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MINISTRY OF WATER RESOURCES

BANGLADESH WATER DEVELOPMENT BOARD

MEGHNA ESTUARY STUDY

DRAFT MASTER PLAN

VOLUME 2 : MORPHOLOGICAL PROCESSES

September 1998

DHV CONSULTANTS BV

in association with

KAMPSAX INTERNATIONAL
DANISH HYDRAULIC INSTITUTE

DEVELOPMENT DESIGN CONSULTANTS
SURFACE WATER MODELLING CENTRE
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1. GENERAL

1.1 Meghna Estuary Study Project (MES)

The Meghna Estuary Study (MES) is a supporting study 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 is being implemented under a co-operation programme between the Governments of Bangladesh, the Netherlands and Denmark. The executing agency is the Bangladesh Water Development Board (BWDB). The co-ordination with other projects under the Flood Action Plan is to be maintained by the Flood Plan Co-ordination Organisation (FPCO), WARPRO.
The overall goal of the Meghna Estuary Study (MES) is:

- to ensure the physical safety
- social security of the people living in the coastal areas and on the islands of the Meghna estuary.

The main goals of the study are:

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

1.2 Objective and scope of the study

The Meghna Estuary system is a very dynamic estuarine and coastal system (Figure 1.1). 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 Meghna river is the highest (Coleman, 1969) and the water discharge the third highest, of all river systems in the world (Milliman,1991).

The changes in tidal flow direction and channel topography, the occurrence of new channels and newly accreted land and abandonment of old ones are the rapid building and destroying processes that exist in the estuary. These processes trigger changes in sedimentation and erosion rates which are directly related to the change in discharge and sediment content.

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, we can say that the overall sediment budget is determined by the continuous redistribution process of the 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 the continuously changing tide flows.

The main objectives of the present study of morphological processes are:

- 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 results presented here, are based upon an analysis of remote sensing imageries, bathymetric data and historical coastline maps, and field surveys and numerical modelling.

This report outlines the well-documented changes in the system's geomorphology over the last centuries and recent decades. Special attention is paid to the geomorphological development of pilot areas for executing pre-feasibility and feasibility studies (Table 1.1). It then goes on to discuss and formulate a hypothesis on the dominant hydraulic and morphological processes underlying these changes. Furthermore a morphological prediction of land formation and char development in the Meghna Estuary system in 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.

This report is executed by MES. The results build on experience and findings from extensive projects undertaken under LRP and FAP 24 and other relevant studies from a morphological and hydrodynamic point of view.

Table 1.1: Summary of the MES Feasibility, Pre-Feasibility and Pilot Projects

Feasibility Level
Nijhum Dwip Development Project
Char Montaz -Kukri Mukri Development Project
Haimchar Erosion Control Project
Pre-Feasibility Level
Rangabali -Char Biswas Development Project
Urir Char -Char Pir Baksh Development Project
Hatia – Manpura Development Project
Pilot Level
Khorki Erosion Control Pilot Project
Haimchar Erosion Control Pilot Project

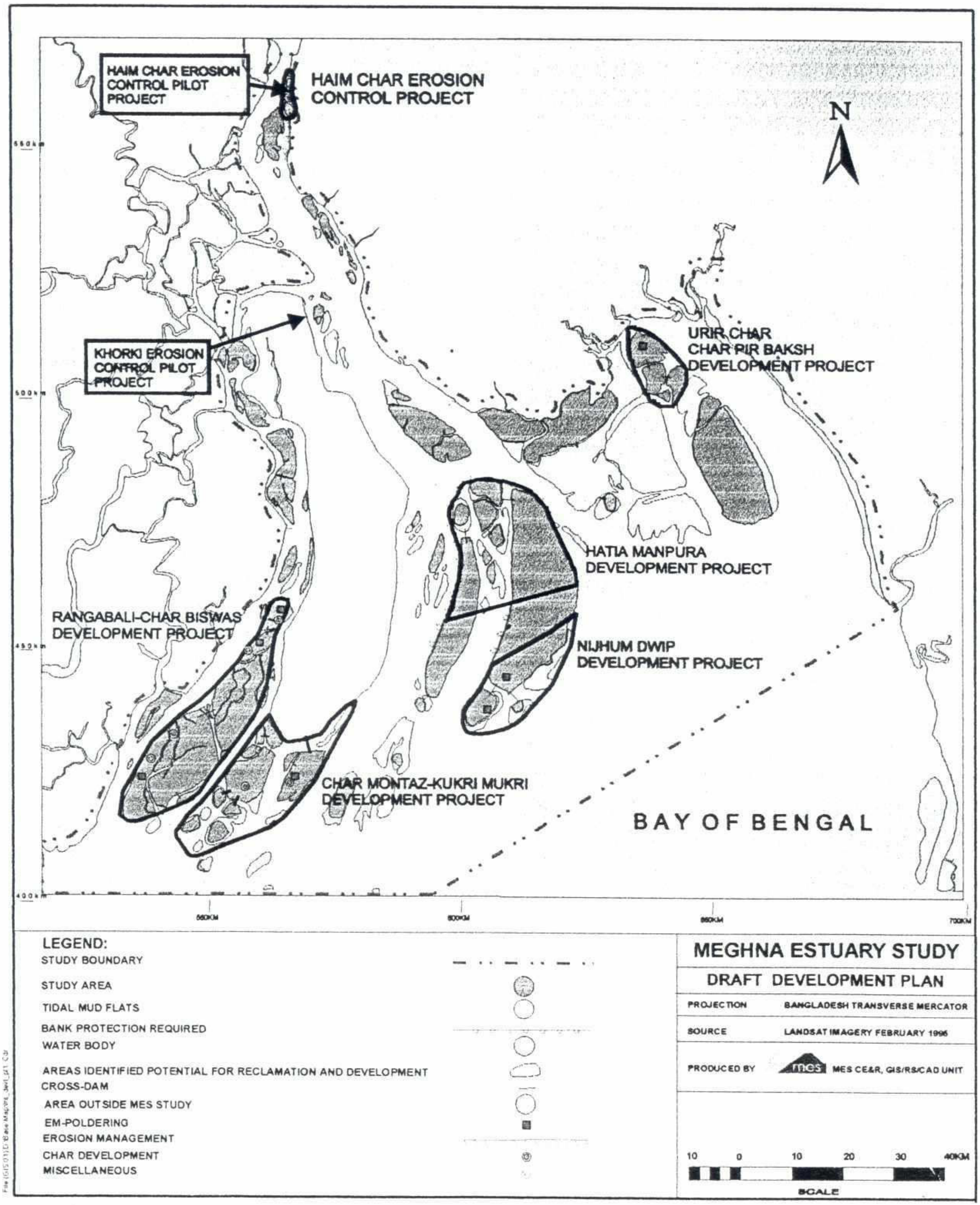
1.3 MERIS database

In this study the **M**eghna **E**stuary **R**esource **I**nformation **S**ystem (**MERIS**) is used to obtain information about morphological and sedimentological, hydraulic and morpho-metric, hydro-meteorological data, historical bathymetric and coastline maps, and other information regarding the Meghna Estuary system. A substantial portion of the **MERIS** databases are based on data from the field and monitoring surveys as well as specific project surveys executed by the Survey and Study Division (SSD, a division of LRP) between 1982 and 1994. **MERIS** also contains data derived from field and monitoring surveys executed by MES.

The remote sensing analysis is carried out by the Environment and GIS Support Project (EGIS). The results of the remote sensing analysis, satellite images and data processing are described in detail in technical note MES-009 "Times series analysis of erosion and accretion" (1997).

Figure 1.1: Meghna Estuary Study area, Feasibility, Pre-Feasibility and Pilot Projects

Figure 1.1: Meghna Estuary Study Area, Feasibility, Pre-Feasibility and Pilot Projects



1.4 Meghna Estuary Study area

The Meghna Estuary Study area covers the Lower Meghna river from Chandpur town to the Bay of Bengal (Figure 1.1). The eastern boundary follows the left bank and the coastline to the mouth of the Karnafuli near Chittagong. The western boundary follows the right banks of the Lower Meghna and Tetulia rivers and the coastline to the bay. The southern boundary covers the eastern area and the off shore islands.

The study area includes the Tetulia and Shahbazpur Rivers, the Hatia River, the Sandwip Channel and the coastal water to the north of Chittagong mainland. The study area is characterised by extensive shallow (mud)flats, numerous small and large islands (e.g. Hatia, Bhola and Sandwip) and chars. 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 (Table 1.2).

Table 1.2: Characteristics of the study area in 1996

	Area (km^2)	Perimeter (km)
Bhola	1,433	270
Hatia	408	98
Sandwip	231	60
Rangabali- Char Biswas islands	394	349
Manpura	137	71
Char Montaz islands	100	88
Kukri Mukri	53	47
Urir Char islands	77	71
Char Gazaria	62	42
Nijhum Dwip	37	23
Damar Char	4	7
Total study area (exc. Bhola)	11,210	2,650
All islands (exc. Bhola)	3,302	2,190

2. THE PHYSICAL ENVIRONMENT IN THE PLANNING PROCESS

2.1 Physical impact indicators

The physical environment is an important component of the multi-disciplinary basis for planning of the development of the estuary. The physical environment imposes several options and constraints, which must be considered along with the many other general planning aspects. At the detailed planning level, a number of feasibility indicators and criteria are related to the physical environment.

Key characteristics that can be influenced directly by conditions within the estuary, and which are in turn suited as indicators of a direct physical impact, are: (i) the salinity; (ii) the flow resistance and the water level; and (iii) the erosive capacity.

Salinity

The salinity determines whether the water is suited for drinking, irrigation, and various other purposes within industry and manufacturing. The effect of salinity is not proportional to the concentration. Rather, the predominant main effects (such as the water being unsuited for drinking or irrigation) occur already with the first fine traces of salinity.

The time and space distribution of salinity in the estuary is largely determined by the following factors: (i) The ocean salinity; (ii) the sea level; (iii) the river discharge; (iv) the flow pattern; and (v) the geometry of the boundary area between the saline and the fresh water regimes.

