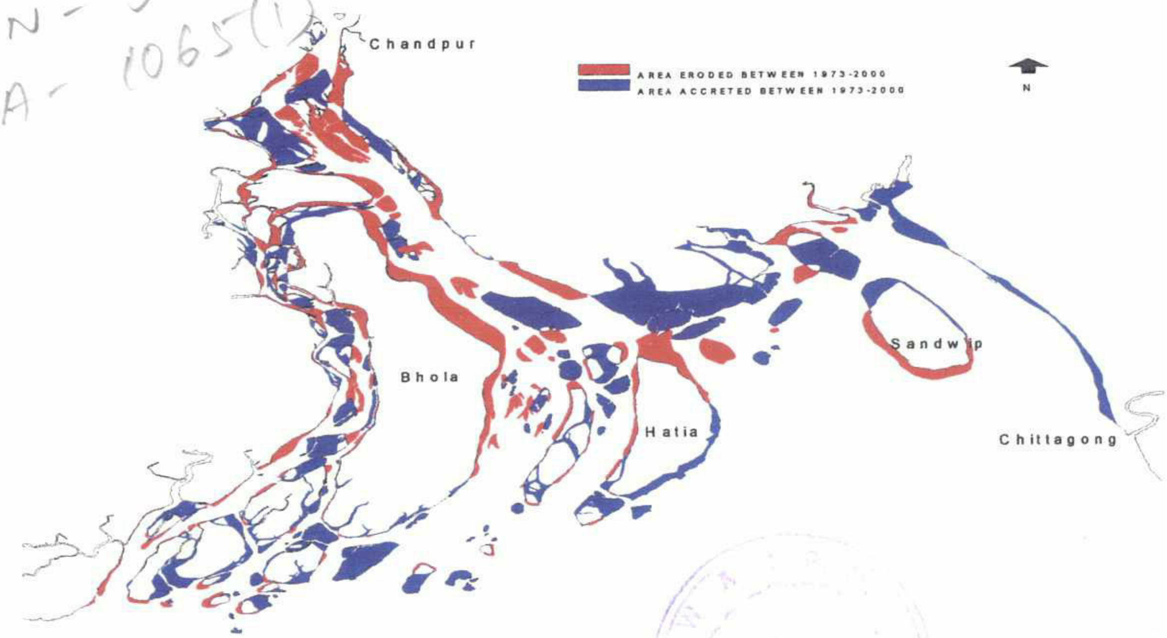
MINISTRY OF WATER RESOURCES

BANGLADESH WATER DEVELOPMENT BOARD

M E S II

Meghna Estuary Study

HYDRO-MORPHOLOGICAL DYNAMICS OF THE MEGHNA ESTUARY



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1 INTRODUCTION

1.1 Meghna Estuary Studies

The Meghna Estuary Studies (MES I and MES II) are supporting studies under FAP 5B of the Flood Action Plan (FAP). The Flood Action Plan (FAP) was initiated after the disastrous floods in Bangladesh in 1987 and 1988, and it was a co-ordinated action to study the flood problems of Bangladesh.

The project has been implemented under a co-operation programme between the Governments of Bangladesh, the Netherlands and Denmark (MES I). The executing agency is the Bangladesh Water Development Board (BWDB). The co-ordination with other projects under the Flood Action Plan has been maintained by the Flood Plan Co-ordination Organisation (FPCO), which evolved into WARPO during the process.

The main goals of the Meghna Estuary Studies (MES) are as follows:

- to collectively gather hydrological and morphological data,
- to increase knowledge of the hydraulic and morphological processes in the Meghna Estuary system,
- to develop appropriate techniques for efficient land reclamation and effective river bank protection, and
- to provide a Master Plan and Development Plan for the estuarine area.

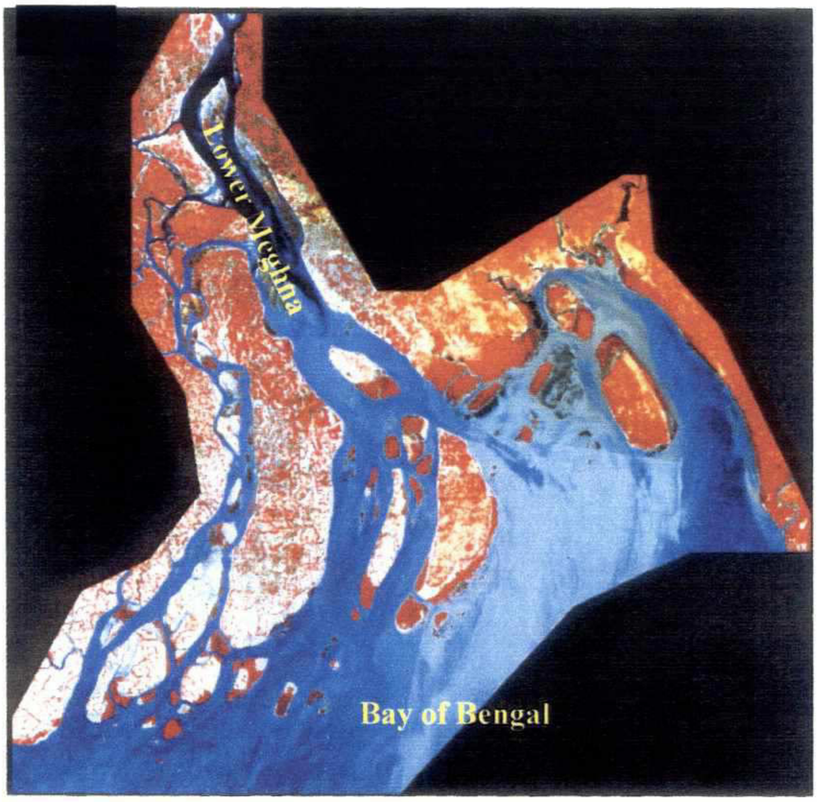
1.2 Objectives and Scope of the present study

The Meghna Estuary is a very dynamic estuarine and coastal system. Here, one of the world's greatest rivers, the Lower Meghna River finds its way to the Bay of Bengal (Figure 1). The Lower Meghna conveys the combined flows of the Brahmaputra (called in Bangladesh Jamuna), the Ganges, and the Upper Meghna. The sediment discharge from the Lower Meghna River is the highest (Coleman, 1969) and the water discharge the third highest, of all river systems in the world (Milliman, 1991). Erosion and accretion rates are high and the area is periodically subject to severe storms and cyclones, these latter accompanied by tidal bores and storm surges.

The knowledge about the physical processes and morpho-dynamic behaviour of the Lower Meghna Estuary system is still fairly limited. A complicated interplay between the forces of the river, tide and the waves creates a complex pattern of sediment displacement in the estuary. Large quantities of sediment are transferred continuously towards the shallow coastal region of Bengal. Since almost no sediment is exchanged with the deeper parts of the Bay of Bengal, the overall sediment budget is determined by the process of continuous redistribution of sediment in the river system upstream. The displacement of sediment is a part of a continuous process of the estuarine-landscape striving to achieve dynamic equilibrium between the physical shape (morphology), and the continuously changing river discharge conditions and tidal flows.

To enhance the knowledge of the complex morphological processes in the Meghna Estuary, a morphological study has been carried out within the framework of the Meghna Estuary Studies in the period 1995 to 2001.

Figure 1 The Meghna Estuary



The main objectives of the present study are as follows:

- to improve the understanding of the estuarine and coastal morphological behaviour and hydro-morphological processes with the aid of remote sensing imageries, historical bathymetric maps and field data on the processes of geomorphological development
- to assess long-term changes in coastal morphology and to discern patterns and tendencies
- to improve the knowledge and understanding of land formation and char development.

This report focuses on the spatial and temporal pattern of erosion and sedimentation and morphological changes of the Meghna Estuary study area. The presented results are based on analyses of remote sensing imageries, bathymetric data and historical coastline maps, and field surveys and numerical modelling.

The report outlines the well-documented changes in the system's geomorphology over the last centuries and recent decades. A morphological prediction of land formation and char development in the Meghna Estuary system on an intermediate time scale (20-30 years) is given based upon an extrapolation of present planform evolution trends and on the knowledge and understanding of the dominant hydrodynamic and morphological processes.

Present knowledge concerning the morphological dynamics of the Meghna Estuary is summarised in this report. More in-depth information is provided in the background document (MES, 1998).

2 APPROACH AND METHODOLOGY

2.1 Approach

A crucial element in the development of long-term plans for human interference in estuarine or coastal waters is the prediction of the impact on the bathymetry and coastlines. In recent years, substantial effort has been put into the numerical modelling of hydraulic and morphological changes in complex situations in the fluvial and coastal areas of Bangladesh. For estuaries and coastal waters, however, this has not yet resulted into sufficiently reliable predictions at mid- and long-term. On the other hand, statistical and empirical techniques applied to field data are useful to extrapolate existing trends, but they can hardly be used as sole predictor if these trends are changing (e.g. due to human interference catastrophic events, sea level rise). In the present study two approaches: numerical modelling and phenomenological approach (it uses statistical/empirical techniques and physical interpretation to identify trends and empirical input/output relations), have been combined to increase the reliability of the predictions at mid- and long-term.

2.2 Methodology

2.2.1 Data collection and analysis

To increase the understanding of the processes that govern the morphological development of the Meghna Estuary, an extensive data collection has been carried out during MES. Data from previous studies (mainly Land Reclamation Project) was recovered, and new data collected. Measurements included amongst others: bed and water levels, current velocities, discharges and salinities. Bed and suspended sediment samples were collected and analysed. Bathymetric surveys were carried out at regular intervals to obtain information on changes of tidal channels and to set up a 2D numerical model of the area. Satellite images were purchased and analysed to examine the changes to the shoreline.

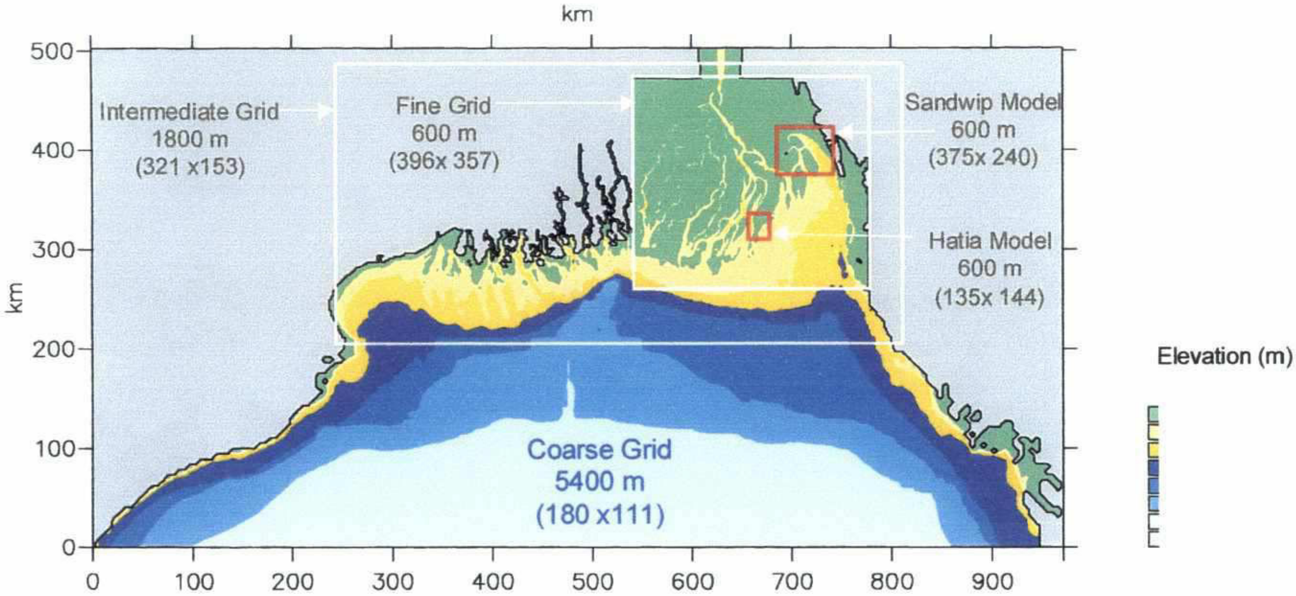
2.2.2 Numerical modelling

A good description of hydraulic phenomena that occur in the estuary is of immense value to understand the complex morphologic dynamics of this area. A well-calibrated 2D numerical model with a sufficient resolution is able to provide this information.

During MES a 2D model of the study area has been developed (SWMC, 2000) using MIKE-21 software. This model consists of several submodels. The resolution varies from 5400m x 5400m and 1800m x 1800m in the Bay of Bengal, through 600m x 600m in the Meghna Estuary and 200m x 200m in the 2 areas of special interest: Hatia-South / Nijhum Dwip area, and Hatia-North / Sandwip area . The model has been regularly updated with the newest bathymetric information obtained from several bathymetric surveys during the course of MES.

Model simulations were used to study the dominant hydraulic and morphological conditions that shape the estuary. To determine the dynamic behaviour of the estuary, simulations were carried out for characteristic conditions (neap tide / spring tide and monsoon / dry period).

Figure 2: Nested 2D model



2.2.3 Remote Sensing

Satellite images were used to assess the morphological changes in the study area. In the present study, 8 sets of four Landsat frames taken in the period between 1973/74 and 2000 were used. The ground resolution of the image sets varies from approximately 80x80 m grid for the image sets of prior to 1990 and 30x30 m grid for the more recent images. Each of the satellite images was georeferenced by using well-distributed ground control points. After georeferencing, a single satellite mosaic covering the entire Meghna Estuary (from the northern border at Chandpur to the seaward border at Chittagong) was prepared for each period from the four frames using the Bangladesh Transverse Mercator (BTM) as the map projection.

The digital satellite images were classified using image-processing techniques to enable the assignment of land and water cover types that were associated with erosion and accretion processes. The major categories of classes that evolved included: land, water, and mud flats (intertidal area).

2.2.4 Analysis of Bathymetric Data and Historical Coastline Maps

The cross-sectional analysis of the channels is based on bathymetric data. Echo soundings have been carried out in a number of well-defined cross-sections and areas in the Lower Meghna Estuary area since the early 80s. These cross-sections give a good coverage of the entire estuary. During MES, yearly hydrographic surveys of selected areas were carried out. In 2000, the whole study area was surveyed to prepare an accurate bathymetric map of the estuary.

The depth data has been used to study cross-sectional developments and changes in sediment volume throughout the period 1981 - 2000. Estimates of the sediment volume have been based on calculations of interpolated depth values using 250x250 m grid squares derived from the echosounding maps. The spatial variability of changes in sediment volume in the Meghna Estuary System has been studied in detail in the pilot areas Nijhum Dwip-Hatia and Urir Char-Char Pir Baksh.

The channel shifting processes in the cross-sections are characterised by the migration rate of the deepest part of the channel, known as the thalweg-line.

The rate and distribution of shoreline erosion and accretion is estimated from the changes to the shorelines derived from aerial photographs of 1956-1957 and satellite images from 1973 to 2000.
The long term morphological changes in the entire coastal area over the last two centuries are based on an analysis of the coastal area maps of 1770s and 1780s (made by the British Geographer James Rennell). These results are compared with findings of (recent) investigations by Eysink (1983), Leedshill-De Leuw Engineers (1968) and Allison (1998).

2.2.5 Analysis of Flow and Sediment Transport Data

The tides have been studied on the basis of water level data collected over the last decade at several gauge and water level stations in the Meghna Estuary Study Area. Statistical analysis of long term water level series have been executed to compute frequency and duration curves of daily water levels, annual maximum and minimum high and low water levels. Discharge measurements have been taken mostly during pre- and post-monsoon along a number of standard flow transects.

Estimates of sediment transport patterns in the system mostly during pre- and post-monsoon are based on sediment transport measurements taken along the standard flow transects. Sediment concentration samples at different heights in the water column as well and bottom samples were taken regularly to record sediment transport and sediment characteristics along the transect. In the laboratory the sediment content and the granulometry of the bottom samples and sediment concentration samples were determined.

2.2.6 Prediction of morphological development

An attempt to predict the morphological development of the Meghna Estuary has been undertaken. As the processes shaping the estuary are of very complex nature and their long term effects are still not very well understood, a process-based prediction is not yet possible. Therefore, a statistical method has been developed to predict the changes in the project area at mid- and long term (15 and 30 years). The movement of shorelines derived from satellite images has been statistically analysed and extrapolated. This way the future position of the shoreline was estimated. The estimates have been compared with the actual trends observed in the estuary. Where required, adjustments to the procedure have been applied, based on the expert knowledge of the area, to insure that the prediction would be in agreement with the processes, which actually take place.

3 ENVIRONMENTAL CONDITIONS IN THE MEGHNA ESTUARY

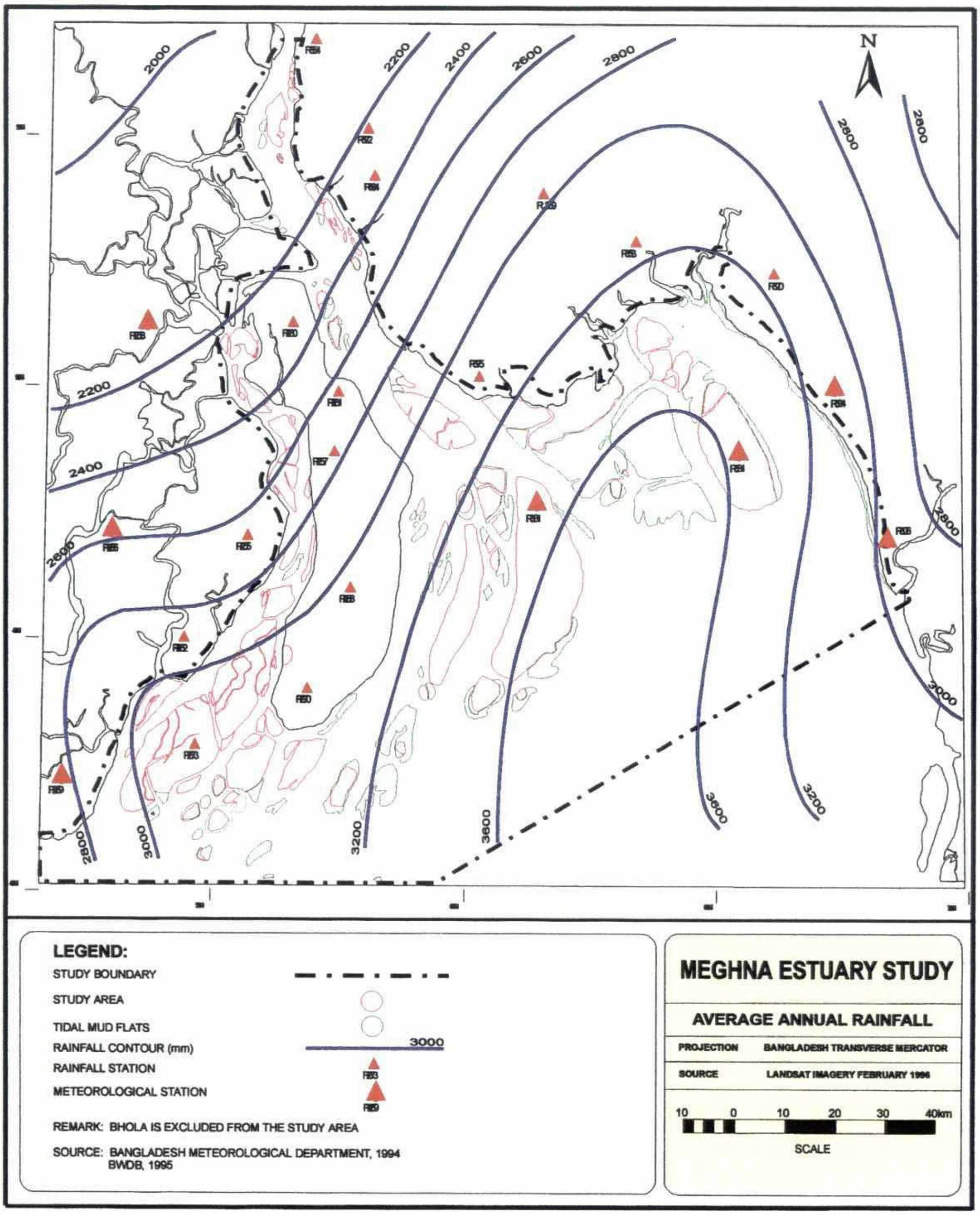
The process of natural development of the Meghna Estuary is governed by the environmental conditions. Rainfall in the catchment is drained by the rivers to the Bay of Bengal. Heavy monsoon rains cause high water levels in the rivers that flood the land, while very high discharge brings enormous amounts of sediments down the rivers to the estuary. The processes of accretion and erosion are strongly influenced by the changes in the river flow, but also by waves. Winds drive the circulation of water in the estuary while cyclones cause high waves and (sometimes catastrophic) floods. Tide coming from the Indian Ocean determines the variation in water levels and the flow in the estuary. Saline seawater penetrates the estuary up to Chandpur during the dry season, while during monsoon the estuary is merely filled with fresh water. Changes in salinity contribute to flocculation and deposition of silts in the estuary.

Knowledge of environmental conditions in the Meghna Estuary is therefore of crucial importance for understanding the morphological processes. These conditions are described in the following chapters.

3.1 Precipitation

The climate of Bangladesh is tropical, with a hot, humid summer (March to June), a rainy monsoon (June to September) with predominantly south-westerly monsoon winds, and a dry, relatively cool winter (September to June) with predominantly north-westerly monsoon winds. The catchment of Brahmaputra-Jamuna-Meghna receives annually an average of 1,500 mm of rainfall, most of which falls during the monsoon months but there are great variations in rainfall across the basin. The average rainfall in the coastal area is about 2000-3600 millimeters per year (Figure 3).

Figure 3: Annual Rainfall in coastal area in Bangladesh



3.2 Wind

The wind regime along the Bay of Bengal shows a typically seasonal variation between the dry season (November-March) and the monsoon season (June-September). During the dry season the prevailing winds are calm and offshore. The prevailing winds during the monsoon season are from the S-SE direction, with an average velocity of about 8-12 m/s. During severe storms and cyclones, very high wind velocities can occur. The highest wind speed, reported during the April 1991 cyclone (CERP-II, 2000), is 62.5 m/s, corresponding to 225 km/h. Most cyclones occur during April-May and October-November, which are the transitional periods between the dry season and the monsoon season.

3.3 Tides

The water movement in the Meghna Estuary is governed by various phenomena. Generally, the tidal motion dominates. However, also river discharges of fresh water play an important role, especially during the monsoon. Due to amplification and deformation of the tidal wave, the tidal pattern in this project area is complex.

The tidal wave from the Indian Ocean travels through the deep Bay of Bengal and approaches the coast of Bangladesh approximately from the south. It arrives at Hiran Point and at Cox's Bazar at about the same time. The extensive shallow area in front of the large delta causes some refraction and distortion. Also some reflection of the tidal wave occurs contributing to a significant amplification of the tidal wave in Hatia and Sandwip Channels. North of Sandwip Island and Urir Char occurrence of tidal bores has been observed.

The water level variation is dominated by a semi-diurnal tide with a considerable variation from neap to spring tides. In the entire coastal area the variation of amplitude from neap to spring is from 0.6 to 1.4 times the average amplitude (FAP 4).

In the western part of the coastal area of Bangladesh the average tidal range is approximately 1.5 m. In the area around Sandwip, the tidal range is significantly higher with an average range of over 4 m. According to the classification of tides proposed by Davies (1964) the tidal range in the study area can be classified as follows (see Figure 4):

- Tetulia river - Chandpur : *Micro-tidal* - tidal range 0-2 m
- South Bhola - Hatia North: *Meso-tidal* - tidal range 2-4 m
- East Hatia-Sandwip: *Macro-tidal* - tidal range >4m.

The maximum high-tide water level is about 6.5 m above PWD and more during cyclone surges.
The maximum current velocities vary from approximately 0.1 - 4 m/s in the tidal channels to about 0.2 - 0.5 m/s in the shallow areas on the mud flats and chars. The amplitude of the tidal velocity shows a neap-spring tide characteristics. During spring tide the flow velocities are normally higher than during neap conditions. Although velocity measurements during monsoon are rare it can be assumed that the velocities are higher than during the dry season.

3.4 Waves

No wave heights have been recorded during severe storms until now. Wave measurements over the period December '96 - March '97 indicate that the wave heights in the landward part of the project area don't exceed 0.4 m due to the moderate wind conditions.

Wave models indicate, that under the prevailing S-SE winds (with a average wind speed of about 8 m/s), the average significant wave height varies between 0.6-1.5 m in the nearshore zone to 0.1-0.6 m in the landward part of the project area. In the dry season the waves are generally less than 0.6 m with peak periods of 3 - 4 seconds. During the monsoon season wave heights exceed 2 m with periods greater than 6 seconds.

Higher waves may occur mainly in the pre and post monsoon periods during cyclones. In a study carried out under Second Coastal Embankment Rehabilitation Project (CERP-II, 2000), the following estimates are given for the offshore wave heights (Table 1):

Table 1. Offshore Significant Wave Heights (m)

Return Period (years)	Wind Speed (m/s)	Water depth (m)		
		20	15	10
5	46.6	7.6	6.1	4.5
10	53.2	8.2	6.6	4.9
25	60.9	9.0	7.2	5.3
70	68.5	9.6	7.8	5.7
100	71.0	9.9	7.9	5.9

The maximum wave height is limited by the water depth. Depth of 20m is representative for a deeper part of the continental shelf. In the estuary, depths are generally lower. Taking into account the cyclone surge, the water depth in the estuary will be less than 5-10m. Waves higher than 0.6-0.8 times the local water depth[1] will break due to insufficient depth. Still, waves higher than 5m can be expected in the outer part of the estuary during a cyclone.

[1] in CERP-II (2000) report a value of 0.9 times water depth at the toe of embankment is suggested for design of embankments

Figure 4: Mean Tidal Range in the Lower Meghna Estuary and Coastal Area

3.5 Salinity intrusion

Salinity data from LRP and MES indicate an enormous seasonal effect due to the influence of huge fresh water discharge from the Lower Meghna River on the horizontal distribution of salinity in the estuary. This distribution is strongly influenced by the fresh water flow in the Lower Meghna River.

Figure 5 shows the movement of the freshwater boundary during the year. During the monsoon (June-September), nearly the whole estuary is filled with fresh water (salinity lower than 2 ppt). A salinity isoline (iso means equal) in Figure-5 indicates the salinity is the same over the whole length of the line and also that the salinity is more than the indicated for that line more seaward of the isoline. Only in the southeast part of the estuary, south of the Sandwip Channel, higher salinities are found. From about 30-40 km south of the mouth of the Karnafuli River towards the deeper part of the Bay, the estuary remains stratified during monsoon. There, a stratified zone with a width of approximately 100 km develops, with a layer of brackish water moving with the tide over a salt wedge. This zone forms a transition between the fresh water in the estuary and the more saline water coming from the Bay of Bengal, with salinity of approximately 20 ppt.

During the dry season (October-March) flow in the Meghna River gradually decreases, and saline water penetrates the estuary. The penetration of saline water ends in the river's mouth. North of Char Gazaria salinities of around 1 ppt are found. The salinities in the main river channels, East and West Shabazpur Channel, are noticeably lower (between 6 ppt and 8 ppt) than in the eastern part of the estuary, with values between 10 ppt and 20 ppt. Salinity measurements during February-March, 2000 (dry season) show that water in the Meghna Estuary is well mixed due to strong turbulent flow. Nearly all measured profiles within the MES boundary are constant over depth and no evidence stratification was found in the dry season. The exchange of water with the deeper parts of the Bay of Bengal is clearly insufficient to bring sea water into the estuary, and the salinities in the area never approach normal sea water salinity (34.5 ppt) but always remain distinctly lower. The system is well mixed by the strong tidal currents, with velocities up to 3-4 m/s. Salinity fronts are observed in the East Shabazpur Channel, with salinity rapidly changing over a distance of a few meters around slack water, when flood channels transport the more saline water up the river while in the adjacent ebb channels the less saline water still flows towards the sea.

Figure 5a&b: Progress of salinity intrusion during dry season and Retreat of saline water during monsoon

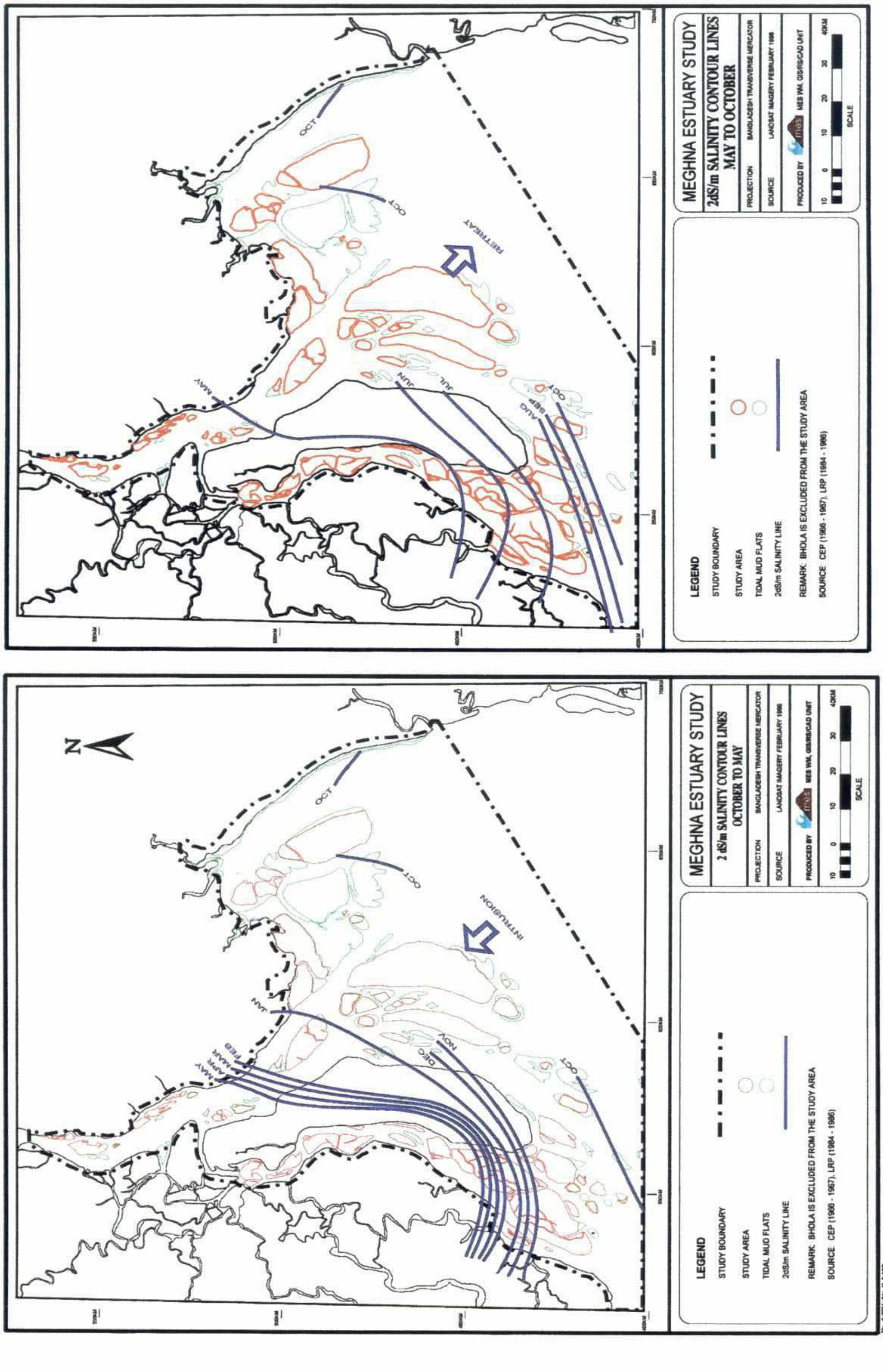


Figure 6b: Retreat of saline water during monsoon

Figure 5a: Progress of salinity intrusion during dry season

3.6 Water levels

The mean water level shows a marked seasonal variation along the Bangladesh coast. The seasonal variation of the mean high water level (from the dry to the wet season) decreases significantly along the Lower Meghna Estuary in southward direction. At Chandpur, the seasonal variation of the mean high water level is about 3 m. In the southern part of the Bangladesh coast, the seasonal variation of the mean high water level changes over the year from about 0.8 m to 2.1m (Khepupara, see Table). The variation is caused mainly by the changes in the fresh water flow from the river system, but also by the seasonal variation in air pressure.

Table 2: Seasonal Variation of the Mean High and Mean Low Water Level along the Bangladesh Coast

Water level station	Seasonal variation of the mean high water level (50% value)	Range of the mean high water level (50% value)	Seasonal variation of the mean low water level (50% value)	Range of the mean low water level (50% value)
Chandpur	1.6 to 4.6	3.0	0.8 to 3.9	3.1
Chitalkhali	1.2 to 3.5	2.3	-0.9 to 0.8	1.6
Ramdaspur	1.5 to 3.6	2.0	-0.2 to 2.0	2.1
Char Chenga	1.4 to 3.0	1.6	-0.7 to 0.2	0.9
Khepurpara	0.8 to 2.1	1.3	-1.2 to -0.2	1.0
Dasmonia	1.0 to 2.2	1.3	-0.3 to 0.9	1.2
Dhulia	0.6 to 2.1	1.5	-0.6 to 1.0	1.6
Feni river	3.0 to 5.0	2.0	dry to 2.46	-

3.7 River Flow

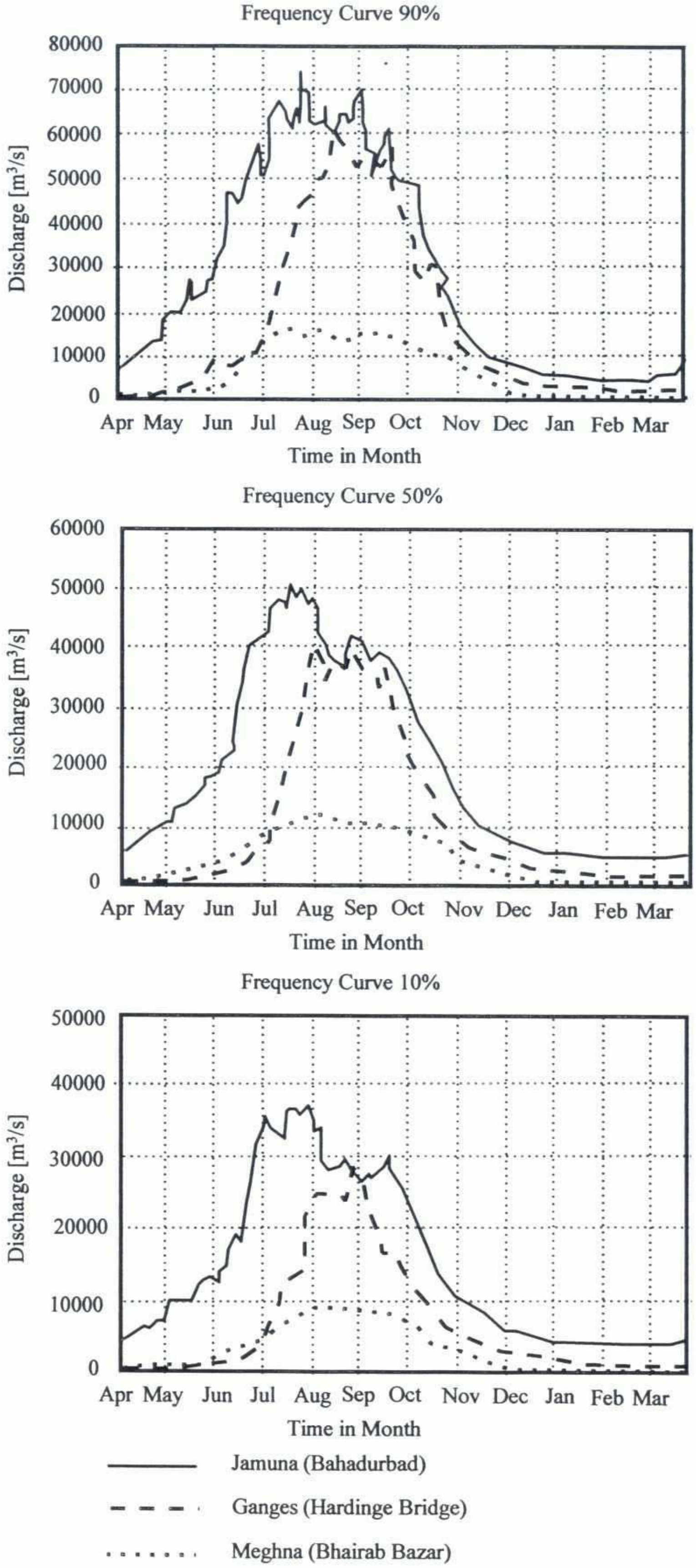
The Lower Meghna River conveys the melt and rainwater from the Ganges and the Jamuna basins, combined in the Padma River, and from the Upper Meghna basin to the sea. The discharges of these three major rivers dominate the river inflow in the Meghna Estuary Study Area.

Long-term records of discharges and water levels are not available at Chandpur. Therefore, the discharge characteristics of Jamuna, Ganges and Meghna (the three main rivers of Bangladesh) are used here to characterise the river inflow characteristics in the Meghna Estuary Study Area.

The river regimes of the Jamuna, Ganges and Meghna are depicted in Figure 6, showing the 90, 50 and 10% exceedance flows for the period 1965-1995 (FAP 24). Clear differences are observed between the Jamuna and Ganges river regimes: the Jamuna rises on a half to two month earlier than the Ganges, whereas flow recession in the Ganges begins somewhat earlier. During August-September the river flows are on average similar. The average discharge of the Jamuna river at Bahadurabad is approximately 21,000 m^3/s. The highest peak flow in Jamuna in the period 1956-2000 occurred in 1998 and amounted to 105,000 m^3/s.

The average discharge of the Ganges River at Hardinge Bridge of (1966-1995) is about 11,000 m^3/s. Since 1934 the highest peak flow amounted to 79,000 m^3/s in 1998. The annual flow volume of the Ganges is about half the Jamuna flow volume. The average discharge of the Meghna River at Bhairab Bazar over the period 1965-1995 is approximately 4,800 m^3/s. Peak values of nearly 20,000 m^3/s have been measured a few times in the past three decades.

Figure 6: 90%, 50% and 10% Exceedance Lows of the Jamuna, Ganges and Meghna for the Period 1965-1995 (FAP 24)



Trends

The annual minimum, mean and maximum water level and discharge time series at Bahadurabad (Jamuna), at Baruria (Padma) and at Hardinge Bridge (Ganges) are presented in figures 8e-8f (source of data: SWMC). The longest record (ver 90 years) is available for Hardinge Bridge on the Ganges, the records for the other two locations are much shorter (45 years for Bahadurabad and 34 years for Baruria). Presented discharge data are calculated from the rating curves. The maximum water levels at all 3 locations show no significant trend. Minimum water levels at Hardige Bridge show a distinct downward trend (Figure 7c). This trend might be caused by the water withdrawal at Farakka Barrage, constructed in the mid-seventies. The same trend can be observed at Baruria (Figure 7d). The annual maximum discharge series at all 3 locations show a distinct increasing trend. The average discharge in the Jamuna at Bahadurabad shows an insignificant increasing trend while the minimum discharge at this location shows no trend (Figure 7b). The minimum discharges in the Ganges at Hardinge Bridge (Figure 7d) and in the Padma at Baruria (Figure 7f) show a distinct decreasing trend., which also can be related to the Farraka Barrage. Also the annual average discharge in the Ganges shows a slightly decreasing trend, and the annual average discharge in the Padma shows a distinctly increasing trend.

The annual characteristics of the water level and discharges illustrate the enormous river dynamics that influences the coastal area (Table 3).

Table 3: Calculated Peak Water Levels and Discharges for Selected Return Periods (source: FAP 25)

		Return Period (year^{-1})				
Station		1:2	1:5	1:10	1:25	1:50
Bahadurabad	Peak level (m PWD)	19.78	20.04	20.21	20.42	20.57
	Peak discharge (m^3/s)	67,000	78,000	85,000	94,000	105,000
Hardinge Bridge	Peak level (m PWD)	14.72	14.80	14.85	14.92	14.97
	Peak discharge (m^3/s)	49,000	59,500	66,500	76,000	82,500
Mawa	Peak level (m PWD)	5.91	6.22	6.44	6.76	7.01
	Peak discharge (m^3/s)	90,000	100,500	106,000	112,000	116,000

Figure 7 a/f: Annual minimum, mean and maximum water level and discharge at Bahadurabad, at Baruria and at Hardinge Bridge (source of data : SWMC)

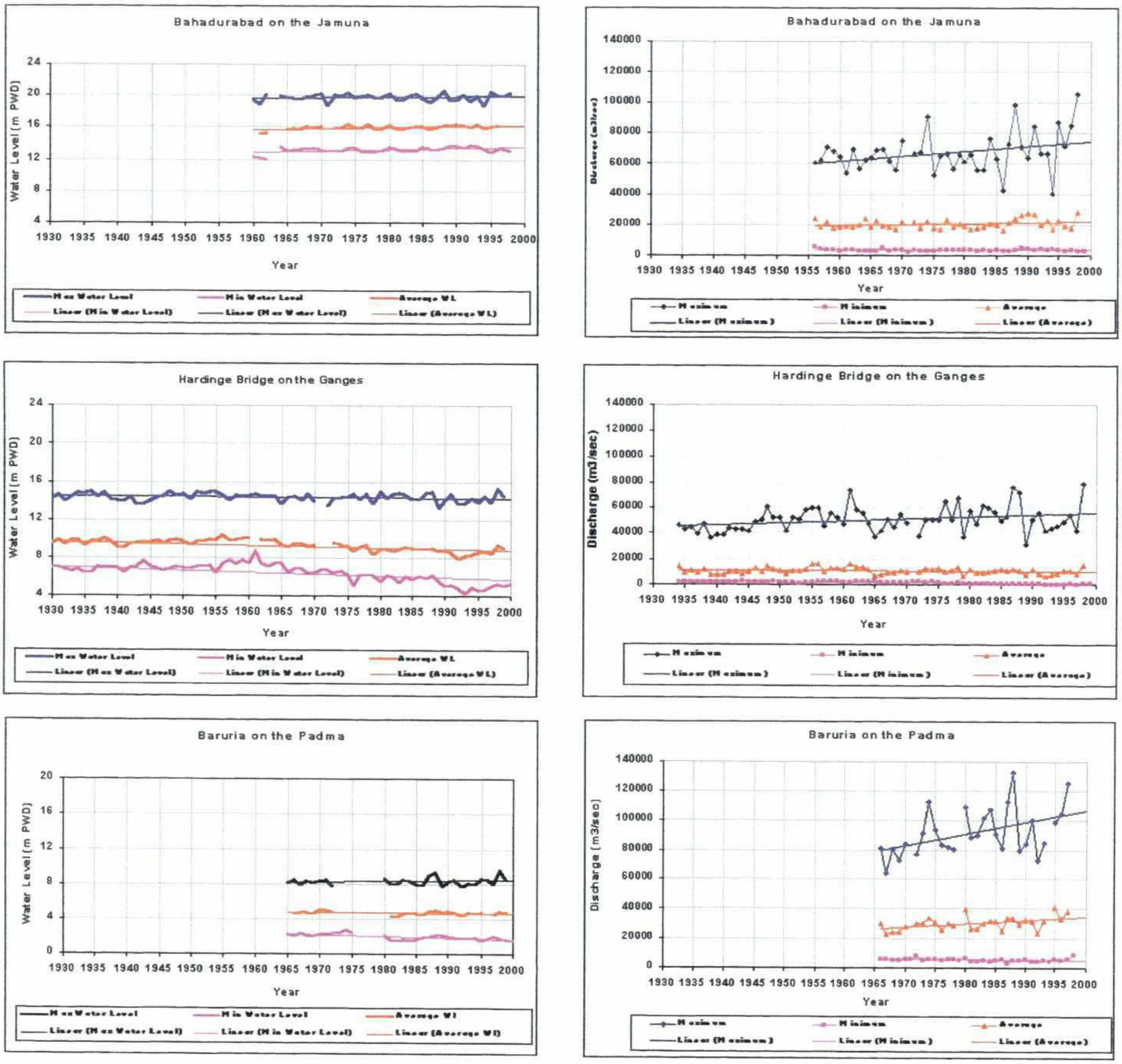


Figure 7 illustrates that the maximum discharges over the period 1967-1973 and over the period 1989-1994 were relatively low compared to the mid eighties (1984-1988) and 1995-1998. The mid eighties (1984-1988) and 1995-1998 were relatively very wet seasons characterised by extremely high water levels and river discharges. It is assumed that the overall river inflow characteristics at Chandpur shows the same trend.

Since no long-term time series are available the river flow characteristics at Chandpur are simulated using a 1D-model (FAP-9B). The calculated peak discharges as well as the maximum water level gradient i.e., slope at Chandpur for various return periods are shown in Table 4.

