The Bahadurabad data apparently correspond to a fairly low n value, in line with the previous observations that the van Rijn and Bagnold predictors "score" better (see also Figure 7.2).

A next step in the derivation of a sediment transport formula is the determination of the influence of the hydraulic roughness. In many sediment transport formulae the hydraulic roughness is included. The reason for it is that in the case of a river bed with bedforms only a part of the total shear stress is assumed to be effective in transporting sediment. The remaining part is required for overcoming the resistance caused by the bedforms. This approach may be valid for cases where bedload is the dominant mode of transport. It is more questionable in cases where the dominant mode of transport is suspension, but nevertheless inclusion of a correction for the roughness leads to a considerable improvement also there.

To study the possible influence of the hydraulic roughness a graph was produced where in the relation between the dimensionless sediment transport ψ and the dimensional shear stress θ the points were marked for the value of the Chézy coefficient. This graph is shown in Figure 7.7. The Chézy coefficient was determined using the following equation:

$$C = \frac{u}{\sqrt{h.i}} \qquad (7\text{-}10)$$

During the sediment transport measurements of the BWDB the local depth h and the local velocity u are known, as the sediment transport measurements are done almost simultaneously with the flow measurements. The slope however is not measured, so for i the overall slope as determined from a hydrological assessment (see Annex 3, Section 7.2) is used.

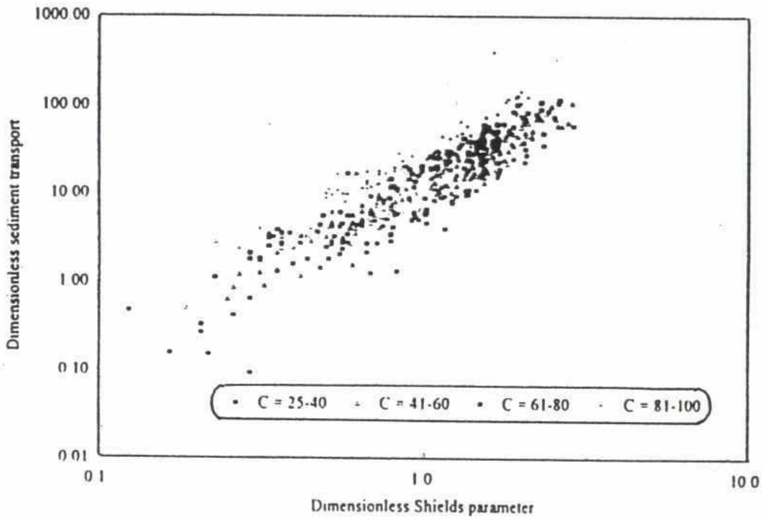


Figure 7.7 Dimensionless sediment transport ψ versus the dimensional shear stress θ for Bahadurabad marked for Chézy values

Inspection of Figure 7.7 reveals that the plotting of the points is strongly correlated with the Chézy coefficient. Low values of C result in low sediment rates and high values of C result in high sediment transport rates. This is also in line with what is expected in view of the possible effect of C as discussed above. It is slightly worrying that very low values of C are obtained, down to 20 $m^{1/2}/s$. This is explained by the combination of local parameters (u,h) with overall slopes. In reality the local slope may deviate substantially from the overall slope (see Chapter 7 of Annex 3).

It was attempted to introduce the apparent influence of C into the sediment transport predictor. Hence the parameter K_1 in the sediment transport predictor:

$$\psi = K_1 \; \theta^{1.83} \qquad (7\text{-}11)$$

This was done by using the data as shown in Figure 7.6 . The resulting equation for K_1 is:

$$K_1 = 0.16 \left(\frac{C}{\sqrt{g}} \right)^{1.45} \qquad (7\text{-}12)$$

Hence one could argue that for prediction of the sediment transport formula for the Bahadurabad the above equation should be used, and in combination with the overall slope this will indeed give a good prediction for Bahadurabad (apart from the problems with regard to the selection of the "best" data - here 1984 -1987 data were used - , which is reflected into the coefficient 0.16). This expression is the one proposed in RSP Special Report 13.

There is, however, a more fundamental problem with the inclusion of a correction factor for C, as done in the study, as is shown hereafter. The problem is related to the fact that in 1-and 2-D morphological models the sediment transport is computed using the local slope as determined from the hydraulic part of the simulation. Use of an overall slope would lead to wrong simulations. The analysis discussed above uses field data from the BWDB. During these measurements in each vertical the following parameters are measured: u, h, and c (whereby s = c.h.u), while for the slope a value is used which was derived from a hydrological analysis of water levels (see Annex 3). This so-called overall slope, hereafter indicated with the symbol i_0, is slightly different for the different seasons (see Chapter 7.2 of Annex 3), but this is not very relevant for the present discussion.

Assume that the sediment transport can be described by the following relation:

$$s :: \theta_0^{\frac{n}{2}} \left[\frac{C_0}{\sqrt{g}} \right]^{\delta} \qquad (7\text{-}13)$$

The index 0 stands for uniform conditions. For n=5 and δ=2, an Engelund-Hansen type of formula is found.

Probably the slope in some point in a cross-section will be different from the overall slope, due to local effects. Assume that the local (energy) slope i_l is given by:

$$i_l = \alpha . i_0 \qquad (7\text{-}14)$$

For these conditions the real Chézy value C_r can be approximated via:

$$C_r = \frac{u}{\sqrt{h.i_l}} \qquad (7\text{-}15)$$

This C_r is approximately equal to the theoretical value C_0 found when using a resistance to flow predictor. However, the Chézy value computed from the measured u and h and using one value for the overall slope, here referred to as C_c is:

$$C_c = \frac{u}{\sqrt{h.i_0}} \qquad (7\text{-}16)$$

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The relationship between C_r and the computed value C_c is:

$$\frac{C_c}{C_r} = \sqrt{\alpha} \qquad (7\text{-}17)$$

The measured sediment transport is, not considering upstream effects, measuring errors and alike, determined by the local slope, hence following an Engelund-Hansen approach, corresponds to:

$$s_m = \gamma \left[\frac{h.i_l}{\Delta.D}\right]^{\frac{n}{2}} \left[\frac{C_r}{\sqrt{g}}\right]^{\delta} \qquad (7\text{-}18)$$

where γ is a proportionality coefficient. Or:

$$s_m = \gamma \left[\frac{h.\alpha.i_0}{\Delta.D}\right]^{\frac{n}{2}} \left[\frac{C_r}{\sqrt{g}}\right]^{\delta} \qquad (7\text{-}19)$$

which can also be written as:

$$s_m = \gamma\ \alpha^{\frac{n}{2}} \left[\frac{h.i_0}{\Delta.D}\right]^{\frac{n}{2}} \left[\frac{C_r}{\sqrt{g}}\right]^{\delta} \qquad (7\text{-}20)$$

Using

$$\frac{C_c}{C_0} = \sqrt{\alpha} \qquad (7\text{-}21)$$

and introducing θ_0 via:

$$\theta_0 = \frac{h.i_0}{\Delta.D} \qquad (7\text{-}22)$$

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it is found that:

$$s_m = \gamma \left(\frac{1}{C_r}\right)^{n-\delta} \theta_0^{\frac{n}{2}} \left(\frac{1}{\sqrt{g}}\right)^{\delta} (C_c)^n \qquad (7\text{-}23)$$

Or:

$$s_m :: \left(\frac{1}{C_r}\right)^{n-\delta} \theta_0^{\frac{n}{2}} (C_c)^n \qquad (7\text{-}24)$$

Considering now that n is in the order of 4 and δ in the order of 2 (Engelund-Hansen), it follows that the power of the term with $1/C_r$ is about 2, hence in a plot of s_m (made dimensionless, hence of ψ) versus θ the effect of the dependence on C_r would show up. The Chézy value varies between 50 and 80 $m^{1/2}/s$, and hence this would give differences in the order of 2.5 (1.6^2). Such a plot would however show a very strong correlation with C_c (power n). As C_c varies between about 30 and 90 $m^{1/2}/s$, this variation would result in scatter in the order of 50 ($3^{3.66}$). Hence the strong correlation with C_c, as shown in Figure 7.* is simply built-in via the use of the overall slope instead of the local slope.

This result can be compared with the sediment transport formula inclusive roughness correction as developed above via correlation analysis (Equation 7-12), which reads as:

$$\psi = 0.16 \left(\frac{C}{\sqrt{g}}\right)^{1.45} \theta_0^{\,1.83} \tag{7-25}$$

Instead of a "scatter" with approximately a power 3.66 (as argued earlier that should be present even if the additional scatter due to C_r is omitted), apparently only a power 1.45 is found. Different possible explanations for this can be proposed:

1. During the BWDB measurements a Binckley sampler was used, that is subject to high forces during fast currents. Hence the cable may be under a substantial angle. This may lead to a lower estimate of the suspended load, as the upper verticals carry on the average less sediment. This explanation would also have an implication for the n-value as higher θ-values are usually found for higher velocities.
2. Higher Chézy-values and hence higher flow velocities could on the average be linked to accelerating flows that are underloaded, while lower flow velocities could be linked to overloading. This would also lead to reduced scatter.

Possibly other explanations can be given as well. It is difficult to verify them without additional studies. It has to be concluded that based on the available data it is not possible to verify the correction for the resistance to flow in the sediment transport equation.

Awaiting the results of more detailed studies (where e.g. the local slope is measured) it is assumed that the C-correction is not different from Engelund-Hansen, and the non-dimensional expression for the sediment transport when using the local slope reads approximately:

$$\psi \;::\; \left(\frac{C_0}{\sqrt{g}}\right)^{2} \theta_0^{\,1.83} \tag{7-26}$$

Regarding the proportionality coefficient the following can be stated. Equation (7-12) and equation (...) should give approximately the same value for average C-values.
For $C_0 = C_r = C_c = 65\ m^{1/2}/s$

$$\left(\frac{C}{\sqrt{g}}\right)^{2} = 5.27 \left(\frac{C}{\sqrt{g}}\right)^{1.45} \tag{7-27}$$

Hence the result of a first attempt to derive an appropriate sediment transport predictor for the Jamuna River (also including the effect of the porosity) reads as:

$$\psi = 0.03 \left(\frac{h.i}{\Delta.D}\right)^{1.83} \left(\frac{C}{\sqrt{g}}\right)^{2} \tag{7-28}$$

where i = local slope and ϵ = porosity (-). If the effect of the porosity would be included

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(important using the sediment transport in combination with the continuity of the sediment (in its 1-D form):

$$\frac{\delta z_b}{\delta t} + \frac{\delta s}{\delta x} = 0 \qquad (7\text{-}29)$$

the formula would read:

$$\psi = \frac{0.03}{(1-\epsilon)} \left(\frac{h.i}{\Delta.D}\right)^{1.83} \left(\frac{C}{\sqrt{g}}\right)^2 \qquad (7\text{-}30)$$

It is of interest to compare this expression with the Engelund & Hansen (1967) predictor, which reads:

$$\psi = \frac{0.05}{(1-\epsilon)} \left(\frac{h.i}{\Delta.D}\right)^{2.5} \left(\frac{C}{\sqrt{g}}\right)^2 \qquad (7\text{-}31)$$

For the conditions of the Jamuna River the value of θ is in the order of 1, hence application of the derived predictor would result in lower predicted sediment transport rates than when using the Engelund & Hansen (1967) predictor. This is not in line with recommendations of e.g. Klaassen et al (1988), which suggest that the actual sediment transport is about 2 times higher than the Engelund & Hansen predictor would indicate. This ultimately is the consequence of using the period 1984 - 1987 as reference, as it was found during this project that most probably the measured values in that period were too low.

7.6 Second attempt on the basis of RSP data

As discussed in the previous Section the use of the field data from the period 1984 - 1987 resulted in a sediment transport predictor that underpredicts the suspended bed material load. Hence a second attempt was made to derive a sediment transport predictor.

This second attempt was different from the initial one in three respects:

- Instead of BWDB data from 1984 - 1987 results from RSP routine measurements were used.
- Data from all RSP routine gauging was used as far as they satisfied the criterion that during the recession of the flood no natural constriction developed. Also the data from Hardinge Bridge and Baruria were excluded for obvious reasons.
- Instead of the overall slope an estimate of the local slope was used for the computation of the dimensionless shear stress θ.

To estimate the local slope is not easy. The local slope was not measured during the surveys (and would also have been difficult, because of the in-built conflict between on the one hand measuring sufficiently local to identify the real local slope and on the other hand the length required to determine the local slope sufficiently accurate). Hence the local slope had to be estimated. During the sediment transport measurements not only the concentration and the depth (used in the previous Section) but also the depth-averaged velocity is determined.

This allows to determine the local slope from the Chézy equation (which formally only holds for uniform flow, but can be used here as a good first approximation):

$$i_l = \frac{u^2}{C^2 h} \tag{7-32}$$

This expression can only be used when the (local) value of C is known. In the present analysis it was assumed that the local Chézy coefficient is given by the expression proposed by DHI (1996), but slightly adapted on the basis of the theoretical/empirical backing given in Chapter 4 of this Annex:

$$C = 26\ h^{0.5} \tag{7-33}$$

For the value of h the value observed during the sediment transport measurements is used. This allows to compute dimensionless shear stress θ via:

$$\theta = \frac{u^2}{C^2\ \Delta\ D_{50}} \tag{7-34}$$

As already discussed in Section 7.4 in total four stations were selected, notably Bahadurabad, Sirajganj, Mymensingh and Tilly. Figure 7.8 provides the observed values of the dimensionless sediment transport rate ψ versus the dimensionless shear stress θ for the four stations. The upper figure provides all data available irrespective of their origin, while in the lower Figure a differentiation is made as to from which station the data are coming. Some observations can be made as to Figure 7.8:

- Values of θ vary between 0.001 and 3. According to Shields (1936) sediment transport vanishes when θ approaches 0.03, hence data points corresponding to these very low values of θ are probably not very reliable. Deleting all points with $\theta <$ 0.015 appeared to have only a small influence on the regression line.
- As can be expected the data for the distributaries relate to lower values of θ, while the Jamuna data correspond to the higher values of θ.
- The slope of the regression line corresponds to approximately n = 1.85 which is amazingly near to the value found in Section 7.6 from the BWDB data (n = 1.83).

On the basis of these points a sediment transport equation was developed applicable for Bangladesh's main rivers. Because of time limitations no separate study was done into the influence of the Chézy coefficient on the sediment transport. For the time being it was assumed that the influence of C can be incorporated in the same way as in the Engelund-Hansen (1967) expression. A subsequent analysis (again using C = 65 $m^{1/2}/s$ as average value) resulted in the following tentative expression for the sediment transport in Bangladesh's main rivers:

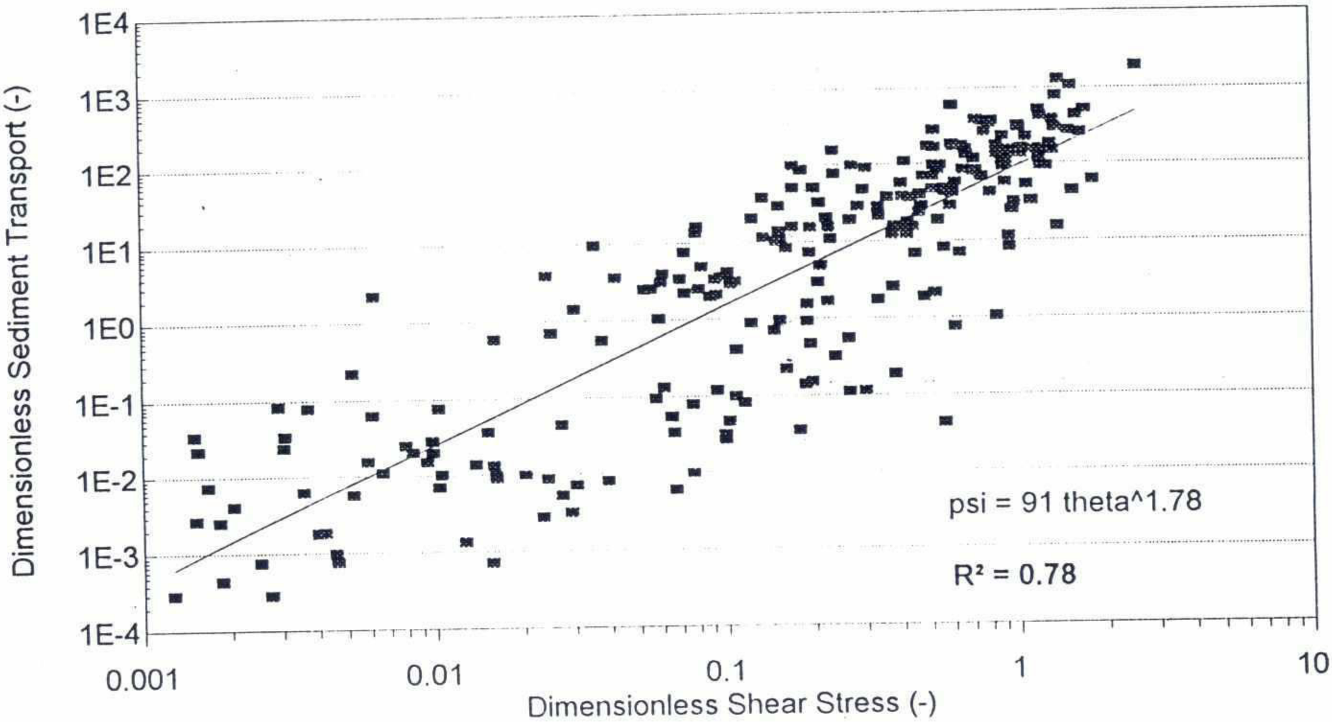
$$s = \frac{0.165}{1-\varepsilon}\sqrt{g.\Delta.D_{50}^{\ 3}}\left\{\frac{h.i}{\Delta.D}\right\}^{1.82}.\frac{C^2}{g} \tag{7-35}$$

where s = suspended sediment transport per unit width (m^2/s), ϵ = porosity (-), g = acceleration of gravity (m/s^2), D_{50} = characteristic particle size, i = slope (-), C = Chézy-coefficient ($m^{1/2}/s$), and Δ = relative density, defined via:

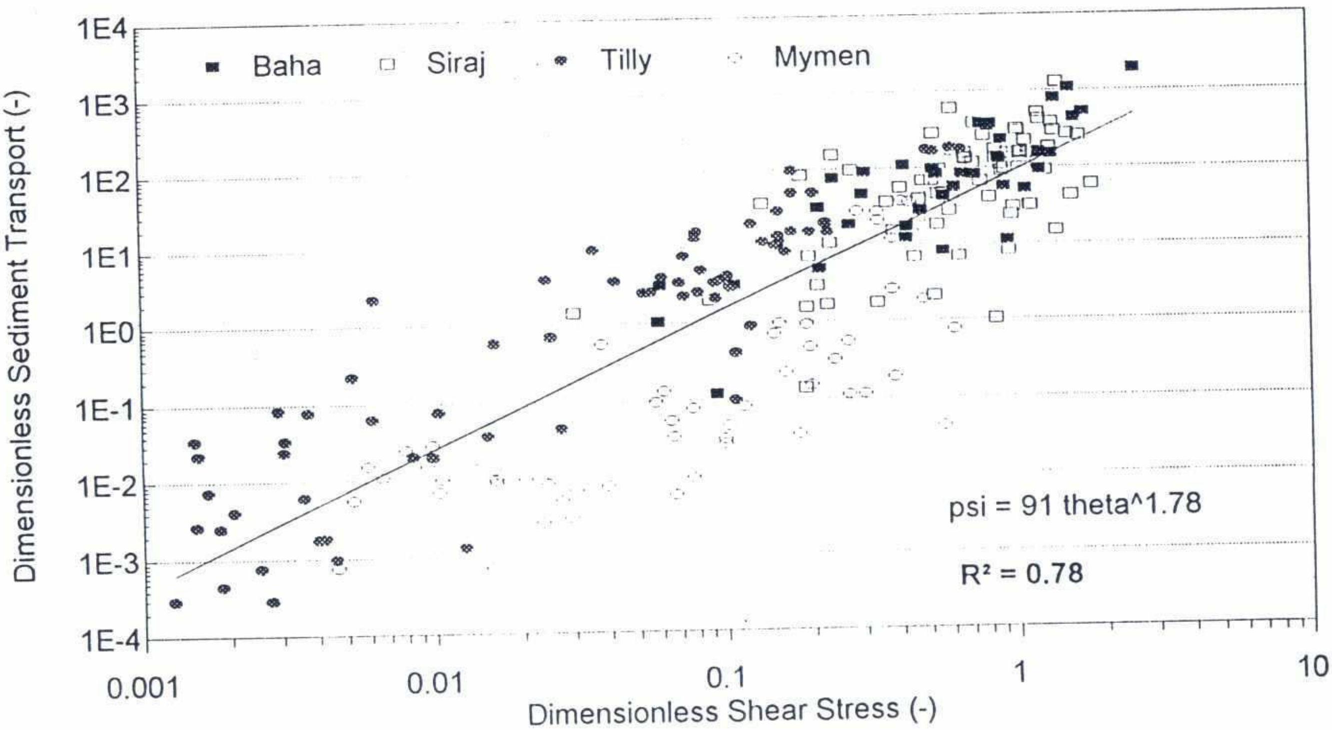
$$\Delta = \frac{\rho_s - \rho}{\rho} \tag{7-36}$$

with ρ_s = density of sediment (kg/m^3) and ρ = density of water (kg/m^3).

This Equation is tentatively proposed for use in 1-D and 2-D mathematical models for the simulation of the morphological phenomena in Bangladesh's main rivers. It can be observed that for $\theta = 1$, this predictor results in 3 times higher sediment transport rates than according to Engelund & Hansen (1967). For a value of $\theta = 2$, this difference reduces (due to the lower value of n/2) to about 2, well in line with earlier suggestions by Klaassen et al (1988).



(a) For all four stations



(b) Differentiated per gauging station

Figure 7.8 Dimensionless sediment transport rate ψ versus the dimensionless shear stress θ based on RSP data from four stations

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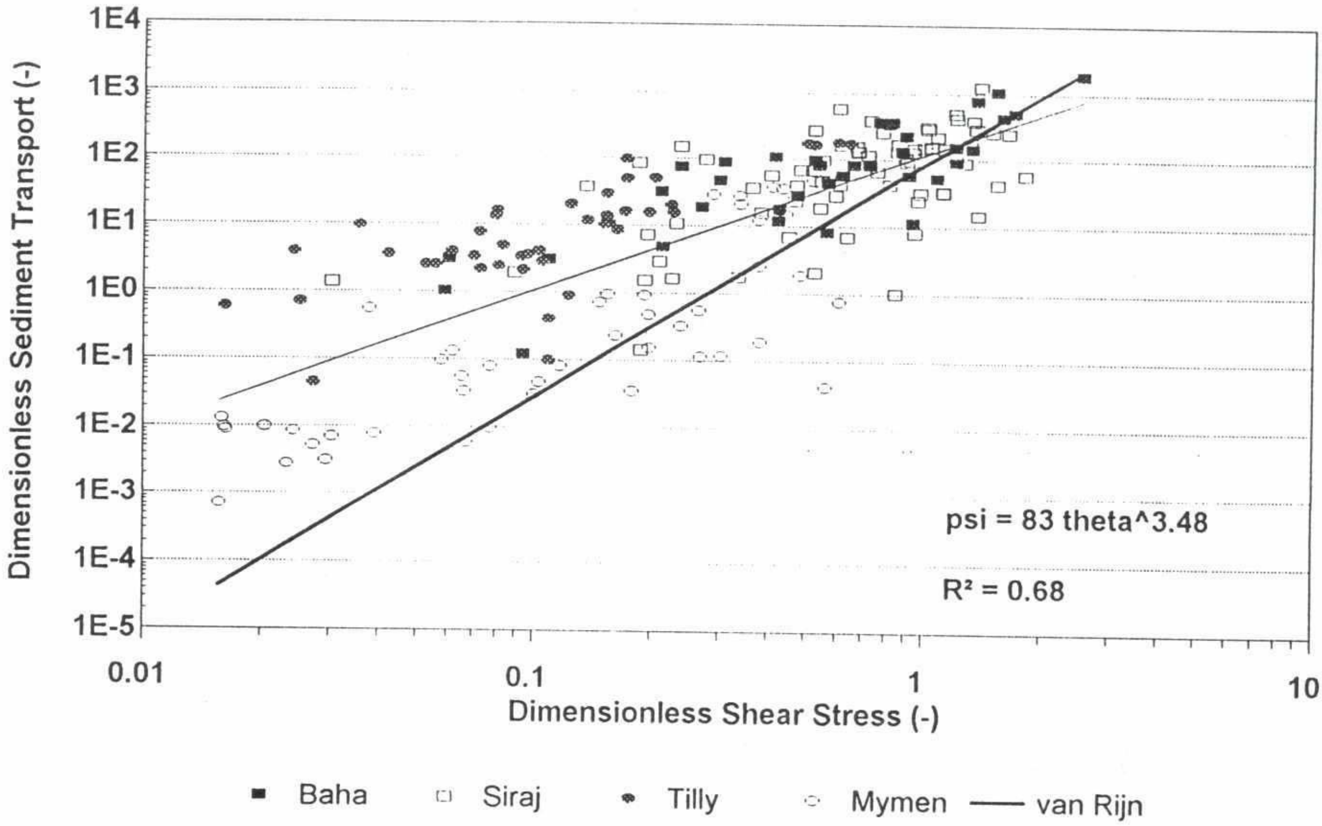

Figure 7.9 Comparison of van Rijn (1984) predictor with RSP data from routine measurements

It is also of interest to compare the predictor developed here with the van Rijn (1984) predictor. This is done in Figure 7.9. As can be observed the van Rijn predictor corresponds fairly well with the data and the predictor developed here for higher values of the dimensionless shear stress θ. For lower values the Van Rijn sediment transport predictor apparently underestimates the sediment transport considerably. Furthermore it can be observed that the van Rijn predictor corresponds to a too high value of n/2.

More studies are needed to improve the predictor developed here. In particular it is recommended to study the influence of C on the sediment transport and, if appropriate, to derive an improved predictor.