The salinity distribution has a visible seasonal variation, in accordance with the river discharge. All year, the salinity is nil or low in the northern and western part of the MES area, including Tetulia River, and high in the southeastern part. In the Shahbazpur Channel, the salinity varies over the year.

Flow resistance and water level

The gross flow resistance of the entire estuary can be illustrated by the water level at Chandpur relative to the water level in the Bay of Bengal. This set-up is related to friction losses and other energy losses through the estuary, and is in turn a determinant of the water level of the upstream river system. The detailed, distributed flow resistance can be illustrated by the distribution of the river outflow between the various branches of the estuary.

The flow resistance can be changed for example by a changed cross-section area or a changed planform. The significance of the flow resistance is its direct influence on (i) the flood risk in the hinterland; and (ii) the general flow distribution in the estuary, which can in turn influence the salinity and the erosive capacity.

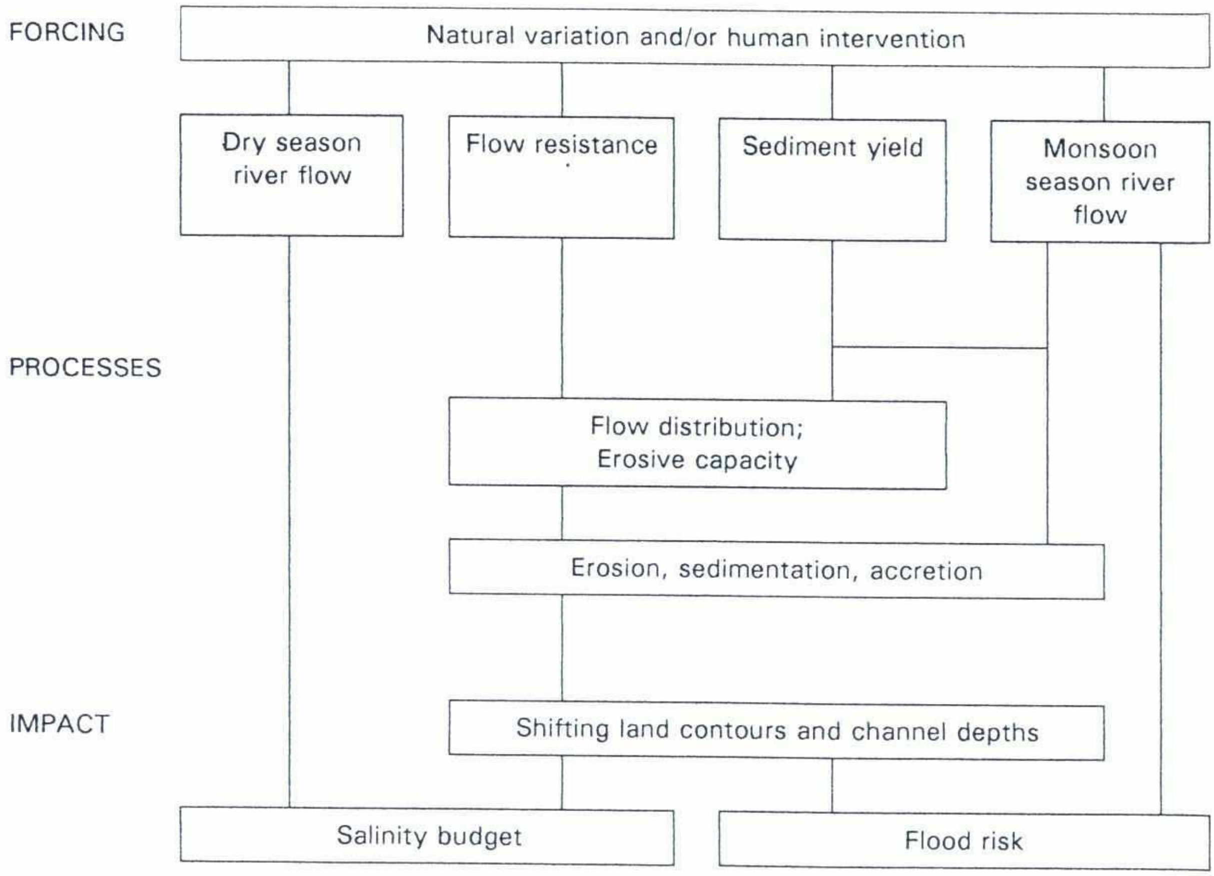
The effect can be described by either (i) the space distribution of the net flow (the flow averaged over a tidal period); and/or (ii) the highest water level reached at a given location in a given period of time. Both characteristics may be conveniently calculated by a hydrodynamic model.

Erosive capacity

In a system like the Meghna Estuary, where the sediment supply can safely be described as excessive, the sedimentation (as well as the erosion and accretion) will be determined by the erosive capacity: the turbulence generated by the current and the waves. If, in a certain area, the erosive capacity decreases, existing erosion will decrease accordingly, or can be changed to a sedimentation process; or existing sedimentation will be enhanced. This is desirable in areas targeted for land development in the Master Plan. If, in another area, the erosive capacity increases, existing sedimentation will decrease, or possibly shift to erosion; or existing erosion will increase. This is undesired for areas targeted for land development, but can be desirable in channels that are planned to be retained for drainage or navigation. In this way, the erosive capacity becomes a key factor in the physical development of the estuary, whether by natural causes or partly due to human intervention.

The erosive capacity is determined by current and waves. In areas with depths more than 2-3 m, the current will be predominant, while on wide shallow flats, the waves may play a role as well. In a large part of the area, however, the current will be the primary force.

Figure 2.1 : Key physical cause-effect relationships in the Meghna Estuary



2.2 Governing processes, hydraulics

General

The cause-effect relationships and their interaction can be conceptualised in different ways. One attempt to summarise the most important physical processes is shown in Figure 2.1. The variable forcing can be divided into external and local determinants. They comprise:

1. Dry season conditions (affecting mainly the salinity):

- changed flow caused by natural climate fluctuations
- changed flow caused by upstream irrigation withdrawal or regulation (such as diversion, or large scale bank protection schemes)
- long term sea level changes.

2. Monsoon season conditions (affecting first the sediment budget, and subsequently the salinity and the flood risk):

- changed flow and sediment yield caused by natural climate fluctuations, earthquakes, etc.; and
- changed flow and sediment yield caused by upstream intervention (such as diversion, large scale bank protection schemes, or deforestation).

3. Local intervention in the estuary (affecting first the flow distribution, and in turn the sediment budget, the salinity, and the flood risk):

- changed flow resistance caused by natural morphological development
- changed flow resistance caused by intervention (such as bank protection, cross dams, etc.)
- changed erosive capacity related to a changed flow resistance (causing a redistribution of the flow)
- changed erosive capacity related directly to intervention (such as bank protection, cross dams, etc.).

It is noted that the monsoon season salinity budget is of equal importance as the dry season salinity budget; only, the latter is critical relative to the former, so if no effects in this regard occur in the dry season, the monsoon season impact can safely be disregarded.

Regarding time scales for response, it is noted that the hydrodynamic effects (including surface water salinity developments) will be rather immediate (occurring within one season or less), while the general morphological effects will develop unevenly and slowly (over several years or even decades).

Salinity

The following developments or interventions can potentially result in a salinisation of areas that are presently entirely or predominantly unaffected by salinity:

- any reduction of the dry season river discharge
- a sea level rise
- deepening of channels in the area south of Tetulia River, either artificially (for navigation), or as a consequence of intervention elsewhere, or due to natural developments.

The primary concern for the salinity is related to the northern and western part of the area, where salinities are presently nil or low, and where any change will inevitably affect the livelihood of many people.

Flow resistance and water level

The following developments or interventions can potentially change or redistribute the flow resistance of the estuary, possibly affecting the local or regional flood risk, the salinity distribution, or the erosive capacity:

- any changes of channel cross-section geometry; but especially in river branches and main tidal channels, and particularly in contracted or shallow reaches, where the flow resistance is already high, compared with the channel as a whole
- any changes of channel lengths (notably of the main flow channels)
- other significant planform changes.

Such changes can well be brought about by natural accretion, as has happened throughout the history of the estuary. From one point of view, many viable interventions are characterised by accelerating an ongoing natural development, rather than generating a new one.

Erosive capacity

The following developments or interventions can potentially redistribute the erosive capacity within the estuary, affecting the deposition of sediments, land accretion, and erosion, and, possibly, the salinity distribution and the flow resistance as well:

- any change of the monsoon season flow
- any redistribution of flow within or between channels.

A redistribution of flow within or between channels can be due to natural developments (wind, erosion or accretion), or due to interventions that cause a local increase of flow resistance. The effects of interventions will largely be related to the current, rather than the waves. A physical intervention can potentially change the current over a large area, but in the MES area the waves will be affected only in its close vicinity.

2.3 Planning objectives

Operational planning targets for the physical environment are suggested in Table 2.1.

Table 2.1: Hydraulic planning objectives

Characteristic	Planning target	
Salinity	1	Preservation of the present fresh water regime
	2	If practical, extension in time and space of the present fresh water regime
Overall flow resistance (of entire system)	1	Should not increase, as compared with present conditions
	2	Should preferably be reduced, as compared with present conditions
Detailed distribution of flow resistance (e.g. between channels)	1	Concordance with planning target for salinity
	2	Concordance with Reference Scenario
	3	Highest water level set-up (during a monsoon season spring tidal period) not to exceed present levels by more than a few cm, depending on location
Erosive capacity	1	Concordance with planning target for salinity
	2	Concordance with planning target for flow resistance
	3	Concordance with Reference Scenario

3. APPROACH AND RESEARCH METHODS

3.1 Approach

In accordance with the aims of the project, the morphological studies and activities should cover a range of levels of concreteness and detail. In the morphological studies, the same as in most of the other elements of MES, three levels of detail and concreteness can be distinguished:

- master plan level which is focused on an intermediate time scale of 25-30 years
- development plan level describing the land development in the coming 5 to 10 years
- pre-feasibility and feasibility level with a time frame of about 0 to 5 years.