Table 4: Calculated Peak Water Discharge and Water Level Gradient at Chandpur for Various Return Periods (source: FAP 9B)

Station	(+m PWD) (m^3/s)	Return Period (year^{-1}) 1:10	1:25	1:50	1:100
Chandpur	Maximum water level gradient	2.32*10^{-5}	2.39*10^{-5}	2.43*10^{-5}	2.47*10^{-5}
	Peak discharge	123,300	136,600	147,400	158,800

3.6 Cyclone Events

The Multi-purpose Cyclone Shelter Preparatory Study (MCSP, 1993) has made a very thorough analysis of various aspects of the generation of cyclones surges and its penetration in-land. The yearly maximum wind speed (anywhere in the Bay of Bengal) was analysed statistically revealing a relationship between return period and wind speed (Table 5).

Table 5: Cyclone Wind Speeds (source MCSP, 1993)

Return Period (years)	5	10	20	25	50	100
Wind Speed (km/h)	165	195	223	233	261	289

It was assumed that a specific cyclone will affect half of the entire coastline, so that only half of the cyclones crossing the Bangladeshi coast will affect a specific section of the coast. Statistically, it means that the wind speed exceeded once every 100 years at a specific section of the coast is exceeded once every 50 years somewhere along the entire coast.

In the Second Coastal Embankment Rehabilitation Project (CERP-II, 2000), design surge heights were determined for a number of polders located along the Chittagong coast (between Teknaf and Feni, and Pathargata in the west of Bangladesh' coast. The surges heights were determined with the two-dimensional hydrodynamic model simulations, using 35 years of cyclone wind data. The calculated heights were statistically analysed. The resulting design wave heights are presented in Table 6.

Table 6: Cyclone surge level (CERP-II, 2000)

Cyclone Surge Level (m PWD)		Return Period (yr)			
Area	Polder	1:100	1:50	1:20	1:10
Pathargata	40/2	8.1	7.1	5.7	4.7
Sitakunda	61/1	9.8	8.8	7.4	6.4
Patenga	62	8.8	7.8	6.4	5.4
Moheskhali	69	7.3	6.3	4.9	3.9
Kurushkhul	66/1	7.3	6.3	4.9	3.9
Teknaf	68	3.9	3.8	3.5	3.4

The surge height increases along the eastern coast when the surge wave is travelling towards north. This is caused by the funnel shape of the estuary which is also the reason for the amplification of the tide in the Sandwip Channel.

4 HYDRAULIC CHARACTERISTICS

4.1 General

The combination of strong river and tidal flow produces a complex flow pattern in the estuary. The resulting hydraulic conditions have been analysed in present study by means of two-dimensional hydrodynamic models. High resolution models with 600m x 600m and locally 200m x 200m grid spacing have been developed (SWMC, 2000) using MIKE21 modelling software. The models are based on the recent bathymetric data and are calibrated and validated with the water level and discharge measurements from 1997 monsoon[2] and 1999 dry season. Each simulation covered a period of 2 weeks and included both neap and spring tide and was therefore considered to represent characteristic conditions occurring in the Meghna Estuary during the low and the high discharge conditions. It is noted, however, that the velocities and discharges in the upper part of the river system calculated by the model are significantly lower than the values measured during the 2000 monsoon, therefore the calibration of the model for this part of the system cannot be considered satisfactory. Still, it can be assumed that the model can fairly well reproduce global flow features in the Meghna Estuary.

4.2 Hydrodynamic conditions during dry season

The dry season is the calm period in the estuary. The wind is weak, and the river discharge is much lower than during the monsoon. Water movement in the estuary is mainly forced by the tide entering from the Bay of Bengal.

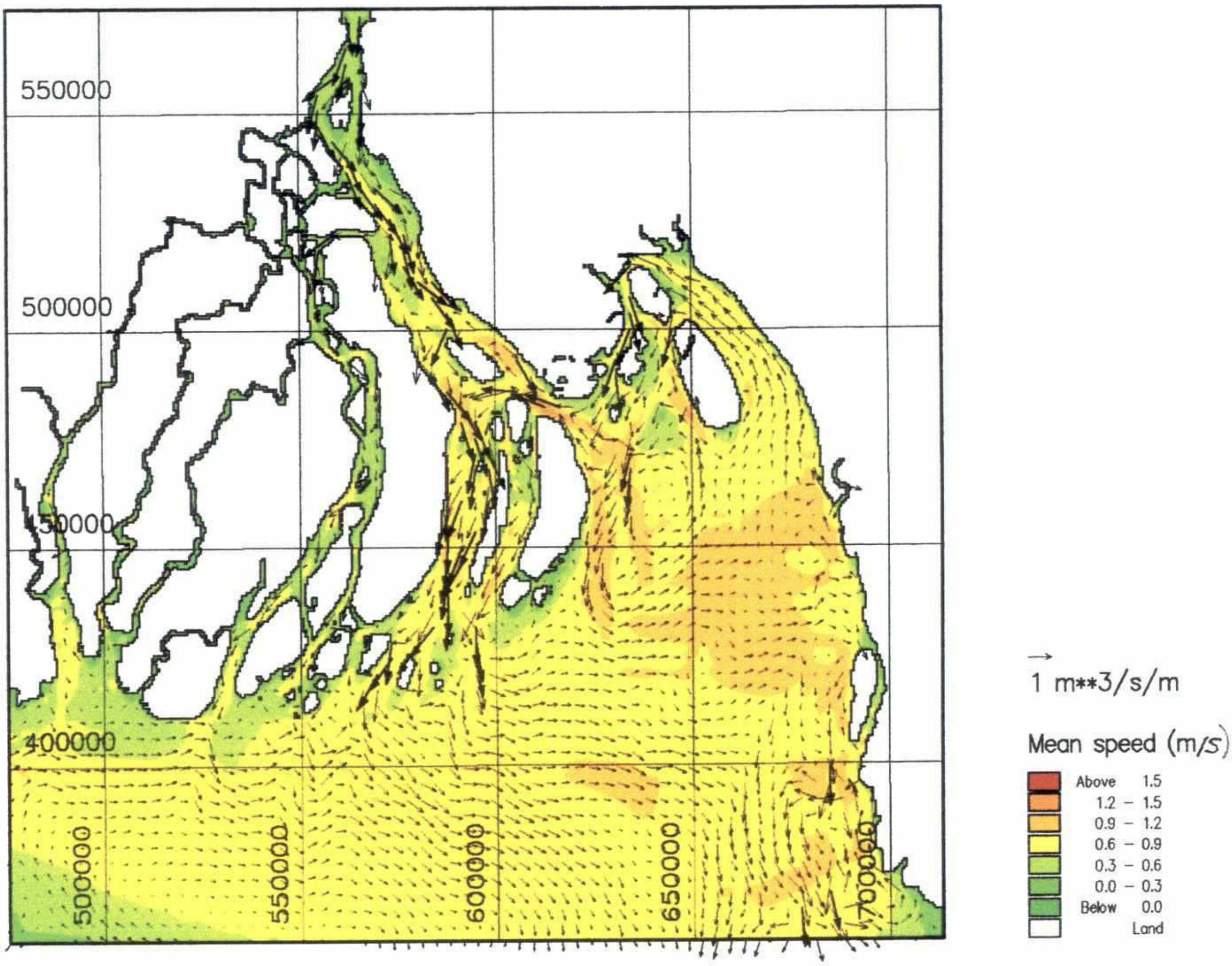
Hydraulic simulations indicate that during the dry period, the highest flow speeds can be found in the North Hatia Channel and around Urir Char. The maximum flow speed is about 2.5-3 m/s. Large flats and complicated flow features north and west of Sandwip can be seen in the results of computations, as well as flats south of Hatia. Rapid changes in the flow direction take place in these areas over very short distance, which is in agreement with the observations. Higher velocities of about 1.5-2.0 m/s are found mainly in the eastern, deeper part of the estuary, and in the Shaphazpur Channel. Lowest speeds of about 0.5-1.0 m/s are found in the upper part of Lower Meghna, where the tidal action is less pronounced.

In Annex A, a series of flow velocity drawings, showing characteristic flow patterns during spring tide is presented.

The residual flow figures from numerical simulations show a net transport of water out of the Meghna Estuary, mainly through the West Shabhazpur Channel, and an easterly flow outside the estuary (Figure 8). A prominent counter-clockwise circulation is found around the Sandwip Island, with a northerly current in the Sandwip Channel and southerly current in the southern part of the Hatia Channel. The anti-clockwise circulation is mainly forced by tides, but influenced by the river discharge. This circulation traps the fresh water from the river in the estuary and thus increases the residence time and may be the reason for the relatively low salinity in the estuary even during the dry season.

[2] The simulation actually shows the hydrodynamics during post-monsoon situation

Figure 8: Residual flow and mean current speed during dry period.



4.3 Hydrodynamic conditions during monsoon

Monsoon is the dynamic season in the estuary. The south-westerly monsoon wind is steady, and the river discharge is high. Furthermore, the mean water level is higher than during the dry season

The flow and water-level distribution of the estuary are jointly forced by the river discharge, the tide, and the wind. The monsoon season is critical with respect to high water-levels, sedimentation and accretion.

The water from the Lower Meghna is conveyed to the sea through the Shabhazpur Channel and through the Hatia Channel. The residual counter-clockwise circulation around the Sandwip Island (Figure 9) is similar to the circulation during the dry period, which indicates that this area is dominated by tides. The net flow and the maximum flow velocities in the Lower Meghna are higher during neap tide than during spring tide, whereas in the Sandwip Channel, due to the domination by tide, maximum velocities are higher during spring tide. Due to higher water level during monsoon, the maximum speeds in the estuary are slightly lower than during the dry period. In the Lower Meghna River, the velocities increase due to increased water flow, with the maximum[3] of 1-2 m/s.

Table 7: Seasonal Variation of Mean Water Level in the Estuary

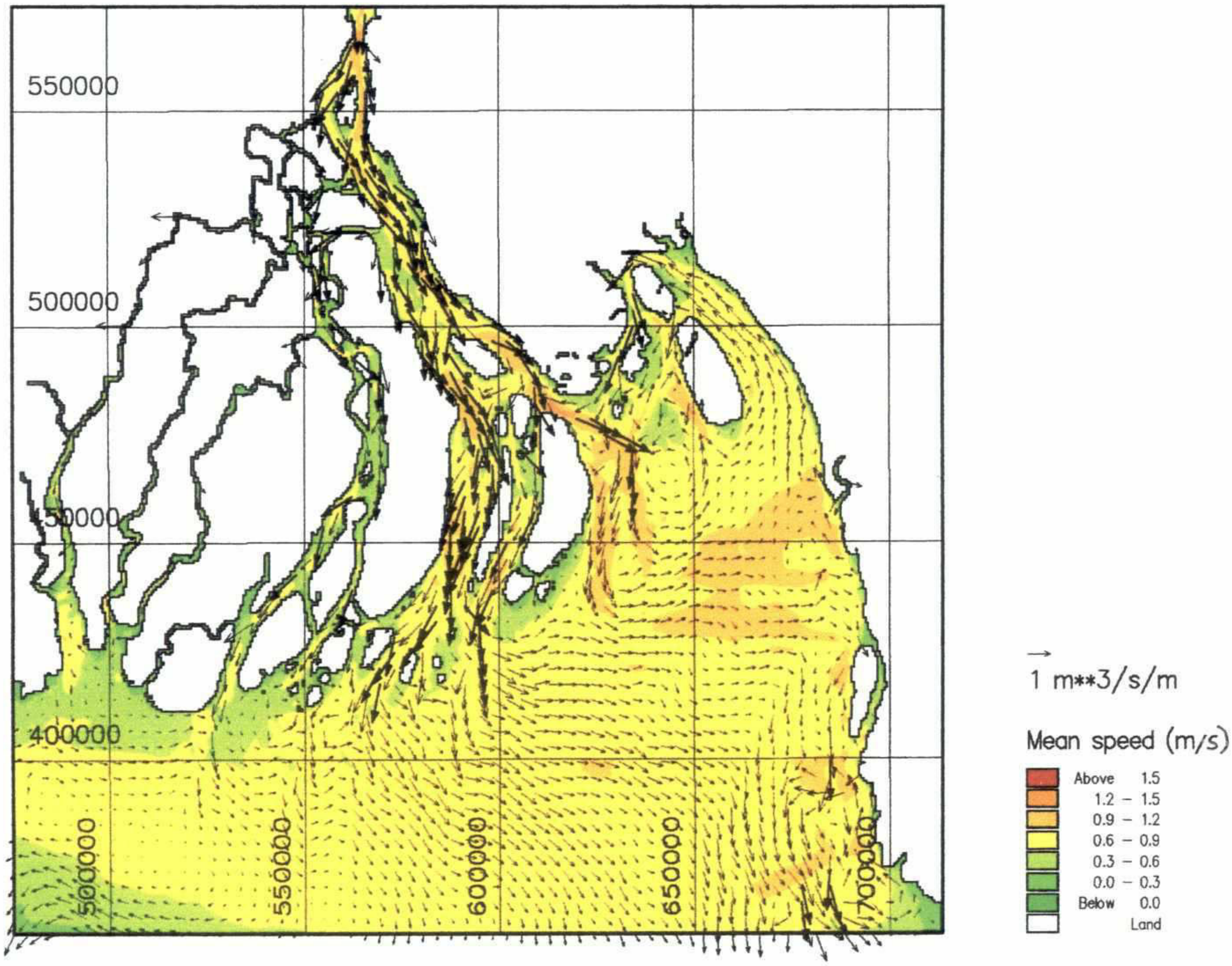
	February	August	September
Chandpur	1.3 m+PWD	4.3 m+PWD	4.0 m+PWD

PWD (Public Works Department) datum values are approximate

In Annex B, a series of flow velocity drawings, showing characteristic flow patterns during spring tide is presented.

[3] In the field measurements in June 2000, velocities of more than 3.5 m/s were measured near Hanar Char.

Figure 9: Residual flow and mean current speed during monsoon.



4.4 Overall flow distribution

The distribution of flow between main channels in the Meghna Estuary as found with the hydraulic simulations is presented in Table 8 and Figure 10 for the dry season, and in Table 9 and Figure 11 for the monsoon.

Dry season

The river flow is mainly conveyed along the western part of the system, through the West-Shahbazpur Channel. The discharge distribution is clearly influenced by the tide.

The net flow through the Hatia Channel at North Hatia appears to be directed northwards, which shows that the flow in this channel is dominated by the tide. The net flow (directed upstream) amounts to about 30% of the river discharge, and is drained back to the sea through the West and East Shahbazpur Channel. About 20% of the total flow is discharged to the sea through the Tetulia River. Table 8 shows also the enormous dynamics of the Hatia Channel at North Hatia and the southern reach of the West Shahbazpur Channel, with the maximum upstream (flood) discharge of more than 600-700% of the river flow, and maximum downstream (ebb) discharge of 370-500% of the river flow.

Table 8: Distribution of Discharge during Dry Season

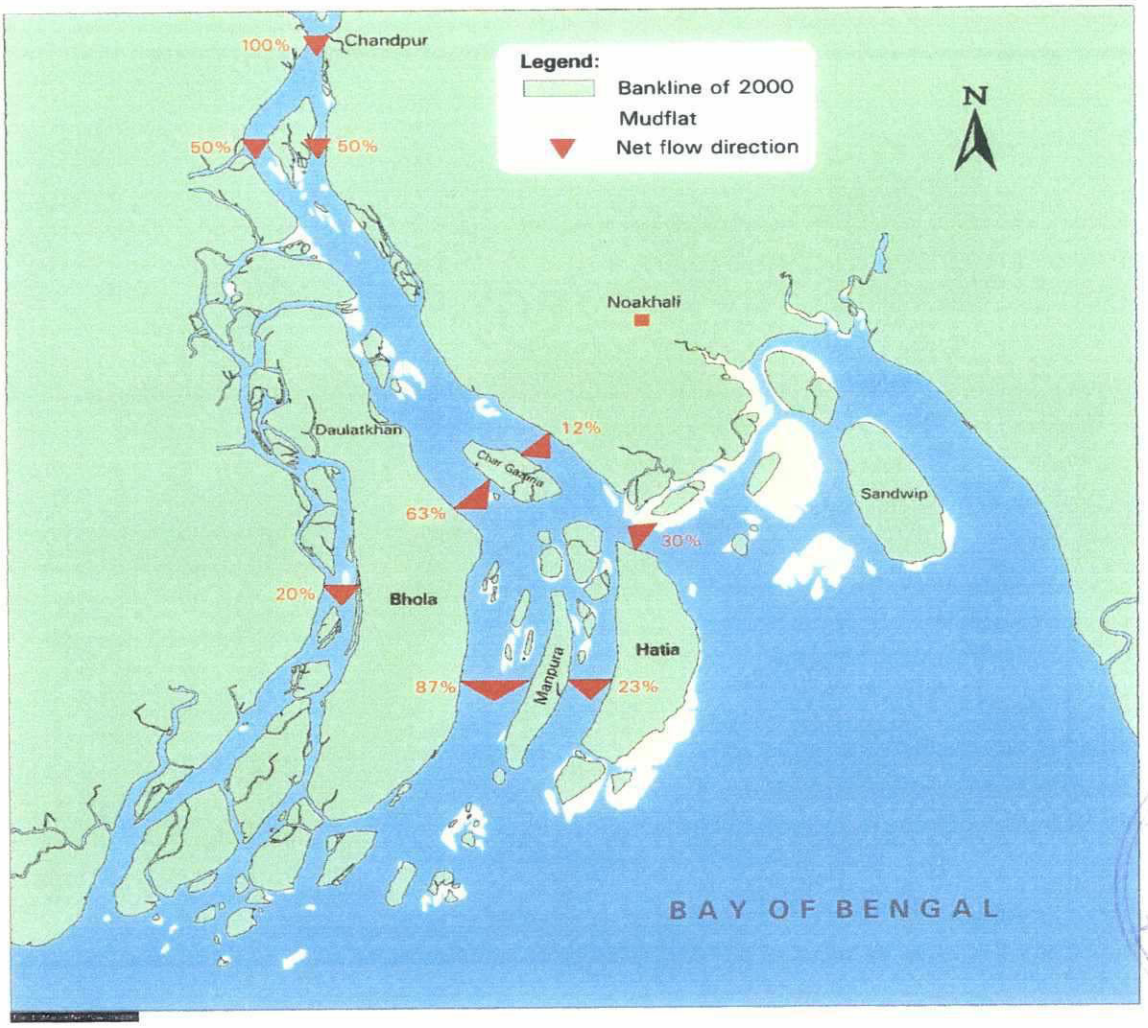
	maximum upstream flow (m^3/s)	maximum downstream flow (m^3/s)	net flow (m^3/s)	maximum upstream flow [1)]	maximum downstream flow [1)]	net flow [1)]
Hatia Channel at North Hatia	134,300	65,550	-5,300	7.6	3.71	-0.30
East Shahbazpur Channel (at level of Manpura)	44,850	30,600	4,100	2.54	1.73	0.23
West Shahbazpur Channel (at level of Manpura)	110,100	88,900	15,350	6.23	5.03	0.87
Tetulia	26,000	21,300	3,500	1.47	1.21	0.20
East Shahbazpur Channel (at level of Char Gazaria)	59,350	36,200	2,100	3.36	2.05	0.12
West Shahbazpur Channel (at level of Char Gazaria)	81,650	62,500	11,150	4.62	3.54	0.63
East Branch near Char Bhairabi	-12,900 [2)]	16,000	8,500	0.73	0.90	0.50
West Branch near Char Bhairabi	-12,400	16,250	8,600	0.70	0.92	0.50

1) as ratio of total river flow (approx. net flow 17,500 m3/s near Chandpur)

2) "-" sign indicates that the actual flow direction is reversed (i.e., negative upstream flow means that flow is directed downstream)

Travelling upstream, tidal wave looses its energy. At the level of Hanar Char, the flow is not reversed any more. The flow is distributed evenly on both sides of the large char in the middle of the river.

Figure 10: Net flow distribution in % of Flow at Chandpur during Dry Season



Monsoon season

Also during monsoon, the river flow is mainly conveyed along the western part of the system, through the West-Shahbazpur Channel. However, compared to the dry season, the direction of net flow through the Hatia Channel at North Hatia is reversed towards the sea, also the East Shahbazpur Channel between Manpura and Hatia contributes more to discharging the river flow. The river discharge is of the same order of magnitude as the tidal flow. This is reflected in a much smaller difference between flood and ebb discharge through both Hatia Channel at North Hatia (200% vs. 150% of the river flow) and the southern West-Shahbazpur Channel (150% vs. 200% of the river flow). The contribution of the Tetulia River remains the same as during the dry season (15%).
It is noted that in comparison with the flow and discharge measurements near Hanar Char in June 2000, the discharge and current velocity calculated by the model are significantly lower. The model underestimates the flow in the upper river system. The discharge distribution in Table 9 has been determined for net flow of approximately 50,000 m^3/s near Chandpur. During monsoon, discharges of more than 100,000 m^3/s are often measured. Numerical experiments show that when upstream discharge increases, significantly more flow is conveyed through the Hatia Channel to the Bay of Bengal.

An additional effort should be put into the calibration of the upstream reach located downstream of Chandpur.

Table 9: Distribution of Discharge during Monsoon Season

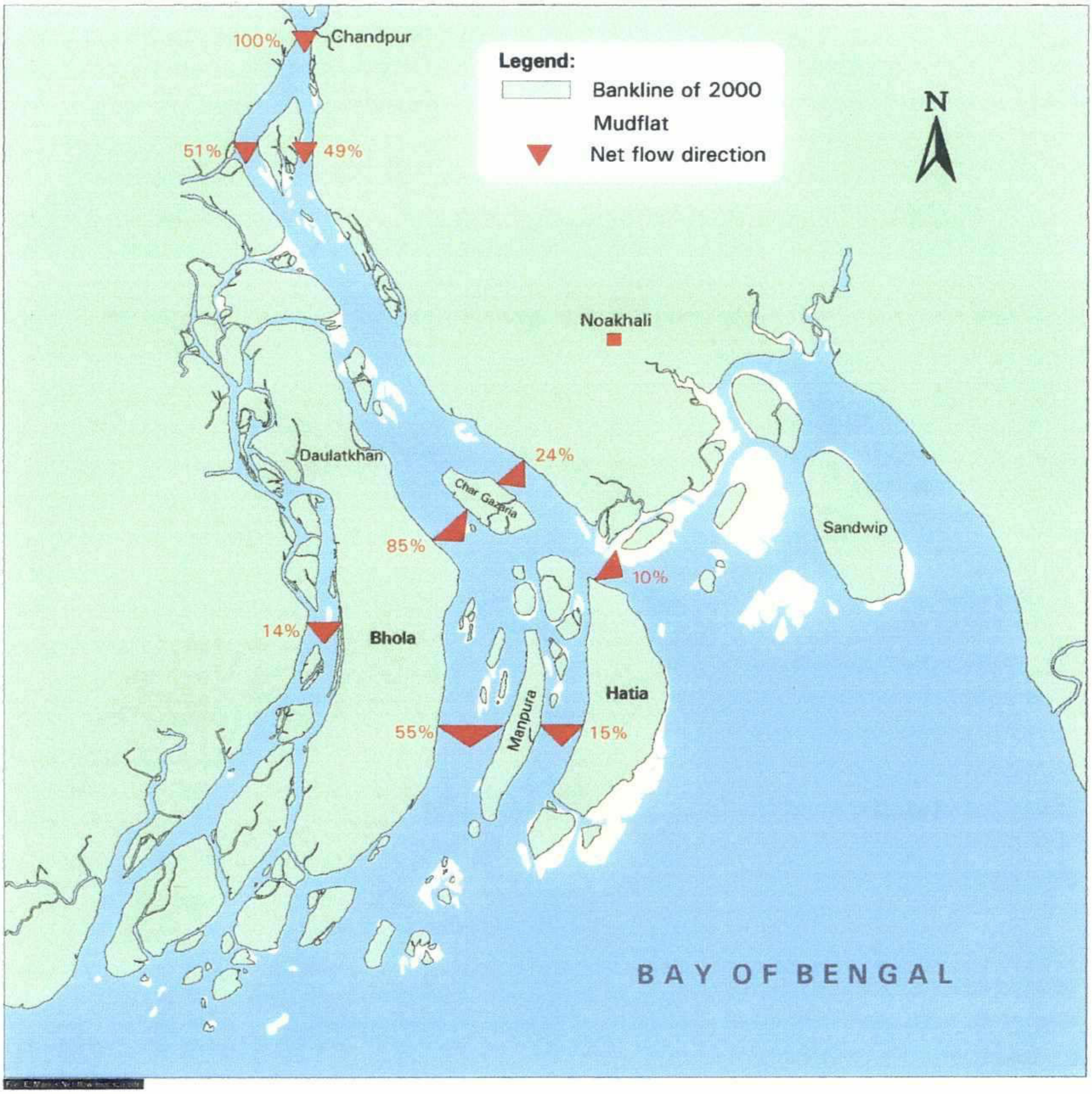
	maximum upstream flow (m^3/s)	maximum downstream flow (m^3/s)	net flow (m^3/s)	maximum upstream flow [2]	maximum downstream flow [2]	net flow [2]
Hatia Channel at North Hatia	104,250	72,900	5,150	2.01	1.41	0.10
East Shahbazpur Channel (at level of Manpura)	33,000	34,250	7,550	0.64	0.66	0.15
West Shahbazpur Channel (at level of Manpura)	75,850	100,650	28,800	1.46	1.94	0.55
Tetulia	17,250	23,900	7,400	0.33	0.46	0.14
East Shahbazpur Channel (at level of Char Gazaria)	42,000	44,050	12,250	0.81	0.85	0.24
West Shahbazpur Channel (at level of Char Gazaria)	46,700	77,100	29,850	0.90	1.49	0.58
East Branch near Char Bhairabi	-11,100 [3]	35,000	25,500	0.21	0.67	0.49
West Branch near Char Bhairabi	-9,250	37,550	26,400	0.18	0.72	0.51

2) as ratio of total river flow (approx. net flow 50,000 m3/s near Chandpur)

3) "-" sign indicates that the actual flow direction is opposite (i.e., negative upstream flow means that flow is directed downstream); measurements in June 2000 indicate that the discharge distribution between east and west channel near Char Bhairabi is about 60/40.

Despite high river discharge, tidal influence is still clearly visible at the level of Char Bhairhabi (near Hanar Char).

Figure 11: Net flow distribution in % of Flow at Chandpur during Monsoon Season



5 GEOMORPHOLOGICAL CHARACTERISTICS

5.1 General

The Brahmaputra - Jamuna - Lower Meghna River flows through the Bengal Basin, one of the most active tectonic zones of the world. The sediment yield of the catchment is very high, resulting from erosion caused by high rainfall in the Himalayas. The spatial and temporal distribution of water and sediment in the catchment governs the behaviour of the rivers and thus influences the behaviour of the Lower Meghna Estuary. The estuarine system is very dynamic and undergoes continuous changes both natural and through the influence of human activities. Changes in physical conditions in the coastal area as well as in the catchment area affect the hydraulic and morphological conditions and processes in the Meghna Estuary Study Area.

The geomorphology of the Lower Meghna Estuary Study Area is influenced by a complex interaction between river and tide. The major distributary system includes the Tetulia, the Shahbazpur and the Hatia channels. The channels of Upper Tetulia and Lower Meghna show morphological behaviour characteristic for braided rivers. The Lower Shahbazpur channel and Hatia as well as the Lower Tetulia show linear tidal ridges and islands indicating reworking of sediments by tidal currents. The tidal currents in these areas play a dominant role in determining the fate of the river-borne sediments. There is an appreciable upstream transport of bed and suspended sediment as a result of deformation of tide during propagation. Sediment is received from both the river and Bay of Bengal, yet most of the sediment received by the river ends up being transported and deposited by tidal currents.

The area around the Upper Shahbazpur channel forms a transitional zone between the braided river dominated morphology and the southern area which is more tide-dominated. The channels around Sandwip island are tide dominated.

The Meghna Estuary system has a funnel shape. The river influence becomes progressively larger in stream upward direction as friction drains tidal energy. Tidal influence extends substantially further upstream than salt intrusion.

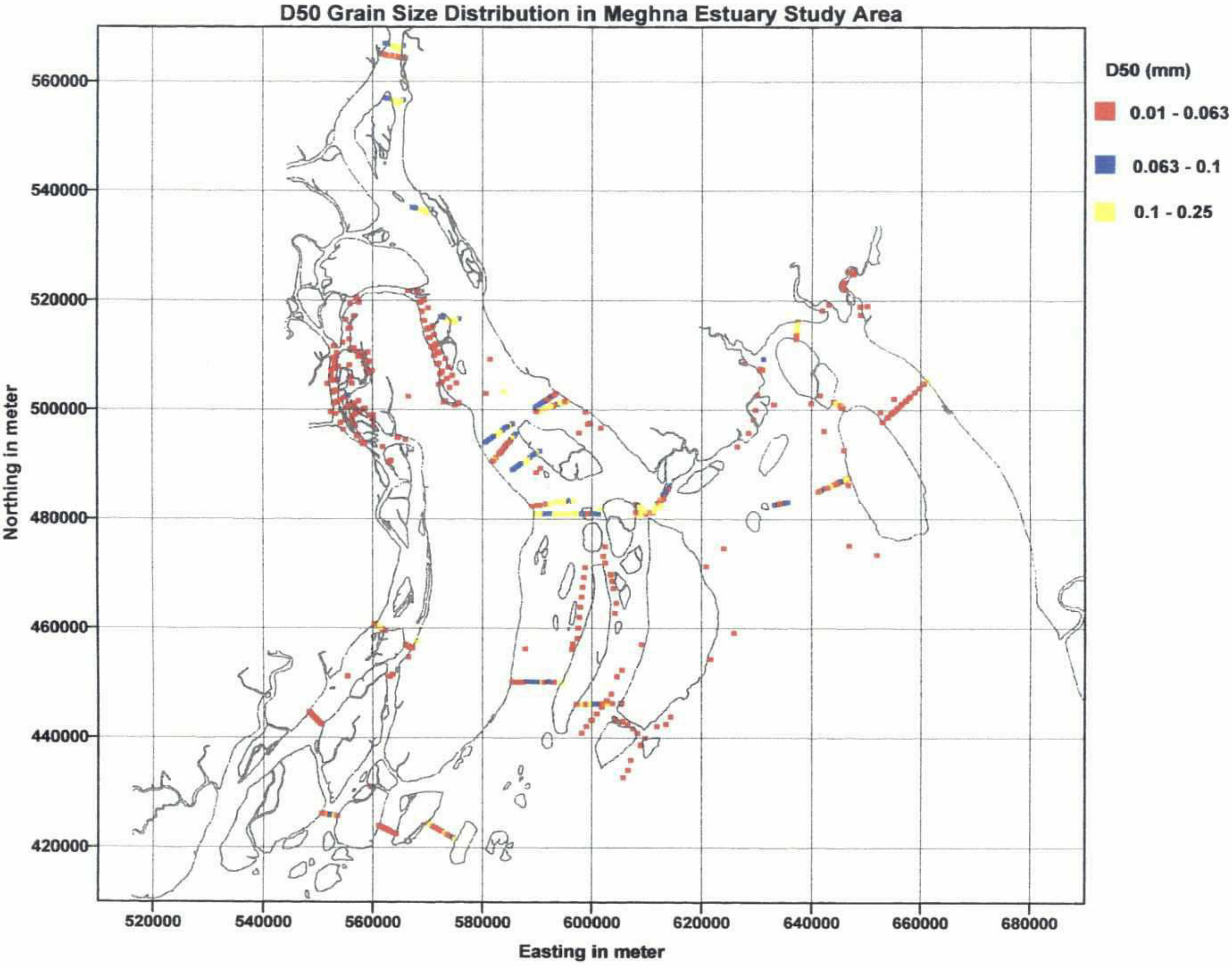
5.2 Sediment Transport Processes

Sediment transport processes form a crucial control in the estuarine processes and evolution of the Meghna Estuary. The estuary is the route by which sediments are transported from the major rivers to the Gulf of Bengal. On their way down the river, continuous deposition, re-erosion and transport alter the composition of sediments. Much of the coarser sediments become trapped on the floodplains of the rivers, only being released at times of flood. The finer fractions are transported into the estuary. There, the estuarine processes act as a filter on the sediment input, and mixing can take place with sediment brought in from the sea. Additionally, chemical alterations can occur within the estuary that can cause the surface properties of some of the constituent particles to alter, affecting their potential deposition.

5.3 Sediment characteristics

Within the Meghna Estuary, concentrations of suspended sediment are generally high, the particles are fine, cohesive, and prone to flocculate, and they are richly organic.
To get insight in the sediment characteristics along the study area, more than 450 samples of bed material were collected by MES. The locations of sampling are shown in Figure 12.

Figure 12: Spatial Distribution of the D50 Grain Size



In the laboratory the granulometry of the samples was determined. The results of the analyses show that the bed consists of fine sand with considerable silts (e.g. silt 20-50%), with a median bed-material grain size varying from 16 to 250 μm.

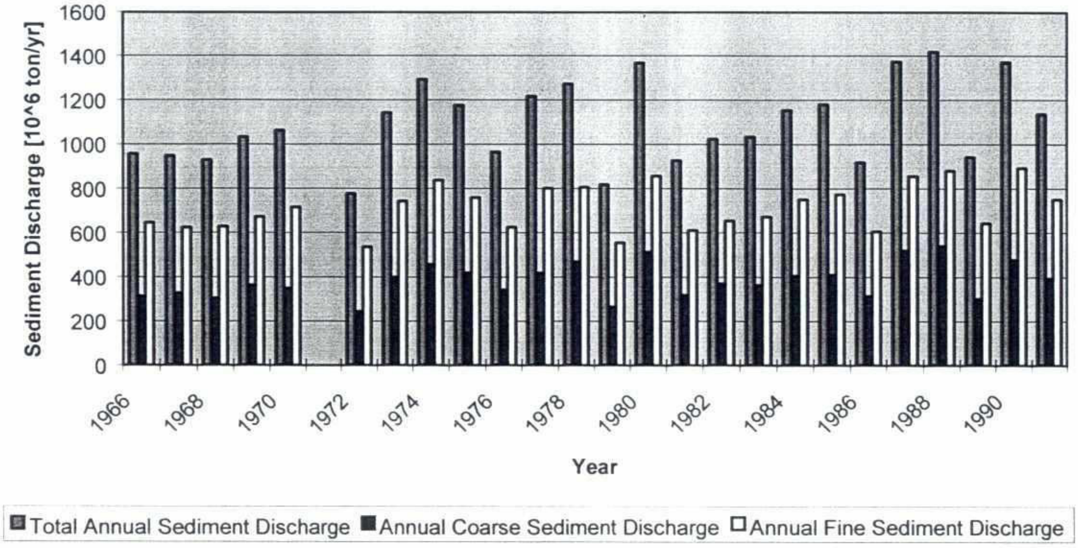
The geometric standard deviation varies from 1.50 to 3.25, which indicates a rather uniform grain size distribution. The results of the measurements indicate that the bed material size varies in the channel in both the transverse direction and along the river. The transverse variation of grain size might be the result of the primary tidal and river flow distribution and secondary flow induced by the bed topography.

Though the average grain sizes along the river vary, there is a trend of finer grain sizes in a downstream direction.

5.3.1 Sediment transport

The morphological development of the entire Lower Meghna Estuary system is strongly affected by the river borne sediment inflow from the main rivers Ganges, Jamuna and Meghna. Long-term records of sediment transport are not available at Chandpur. In this study the annual sediment transport of coarse and fine sediment (<63 μm) of the Ganges and Jamuna river over the period 1966-1991 (FAP 24) is used to characterise the long-term river-borne sediment inflow at Chandpur. Figure 13 shows the annual sediment discharge at the stations Hardinge Bridge and Bahadrubad.

Figure 13: Annual Sediment Discharge of Fine And Coarse Material of the Ganges and Jamuna (1966-1991) (FAP 24)



The averaged total annual sediment discharge of the Jamuna and Ganges over the period 1966-1991 is about 1,100 million ton/year (Figure 13). About 70% of the sediment discharge consists of fine sediment (less than 63 μm). The sediment discharge of the Upper Meghna is negligible compared to the Jamuna and Ganges.

The sediment discharge at the two stations Hardinge Bridge and Bahadurabad is strongly related to the river discharge and to the availability of the sediment. The morphological development of the Lower Meghna estuary on its turn is strongly related to the river-borne sediment inflow.

The morphological changes derived from the time series of satellite images over the period 1973 to 2000 and the annual sediment discharge indicate qualitatively that the net gain of land is related to the amount of river borne sediment discharge.

5.3.2 Sediment concentrations

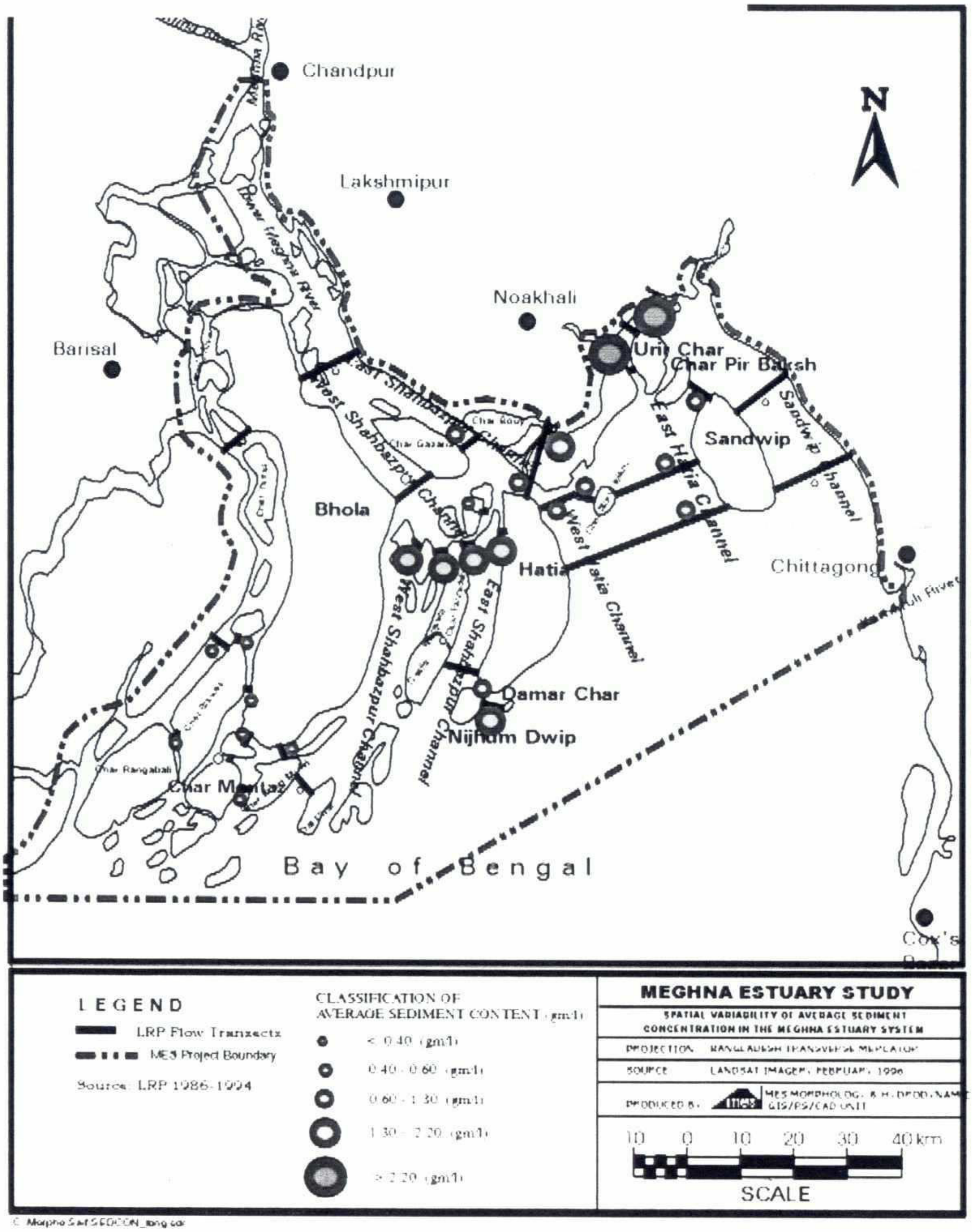
The major part of sediment consists of a mixture of (very) fine sand and silt. It is continuously moved back and forth along the Bangladesh coast and through the tidal inlets into the system. The relatively coarser material is dominantly moved near the bottom (the bottom-transport). The finer particles of sand and the particles of silt and clay are dominantly moved by current as suspended material.

Sediment concentration measurements at different heights in the water column show that the sediment concentration near the bottom is only slightly higher than at the surface. This indicates that the major part of the sediment transport is the transport of vertically well-mixed suspended material.

The spatial variability of the depth averaged sediment concentration in the Lower Meghna Estuary system during dry-season is shown in Figure 14.

Figure 14: Spatial Variability of Average Sediment Concentration in the Meghna Estuary

Spatial Variability of Average Sediment Concentration in the Meghna Estuary System



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The maximum depth-averaged sediment concentration varies between 0.5 - 9 gr/litre. Measurements indicate that the maximum concentration can be found near the Urir Char - Char Balua area and Manpura -North Hatia area.

The sediment concentration measurements by MES and LRP indicate a variation of the sediment concentration during a fortnightly cycle of the spring and the neap tide. The variation of sediment concentration shows a tendency to increase towards the spring tide. The maximum depth averaged sediment concentration at spring tide is about 2-5 times higher than at neap tide.

Salinity measurements conducted by LRP during low river discharge indicate that the high sediment concentration coincided approximately with the zone of salinity intrusion. The lower limit lies at approximately the 10-20 m depth contour, beyond which a vertical gradient in salinity was measured in the water column (Barua, 1990). The upper limit of the sediment concentration appears to be associated with density-driven circulation. This means that the zone of turbidity maximum influences almost the entire estuary during dry season.

5.3.3 Sediment budget

For the long term development of the coastal area it is of utmost importance to know how large portion of the fluvial and marine inflow of sediment is retained in the Lower Meghna Estuary area. These net quantities are relatively small compared to the total quantities transported.

Part of the sediment carried by the flow can be deposited in the channels and on the tidal mud flats, mangroves and salt marshes, in this way reducing depth; on the other hand erosion of the bottom can also develop, with sediment being picked up and transported.

Available bathymetric data have been used to calculate the change in sediment volume. The whole area of the Meghna Estuary has been divided into 7 areas (see Figure 15). In each area, the volume of sediment, accreted and eroded between 1997 and 2000 has been calculated. The calculations are based upon interpolated depth values using 250x250 m grid squares. The results are shown in Table 10. It appears that in the considered period accreting processes have been more dominant than the erosive processes. Calculated net accretion amounts to approximately 306 millions m^3 during three years. The net change is small compared to the actual erosion and accretion volumes: it is about 6% of the total erosion and also 6% of the total accretion. This indicates large dynamics of the estuary, with large displacements of deep channels. The largest erosion is found in the northern part of the estuary (Area 1) and in the middle estuary (Area 2). In these areas also large-scale morphological changes, characteristic for a braided river, are observed: river widens, chars develop in the main reach of the river, deep channels develop along the banks causing extensive erosion. In the southern and north-eastern part of the estuary, accretion dominates: in Area 3 (area between Bhola and Hatia), Area 4 (area between Urir Char, Sandwip and Noakhali mainland) and in south-west (Area 6) accretion distinctly exceeds erosion. In the area east of Sandwip (Area 7) no significant change is observed. In Area 5 (south-east of the estuary), no significant change was found. However, large shallow areas between Hatia and Sandwip were not extensively surveyed due to insufficient water depth, therefore the accretion in that area is probably underestimated.

Period 1997-2000 includes the 1998 monsoon, which was associated with severe floods of duration longer than normal. High flow velocities in the river distributary system may be the reason of high erosion in these areas.

Table 10: Short-term Net Accretion Rate in the Meghna Estuary

Area	Accretion $[10^6\ m^3]$	Erosion $[10^6\ m^3]$	Total area $[km^2]$	Net change $[10^6\ m^3]$	Net change [m/y]
Area 1 (north)	1,055	1,198	448	-143	-0.11
Area 2 (middle)	1,279	1,537	749	-259	-0.12
Area 3 (Hatia-Manpura)	884	628	953	256	0.09
Area 4 (Urir Char-Sandwip)	581	286	473	295	0.21
Area 5 (South-east)	596	612	931	-16	-0.01
Area 6 (South-West)	767	585	933	182	0.07
Area 7 (Sandwip Channel)	263	272	399	-9	-0.01
total	5,426	5,120	4,885	306	0.02

Hydrographic surveys of 1997 and 2000 give a good coverage of most of the study area, yet a 3 years period is rather short for analysis of morphological development. Earlier bathymetric data of LRP, available for four selected areas have therefore been used to analyse sediment budget over the period of more than 10 years. The results of calculations for shorter periods (3-4 years) in Table 10 are consistent with the calculations over a period of over 10 years, and agree with the values in Table 11. All selected areas except for area North Bhola – Char Gazaria show a distinct long-term trend of sedimentation. Net change is small compared to the total amount of erosion and accretion.