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7.7 Verification for Jamuna River

The Jamuna sediment transport predictor for the suspended bed material transport was developed in the previous Section on the basis of RSP data from the period 1993-1995. A next step in the development of such a predictor should be to verify the derived expression versus independent and reliable data.

Such sets of data are not easy to be found, also not because of a number of requirements as far as parameters that should be known, has to be fulfilled. In this respect it is recalled that the local sediment transport is determined by:

- the local energy gradient;
- upstream conditions;
- bed material composition, local and upstream.

To some extent these aspects were already discussed in previous parts of this Annex, notably Chapter 5 and the previous Sections 7.5 and 7.6. Some additional considerations are given hereafter.

The local energy gradient differs from the overall slope for two reasons. Firstly backwater or drawn-down conditions may exist. This is very pronounced near the confluence of the Jamuna and the Ganges Rivers, but these effects occur also at every constriction or widening. Such constrictions can be man-made like the river training works at Hardinge Bridge (or in due time the Jamuna Bridge), but they also occur naturally as a consequence of the continuous changes in planform as a response to the ever varying discharge. Hence uniform conditions are rather an exception than a rule. This type of deviations from the overall slope are to some extent "one-dimensional" as they can be simulated with a 1-D model (see also the next Section 7.8).

Secondly deviations of the local slope from the overall slope are caused by the 2-dimensional bed topography of the river bed. This is in particular pronounced in the braiding Jamuna River, but also in the more meandering rivers like the Ganges and the Padma rivers bars are found that may under certain discharge conditions cause strong local deviations from the overall slope. An analysis of the local slopes as computed in the 2-D flow modelling for Kamarjani showed that locally the slopes can be up to several times the overall slopes. These deviations from the local slope are referred to as "2-dimensional" as they are caused by the 2-D bed topography of the river. They can be present independent from the "1-D" deviations.

As is discussed in Section 5.3 the upstream conditions may have a pronounced influence on the suspended sediment transport. This is due to the retarded adaptation of the suspended sediment verticals. It can only be accounted for when these upstream conditions are taken into account. One way to do that is to use the so-called Galappati approach (Galapatti & Vreugdenhil, 1982), but in rivers like the Jamuna River this very quickly has to include a simulation of the 2-dimensional flow pattern as well.

Finally the composition of the bed material is important, both its size and its mineralogical composition. As is shown in Section 5.3 (see also RSP Special Report 24), the shape of the suspended load verticals is affected by both factors. Due to the sorting the local bed material can be quite different from the average bed material (see the Sections 2.5 and 5.3). This also has an effect on the sediment transport. Furthermore an error may be introduced during the processing of the data, because in the computation of the dimensionless sediment transport rate ψ versus the dimensionless shear stress θ the value of D is used for making them non-dimensional. Due to the fact that n/2 is only 1.82, the effect of the diameter on the relation ψ and θ is only affected with a factor $(D/D)^{0.33}$, which corresponds for a D/D = 2 to an error of 25% only. This is small compared to the other sources of errors in measured sediment transport and computed shear stress.

In total three sets of data for verifications were identified. They are listed in Table 7.5 together with an indication to what extent the criteria listed before are fulfilled.

Verification case	Criterion						
	Independent data			1-D local slopes correct	2-D local slopes correct	Upstream conditions accounted for	Sediment sorting
	River	Location	Measur-ing method				
BWDB Bahadurabad data 1993-1994	No	No	No	No	No	No	No
RSP routine measurements Sirajganj with 2-D morphological model	No	Yes	Yes	Yes	Yes	Yes	No
Ganges and Baruria BWDB sediment transport data	Yes	No	No	Yes	No	No	No

Table 7.5 Data available for verification of the derived suspended bed material transport predictor

The three data sets for verification are briefly discussed hereafter:

(a) BWDB Bahadurabad sediment transport data 1993-1994

BWDB data for 1993-1994 are available for verification. The data relate to a different period and hence are independent in this respect. Apart from that they are for the same river, the same location and the same measuring methods and instruments are used. In the analysis the overall slope is used and the effect of upstream conditions cannot be taken into account. Also the effect of sorting and hence differences in bed material composition are not accounted for as the average bed material size is used in the processing. Finally there are some doubts as to the accuracy of the measurements (see Section 7.4).

(b) RSP routine measurements Sirajganj with 2-D morphological model

For another project DHI is developing a 2-dimensional mathematical model for the morphology of the Jamuna River near Sirajganj. In this model the flow, sediment transport and bed topography changes are simulated. Simulations are done on the basis of the April 1995 bed topography as initial conditions, while the 1995 hydrograph is applied as upstream boundary conditions. The model is two-dimensional and suspended load is simulated separately from the bed load. In the sediment transport module the Galappatti-method is included. Different sediment transport modules can be included. Simulations were carried out with the proposed sediment transport predictor and with the van Rijn (1984) predictor. For more information on the model see DHI (1996). During the 1995 season routine sediment transport measurements were done by RSP, and these can be compared with the predicted sediment transport from the model. Hence this corresponds to the same river but a different location, while also different measuring methods (notably the RSP methods and instruments) were used. Both 1-D and 2-D local slopes are automatically computed in the model, while also the upstream conditions are accounted for via the Galappatti-approach. Only the effect of sorting cannot be properly taken into account as one representative bed material size was used.

(c) Ganges and Baruria BWDB sediment transport data
The available BWDB sediment transport data for Hardinge Bridge can be used for verification as well. The advantage is that they are related to other main rivers in Bangladesh which makes it possible to check whether the proposed sediment transport predictor is applicable for all main rivers in the system as well. Problematic with the use of these data is the fact that it may be assumed that also these data are less reliable, for the same reason as the Bahadurabad 1984 - 1987 data turned out to result in too low predictions of the sediment loads. Another problem with these data is that they are not located in uniform sections. However, by using a 1-dimensional model for river morphology it is possible to correct for the 1-D local slope deviations. A disadvantage is that no 1-D model was available in which the proposed sediment transport predictor could be implemented. The 2-D variations cannot be accounted for in a 1-d model either. Also the effect of the upstream conditions and sorting can not be taken into account.

The first data set is probably less useful for verification purposes. The verification of the derived predictor for the other rivers is discussed in the next Section. Hence here only a comparison can be made with the 2-D modelling in combination with field data for Sirajganj can be used.

The most ideal would have been when the proposed sediment transport predictor could have been incorporated in the 2-D mathematical model. This would have allowed for a direct comparison between the predictions with this model (including 1-D and 2-D local slope effects!) and RSP measurements. Limitations in time and in resources did not allow for this approach. In the DHI model the Van Rijn (1984) is incorporated. It was found that this predictor performed quite good when compared to the RSP field data. See DHI (1996), page 40 and the Figures 5.3.1 and 5.3.2 in that report. As the sediment transport predictor proposed here is almost similar to the Van Rijn (1984) predictor for fairly high values of the dimensionless shear stress θ, implicitly also the proposed predictor is verified.

7.8 Verification for other main rivers

As was already shown in Section 7.4 the sediment transport data from the other two sediment transport stations (Hardinge Bridge on the Ganges River and Baruria on the Padma River), when plotted as the dimensionless sediment transport ψ versus the dimensional shear stress θ, show a much more diffuse picture than the Bahadurabad data. As can be observed in the Figures 7.5(a) and (b) the plots show much more scatter and an eventual regression line would show a much steeper slope. A regression line in Figure 7.5(a) would have the form:

$$\psi :: \theta^{2.5}$$

whereas for Baruria even a steeper relationship would be found.

As it was shown already by Galappatti (1993) that constrictions result in steeper relationships between the dimensionless sediment transport ψ and the dimensional shear stress θ it was expected that the scatter in the data and the similarly abnormal behaviour in Baruria can be explained by the constriction and the confluence in combination with the use of overall slopes rather than local slopes. Hence it was decided to study this with a 1-D morphological model.

Ideally, such a 1-D morphological model should have been equipped with the proposed sediment transport predictor (Equation (7.35)). In that case it would have been possible to explore how the relationship between the dimensionless sediment transport ψ and the dimensional shear stress θ would change for the specific conditions at the constriction and the confluence. At the time the study was carried however there was no access to a model that allowed for the introduction of an empirical relation as Equation (7.35). Hence it was decided to use the Engelund-Hansen (1967) equation with $n = 5$ (and hence the power of the relation between the dimensionless sediment transport ψ and the dimensional shear stress θ $n/2 = 2.5$) and to study how the relation between ψ and θ was affected for the two stations Hardinge Bridge and Baruria.

Hence a 1-D mathematical model of the Jamuna, Ganges and Padma Rivers was made. The schematization used in this so-called GJP model (where GJP stands for the three rivers included in the model) is shown in Figure 7.10. Other characteristics of the model: rectangular cross-section, grain sizes used as indicated in Table 7.2, and resistance to flow according to the empirical relation. For more details see Study Report 13.

In the model both the effect of the constriction at Hardinge Bridge and confluence were studied. For Hardinge Bridge it could be shown that the use of the overall slope resulted in steeper relationship between ψ and θ. When using the local slope as computed in the mathematical model for determining the value of θ, a relation with a more gentle slope is obtained.

In Figure 7.11 some results of the effect of a constriction in combination with the use of the overall and the local slope are presented. In left figure computed values of ψ are plotted versus θ values. The θ values were computed in two different ways, one using the overall slope (corresponding to the way Figure 7.6 was made) and the other by using the local (1-D) slope as found during the simulations from the output of the hydraulic part of the simulation. It can be observed that for the case where the local slope is used the scatter is not present anymore, while when applying a lot of scatter is introduced. Also it can be observed that the use of the overall slope leads to a much steeper slope in the relation between ψ and θ. Hence it can be concluded that the difference in behaviour between Bahadurabad and Hardinge Bridge (and also the different slope in the Figures 7.5 and e.g. 7.6) can be explained by the constriction in combination with the use of the overall slope.

A similar analysis was done for the Baruria station downstream of the confluence. Also here the "abnormal" behaviour as shown in Figure 7.5 can be explained by the specific conditions and the use of the overall slope. For more details reference is made to Study Report 13.

It should be remarked that formally the proposed sediment transport formula (Equation (7.35)) could not be verified for the Ganges and Padma data. The much steeper slope of the relation between ψ and θ could be explained by the specific morphological behaviour of the river at constrictions and near confluences. A formal verification on the Ganges and Padma data is still required though.

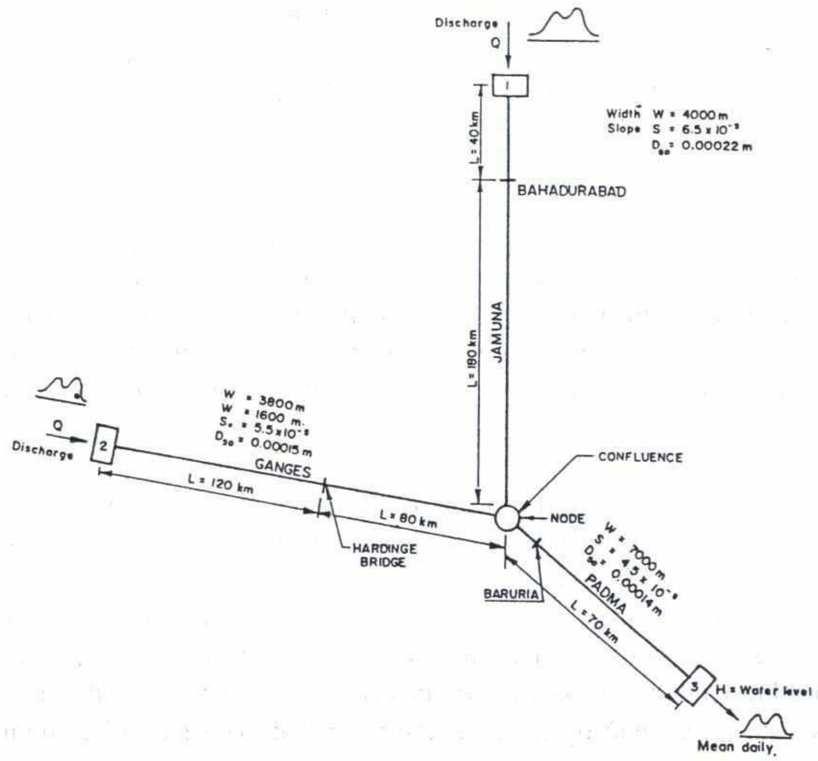
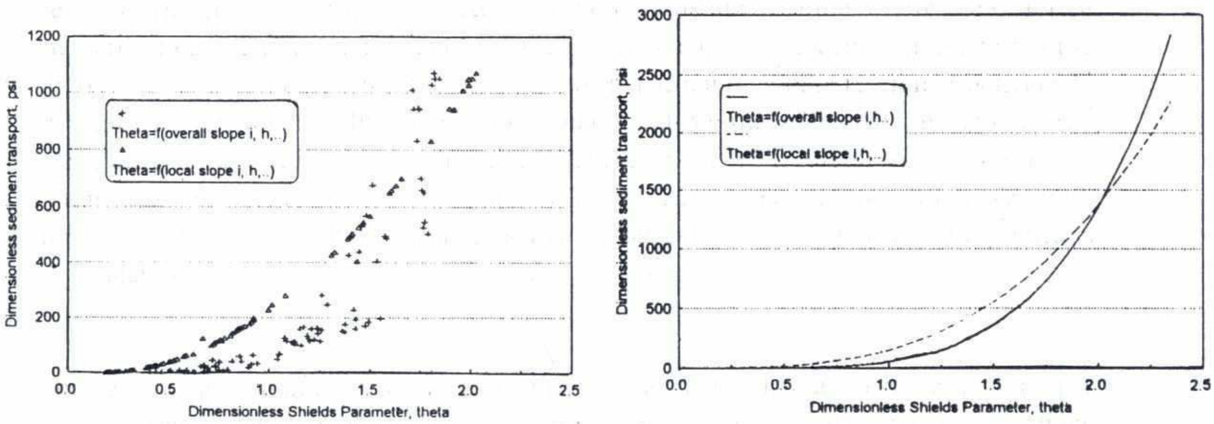


Figure 7.10 Schematized network as used in the GJP model



(a) Use of overall slope versus local slope (b) Regression lines on basis overall and local slopes

Figure 7.11 Simulated relation between ψ and θ for Hardinge Bridge as simulated with a 1-D model

7.9 Correction for near-bed sediment transport

The analysis summarized in the previous Sections deals with the suspended bed material load. Additionally there is also sediment transported near the river bed, either as bed load or in the "unmeasured zone" as a combination of saltation and suspended load. According to Peters (1993) this near-bed sediment transport is very important as it plats a major role in morphological changes. Suspended load verticals adapt to changing flow conditions slower, because the suspended load verticals have to adapt via the setting of the sediment particles. As shown in *RSP Special Report 24,* the adaptation length of suspended load verticals may be up to several kilometres, depending on the particle size considered. The near-bed transport will react much quicker to changes in carrying capacity.

For estimating the total bed material load the near-bed transport has to be added to the suspended bed material load. Under RSP a number of special measurements were carried out to determine the magnitude and relative importance of the near-bed transport. This was done a.o. with Delft bottles on frames. Detailed information is provided in RSP Special Report 12 (see also Annex 2). The most relevant result for the present discussion is presented in Figure 5.5 of Section 5.6 of this Annex. As is shown the average contribution of the near-bed transport varies between about 20 to 60 %. It seems that the contribution of the near-bed transport decreases with increasing sediment transport from on the average about 60 % via some 20 % to (possibly) about 30 % for the highest stages. In particular the slight increase for the highest stages needs further study before a more definitive statement can be made on this.

The above figures however give an indication of the correction needed to include the near-bed sediment transport as well. For low sediment transport rates a multiplication factor of about 2.5 may be required, while for higher sediment transport loads (higher shear stresses) the correction factor decreases to about 1.25 (possibly 1.5). These are only tentative figures which have to be verified by more and more detailed studies. It can be stated that the data obtained so far suggest that earlier estimates of the contribution of the bed load of about 10% (Klaassen et al, 1988) are too low, even for flood conditions.

7.10 Prediction of fine sediments (wash load)

As has been argued earlier in this report (see e.g. Section 5.7) the transport of fine sediments in the large alluvial rivers like the main rivers of Bangladesh is more complicated than for trained rivers in e.g. Europe. Sources of fine sediment are not only the upstream catchment, but probably also quite substantial amounts of fine sediments enter the river due to the erosion of chars and banks of floodplains, and from erosion of low lying (in a certain stage of the recession of the flood wave) stagnant areas, etcetera. As erosion of chars, banks and these low-lying areas is largest during flood conditions, it may be assumed that to some extent the transport of fine sediments can be predicted. Conceptually the transport of sediment would then consists of partly true wash load plus erosion products from the chars and banks minus the deposition of fine sediments in the floodplain (for some details on the latter issue see *RSP Special Report 15* and for a summary Chapter 9 of this Annex).

Although no efforts were made under RSP to study this aspect in some detail, it nevertheless seems to be attractive to make an attempt to link the transport of fine sediments to the bank and char erosion rates plus a more random component linked to the "true" wash load.

7.11 Final remarks

Although quite some efforts were made under this project to study sediment transport processes, many of the observations and conclusions made in this Chapter are tentative only. This is so for a number of reasons: limited number of data, reliability of some data not very high and not all data could be explored fully. Hence there is a clear scope for improvement of e.g. the proposed predictor for suspended bed material load, for the contribution of the near-bed sediment transport and possibly also a predictor can be developed to have at least a rough indication of the transport of fine sediments. Most important however is that detailed studies are continued which will give an improved insight into the sediment transport processes and sediment loads in the main rivers of Bangladesh. In Chapter 12 a number of proposals for further studies are made.

8 Sediment rating curves

8.1 Introduction

The relationship between the discharge and the sediment transport which is calculated from the samples taken in a transit can be expressed by an average curve. This curve, generally referred to as a sediment rating curve, is often an exponential function which can be determined either by regression analysis or from a graph with the data points (discharge, sediment transport) on a logarithmic scale. These curves are widely used to estimate the sediment concentration or the sediment transport for periods during which discharge data are available but sediment transport data are not.

The reliability of the sediment transport calculated from a rating curve depends upon the quantity and reliability of data used to define that rating curve and whether the data are representative for the discharges and sediment transports occurring during the period for which sediment transports have to be estimated. Furthermore, a sediment rating curve between S and Q assumes an unique relationship between the average flow velocity in a cross-section and the shear stress at the riverbed. This unique relationship exists in a steady uniform flow velocity profile, and is described with a logarithmic profile or a power-law profile. And this unique relationship requires a more or less prismatic cross-section of the river. However, in an accelerating or decelerating flow, deviations can be expected relative to a sediment transport curve. These types of flow occur in bends, near bifurcations and near confluences of the channels of a braiding river. Consequently, the sediment rating curves in the main river system in Bangladesh are regression lines fitted to a strongly elongated cloud of data points. In principle, better results can then be obtained with a sediment transport formula, which gives the sediment transport as a function of the bed shear stress. In one-dimensional modelling, these sediment transport prediction formulas are used instead of sediment rating curves.

Since 1966 the sediment transport is measured regularly by BWDB at several gauging stations along the main river system. At the beginning, joint BWDB/RSP measurements, Hydrology analyses of BWDB sediment transport data were separately made, dividing the period of 1966 to 1994 into a number of periods in order to obtain better fitted rating curves, see for instance in SPR 19. Later, it has been noticed that only the sediment transport data of BWDB in the period of 1966-1970 are found reliable. Therefore, only the rating curves using the BWDB sediment transport data measured in that period will be presented here.

8.2 Some theoretical considerations

Sediment rating curves are relations between the sediment transported in the river and its discharge. Such curves can often be expressed as exponential functions. In this report the following notation is used:

$$S = A\,Q^B \qquad (8.1)$$

where S = sediment transport (m^3/s), Q = discharge (m^3/s), and A and B are parameters, which have to be determined empirically.

To explore some theoretical aspects of sediment rating curves here some simple analytical considerations are given. The purpose of this analysis is to get some idea of the value of exponent B for natural rivers. Two simplified cross-sections are used for this analysis, notably (i) a rectangular cross-section and (ii) a cross-section using the at-a-station-relations derived for the different rivers, while it is also assumed that the channel is in equilibrium and uniform flow exists. First a rectangular cross-section is used. As the depth for a wide river for uniform flow conditions is given by:

$$h_n = \sqrt[3]{\frac{Q^2}{B^2 \, C^2 \, i}} \tag{8.2}$$

it holds for a rectangular cross-section that:

$$h_n :: Q^{\frac{2}{3}} \tag{8.3}$$

As:

$$u = \frac{Q}{B \, h} \tag{8.4}$$

and:

$$u :: Q^{\frac{1}{3}} \tag{8.5}$$

using the simplified sediment transport formula:

$$s = m \, u^n \tag{8.6}$$

apparently the relation between S and Q for a rectangular cross-section is:

$$S :: Q^{\frac{n}{3}} \tag{8.7}$$

For n = 4, the value of n derived for the Jamuna River at Bahadurabad, it is found that:

$$S :: Q^{1.33} \tag{8.8}$$

For a more realistic cross-section a similar derivation can be made, but now using the following at-a-station-relationships. These relationships have the form:

$$B = a \, Q^b \tag{8.9}$$

$$\bar{h} = c \, Q^d \tag{8.10}$$

As also in this case Equation (8.4) holds, it follows that:

$$\bar{u} :: Q^{1-(b+d)} \tag{8.11}$$

Hence the relation between S and Q using at-a-station-relationships is found to read approximately:

$$S = B \, s = B \, m \, (\bar{u})^n :: Q^b \left(Q^{1-(b+d)}\right)^n = Q^{n-(n-1)b-nd} \tag{8.12}$$

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This is only an approximate relationship as it is assumed that:

$$\int s(y)\, dy = B\,\bar{s} \qquad (8.13)$$

This is only correct when h does not vary too much along the cross-section.

For the exponents in the at-a-station-relationships reference is made to Annex 5. Using this information, and assuming that for the main rivers in Bangladesh n = 4.0 the theoretically derived exponents for the coarse sediment load in the Jamuna River are presented in Table 8.1. Note that the values for the Jamuna River are slightly adjusted compared to the exponents given by Klaassen & Vermeer (1988), who propose b = 0.51 and d = 0.23, but this has only a minor effect on the exponent of Q in the sediment rating curve.

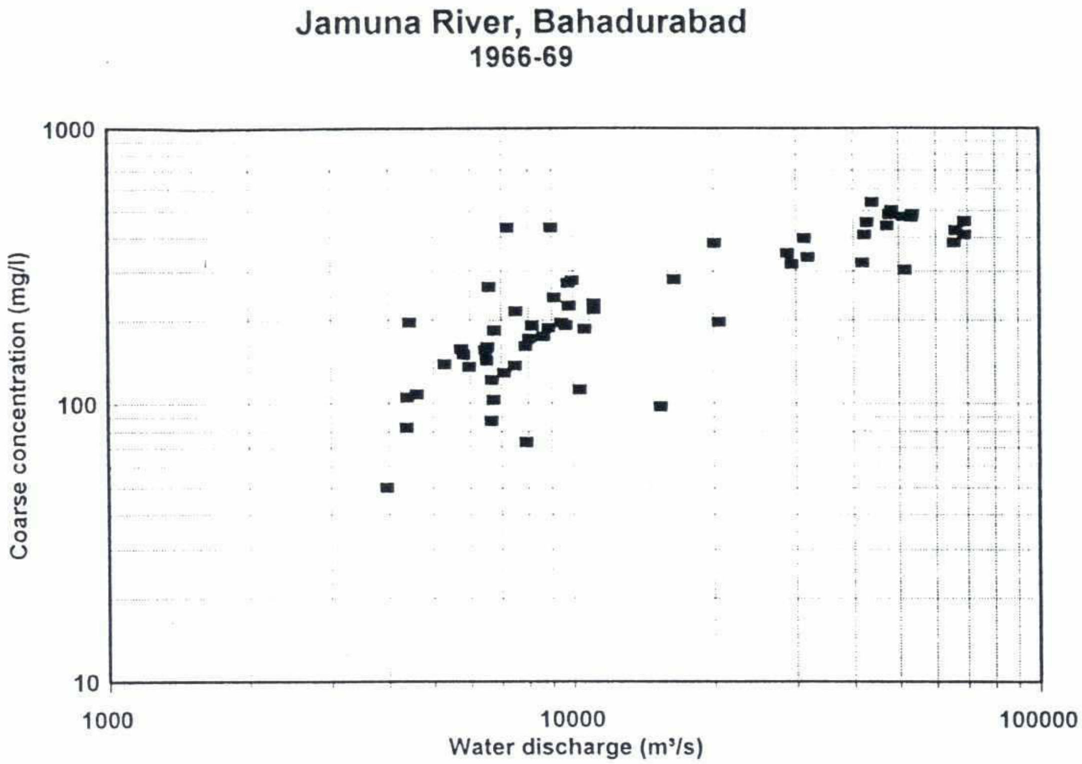
Schematization used for cross-section	At-a-station relationship		Sediment rating curve
	Width	Depth	
Rectangular cross-section	Not applicable	Not applicable	$S :: Q^{1.33}$
At-a-station relationship	$B :: Q^{0.49}$	$h :: Q^{0.22}$	$S :: Q^{1.65}$

Table 8.1 Theoretical values of the exponent in sediment rating curves for the Jamuna River

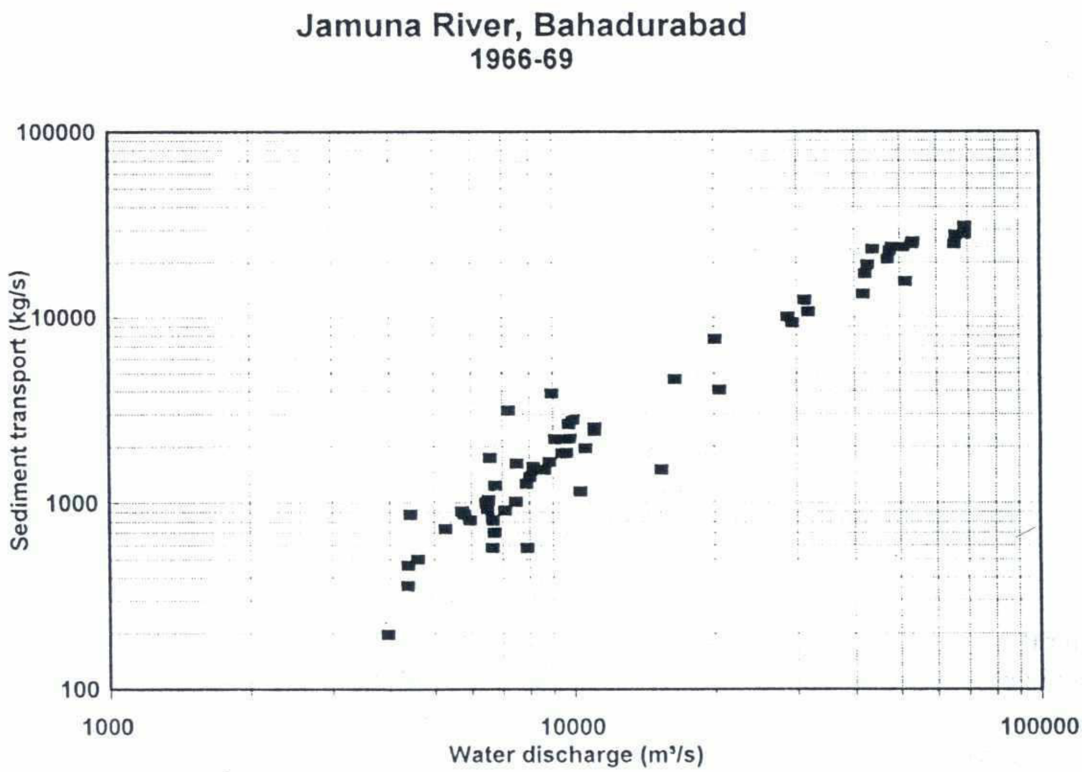
The actual values for a "normal" sediment rating curve in an unconstricted reach where uniform conditions apply, approximately will lie in between the two values given. It may be expected that for lower stages the exponent is more in line with the expression derived from the at-a-station-relationship, while for above bankfull stages (when the at-a-station-relationships are not valid anymore and the variation in depth becomes less) the exponent approaches more the value for the rectangular section. Hence from theoretical perspective it may be expected that sediment rating curves do not have one single slope. In "abnormal" cases, e.g. near confluences and constricted reaches, there can be substantial changes in the sediment rating curves.