The morphological studies at each of these levels are interlinked in an iterative manner. At the master plan level as well as the development plan level, the morphological studies are specifically focused on the general understanding of the actual physical processes and mechanisms which shape the morphology of the estuary system. Based upon this knowledge criteria and priorities are formulated to identify potential land reclamation areas and potential land reclamation projects from a morphological point of view. At the project pre-feasibility and feasibility level, detailed morphological studies for site specific projects are executed (see also Table 1.1). Results of FAP and LRP projects, in particular CDSP "Muhuri feasibility study", are taken into account in the morphological studies.

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 bottom topography 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 in the mid- and long term. On the other hand, statistical and empirical techniques applied to field data are useful to extrapolate existing trends, but they are hardly suited as sole predictor if these trends are changing (e.g. due to human interference, sea level rise). To increase the reliability of the predictions in the mid- and long term, it is necessary to combine two approaches: the numerical modelling approach and the phenomenological approach.

Numerical Modelling Approach

The dominant hydraulic and morphological conditions and processes that shape the morphology in the study area were studied through regional and detailed local 2D models. To determine the dynamic behaviour of the entire estuary system or in site specific areas, computations are carried out under different hydrodynamic conditions during dry and monsoon seasons, neap tide and spring tide. Current velocity and sediment transport patterns and wave conditions are assessed, whereby the consequences of the different impacts and interventions can be quantified and compared.

The results of these computations give qualitative and quantitative information about the spatial and temporal (short term) variation of the water level, current velocity and discharge as well as sediment transport and the rate of sedimentation and erosion. Calculations of the residual current velocities and residual sediment transport give a qualitative indication of the hydraulic and morphological processes and circulation patterns in the Meghna estuary.

Phenomenological Approach

Phenomenological approach uses statistical/empirical techniques and physical interpretation to identify trends and empirical input/output relationships from field data files and observations. This approach requires extensive and reliable data sets on the input side (hydrodynamics, sedimentology, meteorological conditions) as well as on the output side (morphological changes). If sufficient data are available, the morphological response to various input conditions or to human interventions can be assessed using a selection of suitable relationships. The results give an indication of the physical processes at work, and thus the mechanisms underlying the morphological evolution. In this respect observations in comparable situations, if available, can also be of help. Once the input conditions and the I/O relationships have been established, the expected morphological changes on different time scales can be assessed.

3.2 Remote sensing

Earth observing satellites have been operating since 1973, collecting images from much of the earth's surface. The satellite image data used for the Meghna Estuary study consists of six sets of four Landsat frames, acquired over 6 years between 1973/74 and 1996. The ground resolution of the image sets varies from approximately 80 m* 80 metre grid for the image sets of 1973/74, 1979 and 1984 to a ground resolution of about 30 m* 30 metre grid for 1990, 1993 and 1996.

Each of the satellite images was geo-referenced by using well distributed ground control points. A standard 50 ground control points were selected for geo-referencing for each of the images in the time series). After geo-referencing, a single satellite mosaic was made for each period from the four frames using the Bangladesh Transverse Mercator (BTM) as the map projection. The Landsat mosaic covers the entire Meghna Estuary system from the northern border at Chandpur to the seaward border at Chittagong, an area of 16,050 km^2.

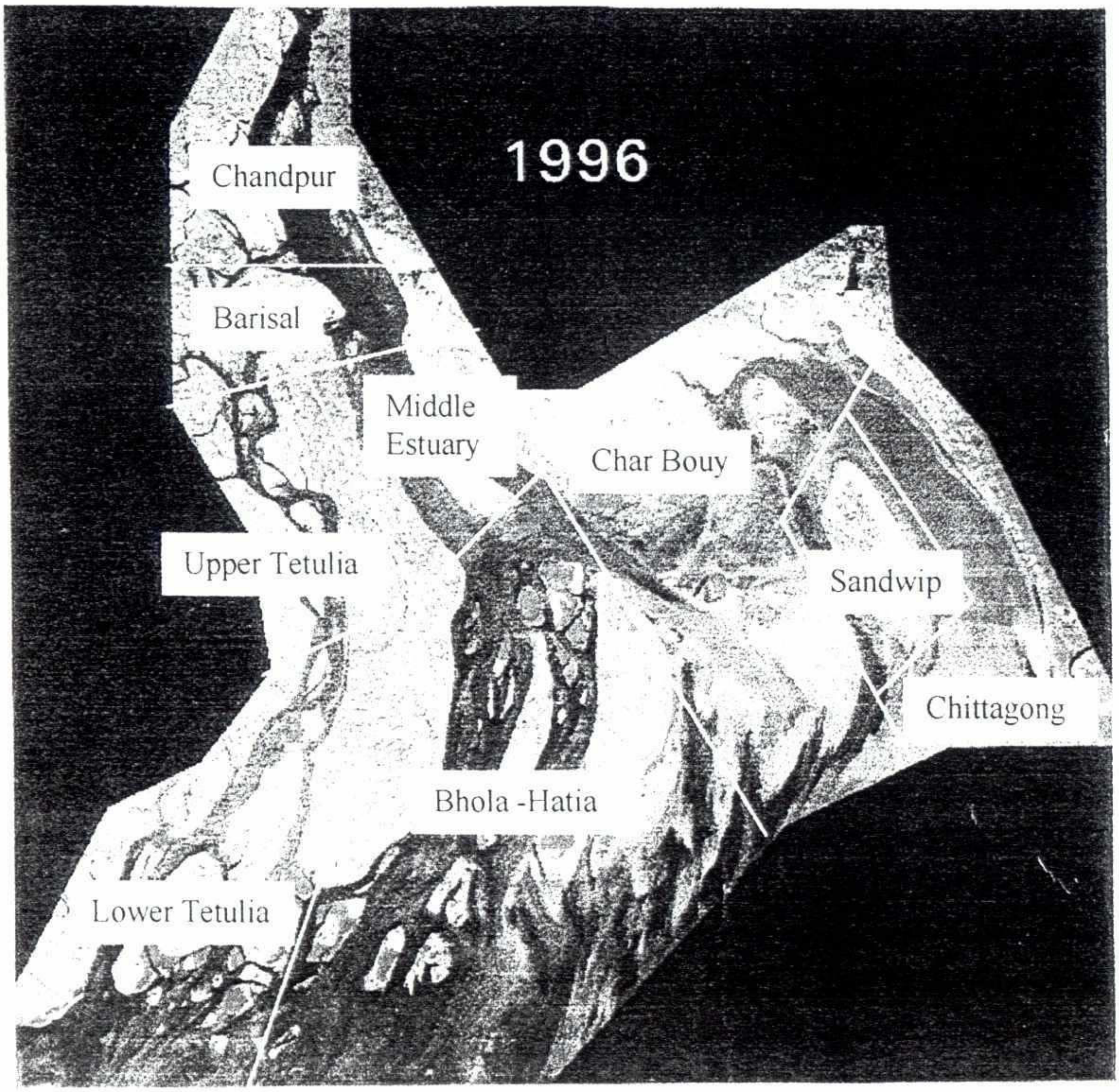
The digital satellite images were classified using image processing techniques to enable the assignment of land and water cover types which were associated with erosion and accretion processes. The major categories of classes which evolved included: land, water, and mudflats (intertidal area). The image pixels of each Landsat image was classified and smoothed by using a migration means clustering routine. The entire time series of smoothed classified data was used to separate the study area into two major zones: upland or non-coastal areas not subject to erosion or accretion; and major rivers and coastal areas subjected to change during the period of analysis. A overall mask was created to screen out areas which were lying outside the project area or non-tidal zones. The non-tidal zone for all the six satellite mosaics is considered as stable land. Although each satellite image in the time series was collected during the dry season when river discharges and water levels were relatively low, the effect of water level variations due to tidal movement are significant for interpretation and classification of the satellite imageries. In the Bay of Bengal, the tidal range varies considerably: near the Sandwip island, for example, the range in tide level shows differences between highest and lowest astronomical tide of about 7.6 metre and between mean low and high water neap tides of 3.2 m. Investigations of water levels for the dates of satellite imageries acquisition showed that most of the data were collected at relatively low and intermediate levels, but within a single mosaic, there is a substantial range in tide levels, especially in the southwestern part of the project area (Table 3.1).

The project area is subdivided into nine subareas to gain a better understanding of the spatial distribution of land cover classes and changes over the time series (Figure 3.1).

Table 3.1: Summary of tide levels on image acquisition dates

Image	Date	Eastern Orbit	Western Orbit
1973-74	2 February 1973		no data
	27 January 1973	low-tide	
	9 February 1974	low-tide	
1979	2 January 1979		mid-tide
	24 February 1979	mid-tide	
1984	19 March		mid-tide
	25 March	high-tide	
1990	24 February 1990		mid-tide
	5 March 1990	high-tide	
1993	15 January 1993		mid-tide
	9 February 1993	low-tide	
1996	9 February 1996		mid-tide
	18 February 1996	low-tide	

Figure 3.1 Meghna study area and locations of the nine subareas



3.3 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 'standard' cross-sections and areas in the Lower Meghna Estuary area since the early 1980s. The locations of the cross-sections are shown in Figures 3.2 and 3.3. These cross-sections give a good coverage of the entire estuary.

The echo soundings are estimated to be accurate to within approx. 0.1 - 0.4 metre (MES; Estuarine Surveys, 3rd draft, June 1998). Normally the echo soundings data cover only the deeper tidal channels. The higher parts cannot be sounded from vessels. Since the higher parts of the shallow (mud)flats and chars cannot be sounded from vessels, levelling data have been collected for these areas by using a hovercraft.

Figure 3.2 : Location of the LRP standard flow transect cross-section.