Figure 15. Division of study area into seven subareas

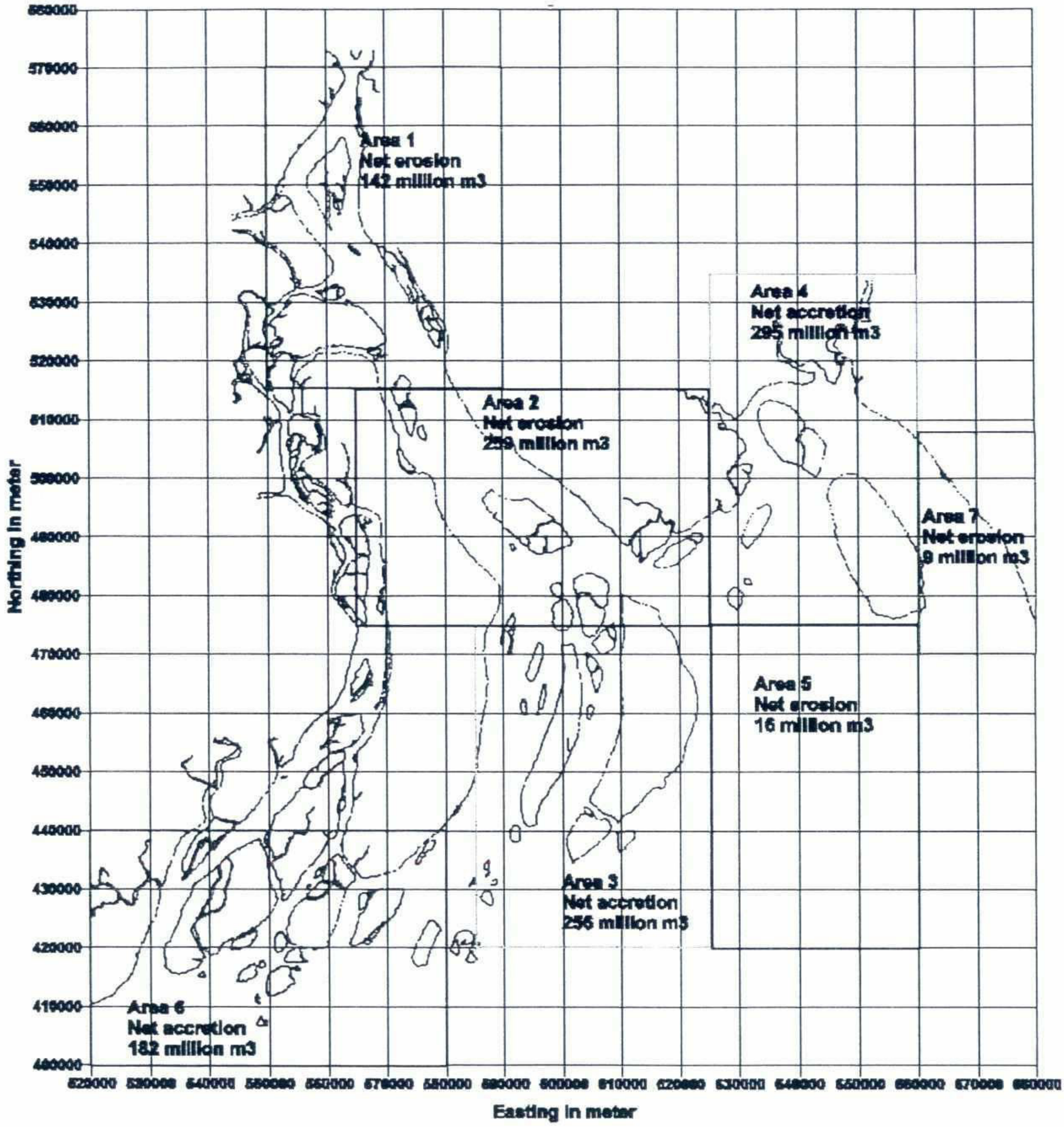


Table 11: Long term Net Accretion Rate in Four Selected Areas

Area (....) = negative value	Period	Accretion $[10^6\ m^3]$	Erosion $[10^6\ m^3]$	Total area km^2	Net change in m/y
North Bhola- Char Gazaria	1986 - 1992	131	272	68	(0.4 - 0.3)
	1986 - 2000	599	651	253	(0.1 - 0)
Manpura – South Hatia	1987 - 1997	197	115	139	0 - 0.1
	1987 - 2000	235	168	157	0 - 0.1
Nijhum Dwip –Damar Char	1988 - 1993	41	22	33	0.1 - 0.2
	1990 -1993	32	12	28	0.1 - 0.3
	1988 - 2000	50	34	31	0 - 0.1
Urir Char - Char Balua	1990 -1994	302	157	247	0.1 - 0.2

The change in the bathymetry of Urir Char area between 1990 and 2000 has been so large that the volume calculation is not possible.

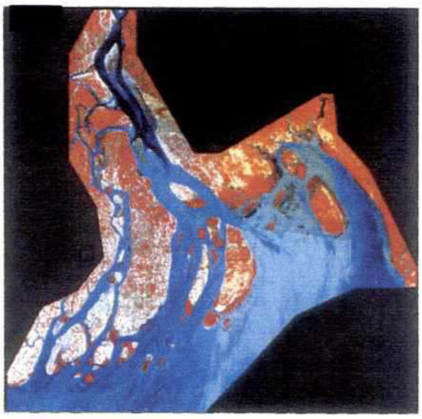
6 GEOMORPHOLOGICAL DEVELOPMENT

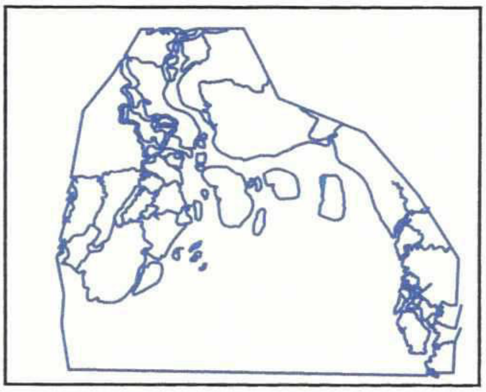
6.1 Geomorphological Evolution during the Last Century

Deltas and estuaries generally are known as areas of a net deposition of sediments either carried by the river or supplied from the sea. The growth of the delta and the accretion of land in the estuaries is a continuous and generally a very gradual natural process interfered by the dynamics of the ever-changing courses of their channels.

A comparison of the 1999 satellite image (Figure 16a) with the 1779 map of J.Rennell (Figure 16b) shows a completely changed system of channels and river courses but a more or less stable coastline west of the Tetulia River. East of the Tetulia river, however, a general tendency of seaward growth of the coastline can be recognised, particularly in the region Bhola island - Hatia island and in the Noahkali district. Although the overall process of accretion is dominant, areas of erosion can be recognised, particularly on the river banks in the north-western part of the project area (North Bhola-Chandpur). This erosion is the result of westward migration of the Lower Meghna Estuary system. Sandwip and the coastal area of the Chittagong mainland are also showing a tendency of erosion. Due to coastal protection measures the trend of erosion near Chittagong mainland has been stopped.

Figure 16: Meghna Estuary (a) Anno 1999; and (b) Anno 1776 (after J. Rennel)





6.2 Long Term Net Accretion rates

Several studies have examined the rates of change for coastal Bangladesh (Table 12). The extent of study area, cartographic methods, interpretation of coastline and/or land features is not precisely known for all of these studies. However, in all cases where the net changes were studied over a period of 20 years or more, there was a net increase of land. The rate of change of 9.9 km^2/y computed for the period 1776-1996 by EGIS (MES, 1997) compares closely with the 7.0 km^2/y computed by Allison (1998). Another, more reliable chart of 1840 prepared by Commander Lloyd was compared (Allison, 1998) against a 1984 satellite image set where the rate of 4.4 km^2/y was computed. The range of net land gain over time periods ranging from 23 to 220 years varies from 4.4 km^2/y tot 29 km^2/y.

A comparison of the rate of change for the period of 1973-2000 with the rate of change for the period 1940-1963 shows that the magnitude of natural processes has been speeded up to some extent due by the construction of the two Meghna cross-dams (1957 and 1964) in the old course of the Lower Meghna Estuary.

Table 12: Comparison of erosion and accretion rates from different studies

Length of study period (years)	Period of study	Net Change for Period (km^2)	Rate of change (km^2/y)	Reference
220	1776-1996	+2187	9.9	EGIS (1997)
192	1792-1984	+1346	7.0	Allison (1998)
144	1840-1984	+638	4.4	Allison (1998)
23	1940-1963	+279	12.1	Eysink (1983)
27	1973-2000	+508	18.8	Present Study
7	1972-1979	+213	30.4[1)]	SPARRSO and ERIM (1981)

1) Area described as "mud flat" was considered as accreted; therefore rate of change is not comparable to the present study.

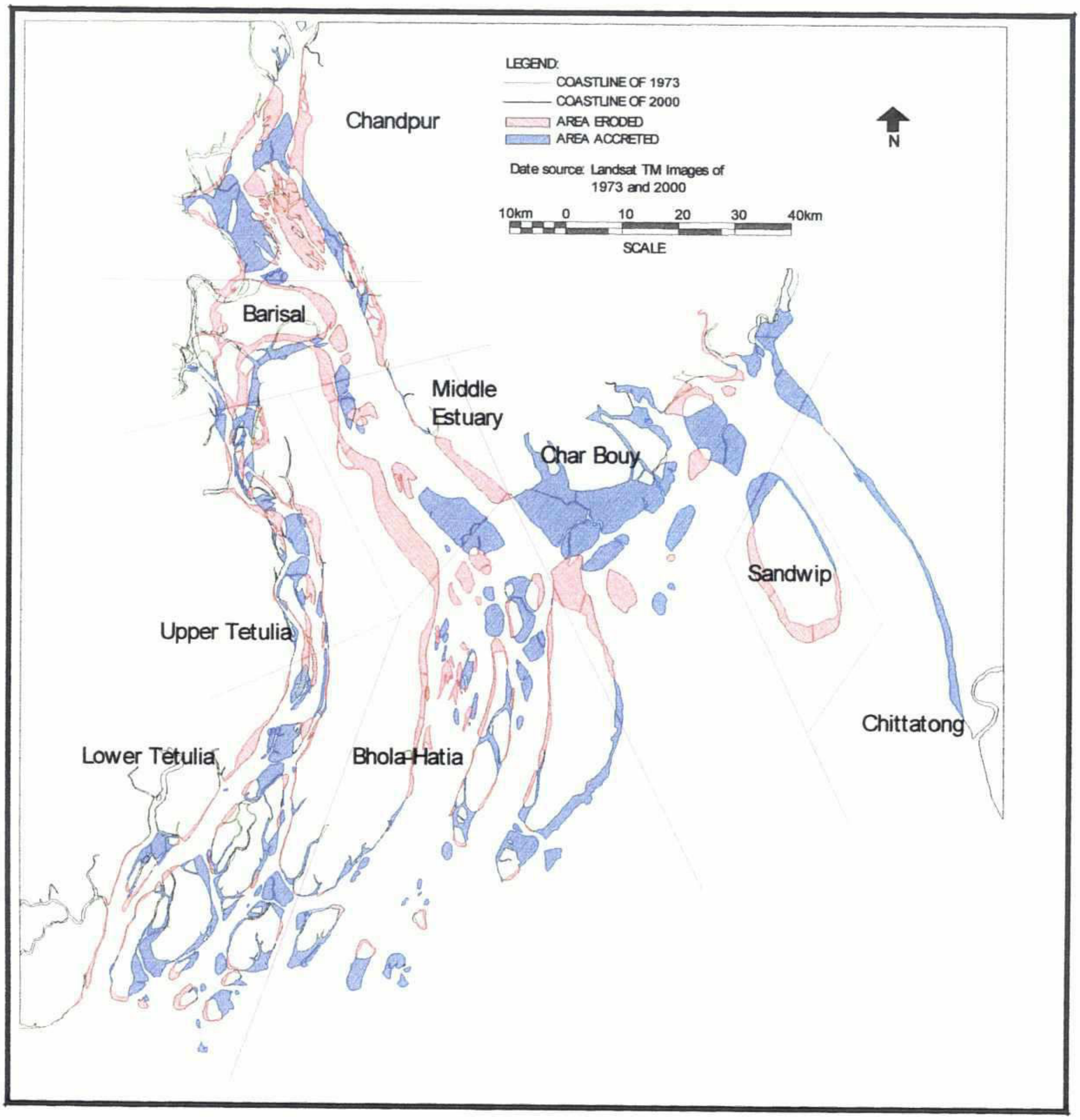
Figure 17: Newly accreted land north-east of Hatia

6.3 Long Term Trends of Accretion and Erosion over the Last Decades

6.3.1 Accretion and Erosion of Land

A time series of digitised satellite images from the period 1973 to 2000 is used to examine the extent of land for each date and to assess the changes due to accretion and erosion in the study area (see Figure 18).

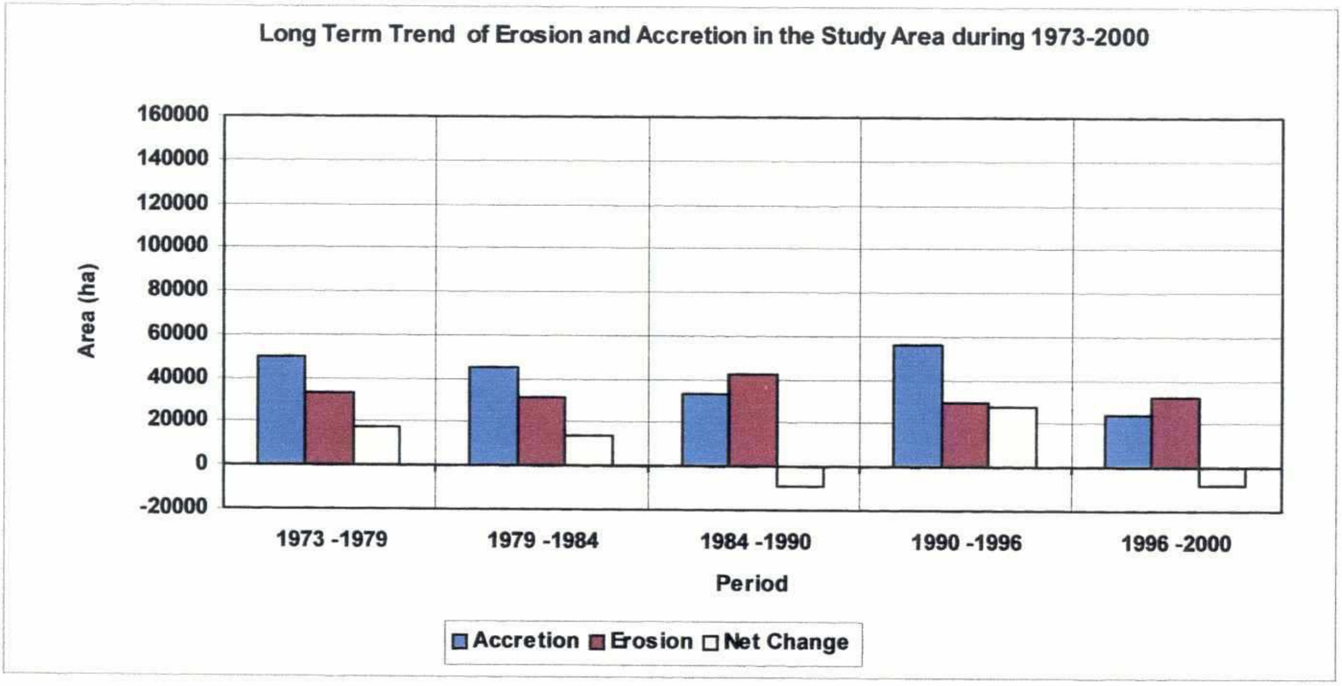
Figure 18: Morphological changes over the period 1973- 000, derived from Satellite Images

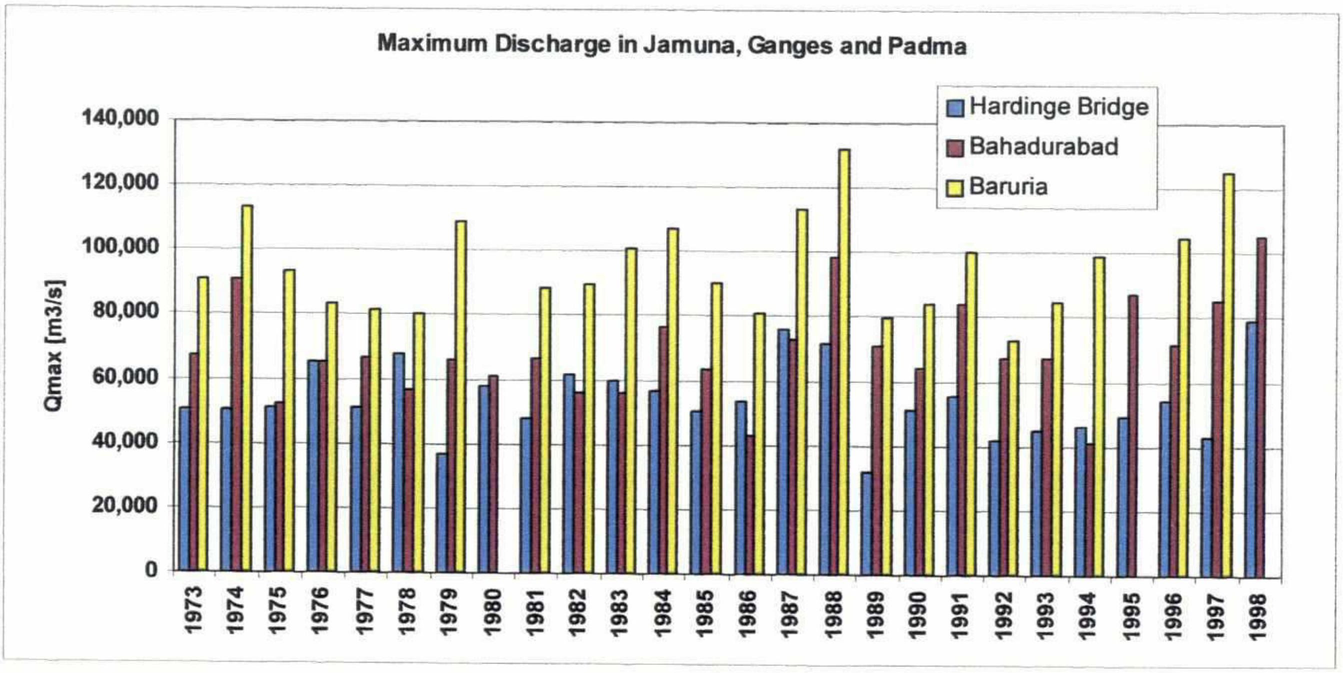


The net change over the considered period shows an overall land gain for the Meghna Estuary system as a whole, for the period 1973-2000 of about 50,800 ha.

The net change over the considered period shows that generally gain of land took place, with exception of two periods: 1984-1990 and 1996-2000, when net loss of land is found. There is a clear relation between the magnitude of maximum discharge in the estuary and the net change of land (Figure 19 a/b). Periods of net loss of land coincide with occurrence of very high monsoon discharges (1986, 1988, 1996, 1998), while gain of land coincides with the periods of lower monsoon discharges in the river system.

Figure 19: (a) Long Term Trend of Accretion and Erosion during 1973-2000; (b) maximum discharge in Jamuna, Ganges and Padma in the same period (source of data: SWMC, 2001)





The annual rate of change for the entire study period ranged from a loss of over 2,100 ha/y during the 1996-2000 period to a gain of over 4,550 ha/y during the period 1990 to 1996 (Table 13).

Table 13: Summary of erosion and accretion in the Study Area

Land Cover Change	Period					
	1973 -1979	1979 -1984	1984 -1990	1990 –1996	1996 -2000	1973 -2000
Accretion for the period (ha)	50,175	45,550	33,505	56,520	23,850	137,168
Erosion for the period (ha)	32,873	31,112	42,410	29,182	32,260	86,366
Net change for the period (ha)	17,302	14,438	-8,905	27,338	-8,410	50,802
Annual rate of accretion (ha/y)	8,363	9,110	5,584	9,420	5,963	5,080
Annual rate of erosion (ha/y)	5,479	6,222	7,068	4,864	8,065	3,199
Annual rate of net change (ha/y)	2,884	2,888	-1,484	4,556	-2,103	1,882

The average annual gain for the entire study period is 1,900 ha/y. Although the long-term trend of gain of new land is dominant in the study area, it should be mentioned that a huge amount of fertile land (in particular old land) is exposed to erosion due to migration and widening of the river system.

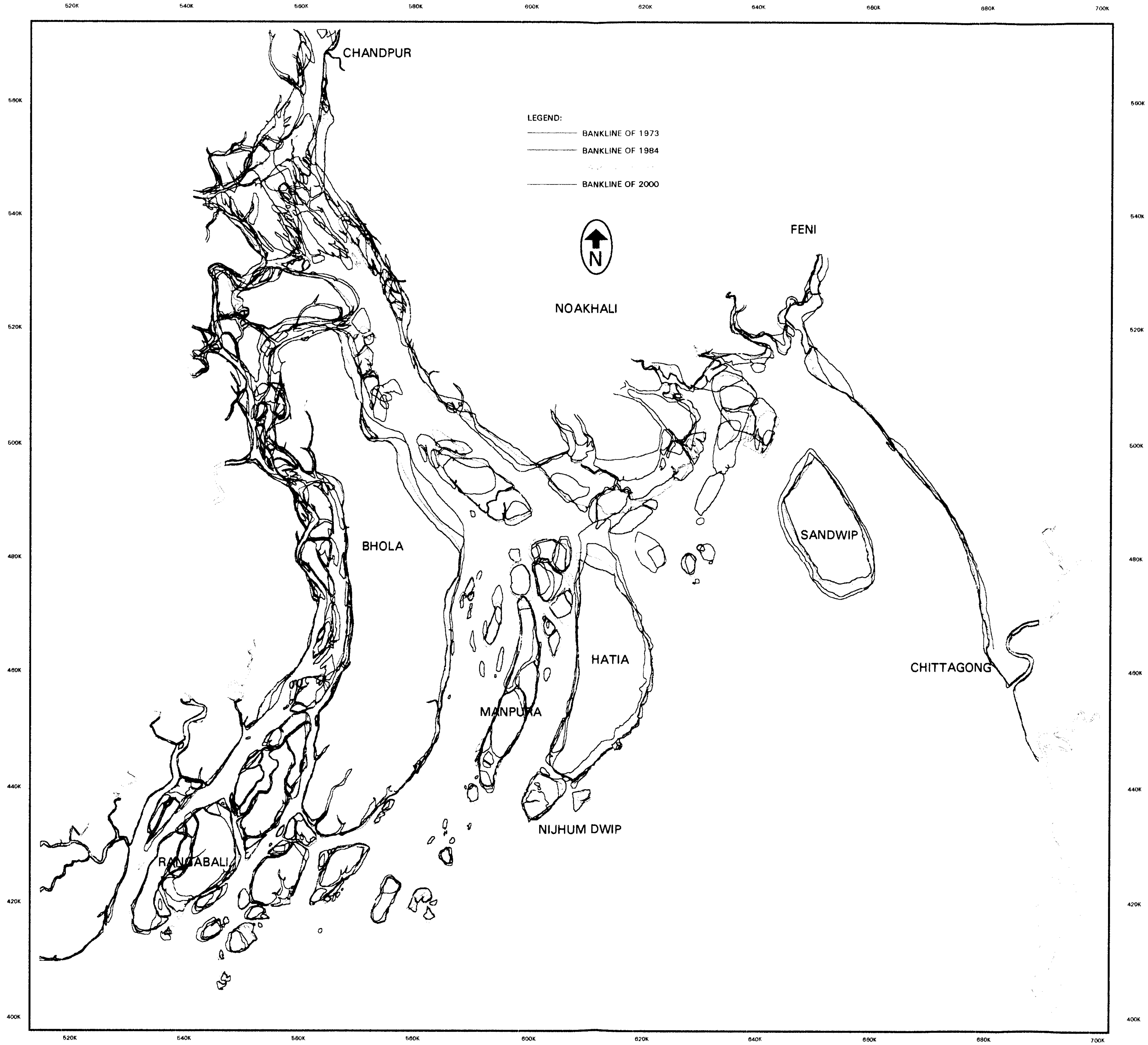
It is furthermore noted that changes to intertidal area and mud flats are not included in this analysis. Analysis of satellite images clearly shows that a considerable amount of sediments is deposited in the area south of Char Balua - Noakhali mainland creating extensive mudflats. However, at present there are no reliable means to quantify this change.

Figure 20: Eroding riverbank of Hatia

6.3.2 Areas Dominated by Accretion and Erosion

The changes to the shoreline in the Meghna Estuary in the period 1973-74 to 2000 are visualised in Figure 21. The position of the shoreline is derived from aerial photographs and satellite images.

Figure 21: CHANGES OF THE SHORELINE IN THE PERIOD 1973-2000



Growth of vast area of new land off the Noahkali coast and Char Bouy can be observed which is associated with an even larger area of mud flat that appears to be emerging land. Between 1996 and 2000 several new large chars appeared in this shallow area.

There are new char areas and new areas of mud flats north-west of Sandwip Island, which continue to grow at high paste. Other large areas of accretion include the very large char in the Lower Meghna Channel that appears to be a consolidation and extension of Char Gazaria. New chars form in the northern extension of Manpura and in the West Shahbazpur Channel. There is a significant accretion at the north-east of Nijhum Dwip, extending this island towards Hatia. A char right east of the channel between Hatia and Nijhum Dwip continues to emerge from the large mud flat.

Filling and enlargement of chars in the extreme south-west of the study area, including Char Rangabali, Char Montaz and Char Kukri Mukri is observed.

Most areas of erosion are associated with widening and migration of the main Lower Meghna and the Shahbazpur and Hatia Channels. The northern end of Hatia retreated 5 to 9 km in the period 1973-2000. In the period 1990-2000 the bankline retreated 2.5 to 3.5 km. Also eastern bank of Bhola suffers from severe erosion, with its most extreme form found west of Char Gazaria. It is believed that these areas are sensitive to changes in river and sediment discharges.

6.4 Recent Accretion and Erosion

Hydrographic surveys of the study area were carried out in 1997 and 2000. The bathymetric maps derived from these two surveys have been compared to analyse the morphological changes that occurred in this 3 year period. Despite relatively short period of comparison, large bathymetric changes can already be detected. The total study area has been divided to 7 subareas (see Figure 20), which are analysed separately. The difference maps showing accretion and erosion patterns in the study area during 1997-2000 are presented in Annex C.

Area 1 (northern reach of Lower Meghna)

Largest changes in this area in the period 1997-2000 are observed at the level of Hanar Char. A large char (Char Bhairabi) developed in the middle stream of the river, deflecting the flow. This char accretes distinctly to the west, towards Gosair Hat. Deep channels are located very close to both river banks. River widens, especially on the western side. Western channel moved to the west by 2-2.5km over a distance of approximately 7 km. Migration of this channel causes extensive erosion. Directly north of this zone, the western channel moved away from the west bank. Comparison of cross-sections in the branches on both sides of Char Bhairabi indicates that the importance of the eastern branch increases. This, once lateral branch increases in size and may become the main branch in the future. This may locally reduce the erosion of the west bank.
At the level of Chandpur, the main channel moved to the west, causing some erosion of the river bank. Downstream of Hanar Char, some accretion occurred along the east bank. This is related to the migration of the channel to the west. The same is observed near Ramgati.

Area 2 (middle estuary)

Largest morphological change in this area is related to the migration of the Hatia Channel. At the level of North Hatia, extensive accretion is observed on the southern side (Noakhali mainland/ Bouy Char), reducing the depth of the channel and forcing the main water flow towards the northern head of Hatia. This results in the migration and strong deepening of the Hatia Channel, and large-scale erosion of the head of the island. Towards north, Hatia Channel passes the accreting area close to Char Bouy and moves north to the east bank, causing erosion near Char Alexander. At the upstream head of Char Gazaria some erosion is observed. Large very shallow flats west of Char Gazaria extended to the west.

This is associated with the migration of the West Shahbazpur Channel, which moved very close to the bank of Bhola causing erosion of the riverbank. Analysis of cross-sections shows that the ration in cross-sectional area of west and east channel on both sides of Char Gazaria changed between 1997 and 2000 from 40% to 20%, which means that the east channel becomes more important in conveying the flow.

Area 3 (Hatia-Manpura)
Compared to Area 1 and 2, this area remained reasonably stable during the period 1997-2000. Erosion at the entrance to the West Shabhazpur Channel, between Bhola and Sonar Char can be seen. Alternating pattern of erosion and accretion in the longitudinal direction can be seen in the West Shabhazpur Channel between Hatia and Manpura. This is related to migration of the main conveyance channel. Accretion west / north-west of Nijhum Dwip, and between Hatia and Nijhum Dwip occured. Accretion is also observed around chars between Hatia and Manpura. This contributes to the overall shallowing of the East Shahbazpur Channel.

Area 4 (Urir Char-Sandwip)
Vast accretion is observed at the northern head of Sandwip. Also some accretion is found along eastern bank of Sandwip, and between Sandwip and Char Piya. A narrow, deep channel along the west bank of Sandwip shows tendency to migrate towards east, causing some erosion. Only a part of Area 4 was surveyed in 1997, therefore no information is available for analysis of morphological development of shallow areas west of Sandwip.

Area 5 (South-east)
In this area, south of Sandwip and east of Hatia, no large bathymetric changes are found. Shallow areas north-east of Hatia extended to the east causing migration of the Hatia Channel to the north at the level of island's northern head, and to the east in the southern course of the channel.

Area 6 (South-West)
This area south of Char Montaz and Rangabali is very dynamic. Distinct bed forms have developed by the combined forces of waves, tidal flow and river flow. These bed forms are very movable. Alternating patterns of accretion and erosion can be observed.

Area 7 (Sandwip Channel)
The Sandwip Channel remained quite stable during the period 1997-2000. A tendency of erosion can be seen in the southern part of the channel, while some accretion is found in the north. Comparison of cross-sections, however, shows that these changes are insignificant.

6.5 Shoreline Migration

Studies of shoreline dynamics have been used to establish the rate and distribution of shoreline erosion and accretion, trends of shoreline migration and patterns of overall shoreline movement. Aerial photographs of 1956-1957 and satellite images from 1973 to 2000 have been used to identify trends in the movement of the banklines. The following areas have been considered in detail:

- Chandpur and North Bhola
- Bhola - Manpura - Hatia
- Sandwip - Chittagong mainland
- Noahkali - Char Balua

The analysis of shoreline changes has been carried out by deriving the positions of west and east banks (north bank in the case of Noakhali-Char Balua and Hatia-North) along about 200 transects spaced at

1000 m to 2000 m intervals. The average rate of migration for each transect is estimated by linear regression of the bankline position over the period 1957-2000.

6.5.1 Shoreline Migration in the Area Chandpur-Daulatkhan (Northeast Bhola)

The shoreline migration in the area Chandpur - Northeast Bhola is strongly related to the lateral migration of the tidal-river system. The northern part of the Lower Meghna Estuary river system has a wide, shallow, braided distributary system. Channels bifurcate, are separated by shallow shoals and islands and are choked by sandy sediments.

The west bank of the Lower Meghna River starting from the downstream of Chandpur towards south up to the northing of about 530 000 N (north of Mehendiganj) shows net accretion (average accretion is about 4 km) and the same bank starting from the north of Mehendiganj towards south up to about 500 000 N (Daulatkhan) experienced net erosion (average erosion is about 2.4 km) between the period 1974-2000. The rate and time trends differ in detail due to local influences such as changes in the growth or erosion of primary island-chars.

Movement of the west bank was more unsteady during the 70's and 80's. Particularly in the areas between Chandpur and North Bhola (533,000 N – 560,000 N) the shoreline moved eastward due to rapid siltation. These peaks of rapid accretion corresponded with the shift of the main channel in an eastward direction that created new island-chars at the west bank. Late in the 80's the chars consolidated and formed new bankline. This area is now subject to severe erosion. The average erosion rate in the area between (533,000 N- 560,000 N) over the period 1990-2000 varies from 50 m/y to more than 300 m/y.

Between 1974 and 2000 the east shoreline moved steadily eastward along most of its length. Only the area between (508,000 N – 516,000 N) remained relatively stable over the last decades. The maximum retreat is found downstream of Chandpur (550,000 N – 565,000 N) and near Char Alexander (495,000 N – 505,000 N). The average retreat of the shoreline is about 90 to 300 m/y. The areas correspond to embayments cut by flow deflected around growing bars and new island-chars near the east bank anabranch of the Lower Meghna River. The bank movement at the level of Char Gazaria is related to the migration of the East Shahbazpur Channel to the east.

The impact of high monsoon floods during 1987-1989 and 1998 in generating accelerated shoreline retreat can be identified in nearly all transects. It can be concluded that the position of the shoreline is very mobile and sensitive to changes in hydraulic conditions. Chars in the Lower Meghna migrate in the downstream direction.

6.1.1 Shoreline Migration in the Area Bhola - Manpura - Hatia

The west bank of Hatia shows a net retreat of the shoreline to the east. The rate of erosion varies between 5 to 50 m/y.

The east bank of Hatia from 468 000 N to about 482 000 N experienced net erosion and the same between 442 000 N and 467 000 N experienced net accretion between 1974 and 2000. The maximum bank erosion takes place at the northern head of the island. The rate of erosion is very close to 300 m/y. This is related to the migration of the Hatia Channel to the south. Data from all the transects indicate that the island is migrating in south-east direction.

The long term shoreline migration of Manpura shows erosion at the west bank and both erosion and accretion at the east bank. The migration rate of the shoreline varies 1 to 25 m/y at the west bank and from 2 to 20 m/y of erosion and 2 to 35 m/y of accretion at the east bank. Infilling of channels occurred between the islands in Manpura which joined together to shape the island. There is a tendency of lengthening in the southern direction.

The small islands between Manpura and Hatia, and between Hatia and Bhola are relatively young islands which started to emerge during the 1970's and 1980's. These islands silted up vary rapidly and extend in southern direction. The shoreline of these islands during the last decades shows a natural tendency to shift in a southward direction. Between 1993 and 2000, large chars emerged right north and northeast of Manpura.

Nijhum Dwip is a relatively young island that started to emerge in the 1950's. During the 1970's and 1980's the higher parts of Nijhum Dwip silted up rapidly to about mean higher high water level. The coastline migration during the last decades shows a natural tendency to extend in an eastward direction.

Analysis of the shoreline development of Damar Char over the last decades indicates that the island started to emerge in the 1980's. The uncovered accreted intertidal areas around Damar Char show a tendency to silt up rapidly.

The shoreline migration of Bhola shows a long-term trend of erosion. The bank erosion rate decreases slightly in southward direction. The long-term bank erosion rate varies from 10 to 150 m/y. The southern part of Bhola shows a tendency of accretion. The accretion rate in the southern part is about 10 to 60 m/y.

6.1.2 Shoreline Migration in the Area Sandwip - Chittagong Mainland

The shoreline migration of the Chittagong mainland shows an overall tendency to shift in westward direction (i.e. accretion). The migration rate increases in northward direction. The rate varies from 5 to over 150 m/y. The maximum migration rate is found around the inlet of the Feni River. During the 1980's and 1990's erosion of the coastline is found near the entrance of the Karnafuli River. The erosion process has now stopped due to coastal erosion protection measures.

The east and west banks of Sandwip show a tendency to erode. The migration rate is about 10 to 100 m/y. The shoreline development at the northern head of Sandwip over the last decades shows a trend of severe erosion during the 1970's, 1980's and the first half of 1990's. This trend reversed during 1996-2000. The movement of the shoreline indicates emergence of a large mudflat at the northern head of Sandwip island. Urir Char is a very dynamic island that tends to move in north-east direction. The south-western part of Urir Char shows a long-term trend of erosion.

6.1.3 Shoreline Migration in the Area Noahkali - Char Balua

The shoreline development in the southern part of Noahkali mainland over the last decades indicates a long-term trend of accretion. The accretion rate varies from 50 to about 400 m/y. Erosion of the shoreline can be recognised near Char Balua due to migration of the tidal channel in northward direction. The erosion rate varies from 80 to 200 m/y.

6.2 Channel Migration and Channel Geometry

6.2.1 Channel Migration

It has been observed that in the course of some years, a few channels in the project area shifted their main conveyance section from one bank to the other (or from one channel to another channel in case of composite cross-sections) due to changes in the hydraulic and morphological regime. Consequently, the position of thalweg (line connecting deepest points in subsequent cross-sections) also shifted and

this was the most significant change observed within the channel systems. It is important to know the position of thalweg in the sense that e.g., sometimes, it can be used to ascertain the setback distance of embankments in coastal areas in conjunction with the coastline migration rate and also to locate a navigation route for large-draft vessels.
To identify trends and to estimate the migration rate of the thalweg, 5 cross-sectional profiles in the project area were selected. These selected cross-sections which cover the area around Bhola-Hatia and the area around Urir Char-Sandwip were profiled more than five times over the last 15-20 years. These two areas are experiencing significant accretion and erosion due to migration of the channels. The trend and migration rate of the thalweg for each cross-section has been examined by plotting the position of the thalweg for each time period.

Figure 22 shows the overall trend of migration of thalweg for the selected cross-sections with arrows indicating the dominant direction of migration and the average rate. The results of the analysis are presented in Table 15.

Table 15: Average Migration Rate of the Thalweg

cross-section	period	average migration rate [m/y]	dominant direction
Bhola -Hatia			
2	1983-2000	270	towards Hatia
4	1983-2000	130	towards Char Bouy
5	1990-2000	600	towards Bhola
Urir Char-Sandwip			
6	1981-2000	nil	
8	1994-2000	440	towards Urir Char

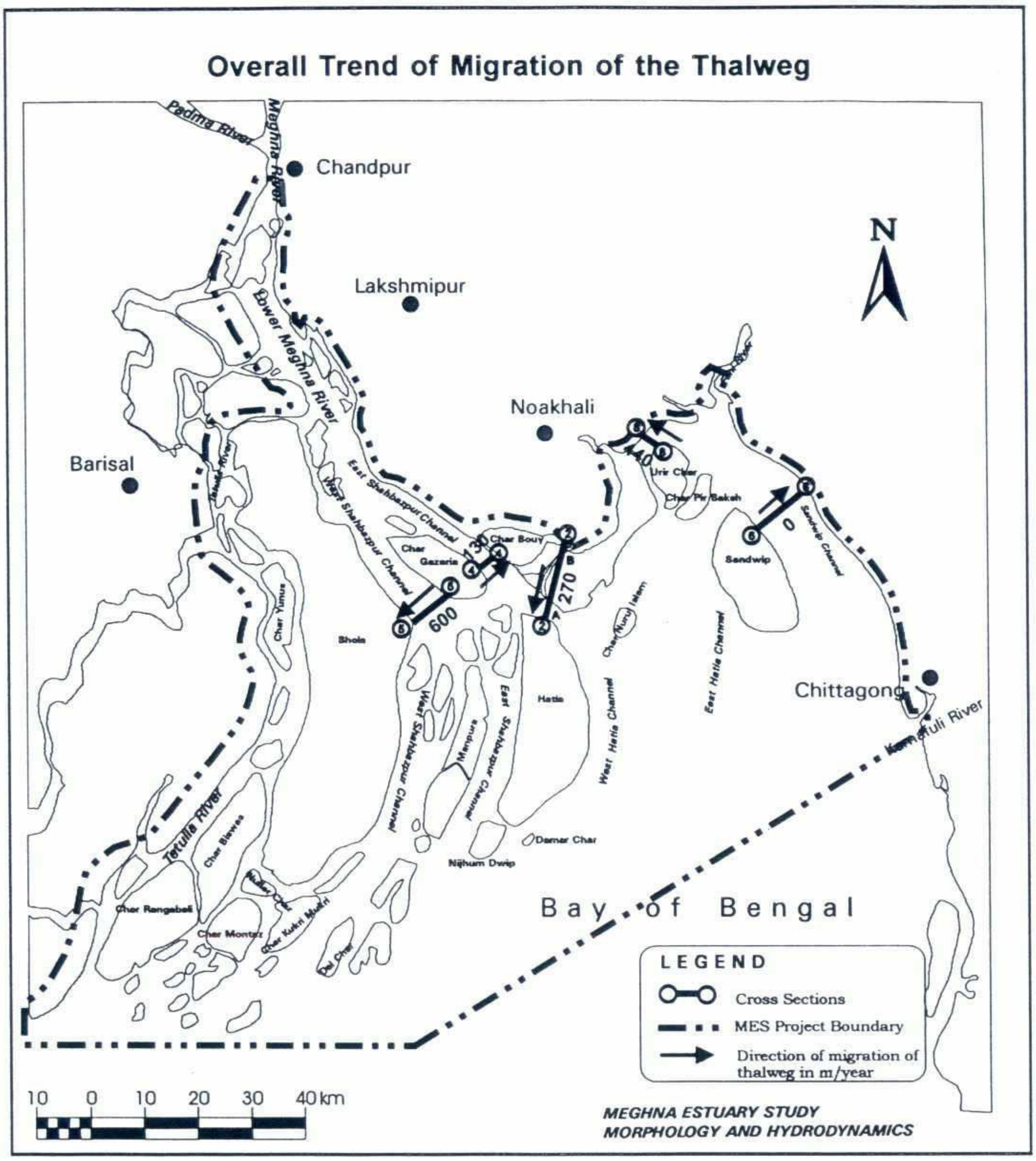
Data of cross-section 2 (figure 23) over the period 1983-2000 indicate that the position of the thalweg was always close to the North Hatia bank which fits very well with the field observation that North Hatia is being continuously eroded. The average migration rate of the thalweg is about 270 m/y. The overall trend of thalweg movement observed at cross-section 4 is towards Ramgati on the Noahkali mainland side. This movement is proceeding at an average rate of about 130 m/y.

Analysis of cross-section 5 (see Figure 24) shows that the main channel shifted from Bhola side towards Char Gazaria between 1983 and 1990, but in 2000 it is located again at the Bhola side. The rate of migration of thalweg towards Bhola in the period 1990-2000 is about 600 m/y indicating that the channel position is very unstable.

Cross-section 6, between Sandwip and Chittagong mainland has a regular shape and the bottom is nearly flat. The deepest part of the channel is located close to Chittagong mainland. The thalweg remained within approximately 400 m during last 18 years and the deepest point is found now at the same place as in 1982.

The area around Urir Char is very dynamic. Data of cross-section 8 show the overall migration pattern of the thalweg is towards Char Balua in the period 1982-1994, but since then the trend has reversed and the thalweg migrated towards Urir Char at approximately 400 m/y.