It should be stressed that the above considerations are only valid for bed material load (usually referred to in the BWDB terminology as "coarse fraction"). For the wash load ("fine fraction") it is not possible to derive an estimate of the exponent of the discharge.

A problem with sediment rating curves is that they are subject to spurious correlation. The independent parameters measured are the sediment concentration and the discharge. The sediment transport is obtained by multiplying the concentration with the discharge. Hence when plotting sediment transport versus discharge, the discharge is in the parameters on both axes. This introduces so-called spurious correlation. Sediment rating curves "look" much better than they actually are, when e.g. not the sediment load but the sediment concentration would be plotted versus the discharge. This point is illustrated in Figure 8.1, where for the same series of measurements both the concentration versus the discharge and the sediment load versus the discharge is plotted. As can be observed the sediment rating curve looks much better than the plot of the concentration versus the discharge, but this is simply spurious. Hence when interpreting sediment rating curves the fact that "they look better than they are" should be taken into account. This does not imply that sediment rating curves are not useful instruments, but they should be used with care.



(a) Concentration versus discharge



(b) Sediment load versus discharge

Figure 8.1 Spurious correlation in sediment rating curves

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8.3 Effect of local conditions

Sediment rating curves are greatly influenced by the local conditions i.e. the condition of the sediment gauging location in a river such as a constriction or a confluence of different branches. In the main rivers viz. the Jamuna, Ganges and Padma rivers, the discharge and sediment gauging stations are located at Bahadurabad, Hardinge Bridge and Baruria respectively. The gauging station near the Hardinge Bridge is in a constricted reach and the Baruria gauging station is just downstream of Ganges/Jamuna confluence. The effect of these locations on sediment rating curves are discussed in the following paragraphs.

In a constriction the sediment transport during monsoon is comparatively higher than that of a normal or a wider section. On the other hand during the dry season the process is reverse: sediment transport is higher in a wider section with degradation of the section, whereas aggradation occurs at the constricted section. This process of sediment transport in a constricted reach of a river can yield a steep rating curve with high value of exponent B. One-dimensional morphological model studies by Galappatti (1993) at Hardinge Bridge showed that the exponent of the sediment rating curve at that location is very much higher (B = 3.19) than elsewhere in the Ganges river (B = 1.43). Similar to Galapati the effect of a constriction has been studied by RSP in a one-dimensional mathematical morphological model (see SPR 13) without a constriction and in another model with a constriction (see Figure 8.2). Similar to the observations of Galapati, the results showed that within the same range of discharges, the sediment rating curve is steeper in a local constriction of a river channel (B = 3.82) than in a channel without a constriction (B = 1.65).

In general no equilibrium exists due to the different hydrographs in the channel of the confluence. The typical flow profile in the confluencing channels will either be a draw down curve or a backwater curve, depending on the variation of discharge ratio among the channels. This will give rise to either degradation or aggradation. Hence, the reaches upstream of a confluence in rivers are adjusting all the time, but are, at the same time, fluctuating around an average bed level (RSP, 1993). Similarly, in the downstream reach of a confluence, aggradation and degradation occur alternate. Such a dynamic system at and around a confluence gives rise to a very scattered sediment rating curve. Baruria sediment and discharge gauging station is located downstream of the Ganges/Jamuna confluence. It was observed that sediment transport data in relation with discharges are very scattered and the rating curve showed a high value of exponent B.

To interpret the observed scatter in the data a one-dimensional mathematical morphological model was also studied for the Padma River by RSP (see RSP 1996). For simplicity, a single cross-section for the Padma river was used in the model. The results of the model showed, that at the confluence, the scatter is very significant and in downstream direction the scatter of the data reduces considerably (see Figure 8.3). The model results show good agreement with the observed derived rating curves based on the discharge and sediment gauging at Baruria. The reason of the scatter in the data can be explained by the comparatively dynamic condition of the confluence of a river.

If the gauging stations are not located in a prismatic cross-section of a river branch, i.e. in a constricted reach or at confluence, it is often observed that the sediment rating curve shows a very high value of exponent B or highly scattered data. These types of rating curves are not representative for the characteristics of the rest of the river reach.

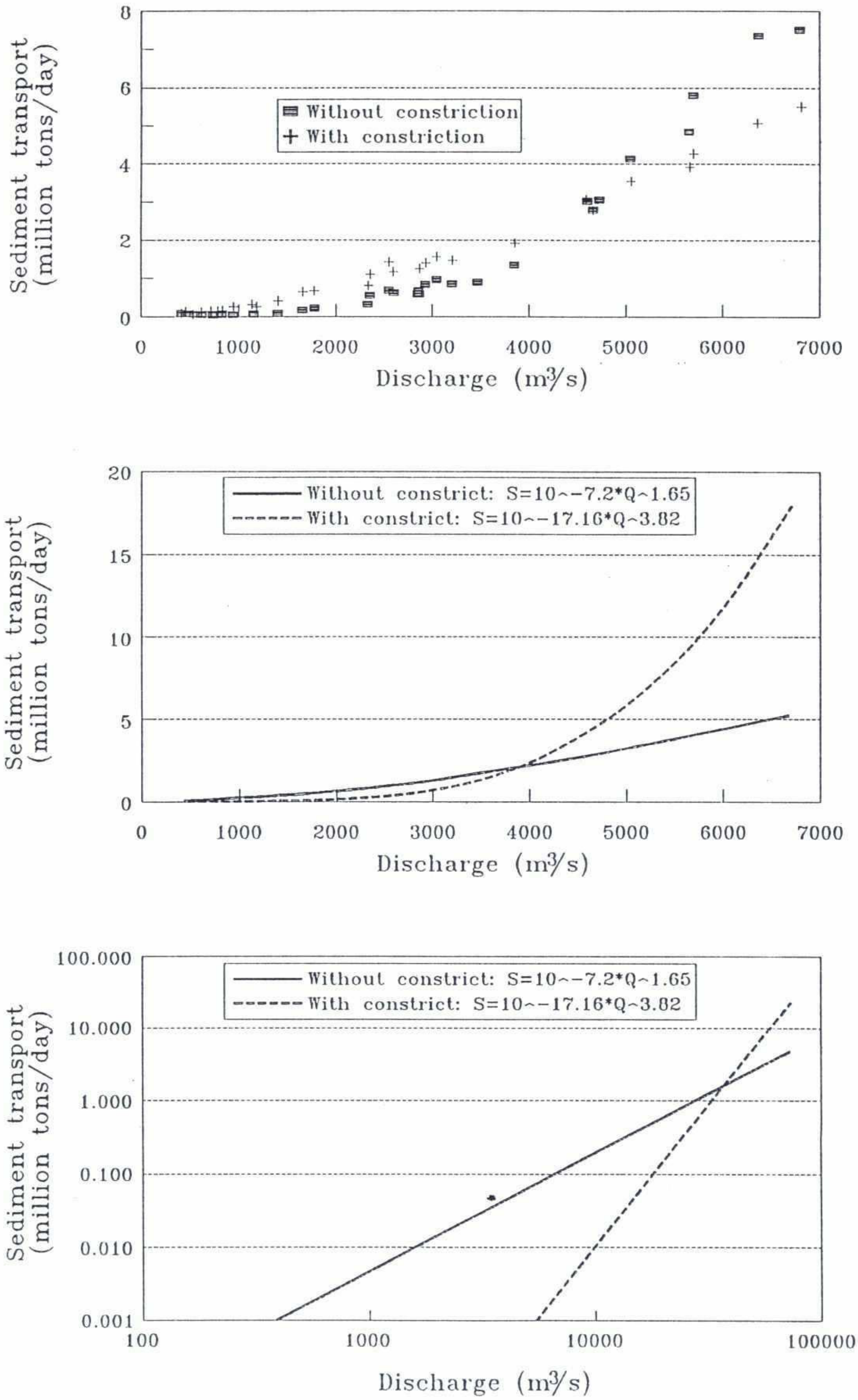

Figure 8.2 Computed sediment transport in the Ganges River with and without constriction (result of one-dimensional model)

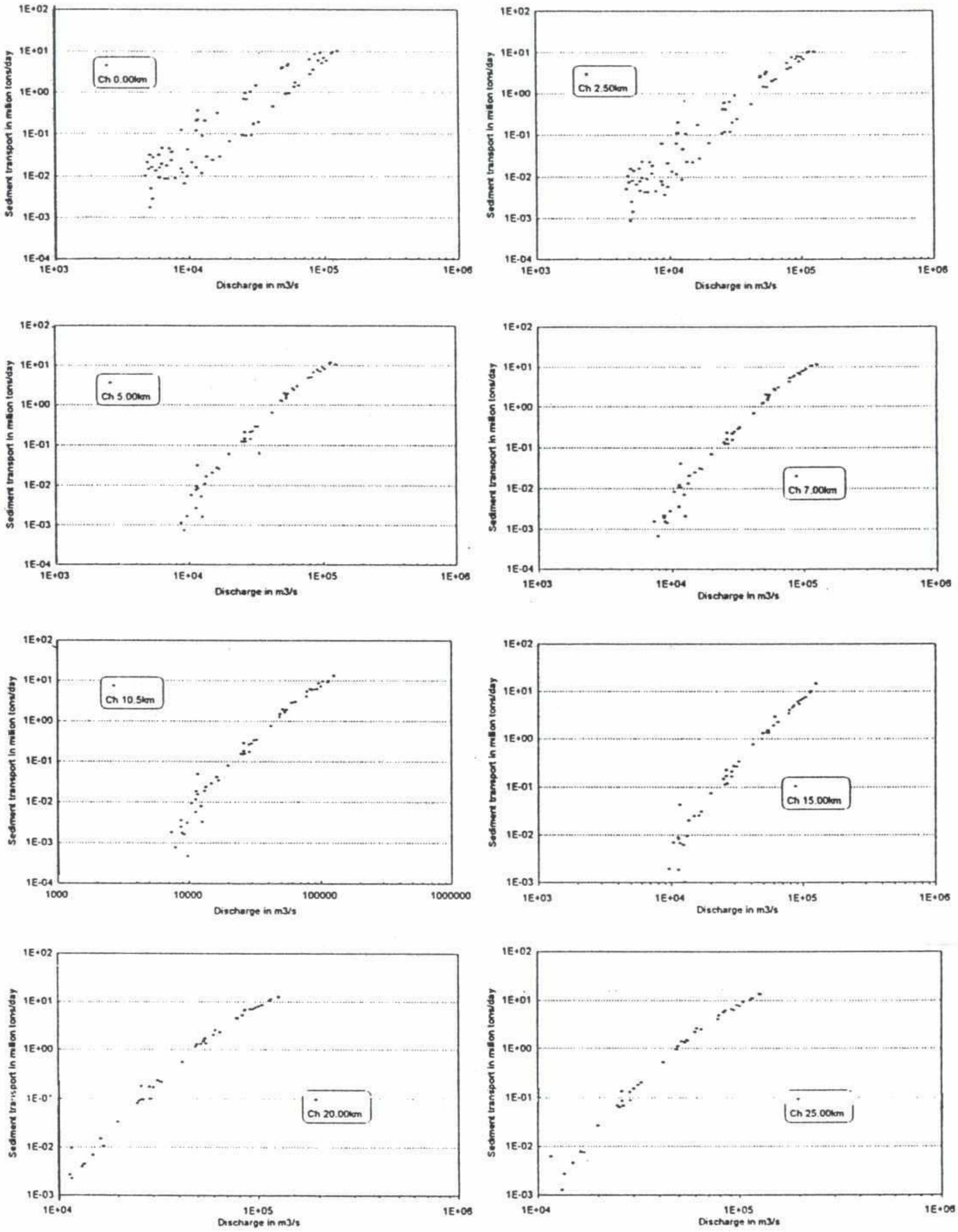

Figure 8.3 Computed sediment transport in the Padma River (result of one-dimensional model)

8.4 Empirical relations

The sediment rating curves are derived by an empirical relation using Equation 8.1. The sediment rating curves were first made in Bangladesh by the Hydrology Directorate of BWDB for seven gauging stations for the years 1966 and 1967. These curves are produced in graphs with the log-transformed discharge in cusecs as the ordinate and the log-transformed sediment transport in tonnes per day as the abscissa. The rating curves were fitted to the data points in the graph by visual estimation (FAO-UNSF, Second Hydrological Survey, Dhaka, April 1969) for the gauging stations at Bahadurabad, Goalundo and Gorai Railway Bridge. The details about those rating curves were discussed in RSP (1994). In later years, sediment rating curves were assessed in various studies on the major rivers of Bangladesh, mainly the Jamuna and Ganges rivers. Often each study has its own approach for the development of a sediment rating curve, depending on the objectives of the study. In general, rating curves were determined for suspended bed material transport, but in some cases also for the total sediment transport (including wash load) and for the total suspended sediment transport.
A review of the rating curves presented by different studies and authors is summarized in SPR-18, *Sediment rating curves and balances.*

The River Survey Project has developed rating curves for the suspended coarse and the fine sediment separately, based on almost all available data of the main river system. The sediment gauging stations which are considered in the study are: Bahadurabad, Hardinge Bridge, Baruria, Goalunda, Taraghat, Jagir and Gorai Railway Bridge. Those rating curves were made for the two different periods, viz. 1966 to 1970 and for the later years. Here the derived values of coefficient A and exponent B are presented in Table 8.2 for suspended bed materials derived from the data measured in the period of 1966-1970.

River	Station	Coefficients	
		$S = A\,Q^B$	
		A $((m^3/s)^{1-B})$	B (-)
Jamuna	Bahadurabad	0.35	1.42
Ganges	Hardinge Bridge	$7.0 * 10^{-6}$	2.52
Padma	Baruria	$4.58 * 10^{-6}$	2.87
	Goalunda	0.007	1.77
Kaliganga	Taraghat	1.77	1.25
Dhaleswari	Jagir	1.15	1.4
Gorai	Gorai Railway Bridge	4.6	1.25

Table 8.2 Coefficients A and B of sediment rating curves for suspended bed material of the main river system, period of gauging is 1966 to 1970.

The River Survey Project has produced the sediment rating curves for both fine and suspended sediment transport for most of the main rivers and distributaries of Bangladesh. In a sediment rating curve the exponent of the discharge B is the important factor in determining the sediment transports. In general, the value of B should vary between 1.3 to 1.7 for the rivers in Bangladesh. From Table 8.2 it can be observed that the value of B for the Ganges and Padma Rivers is much higher than the expected value, the reason of which was mentioned in the previous Section 8.3. These sediment rating curves are used for making sediment balances among the main river system and its distributaries.

9 Sediment balances, floodplain sedimentation and subsidence

9.1 Introduction

A reliable sediment balance of a river reach contributes to the understanding of the main morphological processes which have created the alluvial delta system by sedimentation and erosion of sediments. A sediment balance is the quantitative assessment of the total volumes eroded or deposited sediments between the sediment gauging stations in a river system. Here, the sediment balance of the main river system is considered. This system comprises the Jamuna, the Ganges and the Meghna rivers with the main distributaries Old Brahmaputra River, the Dhaleswari River and the Gorai River. The sediment balance of the main river system is complicated by other phenomena like sea level rise, subsidence of the delta and local tectonics. The influence of these phenomena on the sediment balance are assessed here.

This river system carries an immense amount of sediment, but historical data demonstrate that only minor seaward growth of the delta has occurred during the last 200 years (Coleman, 1969; Eysink, 1983). This observation has led to the suggestion that most of the sediment discharge to the Bengal shelf is funneled down into the 'Swatch of No Ground', a large submarine canyon located west of the present river mouth.

The study of the Bengal fan suggests that this canyon is cut off from the supply of sediment and that the sediments carried by the rivers are trapped on the floodplain and on the lower delta plain (Curray and Moore, 1974; Curray et al, 1982; Curray and Emmel, 1985). As the coastal area of Bangladesh is not growing significantly at present, maybe there appears to be a balance between sediment deposition on the floodplain and the rate of subsidence. Another possibility is that a part of the fine suspended sediment is transported thousands of kilometers into the Bay of Bengal and Indian Ocean.

The analysis of the sediment balance between the sediment gauging stations along the main river system will contribute to the overall assessment of the deposition (or erosion) of sediment on the floodplain.

9.2 Sediment balance

Coleman (1969), has estimated the total sediment transport in the Jamuna and Ganges rivers using the sediment transport data for the period 1958-1962. He reported that combined daily suspended sediment transport of the three major rivers during the flood season was of the order of 13 million tons: 7 million tons transported by the Jamuna River, nearly 6 million tons by the Ganges River, and the Meghna River has only a small contribution to the combined sediment transport. In addition, a number of studies and authors made sediment balances for the main river system of Bangladesh, notably Holeman (1968), BWDB (1972), MPO (1987), French Engineering Consortium (1989), China Bangladesh Joint Expert Team (1991) and Hossain (1992). In preparing these sediment balances different periods of data and different sediment rating curves were used, and different results were found by the different studies and authors. A brief review on previous sediment balances has been presented in several RSP reports, RSP (1993) and SPR 19, *Sediment rating curves and balances*.

The RSP estimated the sediment balance separately for the coarse and fine fractions. For the incoming sediment into the main river system: Jamuna River at Bahadurabad, and Ganges River at Hardinge Bridge and for the outgoing: Gorai River at Gorai Railway Bridge, Padma River at Baruria and at Goalundo, Kaliganga River at Taraghat and Dhaleswari River at Jagir were considered. The obtained result for the sediment balance is presented in Table 9.1. This sediment balance was made by using the RSP derived rating curves, coefficients of which are shown in Table 8.2.

Sl. No	Station	Annual average suspended sediment load in Mt (1966-1989)		
		Coarse (A)	Fine (B)	Total (A+B)
1	Bahadurabad	202	388	590
2	Hardinge Bridge	196	352	548
3	Gorai Railway Bridge	18	29	47
4	Taraghat	2.9	13.7	16.6
5	Jagir	0.8	2.7	3.5
Group 1: Total (1+2-3-4-5)		377	695	1072
6	Goalunda	1.7	9	10.8
7	Baruria	366	520	886
Group 2: Total (6+7)		368	529	897

Table 9.1 Total suspended sediment balance according to RSP

Table 9.1 indicates that the suspended bed material, i.e. the coarse fraction of sediments, are almost in balance for the period of 1966 to 1989. The difference of the fine fraction of sediments between Group 1 and Group 2 of about 175 Mt/year is probably due to sedimentation on the floodplain and to some extent due to channel aggradation.

The RSP analyzed the available BWDB data (for the period 1966-1989). Statistical judgement was carried out in order to remove unusual outlier data. The RSP analysis of the sediment balance *(see SRP 19, Sediment rating curves and balances)* instead ofwas the most detailed assessment of sediment transport data available now. Nevertheless, some uncertainties are remaining. For instance, the sediment rating curves for the gauging stations Hardinge Bridge and Baruria are mainly affected by the local condition, as indicated in the previous chapter. For the sediment balance these rating curves can add some error. Furthermore, the rating curves used for the sediment balance were made by using only a few years (1966-1970) data, which may also add uncertainties to the sediment balance estimates.

9.3 Floodplain sedimentation and subsidence

Existing data suggest that a significant percentage of the sediment discharge of the rivers in Bangladesh is being trapped on the delta plain by subsidence and net aggradation. During the annual monsoon floods, turbid river water inundates floodplain areas, displacing a significant fraction of the population. Milliman and Syvitski (1992) suggest that 40 to 80% of the total sediment load accumulates as silt and clay deposits in the floodplain and lower (tidal) delta plain, supplemented by sandy crevasse deposits adjacent to the river channels (Coleman, 1969). This estimate was based on 1 to 2 cm per year subsidence (tectonic and sediment compaction) rates, averaged from observations of buried forests and river terraces (Yount, 1990). Regional subsidence patterns are surmised to be controlled primarily by underlying tectonic features (fault traces) that also direct the long-term (10s to 100s of years) lateral migration of river channels in the Ganges-Brahmaputra delta (Eysink, 1983). The westward migration and recent (< 200 y BP) avulsion of the Jamuna course and eastward migration of the Lower Meghna are evidence that subsidence may be of considerable influence. The continued lowering of beel areas, such as the Sylhet depression and Gopalganj peat basin, suggests that spatial inequities in sedimentation exist, so that subsidence is not always balanced by input of sediment.

Previous studies of the Bengal Shelf (Kuehl and Allison, in prep.; Kuehl et al., 1989; Segall and Kuehl, 1992) and the associated submarine canyon (e.g. Swatch of No Ground) suggest that questions of sedimentation and subsidence in the floodplain should be approached by direct measurement of sedimentation rates on short and long time scales. These studies should utilise radiotracers coupled with investigations of seismic stratigraphy. Mass budget calculations resulting from these shelf studies have delineated the percentage of river discharge reaching offshore areas. These figures support the aforementioned hypothesis that more than 50% of the total sediment budget is trapped landward of the Bangladesh shoreline. Subsidence rates can be extrapolated from long-term sedimentation data, as well as by independent means. A more extensive review of the literature on floodplain sedimentation can be found in "Sedimentation in the Brahmaputra-Jamuna Floodplain" (ISPAN, 1995).

While the existing data indicate that a significant proportion of the sediment load of Bangladesh rivers is sequestered in the delta plain by subsidence, quantitative information about regional patterns, mechanisms, and an overall budget does not exist. This information is vital for gauging the effects of proposed flood control embankments on floodplain agriculture, land subsidence and groundwater recharge, river migration and avulsion, and marine invasion.

10 Main rivers as sediment conveying network

10.1 Basic considerations

Rivers are systems that are adapted to transport flow and sediment. If the rivers are not fully adjusted, they will respond with either aggradation or degradation. In the case of the main rivers of Bangladesh a fairly complicated network is existing, because these rivers are connected at confluences, while the distributaries play a role in internally diverting part of the flow and sediment to other places in the network. Major confluences are the Jamuna-Ganges confluence and the Padma-Meghna confluence. Major distributaries are the Old Brahmaputra River diverting part of the flow and sediment from the Brahmaputra to the Upper Meghna, the Dhaleswari essentially doing the same but only slightly more downstream. The Gorai River and the Arial Khan divert part of the flow of the Ganges and the Padma, respectively, away from the system towards the Bay of Bengal via a complicated network of partly tidal rivers in South-West Region. Figure 10.1 provides an overview of the network of main rivers in Bangladesh.

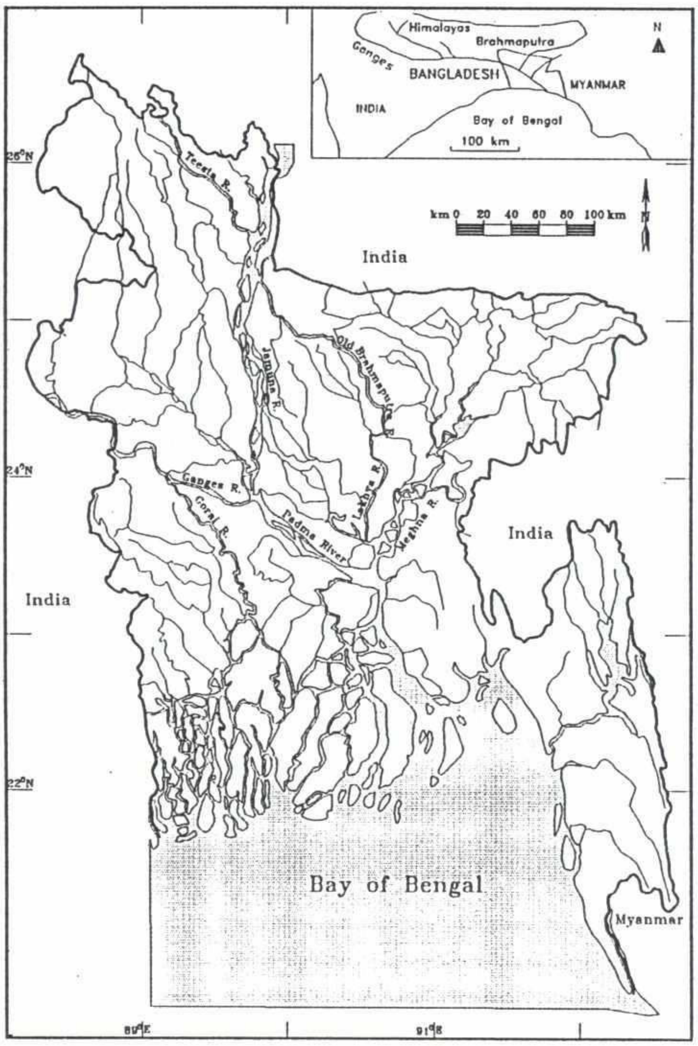

Figure 10.1

The main rivers in Bangladesh as a network

In the previous Chapters the existing knowledge on sediment transport in the main rivers in Bangladesh was discussed and summarized. This has led to a fairly good insight into (i) the sediment transported in the different main rivers and (ii) the composition of the bed material. In this Chapter this will be combined with information from Annex 3, notably data on slopes and discharges in the main rivers.