Figure 3.2: Location of the LRP Standard Flow Transect Cross-section

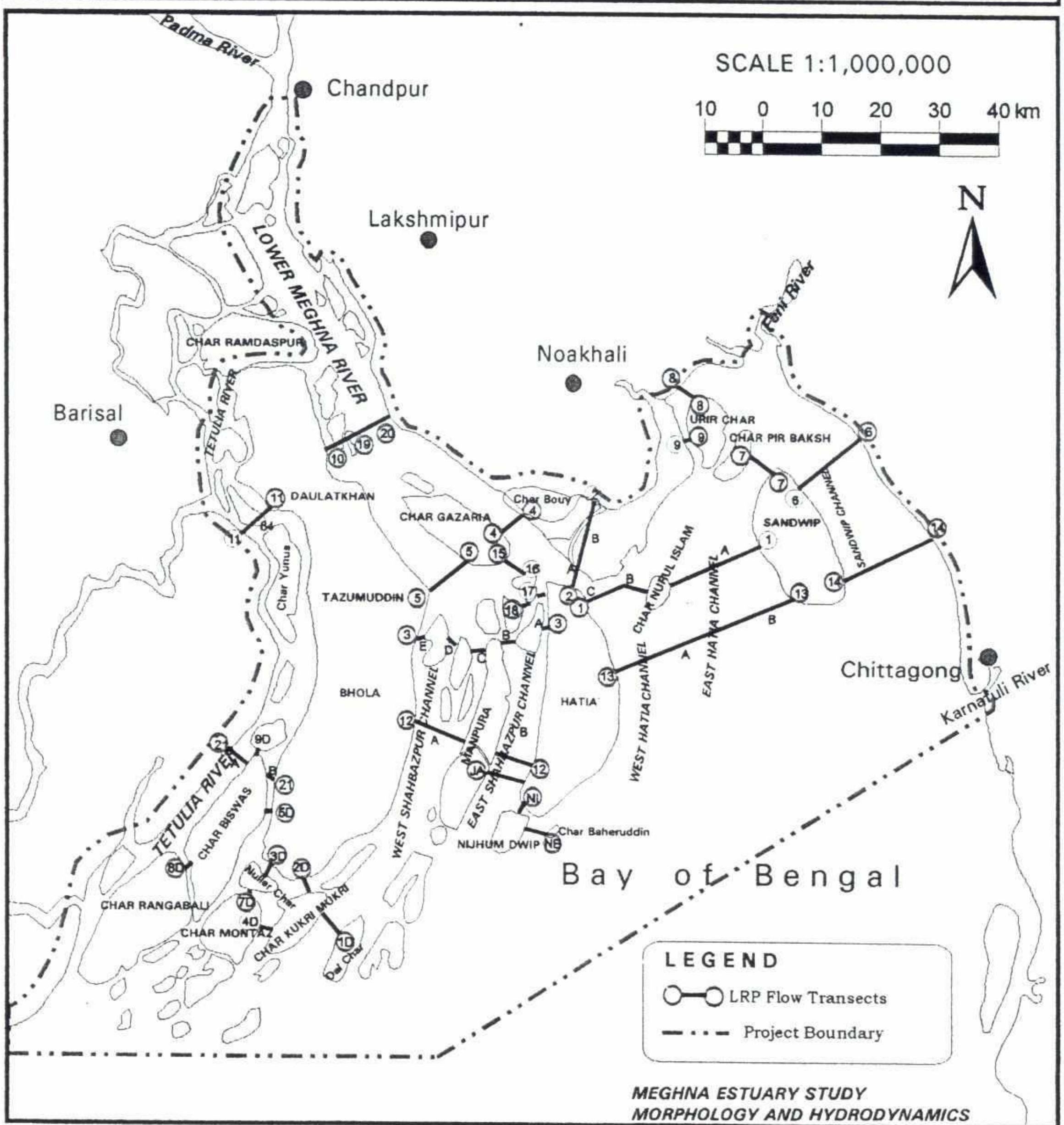


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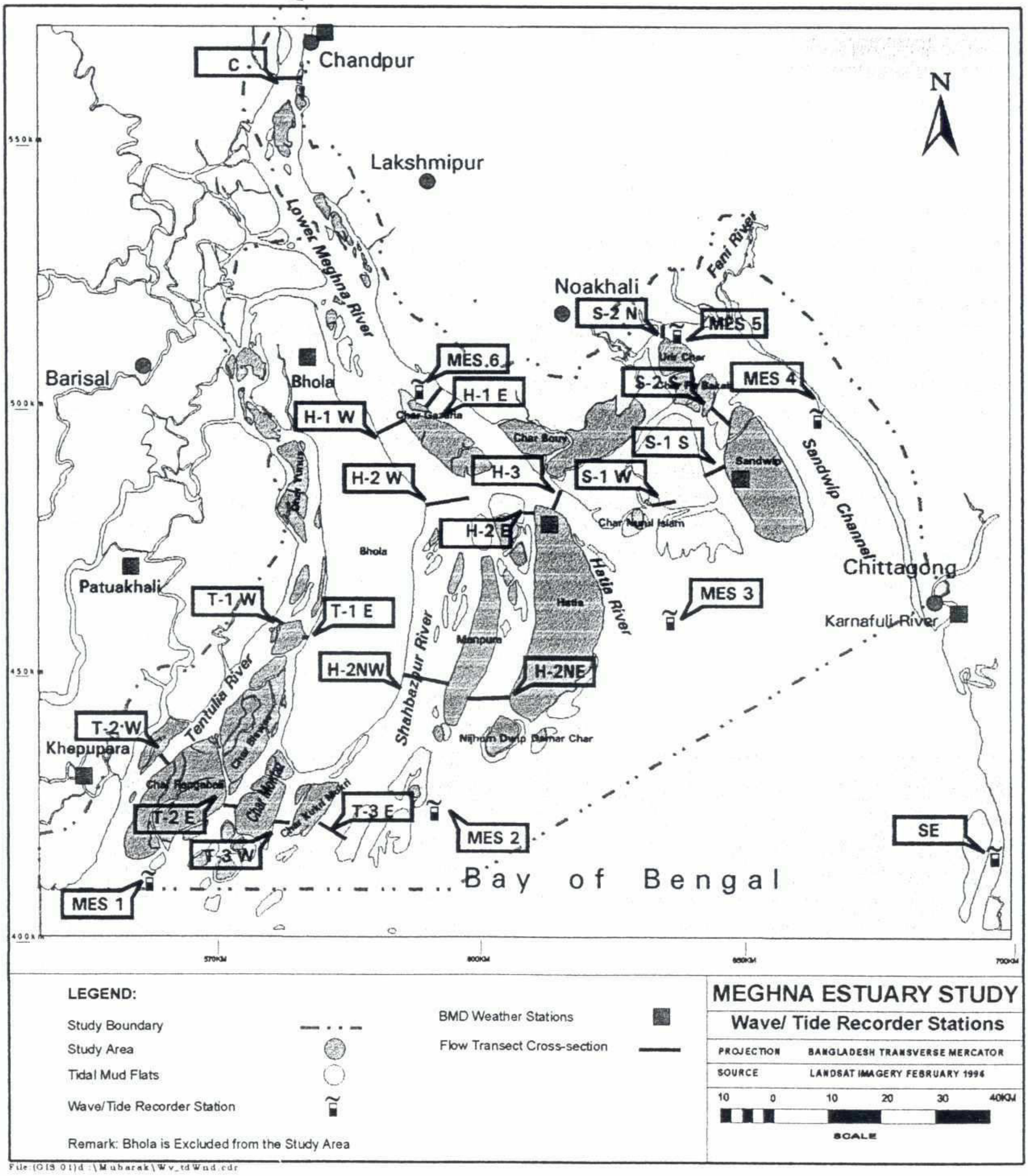
Figure 3.3 : Location of MES wave/tide recorder stations, standard flow transect cross-sections and BMD weather stations

Figure 3.3 Location of MES Wave/Tide Recorder Stations, Standard Flow Transect Cross-sections and BMD Weather Stations



The depth data has been used to study cross-sectional developments and changes in sediment volume throughout the period 1981 - 1997. Estimates of the sediment volume have been based on calculations of interpolated depth values using 100x100 metre and 200x200 metre grid squares derived from the sounding maps. The spatial variability of changes in sediment volume in the Meghna Estuary System has been studied in detail in four subareas: the area around

North Bhola - Char Gazaria, the area Manpura - Hatia, the area around Nijhum Dwip - Hatia and the area around Urir Char - Char Balua.

Changes in the geometry and the shape of the cross-sections are obtained and characterised by calculating the depth versus cross-sectional area (below MSL) and by the width-depth ratio. 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 movement of the shorelines of aerial photographs of 1956-1957 and satellite images from 1973 to 1996.

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 were compared with findings of recent investigations by Eysink (1983), Leedshill-De Leuw Engineers (1968) and Allison (1998).

3.4 Data on the processes of morphological development

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 (Figure 3.3). The water level data are measured relative to a Datum, under MES the PWD datum is used. The zero values of the gauges have been verified in the field with the BWDB benchmarks located at the stations. Detailed information about the zero values and characteristics of the gauges as well as benchmarks are given in Technical Note MES-008 'Static GPS Survey'.

The major tidal harmonic constituents have been computed to characterise the tidal variations in the water level at each station. 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. However, since most of the gauge stations have no long term water level data (more than 5 years) extreme statistical value analysis in terms of extreme return periods are estimated only for 7 stations. Discharge measurements taken during pre- and post-monsoon along a number of standard flow transects in the project area over the 1985-1997 period have provided data on the spatial distribution of discharges and current velocities in the Meghna Estuary system.

During LRP, the vertical flow velocity profiles were measured by using propeller type direct reading current meters (Ott and SEBA current meter propellers). The discharges were estimated by applying the standard velocity-area method (Barua and Koch, 1986). In this method, the cross-sectional area is divided into representative subareas (Figure 3.4). In each of these subareas the depth-averaged current velocity is multiplied by the average depth at the two verticals and the spacing between the two verticals. The total discharge is then found by the summation of all these subareas.