Figure 22: Overall Trend of Migration of the Thalweg

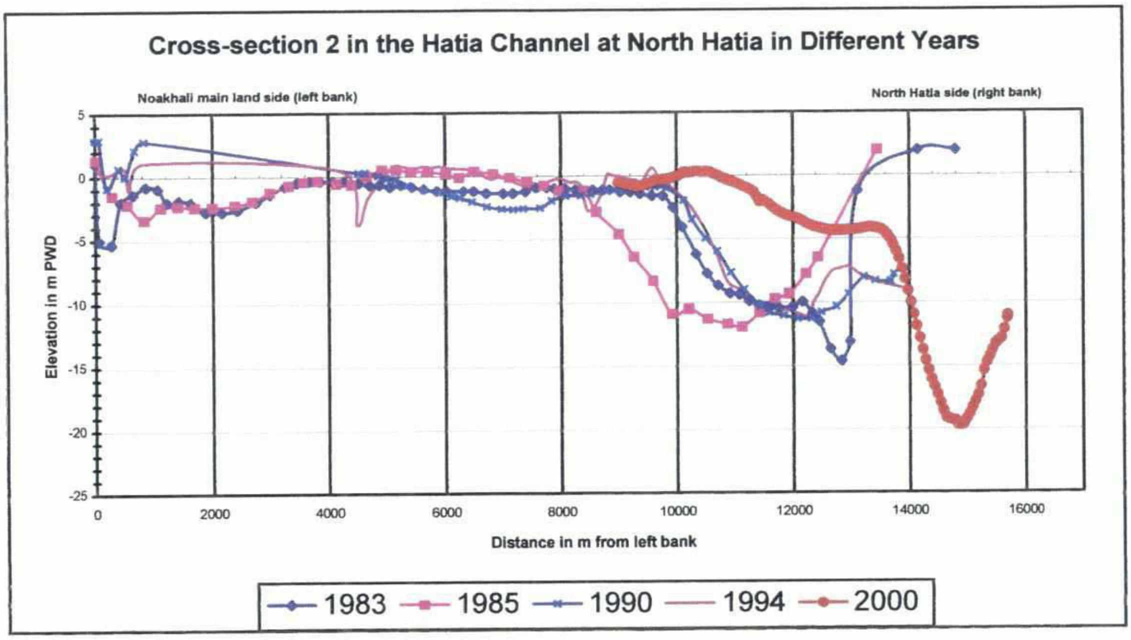


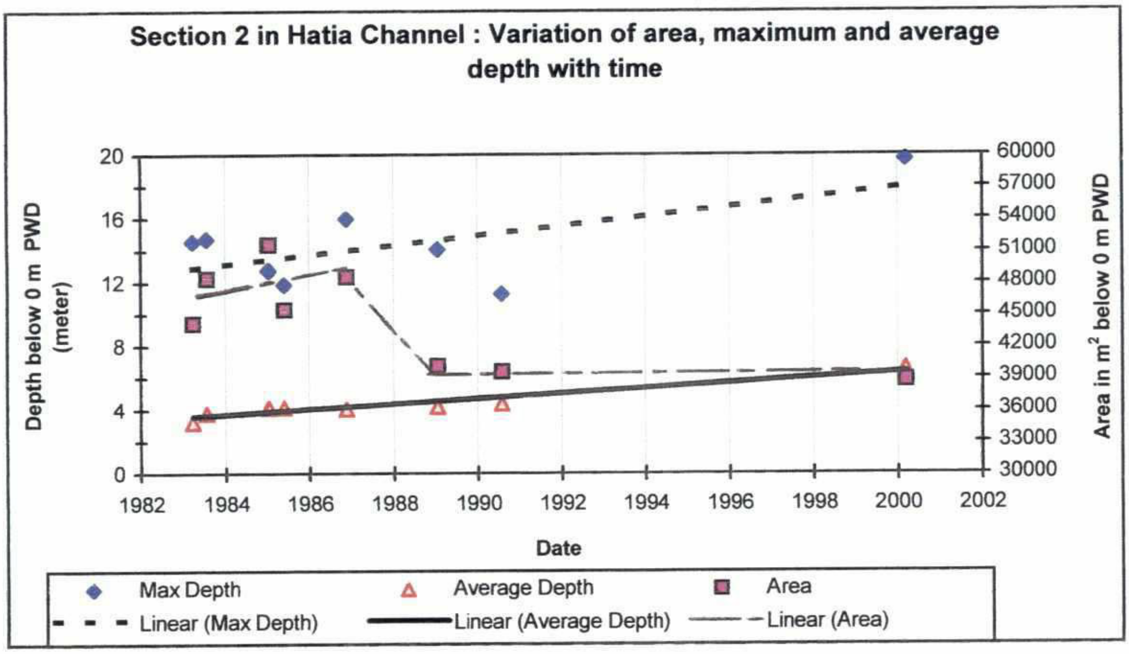
6.2.2 Channel Geometry

The cross-sectional data contain important information on channel characteristics and horizontal and vertical stability. In the present study 7 cross-sections have been selected for detailed analysis considering average and maximum depth and cross-sectional area.

These selected cross-sections, which cover the area around Bhola-Hatia and the area around Urir Char-Sandwip have been profiled more than five times over the last 15 years.

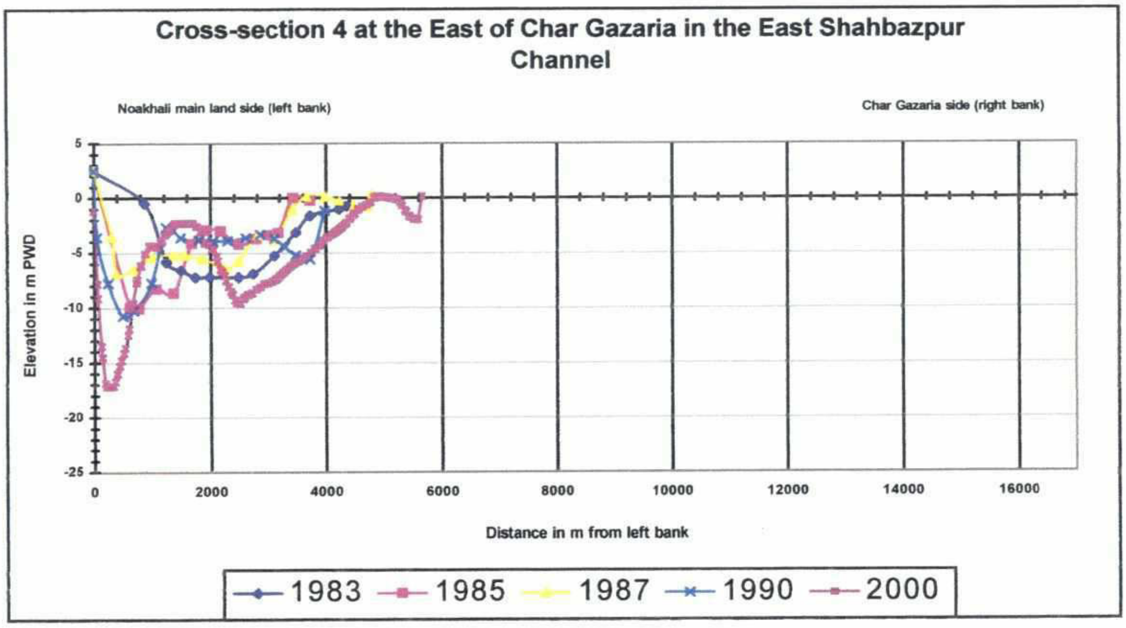
Figure 23: Long term changes in cross-section 2 between North Hatia and Noakhali

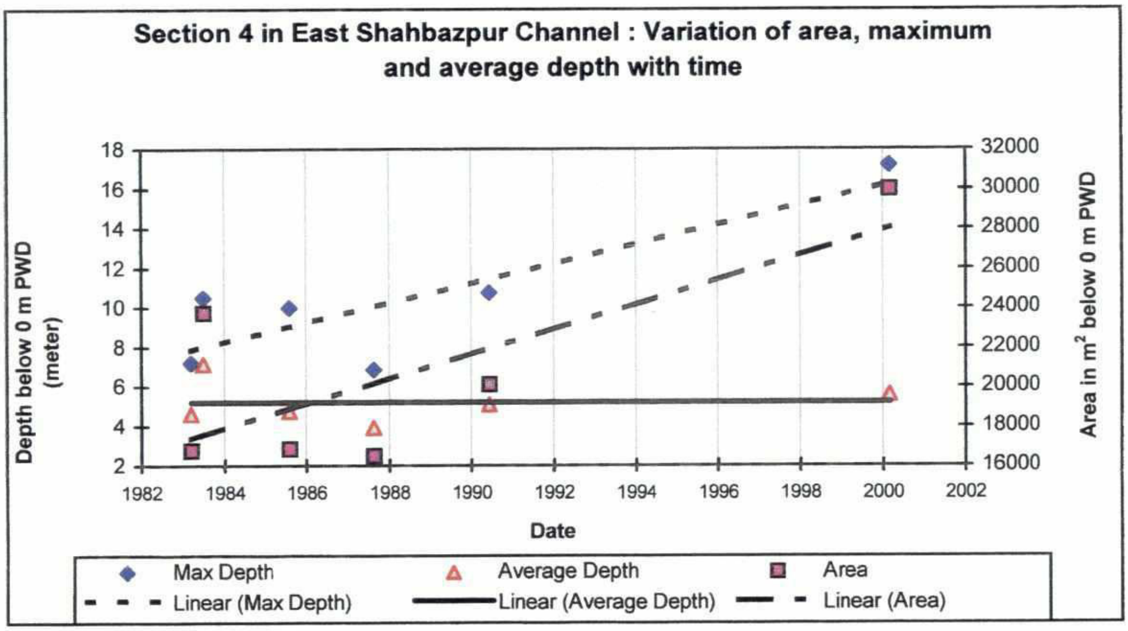




Shape of the cross-section 2 (Figure 23) in Hatia Channel at North Hatia has changed dramatically over the years. The width of this once 15 km wide, relatively shallow channel is reduced at present to 5 km due to the land forming on the Noakhali side. The main conveyance section becomes smaller and deeper. The maximum depth increased from about 12-15 m in the 80's to over 20 m in 2000. The area of the cross-section remained stable up to 1987, then decreased in 1987 and from 1987 to 2000, the area remained more or less the same. The channel moves towards Hatia causing severe erosion of the northern head of the island.

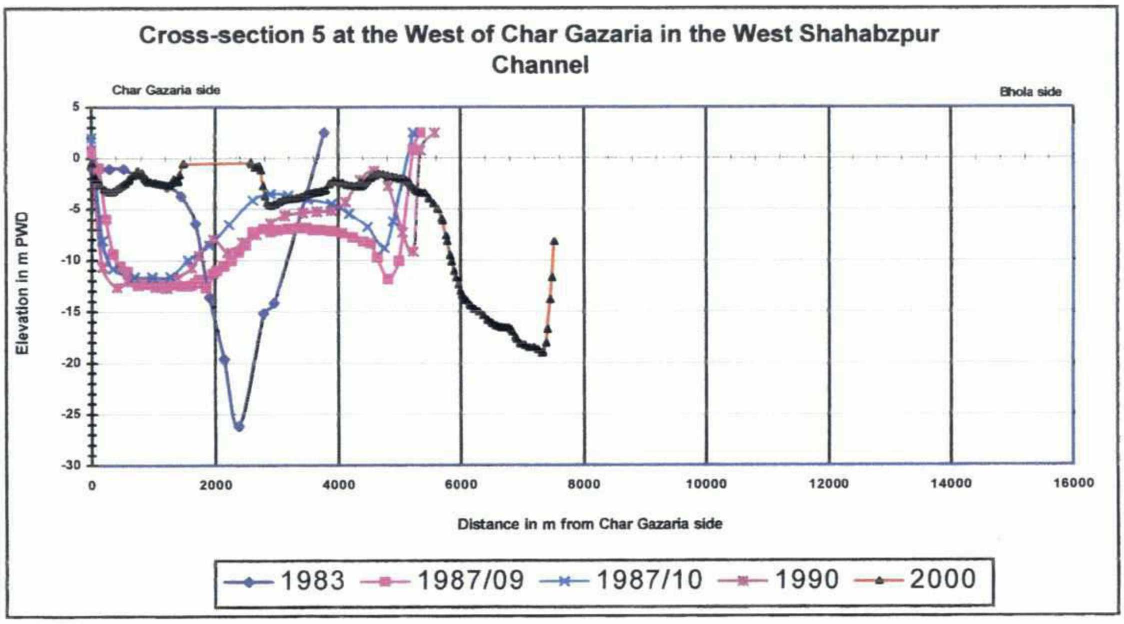
Figure 24 : Cross-section 4 at the East of Char Gazaria in the East Shahbazpur Channel





The East Shahbazpur Channel (Figure 24) widens. Cross-sectional area at the east of Char Gazaria increased by 250% compared to 1990. The main conveyance section became narrower and deeper (18 m compared to 10 m in the 80's). This section moves towards east causing erosion of the Noakhali coast.

Figure 25 : Cross-section 5 at the West of Char Gazaria in the West Shahbazpur Channel



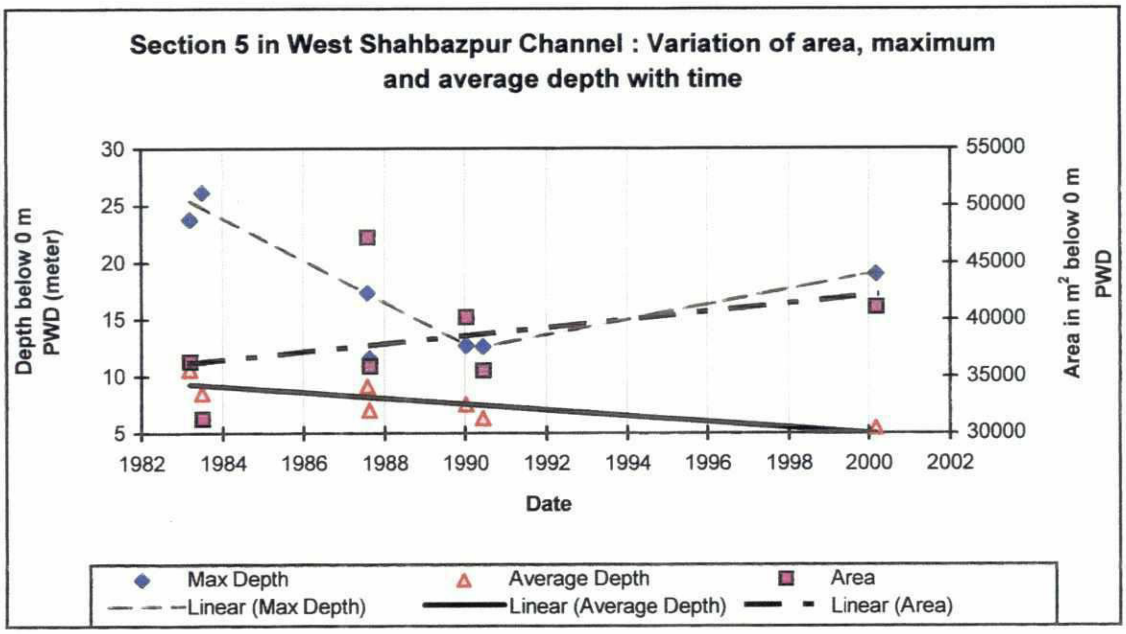
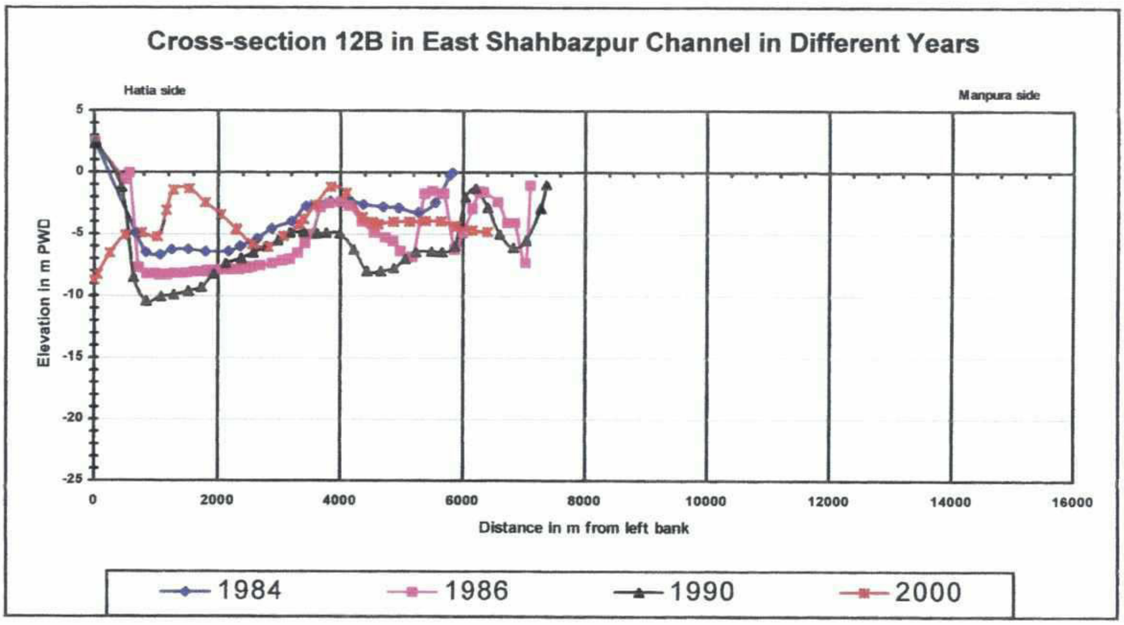
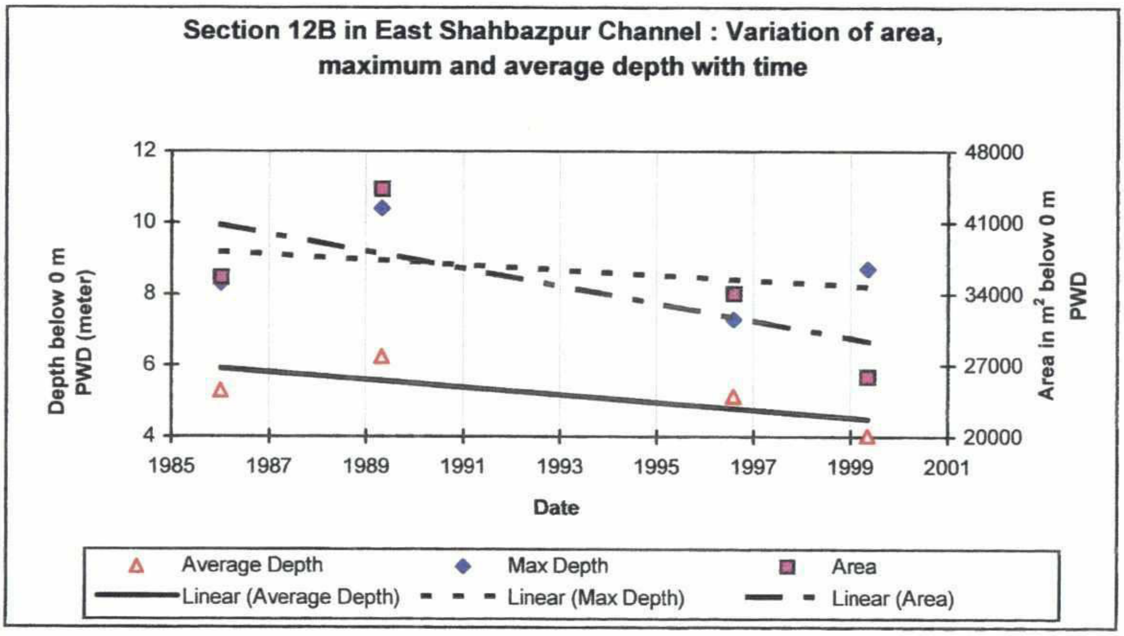


Figure 25 the dynamics of channels in the Meghna Estuary: the West Shahbazpur Channel at the west of Char Gazaria, once a very deep (26 m in 1983) and narrow channel, is now much wider and less deep. Between 1983 and 1987, however, this channel became wider and shallower. At present, the cross-sectional area increased slightly, and the main conveyance section deepened to about 20 m and moved westwards towards Bhola.

Figure 26 : Cross-section 12B between Hatia and Manpura in the West Shahbazpur Channel

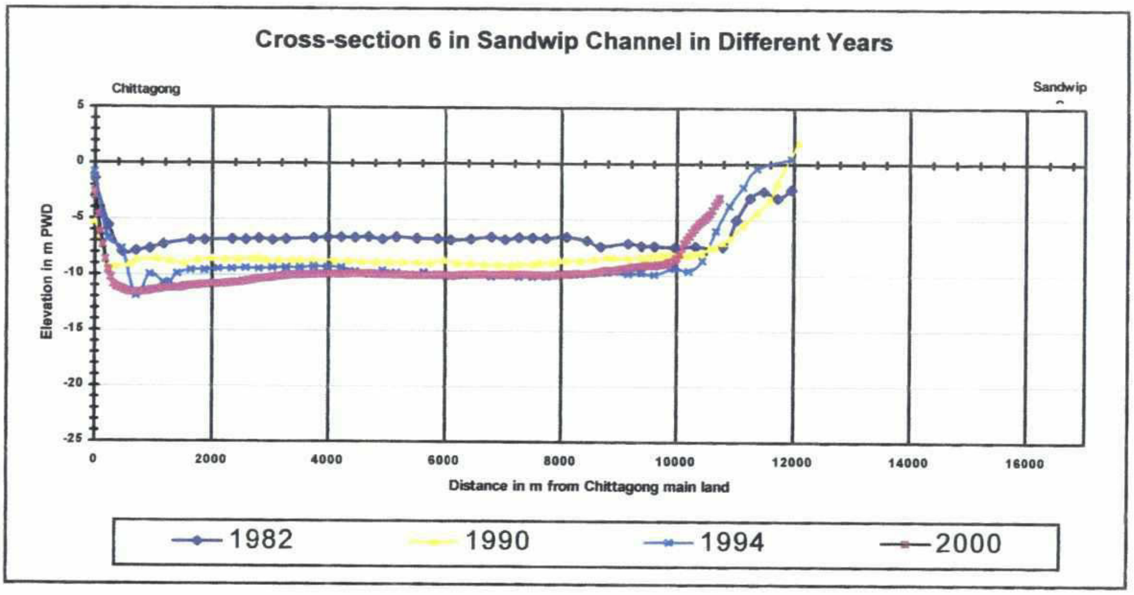


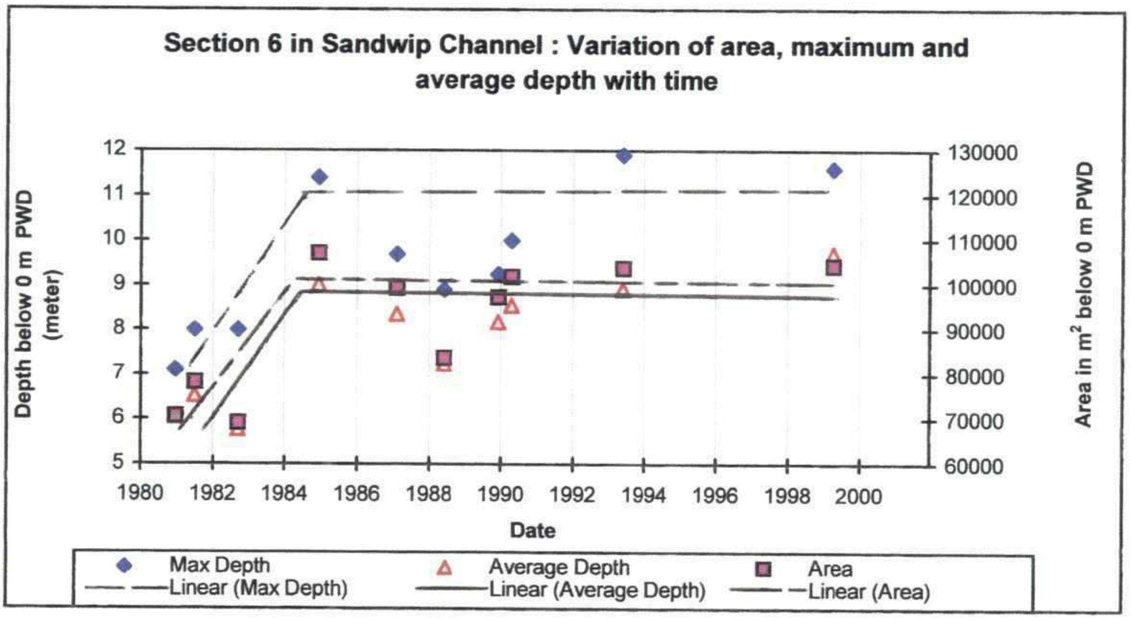


Cross-section between Hatia and Manpura in the East Shahbazpur Channel (Figure 26) is also very dynamic, frequently changing its shape. Shallows appear and disappear in the mid section. Deepest part moved towards Hatia causing erosion of riverbanks. The cross-sectional area and the average depth show a distinct tendency to decrease.

Generally, in the western part of the estuary, influenced mainly by the river flow, the deepest sections of channels, once located in the middle of the cross-section, show now a tendency to move close to the river banks, undercutting them. At the same time shallows and chars develop in the middle part of the cross-sections.

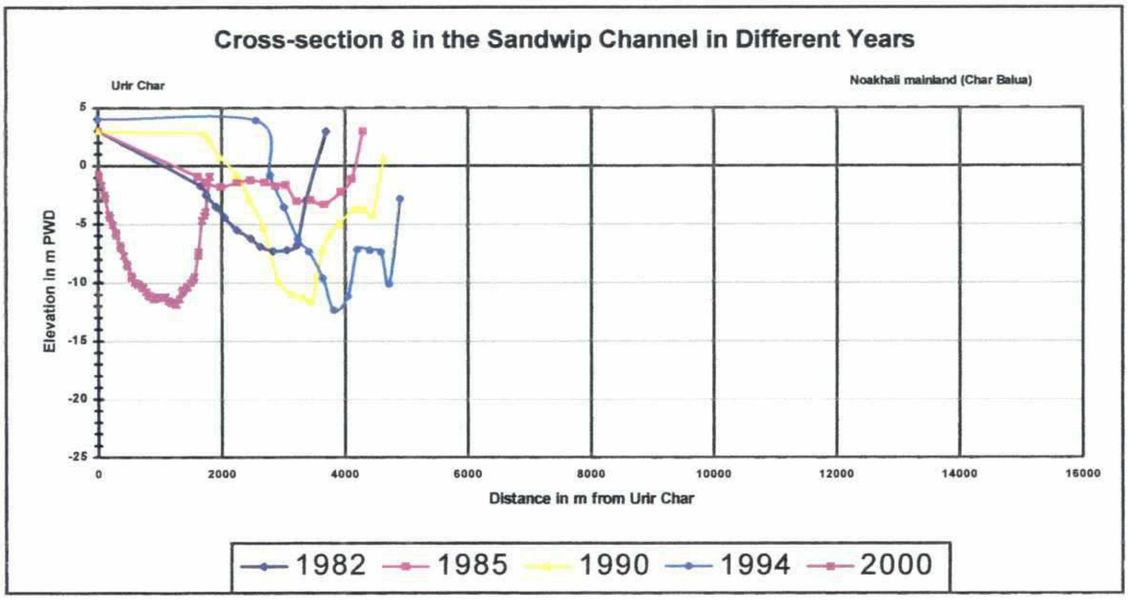
Figure 27 : Cross-section 6 at the Northeast of Sandwip in the Sandwip Channel

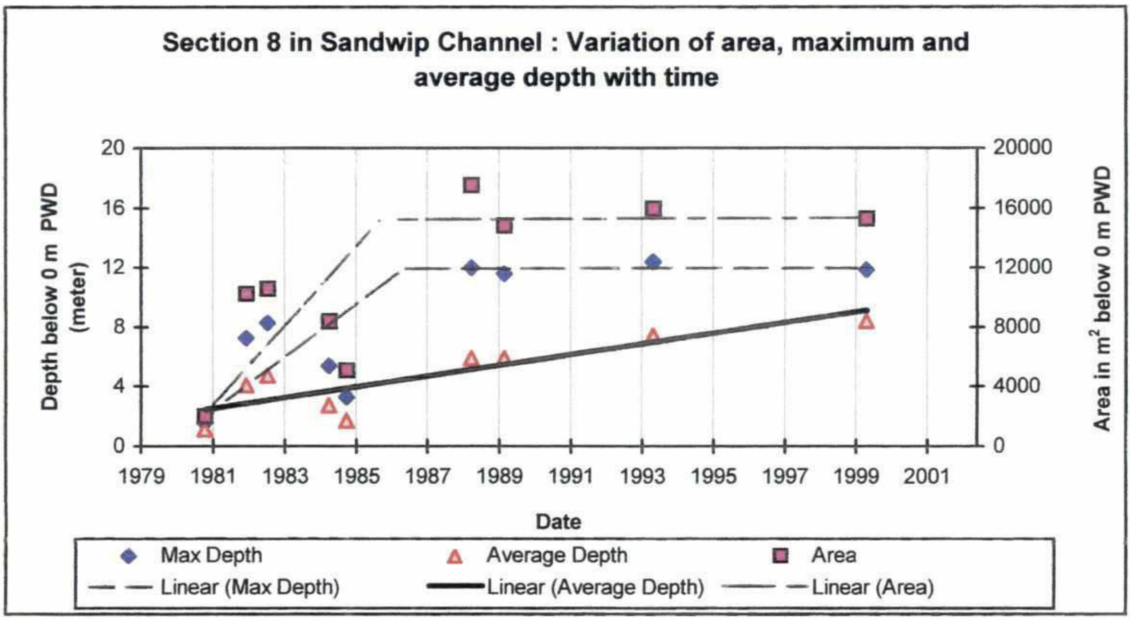




Cross-section 6 in the Sandwip Channel (Figure 27) shows a long-term trend to stabilise in depth and in cross-sectional area. The cross-section is very wide (more than 11 km) and nearly flat. Since 1985, the average depth and cross-sections remained nearly constant, which indicates that the channel is quite stable.

Figure 28 : Cross-section 8 between Urir Char and Noakhali Mainland





Analysis of the cross-section between Urir Char and Noakhali mainland indicates that the maximum depth increased from 7 m in 1982 to 13 m in 1994 (Figure 28). This cross-section has undergone enormous metamorphose due to a very dynamic character of the chars in this area. Between 1989 and 2000, the cross-sectional area remained quite stable.

7 ANALYSIS OF DOMINANT HYDRAULIC AND MORPHOLOGICAL PROCESSES

7.1 Introduction

Important factors that shape the Lower Meghna Estuary Area are the hydrodynamic factors: tides, river inflow, estuarine circulation, waves and atmospheric forcing. The resulting estuary is primarily a consequence of the interaction of these factors acting all over the estuary or in specific parts of it. Interactions between these factors are complex, and mostly non-linear. Evidence of this are the geomorphologic changes that occur in the estuary with the sediment transport processes. The general sedimentology of the Lower Meghna Estuary is the consequence of many conditions. One of the most important is the sediment source, which may be the river, the adjacent delta and shelf from which sediment is transported by littoral currents and introduced into the estuary by upland flow tidal action or littoral drift. Except in the shallow sandy areas of the nearshore zone and at the upper part of delta front (e.g. south and east side of Hatia, the east side of the Sandwip Channel), the importance of littoral drift is negligible compared to tidal action. Furthermore, within the estuary proper, sediment distribution is extremely variable reflecting the hydrodynamic conditions and the particular transport processes that are dominant in each portion of it. In the next paragraphs all these aspects are treated in detail.

7.2 River and Tidal Dynamics in the Meghna Estuary

The circulation patterns, particularly in the lower portions of the Meghna Estuary Area are highly affected by river and tidal dynamics, resulting in characteristic morphological patterns.
Flow friction and river flow decrease the tidal effect land inwards as the river influence becomes progressively larger. The tidal influence reaches about as far as the Ganges-Jamuna confluence. At Baruria still some tidal influence is felt in winter.

The degree of salt intrusion depends on season and climatic conditions. Salt intrusion is an important factor that affects the sediment transport dynamics and hydro-morphological conditions in major portions of the coastal area, in particular during pre-monsoon and post-monsoon. During the monsoon period the salinity in the Meghna Estuary area drops considerably and the water becomes almost completely fresh in the major part of the area (see Chapter 3.5).

The velocities in the Lower Meghna River usually decrease in downstream direction as flow expands into the estuarine section of greater cross-sectional area near the river mouth. In the transition zone of the Lower Meghna Estuary area fresh water encounters and mixes with saltwater; sediment-transporting capacity diminishes and sediments are deposited. The periodic rise and fall of tide results in the temporary storage of large volumes of sea water in the estuary during high tide, followed by drainage at low tide. The volume of water exchanged by tide -the tidal prism- during pre-monsoon and post-monsoon is at least an order of magnitude greater than the river discharge.

The tidal prism in the Lower Meghna Estuary system varies significantly over a spring-neap cycle and shows seasonal effects. It is assumed that the Lower Meghna Estuary system displays large variations in mixing and therefore in density circulation.

In the major part of the Lower Meghna Estuary, the effects of the tide produce bi-directional currents and high shear stresses during peak flows. Although residual flow will be directed downstream, reversals in tide will periodically shift the fluvial-marine interface up and down the distributary channels. Under low tidal energy conditions (neap-tide) or high river discharge outflow conditions, the fluvial-marine interface shifts in seaward direction. The fluvial-marine interface shifts upstream under high tidal energy conditions (spring-tide) and under low river discharge conditions.

In terms of sediment dynamics, one of the most important morphological aspects of the Lower Meghna Estuary is the way in which tide propagates upstream. The speed at which tide moves up the estuary is a direct function of water depth. Because of this depth dependence, tidal waves are deformed during upstream propagation as flood crests overtake ebb troughs, in an extreme case forming tidal bore in the channel north of Urir Char.

The result of this is twofold. Firstly, flood velocities will exceed ebb velocities, but be of shorter duration. Secondly, the period of high-water slack will become longer than that for low-water slack. Consequently, the degree of tidal asymmetry increases upstream, magnifying the differences between ebb and flood velocities and slack-water duration.

Figure 29: Magnitude of the Major Tidal Constituents (M2, S1) along the Lower Meghna Estuary

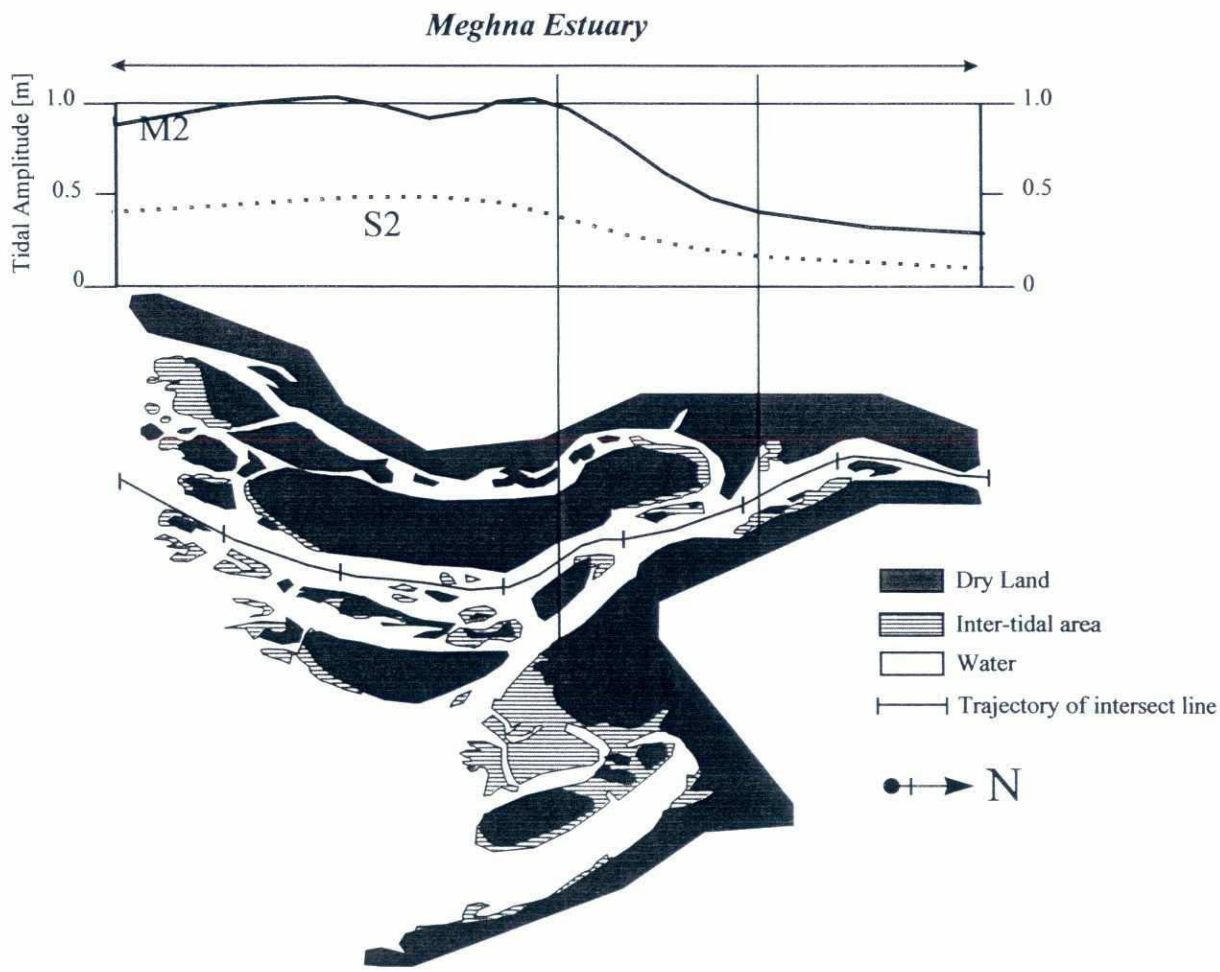


Figure 29 illustrates the effect of deformation of the tides along the Lower Meghna Estuary. This figure shows that tides also tend to increase in amplitude from upstream convergence. Decrease in depth and width resulting from the characteristic funnel-shaped geometry forces the tidal wave through progressively smaller cross-sectional areas. However, frictional dissipation from the bottom and banks of the estuary occurs with convergence of tidal energy, and tends to counteract it, thus decreasing the amplitude. System in which the effects of convergence exceed frictional dissipation, which is the case in the Lower Meghna Estuary, is referred to as hyper-synchronous.

The effect of this will be that tidal currents actually reach their maximum speeds part way up the estuary; ultimately, however, tidal energy is diminished and both amplitude and speed decrease.

7.3 Dynamics of Estuarine Sediments

The extension of tide into the Lower Meghna estuary has a substantial effect on both bed-load and suspended-load dynamics. Tides can affect sediment dynamics by:

- producing bi-directional sediment transport,
- creating dominant ebb or flood transport pathways
- producing net landward bed-load transport
- prolonging flood-tide deposition of fine-grained sediment
- allowing formation of a tide-induced turbidity maximum due to salt intrusion
- importing a fortnightly rhythm that is important in the formation of fluid mud deposits.

Although each of the above is controlled by tidal interactions, not all are equally well developed within the Lower Meghna Estuary and the influence is often seasonally and climatically dependant.

The reversals in tide that produce bi-directional currents also produce patterns of bi-directional bed-load and suspended load transport, in particular under spring-tide and low river discharge conditions. Typical current speeds of 1 to 3 m/s which are measured in the East-Shahbazpur channel as well as in Sandwip channel, are sufficient to keep sediments in motion for much of the tidal cycle, forcing channels to continuously adjust to erosion and deposition. This adjustment often leads to mutually evasive currents and pathways of sediment transport, such that some channels may be dominated by ebb transport and others by flood transport.

Pre-monsoon and post-monsoon measurements in the East Shahbazpur channel indicate a net upstream sediment transport during spring-tide. This net upstream sediment transport can be found up to Char Bouy. It is possible that this upstream sediment transport of fine grained sediments might be caused by the response to a time-velocity asymmetry. The net upstream transport continues to upstream of Char Bouy. In the East-Hatia Channel the flood transport of fine sediment seems to be balanced by ebb transport where flow becomes concentrated during falling tide.

Periods of slack water affect sedimentation by providing an opportunity for deposition of muds. Longer periods of slack water following flooding tides, as a result of tidal deformation, will favour deposition of sediment in the upstream reaches of the Lower Meghna Estuary. Over numerous tidal cycles processes of infilling are likely to be enhanced.

The ability of ebbing tides to erode these deposits could be diminished by the fact that (i) there is a time delay between the moment at which flood current of decreasing speed can no longer hold particles of a given size in suspension and the moment at which they reach the bottom and, (ii) there is a difference between the maximum speed at which deposition of given particle sizes can occur and the minimum speed for the same material to be eroded by ebbing current.

7.4 Tidal Turbidity Maximum

Sediment concentration measurements under pre-monsoon and post-monsoon conditions in the Shahbazpur channel indicate a high suspended sediment concentration around north Hatia - Manpura area as well as in the channel around Char Balua - Char Pir Baksh. This high suspended sediment concentration might refer to the so-called turbidity maximum. The turbidity maximum is a zone which contains suspended sediment concentrations higher than both in the river or further seaward in the estuary. It is generally located at, or somewhat landward of the head of the salt intrusion, where salinities are about 1-5 ppt.

The energetic tidal flow is capable of maintaining high concentrations, and there are a number of processes that concentrate the suspended sediment, and prevent particles from dispersing. The peak concentration of suspended sediment in the turbidity maximum varies between wide limits. Despite the differences due to sediment availability in the Shahbazpur channel and Char Balua and Char Pir Baksh have maxima with concentrations of the order 1-9 gram per litre.

The turbidity maximum contains a high portion of a narrow size range of mobile fine sediment, and plays a central role in the circulation of fine sediment within the Lower Meghna Estuary area, as well as probably determining the rate of transport of sediment from the river to the sea. The concentrations of sediment in the turbidity maximum appear to remain almost constant when averaged over a reasonable time, so that residence time of grains in the turbidity maximum must be considerable.

The turbidity maximum responds to changes in river flow, with the maximum moving downstream with increasing flow. The mass of sediment in the turbidity maximum also increases. However, a movement of the turbidity maximum down the estuary involves expansion into an increased cross-sectional volume, and this could decrease the concentration even though the total mass increases.
The seasonal changes in river flow suggest that sediment can accumulate in the upper estuary during pre-monsoon and post monsoon, and can be redistributed down the estuary during monsoon.

A feature of macro tidal conditions (e.g. Sandwip area) is the large difference in tidal range between spring and neap tides. Because of the considerable variation of velocities, there are changes in position and magnitude of the turbidity maximum.

At spring tide the turbidity maximum has its highest concentration, as the currents are able to erode and sustain more sediment in suspension, and it will be located further up the estuary. This is due to the fact that there is a higher mean sea level in the upper estuary at springs than at neap tides, arising because the increased range at spring tides involves a large extra volume of water at high tide, but only a slight volume difference at low tide, relative to the neaps.

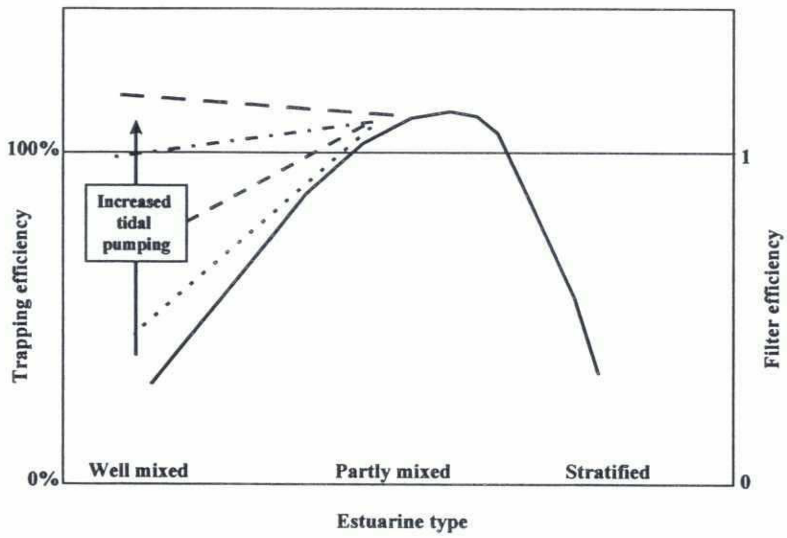
During decreasing tidal amplitude towards neaps, the peak currents decrease, and less material is capable of being re-eroded and suspended. Additionally, the durations of slack water increase, enhancing deposition.

7.5 Residual Circulation and Estuarine Trapping

The river-borne sediments become trapped by the tidal pumping and residual circulation, and mix with material brought in from the sea. In this respect the process of mixing is an important factor. The process of mixing involves continuous erosion, deposition and exchange of sediment within the estuary: the fine sediment cycling through the turbidity maximum and somewhat coarser sediment cycling round the ebb-flood channel systems. Individual particles may spend a considerable time moving within the system before being finally deposited, or passing through to the sea.

Some of the particles entering from the river will remain in suspension and pass through the estuary fairly quickly particularly at times of high river floods (in particular during monsoon period). However, a significant proportion will undergo many cycles of deposition on the bed followed by resuspension, with the deposition occurring at a number of points along the estuary which form temporary sinks for the sediment particles operating for a variety of time-scales.
The trapping efficiency of the estuary is the ratio of the fluvial sediment input, to that accumulated in the estuary (Figure 30).

Figure 30: Variation of Trapping and Filter Efficiency of Various Estuary Types (after K.R. Dyer, 1988)



From literature it is known that for partially mixed estuaries the trapping efficiency can exceed 100%, since the fluvial sediment is only part of that accumulating. The minor part of that drawn in from beyond the estuary mouth is likely to be coastal or marine material, but much will be fluvial material exported at higher river flow stages. Additionally in well-mixed estuaries tidal pumping becomes significant in transporting sediment up-estuary into the turbidity maximum, with the degree of tidal pumping depending on the tidal characteristics, as well as those of the sediment.

Measurements indicate that the Lower Meghna Estuary can be classified as a well mixed to partly mixed estuary. According to Figure 30 it can be assumed that the trapping characteristics of the Lower Meghna Estuary is likely to be fairly sensitive to the topography of the estuary, in its effect on the tidal velocity field, and on the river discharge which affect the stratification and the gravitational circulation. The shape of the estuary is not regular. There are major differences in spring and neap tidal conditions. It all result in the process of ongoing settling and eroding of the same sediment particles and only a relatively small portion of the settled amount permanently settles on the bed when there is net accretion.

The trapping thus undergoes considerable short term and seasonal variability. The sediment particles can be continually cycled from one part of the estuary to another through the turbidity maximum. The major sites of this interchange are the tidal areas (e.g. south of the Noahkali mainland) which show deposition rates of the order of 0.1 to 0.3 m/y.

Seasonal effects in river discharge have also an influence on the trapping efficiency of the estuary. The zone of turbidity maximum changes with the variations in river discharge that influence the sedimentation and resuspension process in the estuary. This can result in resuspension of sediment deposited during monsoon conditions followed by deposition in the river in upstream direction instead of downstream direction.