The main purpose is to check the consistency of the available data. At the same time however a fairly essential issue in the Terms of Reference is addressed. According to this ToR the River Survey Project had to "undertake a programme of studies to investigate key characteristics of the behaviour of the river system" (quoted from the Terms of Reference). Hence it is felt appropriate to attempt to take an integrated look at the river system as a whole, as this system is more than the individual rivers. Also their interaction has to be considered.

Such an integrated look was already presented in Study Report 3, indeed at the same time considering the consistency of the available data. This was done by combining the knowledge on the annual sediment loads and the particle size distributions, with information on the discharges in the main rivers. This allowed to draw some preliminary conclusions regarding (i) the consistency of the data, and (ii) which data on the river system as presented in the previous Chapter as "the" characteristics of the main rivers possibly are doubtful and needed further study. In Phase 2 of the River Survey Project additional data were collected and these allow for a more refined analysis than was possible during the preparation of Study Report 3.

As part of assessing the consistency of the available and to check the present understanding of the river system it is appropriate to study the conditions in the points where the different reaches are linked. These are typically (1) the offtakes and (2) the confluences. For some reflections on the phenomena happening at offtakes and confluences, reference is made to Study Report 1, Section 3.6. In that Section in particular the time-dependent behaviour was discussed, but it was not illustrated with actual data from the main rivers in Bangladesh. To study this *time-dependent behaviour* detailed data are required that are even now not available, but now more insight is existing owing to some studies carried out in Phase 2. Reference is made to Section 7.7 of the present Annex and Chapters 9 (on offtakes) and 10 (confluences) of Annex 5.

It is however quite possible to use *time-averaged* data, hence data available over a longer period. A disadvantage is that these data are not always collected very near to the offtake or confluence. For example to study the Old Brahmaputra as offtake from the Brahmaputra River data on the sediment transport in the distributary are only available at Mymensingh, some 110 km downstream of the offtake. Over short periods the sediment transport at Mymensingh will generally be different from the sediment transport directly downstream of the offtake. Assuming that the river is neither aggrading nor degrading and averaging over along period, the sediment entering via the offtake should be equal to the sediment transported at Mymensingh.

10.2 Approach

In the following the system of main rivers in Bangladesh is schematized here to a network of channels ("conduits"), that transport both flow and sediment. Here only limited attention needs to be paid to the actual morphology (shape) of the rivers. The approach used here is based on two methods, one is the application of an improved form of Lane's balance and the other one on the application of continuity considerations around the confluences and offtakes.

10.2.1 Improved Lane's balance

If a river is in equilibrium (on the average neither aggrading nor degrading) the river morphology is so adjusted that with the available flow the supply of sediment to the channel can be transported. This is valid for all sections. Also near confluences and offtakes where temporary storage of sediment may take place there is on the average equilibrium as later (in the hydrological year) this temporary storage will be compensated for by larger sediment transports.

Hence given the discharge and its variation over time the channel will adjust its morphology in such a way that it will be able to transport the supplied annual sediment transport load. This is expressed in a simplified way in Lane's balance that reads as (Lane, 1955):

$$S.D :: Q.i \qquad (10\text{-}1)$$

where S = sediment transport (m^3/s), D = representative bed material size (m), Q = discharge (m^3/s) and i = slope of the river (-). The balance expresses that when e.g. the sediment load of a river decreases while the discharge and the sediment size remain the same, the slope of the river will decrease.

It can be shown (Jansen, 1979) that in principle this balance can be derived by combining the Chézy equation and a simplified sediment transport formula which reads as:

$$s = m.u^{n} \qquad (10\text{-}2)$$

where s = sediment transport per unit width (m^2/s), m = coefficient incorporating e.g. the effect of roughness and particle size, u = velocity (m/s) and n = power. See also Section 7.4 of this Annex for background information on this simplified predictor. Klaassen (1995) extended the balance to include effects like the width and the variation of the discharge. This *improved version of Lane's balance* reads (see Klaassen, 1995 or Appendix 2 of Study Report 5):

$$V.D^{p}.B^{\frac{n-3}{3}} :: \alpha_{Q}.\overline{Q}^{\frac{n}{3}}.i^{\frac{n}{3}} \qquad (10\text{-}3)$$

where V = yearly sediment transport, here expressed in tons.

Assuming that the width of a river is related to the (average) discharge via:

$$B :: Q^{0.5} \tag{10-4}$$

it follows that:

$$V.D^{p} :: \alpha_{Q}.\overline{Q}^{\frac{n+3}{6}}.i^{\frac{n}{3}} \tag{10-5}$$

The previous equation is derived from regime considerations. Formally such a relation was only found to be valid for bankfull discharge, but assuming that there is a fairly constant ratio between the average discharge and the bankfull discharge, it may be used in its present form as well.

Assuming that all the other relevant parameters (in particular the roughness coefficient C) are constant it can be derived that

$$i_{e} :: \sqrt[\frac{n}{3}]{\frac{V.D^{p}}{\alpha_{Q}.\overline{Q}^{\frac{n+3}{6}}}} \tag{10-6}$$

where i_e = "equilibrium slope" according to the improved Lane's balance.

The above equation holds for a river with a single channel. If a river has more channels (like is the case with a braided river), then the discharge and the sediment transport is divided over all these channels. If the number of channels is k (and it is assumed that these channels have all the same dimensions), then the average discharge and the yearly volume of sediment transported per channel is Q average/k and V/k per channel. Introducing this in the above equation (Klaassen, 1995), results in:

$$i_{e} :: \sqrt[\frac{n}{3}]{\frac{k^{\frac{n-3}{6}}\ V.D^{p}}{\alpha_{Q}.\overline{Q}^{\frac{n+3}{6}}}} \tag{10-7}$$

It can be observed that more channels result in a (slight) increase in slope. For example for k=3 and n=5, the slope increases with about 20%.

The above equation can also be written as:

$$i_{e} = K \sqrt[\frac{n}{3}]{\frac{k^{\frac{n-3}{6}}\ V.D^{p}}{\alpha_{Q}.\overline{Q}^{\frac{n+3}{6}}}} \tag{10-8}$$

where K = coefficient in which e.g. the effect of the Chezy coefficient and the proportionality coefficient in the regime equation for the width are incorporated.

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For the time being it is assumed that K is constant for the different rivers in Bangladesh once they have reached "equilibrium" conditions (or in other words once they are in regime). It is of interest to combine the different data on the main river system to estimate the equilibrium slope. Comparing this with the actual (water level) slope may provide better insight in the consistency of the data.

10.2.2 Continuity equations

The different channels are linked at confluences and bifurcations. Around these linkages *continuity equations* can be applied. Different continuity equations can be applied, continuity of flows, of sediment loads, of particle sizes and for the mineralogical composition.

The continuity for flows is discussed in Chapter 6 of Annex 3. In view of the relative unimportance of the storage (long flood waves) it simply states that the incoming flow corresponds to the outflowing flow, hence e.g.:

$$Q_{Jamuna} + Q_{Ganges} = Q_{Padma} \tag{10-9}$$

For the continuity of sediment, storage is important in particular near confluences. Over the hydrological year the bed level upstream ànd downstream may very considerably (see Chapter 10 of Annex 5). Bed level variations are an indication that there are gradients in the sediment transport as is clearly shown by the general form of the 1-dimensional continuity equation for the sediment (see Jansen, 1979), which reads:

$$\frac{\delta z_b}{\delta t} + \frac{\delta s}{\delta x} = 0 \tag{10-10}$$

where z_b = bed level (m), t = time (s) and x = longitudinal coordinate (m). The continuity of sediment loads should hence be expressed over a longer period to cope with these temporal storages. Hence the continuity equation for the sediment around a confluence would read:

$$\int S_{Jamuna} dt + \int S_{Ganges} dt = \int S_{Padma} dt \tag{10-11}$$

where the integration should be done over a longer period (at least several hydrological years). This equation can also be written as:

$$V_{Jamuna} + V_{Ganges} = V_{Padma} \tag{10-12}$$

where V = annual sediment load. These types of continuity equations were already adressed (and in more detail) in the previous Chapter 9, in Section 9.2, but only for the Jamuna-Ganges-Padma system and only on the basis of empirical sediment balances. In this Chapter sediment balances are made for the Meghna-Padma confluence as well. Different from Chapter 9 the estimates of the sediment transport rates will be based on the sediment transport predictor developed in Chapter 7 of this Annex.

In addition continuity equations for particle size and for mineralogical composition are used. The form these continuity equations take is indicated hereafter. Assume that two upstream rivers (numbered 1 and 2) are linked to a downstream river (number 3). Assume that the annual sediment loads are given by V_1, V_2 and V_3, respectively. Consider a particle of size D_i. The probability of occurrence of such a particle is given by p_{i1}, p_{i2} and p_{i3}.

It can be shown that the realation between p_{i1}, p_{i2} and p_{i3} reads as:

$$p_{i3} = \frac{p_{i1}.V_1 + p_{i2}.V_2}{V_3} \qquad (10\text{-}13)$$

This equation holds for any i. Similar equation can be derived for the mineralogical composition, where the mineralogy takes the role of D_i, and p_i is relates to the percentage of quartz, heavy minerals, mica, etcetera. Application of these formulae allow for checks on the annual sediment loads, the particle distributions of the bed material and the mineralogical composition. This will be done in Section 10.5.

For the offtakes comparisons similar relations can be developed. In addition an analysis can be made to check whether selective withdrawal of sediments is taking place. This could take the form that only finer sediments are entering into an offtake, or that an offtake withdraws relatively much sediment. This is explored in Section 10.6.

10.3 Data used

In the previous sections each of the main rivers in Bangladesh, together with their distributaries, were described and a summary was given of the present knowledge in their characteristics and behaviour.

First an overview of the available information on the river system will be given. Reference is made to the Figures 10.1(a), 10.1(b), 10.1 (c) and 10.1(d). Figure 10.1(a) provides an overview of the average discharges in the main rivers and the distributaries. Note that here the average discharges are used, as these give a first estimate of the carrying capacity of the different reaches. For really assessing the carrying capacity of the different rivers the factor α_Q (see Study Report 5, Annex 2) has to be assessed as well. This factor is about 1.2 for the Jamuna and Ganges River, 1.15 for the Padma and Lower Meghna River, while it is assumed here that for the distributaries which have more the character of seasonal rivers, a value of 1.3 is more appropriate. For the time being a more exact dtermination does not seem warranted in view of the inaccuracy of the other parameters in Lane's balance.

The Figures 10.1(b) and 10.1(c) present the best estimates of the yearly amounts of sediment transported in the main rivers and distributaries. Both data on the bed material transport (Figure 5.58) and the wash load (Figure 5.59) are presented. Figure 10.1(d) provides an overview of the present estimates of the D_{50} of the bed material in the various rivers. For the application of the improved Lane's balance also the number of channels is needed. Based on the availalbe information (see e.g. Section 5.5 of Annex 5) estimates of the value of k is made. For the time being it is assumed that for all main rivers, apart for the Jamuna/Brahmaputra system, $k = 1$. For the Jamuna/Brahmaputra system it is assumed that $k = 3$ (Klaassen & Vermeer, 1988b).

River	$\bar{Q}$ (m^3/s)	α_Q (-)	V (10^6 tons)	D_{50} (mm)	k(-)
Jamuna River	20,400	1.2	200	0.21	3
Ganges River	10,600	1.2	190	0.12	1
Padma River	28,400	1.15	370	0.09	1
Upper Meghna	4,500	1.3	1	0.14	1
Old Brahmaputra	550	1.3	2	0.15	1
Dahleswari River	1,000	1.3	3	0.16	1
Gorai River	1,200?	1.3	17	0.15	1
Arial Khan River	2,570	1.3	?	0.15	1

Table 10.1 Summarized data of the various rivers in Bangladesh

For the assessment of the conditions at the confluences and the offtakes it is required to have insight into the bed material characteristics of the different rivers. Both the particle size distribution and the mineral composition is important. The available data (partly taken from Study Report 3 and the related Consultancy reports, and partly from FAP24 special surveys e.g. Study Reports 8 and 14) are summarized in Table 10.2.

10.4 Consistency check on slope of main rivers

For checking the consistency of the data the improved Lane's balance is used. To do this, for each of the rivers the value of i_e/K is computed and this value is compared with the actual value of the slope i of the various rivers. For this it is required to assume values for n and for p, the powers of the velocity in the transport equation and the power of the particle size. Based on the analysis reported in Chapter 7, in particular the results reported in the Sections 7.5 and 7.7, for n a value of 3.8 is used. For p a value of 1 is used, in line with the assumed shape of the sediment transport predictor.

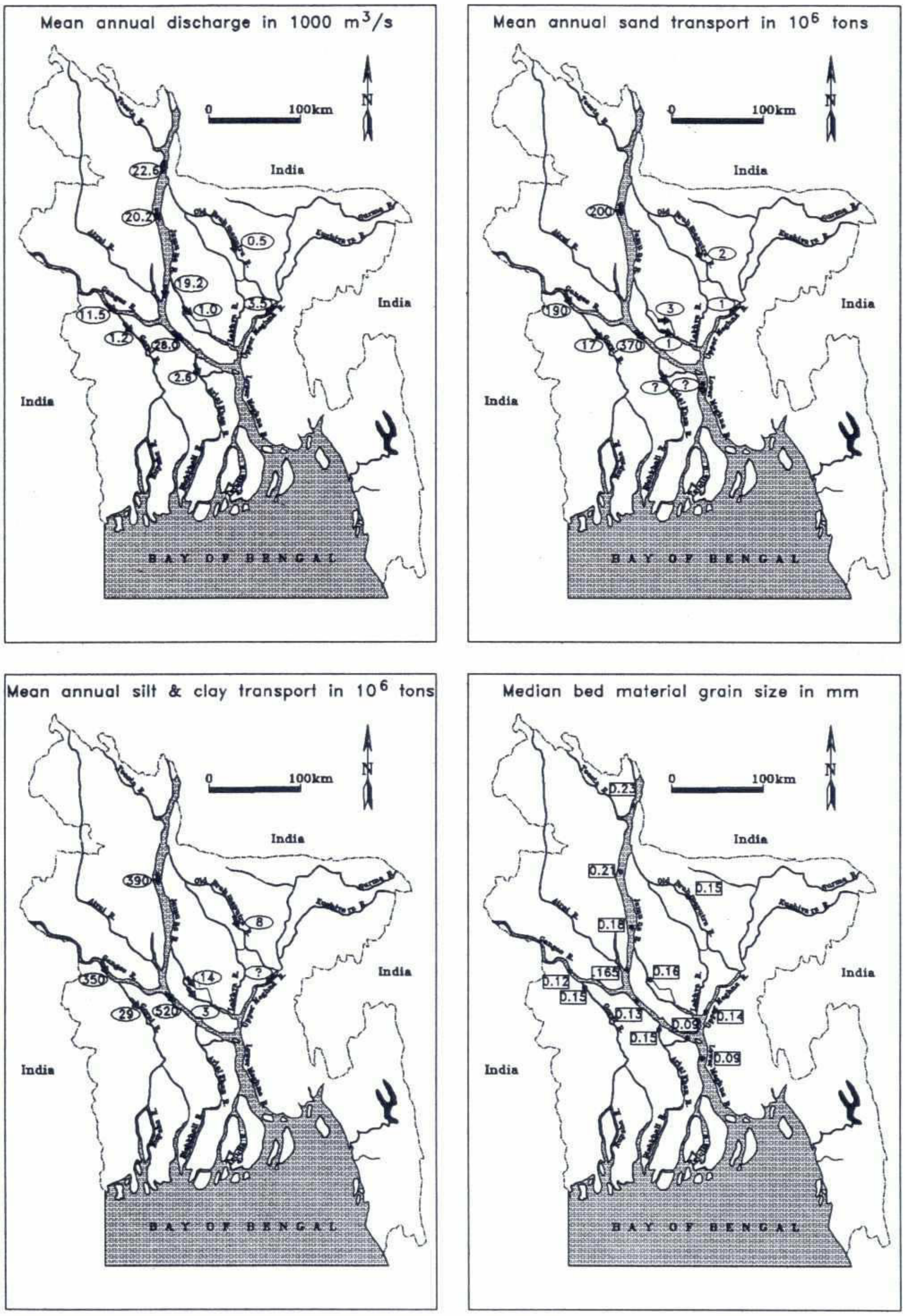

Figure 10.2 Summary of available data on discharges, sediment loads and bed material composition

River	Reach	Characteristic particle size bed material				Mineralogical composition			Source[2])
		D_{16} (mm)	D_{50} (mm)	D_{84} (mm)	sigma g (-)	Quartz, etc.[1]) (%)	Mica (mm) (%)	Heavy minerals (%)	
Brahmaputra River	Chilmari	0.16	0.23	0.31	1.40				JBS
Brahmaputra River	Upstream of conflu-ence with Teesta River	0.12	0.19	0.27	1.5	77	10	11	SR 14
Teesta River	Upstream confluence with Brahmaputra River	0.07	0.12	0.19	1.65	67	21	12	SR 14
Jamuna River	Bahadurabad	0.13	0.20	0.29	1.52	65	26	8	SR 8&14
Jamuna River	Sirajganj	0.13	0.19	0.29	1.55	66	20	15	SR 8&14
Jamuna River	Aricha (upstream of confluence with Ganges River)	0.11	0.1717	0.23	1.44				JBS
Ganges River	Upstream confluence with Jamuna River	0.10	0.14	0.21	1.43	69	18	13	SR 8&14
Padma River	Mawa	0.09	0.13	0.19	1.43	71	9	20	SR 14
Padma River	Upstream of conflu-ence with Upper Meghna River	0.02	0.09	0.19	3.36				FAP9B
Upper Meghna River	Bhairab Bazar	0.06	0.16	0.25	2.22	78	9	13	SR 14
Upper Meghna River	Upstream of conflu-ence with Padma River	0.04	0.14	0.25	2.64				FAP9B
Lower Meghna River	Chandpur	0.02	0.09	0.19	3.33				FAP9B
Old Brahmaputra River	Downstream offtake for Jamuna River	0.11	0.14	0.22	1.42				SR 8
Old Brahmaputra River	Mymensingh	0.11	0.2	0.35	1.78				SR 8
Dhaleswari River	(New) offtake from Jamuna River	0.12	0.17	0.25	1.48				FAP20
Dhaleswari River	Tilly	0.11	0.16	0.26	1.59				Routine gauging
Gorai River	Downstream offtake from Ganges River	0.13	0.18	0.23	1.32	83	11	6	SR 14
Arial Khan	Downstream offtake from Padma River	0.09	0.14	0.21	1.53				Routine gauging

Notes: [1]) In this figure are also feldspar and rock fragments included
[2]) Due to using data from different sources there may be some minor discrepancies with other data in this report.

Table 10.2 Particle size distribution and mineralogical composition of the bed material at some selected locations along the main rivers

For the computation of i_e/K the data on flows, sediment transport, number of channels and D_{50} for the main rivers as given in Table 10.1 are used. The results of the computation of i_e/K are presented in Table 10.3, together with the overall slopes of the main rives as determined in Chapter 7 of Annex 3.

In Figure 10.3 the actual value of the slope of the various rivers is plotted versus the parameter i_e/K, the latter parameter being an indicator of the equilibrium slope. Of course the value of K is not known, but assuming that all rivers are in equilibrium there should be a linear relationship between the actual slope i and i_e/K, which actually should go through the point (0,0). As can be seen in Figure 10.2 there is quite some scatter though.

River	Notation	i_e/K	i (10^{-5})
Jamuna River	J	0.0038	7
Ganges River	G	0.0037	5
Padma River	P	0.0021	5
Upper Meghna River	UM	0.0003	2
Old Brahmaputra River	OB	0.0027	6
Dhaleswari River	D	0.0022	6
Gorai River	Go	0.0053	3.6
Arial Khan River	AK	-	?

Table 10.3 Computed values of i_e/K and overall slopes

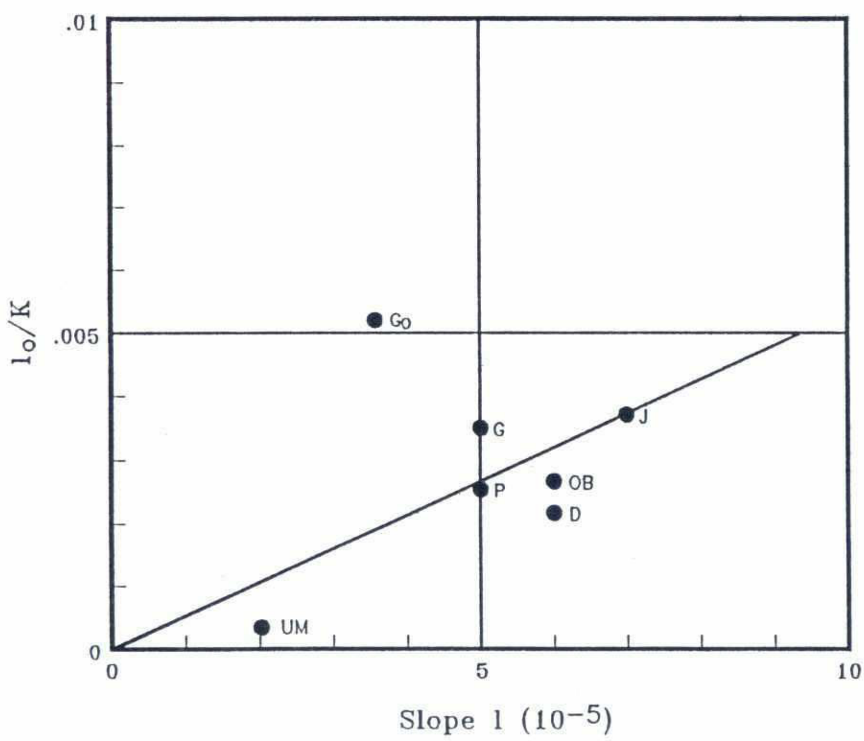

Figure 10.3 Plot of i_e/K versus slope i

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However, a line can be drawn which on the one hand does go through the point (0,0), as one would expect from theoretical considerations, and on the other hand fairly fits most of the plotted points. This line is drawn in the figure as well. Note that the Jamuna River, the Padma River, the Ganges River, the Old Brahmaputra River and possibly even the Dhaleswari River are approximately on this line.

The interpretation of Figure 10.3 should be done carefully. In fact two aspects are tested at the same time, notably (i) the consistency of the data, and (ii) whether the rivers are in equilibrium (only in that case the improved Lane's balance is applicable). Only when the data are correct and when the rivers are in equilibrium, one would expect that the points are located on one line. A deviation form the line means either that the data are not correct or that the river is not in equilibrium. In principle it is even possible that a point is on the line, but that the river being not in equilibrium is hidden by the data being incorrect.

In the graph it can be observed that there are two rivers that are definitely lying outside the line of "equilibrium". These are the Gorai River and the Upper Meghna River. The following remarks are made in this respect:

- The Upper Meghna River is typically an "out-of-regime" river. Presently it carries only the discharge of the Kushiara and the Surma Rivers and some of the rivers draining the Shilong hills. Previously it used to carry the discharge of the Brahmaputra River. It may be expected that this river is still in a transition phase. Furthermore its catchment is heavily affected by subsidence, resulting in hardly any sediment being carried into the lower reaches. In due time its slope will be much less than it is presently. For a more extensive discussion see also Chapter 5 of Annex 5.
- Regarding the Gorai River it is clear that the equilibrium slope is much higher than its present slope. For the time being it is assumed that this is due to the different data on the river system, as used here in the report, not being adjusted to each other. Hence this indicates that a further screening of the data is required. Another explanation can be that presently the Gorai River is not in equilibrium, e.g. because it is being overloaded at its mouth. See laso Section 9.3 of Annex 5, where the Gorai offtake is discussed in more detail.

For the time being it is concluded the data available on the main rivers are fairly consistent. Furthermore it is tentatively concluded that most of the main rivers, apart from the Upper Meghna River and the Gorai River, appear to be about in equilibrium as far as their overall slope is concerned. This would imply that no major aggradation or degradation would occur.

10.5 Confluences

To further check the available data and at the same time improve the understanding of the system a closer look at the river data for two confluencing channels is made. In the main river system of Bangladesh there are two major confluences, the Jamuna-Ganges confluences (hereafter referred to as J-G) and the Padma-Upper Meghna River (P-UM) plus the confluence of the Teesta with the Brahmaputra River.

The first aspect that can be studied is the sediment balance over the confluence. This balance of course reads (conform Equation (10-12)):

$$V_1 + V_2 = V_3 \qquad (10\text{-}14)$$

where V_1 = yearly volume of sediment transported in first upstream river (m^3), V_2 = same of second upstream river (m^3), and V_3 = same of downstream river (m^3). In Chapter 8 the sediment balance was studied on the basis of S-Q-relationships for the J-G-confluence on the basis of sediment transport data in Bahadurabad, Hardinge Bridge and Baruria. The P-UM-confluence cannot be studied in this way, as there are no sediment transport data available for the Lower Meghna River.