In large channels, the method requires a long time for completing the discharge measurements, unless a number of vessels are available to do the measurements jointly. Therefore, the MES project applied the moving boat discharge gauging method or the so-called ADCP method for discharge estimations. The ADCP method used by MES, samples the 'entire' vertical current profile as the survey vessel sails one time across the channel. The cross-section discharges and flow velocities are continuously measured along the transect lines by using a acoustic Doppler current profiler (ADCP600) and electromagnetic recording current meters (InterOcean S4). In order to cover the full tidal cycle, the S4 is installed 2-3 metre below the surface in the same flow channel as the transects for at least 25 hours.

Figure 3.4 : Illustration of the velocity-area method for calculation of the cross-sectional discharge

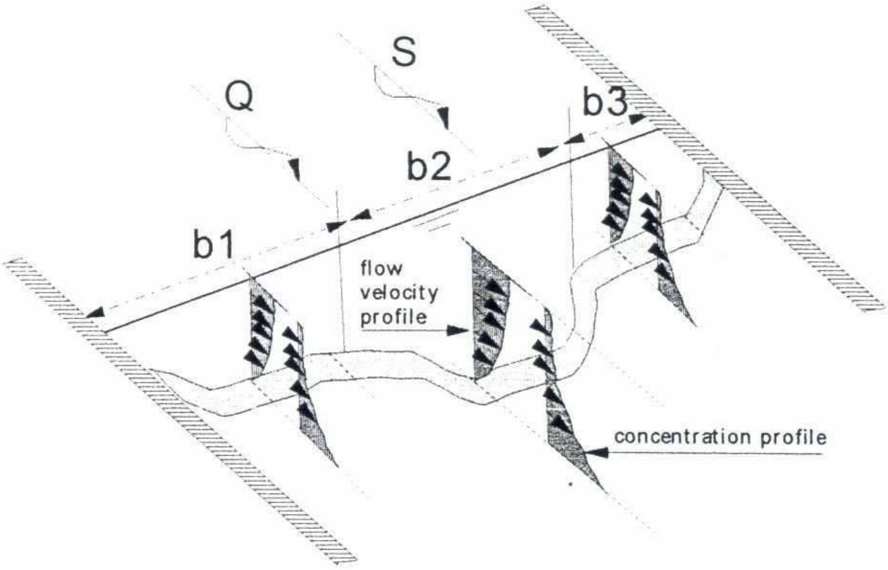
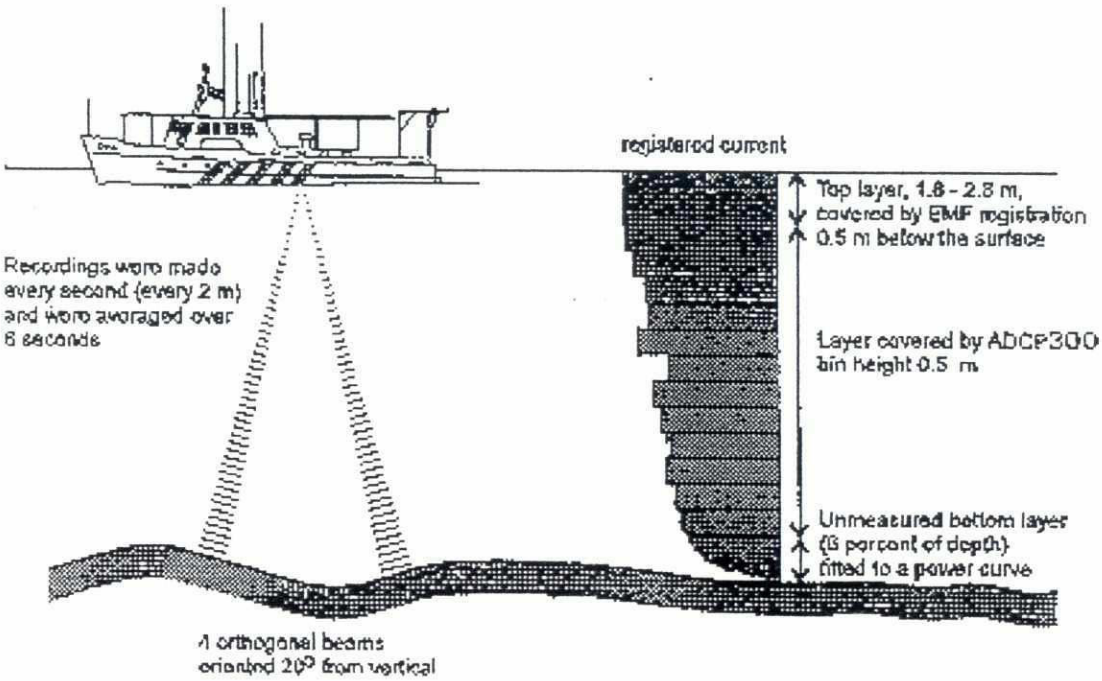


Figure 3.5 : The ADCP-EMF moving boat method used by MES



The principle of the method is shown in Figure 3.5. The horizontal and vertical positioning of the survey vessel and tender is estimated by using GPS satellites and RTK relative to a network of reference benchmarks.

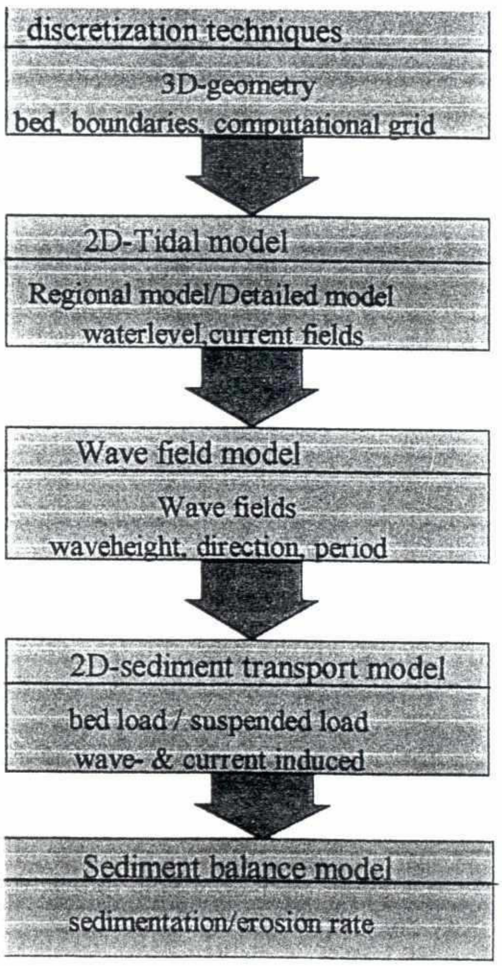
Estimates of sediment transport patterns in the system during pre- and post-monsoon are based on sediment transport measurements taken along the standard flow transects in the project area over the period 1985-1997. Sediment concentration samples at different heights in the water column as well and bottom samples were taken regularly during the standard flow

transect measurements to record sediment transport and sediment characteristics along the transect. During these transect measurements, salinity and temperature were also recorded. The laboratory in Chittagong (SSD) and the SWMC determined the sediment content and the granulometry of the bottom samples and sediment concentration samples.
To characterise the meteorological conditions during MES sampling, wind speed and direction have been collected at nine meteorological stations in the project area.

3.5 Hydrodynamic modelling

The observed geomorphological and hydraulic changes have been compared with several empirical models to establish hypotheses on the dominant hydrodynamic and morphological processes in the Meghna Estuary system. Although no generally accepted empirical model exists to predict reliably the dominant sediment transport process on tidal shoals and in tidal channels as a function of some physical and geometrical parameters, it is shown by several investigators (Kana et al., 1988, Oertel, 1988, Walton et al.,1976) that there is a direct correlation between them. Numerical models have been applied to further develop and verify these hypotheses. In recent years, substantial effort has been put into the numerical modelling of morphological changes in complex three dimensional situations (Watanabe 1985., O'Connor et al. 1989, Wang 1989). For estuaries, tidal inlets and coastal waters, however, this has not yet resulted in sufficiently reliable morphological predictions for intermediate time scales (20-30 years). On the other hand numerical morphological models, based upon principal hydrodynamic laws, have proven very useful for giving insight into the actual coastal morpho-dynamics and related sediment transport processes (De Vriend et al., 1989). Most of the numerical models used in the hydraulic and morphological field are characterised by the flow chart in Figure 3.6.

Figure 3.6 : General outline of the 2 DH numerical morphological model



They contain modules for tides, (if necessary) waves, currents and sediment transport and a sediment balance module. In many model systems this is the final result, which is translated into morphological evolution by expert interpretation. Some other systems contain a time loop mechanism in order to simulate morphological evolution. These model systems, however, are still in their research phase and applications are usually restricted to short term evolution, e.g. due to one or a few storms or neap-spring tide periods.

The hydraulic and morphological models to be discussed in the Meghna Estuary Study belong to the former type, called "initial models". For simulation of hydraulic and morphological characteristics in the Meghna Estuary area, it is necessary to identify the relevant physical processes and the primary driving mechanism behind sediment motion. Preliminary analysis of physical processes in the Meghna Estuary led to the following composition of constituent models:

- 2-D tidal model. This should solve the complete shallow water equations, including the tide, the river discharge and wind stress as driving forces. At present, wave-driven currents are assumed to be of minor importance in the Meghna estuary. Of course, the model should include a flooding and drying mechanism for large shallow areas (such as North-Sandwip, Urir Char, North Hatia). The model will be established as a structure of nested models with a grid size down to 100 - 200 metres.

- Wave field model. This should include 2D-propagation, generation by wind input and dissipation by bottom friction and breaking. To avoid focusing and funnelling of wave energy, a refraction model (bottom and current refraction) taking into account the directional spread of the wave field seemed to be the best solution for the time being. The Mike-21 programme package includes these effects. The wave models will be used for representative wind directions.

- Sediment transport model. This should apply to a wave/current environment, and take account of relaxation effects (specially in the case of fine sediments) in the suspended load concentration. For the time being an applicable model will be used, consisting of a transport formula and a pick-up/ advection, deposition model for the suspended sediment.