Sediment transport measurements indicate that a huge amount of sediment is transported through the estuary rather than being deposited in the estuary. This might be an indication that the overall long term trapping effect of the estuary can be classified as low. Assuming that the annual sediment transport amounts to1-1.5 billion m^3, and that the yearly deposition is about 100 million m^3 (in section 5.3.3, net accretion of about 306 million m^3 during 1997-2000 was calculated, the trapping efficiency is roughly estimated at 7-10%. Interventions might have a positive effect on the filter efficiency of the estuary. More investigations are needed to enhance the physical knowledge about this trapping effect and its sensitivity to variations in river and sediment discharge in relation to interventions.

7.6 Waves

In general the influence of the waves in the Lower Meghna Estuary is limited to the shallow nearshore zone and the intertidal areas, and is less important (from the morphological point of view) than the influence of currents. The wind-induced waves often have an important influence on the erosion and deposition processes. Waves generate an orbital velocity that is superimposed on the current velocities thus stimulating erosion from the bottom and preventing settling of suspended sediment. Near the coast the waves may break thus generating a lot of turbulence in the water which is even more effective in generating erosion. Also a net water movement is induced which can transport the sediment brought in suspension. In the case of a net flood flow the suspended sediment can be transported onto the higher parts of the shallow intertidal area where a major part of the sediment can be trapped. If a net ebb current is dominant the flow becomes concentrated in the gullies and sediment is ejected as plumes into the main channels. Generally, wave climate in the estuary is rather mild due to limited depth. Only the most southern part of the estuary is exposed to larger waves (more than 2m during monsoon), up the estuary wave action is damped by breaking on shoals. During cyclones, waves higher than 5m can occur. These waves can cause severe damage and lead locally to large land loss, especially at the outskirts of the estuary. On a larger scale, however, cyclonic events are believed to be too incidental to be relevant from a morphological point of view.

7.7 Bank Erosion Processes

Bank erosion along the Lower Meghna Estuary is mostly related to bank failure. Two types of bank failure generally occur: liquefaction and flowage of material, shearing away of bank materials. The former type of bank failure occurs below the low water level or in the zone of low and high water level. Generally they occur during the recession of flood hydrograph. Recession rates of water level directly influence the rate of failure. The most common processes of bank failure along the Lower Meghna Estuary is due to shearing, caused by flow attacking the bank or over-steepening of the bank by a thalweg approaching the bank. In that case the flow in a river bend attacks the toe of the river bank, removing the sediment from the toe, resulting in an over-steepening of the river bank and causing the bank failure by slumping. A combined effect of flow attacking the bank and wave activity can increase the bank erosion rate drastically especially during the monsoon period. An important factor is the near bank flow pattern which is determined by the flow and the channel geometry. Bank material properties determine the cohesiveness of the bank, an important parameter for the type of bank erosion, and is also important for how quick erosion products are transported by the river and thus determine the time needed for the typical toe-erosion-failure-transport important for mass failures. From the field surveys it seems that in areas along the river where the clay content of the bank material is low the banks are very sensitive to erosion.

Also vegetation plays an important role in bank erosion processes along the Lower Meghna Estuary. Vegetation increases the cohesiveness of the soil. Groundwater flow may also have an important effect on the bank erosion, especially during the recession of flood.

Banks of many islands in the Meghna Estuary (e.g. north-western banks of Hatia, eastern bank of Bhola) are very steep, built of unconsolidated silt / clay layers and prone to excessive erosion by current. Stability of these banks is further undermined by the waves that develop along and behind large ships sailing close to a bank. As the channels in the Meghna Estuary tend to deepen and to move closer to the river banks, the ships sail still closer to the banks to avoid shallow water. The side effect of this is an increase in waves attacking the weak slopes and as a result an increased erosion. This effect has not been studied in depth by MES, but may be an important factor contributing to the excessive erosion observed in the estuary.

The average bank erosion rate at the right and left bank in the area between Chandpur-North Bhola is higher than in other areas due to the migration and widening of the Lower Meghna Estuary channel. In particular the migration rate was very high in period between 1984 till present. The variation of average bank erosion along the channel might be due to the number of higher flood events during this period. Analysis of satellite imageries over the last decades show that the maximum bank erosion can be found at the outer bank of the curved channels. This indicates that there is a relation between bank erosion rate and the curved channel. Hickin and Nanson (1985) found an empirical relation between bank erosion and the ratio between the river width and the radius of curvature. Hickin and Nanson conclude that the maximum erosion occurs at values of R/B of about 2.5. Their findings agree with the results of the analysis of the bank erosion rate. The maximum bank erosion rate in the Study Area is found at the right bank near Haim Char. The ratio between river width and bend radius in this area is about 2.5 - 2.6.

7.8 Conceptual Model of Shaping Processes

Combining the results of bathymetric, hydraulic and morphological analyses with results from numerical modelling has led to the definition of a conceptual model of the geomorphologic processes dominating the development of the coastal area of the Lower Meghna Estuary.
In this conceptual model of driving processes, the Meghna Estuary can be divided into three zones where separate driving forces can be distinguished. In these zones the processes can be described as (i) Marine-dominated, (ii) Mixed-energy, or (iii) River-dominated. All of these zones have their own characteristics concerning sedimentation and erosion. The conceptual model itself has to be divided into two parts, consisting of the monsoon period and the dry-season period. These two periods will be discussed in the following sections.

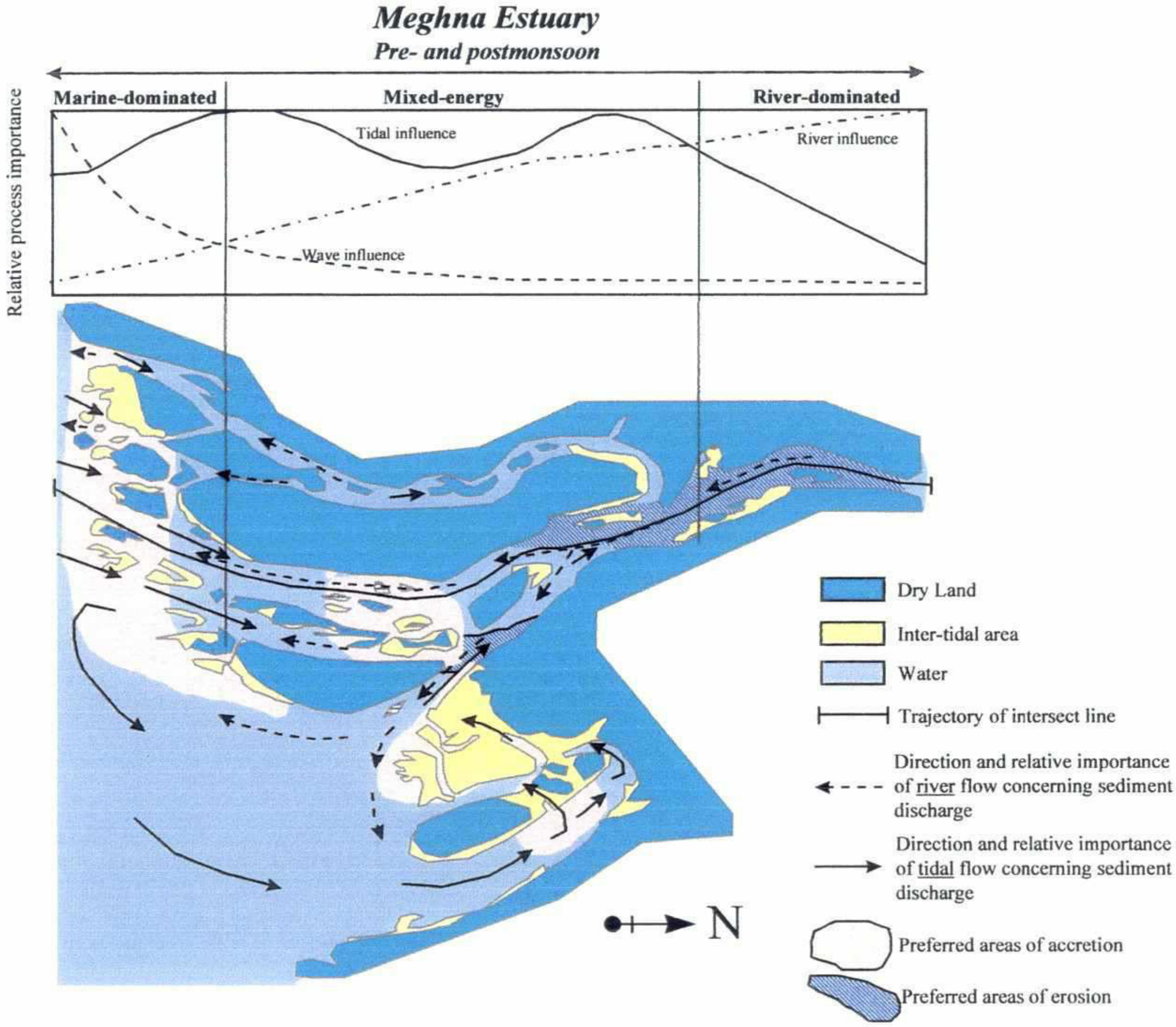
Dry-season period

During the dry-season a relatively large part of the estuary can be described as a well-mixed to a partly mixed system (Figure 31). The sediment trapping efficiency in this area is place and time dependent. The turbidity maximum moves up and down the estuary along with the tidal intrusion. Local shallowing and deepening of the channels results in a spatially varying pattern of energy conditions that has its reflection on erosion and sedimentation (Figure 30).

The southern part of the estuary can be described as Marine-dominated. A relatively important factor in this area is the wave action that results in a net landward transport of sediments, causing accretion on mud flats.

Interaction between tidal currents and river currents forms net circulation patterns in the vicinity of the Sandwip area. This net circulation patterns seems to be acting as a sediment trap. Satellite images taken during the last two decades show a rapid accretion of the mudflats resulting in shallowing of the nearshore waters and growth of new chars at the northern edge of the estuary (south of Noahkali mainland).

Figure 31: Conceptual Model of Dominant Geomorphological Processes during Dry-season



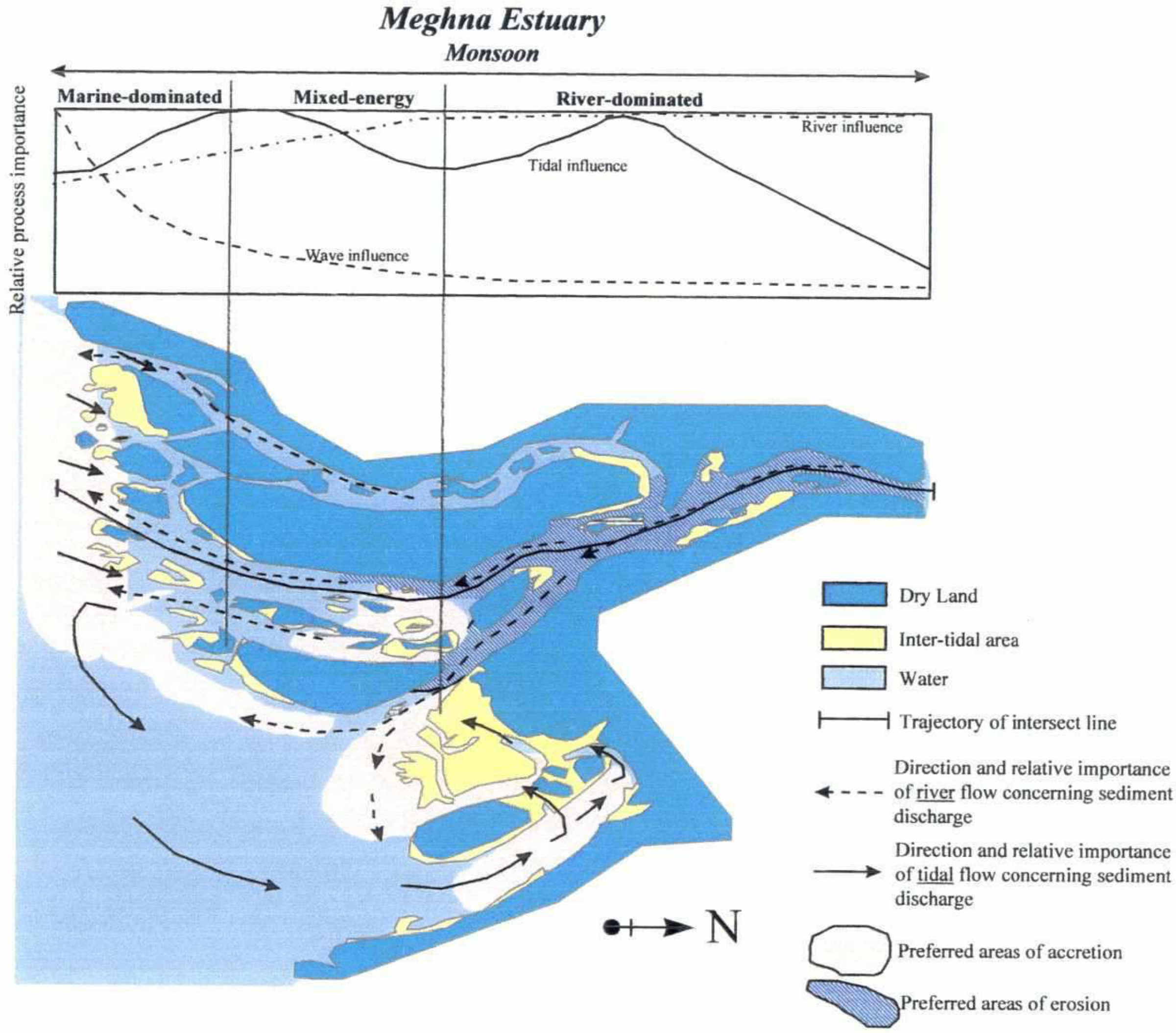
Monsoon period

In a large part of the estuary the processes during monsoon can be classified as river dominated (Figure 32). The marine dominated zone does not change significantly in size. This results in a compression of the Mixed-energy zone and probably in a limitation of the tidal intrusion into the estuary. Energy conditions governing the erosion sedimentation processes differ significantly from those in the dry season. Compression of the Mixed-energy zone results in a situation where the energy dissipation takes place in a smaller area, resulting in higher energy conditions which lessen the change in permanent sedimentation.

Another effect of the higher river discharge is an enlargement of the net circulation around Sandwip Island. The effect of this enlargement on sedimentation and erosion processes in this area is unclear at this moment. Enlargement of the net circulation could lead to sedimentation in deeper parts. The higher suspended sediment load of the river discharge could speed up this effect, leaving a surplus of sediment to be deposited on the intertidal flats between Hatia and Sandwip.

What remains obscure is the intensity of the sedimentation process in time. Whether the largest accretion takes place during the dry-period or during the monsoon is unknown at this time. Further investigations are required to be able to complete this part of the conceptual model and validate the hydrodynamic and sediment transport model results.

Figure 32: Conceptual Model of Dominant Geomorphological Processes during Monsoon



8 EXPECTED MORPHOLOGICAL DEVELOPMENT

8.1 Prediction methods

One of the most important topics of the present study is the prediction of morphological development in the study area. Extensive erosion causes retreat of the shoreline in some areas of the estuary, with Hatia North (retreat rate of more than 300 meters per year) being the most illustrative example. On the other hand, a very fast accretion is observed in other areas. The Noakhali mainland is extending steadily southwards. New chars emerge in the estuary, while existing chars disappear.
There is no readily available prediction method for mid and long-term (15-30 years) morphological development at the scale of problems comparable with the problems met in the Meghna Estuary. Dependent on the considered spatial and time scale, different prediction methods can be applied. In the present study, process-based methods have been applied for short-term predictions. Semi-empirical formulations have been used to estimate long-term rate of accretion. The expected changes to the shoreline due to erosion and accretion areas have been identified by means of extrapolation of present trends, supplemented with the expert knowledge of the estuary.

8.1.1 Numerical modelling

Simulations with the 2D model of the area have provided detailed information on the characteristic hydraulic conditions in the estuary. Circulation patterns, residual flow, tidal flow are important indicators for the short-term morphological development.

An attempt was made to describe the behaviour of silts in the estuary using suspended sediment transport model MIKE21-MT (SWMC, 2000a). This model can (in theory) give an indication of erosion and accretion patterns and signal areas prone to siltation. However, this model failed to adequately describe the sediment processes occurring in the Meghna Estuary. Many parameters in the model had to be assumed, as their value could not be derived from the measurements. Also, the model assumes that many parameters (like sediment characteristics) are constant in the whole modelled area. This assumption is too crude for an area of the size of the Meghna Estuary. However, it can be expected that this model can be successfully used in future to study confined areas where the characteristics of sediments is known and can be assumed constant.

8.1.2 Semi-empirical methods

In a number of feasibility studies carried out under MES, morphological effects of closing tidal channels have been studied. Closure of a channel causes a decrease of current velocities in the channel. This in general results in an increase of accretion and forming of new land along the dam and the banks of the closed channel. Semi-empirical formulations as proposed by Eysink (1983) were used to predict the size of accreting land.
The rate of accretion is taken proportional the area which will ultimately emerge:

$$dA/dt = \alpha\,(A_0 - A)$$

where: A is the area of accreted land with a certain level above mean sea level at time t after closure, A_0 is the area of ultimate accretion, and α is an empirical constant.
Integration of the expression above yields the following equation:

$$A = A_0\,[\,1 - \exp(-t/\tau)]$$

where τ is the characteristic accretion time.

This relationship was applied with a good result in accretion studies in the Netherlands. The value of A_0 can be determined from the local situation. The characteristic accretion time can be obtained from the settling rate of sediment in the channel.

When sediment-laden water enters areas with reduced flow, part of the sediment will settle, particularly around slack water, and will not be eroded again during next ebb or flood. It can be demonstrated that the settling rate is proportional to:

(i) the average silt content in the water (c),

(ii)the relative reduction of the total flow velocity squared $(\Delta u/u)^2$,

(iii) the maximum water depth (h),

(iv) the relative inundation time (T)

This leads to the following expression, which roughly describes the shoaling rate due to a cross-dam:

$$dh/dt = -\beta\, c\, T\, (\Delta u/u)^2\, h$$

where β is a constant.

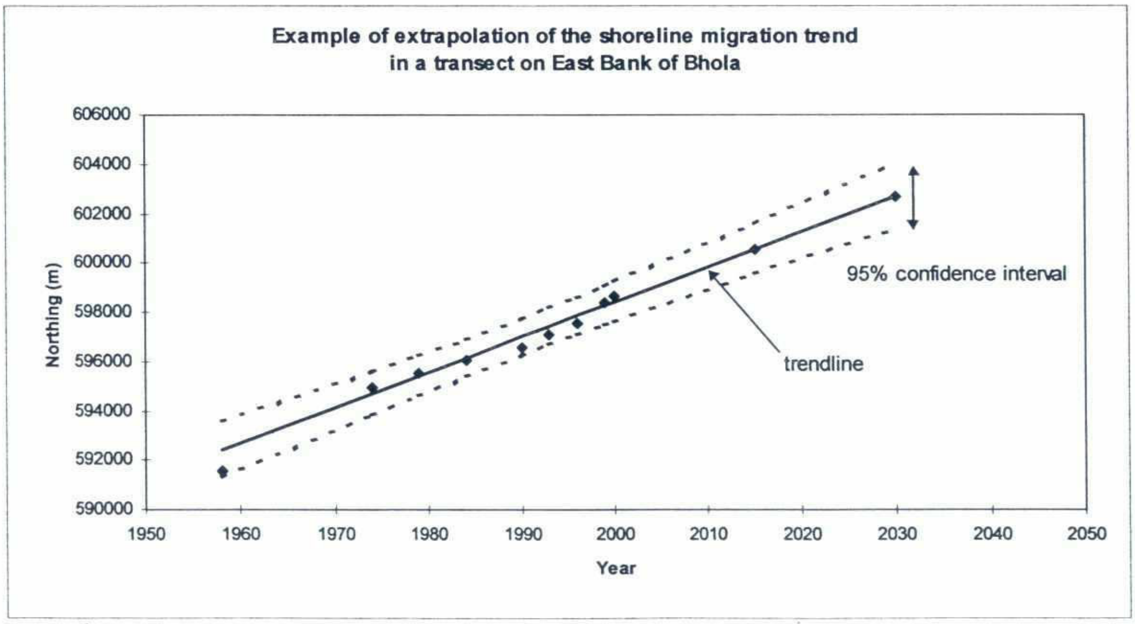
Solving the above equation a shoaling curve is obtained for the areas close to the dam, where velocities are negligible. From the initial accretion rate the characteristic accretion time τ can then be calculated, and then the size of accreted area as a function of time can be estimated.

The above-described method was used during MES in several feasibility studies to calculate the expected gain of land after closing tidal channels with a cross-dam (Nijhum Dwip Integrated Development Project Vol 3 Part 1 Draft Development Plan, MES).

8.1.3 Statistical methods

The process of continuous changes of the shoreline in the Meghna Estuary has been studied using trend analysis. The shoreline positions were derived from aerial maps and satellite images from the period 1957-2000 were processed as described in Chapter 6.5. Transects approximately perpendicular to the bankline were drawn every 1000-2000 m along the riverbanks, coastline and banklines of main islands. A timeseries of positions of the bankline in a transect in each of considered nine years (1956, 1974, 1979, 1984, 1990, 1993, 1998, 1999 and 2000) has been used as a basic data set. Linear trend analysis has been carried out on each data set (see Figure 33).

Figure 33: Example of trend analysis and extrapolation of existing trend over 30 year-period



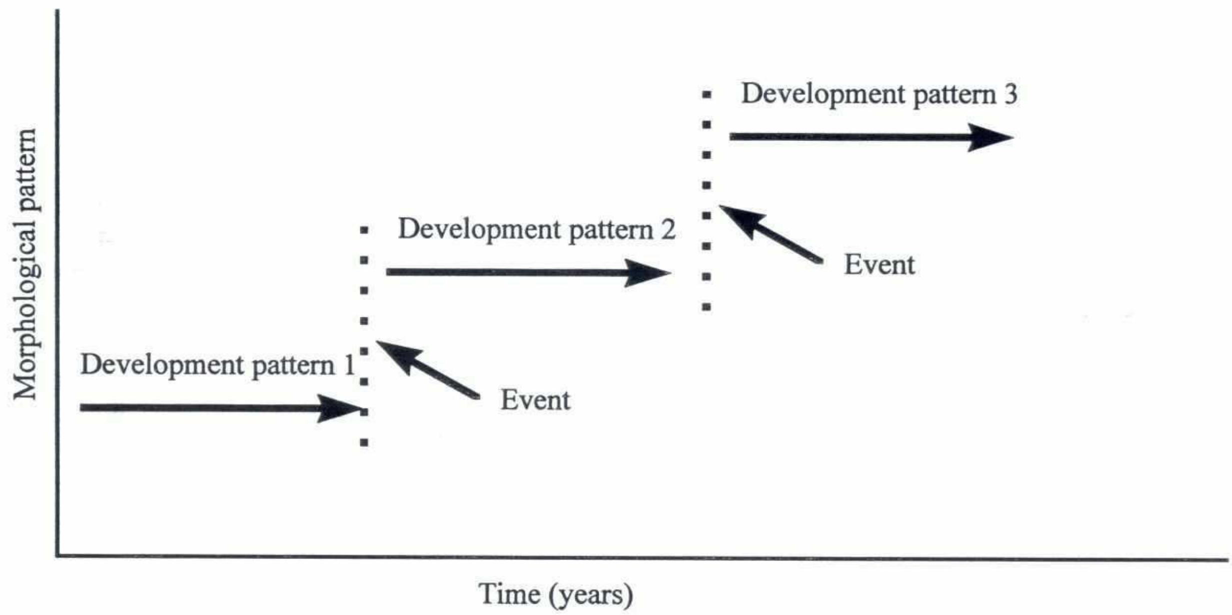
The average migration speed is obtained from the slope of the trendline. For each transect, a 95% confidence interval around trendline has been determined. The existing trends are extrapolated over the time horizon of 30 years. Points with low relative accuracy of migration rate have been disregarded. The obtained prediction is compared with the development, which is expected on the basis of processes observed in the estuary (hydrodynamic conditions, migration of channels, sediment supply, etc.).

Several extrapolation methods have been tested on the present data set (linear, exponential, square extrapolation). No significant difference in the results was found.

8.2 Prediction of morphologic development

The historical development of Meghna Estuary appears as a series of periods of continuous development according to some pattern, interrupted by shifts from one pattern to a new one. The shifts can be regarded as (catastrophic) 'events' (Figure 34)

Figure 34: The Historical Development of Meghna Estuary appears as a Series of Periods of Continuous Development Pattern Interrupted by (Catastrophic) Events



Within each pattern, the morphological processes can be mapped empirically, or even by their cause-effect relationships, and the development can be predicted. The morphological development can be predicted as long as a pattern persists, but only until the next shift to a new pattern. The shifts from one pattern to another can be due to some event, an extreme flood, a channel being blocked, a new main channel being formed, or perhaps an earthquake or severe cyclone. The shifts are difficult to predict with any certainty, and it is even more difficult to project the development beyond a shift.

We do not know much about the shifts from one development pattern to the next one - how often they occur, and why. Such knowledge, however, is the key to a medium term or long-term prediction of the planform development. An improved insight into the processes that can be observed today is only one small step in the right direction.

In this study, the expected planform evolution of the Meghna Estuary on the long-term (30 years) time scale has been obtained by extrapolation of existing trends and patterns in the geomorphological development over the last decades. Catastrophic events, which might trigger a shift in morphological development and patterns are not taken into account.

Figure 35 shows the expected position of the coastline in 2030. The expected position of the coastline is mapped by linear extrapolation of the trends over period 1957-2000 and morphological expertise. For reference, also the erosion and accretion in the period 1973-2000 are presented in the same figure. The morphological trends indicate that the process of erosion and widening of the Lower Meghna River in the area between Chandpur - Bhola will continue over the next decades. The average channel depth is expected to decrease slightly. The channel and coastline are very mobile and sensitive to changes in hydraulic conditions. The shifting patterns and bifurcation of the braiding river channel are indicated in the map qualitatively. It can be expected that new chars will develop in the braided river and migrate in downstream direction. The extrapolation of the position of the coastline in this area can be seen as a potential maximum retreat of the bankline.

In the middle estuary, the shoreline of the islands around Manpura and Hatia will extend in south-east direction. The main islands Manpura and Hatia will shift also in south-east direction. The heads of these islands will be exposed to severe erosion if no protection measures are taken.

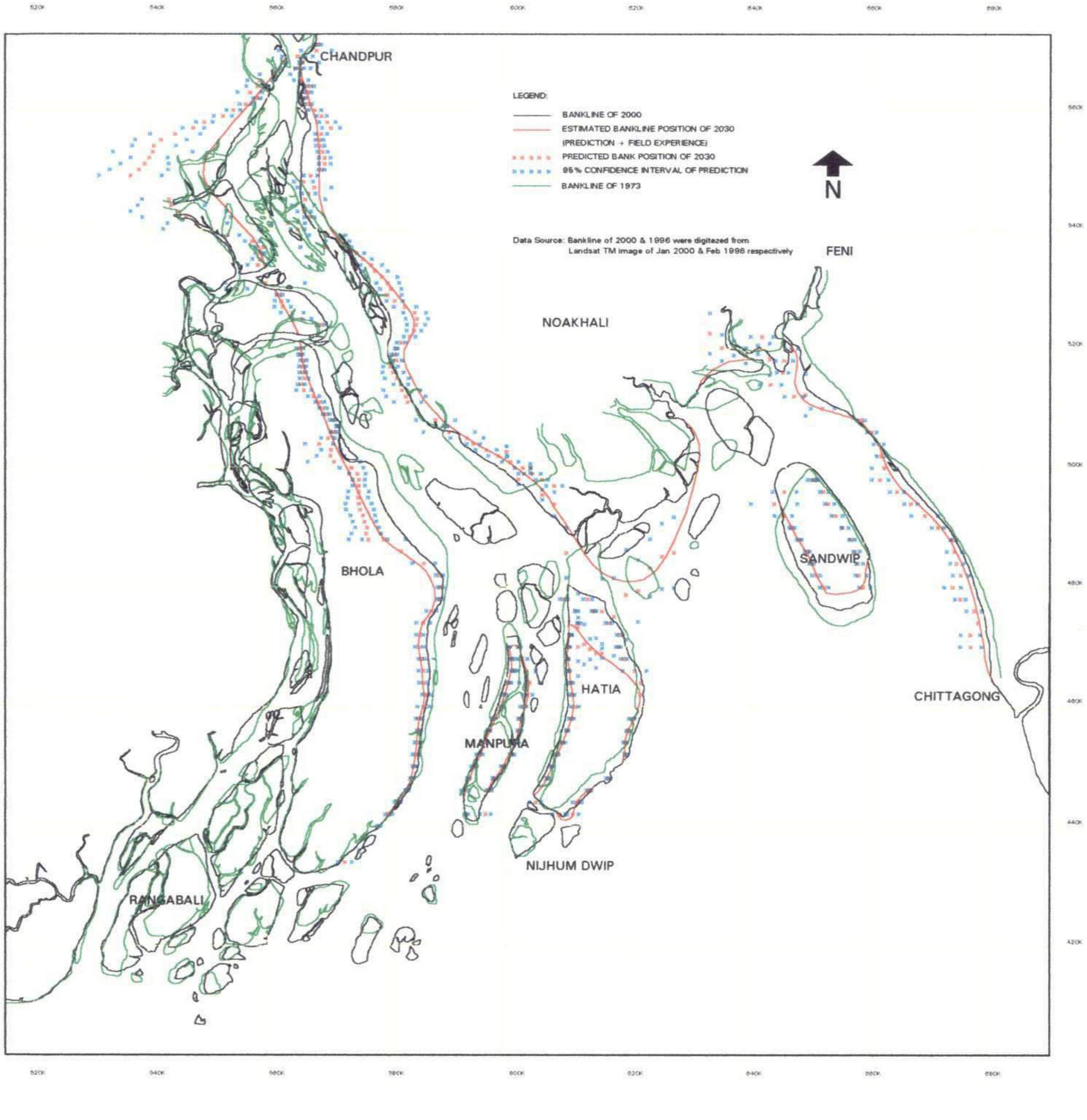
Without further embankment and erosion protection measures, the erosion process and retreat of the northern and east coastline of Bhola towards west will continue during the next decades. The coastline along the Tetulia River is relatively stable and will not change much.

The areas around Nijhum Dwip, Rangabali- Kukri-Mukri will extend eastward and new islands will develop. The coastline of Noahkali mainland area will extend in southern direction.

The long-term morphological trend around Sandwip-Urir Char indicates net sedimentation. In this highly dynamic environment, zones with strong sedimentation will alternate with zones with strong erosion spatially and temporally. The tendency of silting up of the Sandwip Channel will continue but the rate will be relatively slow.

It is to be noted that the rate of land formation is relatively slow compared to the huge amount of river-borne sediment supply. It is assumed that a substantial amount of the river-borne sediment will be accreted in the deeper part of the delta and Bay of Bengal.

Fig. 35: Predicted shoreline position in 2030



8.3 Potential Land Reclamation Areas and Land Levels

In view of the expected morphological development in the five pre-feasibility and feasibility projects identified in the MES Development Plan (Table 14), an analysis is done to examine the possibilities for empoldering the areas. In this analysis the young Noahkali intertidal area is discussed as well, because with its present development trend it has good prospect for land reclamation.
Table 14 gives a qualitative synthesis of the importance of several hydrodynamic and morphological aspects and the sensitivity for risk of events at present per study project. In this synthesis an idea is given about the empoldering suitability of each area and the time span before which this can be realised. Furthermore, the table displays the hydrodynamic and morpho-dynamic changes after implementation of the planned intervention measures (construction of cross-dams etc.). It shows the speeding up of the accretion process and the expected morphological side effects due to the interventions.
The present potential for development and the intervention aspects are discussed separately on the basis of hydrodynamic and morphological aspects.

It is obvious that the overall energetic conditions become higher from west to east. The energetic conditions in the west are low to moderate. The water is in general fresh to brackish. The water level and salt content show seasonal variation due to temporal variation in river discharge and the variability decreases with increasing distance from the river through the estuary to the sea.
The tidal range increases significantly from west (0-2 m) to east (more than 4 m). The most eastward situated chars (Urir Char-Sandwip) are subjected to relatively high current velocities and wave heights, a higher salt content and sediment concentration.
Due to the highly dynamic environment in the east, an unambiguous morphological trend cannot be given: zones with strong sedimentation rate (north) alternate with zones with strong erosion (south).
The chars and flats located at the northern edge of the estuary (North Hatia, South-Noahkali area, Urir Char-Sandwip) are younger than the chars located more to the west. This is reflected in a lower actual land level around Sandwip-Urir Char and for this reason it will take longer before the empoldering level, set at MHWL-spring is reached (in the order of 20-40 years).
Around Char Montaz and Nijhum Dwip the process of sedimentation dominates and the prospects for new land reclamation are favourable. The expected time period before which reclamation cannot be started is about 15-30 years.
With the execution of the planned interventions the overall energetic conditions will remain more or less the same. Local changes, for instance near the dams, will encourage the potential accretion rate.
Negative morphological side-effects are expected to be nil close to the chars in the west and around Nijhum Dwip. In the North Hatia-Manpura area the morphological changes can be significant due to the closing of the East Shahbazpur Channel. Model studies indicate that the East-Shahbazpur Channel will silt up rapidly and this will encourage of the erosion process at east-side of Bhola. Around Urir Char-Sandwip the negative morphological side-effects might be significant as well. These morphological side effect should be studied in detail.
When the intervention are implemented, the time that is needed by emerging land area to become suitable for empoldering is speeded up by a factor of 2 to 3 (feasibility study for Nijhum Dwip cross-dam).

The older chars with a higher actual land level (Rangabali-Char Biswas, Char Montaz-Kukri Mukri, Nijhum Dwip) can be reclaimed within 5 tot 15 years. The favourable hydrologic (less energetic) conditions, and the availability of more fresh water provide the best environment for empoldering. Reclamation of the younger chars with a lower actual land level and higher dynamic conditions (North Hatia-Manpura and Urir Char-Sandwip), can be expected in about 10-20 years. The Noahkali intertidal area is still in a very early stage of development. Because no intervention measures have been planned here, the time span before which empoldering possibilities cannot be started remains long, 20-40 years.

Table 14: Qualitative Synthesis on the Empoldering Suitability

	Rangabali-Char Biswas	Char Montaz-Kukri Mukri	Nijhum Dwip	North Hatia-Manpura	Noakhali intertidal area	Urir Char-Sandwip
A. Potential for development						
Hydrodynamic aspects						
Overall energetic conditions	low-moderate	low-moderate	moderate	moderate-high	moderate-high	very high
Water level range (river)	low-moderate	low-moderate	moderate	high	moderate-high	moderate
Tidal range	micro-meso	micro-meso	meso	meso	meso-macro	macro
Currents	low	low-moderate	low-moderate	moderate	moderate-high	high
Wave height	moderate	moderate	moderate	low	low-moderate	mod. -high
Salinity	fresh-brackish	brackish-fresh	brackish-fresh	fresh-brackish	salt	salt
Risk sensitivity						
flood risk (river)	moderate	moderate	moderate	high	very high	low
cyclone risk	moderate	moderate	high	moderate	high	high
Morphological aspects						
Overall conditions for land development	positive	positive	positive	positive/ negative	positive	positive/ negative
Morphological trend	sedimentation	sedimentation	sedimentation	erosion - sed.	sedimentation	erosion -sed.
Sediment concentration	low-moderate	low-moderate	moderate-high	moderate-high	high	(very) high
Actual Land Level	MHWLs	MHWLs	MHWLs	MLWL-MHWLs	MLWL	MLWL-MHWLs
Time period in which area is unsuitable for empoldering (y)	15-30	15-30	10-30	20-40	20-40	20-40
B. After intervention						
Hydrodynamic aspects						
Overall energetic conditions	low-moderate	low-moderate	low-moderate	low-high	moderate-high	low-very high
Water level range (river)	moderate	moderate	low	high	moderate-high	low
Tidal range	micro-meso	micro-meso	meso	meso	meso-macro	macro
Currents	low	low	low	low-moderate	moderate-high	low-high
wave height	moderate	moderate	moderate	low	low-moderate	mod. -high
Salinity	fresh-brackish	fresh-brackish	fresh-brackish	fresh-brackish	salt	salt
Morphological aspects						
Expected morphological side-effects	nil	nil	nil	nil-significant	nil	nil-significant
Potential Accretion rate	moderate-high	moderate-high	high	high	high	high
Time period before in area is unsuitable for empoldering (y)	5-15	5-10	5-10	10-20	10-20	10-20

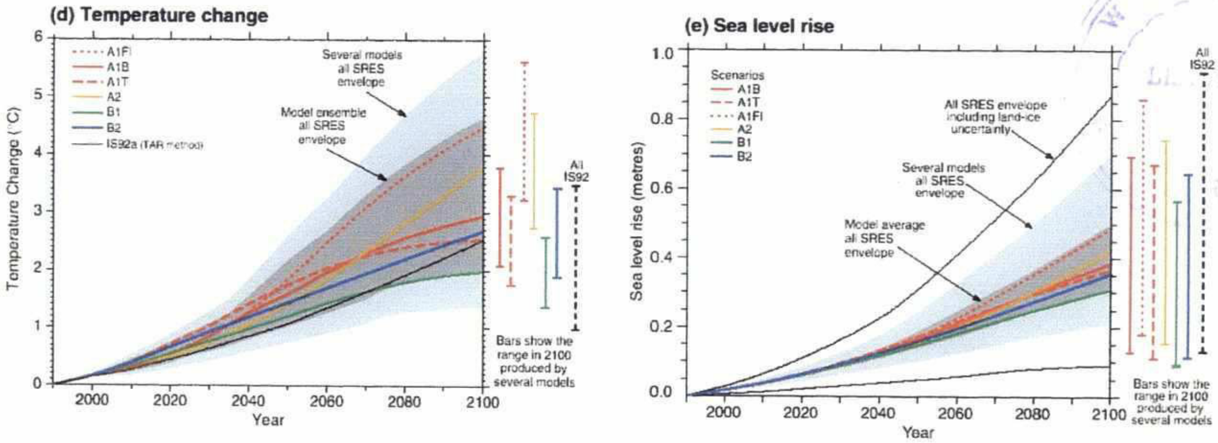
8.4 Sea-Level Rise

The coast of Bangladesh is an area with high ecological values, characterised by a large variability in hydraulic and geomorphological subsystems (channels, shoals and tidal flats), representing a wide range of habitats for different organisms. Especially the intertidal shoals and mudflats, which are highly productive and represent important feeding grounds for bird populations and a nursery for fish and prawns, are expected to be vulnerable to changes.

An increase of the greenhouse effect may imply a shift in radiation budget, a general temperature increase, changes in wind and cyclone characteristics and in global circulation (IPCC, 2001).

A potential effect of a general increase of temperature is an increased sea level rise (SLR). Predictions in this respect however show large uncertainties especially in relation to the timing, the extent and regional patterns (IPCC, 2001). The global temperature is projected to rise by 1.4 ^{0} to 5.8 ° over the period 1990-2100 (Figure 36). As a result of thermal expansion and loss of mass from glaciers and ice caps, global mean sea level is projected to rise 0.09 m for the most optimistic climate to 0.88 m for the most pessimistic scenario, with approximately 0.50 m as best estimate (Figure 36). Little is known on potential changes in wind- and wave characteristics and related cyclones and storm surges.

Figure 36: Temperature Change and Sea Level Rise for the full range of climate change scenarios (IPCC, 2001)



The present study is restricted to the effects of an increased sea level rise on the geomorphology of the Meghna Estuary system, assuming other controlling factors (e.g. temperature) to remain constant. It is expected that the Meghna Estuary system will be most sensitive to accelerated sea level rise. Firstly, a large part of the coastline of Bangladesh consists of loose alluvial and marine deposits. Such a coast will easily adapt itself to changing water levels and waves. Moreover, large deltas and estuaries are found around the world which experience a delicate balance between tidal forcing and estuarine processes. This balance can be easily disrupted by accelerated sea level rise. Secondly, the coast of Bangladesh and the islands are concentrations of socio-economic activities and contain many important (locally) food-producing areas. Accelerated sea level rise in combination with an increased frequency of storm surges, cyclones and high waves may be detrimental to many of these areas due to increase risk of flooding.

The extent to which sea level rise well affect the estuary depends on various factors. To be mentioned are the speed of ongoing sedimentation in relation to the sea level rise, the fact that if an area is embanked or not, the supply of upstream sediment, etc.

Finally, intertidal areas and marginal seas are valuable ecosystems, vital for biomass production and indispensable for the survival of many species. In those areas where the ecosystem cannot adapt to these changes, loss of low lands and biodiversity will be results.

The history of the Lower Meghna Estuary system teaches us that the sediment inflow of the three main rivers Ganges, Jamuna and Meghna contributes to the elevation of the coastal area of Bangladesh. The Lower Meghna Estuary system consisting of islands, outer delta, tidal inlets and tidal basins, has managed to adapt in the past to the rising sea level by moving seawards. Although channels, chars and mudflats and island coastlines can undergo highly dynamic changes locally, the basic morphological character of the Lower Meghna Estuary system as a whole has barely changed in the past centuries. Due to the prevailing hydro-morphological conditions and sea level rise the system showed a tendency to shift and extend in seaward direction.

Humans will try to fix the position of the upstream river catchment areas as well as part of the island coast and most of the mainland coast over the next decades, limiting the Lower Meghna Estuary system's freedom of movement.
In the upstream river catchment areas a rapid human population growth accelerates the exploitation of the resources and consequently the river hydro-morphology will change in response to that.

Fixing larger portions of the islands and the coast can disturb the balance between the sediment supply of the rivers and thus sedimentation in the mudflats. If this state of imbalance should mean that the sea level rises more quickly than the rate of sedimentation in the Lower Meghna Estuary area, the tidal basins will not receive sufficient sediment in order to sustain the intertidal areas. Were this to be the case, the coastal area, mudflats and mangroves would be swallowed by the sea.
The impact of eustatic sea level rise on the morphology will increase due to local subsidence caused by offshore activities (gas extraction).

A rise in sea level would normally reduce the rate of sediment input into the estuary, because of preferential deposition in the lower flood plains of the rivers. However, global warming is likely to increase the storminess of the weather and the rainfall. With the increased incidence of floods, sediments are likely to be flushed into the estuary. Within the Lower Meghna Estuary system deposition would produce an expansion of the intertidal mudflat levels.

If sedimentation on the mangrove surface and salt marshes are insufficient to keep up with sea level rise, there would be a progressive narrowing of the vegetation zones, which may lead to a further reduction in the sedimentation rate. The deeper water in the channels would lead to move active wave attack on the intertidal zone, as well as a change in the tidal regime. A combined effect of flow attacking and wave activity might increase the bank erosion rate drastically.

Prediction of the future sediment patterns in the Lower Meghna Estuary and the infilling rates depends on a complex of interacting processes. To estimate the effect of an accelerated sea level rise in combination with changes in river discharge and sediment inflow as well as human interventions on the coastal area more physical knowledge of the system's behaviour and reliable predictive hydro-morphological models are needed. Because of the influence of time in the sedimentary reactions to the flow, 2D-tidal models as developed under MES will only be of restricted use. Consequently, estuary sedimentation and hydrodynamics are a challenging area of interest where direct collaboration between the disciplines, and combined field, laboratory and modelling work is essential which should be anchored on an institutional level.

8.5 Anthropogenic Controls and Integration of Coastal and River Zone Management

In the coastal area as well as in the upstream river catchment areas, a rapid human population growth accelerates the exploitation of the resources and consequently the coastal and river hydro-morphology changes in response to that. This acceleration of the resource exploitation is in the form of increasing extensive and intensive deforestation and cultivation of areas, water management initiatives, floodplain developments, dredging, offshore activities, river and estuarine training, cross-dams constructions etc. Whilst the influence of these factors on river and estuarine system is often only qualitatively known, it can however induce very important changes in the river and estuarine system. Some qualitative indications show that the sediment transport through the Ganges River is decreasing but the same is increasing for the Jamuna River (Hossain, 1992). If these controlling factors change in the near future in such a way that they significantly affect the sediment inflow or sediment transport circulation patterns in the estuarine system, then the system will respond to such conditions in a positive or negative way. From a morphological point of view it is necessary to integrate coastal and river zone management for sustainable development of the delta and coastal area of Bangladesh.

9 SYNOPSIS AND CONCLUSION

9.1 Method and Approach

This report focuses on the spatial and temporal pattern of erosion and sedimentation and morphological changes of the Meghna Estuary study area. It outlines the well-documented changes in the system's geomorphology over the last centuries and recent decades. The results presented are based upon analyses of remote sensing imageries, bathymetric data and historical coastline maps, and field surveys and numerical modelling. Hydraulic and morphological conditions and processes that shape the morphology have been studied with regional and detailed local 2D-numerical models. Simulations for characteristic flow and tidal conditions (monsoon and dry period, full tidal cycle) were used to determine the behaviour of the entire estuary system. Based upon the findings of the field data and numerical model simulations, hypotheses are formulated on the dominant hydraulic and morphological processes underlying these changes.