An alternative way of studying the sediment balance at confluences is by using an appropriate sediment transport formula for all three reaches. By introducing the relevant information on $\bar{Q}$, α_Q, B, i, D, C, etcetera it is possible to compute the yearly sediment transport rates for all concerned river reaches, and in a next step the balance can be made up. This was done for both the J-G confluence and the P-UM confluence. The results are presented in Table 10.5. In computing the sediment transport the FAP24 predictor was used, which reads (see Chapter 7):

$$\bar{S} = B.\sqrt{g\Delta D^3}.\frac{0.16}{1-\epsilon}.\left(\frac{h_n i}{\Delta D}\right)^{1.83}\left(\frac{C}{\sqrt{g}}\right)^{1.45} \qquad (10\text{-}15)$$

where h_n relates to $\bar{Q}$. Furthermore it was assumed that the cross-section can be schematized to a rectangle. The yearly quantity of sediment transported is found from:

$$V = \bar{S}.\alpha_Q.365.24.60.60 \qquad (10\text{-}16)$$

		Data								
Confluence	River reach	$\bar{Q}$ (m^3/s)	α_Q(-)	i (m/km)	B (m)	C ($m^{1/2}/s$)	h_n (m)	D (mm)	V (Mm^3)	$V_{u1}+V_{u2}$ (Mm^3)
Jamuna R.	Jamuna	20,000	1.2	0.06	4,000	60	4.9	0.16	51	
Ganges R.	Ganges	15,000	1.2	0.05	3,500	60	4.7	0.12	32	
	Padma	35,000	1.15	0.05	4,000	60	7.5	0.13	106	83
Padma R.	Padma	35,000	1.15	0.05	4,000	60	7.5	0.09	154	
Upper Meghna R.	Upper Meghna	4,500	1.3	0.02	500	60	10.4	0.14	3	
	Lower Meghna	40,000	1.15	0.05	5,000	60	7.1	0.09	166	157

Table 10.4 Sediment balance for confluences using Engelund-Hansen sediment transport predictor

The following observations can be made upon inspection of Table 10.4:

1. Regarding the confluence of the Jamuna and the Ganges Rivers it can be observed that the combined yearly sediment transport (even when using the Engelund-Hansen predictor and using the strong simplification of uniform flow and extremely schematized cross-sections) is only about 20% smaller that the yearly transport capacity of the Padma River. This indicates that the data given in Table 10.4 for the Jamuna, Ganges and upper reach of the Padma River are apparently acceptable for a first assessment of the riverine conditions, as they are fairly consistent when used in this way.
2. The same can be stated regarding the confluence of the Upper Meghna and Padma Rivers: the difference is about 5% even for the very crude schematization used.

It is also possible to compare the predicted sediment transport rates with the measured ones. This can be done for the reaches near the confluences but here also the reach near Bahadurabad is considered. The same approach as used before was applied, and it was furthermore assumed that the bed material consists of sand with a density of 2,650 kg/m^3 and a porosity of 0.4. This yields for the density of the sand with pores included a value of about 1,600 kg/m^3. The result of the application of the FAP24 sediment transport predictor is presented in Table 10.5, together with the measured yearly sediment transport rates.

It can be observed from this table that the predicted sediment transport is between 2 and about 4.5 times less than the actually measured bed material load. It is recalled here that in the Jamuna Bridge Study a multiplication factor of 2 was used, which seems fair for the Jamuna River and the Padma River as well. For the Ganges River apparently a higher value is needed. Further analysis in this respect appears needed. **(Section still to be adapted)**

River	Station	Yearly sediment transport rate (10^2 Mtons) Predicted	Measured	Ratio
Jamuna River	Bahadurabad	1.1	2.0	1.85
Ganges River	Hardinge Bridge	0.4	2.0	4.6
Padma River	Baruria	1.6	3.7	2.3
Lower Meghna River	Chandpur	2.3	unknown	-

Table 10.5 Comparison of predicted (Engelund-Hansen, 1967) and measured yearly sediment transport rates

(Figures still to be adapted)

Furthermore it is possible to compare the particle size of the bed material downstream of the confluence with the particle size of the two confluencing rivers. In principle it is required to apply Equation (10-13) to every fraction and thus construct a new gradation curve for the downstream sediment. Only when this curve is available an accurate estimate of D_{50} can be obtained. An approximation for D_{50} is obtained via the following formula:

$$D_{50_d} = \frac{V_{u1} \cdot D_{50_1} + V_{u2} \cdot D_{50_2}}{V_{u1} + V_{u2}} \tag{10-17}$$

Application of this formula to the Padma River downstream of the J-G-confluence yields a predicted particle size of $D_{50} = 0.14$ mm. The observed value is 0.13 mm. Hence also this indicates that the data collected here can be considered to be fair. The particle size of the lower reach of the Padma River is the same as in the upper reach of the Lower Meghna River. Although the bed material of the Upper Meghna is coarser, this is in line with the above formula, because the yearly transport of the Upper Meghna River is almost negigible ($V_2 = 0$ leads to equal D_{50}'s for the rivers 1 and 3).

Finally the mineralogical composition is used to study the different data in conjunction. Data are avilable for two confluences: in addition to the Jamuna-Ganges confluence also data are available for the Teesta-Brahmaputra confluence. There are no data on the sediment transport of the Teeta River available, but a preliminary estimate of the annual sediment load of the Teesta was made under the Jamuna Bridge Study, Phase 2 (RPT et al, 1990). In line with that estimate here it is assumed that the sediment load of the Teesta River is 10% of the Brahmaputra load. The results of the application of Equation (10-13) to the different minerals in the bed material are presented in Figure 10.4. The percentages from the upstream river reaches are plotted versus the measured percentages.

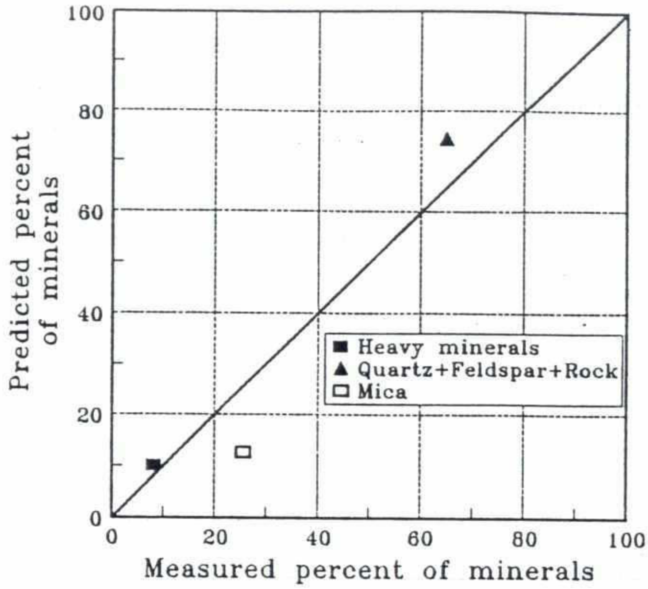
Upon inspection of this Figure the following observations can be made:

- For the Brahmaputra-Teesta confluence the predicted percentages for heavy minerals and for the quartz + feldspar + rock fragments are almost the same as the measured values. This appears to support the estimated sediment transport of the Teesta and provides credence to the measured percentages.

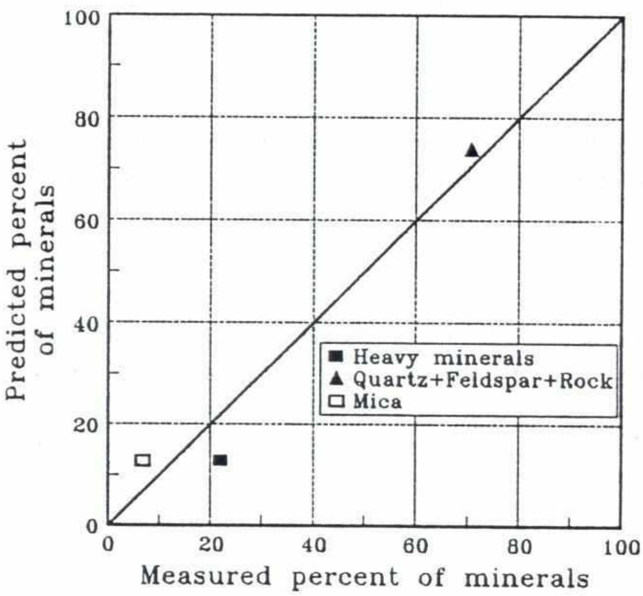
- The measured mica percentage is about twice the predicted value. This sheds some doubts on the measured mica concentrations near the Teesta River.

- The measured mica content at Mawa is smaller that predicted using data from the Ganges near Hardinge Bridge and the Brahmaputra near Sirajganj. This could very well be explained by the softness of mica and the subsequently large abrasion.

- The heavy mineral percentage in Mawa may point to strong selective sorting, as it cannot be explained from the percentages coming from the upstream rivers.



a. Bahadurabad



b. Mawa

Figure 10.4
Check on consistency of data near confluences via the mineralogy of the bed material

Generally, it seems that also the mineralogical data seem to support earlier statements made and suggest that the relative magnitudes of the estimates of the sediment transport of the Brahmaputra and Ganges Rivers is fair. For more details see Study Report 14.

10.6 Offtakes

First the offtakes from the main rivers are studied. Data (among others, in Table 10.1) on the discharge and sediment transport rates downstream of three out of the four offtakes in the main river system are available. See also the overview in Table 10.6.

	Data used					
Offtake studied	**Main river upstream**		**Main river downstream**		**Distributary downstream**	
	Upstream station	Chainage (km)	Downstream station	Chainage (km)	Downstream station	Chainage (km)
Brahmaputra R.- Old Brahmaputra R.	Not available	-	Bahadurabad	10	Mymensingh	150
Jamuna R.- Dhaleswari R.	Bahadu-rabad	100	None	-	Tilly Taraghat	100 100
Ganges R.-Gorai R.	Hardinge Bridge	20	None	-	Gorai Rail-way bridge	5
Padma R.- Arial Khan/ Dubaldia R.	Baruria	75	None	-	None	-

Table 10.6 Offtakes studied and stations for which data were used with their approximate chainage

To characterize an offtake an important parameter is the amount of sediment that is carried into the distributary. The ratio of sediment entering into a distributary and sediment carried in the main river is a function of:

- the ratio of water entering into the distributary and the flow in the main river,
- the non-uniformity of the sediment concentration vertical (often expressed via u_x/w), and
- the geometry of the offtake.

Regarding the second aspect it can be stated that if the sediment considered is very fine (e.g. in the case of wash load), then the ratio of sediment entering is equal to the ratio of water entering. Regarding the importance of the geometry of the bifurcation it should be stressed that this factor is only important if the concnetration vertical is non-uniform. Furthermore it should be outlined that in the case of Bangladeshi rivers the sediment division is determined not only by the overall (say bankfull) geometry, but also by large bars that travel through the river systems.

In Figure 10.5 the relative quantities of sediment diverted are plotted versus the relative discharges that has entered the distributaries. Relative, because the data on the distributaries were divided by the data on the main river upstream. The data used are the long term averages for all the stations, hence the graph should be understood as to refer to the average inflows. This implies that it cannot be used to predict the momentary inflow of sediment into a distributary.

Figure 10.5 provides information for both the wash load and the bed material load. For the wash load it can be observed that the sediment distribution is only slightly smaller than the discharge distribution, which is logic (see above). For the Old Brahmaputra and the Dhaleswari Rivers the ratio of diverted bed material is about 1/3 to 1/4 of the discharge ratio. These values are quite acceptable, considering data from other studies on bifurcations (see e.g. Akkerman (1992) or Barneveld et al (1992)).

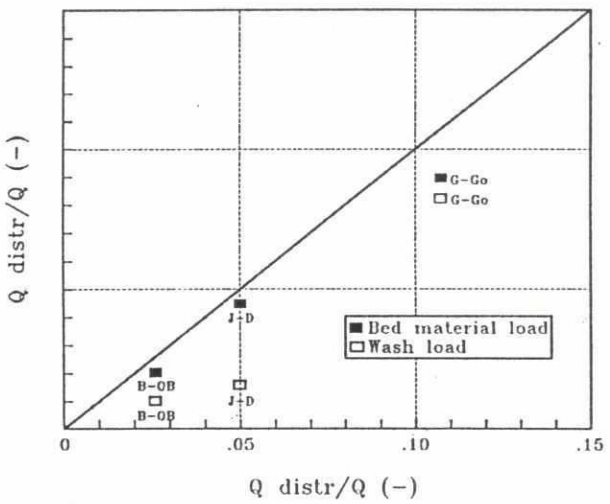


Figure 10.5
Average sediment distribution at the offtakes

The above values can be used as a first estimate in e.g. mathematical models of the One-dimensional river morphology of the river system. Note that FAP1 has assumed that the ratio for the sediment equals the ratio for the water in the development of a 1-dimensional model for the Brahmaputra River (Halcrow, 1992), whereby it should be realized that for the main river this diversion of sediment is very minor (and hence the results of the model of the main river are not very sensitive for it).

Furthermore it can be seen in the figure that the ratio for the bed material entering the Gorai River is even higher than the ratio for the wash load. This is not a very logic result, and this may imply that the estimate of the quantities of bed material entering the Gorai River may not be realistc. A lower value of the sediment load would also result in a reduction of the value of i_e/K in Figure 10.3.

Finally it is of interest to compare the particle size of the bed material in the distributary to that of the main river at the point of the offtake. This is done in Figure 10.6. The characteristic particle sizes D_{50} in the main rivers are estimated as 0.22 mm (B-OB), 0.18 mm (J-D), and 0.12 mm (G-Go), and in the distributaries conform Table 10.1. It can be seen that for the two Brahmaputra distributaries the particle size of the bed material is slightly less while in the Gorai River the bed material is apparently slightly coarser than in the Ganges River. The latter may or may not be very logic and calls for further study.

Finally the mineralogical properties are used to study the conditions at offtakes. Unfortunately only data are available on the offtake of the Gorai from the Ganges. In Figure 10.7 the percentages of the different minerals in the bed material of the Ganges and of the Gorai are compared. It can be concluded that the mineraligical characteristics of the bed material of the Gorai are very much similar to the properties of the Ganges River. A tentative conclusion could be that apparently there is so much sorting taking place at the offtake.

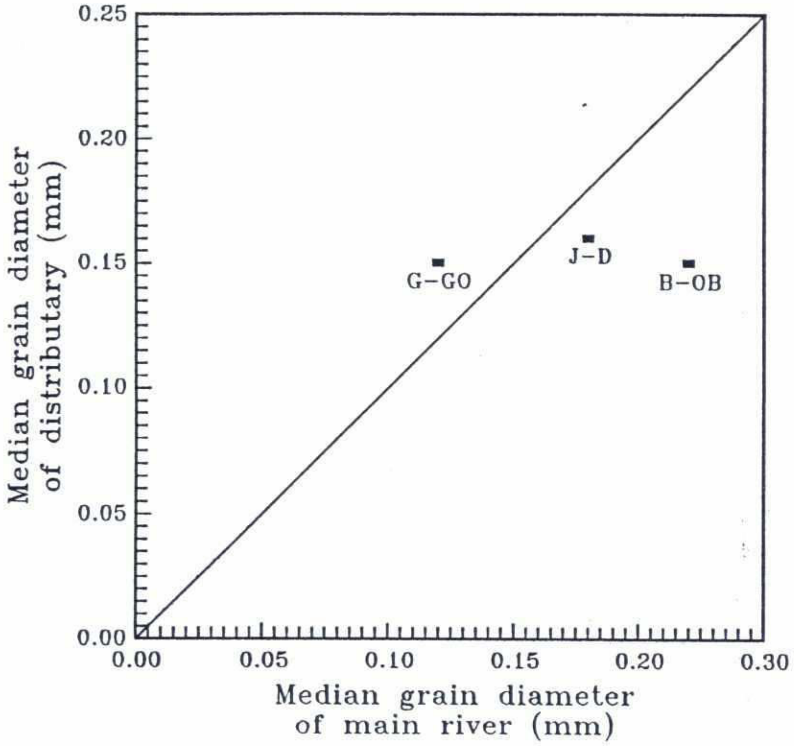


Figure 10.6 Comparison of bed material size of main river with the distributaries

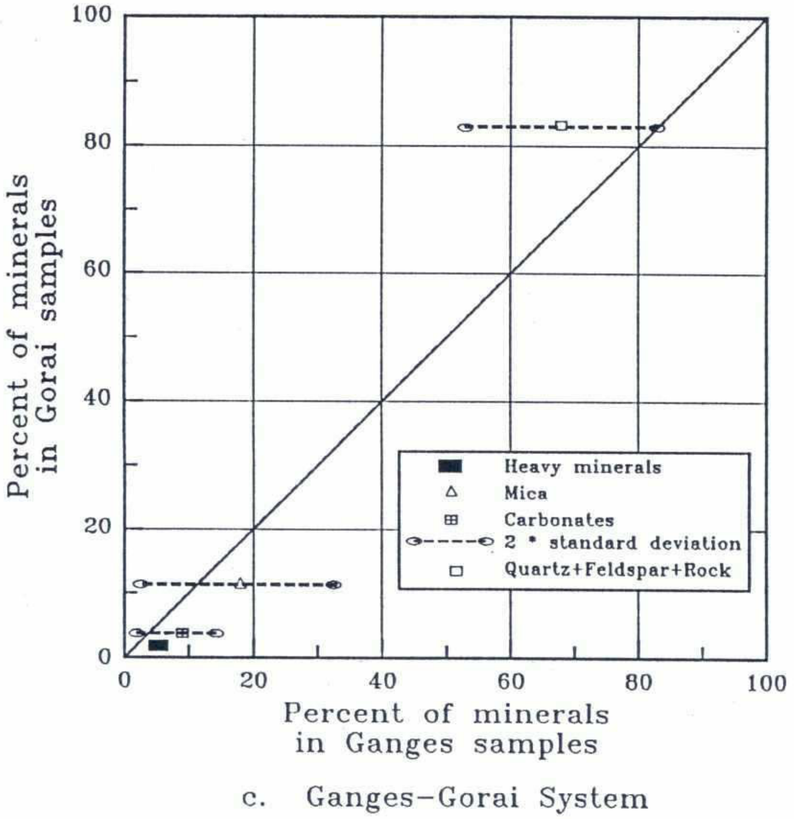


Figure 10.7 Comparison between mineralogical properties of Ganges and Gorai Rivers

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11 Qualitative impact assessment of FAP

11.1 Introduction

In the Terms of Reference of FAP24 it is stated that in phase 1 of the project "a preliminary assessment of the morphological characteristics of the rivers, their shifting characteristics and expected response in qualitative terms as different components of the FAP are implemented" has to be made. In this Chapter this qualitative assessment is presented.
The qualitative assessment made in this report is indeed only a very first estimate to assess the impact of FAP on the river system. This is so for a number of reasons. First of all the understanding regarding the river system, the interaction between the different reaches and the importance of overland flow is still very meagre. This limits the possibilities for making predictions.

Another and even more serious drawback is that more future "equilibrium" conditions may be possible. In that case, the one that will finally materialize depends fully on the intermediate conditions. This can be illustrated by considering the role of the distributaries in the system. If during the intermediate conditions the stages near bifurcations are for some decades larger than they used to be and if at the same time less sediment is entering (e.g. due to a favourable local plan-form), the dying of the distributaries (which was observed in Study Report 1) may be reversed to a distributary increasing in importance again. The same holds for human interference; owing to the implementation of remedial measures, it is possible that the system develops in a slightly different direction. This should be taken into account when evaluating the present assessment of FAP.

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11.2 Approach

11.2.1 General

The approach taken here is to accept the results of the analysis by FAP25 as far as the impact of FAP on hydraulic conditions is concerned. Hence Annex 2 of the FAP25 Flood Hydrology Study is used here as a basis.

Regarding the morphological changes, which result again in changes of discharges and stages, a distinction is made between the ultimate effects and the intermediate effects. The *ultimate effects* relate to a new equilibrium condition and they will be approached after a long time only. Preliminary estimates on the basis of a one-dimensional morphological model investigation under the Jamuna Bridge Study (see RPT et al., 1990) indicate that bed degradation and aggradation for the main rivers in Bangladesh due to local changes in the system have a time scale in the order of 50 to 100 years. Changes in plan-form probably have a time scale in the scale of several centuries. This means that only after a fairly long period a new equilibrium will have established. *Intermediate effects* are related to the transition between the present conditions and the new equilibrium. Hence these are of more interest for the coming decades. Ultimate conditions can be determined using Lane's balance (see Annex 2), in combination with estimates of changes in width and plan-form (number of channels and sinuosity). Intermediate conditions are usually assessed using one-dimensional morphological models, but here, only some qualitative considerations are given.

Because of the complexity of the system (several bifurcations and confluences), the estimate for the future equilibrium conditions is done in some steps. First estimates are made of the impact of the hydraulic changes on the ultimate slopes of the main rivers using an improved Lane's balance and (in a second step) the consequences for the water and sediment distribution at the main offtakes are assessed. Then also the possible effects on the distributaries are estimated. In first instance the analysis is limited to the ultimate effects, but subsequently also the intermediate effects are indicated. The assessment is completed with a discussion of some elements that can not easily be included in even a qualitative assessment: changes in width and plan-form. Also the possible impact in relation to natural developments are reviewed in the discussion.

In line with the approach adopted in Study Report 1, here the main river system of Bangladesh is considered as a process-response system. A process-response system consists of a cascade system, in which water and sediment are cascading downstream and a number of morphological systems. Here these morphological systems are river reaches. These reaches are mutually connected at bifurcation and/or confluences may be split up in more reaches if there is a substantial change in flows, yearly sediment transport or particle diameters. The morphology (the "form" of rivers, hence the river characteristics) of river reaches is determined by the flows they carry, the yearly volume of sediment transport and its size characteristics and conditions (clayey outcrops, previous plan-form and channel conditions, if the river is still adjusting to new conditions).

11.2.2 Application of Lane's balance for ultimate conditions

The approach adopted here for the qualitative assessment of the ultimate conditions by the application of Lane's balance. This balance, proposed by Lane (1955), is applicable for the ultimate equilibrium conditions in a river. In an adapted form (see Klaassen, 1994 and Annexure 2) for a system with one channel this balance reads:

$$V\, D^{p}\, B^{\frac{n-3}{n}} :: \alpha_Q\, \bar{Q}^{\frac{n}{3}}\, i^{\frac{n}{3}} \tag{11.1}$$

where V = yearly sediment transport, D = particle size, B = width of river, α_Q = coefficient related to the deviation of the discharges in the river from the average discharge conditions, Q = average discharges in the river, and i = slope of the river. The coefficients p and n are representative for the sensitivity of the sediment transport for changes in the velocity and the particle size respectively, where it is assumed that:

$$S \propto m_l\, D^{-p}\, u^{n} \tag{11.2}$$

where s = sediment transport per unit width and u = average flow velocity. The values of p and n officially still have to be assessed for the various rivers in Bangladesh. It was demonstrated in e.g. Klaassen et al (1988), that the Engelund-Hansen sediment transport predictor holds with some minor adjustments for the Jamuna River. For the time being it is assumed that for all the main rivers in Bangladesh this predictor gives a fair estimate. Hence, as is demonstrated in Annexure 1, p = 1 and n = 5. The value of m_1 is not relevant when comparisons between equilibrium conditions are made.

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The response of a river system to changes in e.g. the flow rates in the river, supposing that all the other factors remain the same, can be determined with Lane's balance. As is shown in Annexure 2, it holds that for a change of Q_0 to Q_1 the slope of the river changes according to:

$$\frac{i_1}{i_0} = \frac{Q_0}{Q_1} \tag{11.3}$$

If also the width of the river may change, e.g. according to a regime relation (B :: $Q^{0.5}$), then the above Equation (11.3) transforms to:

$$\frac{i_1}{i_0} = \left(\frac{Q_0}{Q_1}\right)^{\frac{n+3}{2n}} \tag{2.4}$$

This implies in most cases a less serious increase of the ultimate slope of the river, as (for n > 3) the power of Equation (11.4) is less than that of Equation (11.3). Similar relations can be derived for the diversion of water, e.g. for the case a distributary is starting to take more water than before. Lane's balance is used here to make a quantitative assessment of the impact of FAP.

Although the application of Lane's balance has some limitations, it is felt that the results will be fair when applied to the main rivers. For the distributaries it holds however that they are much more dependent on the intermediate conditions (see hereafter) and on the water and sediment distribution at the offtakes (see Section 3.4).

11.2.3 Intermediate changes

Intermediate changes are changes that occur in the period of transition (until a new equilibrium has established). These changes relate to (i) changes in bed levels and (ii) changes in width and plan-form. As outlined in Section 1.4, these changes have usually different time scales. Hence it may be allowable to assume that during at least the first decades of the transition period the plan-form characteristics of the rivers are not adjusting too much. Hence the application of a one-dimensional approach may be acceptable for this first period. In this stage the application of such a model does not seem warranted within the present analysis, because as is indicated in the previous chapter the more quantitative assessment of the FAP impact will probably be done within the frame-work of a separate project. Hence here a more qualitative approach is used.

The approach taken here is that the results of the analysis by FAP25 (as laid down in FAP25 (1993)) are accepted and on that basis the effect on the bed levels and on the discharge and sediment distribution at the bifurcations are assessed. The possible consequences for the development of the distributaries is outlined and in a second step the possible impact on the main rivers is indicated. The possible consequences for the final equilibrium are indicated subsequently together with the effect on the equilibrium stages, discharges and bed levels. In doing this it will be found that the present system may develop in different directions, depending on the intermediate conditions. Hence it will be found that it is impossible to indicate beyond any doubt the future state of the river system. For more details on these aspects see Section 5.4 and the discussions in Chapter 6.