- Sediment balance. This module should determine the sedimentation/erosion rate from the divergence of the transport field.

The model components are linked at the software level through the Mike-21 programme system, providing steering facilities, interfaces between the constituent models and a range of utility programmes and easy access to pre- and post-processing facilities.

However, the data base generated by the Meghna Estuary Study will not be adequate to produce reliable results of the sediment transport and sediment transport balance, therefore the sediment transport and morphological computations will be performed separately from the hydro-dynamic calculations with Mike-21.

4. PRESENT CHARACTERISTICS AND PHYSICAL FEATURES

4.1 Geology and geomorphology

With an overall length of nearly 3,000 km and a catchment area of around 1,600,000 km^2, the Brahmaputra - Jamuna - Meghna is one of the world's greatest rivers (Figure 4.1). The river flows through the Bengal Basin, one of the most active tectonic zones of the world. This tectonic activity is related to the ongoing collision of the Indian Plate against the main Eurasian Plate. The Indian Plate, carrying the Indian subcontinent, continues to move north at a rate of about 5 cm per year. Its forward edge is subducted underneath the Eurasian Plate, thus elevating the Tibetan Plateau and creating the geologically still young and erodible Himalayan mountain range (Figure 4.2). This process involves a thrusting movement in which great slabs and slices are sheared off the top of the subducted plate and stacked atop one another. Further away from the forward edge, the advancing Indian Plate is broken into crustal blocks by internal stresses and deformation due to the collision. The resulting tectonic activity has greatly influenced the basin's river courses.

The catchment receives an average of 1,500 millimetres of rainfall per year, most of which falls during the monsoon months (June - September) but there are great variations in rainfall across the basin. The average rainfall in the coastal area is about 2,000-3,600 millimetres per year (Figure 4.3). The sediment yield of the catchment is very high, resulting from erosion caused by high rainfall in the active orogeny of the Himalayas. The spatial and temporal distribution of water and sediment in the catchment govern the behaviour of the rivers and this will influence also the behaviour of the Lower Meghna Estuary area. It is obvious that the Lower Meghna Estuary area is a dynamic estuarine system undergoing continuous changes both naturally and through the influence of human activities. Changes in physical boundary conditions in the coastal area as well as in the catchment area will affect the hydraulic and morphological conditions and processes in the Meghna Estuary Study area.

Table 4.1: Factors controlling the development of the Lower Meghna Estuary

Climate	Tropical and subtropical
Type of coasts	Collision /Marginal sea
Coastal lithology	Soft-rock
Sediment	High silt content
Tidal range	Macro-tidal to Meso-tidal
River stability	Braiding rivers
Coastal stability	Submerging
Neotectonism	Present
River discharge and sediment load	High
Marine diffusive forces	
Waves	Low to Moderate
Littoral current	Low
Tidal currents	Low to High
Salt incursion	Low to High
Sea level rise	Low
Water temperature	Moderate to High
Atmospheric influence	
Wind and Cyclone	Low to High
Seasonal variation	Dry and Monsoon period
Rainfall	High
Temperature and Humidity	Moderate to High
Human influence	
Bank and erosion protection	Low
Dredging	Low
Estuarine and River training (spurs, cross dam, dikes)	Low

Figure 4.1 : The catchment areas of the three major rivers of Bangladesh

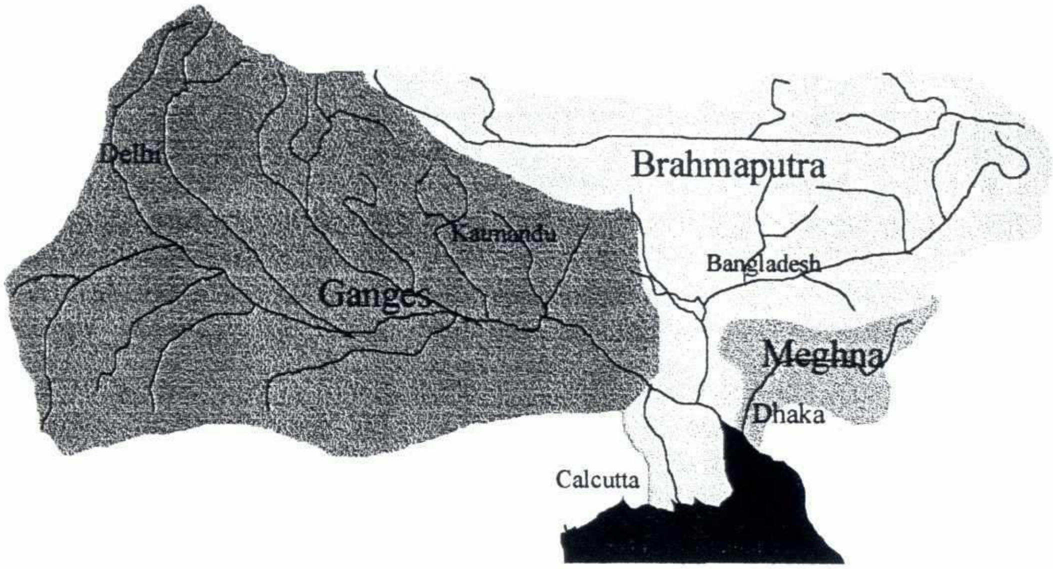


Figure 4.2: Generalised geological map of Bangladesh

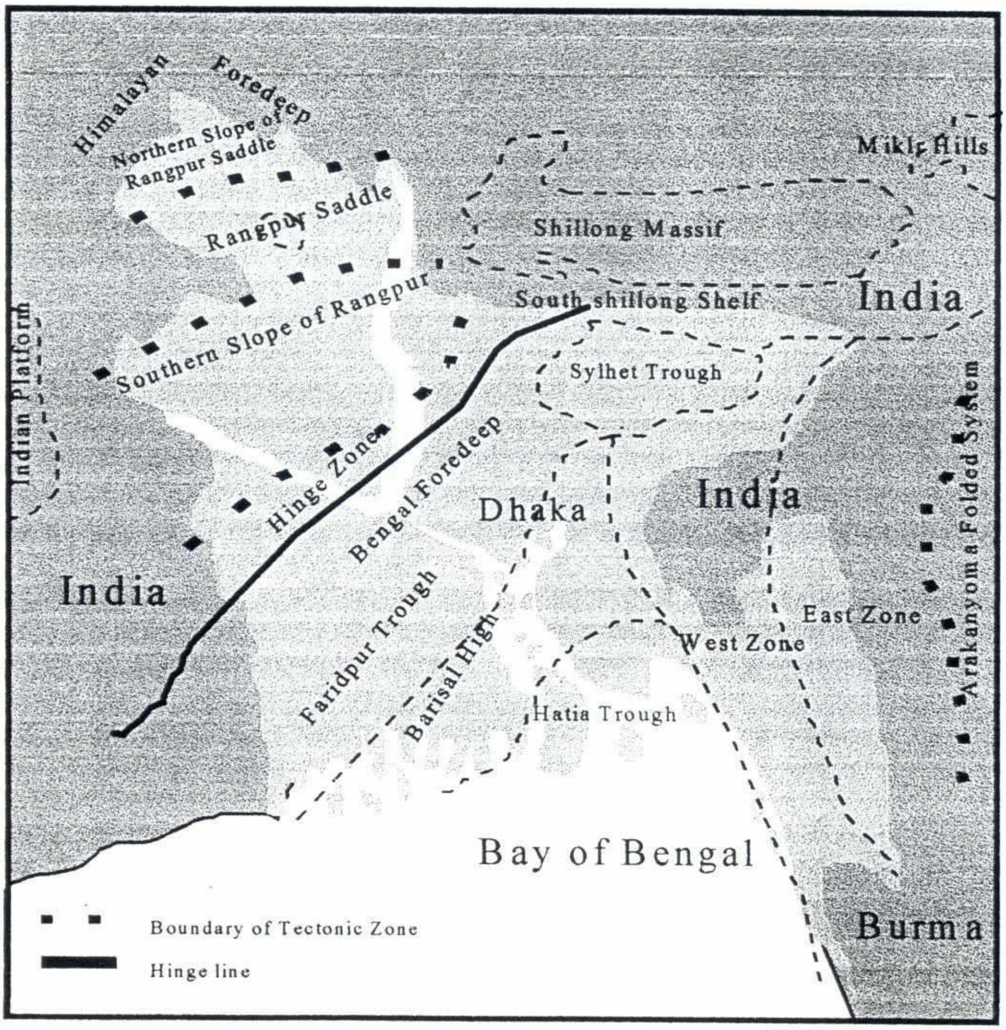
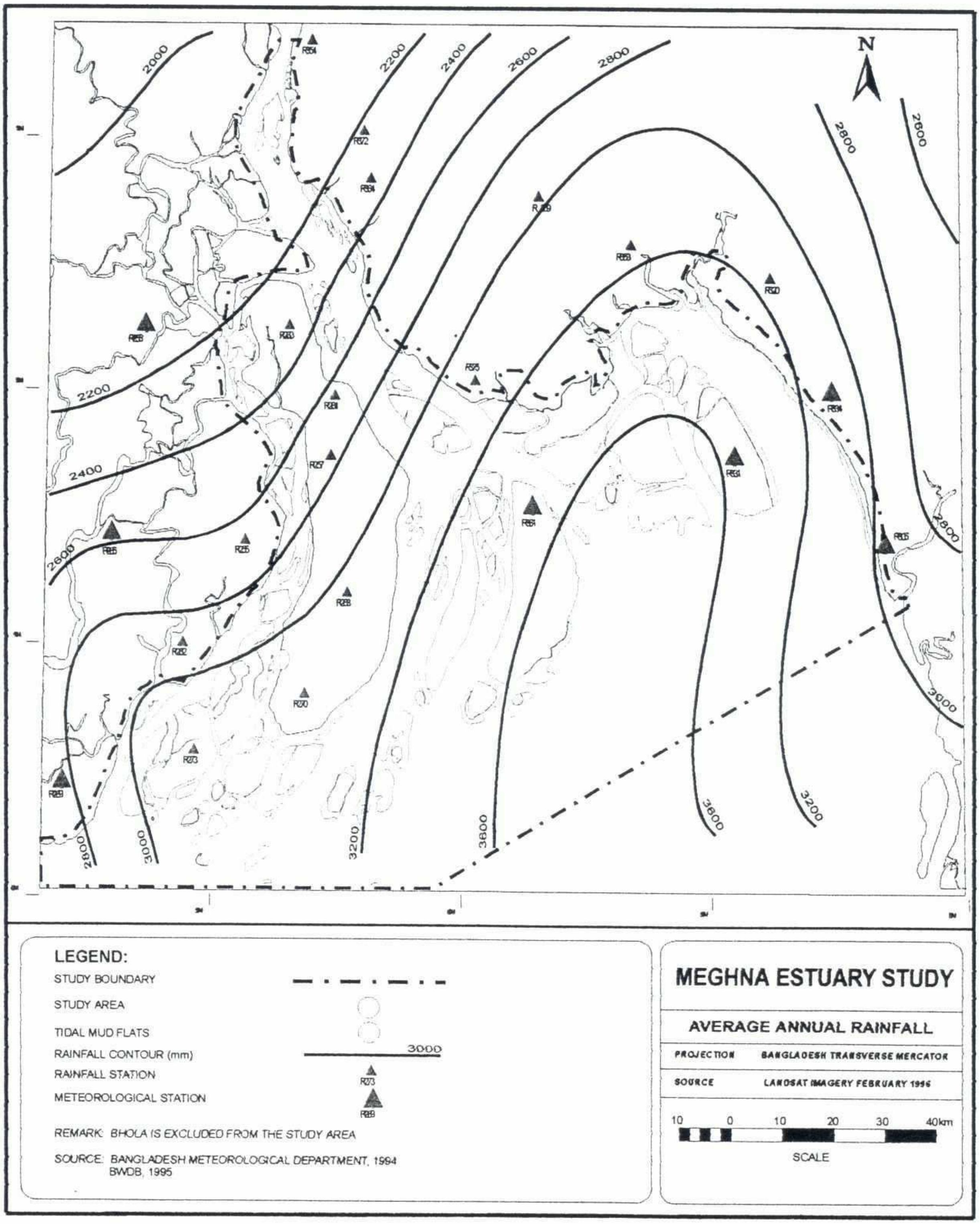