A morphological prediction of land formation and char development in the Meghna Estuary system on an intermediate time scale (15-30 years) is given based upon an extrapolation of present planform evolution trends and on the knowledge and understanding of the dominant hydrodynamic and morphological processes.

9.2 Hydraulic and Morphologic Characteristics

The Meghna Estuary is a very dynamic estuarine and coastal system. Here, at the northern end of the Bay of Bengal, the combined flow of two of world's largest rivers, Ganges and Brahmaputra (Jamuna), finds its way through the Lower Meghna River to the sea. Erosion and accretion rates are high and the area is periodically subject to severe storms and cyclones, these latter accompanied by tidal bores and storm surges. The sediment discharge from the Lower Meghna River is the highest and the water discharge the third highest of all river systems in the world. The annual river-borne sediment load of Lower Meghna amounts to more than a billion tons and is dominated by silt to fine sand. The river discharge varies between approximately 10,000 m^3/s during dry-season to more than 100,000 m^3/s during monsoon.

The changes in tidal flow direction and channel topography, the appearance of new channels and newly accreted land and abandonment of old ones are the rapid building and destroying processes that shape the estuary. These processes trigger changes in sedimentation and erosion rates, which are directly related to the change in discharge and sediment content. The study area is characterised by extensive shallow (mud)flats, numerous small and vast islands (e.g. Hatia, Bhola and Sandwip) and chars. The major distributary system of the Lower Meghna includes the Tetulia River, the Shahbazpur and the Hatia channels. The total study area is approximately 11,210 km^2. The area of the islands is about 3,302 km^2. Considering the degree of exposure to marine processes, the length of Bangladesh coastline is about 2,650 km.

The knowledge about the physical processes and morpho-dynamic behaviour of the Lower Meghna Estuary system is still fairly limited. A complicated interplay between the forces of the river, tide and the waves creates a complex pattern of sediment displacement in the Lower Meghna Estuary system. Large quantities of sediment are transferred continuously towards the shallow coastal region of Bengal. Since almost no sediment is exchanged with the deeper parts of the Bay of Bengal, the overall sediment budget is determined by the process of continuous redistribution of sediment in the river system upstream. The displacement of sediment is one part of a continuous process of the estuarine-landscape striving to achieve dynamic equilibrium between the physical shape (morphology), and the constantly changing river discharge conditions and tide flows.

Tides

The water level variation is dominated by a semi-diurnal tide with a considerable variation from neap to spring tides; 0.6 to 1.4 times the average amplitude.

The area around Sandwip island is macro-tidal with variation in tidal range of about 3 to 6 m. The area between Bhola and Hatia (Shabhazpur Channel) is meso-tidal, with tidal range of 2 to 4 m. Tetulia River and the upper reach of Lower Meghna upstream of Char Gazaria are micro-tidal, with tidal range less than 2 m. The maximum current velocities in the study area vary from approximately 0.1-4 m/s in the tidal channels to about 0.2 - 0.5 m/s in the shallow areas.

Water Level

The mean water level shows a marked seasonal variation along the Bangladesh coast. The seasonal variation of the mean high water level (from dry to the wet season) decreases significantly along the Lower Meghna Estuary in southwards directions. The seasonal variation of the mean high water level at Chandpur is about 3 m. The variation in the southern part of the Bangladesh coast is about 0.8 to 2.1 m.

Extreme value analysis of water level data indicates a spatial variation in extreme values of water level in the Meghna Estuary Study Area. For a return period of 1:20 year the extreme water levels vary from 3.2 m at Khepupara in the western part to about 6.7 m at the downstream-side of the Feni Regulator in the north eastern part of the estuary.

Salinity

Salinity data indicate an enormous seasonal effect due to the influence of the huge fresh water discharge from the Lower Meghna River on the salinity in the coastal area. During monsoon (mid August to mid October) the salinity in the estuary drops considerably and the water becomes almost completely fresh. After the monsoon the salinities rise again and the seawater intrudes into the Study Area. However, even during the period with low river discharges the salinities in the area never approach normal seawater salinity (34.5 ppt) but always remain distinctly lower. The steepness of the salinity gradient during dry-season is maximum in the zone Rangabali-Kukri Mukri - North Hatia - Sandwip. The maximum values for the salinity gradient vary from $1.0*10^{-4}$ to $1.0*10^{-3}$ ppt/m.

Transition from Braided River to Tide-Dominated Morphology

The Upper Tetulia River and Lower Meghna River between Chandpur and North-Bhola show morphology of braided river type. The area around Char Gazaria forms a transitional zone between the braided river dominated morphology and the southern area, which is more of micro and meso tidal character. The Lower Shahbazpur channel and Hatia channel as well as the Lower Tetulia River show linear tidal ridges and islands, indicating reworking of sediments by tidal currents. The tidal currents play in these areas the dominant role in determining the fate of the river-borne sediments. The eastern part of the estuary has a distinctly macro-tidal character.

The Meghna Estuary system has a funnel shape. The river influence becomes progressively larger in stream upward direction as friction drains tidal energy. Tidal influence extends substantially farther upstream than salt intrusion. There is an appreciable upstream transport of bedload and suspended load sediment as a result of deformation of tide propagation. Sediment is received from both the river and from Bay of Bengal, yet most of the sediment received by the river ends up being transported and deposited by tidal currents.

9.3 Morphological Changes during the Last Centuries and Decades

- **Morphological changes during the last century**

Comparison of a present shape of the Meghna Estuary with the map prepared by James Rennell (1779) shows that net gain of land area is about 2,200 km^2, i.e. approximately 10 km^2 per year as an average rate of land area increase over the last 220 years. Rennell's map of 1779 indicates a completely changed system of channels and river courses but a more or less stable coastline west of the Tetulia River. East of the Tetulia River, however, a general tendency of seaward growth of the coastline can be recognised, particularly in the region Bhola island- Hatia island and in the Noahkali district. Although the overall process of accretion is dominant, areas of erosion can be recognised, particularly on the riverbanks in the north-western part of Study Area (North Bhola-Chandpur), on Sandwip and the mainland of Chittagong.

- **Morphological changes during the last decades**

Gain of Land

The net change by period shows an overall land gain in the Meghna estuary system as a whole, for the period 1973-2000 of about 50,800 ha. The net change over the considered period shows that generally gain of land took place, with exception of two periods: 1984-1990 and 1996-2000, when net loss of land is found. The annual rate of change for the entire study period ranged from a loss of over 2,100 ha/y during 1996-2000 period to a gain of over 4,500 ha/y during the period 1990 to 1996. The average annual gain for the entire study period is 1,900 ha/y. There is a clear relation between the magnitude of discharge entering the estuary and the net change of land. Periods of net loss of land coincide with occurrence of very high monsoon discharges (1986, 1988, 1996, 1998), while gain of land coincides with the periods of lower monsoon discharges in the river system.

Areas dominated by natural accretion

In the period 1973 to 2000 a vast area of new land emerged off the southern coast of Noahkali, which is associated with an even larger area of mud flat, which appears to be emerging land. A distinct sedimentation trend can be observed around southern coast of Noahkali over the last decades. There are new char areas and new areas of mudflat north-west of Sandwip island. Other large areas of accretion include the very large char at the head of Shahbazpur Channel, which appears to be consolidation and extension of Char Gazaria, the extensive area north of the Tetulia off-take, and the filling and enlargement of the chars in the extreme south-west of the study area, including Char Rangabali, Char Biswas, Char Montaz and Char Kukri Mukri. New chars form in the northern extension of Manpura and in the West Shahbazpur Channel. There is a significant accretion at the north-east of Nijhum Dwip, extending this island towards Hatia. With respect to the large areas of accretion in the south-west part of the study area, it is seen that the major gain of land took place in the period 1984 to 1990 and 1993 to 1996. This might be explained by the extremely high river discharges carrying huge amounts of sediment load during 1988 and 1995.

Areas dominated by natural erosion

Erosion of existing valuable agricultural land and homesteads has been identified as the main problem in the estuary. Most areas of erosion are associated with widening and migration of bank lines of the main Lower Meghna, Shahbazpur, Hatia and Sandwip Channels. The retreat of the west bank and east bank of the Lower Meghna varies from 50 m to more than 300 m/y. Largest erosion on the west bank is found at the level of Char Bhairabi (oposite of Hanar Char) and opposite of Char Gazaria. Erosion of the east bank of the Lower Meghna around Haim Char is about to engulf the already retired embankment of the Chandpur Irrigation Project. Also the east bank near Char Alexander is severely eroded. The north and north-east banks of the Hatia and Bhola to downstream of Tazumuddin are affected by erosion. The entire north and west coast of the Hatia island is experiencing erosion except the extreme small south-west part located at the north of the entrance of the Nijhum Dwip channel from the Shahbazpur channel. Retreat of the northern head of Hatia is about 300 m/y. Southeast, south and the entire west coast of Sandwip are erosion-affected areas. The retreat of the west-side of Sandwip is in the order of 10 to 100 m/y.

The natural development in the past as shown by the historical maps clearly indicates that most of the land gains and losses can be explained by the migration of main conveyance part of channels or by migration of island and, hence, only replace valuable old land, which is eroded elsewhere, in course of time.

Channel Geometry

The cross-section of the West Hatia Channel at the tip of Hatia island undergoes dramatic change. Once 15 km wide, it is now reduced to only 5 km. The cross-sectional area has remained more or less unchanged over last 18 years. A very deep (more than 20 m), narrow channel migrates towards the northern head of Hatia causing heavy erosion of the riverbank.

The cross-sectional area of the East-Shahbazpur channel between Char Gazaria and Noahkali mainland increased by 250% compared to 1990. Main conveyance channel became much narrower and deeper, and shifted close to the east bank. The cross-sectional area of the West-Shahbazpur Channel between Char Gazaria and Bhola shows a distinct trend to increase over the period 1981-2000. The main conveyance channel becomes deeper and migrates towards Bhola causing erosion of the riverbank. The observed trends and changes in the channel geometry might be the result of a long-term change of the major distributary system of the Lower Meghna River. In recent years, a tendency of widening of the river can be observed, with large chars and shallows emerging in the mid-channel and deep channels moving towards the banks undermining their stability. These changes may be related to the 1998 monsoon.

9.4 Sediment Transport and Sediment Budget

Sediment Characteristics

The bed of the Lower Meghna River consists of silt and fine sand with a median bed material grain size varying from 16 to 200 μm. The bed material size varies in both the transverse and downstream direction of the river. A major part of the bed-material (70%) has a median grain size less than 75 μm. The maximum depth averaged sediment concentration varies between 0.5 and 9 g/l. During spring tide the concentration is about 2-5 times higher than during neap tide. Maximum sediment concentration values have been found near the Urir Char-Char Balua area and Manpura-North Hatia area.

Sediment budget

Approximately overall sediment budget in the study area over the period 1997-2000 indicates that the deposition processes exceed the erosion processes. Net accretion during this 3-year period amounts to approximately 300 million m^3. However, the net change in the sediment volume is small (about 6%) compared to the total accretion and erosion. Erosion dominates in the northern part of the river system. Erosion in the Lower Meghna from the northern end down to northern head of Hatia is about 0.1 - 0.2 m/y. High rate of accretion (approximately 0.2 m/y) is found in the north-east of the estuary, between Noakhali mainland, Urir Char and Sandwip. Also the area between Bhola and Hatia, and the south-west end of the estuary are accreting, with an accretion rate of 0 - 0.1 m/y. In other areas in the estuary, erosive and depositing processes are more or less in balance.

Sediment transport
The average total annual sediment discharge of the Jamuna and Ganges over the period 1966-1991 is about 1,100 million t/y. The sediment discharge of the Upper Meghna is negligible compared to the discharge of the Jamuna and Ganges. It is assumed that the net gain of land in the southern part of Bangladesh is related to the amount of river borne sediment discharge: during periods of high river borne sediment discharge (monsoon), the net gain of land and intertidal areas is higher than during low periods of river borne sediment discharge.

9.5 Dominant Hydraulic and Morphological Processes

Waves
According to the indicative model simulations of situations with and without waves, the over-all sediment transport is clearly determined by the flow, rather than by the waves. This is even the case for the characteristic northward sediment transport through Sandwip Channel, which has supplied the material for accretion of the Muhuri area and the area north of Sandwip. In Sandwip Channel, irrespective of the waves, sediment concentrations are so high that they approach a dynamic equilibrium between settling and resuspension.

Still, the waves will have some effect on erosion and accretion. Wave breaking on low chars will enhance the mobility of the bed material, and will expose it to further advective transport. Along wave-exposed banks, depending on the sediment type, a littoral drift can occur due to a wave-generated littoral current. Sandy beaches are rare in the estuary, but do occur at places that face south towards open waters, where the sand is deposited by a natural sorting of the material.

Sediment transport patterns
The sediment supply from the catchment to the estuary is much less in the dry season than during the monsoon. In the northern part of the estuary, where the flow is jointly influenced by the river flow and by the tide, the transport capacity decreases in the dry season, further reducing the supply of sediments to the southern parts. In the southern part, where the flow is predominantly determined by the tide all the year round, the transport capacity decrease is small, so a gross loss of material from this area will occur (as the supply is reduced while the loss is unchanged).

During the monsoon, the supply of sediments is at its peak, as well as the transport capacity of the main net flow channels (while, in the pure tidal channels, the transport capacity is more or less the same all year). In this season, the major erosion and accretion take place.

As it is the case all year, the loss of material from the estuary is related to the transport capacity in its southern part, through which the material must pass before it is eventually discharged to the Bay of Bengal. This area is tide-dominated, so the seasonal transport capacity variation is small. Therefore, since the supply of material is high, material will accumulate within the estuary during the monsoon.

Tidal Turbidity Maximum
Sediment concentration measurements under pre-monsoon and post-monsoon conditions in the Shahbazpur channel indicate a high suspended sediment concentration around north Hatia - Manpura area as well as in the channel around Char Balua - Char Pir Baksh. This high suspended sediment concentration might refer to the so-called turbidity maximum.
The energetic tidal flow is capable of maintaining high concentrations, and there are a number of processes that concentrate the suspended sediment, and prevent particles from dispersing. The peak concentration of suspended sediment in the turbidity maximum varies between wide limits. Despite the differences due to sediment availability in the Shahbazpur channel and Char Balua and Char Pir Baksh, these areas have maxima with concentrations in the range of 1-9 g/l.

The turbidity maximum contains a high portion of a narrow size range of mobile fine sediment, and plays a central role in the circulation of fine sediment within the Lower Meghna Estuary area, as well as probably determining the rate of transport of sediment from the river to the sea. The concentrations of sediment in the turbidity maximum appear to remain almost constant when averaged over a reasonable time, so that residence time of grains in the turbidity maximum must be considerable.
The seasonal changes in river flow suggest that sediment can accumulate in the upper estuary during pre-monsoon and post monsoon, and be redistributed down the estuary during monsoon.

Residual circulation and estuarine trapping
The river-borne sediments become trapped in the estuary by the tidal pumping and residual circulation, and mix with material brought in from the sea. The process of mixing involves continuous erosion, deposition and exchange of sediment within the estuary: the fine sediment cycling through the turbidity maximum and somewhat coarser sediment cycling round the ebb-flood channel systems. Individual particles may spend a considerable time moving within the system before being finally deposited, or passing through to the sea.
Some of the particles entering from the river will remain in suspension and pass through the estuary fairly quickly particularly at times of high river. However, a significant proportion will undergo many cycles of deposition on the bed followed by resuspension, with the deposition occurring at a number of points along the estuary which form temporary sinks for the sediment particles operating for a variety of time-scales.
Measurements indicate that the trapping efficiency of the estuary, which is the ratio of the fluvial sediment input to that accumulated in the estuary, might be very sensitive to changes in hydraulic conditions. More investigations are needed to enhance the physical knowledge about this trapping effect and its sensitivity to variations in river and sediment discharge.

Accretion and erosion trends
Comparison of results of bathymetric surveys from 1997 and 2000 shows that deposition processes in the study area exceed erosion processes. An overall sedimentation trend can also be seen near the edge of the delta front where new island and intertidal area are formed and silted up. A dominant erosion trend at North-Hatia and North-Bhola is observed. Largest erosion is found in the upper reach of the estuary, in the Lower Meghna between Chandpur and Char Gazaria. There, river widens, chars appear in the middle river section. Flow in these areas is deflected towards the banks, which suffer severe erosion as the deep channels come very close to bank. The morphology of the Upper Tetulia River is relatively stable compared to the Lower Meghna Estuary. Alternate erosion and sedimentation patterns along the Lower Meghna River, in particular in the area between Chandpur and north-Bhola, might indicate that the channel is very mobile and sensitive to river discharge and tidal conditions. The East-Shahbazpur Channel is, compared to the West-Shahbazpur Channel, relatively stable and tends to silt up slowly. In both channels a tendency of silting up associated with development of deep channels along the bank can be seen. The same process is observed in the North-Hatia Channel. The Sandwip Channel remains quite stable. A slight tendency of silting up in the northern part and erosion in the southern part is observed. The east-side and southeast-side of Hatia tend to silt up slowly. Sedimentation is dominant in the shallow areas around Nijhum Dwip and the area around Rangabali-Kukri Mukri. Excessive sedimentation and formation of mudflats and new land south of Noakhali mainland is observed.

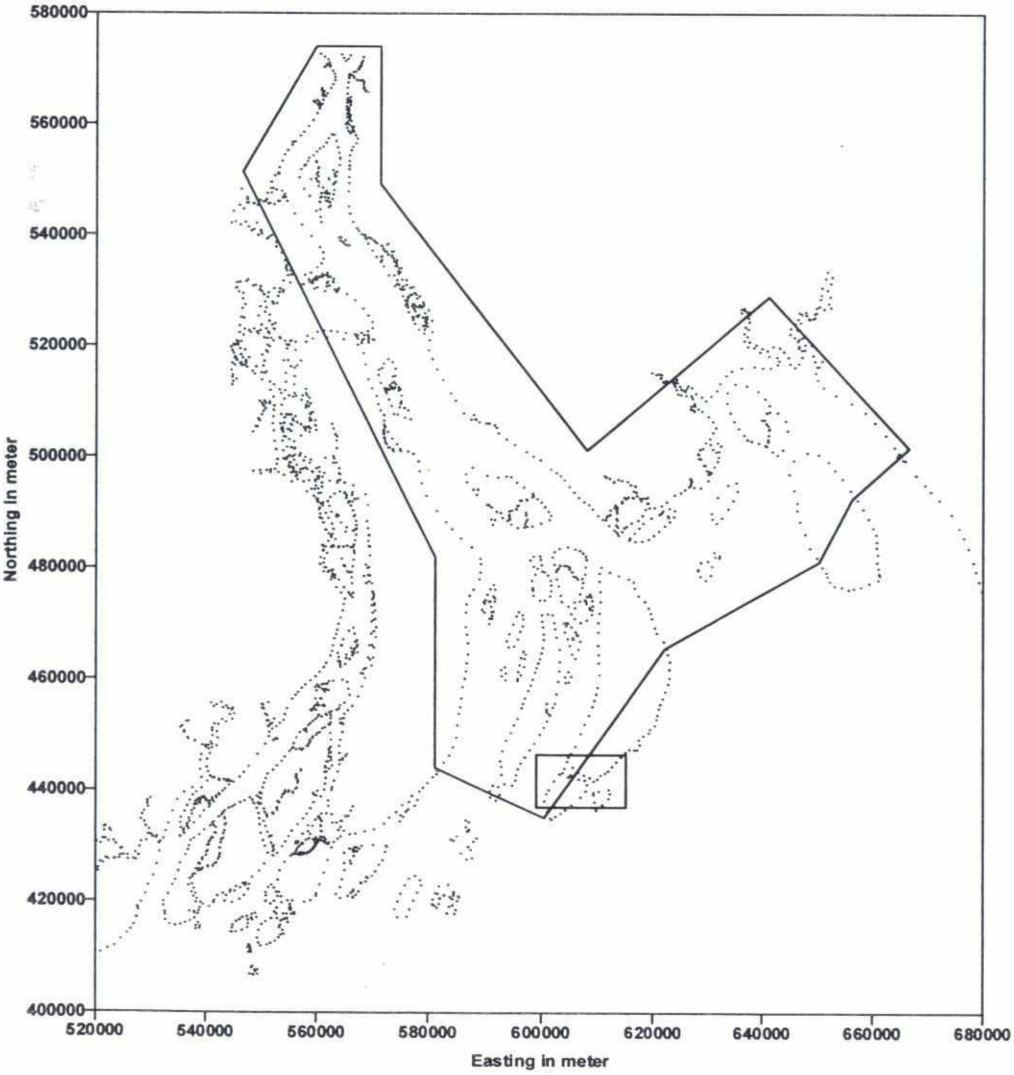
10 RECOMMENDATIONS

10.1 Morphological study

In the course of the project, MES collected an extensive amount of information related to physical processes in the Meghna Estuary. These processes have been studied to obtain an in-depth understanding of the behaviour of the estuary. Information obtained in other projects, either prior or running in parallel has been acquired and assimilated. Still, it appears that the physical reality found in the Meghna Estuary is rather complex and that scientific concepts fail to describe it in an appropriate way. General patterns in the morphological development of the estuary have been recognised, yet many of the underlying processes are still not well understood. It is, therefore, recommended to continue research efforts both in gathering information and in transforming this information into conceptual and mathematical models. More study of the morphological behaviour of the Meghna Estuary is needed. In particular, attention should be paid to the most dynamic areas (see Figure 37):

- (i) northern, braided-river part down to Char Gazaria;
- (ii) East and West Shabhazpur Channel from Char Gazaria down to southern extent of Manpura and Hatia;
- (iii) area of massive accretion: Bouy Char / Noakhali; and
- (iv) area near Urir Char / northern Sandwip Channel.

Figure 37: Areas of special interest for future morphological studies



Also the morphological development area of the pilot projects at Nijhum Dwip and Hanar Char (and the new pilot project areas to be defined in the future) should be studied in detail. A lot of information from these areas has been collected, and this collection should be continued. Future morphological study of the erosion control projects should include detailed bathymetric surveys. Obtained information is to be used to determine the maximum depths of a channel in front of an eroding bank, and to study the interaction between the channel and a series of erosion control structures.

The morphologic study should comprise the following topics:
(i) large-scale morphological development (from yearly bathymetric surveys)
(ii) changes to the channel system (thalweg migration, changes to cross-sections)
(iii) morphological behaviour of areas close to the main bifurcation points
(iv) predictions of bank erosion
(v) detailed study of pilot areas
(vi) analysis of climate change related impacts as well as accelerated sea level rise

It is recommended to continue field surveys of MES, concentrated in the above-mentioned areas, and to use the results to improve the existing 2D numerical model of the estuary. It is also recommended to continue efforts in remote sensing. This will be further detailed in the following chapters. A recommendation for a survey program is detailed in Annex D.

10.2 Field Survey

Bathymetric survey

The project area has complex hydraulic and morphological characteristics and also transient in nature. Bathymetry (it affects navigation, flooding, erosion/sedimentation, etc.) and flow distribution and sediment transport distribution (as the primary variables of the physical system) data of priority project areas as well as selected areas of the estuary should be collected taking into account the future development activities. Experience shows that there is inherent uncertainty regarding the morphological development and prediction. A changed distribution of tidal and river outflow will result in changed erosion and accretion pattern, in turn can induce loss of land, and damage to coastal structures, such as embankments.

More bathymetric data and levelling data is needed to enhance the knowledge about the dominant process in shallow areas and their sediment budget characteristics. The extensive surveys of 1997, 2000 and 2001 provided already material for observation of overall morphological trends in the estuary (migration of channels, erosion and accretion). These surveys should be continued in the future at regular time intervals (preferably on a yearly-basis for the most dynamic areas, as shown in Figure 46, and on a 3-5 yearly basis for the whole estuary) to be able to follow morphological changes. The spatial resolution of the surveys should be kept the same as in the previous surveys to ensure that the obtained results are comparable. More fixed cross-sections should be defined. At each cross-section, 2-3 closely spaced lines (100 m spacing) should be echosounded.

Critical areas (bifurcation points and channels along Char Bhairabi and Char Gazaria, Hatia Channel between Hatia and Char Bouy), and areas of special interest (pilot project areas Nijhum Dwip, Hanar Char and any new pilot projects to be defined in the future) should preferably be surveyed 3 times a year (before, during and after monsoon) to obtain a better insight in the changes during heavy monsoon flows. For proper monitoring of pilot projects, locally a high density of survey lines (spacing of approximately 10m) will be required.

At present, very little knowledge regarding the southern extent of the estuary (not covered by the surveys) is available. It is recommended to extend the area covered by the surveys to the south, to 20 m depth line. Foreshore of the eastern coast should be covered by survey down to St. Martin's Island. Also Sunderbans should be surveyed, as it is an area of interest of PDO/ICZM.

Vertical positioning

The vertical levelling system using satellite signals (RTK) should be evaluated and either improved or replaced by another system. A method using a combination of water level measurements and 2D model predictions, locally corrected for measured water levels, applied in processing of 2000 and 2001 surveys, should be considered as a replacement of RTK. The zero levels of the temporary gauges installed during the survey should be tied to the existing benchmarks.

Discharge, velocity and water level measurements

Velocity and discharge measurements need to be continued. Of special interest is the flow distribution over the main channels of the estuary, downstream of main bifurcation points. This should be measured both during dry season and monsoon. Discharges should be measured frequently in Lower Meghna to obtain a rating curve for Chandpur. This rating curve is amongst others important for improvement of the northern boundary in the 2D model of the Meghna Estuary.

The zero levels of established water level gauges should be verified and tied to PWD. Future morphological studies could benefit from referring to the same datum. Automatic water level gauges should be installed at remote stations.

Combined velocity and sediment concentration measurement

The behaviour of suspended sediment in the Meghna Estuary is very complex. It has been suggested that the vertical current velocity profile is influenced by the vertical density gradients caused by varying sediment concentrations. This hypothesis can be tested by a simultaneous measurement of vertical current velocity profile and sediment concentration profile.

Sediment sampling

More sediment data should be collected. These should include concentrations of suspended sediment, settling velocities, grading curves and mineralogical analysis of suspended sediment and soil samples.

Salinity measurements

Salinity distribution in the estuary should be monitored. Of special interest is the inland protrusion of saline water during the dry season, as it affects agriculture.

Wave measurements

Wave action can be a serious threat for embankments. So far only very few wave measurements are available. Hardly any data exists for calibration and validation of the existing wave models. It is recommended to install wave buoys in several points at the southern limit of the estuary. Recorded data should be retrieved regularly as the probability of loss of equipment is high.

Water quality measurements

Water quality in the study area should be followed. Some crucial parameters (to be defined by PDO/ICZM) should be measured in situ or the laboratory.

Storage of data

Field surveys produce large amount of data. This data should be processed according to standard procedures and stored in special-purpose database, to allow for an easy access to the data. During MES, MERIS database was created. It is recommended to extend and improve this database.

Survey Unit
During MES, all field survey work has been carried out by the Survey Unit Anwesha. This unit consists of highly skilled professionals, who can operate advanced survey equipment. This experience is unique in Bangladesh. Field surveys yield enormous amount of data that needs to be adequately processed and managed. Staff of MES has extensive experience in this field, gathered in the course of the project. It is of the ultimate importance that after MES is finished, this experience, both in gathering information and in its processing and managing is not lost.

10.3 Numerical modelling

The area covered by the existing 2D hydrodynamic model is subject to large changes (shifting of channels, erosion, accretion, movement of banklines). To maintain accurate description of hydraulic conditions the model should be enhanced by updating bathymetry at regular intervals (1-2 yearly), using the results of bathymetric surveys. More work should be done on calibrating the model using recent discharge and velocity data. Description of northern boundary and the friction map in the upper part of the river system in the model should be improved, as at present the model cannot represent flow conditions properly: the predicted tidal amplitude at Chandpur and the computed velocities in Lower Meghna under monsoon conditions are too low compared with the measurements. Under low discharge conditions, the simulated tidal amplitude at Chandpur is too large.
Application of cohesive sediment transport model in confined areas should be considered to estimate potential of accretion.
Morphological impact of closing tidal channels (e.g., Nijhum Dwip) to promote accretion can be studied with 1D models like Mike-11. Such a model can be calibrated using the dataset from monitoring of the Char Montaz cross-dam.
Wave models developed under MES and CERP-II should be validated using wave measurements.

To estimate effect of an accelerated sea level in combination with changes in river discharge and sediment inflow as well as human interventions on the coastal area, more physical knowledge of the system's behaviour and reliable predictive hydro-morphological models are needed.

To estimate the effect of accelerated sea level rise in combination with changes in river discharge and sediment inflow as well as human interventions on the coastal area, more physical knowledge of the system's behaviour and reliable predictive hydromorphological are needed.

Developed models should be implemented at the office of the organisation, which will continue MES activities. This is of particular importance for the 2D flow model of the estuary, which is required for the processing of the data for bathymetric surveys.

10.4 Remote sensing

Large scale changes in the estuary can very well be derived from satellite images. A large dataset of these images has already been collected. New images should be acquired and processed. Methods of determining changes to areas of erosion and accretion, especially considering mud flats and intertidal zone, should be improved. Improvement of classification of a satellite image can be achieved by performing field measurements of the same spectroscopic band as measured by the satellite at the time satellite is passing and comparing the field measurement with the satellite measurement (ground truthing). Determination of sediment concentration can be attempted using this method. Remote sensing techniques are available for estimation of wave climate. Use of these techniques for calibration of wave models should be considered.

10.5 Morphological predictions

During MES a prediction method for bankline migration has been developed, based on extrapolation of existing trends. The database of bankline positions contains data from 1956. It is recommended to regularly (1-2 yearly) update this database with the bankline positions derived from recent satellite images, and to update the predictions. This way changing trends can be signalled and predictions enhanced. Changes to the banklines of the Tetulia River should also be included in the analysis.

11 REFERENCES

Allison, M.A. 1998.
Historical changes in the Ganges-Brahmaputra delta front. Journal of Coastal Research (in preparation).

Coleman, J.M. 1969.
Brahmaputra River: Channel processes and sedimentation, Sediment Geol., 3 (1969), pp.129-239.

Chow, Ven Te., D.R. Maidment., L.W. Mays. 1988.
Applied hydrology. McGraw-Hill Book Company.

De Vriend, H.J., Louters, T., Berben, F., Steijn, R.C., 1989.
Hybrid prediction of a sandy shoal evolution in a meso-tidal estuary. In: R.A.Falconer, P.Goodwin and R.G.S. Matthew (Editors), Hydraulic and Environmental Modelling of Coastal, Estuarine and River Waters, Int. Conf. Bradford, England, Chapter 14: pp. 145-156.

Dyer, K.R. 1988.
Fine sediment particle transport in estuaries. In: J.Dronkers and W.Leussen (editors), Physical Processes in Estuaries. Springer-Verlag, Berlin, pp. 295-320.

Eysink, W.D. 1983.
Basic considerations 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 no. 15.

Government of the People's Republic of Bangladesh, Ministry of Water Resources, Bangladesh
Water Development Board: Geodetic (BM) survey by RTK-GPS. Final Report submitted to Meghna estuary Study (FAP5B) by Surface Water Modelling Centre, June 1996.

Government of the People's Republic of Bangladesh, Ministry of Water Resources, Bangladesh
Water Development Board: Numerical modelling of hydrodynamics, salinity, waves and sediment transport in the Meghna Estuary. DHV Consultants BV and associates, June 1998.

Hayes, M.O., 1975.
Morphology and sand accumulations in estuaries. In: L.E. Cronin (Editor): Estuarine Research, Vol.2, Geology and engineering, pp. 3-22, Academic Press, New York.

Hayes, M.O., 1979.
Barrier island morphology as a function of tidal and wave regime. In: S.P.Leatherman (Editor), Symposium on Barrier Islands, pp. 1-28, Academic Press, New York.

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.

IPCC, 2001.
Third Assessment Report of Working Group I of the Intergovernmental Panel on Climate Change, Summary for Policy makers, January 2001.

Kana, T.W., Mason, J.E., 1988.
Evolution of an ebb-tidal delta after an inlet relocation. In: Lecture Notes on Coastal and Estuarine Studies, D.G. Aubrey, L.Weishar (Editors), Hydrodynamics and Sediment Dynamics, Vol. 29, pp. 382-411.

Leedshill-De Leuw Engineers. 1968.
Coastal Embankment Project, Engineering and Economic Evaluation, Volume 1, Dacca, East Pakistan.

O'Connor, B.A., Nicholson J., 1989.
Modelling changes in coastal morphology. Proc. A.S.C.E. Int. Symposium on Sediment Transport Modelling, S.Y. Wang (Ed.), pp. 160-165.

57

Oertel, G.F., 1988.
Processes of sediment exchange between tidal inlets, ebb tidal deltas and barrier islands. In: D.G. Aubrey & L. Weishar (eds), Lecture Notes on Coastal and Estuarine Studies, Hydrodynamics and Sediment Dynamics, Vol. 29: 297-383.

MES. 1997 MES Guidelines on execution of estuarine surveys.
Internal document, Meghna Estuary Study. Revised, February 1997.

MES. 1997 MES Guidelines on data processing, estuarine surveys.
Internal document, Meghna Estuary Study. Revised, February 1997.

MES. 1997 Sediment analysis procedures.
Submitted to Ministry of Water Resources, Bangladesh Water Development Board, by DHV Consultants BV and associates, June 1997. Technical note MES-005.

MES. 1997 Static GPS survey.
Submitted to Ministry of Water Resources, Bangladesh Water Development Board, by DHV Consultants BV and associates, June 1997. Technical note MES-008.

MES. 1997 Times series analysis of erosion and accretion
Submitted to Ministry of Water Resources, Bangladesh Water Development Board, by DHV Consultants BV and associates, June 1997. Technical note MES-009.

MES. 1997 Estuarine survey procedures.
Submitted to Ministry of Water Resources, Bangladesh Water Development Board, by DHV Consultants BV and associates, June 1997. Technical note MES-010.

MES. 1997 Assessment of marine survey capabilities.
Submitted to Ministry of Water Resources, Bangladesh Water Development Board, by DHV Consultants BV and associates, June 1997. Technical note MES-011.

MES. 1998 Estuarine Surveys, 3rd Draft June 1998.
Submitted to Ministry of Water Resources, Bangladesh Water Development Board, by DHV Consultants BV and associates, June 1998

MES. 1998 Draft Master Plan, vol. 2, Morphological Processes, September 1998
Submitted to Ministry of Water Resources, Bangladesh Water Development Board, by DHV Consultants BV and associates, June 1997
to be read in conjunction with Addendum published in June 2001

MES. 1998 Feasibility Study, Nijhum Dwip Integrated Development Project in the Meghna Estuary Study, Submitted to Ministry of Water Resources, Bangladesh Water Development Board by DHV Consultants BV and associates, June 1997

MES. 2000 Salinity Surveys September 1999 and February-March 2000.
Submitted to Ministry of Water Resources, Bangladesh Water Development Board, by DHV Consultants BV and associates, October 2000. Technical Note MES-027

MES. 2001 Addendum to Draft Master Plan Volume 2, Morphological Dynamics of the Meghna Estuary System
Submitted to Ministry of Water Resources, Bangladesh Water Development Board, by DHV Consultants BV and associates, June 2001. Technical Note MES-029

MES. 2001 Float tracking and ADCP measurements monsoon 2000, Meghna Estuary Study.
Submitted to Ministry of Water Resources, Bangladesh Water Development Board, by DHV Consultants BV and associates, June 2001, Technical note MES-030

MES. 2001 Analysis of shoreline changes in the Meghna Estuary, Meghna Estuary Study.
Submitted to Ministry of Water Resources, Bangladesh Water Development Board, by DHV Consultants BV and associates, June 2001, Technical note MES-031

MES. 2001 Analysis of bathymetric changes in the Meghna Estuary, Meghna Estuary Study.
Submitted to Ministry of Water Resources, Bangladesh Water Development Board, by DHV Consultants BV and associates, June 2001, Technical note MES-0032

Milliman, J.D. 1991.

Flux and fate of fluvial sediment and water in coastal seas. In: Mantoura, R.F.C., Martin, J.-M. & Wollast, R. (eds). Ocean Margin Processes in Global Change. John Willey and Sons Ltd., Chichester, pp. 69-89.

Perillo G.M.E. 1995.
Geomorphology and Sedimentology of Estuaries. Developments in Sedimentology 53

Space Research and Remote Sensing Organization (SPARRSO) and Environmental Research Institute of Michigan (ERIM). 1981.

Final Report. Measurement of Land accretion in the coastal zone of Bangladesh by the analysis of Landsat digital data. UNDP/FAO contract no. DP/BGD/79/004-l/AGOF.

Umitsu

SWMC, 2001.
Two-dimensional general model of the Meghna Estuary, Second update report, April 2001, submitted to MES by Surface Water Modelling Center

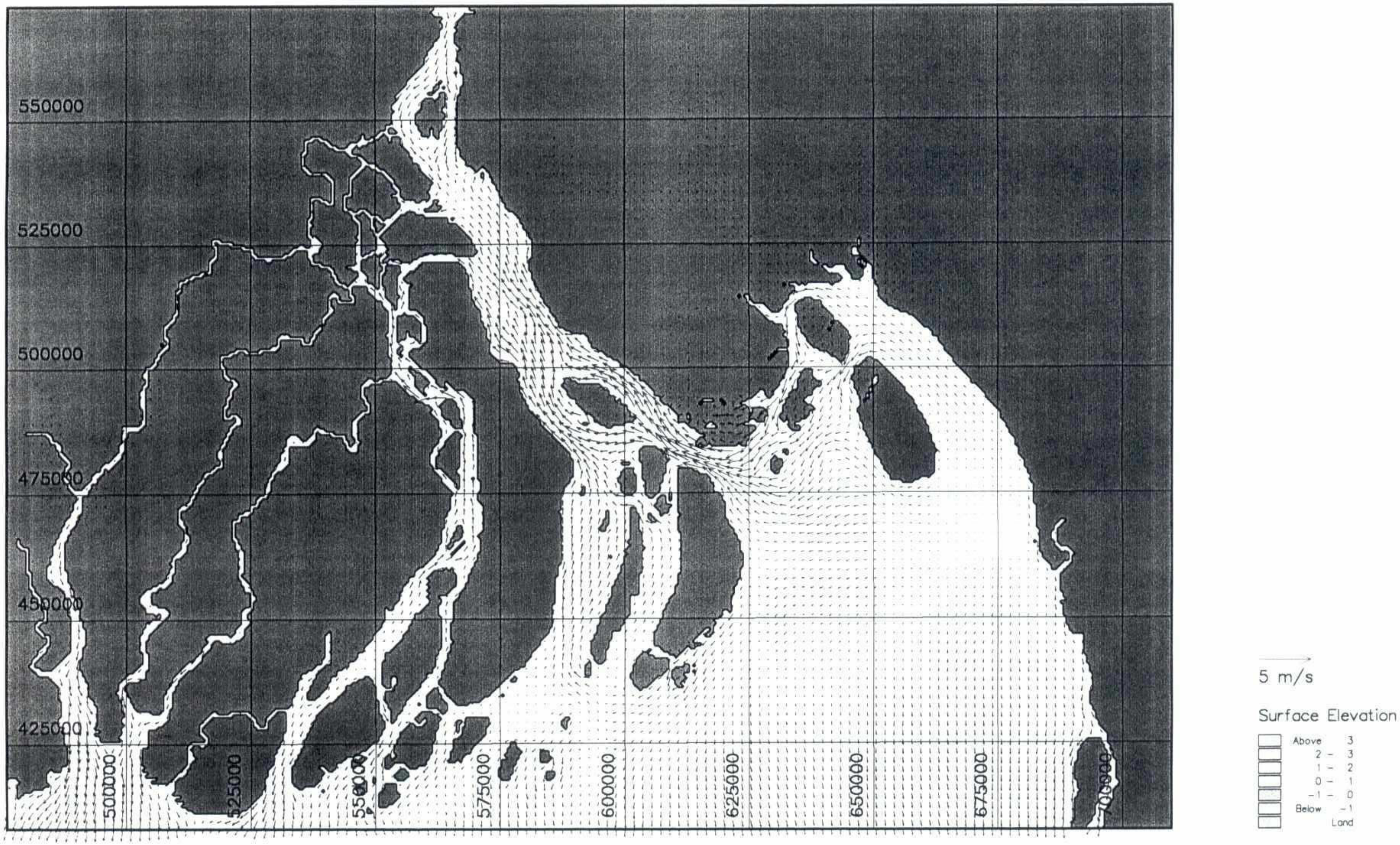
Walton, T.L. & W.D. Adams, 1976.
Capacity of inlet outer bars to store sand. Proc. 15th Conf. Coast. Eng., New York, ASCE, Vol.2: 1919-1937.

Wang, Z.B., 1989.
Mathematical modelling of morphological processes in estuaries. In: Communications on hydraulic and geotechnical engineering, Report no. 89-1, Doctoral thesis of Faculty of Civil Engineering, Delft University of Technology, pp. 1-208.

Watanabe, A., 1985.
Three-dimensional predictive model of beach evolution around a structure. Proc. Water Wave Reseach Conf., Hannover West Germany, pp. 123-141.