11.2.4 Natural changes, effect of other developments and FAP impact

As is outlined in Study Report 1, there are strong indications that the main river system of Bangladesh is still in an adjustment stage as a response to (1) the major change in course of the Brahmaputra River some 200 years ago and possibly (2) recent tectonic movements. Hence the possible impact of FAP will materialize in combination with future adjustments of the river system. As far as the various river reaches are concerned, the adjustment as a response to natural changes can be summarized as follows:

- The Jamuna River upstream of Sirajganj is still widening and possibly moving in Western direction.
- The plan-form of the Jamuna River South of Sirajganj is still widening and possibly still becoming more braided (increasing braiding index = average number of parallel channels).
- The Padma River near Mawa appears to be constricted (due to clay out-crops ?) and is possibly adjusting its width very slowly. In due time (many centuries ?) its width may become comparable to the Jamuna River (widening from the present 3 km as a minimum to 15 km ?), with a related increase in slope (see Lane's balance and Annexure 1).
- The Upper Meghna River is in a process of adjustment from a braided river to a meandering one.
- Both the Old Brahmaputra and Dhaleswari River seem to loose importance. It could be that in due time (and without human interference) these distributaries are "dying".

Apart from adjustments to natural changes, also other developments may have their effect on the behaviour of the main river system of Bangladesh. These developments, mostly related to human interference with the river and changes in the catchment (also as consequence of human activities) amongst others are:

- Deforestation in the catchment (and more generally changes in land use) that could result in more sediment production and higher flood waves.
- Embankments in the Indian parts of the catchment.
- Major water diversions.
- Sea level rise.

It is worthwhile to note that already some exploring computations regarding the effect of such changes were done under both Jamuna Bridge Study (RPT et al., 1990) and within the framework of FAP1. Although not done here, it is possible to include the outcomes of these exploring studies in an analysis of possible future directions in which the riverine conditions may go. In this respect it was found that the non-linearity of the describing system of equations plays a minor role only, hence that the effect of e.g. sea level rise for a first assessment can simply be added to the outcome of the present analysis. This holds only for aggradation and degradation; width and plan-form changes are much more complex and need special attention in a later stage.
The impact of FAP implementation will be noticeable as superimposed on these "natural" adjustments, which can only be assessed roughly as they belong to almost unpredictable natural behaviour and to developments which can not be foreseen. This makes it more difficult to make estimates of the real future development and subsequent changes in stages, discharges and bed levels in the different branches of the main river system.

11.3 Main river system of Bangladesh

11.3.1 General

In Study Report 1 an extensive description of the river system of Bangladesh is included. It is assumed that the reader is familiar with this description and hence with the main river characteristics. The main river system in Bangladesh consists of the lower reaches of the three large rivers that enter into the Bay of Bengal via Bangladesh, notably the Brahmaputra River, the Ganges River and the Meghna River. More specifically the following rivers are considered to belong to the main river system in Bangladesh (see Figure 11.1):

- Brahmaputra/Jamuna River,
- Ganges River,
- Upper Meghna River,
- Padma River,
- Lower Meghna River,
- Old Brahmaputra River,
- Dhaleswari River,
- Gorai River,
- Dubaldia/Arial Khan Rivers.

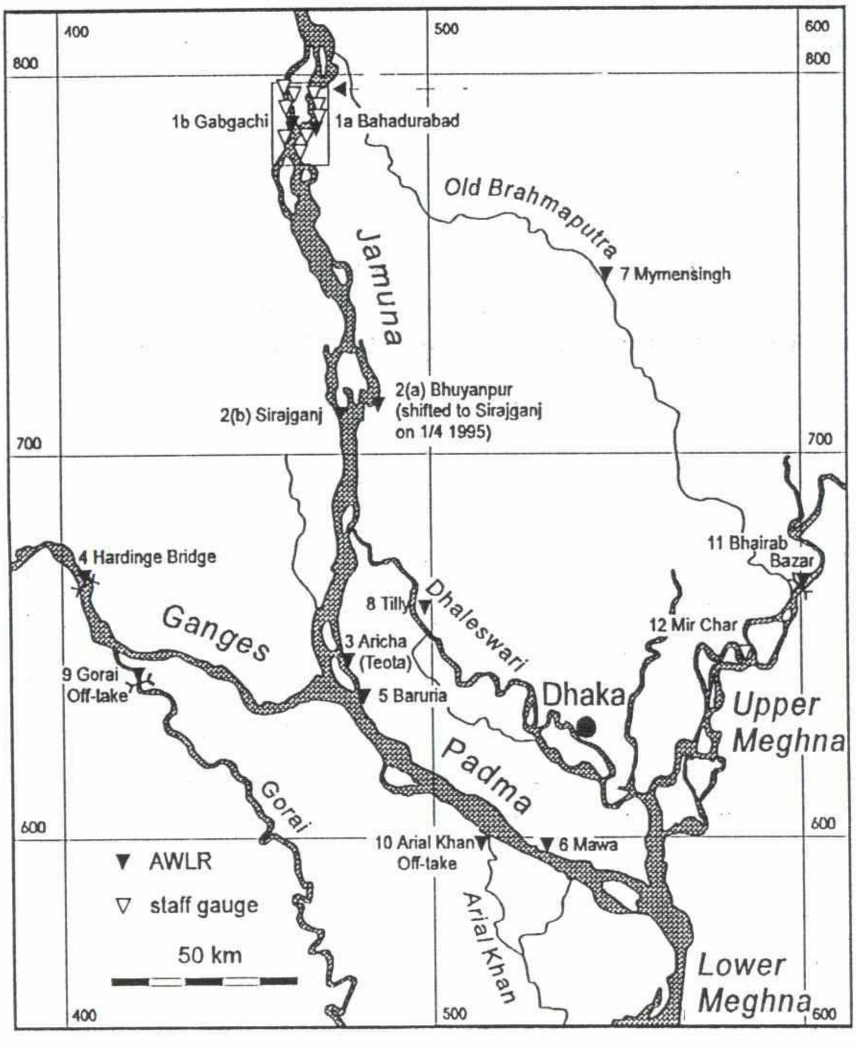


Figure 11.1

Main river system in Bangladesh with key hydrological stations.

Hereafter the main river system is divided into:

- Main rivers,
- Distributaries.

The distributaries branch off from the main rivers and hence depend for their discharge and sediment mainly on these main rivers. Apart from that, they also have a function for local drainage of excess rainfall in the areas adjacent to them.

The main rivers are the first five rivers of the above listing (Brahmaputra/Jamuna River, Ganges River, Upper Meghna River, Padma River and Lower Meghna River) and the distributaries are the remaining four (Old Brahmaputra River, Dhaleswari River, Gorai River and the Dubaldia/Arial Khan Rivers). In line with study Report 1 the Padma and the Lower Meghna River are considered here as one river system. The reasoning behind this is that the Lower Meghna is nowadays more the continuation of the Padma River rather than the lower reach of the Upper Meghna River.

11.3.2 Main Rivers

The following main rivers belong to the main system in Bangladesh:

- Brahmaputra/Jamuna River,
- Ganges River,
- Upper Meghna River,
- Padma River,
- Lower Meghna River,

In the following Table 11.1 the main characteristics of these five rivers are summarized. Note that in particular the characteristics are given which are of relevance for Lane's balance. For the width B the combined width of the channels is given for a braided system.

River	Q average (m^3/s)	α_Q (-)	V ($10^6 m^3$)	D_{50} (mm)	B (km)	i (10^{-3}m/m)
Brahmaputra/Jamuna River	20,400	1.2	206	0.23-0.15	4	0.1-0.06
Ganges River	10,600	1.2	195	0.12	3-5	0.05
Padma River	28,400	1.15	361	0.09	4-10	0.05
Upper Meghna River	4,500	1.2	12.5	0.14	0.5	0.02
Lower Meghna River	n.a.	1.2	n.a.	0.09	2.5-5	0.05

n.a. = not available

Table 11.1 Some characteristics of the main rivers

For the response of these rivers to changes, e.g. as a consequence of FAP, it is important to distinguish the main rivers as to the number of freedoms they have in adjusting to changed conditions. Further on the concept of a river as a cascade system, the imposed variables in a reach are the average discharge Q, α_Q (representing the duration curve), V and D_{50}. The dependent variables in a reach are the number of channels, the width of the channels and the sinuosity of these channels and the slope of the water surface (corresponding to the slope of the river bed for uniform conditions). The water depth is also a dependent variable and varies for varying discharges. Most of the main rivers (and the distributaries) in Bangladesh are fairly simple as they are meandering (implying that the number of channels is 1). Only braided reaches have a large number of freedoms.

The dependent characteristics of the main rivers can be described as follows:

- Brahmaputra/Jamuna River
  Braided river with a braiding index of 3 upstream and 2 downstream. Sinuosity of the braided channels is about 1.1.
- Ganges River
  Meandering river with a fairly straight overall course and a sinuosity of about 1.3. Near Hardinge bridge a stable section, but at downstream the river widens again, resulting in the development of alternate bars travelling through the system.
- Padma River
  Straight river constricted in width probably due to clayey outcrops. If width was free to adjust the river would probably be a braided river with a braiding index of 3. In the constricted reach (near Mawa) alternate bars are travelling through the system.
- Upper Meghna River
  A river in transition from a braided system to a meandering one. Due to the very low sediment loads (probably as a result of the subsidence of the upstream reaches) this adaptation takes place at a very slow rate.
- Lower Meghna River
  A fairly straight river, which is quite constricted near Chandpur due to the sharp bend. More downstream the tidal influence is gradually taking over.

As will be shown later only the Brahmaputra/Jamuna system may react in a more complicated way than indicated by Lane's balance. This is due to the fact that a braided river system may change its number of channels as well. It can be shown that an increase in braiding index, together in combination with $B :: Q^{0.5}$ for the individual channels, results in a slight increase in slope of the river (Klaassen, 1994).

11.3.3 Distributaries

There are four distributaries which belong to the main river system in Bangladesh.

- Old Brahmaputra River,
- Dhaleswari River,
- Gorai River,
- Dubaldia/Arial Khan Rivers.

These distributaries are actually all some kind of overflow rivers. In particular during the flood season they carry flow.

The main river from which they "originate" is listed here:

• Old Brahmaputra River	from	Brahmaputra River
• Dhaleswari River	from	Jamuna River
• Gorai River	from	Ganges River
• Dubaldia/Arial Khan Rivers	from	Padma River

The Old Brahmaputra and the Dhaleswari Rivers are connected to the main river system at the downstream end as well. The Old Brahmaputra via the Lakhya to the Upper Meghna and the Dhaleswari River directly to the Upper Meghna River (see Figure 3.1).

All distributaries are meandering rivers, although the Old Brahmaputra as the former course of the Brahmaputra River still has some braiding tendencies.

11.3.4 Offtakes and confluences

The off-takes are important (upstream) links between the main rivers and the distributaries, while the confluences are the (downstream) links between the main rivers mutually or between the main rivers and some of the distributaries. For the development of the distributaries the off-takes are the crucial elements. At an off-take the flow and the sediment transport entering into the distributary are determined by the downstream conveyances, the local geometry of the offtake and the relative size of the bed material: for very fine sediment the geometry of the offtake becomes less important.

In Study Report 1 the importance of the off-takes is discussed extensively. If more sediment is entering into the off-take than can be transported over a longer period, the distributary will start to aggrade. As a consequence less water is entering and hence this may start a self-accelerating process. It has been shown that most off-takes are unstable: either the distributary begin to 'die' or gradually the distributary takes the function of the main river. Much about this is still unknown, but in general it can be stated that the flow and sediment distribution is controlled by 2 and even 3 dimensional conditions which cannot be predicted easily.

For the present assessment it is important to underline that the off-takes really start to function only during higher stages. Any change in the stages in the main river will affect the flow (and sediment transport) entering into the distributary. In particular a decrease of stages will result in less water entering into the distributary and depending on the quantities of sediment entering the distributary, it will silt up. It may work out the other way around also: degradation of the distributary may result in its increasing importances.

11.4 Selection of scenarios used for assessment

11.4.1 General

To assess the impact of FAP it is of course required to know which plans will be implemented under FAP. A problem is that an integrated plan has not yet been developed for Bangladesh. This also can not be expected in this stage as some of the FAP projects are still under study and an integrated plan is only scheduled to be developed over the coming years. The present preliminary impact assessment should therefore be seen as one of the steps towards the development of such an overall plan, in which costs, benefits and impacts (together with preventive and remedial measures) are included in a balanced way.

Nevertheless some assumptions have to be made to be able to make an assessment as to possible developments. Different scenarios as far as possible developments are concerned (each comprising a selection from the different options of the Flood Action Plan) were developed recently by FAP25 and these will be considered for acceptance here as well.

11.4.2 FAP25 scenarios

Scenarios for development under FAP consists mainly of embankments and bank protection works. Regarding the latter only comprehensive plans have been developed for the Jamuna River within the frame-work of FAP1 and to some extent for the Lower Meghna River under FAP9B. Although it may be reasoned that the envisaged bank protection works may (slightly?) affect the riverine conditions, in particular if the rivers are shifting due to tectonic effects, the effect of river training works is not taken into account here. Hence the development scenarios are limited to embankments. These embankments may have two types of effects:

- reduction of overland flow;
- reduction of flood conveyance.

If overland flow is away from the main rivers, embankments will cause the main rivers to carry more flow during the floods. Hence the average discharge increases.

In Annex 2 of the FAP25 Flood Hydrology Study, in total 8 different scenarios for the construction of embankments have been studied. The characteristics of these 8 scenarios are summarized in Table 11.2. For each of the regional studies (FAP1 through FAP6) embankment options proposed are listed in the second column from left. On the right side of the table, different scenarios for possible development are given. They differ from fairly modest ones (Scenario 2 consists of the Brahmaputra Right Embankment - in fact already present - and an embankment along the Lower Meghna River - also already present over large distances - in combination with Ganges LE and embankments along the left side of the Jamuna and along the Dhaleswari) to comprehensive plans like scenario 5 (including the embankments along both sides of almost all the main rivers and distributaries). In Annexure 3 a more extensive discussion is given of the different measures that could be taken. This Annexure is a copy from a part of Annex 2 of the mentioned Flood Hydrology Study (FAP25, 1993).

The scenarios not only include FAP components but also some other "miscellaneous" possible developments (Jamuna Bridge and a sea level rise of 0.35 m) are part of some scenarios. According to FAP25 the Jamuna Bridge causes backwater in the upstream reaches, but it appears that the important constriction scour, which reduces the backwater considerably (Klaassen & Vermeer, 1988), was not taken into account by FAP25.

11.4.3 Selection of scenarios for assessment

As indicated in Section 4.2 in total 8 scenarios's were investigated in the Flood Hydrology under FAP25. "The simulation programme has been prepared on the basis of discussions with the Flood Plan Coordination Organization (FPCO), FAP1 and the regional FAPs (FAP25, 1993). The simulation programme is a slightly adapted version of the programme presented in the

Main text of the FAP25 Flood Hydrology Programme. Also here these 8 scenarios have been accepted for consideration.

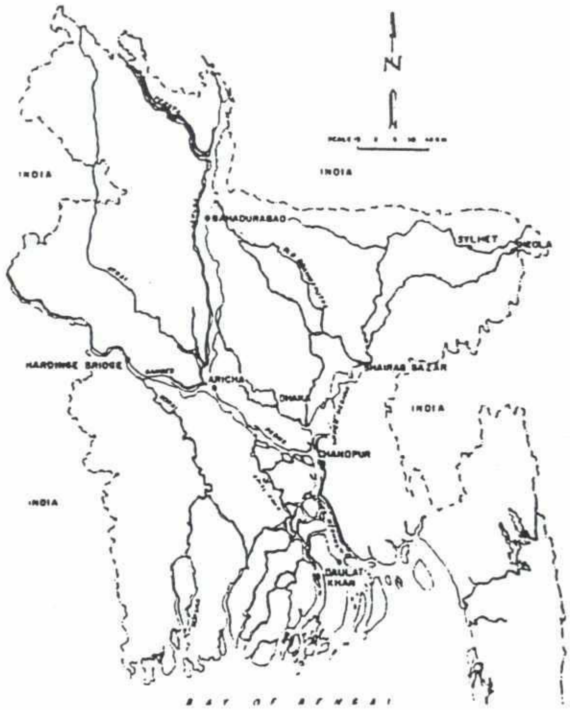
For the present assessment it was deemed sufficient to consider only the scenarios 3 and 5. Scenario 3 is the scenario for which a long term simulation (1965-1989) was undertaken for the establishing of hydrological design criteria along the major rivers and is considered as one of the most likely future protection scenarios (FAP25, 1993).

Scenario 5 is the most severe as far as the implementation of works is concerned. In fact it includes all possible embankments together with Jamuna Bridge. Only sea level rise is not included. Figure 11.2 gives an overview of present conditions and the project components proposed for the scenarios 3 and 5. The other scenarios are probably causing less serious impacts as the related changes in hydraulic conditions are less serious as well.

FAPs	OPTIONS	SCENARIOS							
		1	2	3	4	5	6	7	8
FAP1	Brahmaputra RE, present alignment	X	X	X	X	X	X	X	X
FAP2	Ganges LE		X	X	X	X	X		X
FAP3 & FAP3.1	Jamuna LE(N), West of Chatal		X	X	X	X	X		X
	Jamuna LE(S), Western alignment					X	X		
	Dhaleswari LE, to Katalia		X	X	X	X	X		X
	Dhaleswari LE, D/S Katalia					X	X		
	Padma LE					X			
	Dhaleswari RE					X			
	Old Brahmaputra, RE + LE & Lakhya					X	X		
FAP4	Ganges RE				X	X	X		
	Padma RE					X			
FAP5	Lower Meghna LE	X	X	X	X	X	X	X	X
FAP5B	Lower Meghna RE								
FAP6	Upper Meghna LE					X	X		
	Upper Meghna RE					X			
MISC	Jamuna Bridge at ch. 170.75			X		X	X		X
	Sea Level Rise (+35 cm)							X	

Table 11.2 Scenarios simulated by FAP25 (FAP25, 1993)

In principle there is a complicating factor when assessing morphological impacts. Morphological changes are changes that progress both in space (in x-direction for one-dimensional approaches) and in time (hence in t-direction). The different FAP components as included in Scenario 5 will not be implemented at the same time. It makes however quite some difference whether certain measures are implemented at the same time, or whether the implementation is spread over a period of say 50 years. Hence scenarios for morphological assessment do not only consist of the projects to be implemented but also the moment at which they become effective. A good example of such "morphological scenarios" are the scenarios used under the Jamuna Bridge Study (see RPT et al, 1990).



(a) Present condition (Scenario 1)

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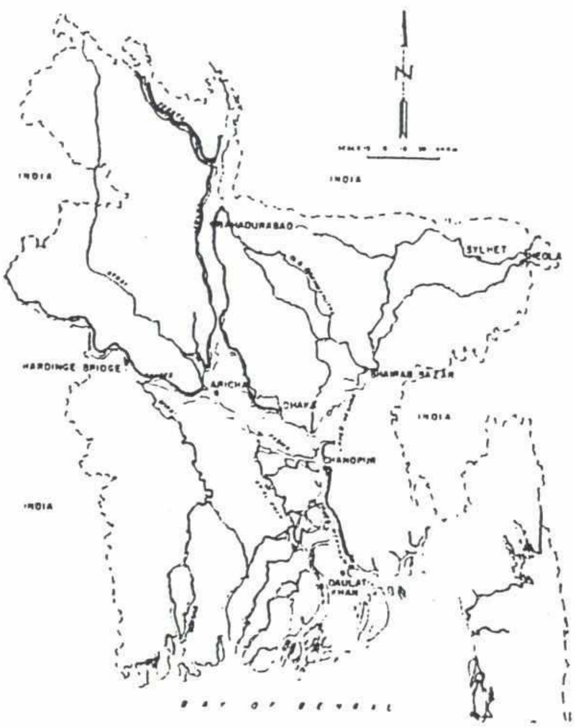
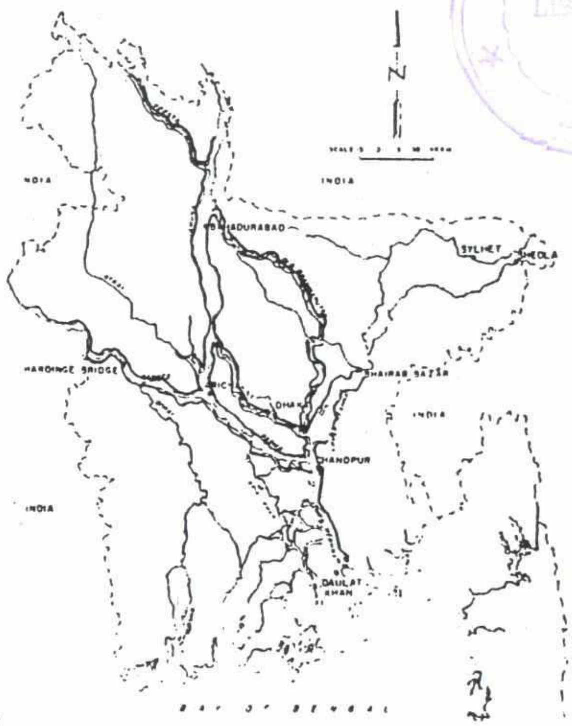


(b) Scenario 3



(c) Scenario 5

Figure 11.2 Present condition (a), compared with Scenarios 3 (b) and 5 (c)

For the time being it will be assumed that all projects as included in Scenario 5 will be implemented at the same time. This gives probably a "worst case scenario", although due to the complicated interaction between the main rivers and the distributaries, there may be scenarios where time is considered as well that may have more serious consequences. This should be studied in a later stage.

11.5 Impact

11.5.1 Introduction

In this chapter a qualitative assessment of the morphological impact of FAP is made. As the morphological changes are triggered by the hydraulic changes, first the hydraulic changes are reviewed. The relevant information, presented in Section 5.2, was derived from the FAP25 study (FAP25, 1993). In the subsequent sections the resulting morphological changes are discussed: ultimate changes, the intermediate changes and the possible changes in stages in the main rivers and in the distributaries. As indicated in the previous chapter the assessment is limited to the Scenarios 3 and 5 (referred to hereafter as SCE 3 and SCE 5, respectively), while it is assumed furthermore that all measures as proposed in these scenarios are implemented at the same time: probably be a "worst case" scenario.

11.5.2 Changes in water distribution and in stages

Here it is of interest to determine the effects of implementation of embankments, according to the two selected scenarios on the water distribution over the main river system and on the stages along the various rivers. For this purpose a comparison should be made between the present and the future conditions.

In the first stage of the FAP25 a general model of the main river system of Bangladesh was set up and calibrated. As basis the so-called RUN 6 is used, supposedly the best simulation of the present conditions. This run extended over the same period of 25 years (1965-1989) as for which SCE 3 was applied. In Annex 2 of the FAP25 Flood Hydrology Study relevant results are presented. Mostly as comparisons between RUN 6 and SCE 3, but also some information can be derived from the comparison between RUN 6 and SCE 5. In the following some of this information is summarized. First on the water distribution and next on the stages.

11.5.3 Water distribution differences

Table 11.3 summarizes the computed differences between the simulations SCE 3 and RUN 6 in discharges in five main stations. As can be observed there is hardly any difference in four out of five stations. Only the discharge in Baruria is on the average about 2500 m^3/s higher for SCE 3. Although not indicated this increased discharge occurs also in the lower reach of the Jamuna River.

A similar comparison cannot be derived straightforward from FAP25 (1993) for the differences between RUN 6 and SCE 5. Some idea about the changes in discharges can be obtained from the changes in stages (see hereafter).

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11.5.4 Water-level differences

In Table 11.4 the differences in stages between the simulations RUN 6 and SCE 3 are summarized on the basis of a simulation of the 25 year period 1965-1989. The location of the stations included in this comparison is indicated in Figure 11.1. Inspection of Table 11.4 leads to the following observations:

- Changes are negligible along the Lower Meghna River, the upper reach of the Ganges River and along the Old Brahmaputra River.

River	Station	Period			
		May-Jun	Jul-Aug	Sep-Oct	Average May-Oct
Jamuna River	Bahadurabad	22	-26	-29	-11
Ganges River	Hardinge Bridge	0	0	0	0
Padma River	Baruria	2155	4066	1382	2574
Upper Meghna	Bhairab Bazar	3	8	-7	1
Old Brahmaputra	Nilukhirchar	3	19	8	10

Table 11.3 Changes in discharges in m^3/s in the main river system (SCE 3 - RUN 6) over a period of 25 years (1965-1989) (from FAP25, 1993)

- Lowering of the water-level, but only to a small extent (less than 0.05 m), can be observed in the Upper Meghna and the Lakhya River. This probably due to more flow passing through the Dhaleswari and Jamuna-Padma River systems. See Table 11.3.
- Water-levels are higher in the Padma and the lower reach of the Jamuna River due to more water passing through this system (see also the above point). Also the lower reach of the Ganges River is affected by this increased discharge via backwater from the confluence.
- Also in Sirajganj and more upstream a substantial increase in stages is observed. This, however, is not caused by an increase in discharge but it is due to not taking into account the constriction scour under the bridge during floods. Hence this computed increase is not realistic (see Section 4.2) and does not lead to morphological changes other than on a local scale.
- Along the Dhaleswari (Kaliganga) system a substantial increase in stages is observed.
- Negligible changes in the Gorai and in the Dubaldia/Arial Khan Rivers.

The above yields a picture of more water being discharged via the main channel system which is of course the consequence of the embankments which block overland flow and limit the conveyance of the floodplain.

No similar information is available for SCE 5, because SCE 5 was not tested versus a 25 year long period of flow. A simulation was made however of the peak stages in the main river system and the distributaries for the years 1986, 1987 and 1988. The results of the simulation for the year 1988 are presented in Figure 11.3. In addition in Annex 2 of the Flood Hydrology Study (FAP25, 1993) simulated differences in peak water-levels for the different scenarios for the years 1986, 1987 and 1988 are presented. Here in particular the differences between SCE 3 and SCE 5 are relevant. Although the results are difficult to generalize, the main differences for SCE 5 compared with SCE 3 are:

- slight increase in water level in the lower reach of the Jamuna River and in the Padma River,
- substantial increase along the lower reach of the Old Brahmaputra and in the Lakhya River.