Figure 4.3 : Annual rainfall

Figure 4.3 Annual Rainfall



Some of the most important controlling factors attributed to the coastal processes and development of the Lower Meghna Estuary are listed in Table 4.1. The listing is not complete and has not been ordered in any specific manner. The geomorphology and characteristics of the Lower Meghna Estuary with its particular circulation patterns is the result of an evidently adequate combination of these factors.

An estuary is, according to the definition of Perillo (1995) *"a semi-enclosed coastal body of water that extends to the effective limit of tidal influence within which sea water entering from one or more free connections with the open sea, or any other saline coastal body of water, is significantly diluted with fresh water derived from drainage, and can sustain euryhaline biological species from either part or the whole of their life cycle".*

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 Upper Tetulia and Lower Meghna channels show a braided river dominated morphology.

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 play in these areas the dominant role in determining the fate of the river borne sediments There is appreciable upstream transport of bed load and suspended load sediment as a result of deformation of tide during propagation. Sediment is received from both the river and the 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 exhibits a funnel shape. The river influence becomes progressively larger in the upstream direction as friction drains tidal energy. Tidal influence extends substantially farther upstream than salt intrusion, and deltaic sedimentation occurs only in the subaqueous environment.

4.2 Wind and cyclones

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 a S-SE direction, with an average velocity varying from about 8-12 m/s.

Figure 4.4 shows the long term wind climate at the international meteorological station of Chittagong based upon time series of 25 years wind data. Due to severe storms and cyclones, the wind velocities exceed Beaufort 12. Most cyclones occur during April-May and October-November, which are the transitional periods between the dry season and the monsoon season. Appendix A describes the chronology of major cyclonic storms and tidal surges in Bangladesh 1797-1995. The characteristics of the wind condition over the period January - June 1997 at nine meteorological stations in the Study area is shown in Appendix B.

Figure 4.4 : Wind climate at the International Meteorological Station of Chittagong (based upon 25 years of wind data)

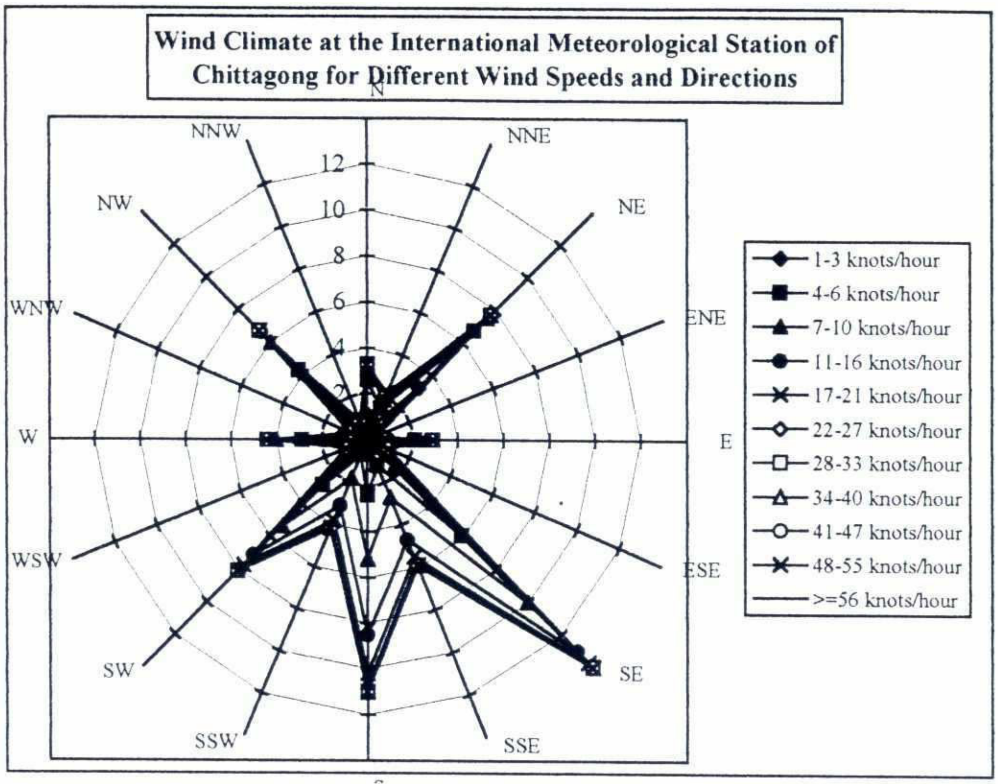
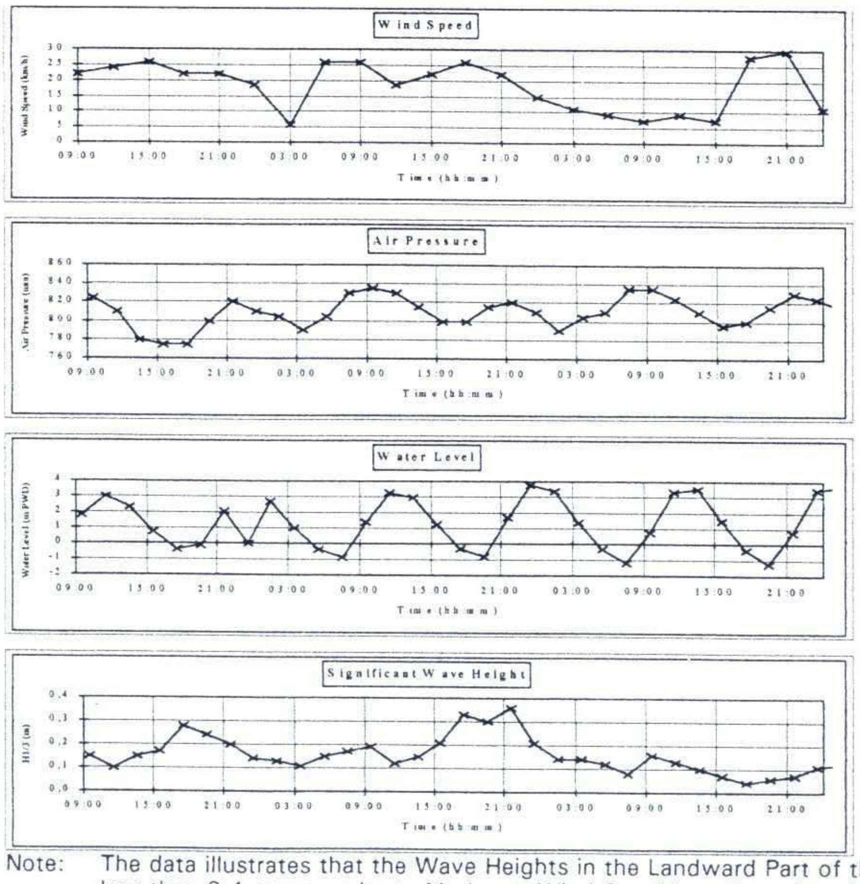


Figure 4.5 : The wave data around Sandwip over the period 20-23 March 1997



Note: The data illustrates that the Wave Heights in the Landward Part of the Meghna Estuary is less than 0.4 metre under to Moderate Wind Conditions (less than 8m/s)

4.3 Waves and surges

No wave measurements have been recorded during severe storms. Wave measurements during the period December 1996 to March 1997 indicate that the wave heights in the landward part of the project area are less than 0.4 metre due to the moderate wind conditions (less than 8 m/s) (Figure 4.5).