ANNEX A

Simulated flow patterns in the Meghna Estuary during dry season



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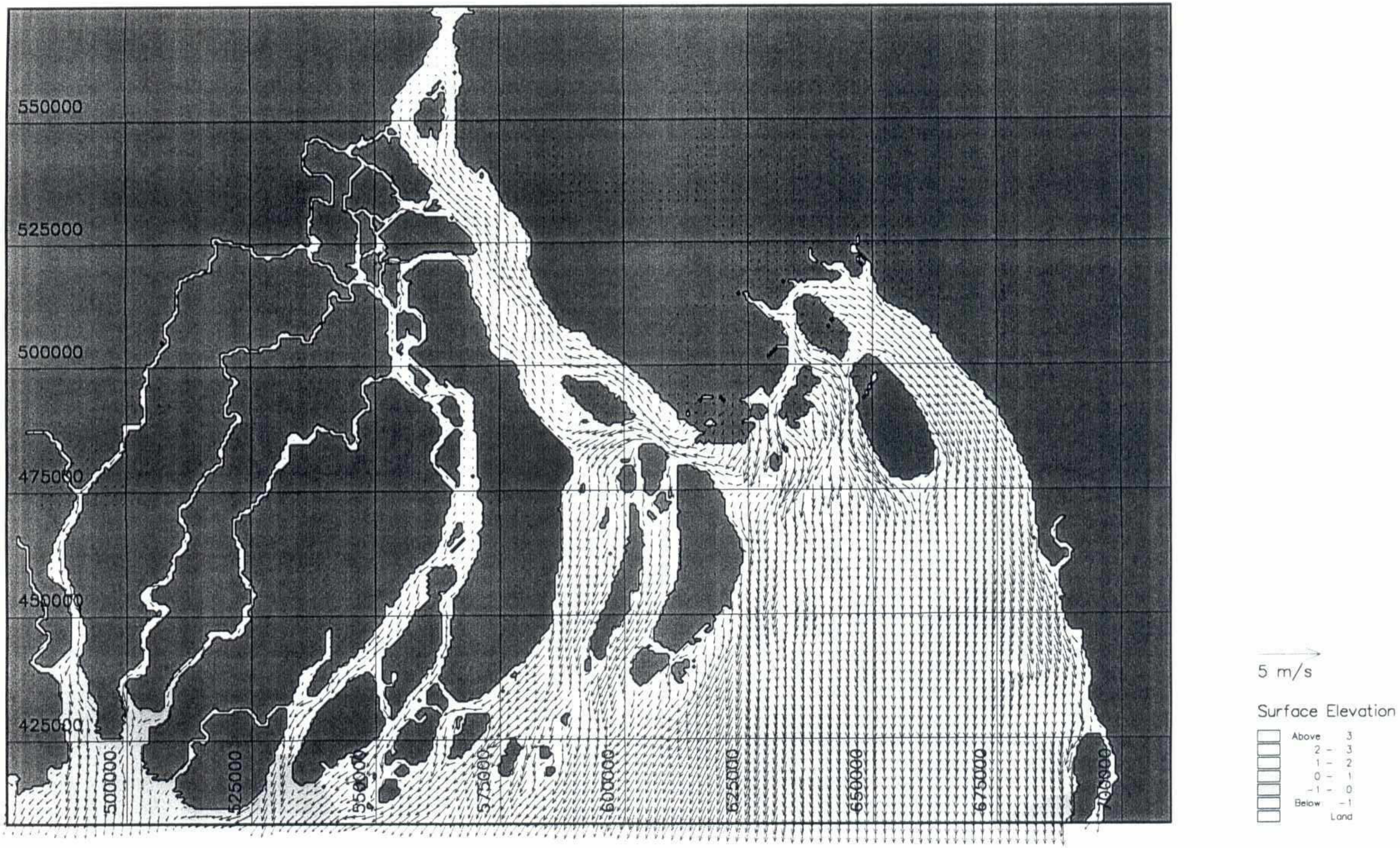

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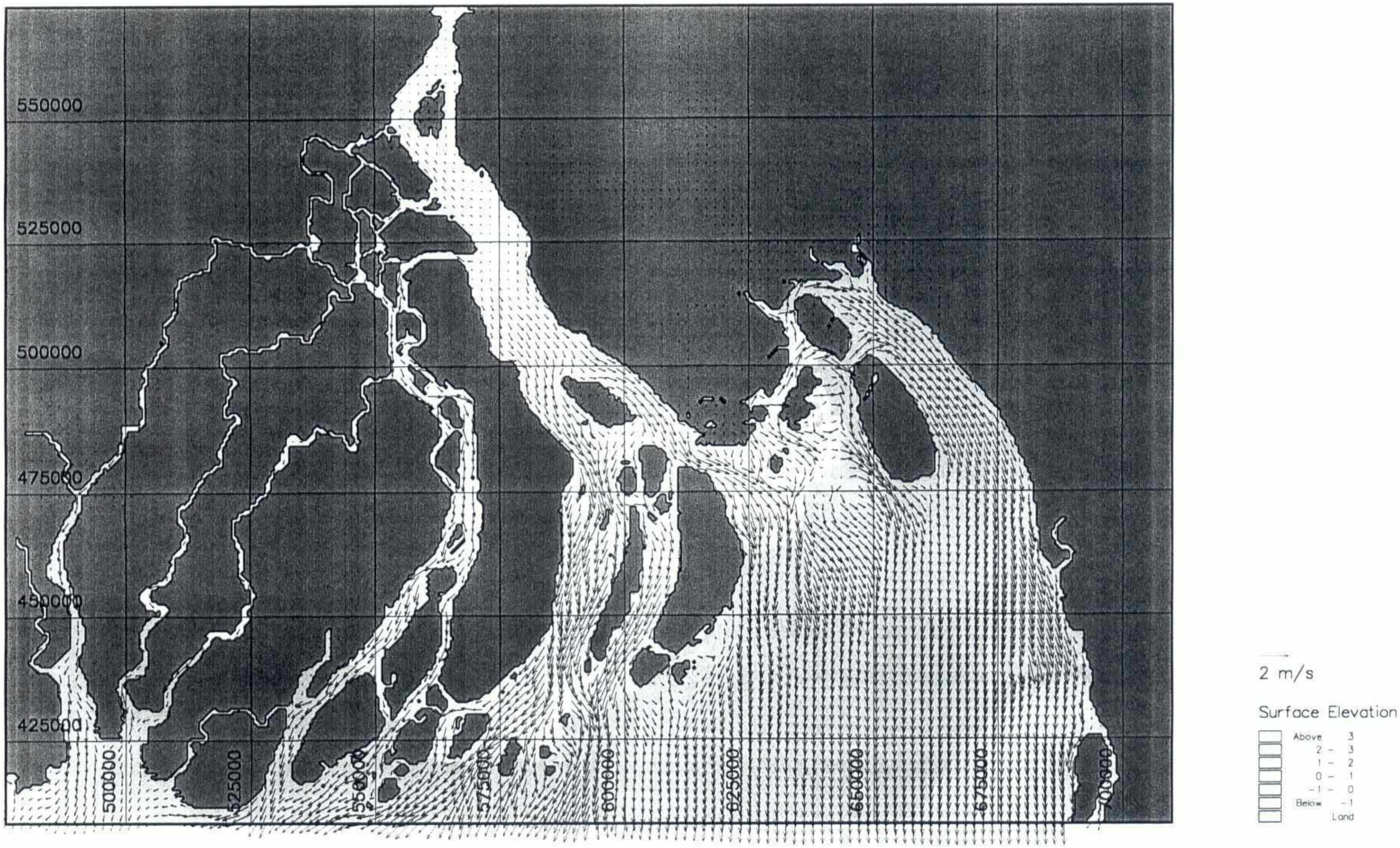

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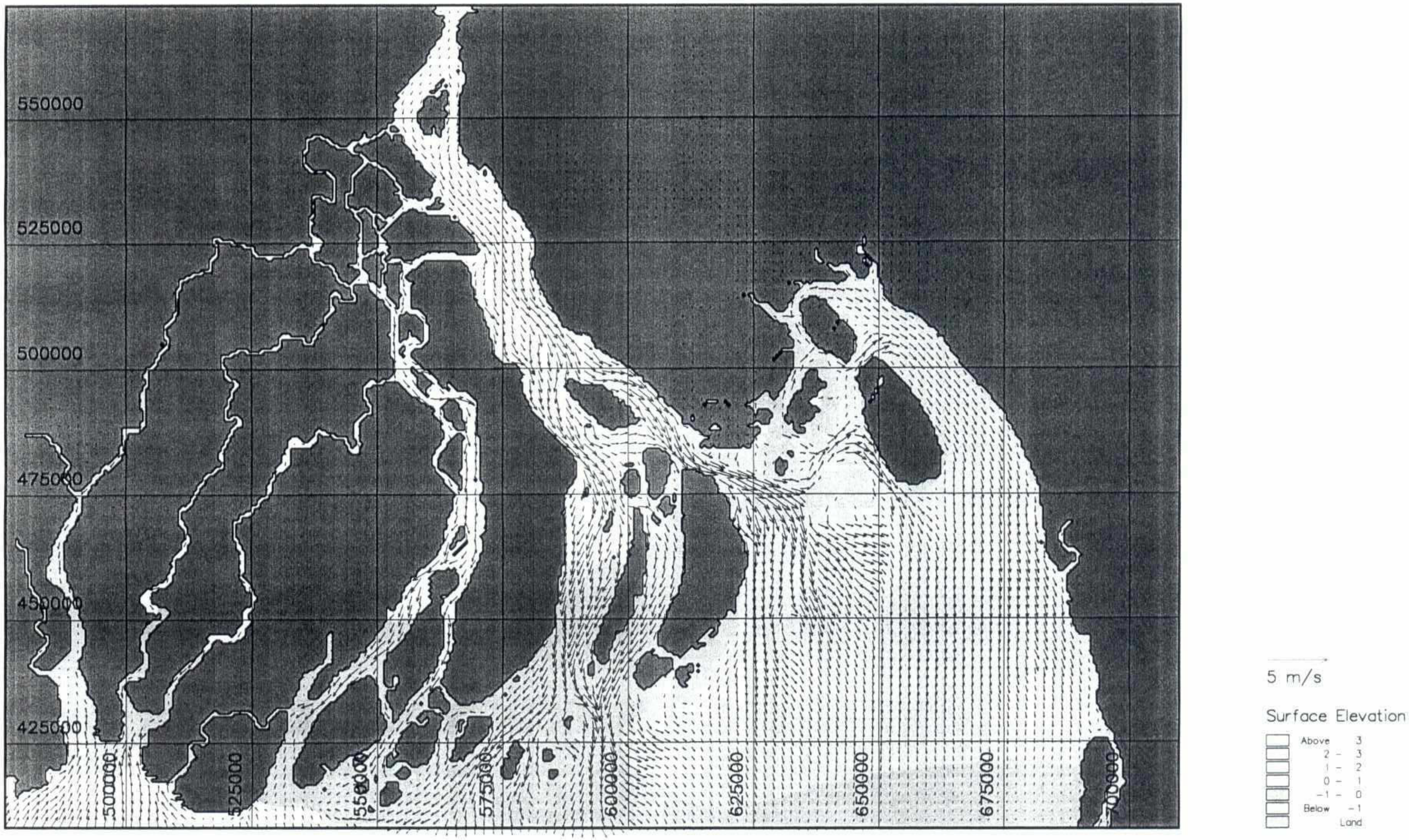

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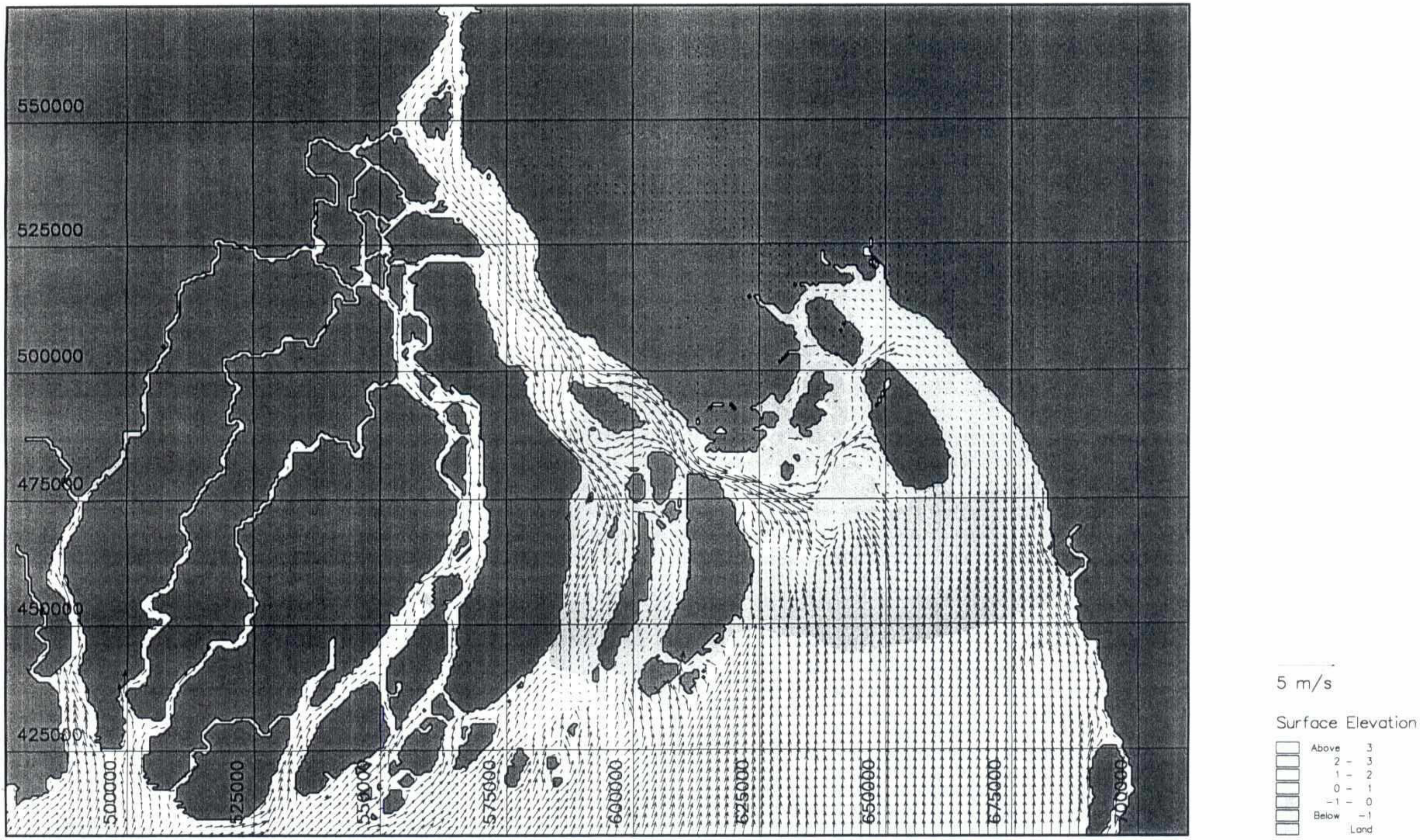

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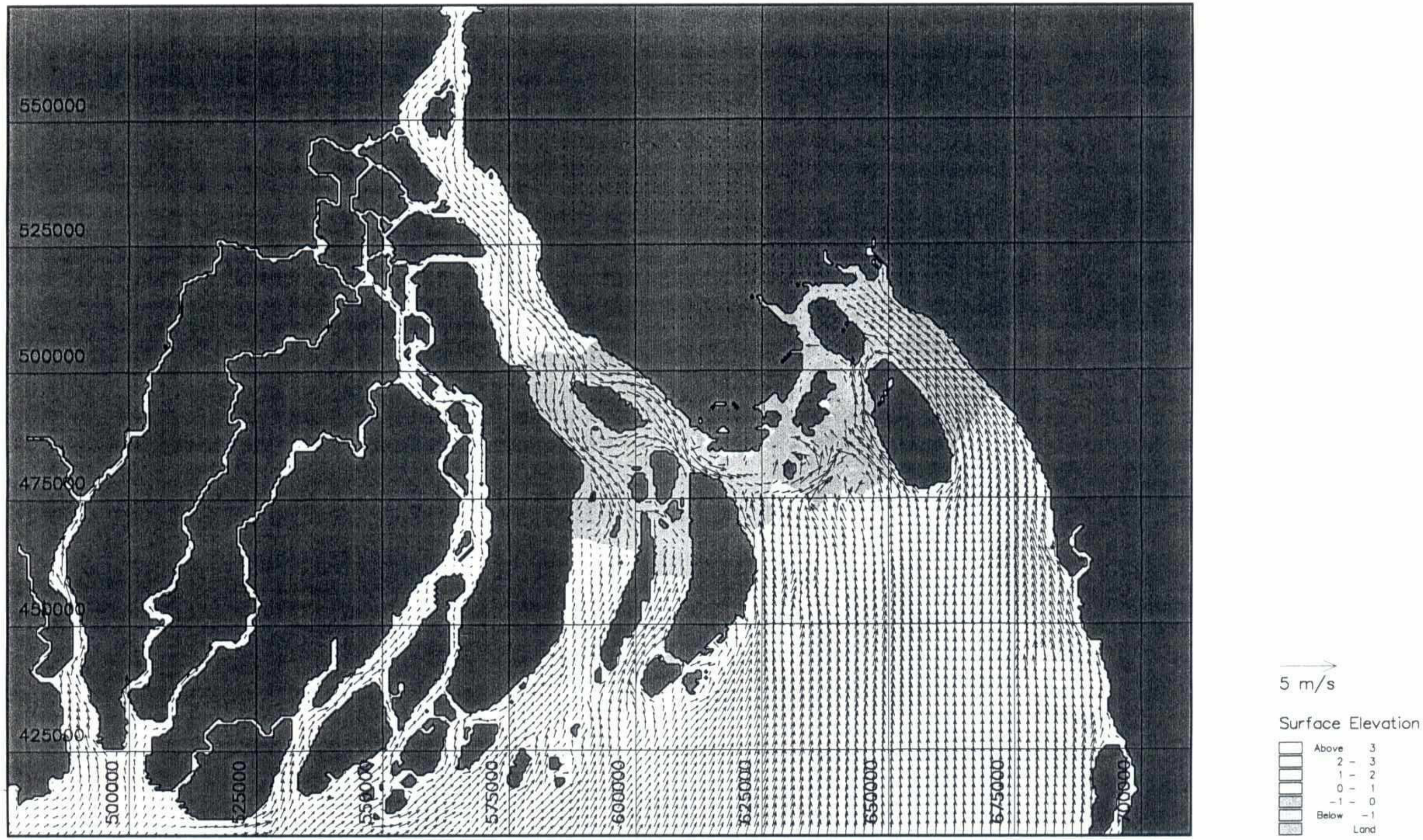

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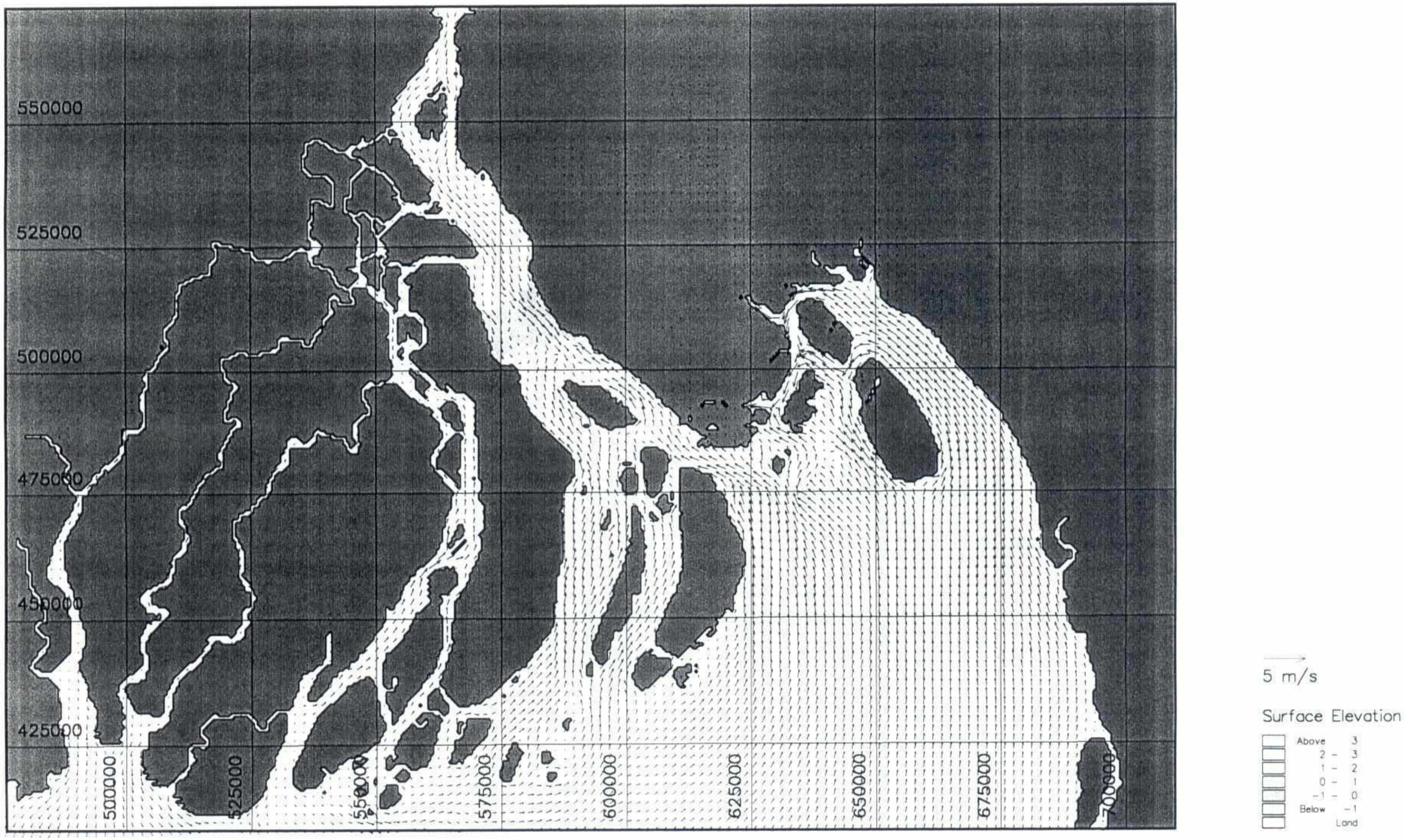

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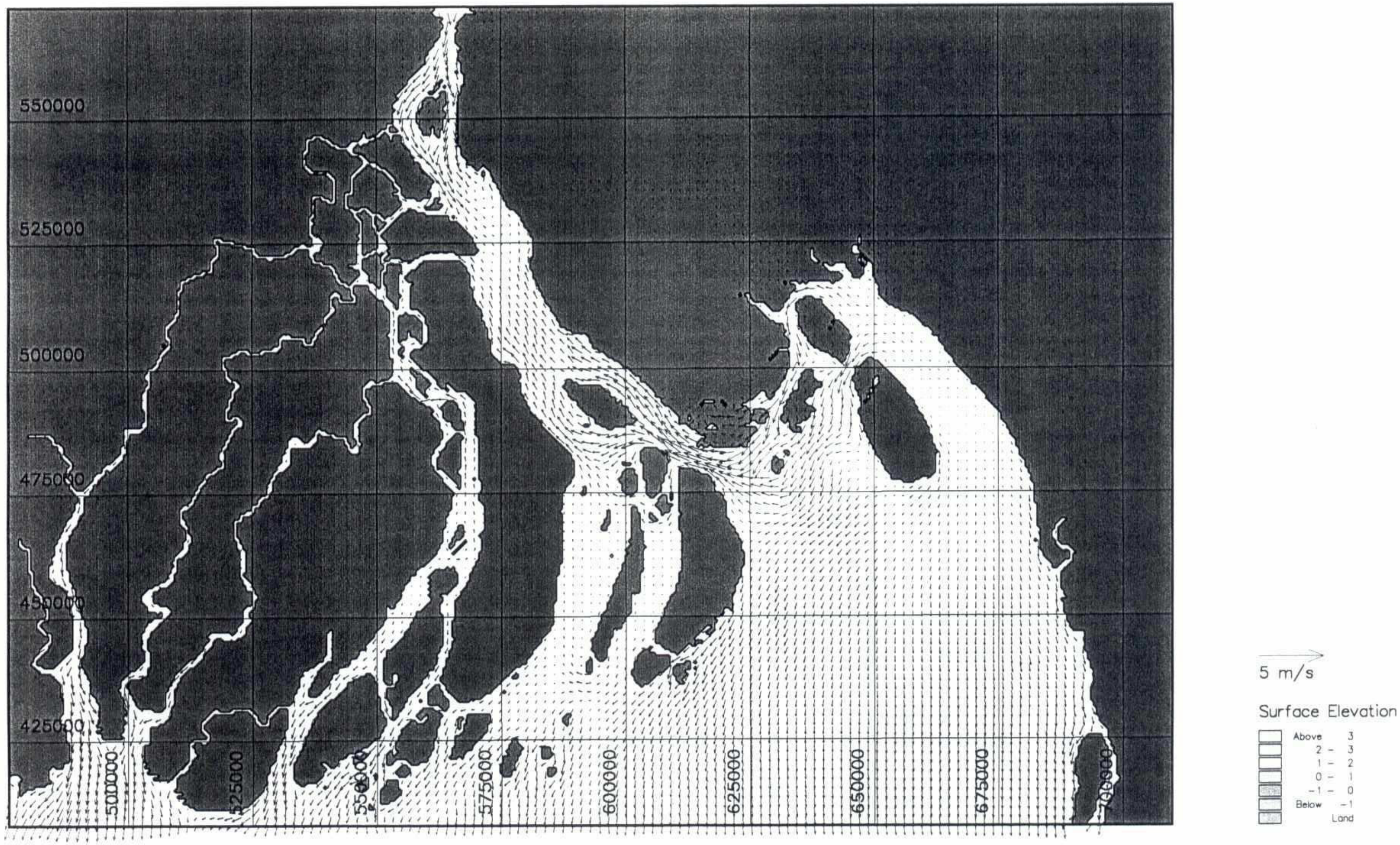
ANNEX B

Simulated flow patterns in the Meghna Estuary during monsoon season



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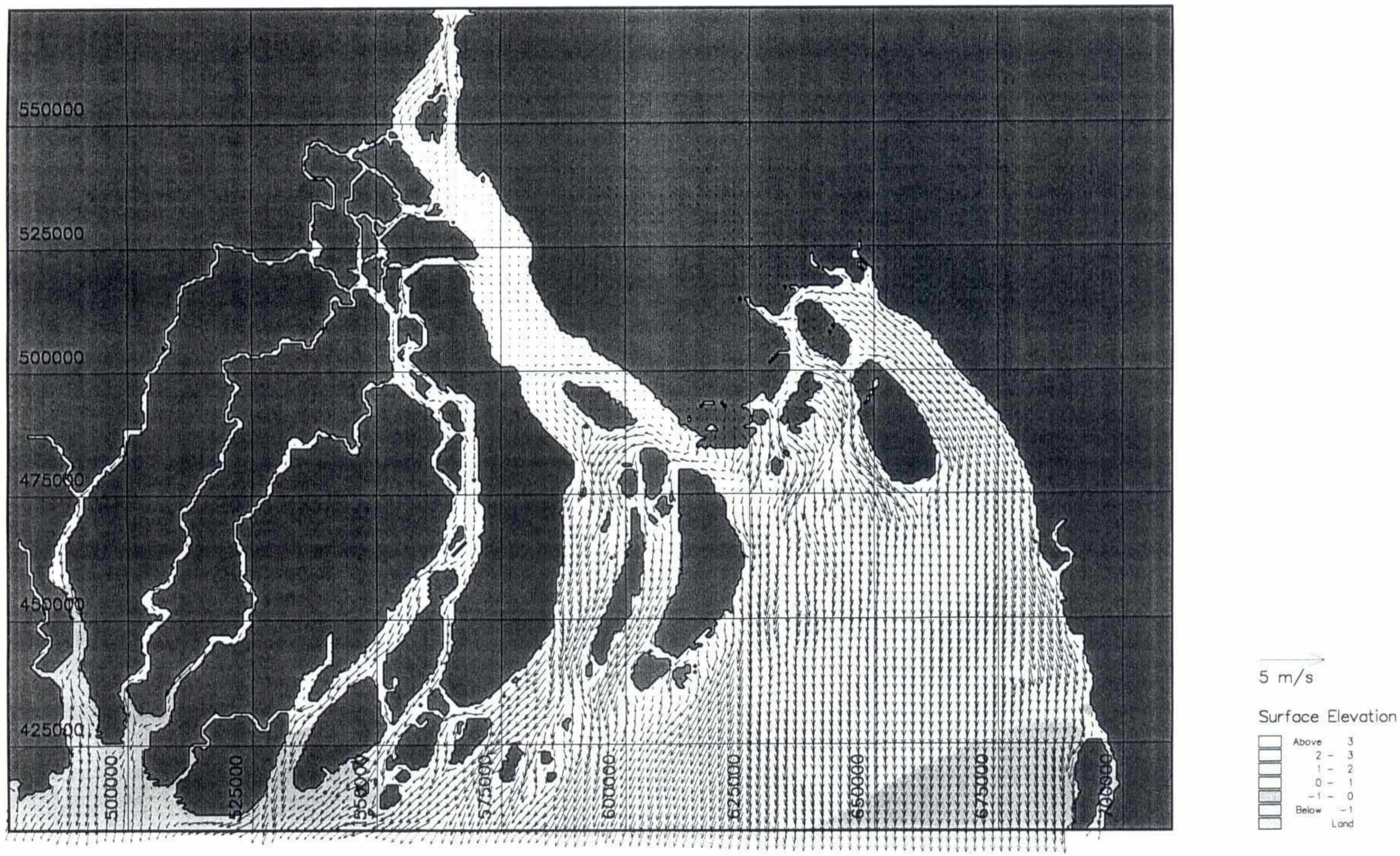

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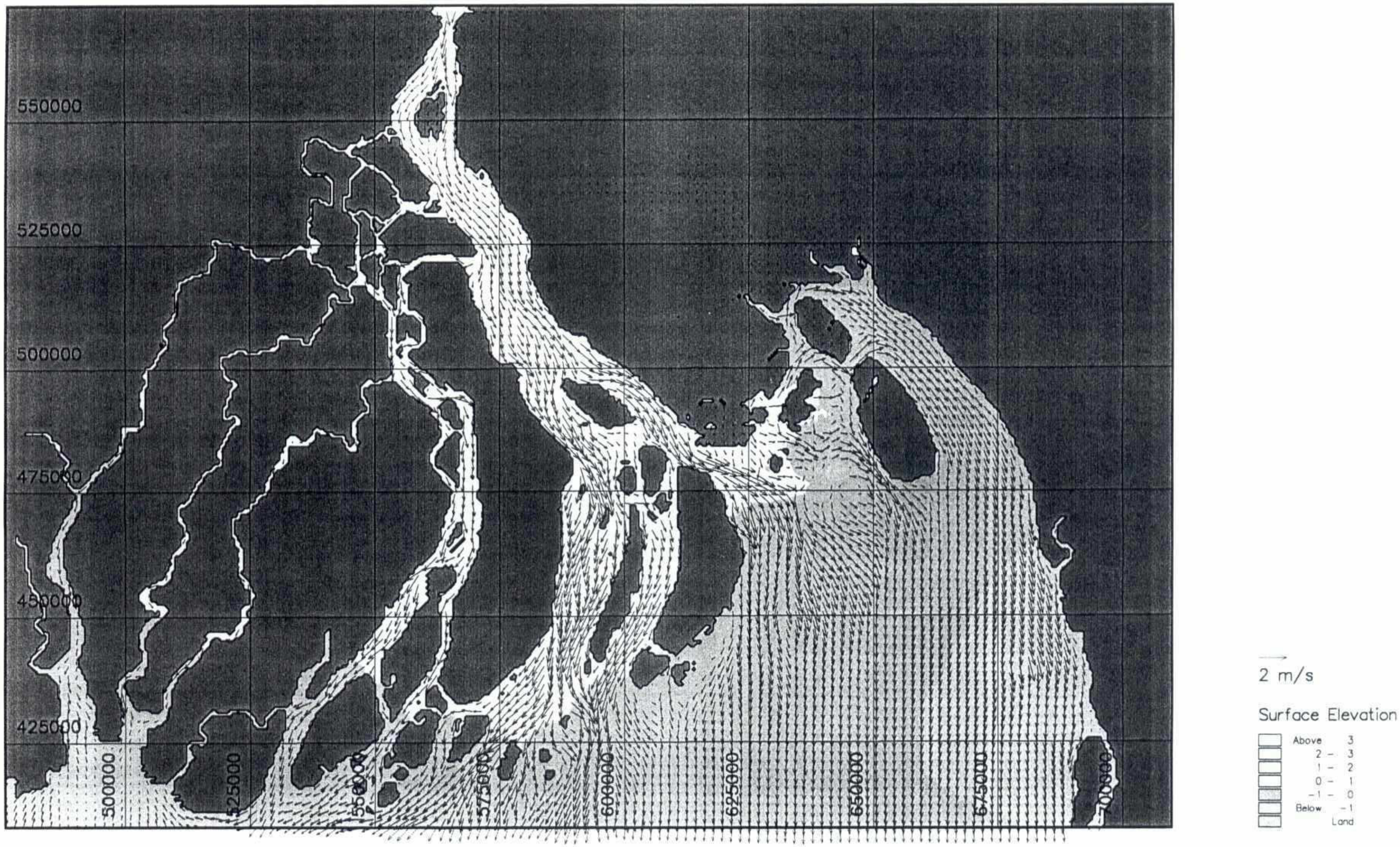

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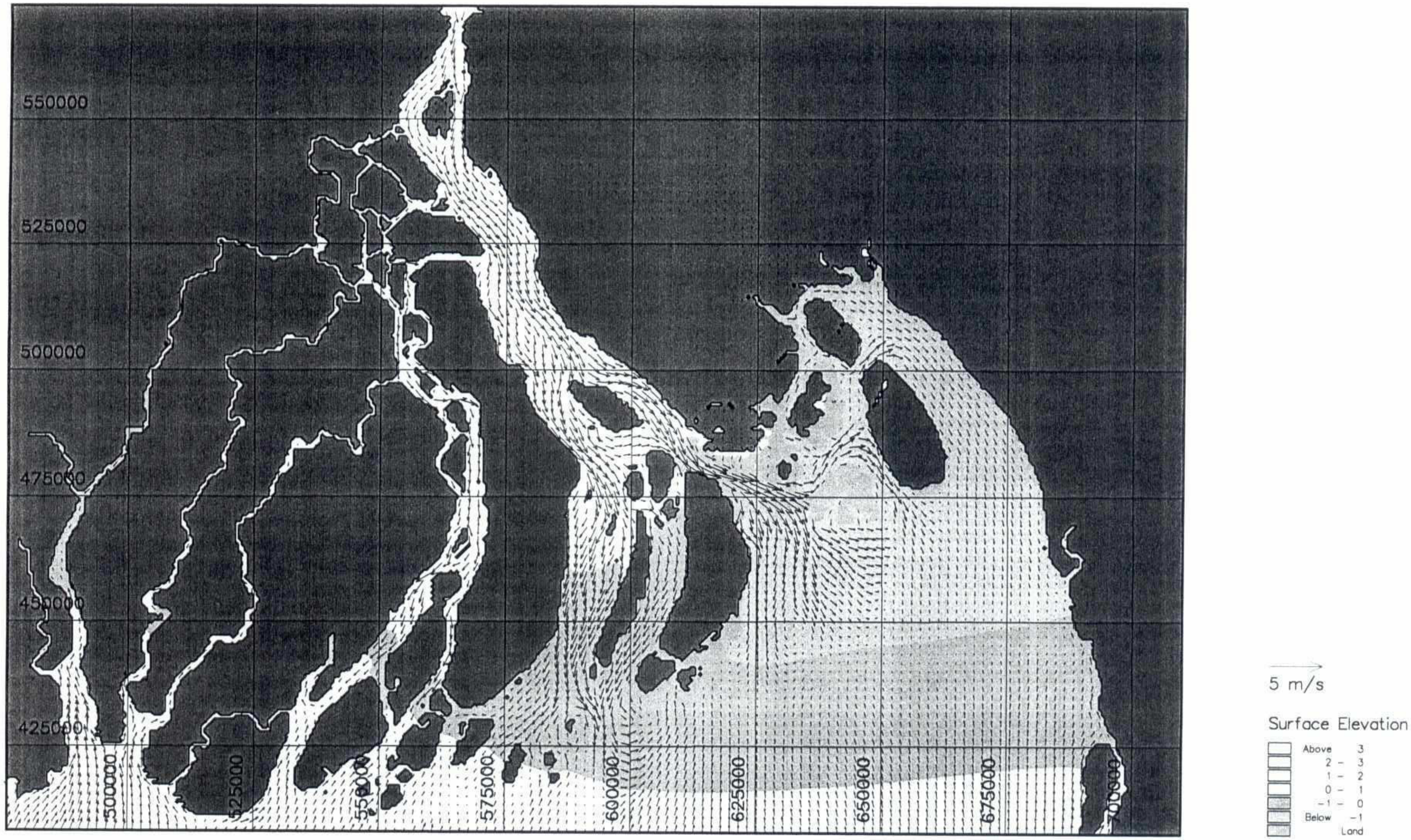

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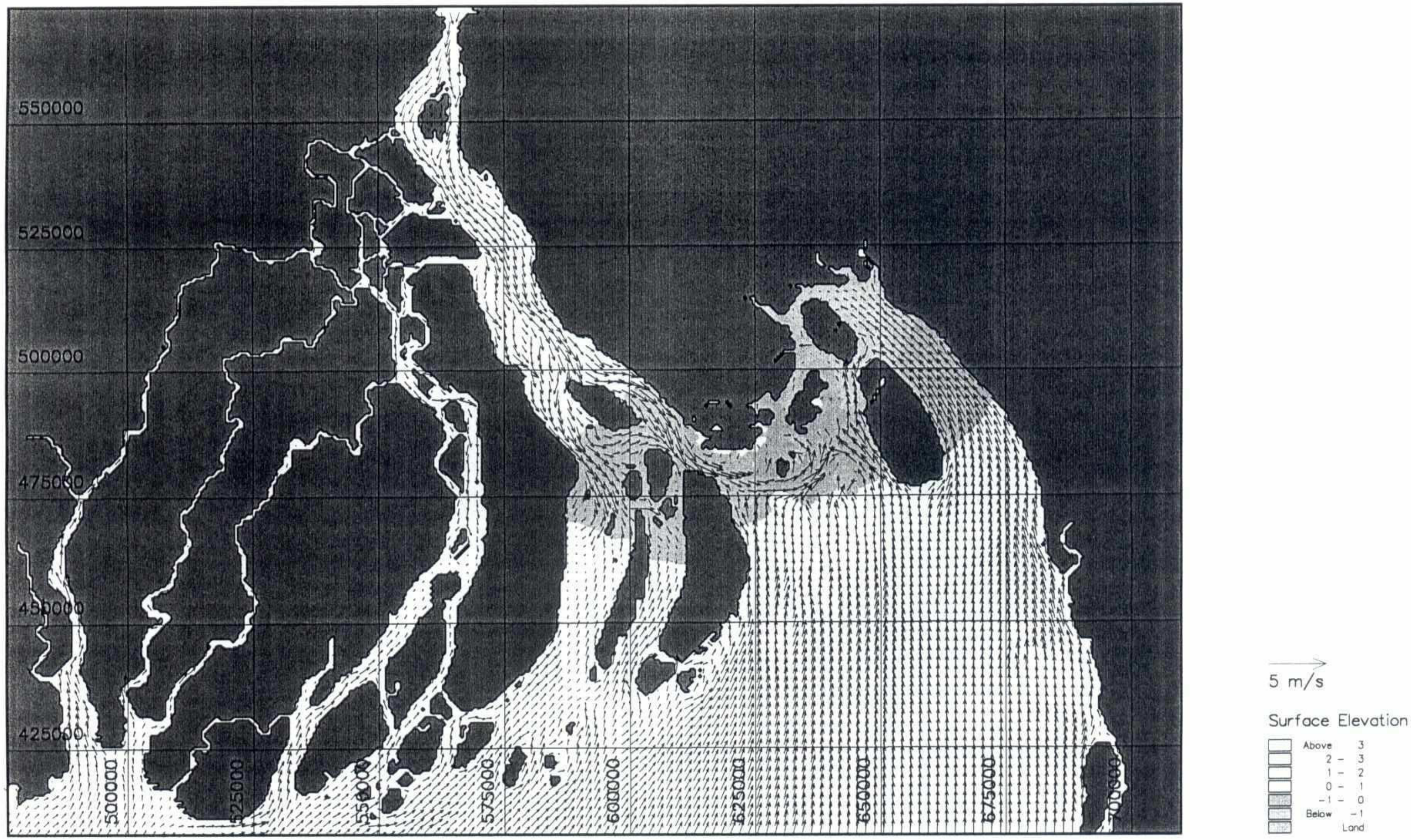

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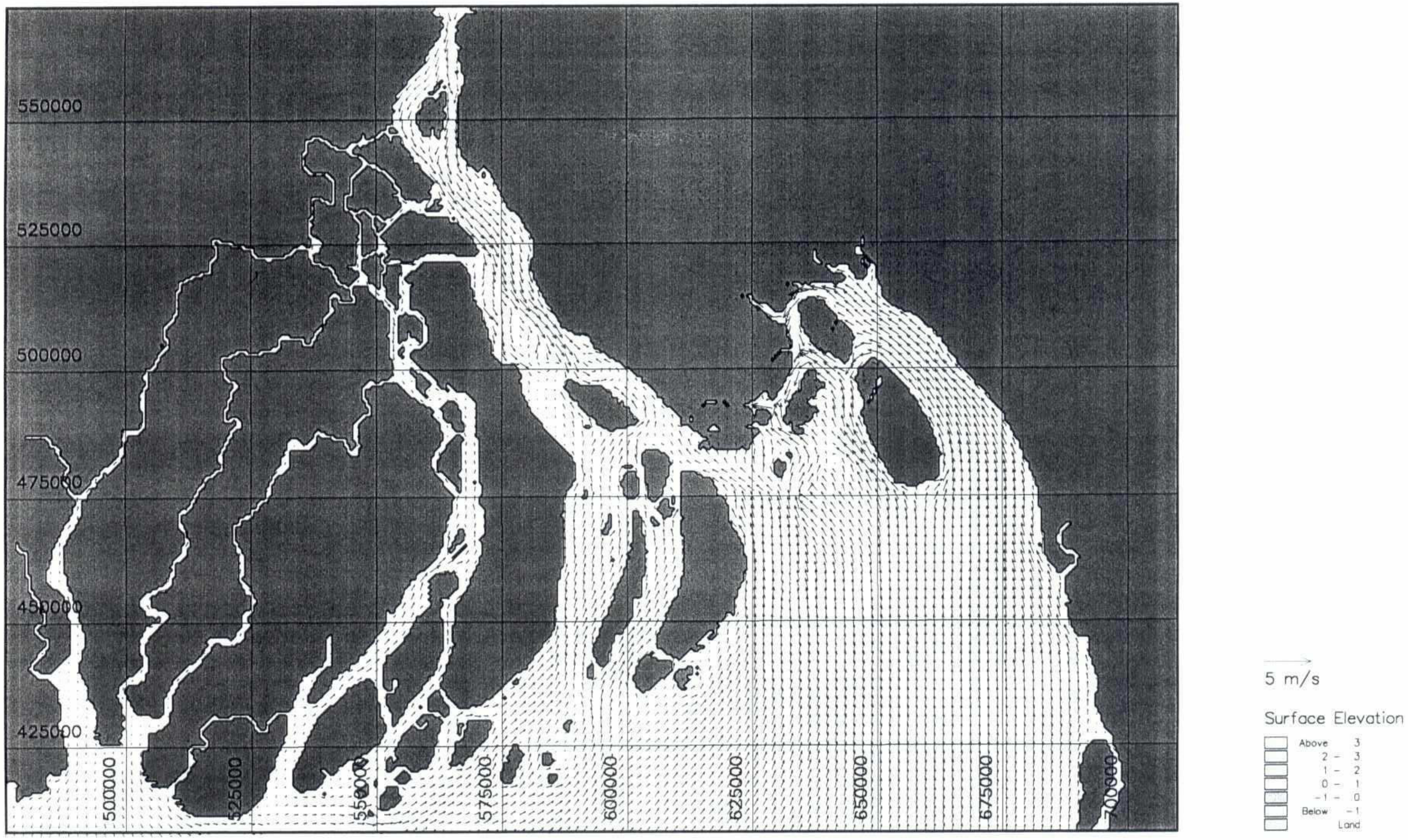

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		Project: MES Area Model	
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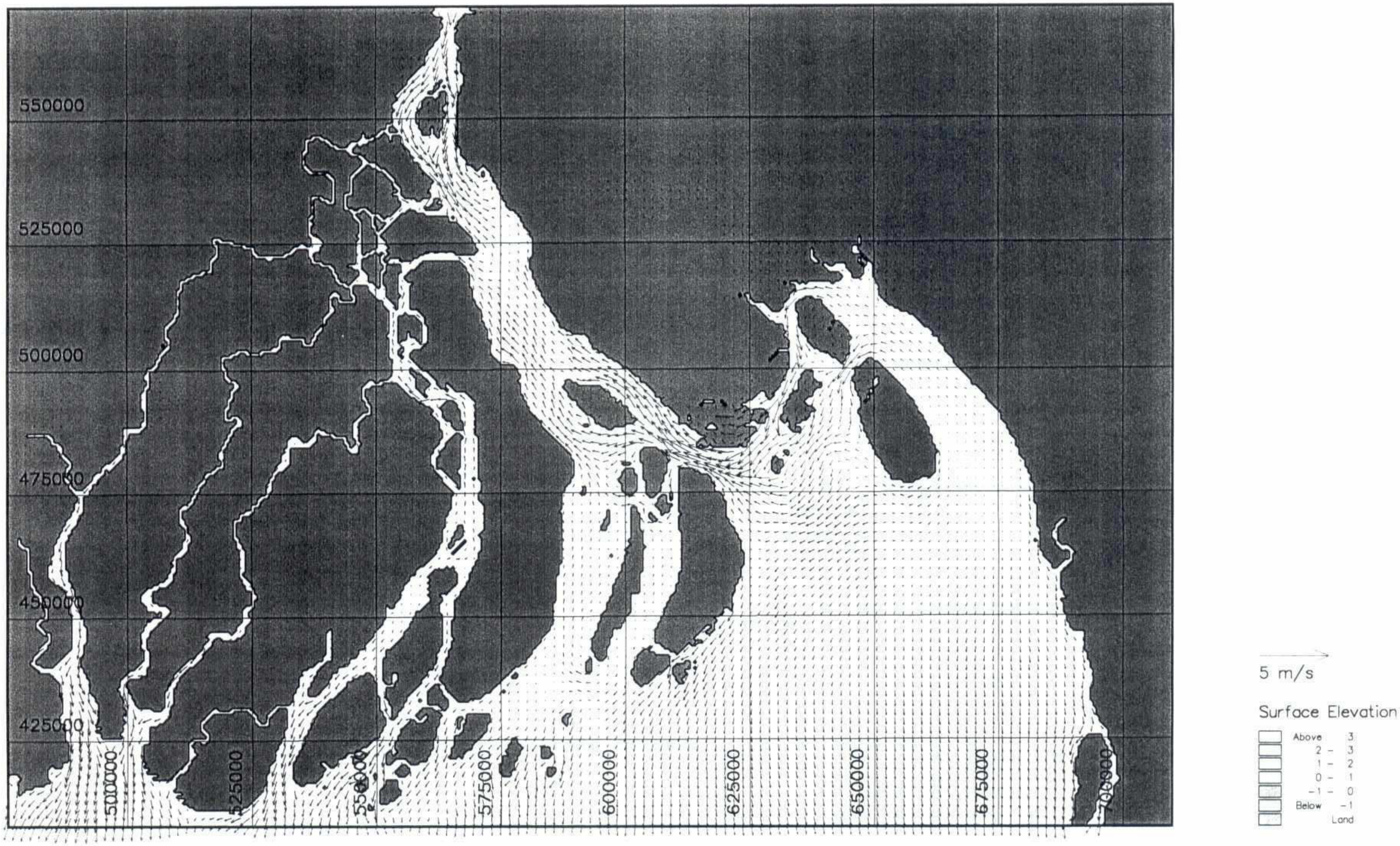