River	Station	Period			
		May-Jun	Jul-Aug	Sep-Oct	Average May-Oct
Jamuna River	Bahadurabad	0.02	0.04	0.03	0.03
	Kazipur	0.16	0.21	0.17	0.18
	Serajganj	0.19	0.30	0.23	0.24
	Porabari	0.15	0.22	0.18	0.18
	Mathuria	0.22	0.19	0.12	0.17
Ganges River	Hardinge Bridge	0.01	0.00	0.00	0.01
	Sengram	0.05	0.02	0.01	0.03
	Mahendrapur	0.08	0.03	0.02	0.04
Padma River	Baruria	0.11	0.12	0.09	0.11
	Mawa	0.04	0.07	0.05	0.05
Upper Meghna River	Bhairab Bazar	-0.01	-0.03	-0.03	-0.02
	Meghna Ferry	-0.02	-0.06	-0.05	-0.05
Lower Meghna River	Chandpur	0.00	0.00	-0.01	0.00
Old Brahmaputra River	Jamalpur	0.01	0.02	0.01	0.01
	Nilukhirchar	0.01	0.02	0.01	0.01
	Toke	0.00	-0.02	0.00	0.01
Lakhya River	Demra	-0.03	-0.05	-0.05	-0.04
Kaliganga River	Taraghat	0.33	0.87	0.66	0.62
Gorai River	Gorai Rly. Bridge	0.02	0.01	0.00	0.01
Atrai River	Baghabari	0.14	0.19	0.14	0.16
Arial Khan River	Madaripur	-0.11	0.14	0.07	0.03

Table 11.4 Water-level differences in m between SCE 3 and RUN 6 for key stations along the main river system over a period of 25 year (1965-1989) (after FAP25, 1993)

For the time being it is concluded that SCE 5 has approximately a slightly more serious effect on the lower reach of the Jamuna and on the Padma River and a more serious effect on the stages in the lower reach of the Old Brahmaputra. Probably on the average the flows in these river reaches are larger than in the present situation and for SCE 3.

11.5.5 Ultimate morphological changes for the main rivers

In a next step the ultimate morphological consequences of the possible changes according to the scenarios 3 and 5 are assessed. The main effect of these scenarios on the main rivers is an increase in stages in the lower reach of the Jamuna River (see Table 11.4) and an increase in flows in the Padma River (see Table 11.3). Although there are no data on flows in the lower reach of the Jamuna river given in FAP25 (1993), it is assumed here that in the lower reach of this river (downstream of the Dhaleswari intake) also increased flows will occur. For the time being nothing is known about the effect of the different scenarios on the transport and distribution of bed material, but it is assumed here that this is not affected by the proposed changes. Hence Lane's balance can be applied assuming that V and D remain the same. Furthermore it is assumed that the analysis can be done on the basis of the average discharge, assuming that the (dimensionless) duration curve does not change (Hence α is assumed to remain the same).

Applying Lane's balance under these assumptions, it is found that the application results in a decrease of the ultimate slope of the river, either according to Equation (11.3) if the width B remains constant, or Equation (11.4) if the width B can change as well. As discussed before the width of the *Padma River* is constricted and it is assumed that the increase in average discharge is not all of a sudden leading to a substantial increase in width of this river. Hence Equation (11.3) is more appropriate.

For the *Jamuna River* the situation is more complicated: the river can adjust its slope i, its total width B, its number of channels k and its sinuosity p. If the number of channels would remain the same,then an increase in discharge would lead to a reduction in slope conform Equation (11.3). An (slight) increase in braiding index (= average number of channels k) is plausible, as a consequence of the (slightly) increased Q. It can be shown that an increase in the average number of k results in an increase in slope, but only marginal. For the time being it is assumed that for the Jamuna River Equation (11.3) is applicable as well. If more insight into the response of a braided system as a consequence of an increase in Q is becoming available, possibly a revision of this assumption can be made.

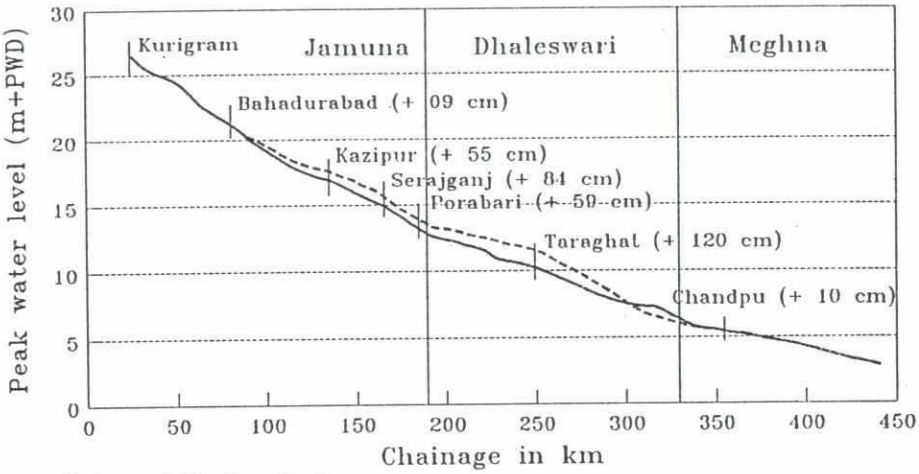
In the other main rivers there are no changes in flows and consequently it can be concluded that the slope of these rivers remains constant. This does not mean that their stages remain the same as well. Due to the reduction of the slope of the Padma and the lower reach of the Jamuna River the stages will reduce in the upstream reaches of these rivers. As a consequence the stages in the Ganges River and in the upper reaches of the Jamuna River will fall as well.

The result of the application of Lane's balance to Scenario 3 is presented in Table 11.5. The following observations can be made:

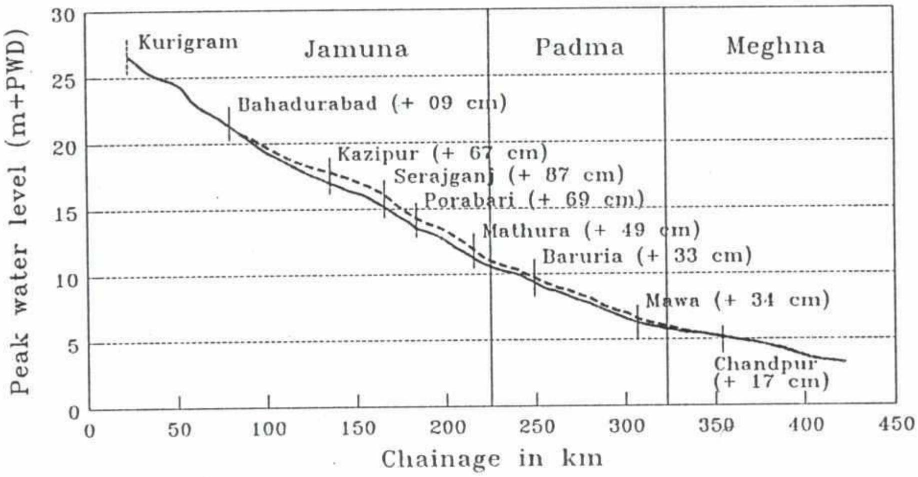
- Only the slopes in the Padma and the lower reach of the Jamuna River will be affected.
- The reduction of slope is about 6% for the Padma River and about 10% for the Jamuna River.
- No changes in slope in the other main rivers.

River	Reach	Parameter					
		Reach length L (km)	Original average discharge Q_0 (m^3/s)	New average discharge Q_1 (m^3/s)	Original slope i_0 (10^{-5})	New slope i_1 (10^{-5})	Lowering water level upstream (m)
Lower Meghna River	Downstream confluence Upper Meghna River	not relevant	40,000	40,000	4	4	0.0
Upper Meghna River	Bhairab Bazar confluence Padma River	not relevant	5,000	5,000	2	2	0.0
Padma River	Confluence Ganges/Jamuna-confluence Upper Meghna R.	100	35,000	37,000	5	4.6	0.4
Jamuna River	Confluence Ganges River-Dhaleswari off-take	85	20,000	22,500	6	5.3	0.6
	Dhaleswari off-take Bahadurabad	not relevant	20,000	20,000	8	8	0.0
Ganges River	Upstream confluence of Jamuna River	not relevant	15,000	15,000	5	5	0.0

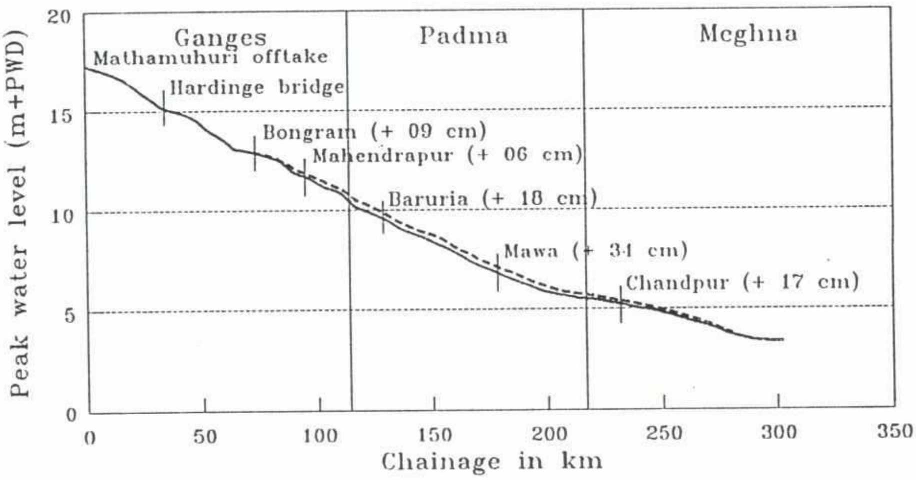
Table 11.5 Results of application of Lane's balance to ultimate conditions for Scenario 3



(a) Jamuna-Dhaleswari-Meghna System



(b) Jamuna-Padma-Meghna System



(c) Ganges-Padma-Meghna System

Figure 11.3 Simulated difference in peak water-levels between SCE 5 and RUN 6 for the year 1988 (FAP25, 1993)

11.5.6 Intermediate morphological changes in the main rivers

The estimates presented in the preceding section relate to the ultimate conditions, due to occur may be after 50 to 100 years only. In this section some considerations regarding the *intermediate* conditions are presented, hence the conditions directly after implementation until the ultimate conditions have almost been reached.

According to Table 11.6 embankments along the main rivers as assumed under the scenarios 3 and 5 will lead to slope reduction and related degradation of the Padma, Ganges and Brahmaputra/Jamuna Rivers. How quickly reduction in slope will materialize, depends in particular on the sediment transport rates. This underlines the need to know fair accurately the sediment transport predictor that is applicable as one of the important elements of a one-dimensional morphological model, required to model the behaviour for the intermediate conditions.

Furthermore it should be noted that during the intermediate period the behaviour of the river may be quite opposite to the ultimate changes. As an example consider the Ganges River. Initially the stages at the confluence of the Ganges and the Jamuna River are higher, implying that in the Ganges River aggradation will take place. Only later the reduction in stages due to slope reduction will take over and the river will start to degrade. A similar phenomenon takes place in the Lower Meghna and possibly the Upper Meghna and the Padma River. The Jamuna River and to a smaller extent the Padma River will start to degrade. The resulting increased sediment transport leads to (temporary) deposition in the Lower Meghna and possibly the Padma River. This will lead to increased stages at the confluence with the Upper Meghna River. This may induce some aggradation, but it is assumed here that the quantities of sediment transported in the Upper Meghna River are too small to lead to substantial bed level changes. The anticipated bed level changes are indicted in Figure 11.4.

11.5.7 Bed levels and stages in main rivers

From the estimated changes in slope of the river, the lowering of the water-level can also be estimated. It should be recalled in this respect that the water-level changes in the Padma River have their effect on the stages in the Jamuna and the Ganges River as well. The results of this assessment are given in Table 11.6 for a number of key stations. It can be concluded that implementation of Scenario 3 would *ultimately* result in a lowering of the water-levels in the Padma, the Ganges and the Brahmaputra/Jamuna River systems varying from almost zero at the downstream end to about 1.0 m in the Jamuna River.

In the preceding section it was demonstrated that the initial and intermediate behaviour may be quite opposite to the ultimate effects. The initial effects are the effects as simulated in the FAP25 study, because there it was assumed that the bed levels would not change (or rather: were not yet changed). This apparently leads to an increase in the stages in all river reaches. In the intermediate period the stages will gradually lower again as the slope of the river gradually reduces due to the increased discharges.

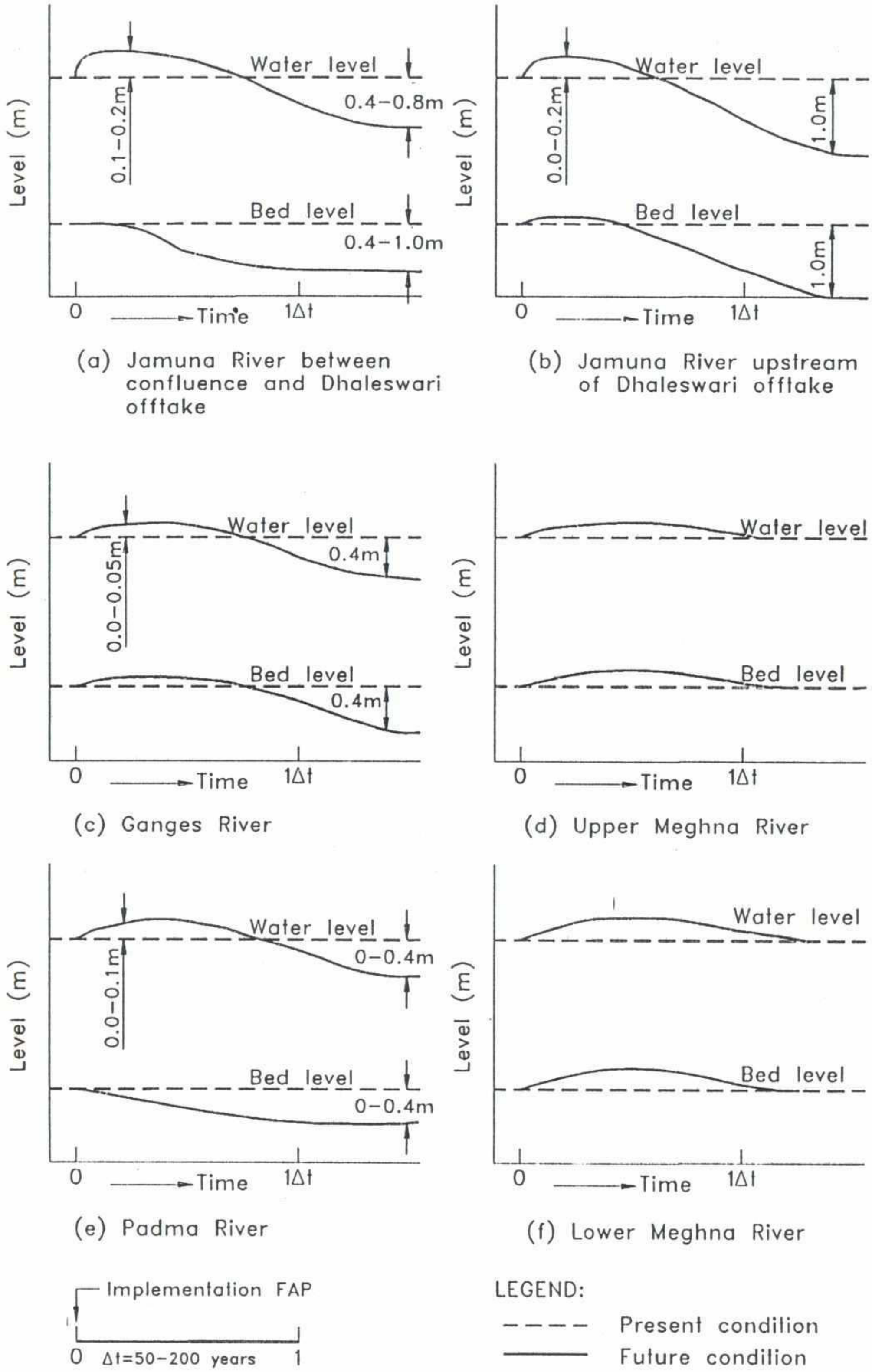


Figure 11.4 Qualitative change of bed levels in the main rivers

Station	River	River(s) downstream	Lowering of water stages		
			Effect of slope change in river (m)	Effect of downstream rivers (m)	Total lowering (m)
Bahadurabad	Jamuna River	Jamuna River- Padma River- Lower Meghna River	0.0	1.0	1.0
Serajganj	Jamuna River	Jamuna River- Padma River- Lower Meghna River	0.6	0.4	1.0
Hardinge Bridge	Ganges River	Padma River- Lower Meghna River	0.0	0.4	0.4
Baruria	Padma River	Lower Meghna River	0.4	0.0	0.4
Bhairab Bazar	Upper Meghna River	Lower Meghna River	0.0	0.0	0.0
Chandpur	Lower Meghna River	None	0.0	-	0.0

Table 11.6 Preliminary estimates of lowering of stages for ultimate conditions for Scenario 3

The general behaviour of the stages in the various river reaches is included in the Figure 11.4as well. Initially or slightly later the stages are higher than the present ones, but they will gradually lower again and in due time they will be lower than they were initially. The indicated changes will occur over the full range of stages, as they are caused by degradation. This degradation causes the rating curve to shift downwards.

The above analysis was on the basis of SCE 3. SCE 5 has a slightly larger impact. Hence it may be expected that the ultimate effects of SCE 5 are slightly larger.

11.5.7 Impact on distributaries

In the foregoing sections only the conditions in the main rivers were considered. The different scenarios, however indicate that already initially there will also be some changes in some of the distributaries as well. According to Table 11.4 (see also Figure 11.3 (a) for SCE 5 during peak conditions) in particular in the Dhaleswari system there will be an increased inflow (due to higher stages in the Jamuna River) and local embankments diverting the flow into the distributaries as well. At initial stage the other distributaries will slightly be affected only (see Table 11.4)

Increased flow in the Dhaleswari may lead also here to slope reduction and degradation, but that depends on the sediment entering the Dhaleswari as well. According to Equation (11.1), however, the slope i will decrease only if $V/Q^{n/3}$ decreases. Hence a substantial increase in sediment entering the Dhaleswari may counteract and even lead to continuing aggradation (as is presently occurring, see Study Report 1). The quantities of sediment entering the off-take depend on the relative amount of flow entering, the particle size, the flow conditions and the geometry of the off-take. In particular the latter is difficult to predict, hence the changes during the intermediate conditions can only be predicted in a stochastic way. There is a clear similarity between the stochastic prediction of plan-form (see e.g. FAP22 reports and/or Klaassen et al. 1993) and the prediction of the future behaviour of the distributaries under the influence of the implementation of FAP. The development of a distributary can only be predicted in terms of a probability of occurrence.

Something similar holds for the ultimate conditions. The ultimate conditions in the distributaries depend on the intermediate conditions as well and hence are difficult to predict in a deterministic way. Still it is felt that the natural tendency for some of the distributaries i.e. gradual silting up will be affected by implementation of the FAP, either by accelerating or by reducing this tendency. Only active interference with the off-takes may allow for the distributaries to remain being important.

Still some qualitative statements regarding the distributaries can be made. Initially the conditions in the *Old Brahmaputra* will hardly change as the backing of the water near Bahadurabad is negligible. Later (after some 50 years ?) the stages will start to lower and hence the flow into the Old Brahmaputra will reduce. This is probably an acceleration of the natural tendency and it will probably lead to the complete dying of this distributary.

Due to the increase of the stages in the Jamuna River, the *Dhaleswari River* and connected rivers like the Buriganga etcetera will initially carry more flow. Depending on the ingress of sediment subsequently the river will start to aggrade or it will degrade. Probably it will be degradation rather than aggradation. Due to this the discharges into the Dhaleswari will increase. In a later stage the lowering of the stages in the Jamuna will exert its influence increasingly, probably leading to the gradual dying of the Dhaleswari.

The *Gorai River* may initially carry some more water, but this tendency will be reversed due to the lowering of the stages in the Ganges River in the intermediate and ultimate conditions.

To predict the future behaviour of the *Dubaldia/Arial Khan River system* is difficult due to the limited knowledge available on this river system. The impact of FAP will be limited as the off-take is near the confluence with the Upper Meghna River where the initial increase in stages and the subsequent degradation are fairly small.

Ultimately there is of course a feed-back from the changes in the distributaries to the main rivers. If some of the distributaries would in due time loose their importance, then the main rivers would have to carry even more discharge with additional slope changes.

Also it should be stated here that SCE 5 probably has larger effects than SCE 3. This, however, has to be checked via a more refined analysis using e.g. a one-dimensional morphological model. This holds for SCE 3 as well: only the application of such a model may give more quantitative insight.

Finally note that ultimate conditions are meant here in relative terms only. Most bifurcations are not stable over longer periods. Ultimately one of the channels usually silts up. In this respect the possible increase in importance of some of the distributaries should possibly be seen as temporary phenomenon on a time scale longer than some centuries. The impact of FAP could delay the dying of the distributaries, in particular if it would be "guided" (see Chapter 6 for a more extensive discussion on this).

11.6 Discussion

In the previous Chapter an qualitative assessment was made of the possible impact of implementation of FAP. It was found that probably the initial increase in stage in due time would be reversed into a reduction of the stages due to slope reduction. Also it was found that the probable "fate" of the distributaries of slow dying can be possibly delayed by the impact of FAP, but it can under certain circumstances and for some distributaries be accelerated. Whether these developments are favourable or not has to be assessed during the preparation of an overall plan for the FAP.
It should be emphasized, however, that the present assessment is of a qualitative nature only. To underline this a number of relevant aspects are discussed here briefly. The following aspects are covered hereafter:

1 How accurate are the predictions ?
2 More ultimate conditions ?
3 Time dependency
4 Uncertainties resulting for off-takes
5 Changes in plan-form etc
6 Timing of measures
7 Influence of other developments ?
8 Implications for FAP24 activities

Re 1 *How accurate are the predictions ?*
Although the present analysis was supposed to be qualitative one, still some figures on changes in stages (and bed levels) are given. The computed changes are subject however to the developments taking place in the distributaries as well. Furthermore the rivers may react in a more complicated way than changing their slope only. Hence the accuracy of the deterministic values in e.g. Table 11.5 are low. Due to different developments the actual values may easily deviated a few decimeter. It is felt however that the general tendency predicted is fair: initially an increase in stages and later a decrease with as ultimate effect an overall lowering.

Re 2 *More ultimate conditions ?*
As indicated before, it is felt that future developments may take different courses depending on elements that could not be included in the present analysis. In particular the (two- and three-dimensional) conditions at the off-takes and how they vary in time will affect the overall development. Hence predictions on the ultimate developments can only be given together with a probability of occurrence. It is stressed here that application of a one-dimensional model will not improve this. A model however will be extremely helpful in evaluating the effects of possible variations at the off-takes and in assessing the probability of certain developments.

Re 3 *Time dependency*
The morphological changes, which are quite important for the overall future behaviour of the main river system in Bangladesh, proceed at a certain pace. This time-dependent behaviour is very important as the ultimate conditions will be reached only after a fairly long period. This underlines the importance of the developing of a one-dimensional time-dependent morphological model of the whole system, in which the existing knowledge on the river system is introduced and the time-dependent behaviour for various scenarios is simulated (using the probabilistic approach needed).

Re 4 *Uncertainties resulting from off-takes*
The major off-takes play a key role in the development of the main river system over the coming decades. The limited understanding of their characteristics and behaviour in time is a major limitation for any impact assessment (and for any prediction of future developments).

Re 5 *Changes in plan-form etc*
In the previous chapter it was assumed that the main rivers in Bangladesh react on changes in discharges mainly by changing their slope. Braided rivers, however, have more possibilities of adjustment. Further studies on the characteristics of braided river reaches in Bangladesh (and elsewhere) are urgently needed to get more insight in braided rivers and their response to changes. More generally it holds that in this limited study no attention could be paid to plan-form changes due to the implementation of FAP projects. The construction of bank protection woks like envisaged under FAP1, FAP9B and FAP21 may lead to plan-form changes opposite the works and more downstream.

Re 6 *Timing of measures*
In the present analysis it was assumed that all FAP projects would be implemented at the same time. This however is not so realistic. It seems more logic that the different projects will be spread over a period of some decades. This will certainly affect the morphological changes due to FAP implementation.

Re 7 *Influence of other developments ?*
In the foregoing the impact of FAP was discussed as if there are no other influences that may affect the conditions in the main river system. The rivers in Bangladesh, however, are subject to ongoing developments due to neo-tectonics and other changes (partly as a consequence of human activities: water diversions, deforestation, sea level rise etc.). As was explained before, the fate of the distributaries is very much determined by local conditions and how these are developing over time. Hence the impact of FAP cannot be assessed independently without these other developments.

Re 8 *Possibility of influencing the development*
Because of the sensitivity of the system for changes, there possibly are options to influence the development of the system by a phased implementation of the different FAP components. This would imply that the order of implementing projects would be influenced by predictions made regarding the effect. There are however also other boundary conditions that have a bearing on the sequence of implementation (not the least the economic feasibility of the various projects), but still this option could be considered in the development of an overall plan. The same holds for application of FAP22 techniques. It can be imagined that application of these techniques to influence the conditions at off-takes in some critical periods may result in a very positive development of the main river system. This should be explored further.

Re 9 *Implications for FAP24 activities*
The present analysis and the above discussion very much supports the selection of study topics for FAP24. Emphasis should be on sediment transport, plan-form and how it is affected by the flow and sediment transport in a reach and in particular the conditions at the off-takes. In addition it underlines the importance of using one-dimensional morphological models to test the present understanding of the systems and to study the sensitivity of the system to changes.

Finally it is remarked that the present assessment is a very preliminary one only. It should be followed by more detailed assessments in due time, in which also the sequence of projects and possible adaptations should be studied as part of the development of a well-balanced FAP.

11.7 Conclusions and recommendations

This Chapter presents the results of a first qualitative assessment of the possible impact of FAP on the main river system. The assessment builds on the results of the FAP25 study (see FAP25, 1993). In particular the morphological response of the system was explored. This morphological response will take place over a period of 50 to 100 years or more. The present assessment was mainly done for SCE 3 (see Chapter 4 and in particular Table 11.3 and Figure 11.2), but also SCE 5 is briefly considered.