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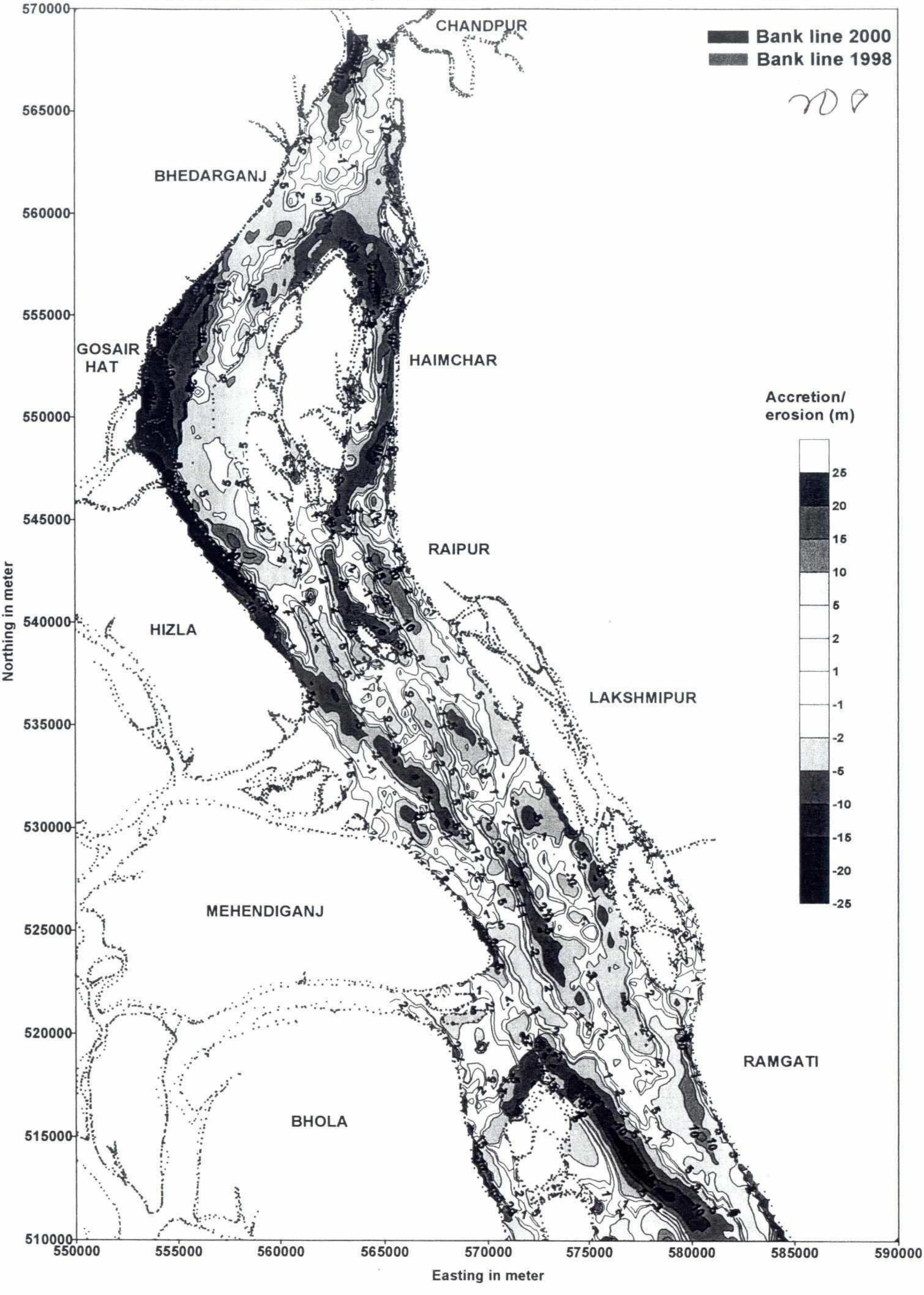
Danish Hydraulic Institute		Client: Meghna Estuary Study II		MIKE 21
		Project: MES Area Model		
File:	Date: Sun Apr 08 2001	Surface elevation and velocity distribution during spring tide Monsoon 1997	Drawing no.	
Scale: 1:1140000	Init: ss			

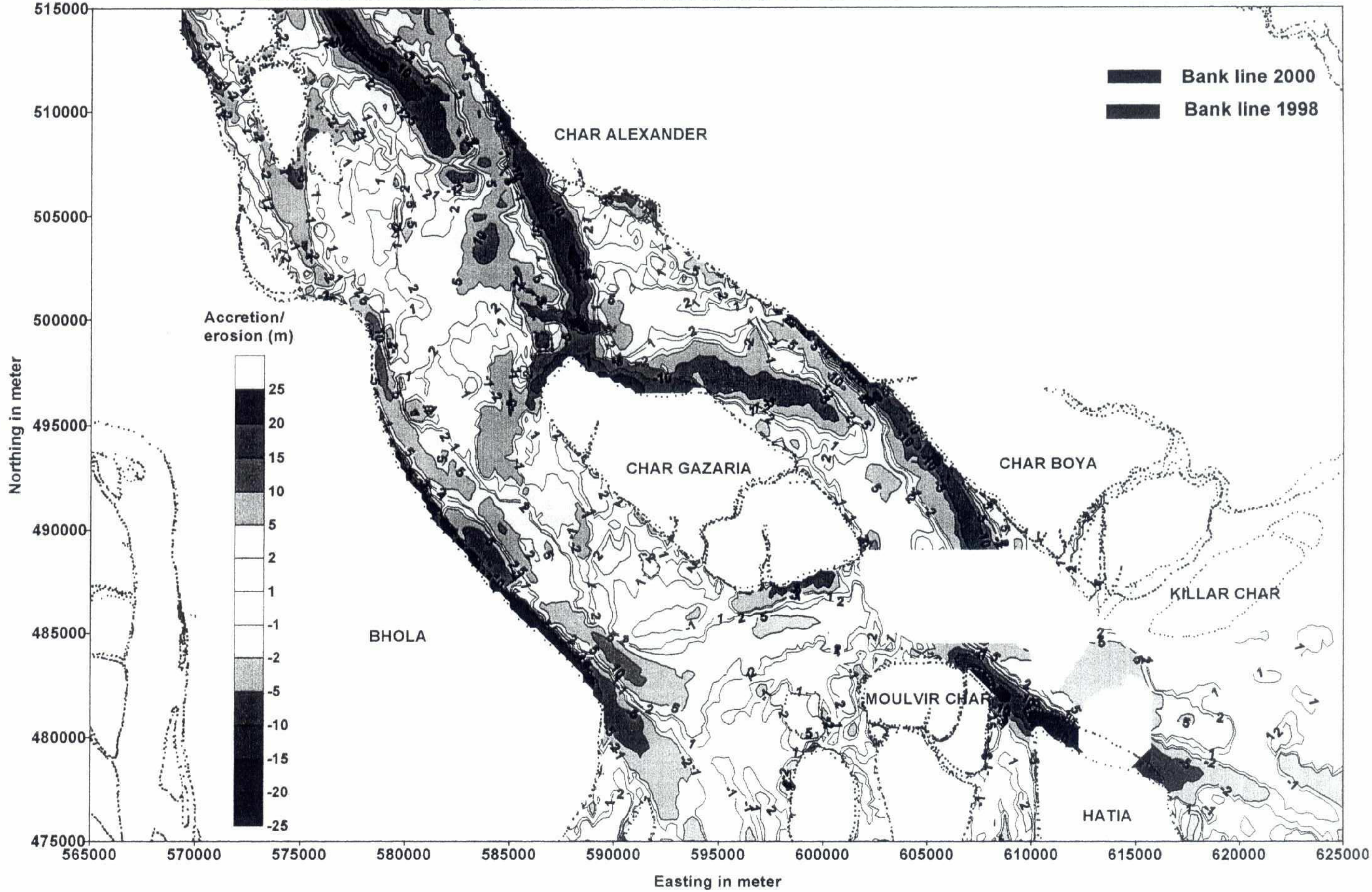
ANNEX C

Bathymetric change maps (1997-2000)

Accretion/erosion (bathymetric change) map for area 1



Aooretion/erosion (bathymetrio ohange) map for area 2



ANNEX D

Recommendation for survey program

Figure D1 : Extent of basic bathymetric survey and position of standard cross-sections

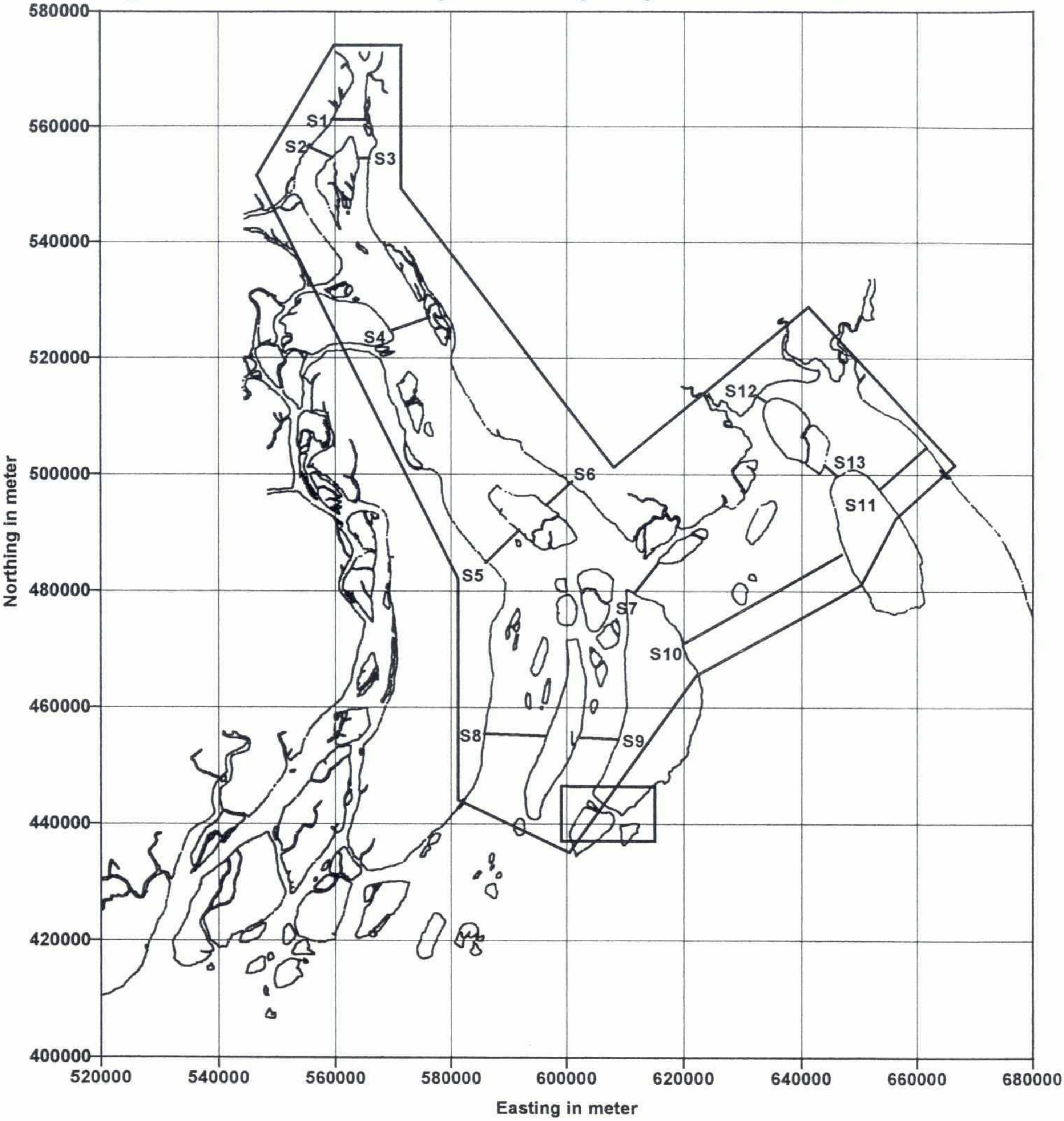


Figure D2 : Extent of of area of special interest for extensive surveying

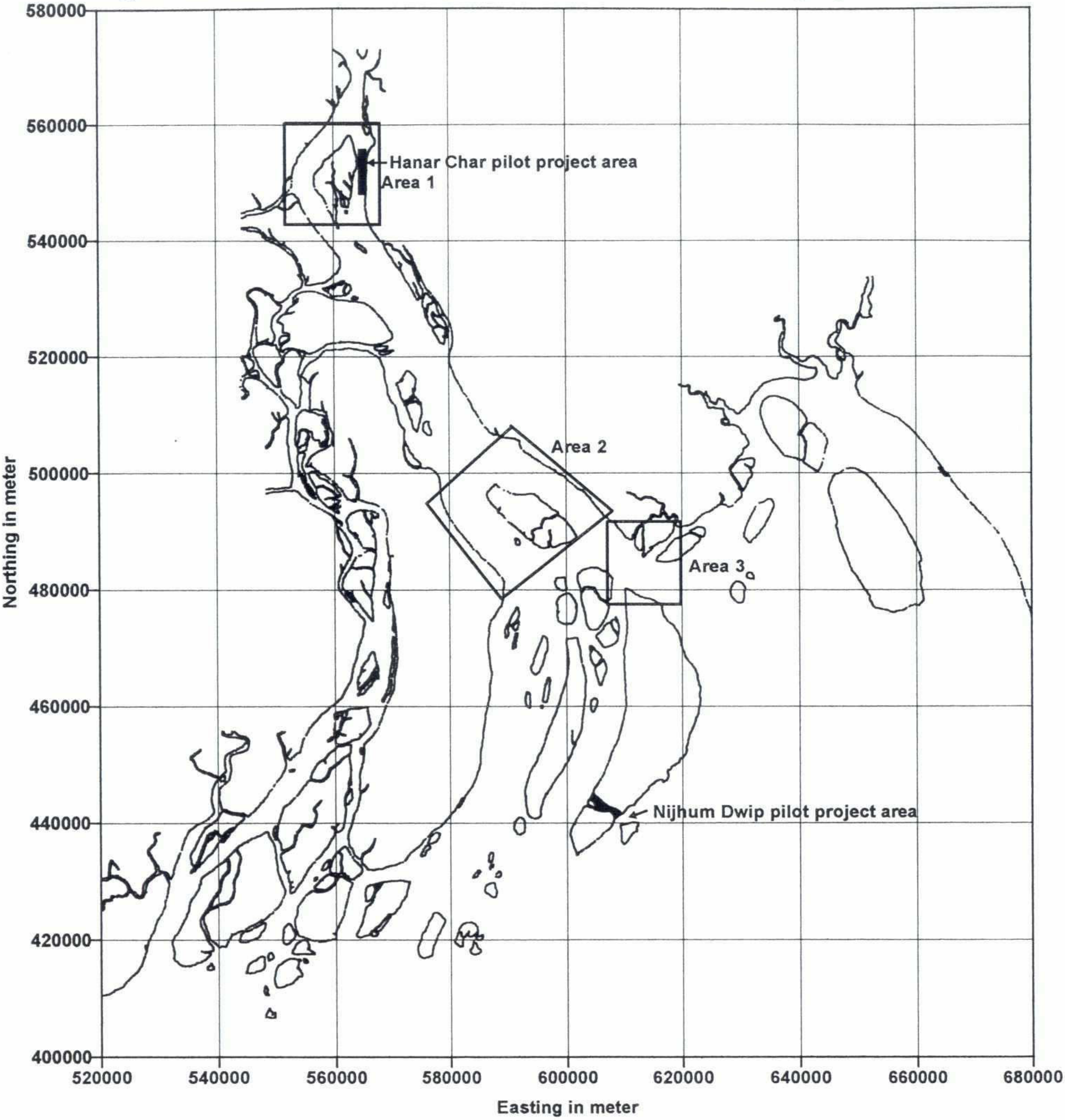


Figure D3 : Location of transects for discharge measurements and areas for velocity measurements

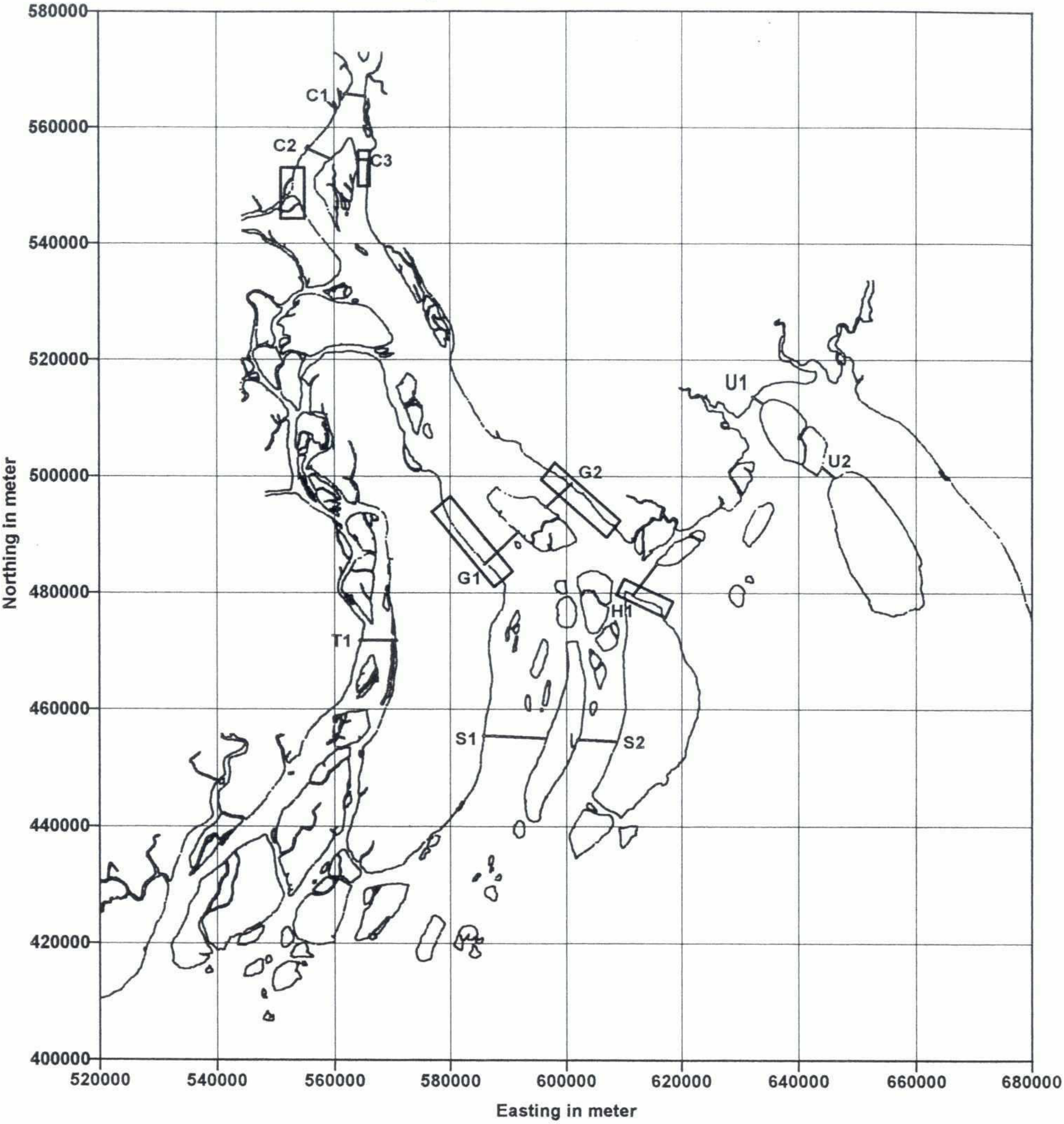
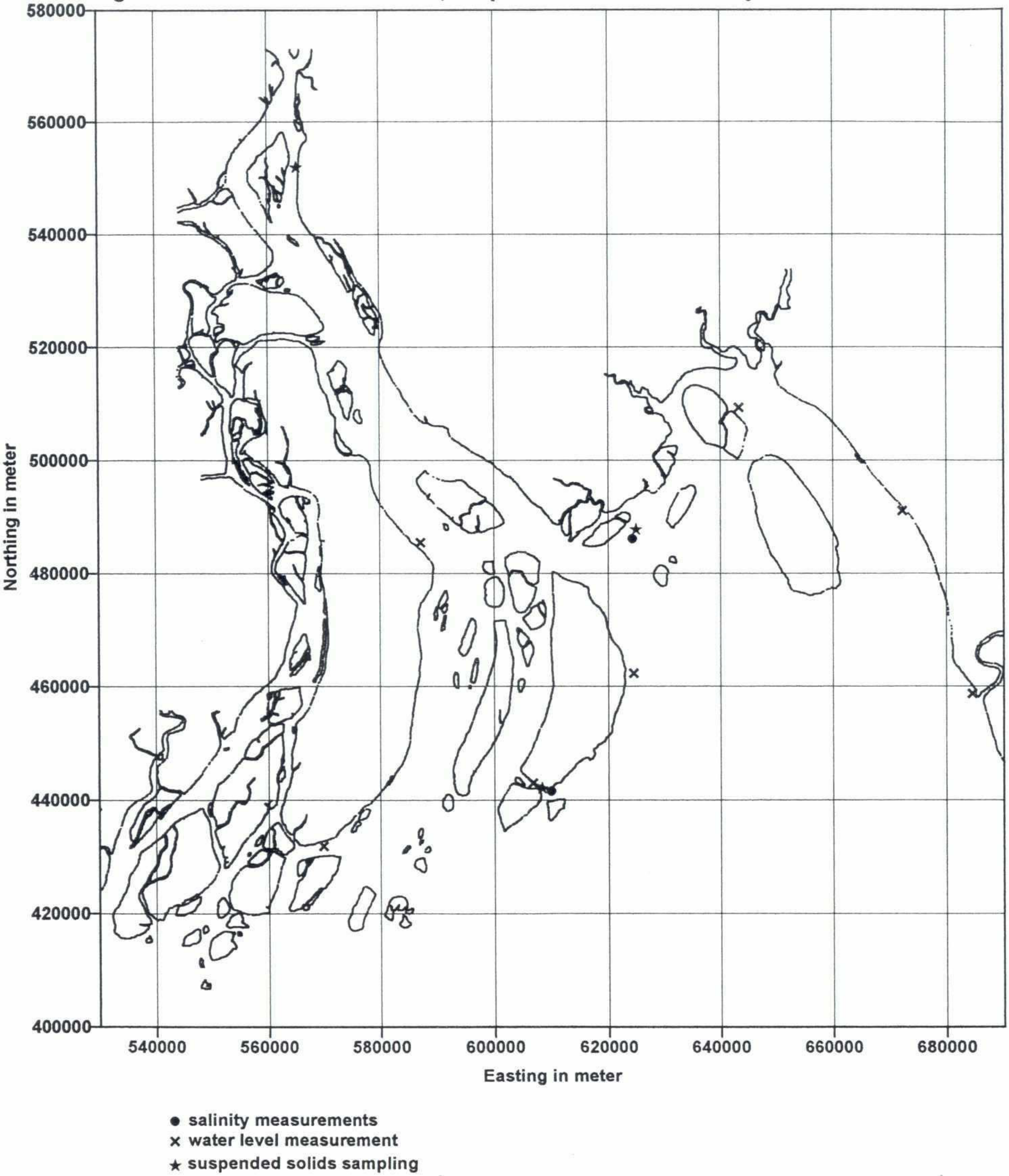


Figure D4 : Location of water level, suspended solids and salinity meassurements



Annex D. Proposed 5-year survey program

Introduction

During MES, regular surveys of the estuary were carried out. During these surveys, an extensive amount of information has been collected and analysed. A continuation of the data collection and analysis is deemed necessary to increase our understanding of processes in the area, and to monitor the physical development and changes in the coastal zone. Only on this basis, reliable predictions of future development can be made. The collected information will provide a necessary input to the work of BWDB and PDO/ICZM.

In the Meghna Estuary, areas of higher and lower dynamics can be distinguished. The most dynamic areas require very frequent observation, while the less changing areas can be monitored less frequently. A yearly update of bathymetry is deemed necessary to get insight in the processes of erosion and accretion in the channels throughout the estuary, which might affect the formation and loss of land in the course of time. Selected areas (e.g., locations where human interventions will be carried out) require even higher frequency in order to obtain more insight in the changes throughout the monsoon. These surveys will provide basic information for further morphologic studies.

Besides basic bathymetric surveys, which will be operated on the routine basis, there is also a need to collect other hydrographic data, like salinity, flow velocity, discharge. Additional bathymetric information will also need to be gathered.

Doing limited survey works with the Survey Unit Anwesha including data processing, the Survey Unit will remain operational and the acquired capabilities of the trained staff will remain up-to-date for any other task in the coastal zone.

The (tentative) survey program will comprise the following elements:
1. basic bathymetric survey
2. detailed bathymetric surveys of areas of special interest
3. survey of the northern Bay of Bengal
4. survey of the Sunderbans
5. survey of the East Coast foreshore
6. discharge and velocity measurements
7. water level measurements
8. sediment sampling
9. wave measurements
10. water quality measurements
11. salinity measurements
12. special measurements
13. land surveys
14. surveys for ground thruthing of remote sensing

These elements are elaborated in more detail in the following text.

Activity 1: Basic bathymetric survey

The basic survey program will comprise a bathymetric survey of the following areas (see Figure D-1):
1. Lower Meghna from 15 km upstream of Chandpur to Char Gazaria
2. West and East Shabhazpur Channel from Char Gazaria to southern end of Manpura and Nijhum Dwip
3. Channel at the north of Hatia and accretion area around Char Bouy,

4. Area between Noakhali mainland, northern Sandwip and Chittagong mainland, including Urir Char and Sandwip Channel
5. Area near the pilot project location Nijhum Dwip

The line spacing will be 600m and 1200m, same as in 2000 and 2001 surveys. Lines will be sailed perpendicular to the channel's axis, using the same alignment as during 2000 and 2001 surveys. This is required to obtain depth charts which are comparable with earlier surveys. In addition, 11 fixed cross-sections will be measured. At each cross-section, 3 parallel lines (100m apart) will be sailed. Alignment of these lines is also specified in Figure D-1. In addition to the measuring procedure as applied by MES (echosounding along parallel transects) it is proposed to measure bed levels during all vessel movements at the time of the survey. Also the echosounder of Anwesha should register the depths when sailing to the location of measurements, and on the way back to the port (RTK-stations will not be set up for this recording, the water levels can be calculated back from the model). This way additional information about the bed forms between the transects and longitudinal profiles will be obtained at no extra cost except of extra storage and post-processing. It is expected that this may significantly improve the quality of prepared bathymetric charts.
This part of the survey will be carried out on a yearly basis, during the dry season.
During the survey, pressure cells will be deployed in the vicinity of the survey areas to register water level. The water levels are required during processing to check the vertical referencing. Whenever possible, pressure cells should be levelled using existing benchmarks.

The processing of data will comprise the following activities according to the method worked out by MES:

- ✓ Removal of spikes and steps in the field data records especially in echo sounding depth and real time kinematics (RTK) level from WGS84 ellipsoid surface (*if quality of satellite signal appears to be poor, like in 2000-survey, use of model simulations to establish water levels should be considered*)
- ✓ Preparation of input files for Geoid model (Gravsoft geoid interpolation and transformation of ellipsoidal height to geoid height in terms of PWD datum)
- ✓ Linking of geoid input files
- ✓ Datum conversion by geoid model and
- ✓ Generation of XYZ (column of easting, northing and bed level) files for surveyed area.

This method of processing is dependent on the quality of vertical levelling determined during the survey using satellite signal (RTK). Experience from the past shows that this quality is often rather poor. In such cases, the water levels can be obtained from the 2D model of the estuary, after introducing some corrections (mainly phase shift) based on field measurements. Knowing water level and water depth, the bed level with reference to the PWD datum can be established.
Furthermore, a recent satellite image of the study area will need to be purchased and the banklines digitised.

The program is meant to cover the following developments:

- *Large-scale morphological developments:* The survey is needed to keep track of the overall morphological developments at a larger scale. E.g. insight to the trends of the overall bottom levels of larger river sections, in the movements of deeper river channels and in the large scale erosion and sedimentation patterns is crucial for any future planning in the coastal zone.
- *Medium scale morphological developments:* After analysis of a time series of survey results, anticipation can take place on erosion attacks, which are to be expected in the short and medium term. Because of the size of the estuary and the facts that the islands and banks are unprotected, the erosion process is a kind of random process. Prediction with the help of mathematical models or physical models is extremely difficult if not impossible. The only sensible way is to follow the tendencies and trends from regular field measurements, and to anticipate on that. In this way earlier predictions can be adjusted accordingly which is important for planning purposes.

Proposed inputs:

- SU Anwesha, 10 weeks or 35 net survey days.
- Morphologist and data processing expert (local): 12 to 16 weeks.
- Hydraulic Software Engineer: 12 to 16 weeks.
- Coastal / Civil Engineer (local): 12 to 16 weeks
- Morphologist, (foreign) : 4 weeks
- Hydraulic and survey advisor (foreign): 2 weeks
- Satellite Images, digital data

Proposed outputs:

- Processed survey data of the Meghna Estuary.
- Analysis of morphological changes and assessments of its impact of the future shapes of the Meghna Estuary.
- Digital and printed maps, showing contours lines and coastal line developments.

Additional surveys and measurements

In addition to the basic survey program, to be executed on the routine basis, extra surveys and monitoring work will be required. This additional program is intended to be flexible, in order to accommodate the information needs of BWDB and PDO/ICZM, and the scope and details of the work should be defined in close cooperation with these organisations. In this document a tentative program for this extra work is given.

Activity 2: Detailed bathymetric surveys of areas of special interest
At present, the following areas of special interest are identified:

- channels around Char Bhairabi; this is an area where the changes in the river system are occurring at an extremely high rate. The main conveyance channel seems to be shifting to the east of Char Bhairabi.
- bifurcation point Char Gazaria and East and West Shabhazpur Channel at the level of Char Gazaria, Char Alexander. Also here large morphological changes are observed.
- Hatia Channel between Hatia island and Char Bouy.

These areas should be surveyed 3 times a year (before, during and after the monsoon season). This means that, in addition to the basic survey, these areas should be surveyed also during and after the monsoon. The spatial extent of these areas is given in Figure D-2. It is important that the same lines as during the basic survey are sailed.
Duration: 2 x 2 weeks; period: (1) September, (2) May (assuming that the overall survey will be carried out in December-January)

In addition, the areas of MES pilot projects:

- Hanar Char pilot project area
- Nijhum Dwip pilot project area should be monitored with a frequency of 3 times per year (before, during and after the monsoon season). For these areas already several detail bathymetric surveys (with approximately 10m line spacing) are available. This gives a very good material to study morphological processes in detail. Therefore, the monitoring at the same spatial resolution should be continued. It is important that always the same lines are sailed.

Duration: 3x 1 week
Frequency: 3 times per year

Activity 3: Survey of the northern end the Bay of Bengal
The bathymetric surveys of MES were limited to shallow areas of the estuary. Additional survey of the southern extent of the estuary (south of the southern extent of MES-project area) is necessary to get a better insight of its form and to improve the existing 2D model. Lines with a spacing of 1200m should be sailed in the direction north- south until the depth contour of 20m is found, starting from the northing 460 000 east of Hatia and 410 000 west of Hatia. As area is expected to be much less dynamic than the rest of the estuary, the frequency of 1 in 5 years is proposed.
Duration: 2 weeks
Frequency: 1 survey in 5 years

Activity 4: Survey of the Sunderbans
Hardly any information is available regarding the morphological development of the Sunderbans. A full bathymetric survey of this area will be carried out. The survey will comprise the major rivers and tidal channels as well as of the bay south of the Sunderbans. Line spacing of 600m will be applied.
Duration: 4 weeks
Frequency: 1 survey in 3 years

Activity 5: Survey of eastern coast foreshore
At present, no reliable bathymetric map of the foreshore south of Chittagong is available. Knowledge of the foreshore and its developments is crucial for the development of design hydraulic conditions for the sea-facing embankments. The prediction of wave action and run up is heavily dependent on the availability of accurate bathymetry. It is proposed to extend the MES area further south along the East Coast to St. Martin's Island. Survey will be executed by sailing lines in east-west direction to 20 km from the shore, with a spacing of 1200m between the lines.
Duration: 2 weeks
Frequency: 1 survey in 5 years

Activity 6: Discharge and velocity measurements
Discharge measurements are important to establish the discharge distribution between the river's branches and to assess the river's dynamics. The magnitude of flow velocity determines together with the bed condition the erosive force of water, but also the potential for accretion. This information is also very important for calibration of the 2D-model of the Meghna Estuary, available at SWMC. As the bathymetry is changing significantly from year to year, this model also requires regular updates and re-calibration. No rating curve for Lower Meghna is available at present. During a period of 5 years, sufficient measurements of discharge can be collected to make a reliable rating curve for Chandpur.

Discharge measurements should be carried out during a full tidal cycle (12hrs 25min) with a frequency as high as possible (at least one measurement per hour, during 13 hours). Measurements should be taken during dry season and during high monsoon, and one during neap tide and one during spring tide. When measurement is intended to determine discharge distribution between river's branches, it should be carried out during consecutive days in separate branches to remain within the same phase of the fortnightly tidal cycle.
Experiences of MES show that float tracking using GPS-receiver is a cheap yet reliable method for measuring discharges, provided that some precautions are taken. Wherever possible, simultaneous ADCP and float track velocity measurements are proposed as required for calibration and estimation of accuracy. Full-tidal cycle measurements at the level of Chandpur are to be carried out more often. Float tracking at a fortnightly basis during high monsoon (August-September) and a monthly basis during the rest of the year is proposed.
In Figure D-3, 10 transects for current measurements and areas for velocity measurements are specified. Discharge measurement in some major branches in the Sunderbans is proposed. This can be combined with the bathymetric survey.

A detailed measuring procedure is given in Appendix D-1.

Velocity measurements with ADCP and float tracks should be carried out during high monsoon in the vicinity of areas which are subject to severe erosion. These areas are (see Figure D-3):

- Hanar Char South II
- Gosair hat (opposite of Hanar Char)
- Char Alexander
- Tazumudin
- Channel north of Hatia

Duration: 1 month for float tracking near Chandpur, 1 month for other measurements

Activity 7: Water level measurements
Water levels are collected at several stations of BIWTA. However, the information from these stations is not always sufficient, either due to lack of a station in an area of interest, or bad quality of data from a station. It is proposed to place 7 pressure cells in the area (see Figure D-4):

- at the mouth of Karnafuli river
- in the Sandwip Channel at the Chittagong mainland side, opposite of the Sandwip island
- east of Urir Char
- east of Hatia
- at the southern end of Bhola
- on Bhola near Tazumudin

These cells should be in operation at least during monsoon (from July to September). Care should be taken to deploy cells sufficiently deep so that they will not fall dry, and to use devices with sufficient range (5m).
Duration: no additional time required. Deploying and picking up of pressure cells should be combined with other survey activities.

Activity 8: Sediment sampling
The information about bed material and suspended sediment, as collected by MES, is limited to certain areas. It is proposed to collect samples during the discharge measurement. The most convenient method will be to collect samples during discharge measurements. Mineralogical analysis of bed samples may reveal the origin of accreted sediments. To be collected:

- suspended solids samples:
  - point samples
  - integrated sample
  - bulk samples
- bed samples
- samples of bank material

Collected samples will be processed in the laboratory. The following parameters will be determined:

- for suspended solids:
  - grading curve
  - concentration
  - settling velocity
- for bed and bank samples
  - grading curve (including lutum (clay) fraction, grains finer than 2 μm)
  - mineralogical composition

<u>Bed sampling</u>
Bed samples will be taken at every 400-500 m along a transect during discharge measurements.

Bank material sampling
10 samples of bank material will be taken on the slopes of both riverbanks (both ends of a transect) during discharge measurements. 5 samples below water line and 5 samples above water line.

Suspended solid samples
Point samples : Point suspended sediment samples will be collected at 0.2, 0.4, 0.6, 0.8 depths and at 0.5 m above the channel bed by pump to ascertain whether there is any significant gradient in concentration of coarse and fine sediments separately or totally over the whole depth at the deepest vertical in a transect, once during max flood current and once during max ebb current. Content of each sample would be about 0.5 l. During one tidal cycle, 10 point samples will be collected in one tidal cycle.

Integrated samples: To get the depth averaged concentration of coarse and fine sediments and the residual sediment transport during a tidal cycle, hourly sampling at every 500 m along a transect (but not more than 5 samples from along a transect; for wider x-sections the sampling distance along a transect would be increased) will be carried out. If 14 samples are taken in a cycle, a maximum of 5x14 = 70 samples will be collected from each transect. Quantity of each integrated sample would vary depending on the time of the tidal cycle and the depth during sampling. Usually, it would vary between 300 ml and 2 litres.

Bulk samples : Bulk samples will be collected at 0.2 & 0.8 depths of the deepest vertical in a transect to get grain size distribution – once during max flood current and once during max ebb current. So, in one tidal cycle, 4 bulk samples will be collected. Quantity of each bulk sample would be 25 l.

The concentration of suspended solids varies considerably during the year due to varying river discharge and sediment supply. This variation can be examined by taking more samples over the year. Also tidal influence can be examined. Additional suspended solids samples will be taken at the following locations:

- Hanar Char
- Nijhum Dwip,
- Char Buoy

This can be combined with the additional bathymetric surveys (3 times per year). At each location, samples will be taken hourly during 13 hours to cover the full tidal cycle. This should be continued during the full 5-year period of the program.

During the survey of the Sunderbands, bed samples and suspended solid samples will be collected (20 samples of each at various locations in the channels).

Duration: 1 week in addition to other survey activities.
Frequency: 3 times per year (same as additional bathymetric surveys)

Activity 9: Wave measurements
Wave action is an important phenomenon which has an impact on the morphological processes in the estuary. Waves form a serious threat to the embankments in the coastal zone. Nearly no information about wave climate in the Meghna Estuary is available. It is proposed to deploy wave buoys at several locations at the southern limits of the estuary. Envisaged locations are: south of Sandwip, south of Rangabali. Also a deep-water buoy can be deployed. Recorded data should be retrieved regularly as the probability of loss of equipment is high. For installation and collection, Anwesha will be used. Retrieval of data can be combined with the additional bathymetric surveys.
Duration: 2 weeks all together
Frequency: single installation, data retrieval 3 times per year (same as additional bathymetric surveys)

Activity 10: Water quality measurements
Water quality in the study area should be followed. Some crucial parameters (to be further defined with PDO/ICZM) should be collected, to be analysed in laboratory. This can be done in parallel to the collection of salinity and suspended sediment samples.
Duration: no additional time required
Frequency: 3-4 times per year

Activity 11: Salinity measurements
Salinity changes throughout the year due to varying discharge of fresh water from the river system, and due to tidal influences. Using fixed measuring points trends in salinity can be examined. It is of special interest to examine the changes in salinity during the dry period with low fresh water supply. It is proposed to carry out salinity measurements together with the discharge measurements (only in transects downstream of Hanar Char), and during the additional bathymetric surveys (3 times per year), together with suspended sediment sampling. Samples will be taken hourly during 13 hours to cover the full tidal cycle. As the estuary is generally well-mixed (except for southern part of Sandwip Channel), there is no need for vertical profiling. This should be continued during the full 5-year period of the program.
In addition, longitudinal profiles of salinity should be obtained. This can easily be done from Anwesha when it is travelling from the port to the place of measurement. Salinity should be measured approximately every 10 km.

Duration: 3 weeks all together
Frequency: 3-4 times per year

Activity 12: Special measurements
Special measurements will be defined during the program according to the needs. It is proposed to carry out a measurement suggested by SWMC/DHI to estimate influence of high sediment concentration on vertical velocity profile. This measurement comprises a simultaneous measurement of vertical velocity profile and vertical sediment profile.
Measurement of the vertical current profile will be done with both ADCP and S4. As S4 only measures velocity at one point, the instrument will be moved in the vertical. Velocity at 5 points, equally distributed over the vertical will be measured, sampling during 2 minutes per point. simultaneously, sediment profiles will be obtained using turbidity meter (contact SWMC), or with the point sample method (see Activity 8), at the same depths as velocity measurement with S4. Settling velocity will be determined with the Owen tube. Water samples will be taken to obtain sediment content.
The current and sediment profiles will be measured continuously during a full tidal cycle (12 hours 25 minutes) during spring tide, in the monsoon. The measurement will be carried out in the Sandwip Channel, in one deep and one shallow location. Sandwip Channel is chosen as the flow there is very energetic (current speeds up to 4 m/s) and the concentrations of suspended sediment high, even during dry season.
Duration: 5 days.
Frequency: single measurement

Activity 13: Land surveys
Land surveys may be necessary for special investigations (to be defined together with PDO/ICZM and BWDB). The support of the Survey Unit Anwesha will be valuable is some cases because of the experience, advanced equipment and accommodation available. The existing benchmarks will be rechecked and corrected, if necessary.
Duration: 3 weeks

Activity 14: Surveys for ground thruthing of remote sensing

Remote sensing offers a potential for further enhancing results of surveys. To be mentioned are large scale land accretion or erosion, vegetation covers, etc. Special surveys might be organised for ground truthing, which is essential for the application of remote sensing.

Duration: 2 weeks

Frequency: as required

Proposed inputs:

- SU Anwesha, 20 weeks or net 75 survey days
- Morphologist and data processing expert (local): 16 to 25 weeks
- Hydraulic Software Engineer: 16 to 25 weeks.
- Coastal / Civil Engineer (local): 16 to 25 weeks
- Morphologist (foreign expert): 6 weeks
- Hydraulic and survey advisor (foreign expert): 4 weeks
- Satellite Images, digital data

Outputs:

- Processed survey data of the Meghna Estuary and outside the area as per requirement
- Digital and printed maps, showing contours lines and coastal line developments.
- Additional information as required by the PDO-ICZM.
- Analysis of morphological changes for a more extended area and assessment of its impact on the future shape of the coastal zone.

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Appendix D-1. Procedure discharge measurements

Discharge measurement using ADCP

The measurement will be carried out using ADCP mounted on Anwesha (or on a tender boat, as the case may be).

The procedure will be as follows:

- fix RTK station;
- fix ADCP properly, check it is aligned with the vessel;
- check all connections to the computer, including the compass;
- set parameters in the configuration file:
  - set number of bins and depth of bins; in most of the Meghna Estuary, 60 bins with a depth of 0.5 m will be sufficient for the measurement (this gives a depth of 30 m); in very deep places, e.g. near Chandpur, where depth is larger than 30 m, 60 bins with a bin depth of 1 m should be used;
  - set depth of the top bin;
  - set draught of the vessel;
- deploy S4 current close to the transect, approximately 2m below water surface; this instrument will continuously register current velocity during the discharge measurement;
- deploy pressure cell close to the place of measurement (connection to datum not required);
- perform actual measurement by sailing the transect forth and back; the measurement will be repeated as often as possible, but at least 13 times during 13 hours;

Additional requirements:

- prior to the discharge measurement, bottom tracking velocity will be determined with ADCP from a still-standing (anchored) vessel; this velocity will be noted on the log-sheet;
- after completion of measurement, discharge measured by both QGPS and bottom tracking method will be written on the log-sheet

To be delivered to the manager of post-processing:

- all data files with ADCP data (ACQ, HSB, raw data),
- data retrieved from the pressure cell,
- log-sheet containing standard information,

Discharge measurement using float tracking

Discharges can be calculated from flow velocities measured by float tracking. This is a relatively cheap way to determine the discharge. In MES measurements, a GPS was attached to a floating device in order to record the floats positions over time. From this displacement, the current velocities can be calculated.

The procedure for float tracking used by MES, is to use a country boat or speedboat to drop the GPS, attached to the float, at a predefined location. The GPS must be programmed to record its position every 30 seconds. The float is retrieved from the water after a predefined time or at a certain position.

Every float line has to cross a bathymetric cross section to calculate the discharge. The details of the discharge calculation are given in (ref 1).

The spatial resolution of the flow velocities is equal to the number of floats used. The time period between start time and end time of the float lines can be short, as only one reliable flow velocity over a transect line is necessary for the discharge calculation, so the floats can be used twice for one discharge calculation. First, the floats can be used for example in the eastern part of a channel and after that, they can be picked up and dropped in the western part. For a relatively narrow channel of four kilometers, this procedure can take less than 30 minutes. This limits the error due to changing current velocities due to tidal movement. For a wide channel of ten kilometers more floats and more boats should be used. Spacing of floats should be defined in agreement in bathymetry.

Recommendations

Several tests can be done to improve the quality of the calculation of discharge from float tracking. The following recommendations can be made:

- Record the error in the position reading from the GPS at the start and end of the float line. The newest version of Garmin GPS (e-trex) has this option.
- Keep one GPS stationary (on land). The apparent movement of this GPS is the error of the signal. This error registration can be used to correct the floats position. This is the same principle as used for the height registration of RTK positioning.
- Several bathymetry transects for the calculations of discharge should be sailed during the year as bathymetry changes rapidly, especially during monsoon.
- The float track should be done simultaneously using as many floats as possible to increase the resolution of the velocity measurements.
- Discharge should be determined for several adjacent transects. The ends of the bathymetry should be at the bank lines. The discharges from the two cross sections should be the same for reasons of continuity. If the results are consistent, the average discharge of these two cross-sections can be used.
    - If the relation between morphological changes and flow velocities from float tracking is going to be studied, float tracking and bathymetric surveys should be done over a larger area than the immediate area of interest. Bathymetric surveys should be repeated using the same survey lines and with local water level recording (using e.g., pressure cell) to increase precision.

ref.1 Meghna Estuary Study, Float tracking and ADCP measurements, monsoon 2000. Technical note MES-030, June 2001