Based on the outcome of this exploring study the following conclusions can be drawn:

- The increase of the stages conform the predictions by FAP25 due to the implementation of FAP will only occur initially.
- The initial increase in stage would probably in due time be reversed into a reduction of the stages due to slope reduction.
- The "fate" of the distributaries of slowly dying can be possibly delayed by the impact of FAP, but it can under certain circumstances and for some distributaries be accelerated.
- The future conditions can partly be determined deterministically: the complications due to the off-takes induce some probabilistic behaviour as well.
- There may be some scope for influencing the future developments by selecting a certain sequence of projects for implementation under FAP. This may in particular be beneficial for the distributaries.
- The results of the assessment support the selection of study topics for FAP24.

Based on the above conclusions the following recommendations are made:

- To study in a one-dimensional morphological model the initial, intermediate and ultimate response of the main river system to implementation of FAP.
- To specifically use this model to explore the stochastic behaviour of the system and to study the influence of possible natural developments and the influence of certain strategies of implementation of the FAP components.
- To concentrate the FAP24 studies on the already selected topics: sediment transport rates, plan-form characteristics and how they are influenced by changes in flow and sediment transport, and off-takes (in addition to survey techniques).

12 Proposed further studies

This Annex has presented an overview of studies carried out under the River Survey Project (FAP24) in the field on sediment transport processes in the main rivers of Bangladesh. At the same time it provided a state-of-the-art of the understanding of sediment transport 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 2), could not be initiated due to the limited human resources available for the study component of the project. As a consequence many aspects of sediment transport in 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 in either M.Sc. or Ph.D. studies form 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 sedimentological 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. An overview of the proposed study topics is given in Table 12.1, together with a tentative ranking.

12.1 Additional measurements

The following additional measurements are proposed:

1 ***Bed material sampling***

On the following rivers hardly any information on the bed material composition is available:

- Ganges upstream of Hardinge Bridge
- Dhaleswari River
- Surma and Kushiara

Samples to be taken every 5 km, left, middle and right.

2 *Mineralogy of sediments*

During the RSP only a limited study could be carried out into the mineralogical composition of the bed material and of the transported sediments. This study should be expanded upon substantially. This study involves drawing up a sampling programme, taking samples, processing of samples, and interpretation of the results along the lines of SPR 14.

3 *Composition of banks, floodplains and chars*

Sampling the composition of the eroding banks of all main rivers. Sampling of floodplains e.g. via vibra-coring to determine the composition. Very essential is a carefull selection of representative sampling sites based on distinguishing different depositional environments.

4 *Composition of the subsoils of the rivers*

The preparation of a geological profile of the rivers, on the basis of existing borings in or on both sides of the rivers. Interpolation may provide a first assessment of the composition in terms of type of material, particle size, and mineralogy of the soils and may allow for an identification of areas with geological controls. If appropriate additional boring can be made and analyzed.

Topic		Proposed studies	Ranking
Additional measurements	On a regular basis	None	–
	Once	• Bed-material sampling	2
		• Mineralogy of sediments	2
		• Composition of banks, floodplains and chars	2
		• Composition of subsoil of rivers	3
		• Geological controls	1
Special studies	Bed material	• Longitudinal sorting, abrasion and subsidence	3
		• Deposition of fine sediments	2
		• Formation of controls	3
	Resistance to flow	• Contributions to resistance to flow	1
		• Low resistance during floods	1
	Bedforms	• Occurrence of bedforms	3
		• Slope of lee-side of dunes	2
	Sediment transport patterns	• Areas with intense morphodynamic activity	2
		• Flow and sediment transport over dunes	3
	Floodplain sedimentation	• Rates of floodplain sedimentation	1
		• Overall floodplain sedimentation	2
		• Floodplain sedimentation and subsidence	2
	Morphological impact assessment	• Impact assessment implementation FAP/NWMP implementation (one-dimensional)	1

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 12.1 Proposed study topics on sedimentological characteristics

5 *Geological controls*

Sampling of known geological controls: Mawa, Sara (others more upstream along the Ganges River to determine characteristics (in particular clay content) in view of the possible development of hard points along the Jamuna River.

12.2 Special studies

The following special studies are proposed:

1 ***Longitudinal sorting, abrasion and subsidence***
Based on the mineralogical composition, the abrasion characteristics of them and the downstream fining an estimate can be obtained of the required subsidence. For this the approach used by Parker (1989) can be used.

2 ***Deposition of fine sediments***
More detailed study into the locations where fine sediments settle in the riverine environments. Possibly combined with studies into consolidation of these deposits and resistance against erosion after some consolidation.

3 *Formation of hard points*
Identification of potential hard points under development (in former bartails) e.g. using satellite imagery, and sampling plus subsequent analysis of resistance to erosion.

4 *Contributions to resistance to flow*
Assessment of different contributions to resistance to flow: bedforms, bars, vegetation, others. Combined with local slope measurements and flow measurements.

5 *Low resistance to flow during floods*
Special study into the cause of the extreme low resistance to flow during floods in e.g. the Padma River, including analysis of very accurately measured velocity profiles.

6 *Occurrence of bedforms*
Inventory of occurrence of bedforms. Development of understanding via testing of hypotheses. Interpretation using simple parameters, but also considering 3-d environment and morphological changes (deposition or erosion) taking place.

7 *Slope of lee-side of dunes*
Relation to resistance to flow together with modelling of sediment diffusion into the eddy downstream of dunes, combined with measurements with ADCP.

8 *Areas with intense morphological activity*
Identification of such areas. Linking of them to morphological processes. Importance for overall sediment transport. If appropriate, development of prediction method, e.g. for inclusion in 2-D morphological models.

9 *Sediment plumes and sand arrows*
Occurrence, explanation, identification on satellite imagery; importance for overall sediment transport.

10 ***Flow and sediment transport over dunes***
Concentrating on boils and their importance for the overall sediment transport

11 ***Floodplain sedimentation***
Continuation of studies into floodplain sedimentation, analogous to studies carried out by RSP.

12 ***Overall floodplain sedimentation***
Extrapolation of results from isolated sampling of floodplain sedimentation via approach Narinesingh (1995).

13 ***Floodplain sedimentation and subsidence***
Vibra-coring and dating of samples at selected sites in the floodplain. See under (3) of Additional studies in this Section.

14 ***Morphological impact assessment implementation FAP/NWMP implementation (one-dimensional)***
Extension of morphological impact assessment carried out under this project (see Section 7.4). Use of a one-dimensional morphological model for intermediate conditions using existing data on the main rivers.

References

ACKERS, P. & W.R. WHITE (1972), Sediment transport: new approach and analysis, Journ. Hydr. Div., ASCE, Vol. 99, no. HY11, pp. 2041-2060.

ALAM, M.K. (1988), Geology of Madhupur Tract and its adjoining areas in Bangladesh, Geological Survey of Bangladesh Records, Vol. 5, Part 3, 23 pp.

ALAM, M.K. AND M.M. HOSSAIN, (1988), Sediment transport in the River Jamuna, Jr. Institution of Engineers, Bangladesh, Vol. 16, No. 2, pp. 17-26

ALLEN, J.R.L. (1982) Sedimentary Structures: their character and physical basis, Elsevier, Amsterdam, 539 pp.

ASHLEY, G.M. (1990) Classification of large-scale subaqueous bedforms: a new look at an lod problem. Journal of Sedimentary Petrology, 60, 1, 160-172

BAAS, J.H. (1994) A flume study on the development and equilibrium morphology of small-scale bedforms in very fine sand, Sedimentology, 41, 185-209

BAGNOLD, R.A. (1966), An approach to the sediment transport problem from general physics, Geological Survey Paper 422-I

BANGLADESH WATER DEVELOPMENT BOARD (BWDB), 1972, 'Sediment Investigation in the main rivers of Bangladesh', BWDB Water Supply Paper No. 359.

BARI, M.F. and M.K. ALAM, (1979), Sediment transport in the Ganges, Journ. Institution of Engineers, Bangladesh, Vol. 7, No. 4, pp. 13-19

BASET SARKER, A., G.J. KLAASSEN AND M.Th. RADU (1984), Reducing sediment problems of the Ganges-Kobadak irrigation project (Bangladesh), Prepared for Intern, Conf. on "Channels and channel control structures", Southampton

BENNETT, S.J. & BEST, J.L. (1995) Mean flow and turbulence structure over fixed two-dimensional dunes: implications fo sediment transport and bedform stability, Sedimentology, 42, 491-513

BEST, J.L. (1993) On the interactions between turbulent flow structure, sediment transport and bedform development: some considerations from recent experimental research. In: Clifford, N.J., French, J.R. & Hardisty, J. (eds), Turbulence: Perspectives on Flow and Sediment Transport Wiley and Sons, Chichester, UK, 61-92

BEST, J.L. (1996) The fluid dynamics of small-scale alluvial bedforms, In: Carling, P.A. and

BEST, J.L. & BRIDGE, J.S. (1992) The morphology and dynamics of low amplitude bedwaves on upper-stage plane beds and the preservation of planar laminae, Sedimentology, 39, 737-752

BRISTOW, C.C., (1987), Brahmaputra River: channel migration and deposition, The Society of Economic Paleontologists and Mineralogists, pp. 63-74

CBJET(1991), Project on the Brahmaputra River in Bangladesh, Report of the China-Bangladesh Joint Expert Study Report on Flood Control and River Training Team, Vol. 1, Analysis of hydrology and river morphology of the Brahmaputra River, Vol. 2 General plan and design of embankment along the Brahmaputra river, Vol. 3 General plan and design for realignment project of the Brahmaputra river

CHANG, H.H. (1988), Fluvial processes in river engineering John Wiley and Sons, Singapore

CHINA-BANGLADESH JOINT EXPERT TEAM (CBJET), 1991, 'Study Report on Flood Control and River Training Project on the Brahmaputra River in Bangladesh'.

COLEMAN, J.M. (1969), Brahmaputra River: channel processes and sedimentation. Sedimentary Geol., Vol.3, Nos.2-3, pp. 129-239

CURRAY, J.R. AND MOORE, D.J., 1974, 'Sedimentary and tectonic processes in the Bengal deep-sea fan and geosyncline. In Burk, G.A. and Drake, C.L., (eds), Geology of continental margins, New York, Springer Verlag, pp. 617-627.

CURRAY, J.R., EMMEL, F.J., MOORE, D.G. AND RAIT, R.W., 1982, 'Structure, tectonics, and geological history of the northeastern Indian Ocean. In Narin, A.E, and Stehli, F.G., (eds), The ocean basins and margins, Vol. 6, New York, Plenum Press, pp. 399-450.

CURRAY, J.R. AND EMMEL, F.J., 1985, Bengal fan, Indian Ocean. In Bouma, A.H., Normark, W.R., and Barnes, N.E., (eds), Submarine fans and related tubidite systems. New York, Springer Verlag, pp. 107-112.

DANISH HYDRAULIC INSTITUTE, 1996, Mathematical morphological model of Jamuna River, Jamuna Bridge site, Dhaka, Bangladesh

DALRYMPLE, R.W. & RHODES, R.N. (1995) Estuarine dunes and bars, in: Perillo, G.M.E. (ed), Geomorphology and Sedimentology of Estuaries, Elsevier, 359-422

DAWSON, M.D. (eds), Advances in Fluvial Dynamics and Stratigraphy, John Wiley and Sons, Chichester, UK, 68-125

DELFT HYDRAULICS/DHI (RSP), 1995, 'Sediment rating curves and balances', Special Report 19.

DE VRIES et al. 1990,

ENGELUND, F. & E. HANSEN (1967), A monograph on sediment transport in alluvial streams, Copenhagen, Teknisk Vorlag

EYSINK, W.D., 1983, 'Basic consideration on the morphology and land accretion potentials in the estuary of the Lower Meghna River', Land Reclamation Project, Bangladesh Water Development Board, LRP Technical Report # 5, pp. 85.

FAO-UNSF Second Hydrological Survey in East Pakistan (April 1969), Sediment Investigations.

FAP25 (1993), Flood Hydrology Study, Annex 2, Krueger Consult/BCEOM, Prepared for FPCO

FRENCH, R.H. (1987) Open-channel hydraulics, Mc-Graw Hill International Editions, Civil engineering series, Singapore

FRENCH ENGINEERING CONSORTIUM, 1989, 'Feasibility study for flood control in Bangladesh, Vol. 2.

GALAPPATTI, R. and Vreugdenhill, 1982,

GALAPPATTI, R. 1983, A depth-integrated model for suspended load, Communications on Hydraulics 83-7, Dept. Civil. Eng. Delft University, The Netherlands

GALAPPATTI, R. (1993) One dimensional morphological modelling in Bangladesh: methodology and constraints. International workshop on morphological behaviour of major rivers in Bangladesh, Dhaka, Bangladesh.

GLYSSON, G.D. (1987), Sediment transport curves, U.S. Geological Survey, Open file report 87-218.

GOSWAMI, D.C.(1985), Brahmaputra River, Assam, India: basin denudation and channel aggradation, Water Resources Research, Vol. 21, No. 7, pp. 959-978.

GRAF,W.H., 1971, Hydraulics of sediment transport, Mc Graw Hill, New York, USA

HALCROW (1992), River Training Studies of the Brahmaputra river, First Interim Report, Main Report, Annex 4: Geomorphology, Annex 6: River Engineering

HASKONING/DELFT HYDRAULICS/BETS (1992), Meghna River Bank Protection Short Term Study, Volume II, Annex A Hydrology

HASKONING/DELFT HYDRAULICS/BETS (1992), Meghna River Bank Protection Short Term Study, Volume II, Annex B River Morphology

HOLEMAN, J.N., (1968) 'The sediment yield of the major rivers of the World', Water Resources Research, Vol, 14, No. 4, pp. 737-747.

HOSSAIN, M.M., (1992), Total sediment load in the Lower Ganges and Jamuna, Journ. Institution of Engineers, Bangladesh, Vol. 20, No. 1-2, pp. 1-8.

INTERNATIONAL Engineering Company, 1964, East Pakistan Water and Power Development Authority Master Plan, San Francisco, USA

ISPAN, (1995), A Study of Sedimentation in the Brahmaputra-Jamuna Floodplain

JACKSON, R.G. (1976) Sedimentological and fluid dynamic implications of the turbulent bursting phenomenon in geophysical flows, Journal of Fluid Mechanics, 77, 531-560

JANSEN, P.PH. ET AL., (1979), Principles of river engineering, the non-tidal alluvial river, Delftse Uitgevers Maatschappij, Delft, The Netherlands

JULIEN, P.Y. & KLAASSEN, G.J. (1995), Sand-dune geometry of large rivers during flood, Journal of Hydraulic Engineering, 121, 657-663

KHAN, H.R., (1973), Effect of sediment discharge and slope on alluvial river patterns, Jr. Institution of Engineers, Bangladesh, Vol. 1, No. 2-3, pp. 51-58.

KHAN, H.R. (1975), Roughness coefficient for some rivers in Bangladesh, Journ. Institution of Engineers, Bangladesh, Vol. 2, No. 4, pp. 105-112.

KLAASSEN, G.J. (1991),

KLAASSEN, G.J. (1994), River dynamics : Volume 1 Introduction into River Dynamics, IHE Delft, Lecture notes

KLAASSEN, G.J. (1995), Lane's balance revisited, Proc. 6th Intern. Sedimentation Symp., New Delhi (India), pp. 671-686

KLAASSEN, G.J., E. MOSSELMAN and H. BRUHL (1993), On the prediction of planform changes in braided rivers, Proc. Intern. Conf. Hydroscience and engineering, Washington, USA

KLAASSEN, G.J. & K. VERMEER (1988), Constriction scour in large braided rivers, Proc. Intern. Conf. on Fluvial Hydraulics, Budapest, Hungary

KLAASSEN, G.J., OGINK, H.J.M. AND VAN RIJN, L.C. (1986), Delft Hydraulics Research on bedforms, resistance to flow and sediment transport, in: Proceedings 3rd International Symposium on River Sedimentation, 25 pp

KLAASSEN, G.J., VERMEER, K. & UDDIN, N. (1988), Sedimentological processes in the Jamuna (Lower Brahmaputra) river, Bangladesh, in: Proceedings International Conference on Fluvial Hydraulics, Budapest, Hungary, 381-394

KOSTASCHUK, R.A. & ILERSICH, S.A. (1995), Dune geometry and sediment transport: Fraser River, Britisch Colombia. In: Hickin, E.J. (ed) River Geomorphology, John Wiley and Sons, Chichester. 19-36

KUEHL, S.A., HARIU, T.M. AND MORE, W.S., (1989), Shelf sedimentation off the Ganges-Brahmaputra River System: Evidence for sediment bypassing to the Bengal Fan. Geology, 17:1132-1135

LANE, E.W. (1955), The importance of fluvial geomorphology in hydraulic engineering, Trans. Am. Soc. of Civil Engrs., pp. 745-1 - 745-17

LELIAVSKI, S. (1955), An introduction to fluvial hydraulics, London, Constable and Comp. Ltd.

LEOPOLD, L.B., M.G. WOLMAN and J.P. MILLER (1964), Fluvial processes in geomorphology, San Francisco, W.H. Freeman and Cy.

LUKANDA, M., J.J. PETERS, P. SWARTENBROEKX, P. and P. CORNET (1992), Applicability of sediment transport theories to large sandbaed rivers, Proc. Intern. Symp. on River Sedimentation, Karlsruhe (FRG), pp. 327-337

LYN, D.A., (1993), Turbulence measurements in open-channel flows over artificial bed forms, J. Hydraulic Engineering, 119, 306-326

MACKIN, J.H. (1937), Erosional history of the Big Horn Basin, Wyo., Geol. Soc. Am. Bull., Vol. 48, pp. 813-894

McLEAN, S.R., NELSON, J.M. & WOLFE, S.R. (1994) Turbulence structure over two-dimensional bedforms: implications for sediment transport. j. Geophysical Research, 99, 12 729-12 747

MIERLO, M.C.L.M. VAN & RUITER, J.C.C. (1988), Turbulence measurements above artificial dunes. Rept. TOW A55 Q789, pp. 1-42. Delft Hydraulics

MILLIMAN, J.D. AND SYVITSKI, J.P.M., (1992), Geomorphic/tectonic control of sediment discharge to the ocean: the importance of small mountainous rivers. Journal of Geology, 100:525-544

MONSUR, M.H. (1995), An introduction to the Quaternary geology of Bangladesh, Publ. Rehana Akhter, Dhaka, Complimentary Research of IGCP 347

MORGAN J.P. AND McINTYRE W.G. (1959), "Quaternary Geology of Bengal Basin, East Pakistand and India", Bulletin of the Geological Society of America, Vol. 70, pp. 319-342

MPO, (1987), Technical Report No. II. Floods and Storms. HARZA Engineering Company International

NEDECO (1967), East Pakistan Inland Water Transport Authority, Surveys of Inland Waterways and Ports, Volume III, Hydrology and Morphology, Part B Hydrological and morphological phenomena, and Part C Improvement of waterways and inland ports

NELSON, J.M., McLEAN, S.R. & WOLFE, S.R. (1993), Mean flow and turbulence fields over two-dimensional bedforms. Water Resources Research, 29, 3935-3953

OGINK, H.J.M. (1985), The effective viscosity coefficient in 2-D depth-averaged flow models, 21st congress of the International Association for hydraulic research, Melbourne, Australia

OGINK, H.J.M. (1988), Hydraulic roughness of bedforms, Delft Hydraulics Report M2017

PARKER, 1990

PETERS, J.J. (1993), Morphological studies and data needs, Proceedings International Workshop on Morphological Behaviour of the Major Rivers in Bangladesh, Dhaka. 12pp

PETERS, J.J. (1977), Sediment transport in the Zaire River, In NIHOUL, J.C.J. (1977), Bottom turbulence, Proc. 8th Intern. Liege Colloquium on Ocean Hydrodynamics, Vol. 19, pp. 221-236

PETERS, J.J. (1978), Discharge and sediment transport in the braided zone of the Zaire estuary, Netherlands Journal of Sea Research, Vol. 12, no. 2/3, pp. 273-292

PETERS, J.J. (1981), Water and sediment gauging in the Zaire (Congo), Proc. XIXth IAHR Congr., New Delhi (India), Subject A(b), Paper no. 8, pp. 173-182

PETERS, J.J. (1988), Etudes recente de la navigabilite, Academie royale des Sciences d'Outre-Mer, Proc. Symposium "L'Acces maritime au Zaire", pp. 89-110 + 25 fig.

PETERS, J.J. and A. GOLDBERG (1989), Flow data in large alluvial rivers, Proc. Conf. on Computational modelling and experimental methods in hydraulics (Proc. Hydrocomp '89, Dubrovnik, Yugoslavia), Elsevier, London, pp.77-86

PETERS, J.J. (1994), Report on seventh mission of the Project Advisor, Flood Plan Coordination Organization, Dhaka, Bangladesh

RAUDKIVI, A.J. (1966), Bedforms in alluvial channels, Journal of Fluid Mechanics, 26, 597-614

RAUDKIVI,A.J., 1976, Loose boundary hydraulics, Pergamon Press, Oxford

RIBBERINK, J.S., 1987, Mathematical modelling of one-dimensional mrphological changes in rivers with non-uniform sediment.

RIVER SURVEY PROJECT FAP24 (1993), Selection of Study Topics Phase 2, DELFT HYDRAULICS/Danish Hydraulic Institute, FAP24, Study Report 1, Prepared for FPCO

RIVER SURVEY PROJECT FAP24 (1994), Morphological Studies Phase 1, DELFT HYDRAULICS/Danish Hydraulic Institute, FAP24, Study Report 3, Prepared for FPCO

RPT/NEDECO/BCL, 1987, Jamuna bridge Appraisal Study. Phase 1, Final Report

RPT/NEDECO/BCL (1987), Jamuna Bridge Study Phase 1: Characteristics and configuration, Annex C - Hydrology, River morphology and River Engineering

RPT/NEDECO/BCL (1989a), Jamuna Bridge Study, Phase II Study, Feasibility Report, Annex A: Hydrology

RPT/NEDECO/BCL (1989b), Jamuna Bridge Study, Phase II Study, Feasibility Report, Annex B: River Morphology

RPT/NEDECO/BCL (1990), Jamuna Bridge Project, Phase II Study, River Training Works, Design Report, Volume II: Model investigations, RPT/NEDECO/BCL, prepared for JMBA

RRI/L&P/CNR/DELFT HYDRAULICS (1993), Final report planning study, Vol. II: Annex 1 - River training and Morphological response, Annex 2 - River morphology, Bank Protection and River Training (AFPM) Pilot Project

RIJN, L.C. van (1984), Sediment transport, (a) Part I Bed load transport, (b) Part II Suspended load, Journ, Hydr. Engng., ASCE, Vol. 110, (a) pp. 1431-1456, (b) pp. 1613-1641

RIJN, L.C. VAN (1984), Sediment transport, part III: bedforms and alluvial roughness, Journal of Hydraulic Engineering, 110, 1733-1755

RIJN, L.C. VAN (1990), Principles of fluid flow and surface waves in rivers, estuaries, seas and oceans, Aqua Publications, The Netherlands

RIJN, L.C. VAN (1993), Principles of Sediment Transport in Rivers, Estuaries and Coastal Seas, Aqua Publications. Amsterdam

RIJN, L.C. VAN (1993), Principles of sediment transport in rivers, estuaries and coastal areas, Aqua Publications, Amsterdam

SCHUMM, S.A. & B.R. BRINKLEY (1994), The variability of large alluvial rivers, ASCE, ISBN 0-7844-0054-7, 467 pp.

SEGALL, M.P. AND JUEHL, S.A., (1992) Sedimentary processes on the Bengal continental shelf as revealed by clay-size mineralogy. Continental Shelf Research, 12:517-541

SOGREAH/HALCROW/LAHMEYER (1992), Jamalpur Priority Project Study, Char study report Vol.1

SOUTHARD, J.B. & BOGUCHWAL, L.A. (1990), Bed configurations in steady unidirectional water flows. Part 2. Synthesis of Flume data, Journal of Sedimentary Petrology, 60, 5, 458-479

THORNE, C.R. (1993), Planform pattern and channel evolution of the Brahmaputra River, Bangladesh, Proc. Meeting Braided Rivers: Form, Process and Economic Applications, 1992, Geological Society, London

THORNE, C.R. AND A.P.G. RUSSEL, (1993), Geomorphic study of bankline movement of the Brahmaputra river in Bangladesh, Proc. 5th annual seminar of Scottish Hydraulics Study Group on sediment transport processes and phenomena, Edinburgh, U.K.

WAN, Z. (1983), Some phenomena associated with hyperconcentrated flow. In: Mutlu Sumer, B. & Müller, A (eds) Mechanics of Sediment Transport, Proceedings of Euromech 156, Balkema, Rotterdam, 189-194

WINKLEY, B.R., E.J. LESLEIGHTER & J.R. COONEY (1994), Instability problems of the Arial Khan River, Bangladesh, In: SCHUMM, S.A. & B.R. BRINKLEY (1994), The variability of large alluvial rivers, ASCE, ISBN 0-7844-0054-7, pp. 269-284

WIJBENGA, J.H.A. & G.J.KLAASSEN (1981), Changes in bedform dimensions under unsteady flow conditions in a straight flume, Proc. 2nd Intern. Conf. on Fluvial Sediments, Keele, U.K., 14 pp (also Delft Hydraulics Publ. 260)

YALIN, M.S. (1992), River Mechanics, Pergamon Press, 219 pp

YANG C.T. and Stall, J.B. (1976), Applicability of unit stream power equations, Journal Hydraulic Division, ASCE, Vol. 102, no. HY5, pp. 559-568.

YANG, C.T. (1993), Incipient motion and sediment transport, Journ. Hydr. Div., ASCE, Vol. 99, no. HY10, pp.

YOUNT, J.C., (1990), Accelerated exploration for mineral resources and modernization of the Geological Survey of Bangladesh, phase II, USGS Internal Report: Coastal Mapping Project.