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 metre in the nearshore zone to 0.1-0.6 metre in the landward part of the project area. In the dry season the waves are generally less than 0.6 metre with peak periods of 3 - 4 seconds. During the monsoon season wave heights exceed 2 metres with periods greater than 6 seconds. These higher waves may occur mainly in the pre- and post-monsoon periods during cyclones. Under these extreme conditions wave heights of more than 5 metres occur. Although such cyclonic surges may cause a lot of damage, they are believed to be too incidental to be relevant from a morphological point.

4.4 Tides

The tidal movement and response in the Bay of Bengal had been studied and described in many previous regional studies (e.g. Southwest Regional Plan (SRP),1980; Land Reclamation Project (LRP); South West Area Water Resources Management Project (SWAWRMP,1993.)

The water movement in the project area is governed by various phenomena. Generally, the tidal motion dominates. However, river discharges of fresh water also 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 faster 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 of the tidal wave. Also some reflection of the tidal wave occurs contributing to an increase of the tidal wave in the Hatia and Sandwip channels.

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 spring to neap is from 0.6 to 1.4 times the average amplitude (FAP 4). In the western part of the Bangladesh coastal project area the average tidal range is approximately 1.5 m. In the area around Sandwip, the tidal range is higher with an average range of around 4 metres or more.

According to the classification of tides proposed by Davies (1964) the tidal range in the study area can be classified as follows (Figure 4.6):

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

The maximum high tide water level is about 6.5 metre 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 mudflats and chars. The amplitude of the tidal velocity shows a neap-spring tide characteristic. During spring, the tidal 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.

4.5 Salt incursion

Salinity data from LRP and MES 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. Approximately during the period from mid-August to mid-October the salinity in the Meghna Estuary Study area drops considerably and the water becomes almost completely fresh (Figure 4.7).

After the monsoon the salinities rise again and the sea water intrudes into the study area. However, even during the period with low river discharges the salinities in the area never approach normal sea water salinity (34.5 ppt) but always remain distinctly lower. Figure 4.7 and 4.8 show the approximately maximum and minimum salinities in the Study area during the dry season and respective wet seasons. The data of the salinity measurements in the Study area indicate a well mixed estuary both in the winter and in the monsoon period. The salinities at the bottom only slightly exceed the surface salinities.

Figure 4.6 : Mean tidal range in the Meghna Estuary and coastal area

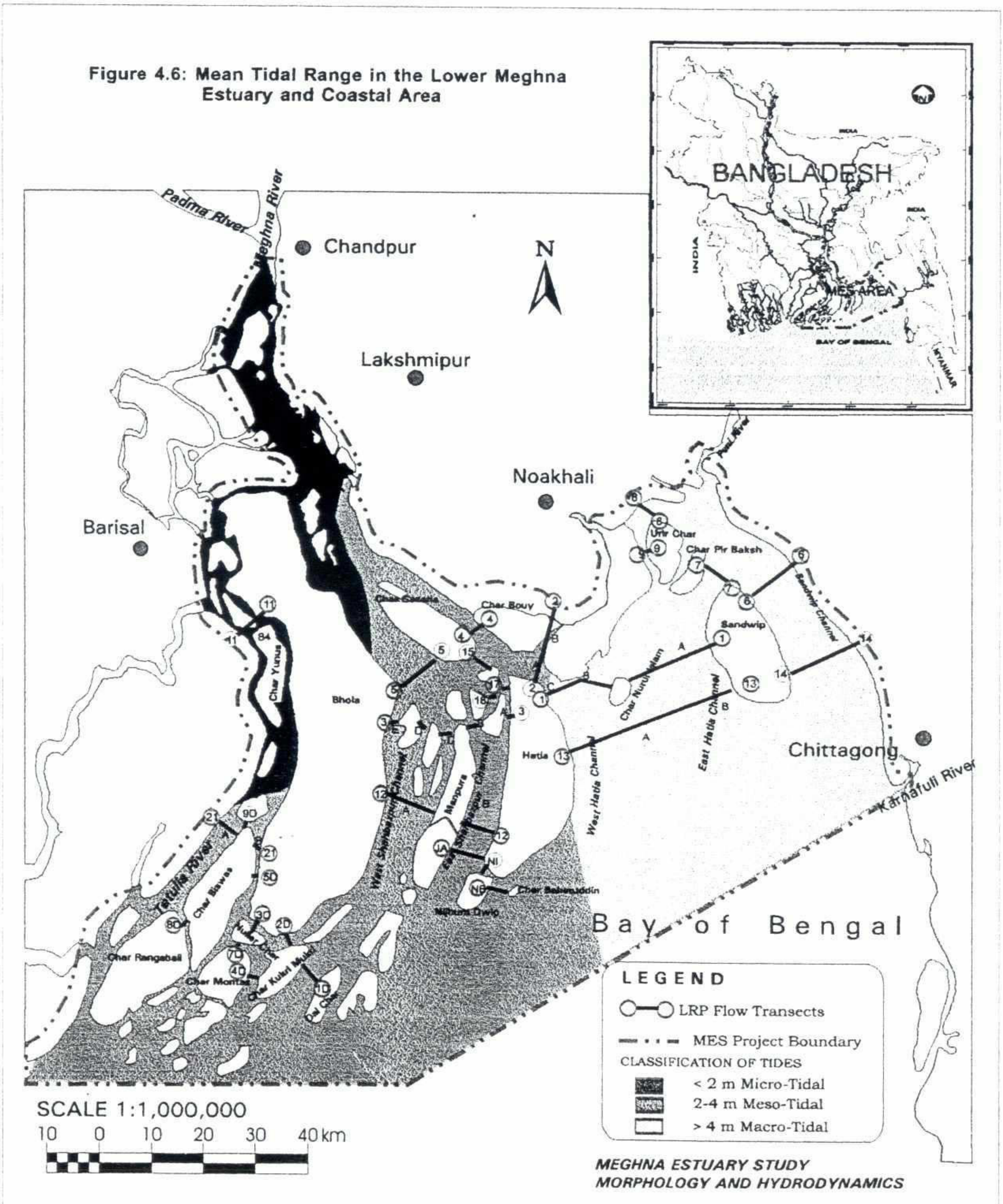


Figure 4.7 : Progress of salt incursion during May-October

Figure 4.7 Progress of Salt Incursion during May-October

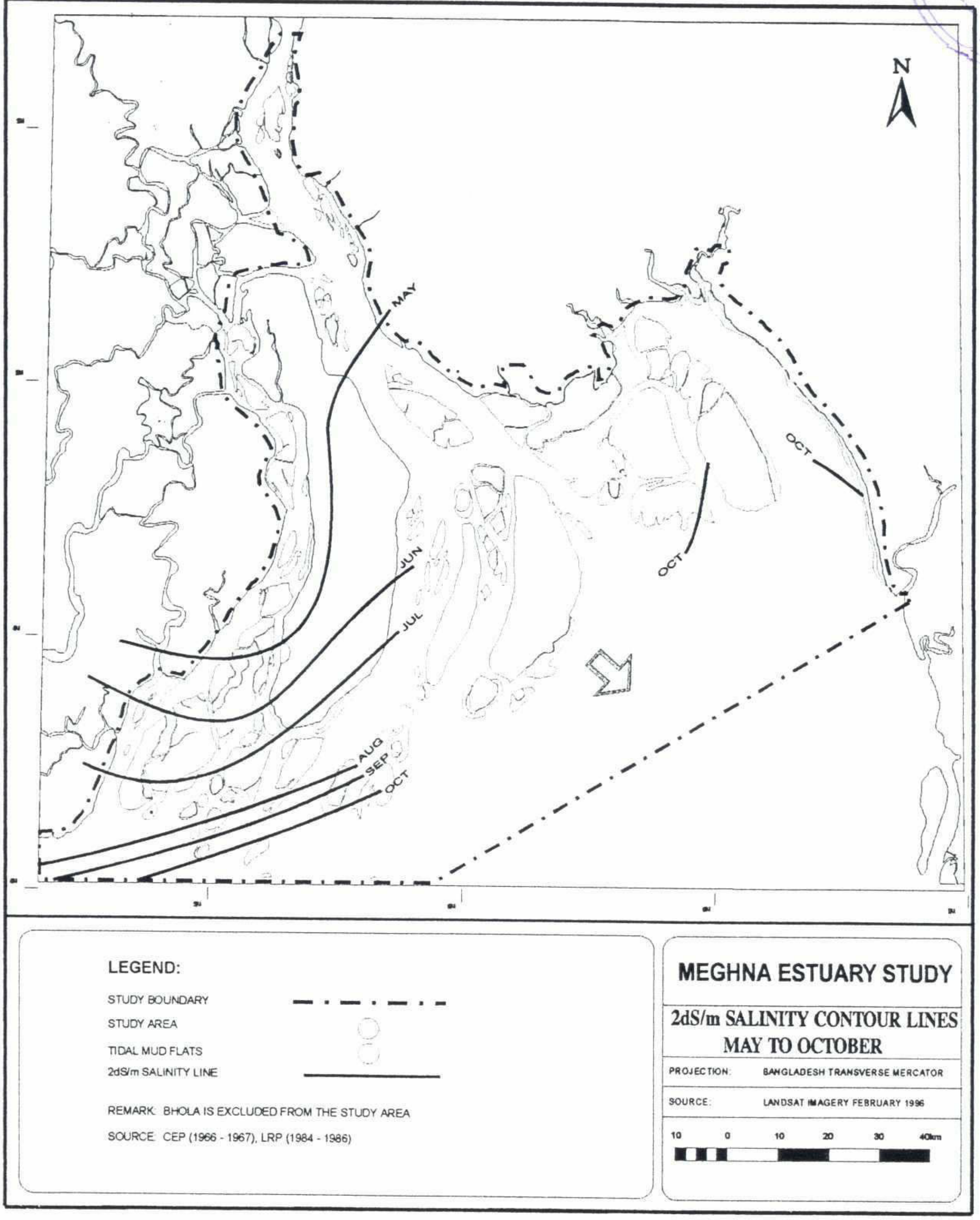
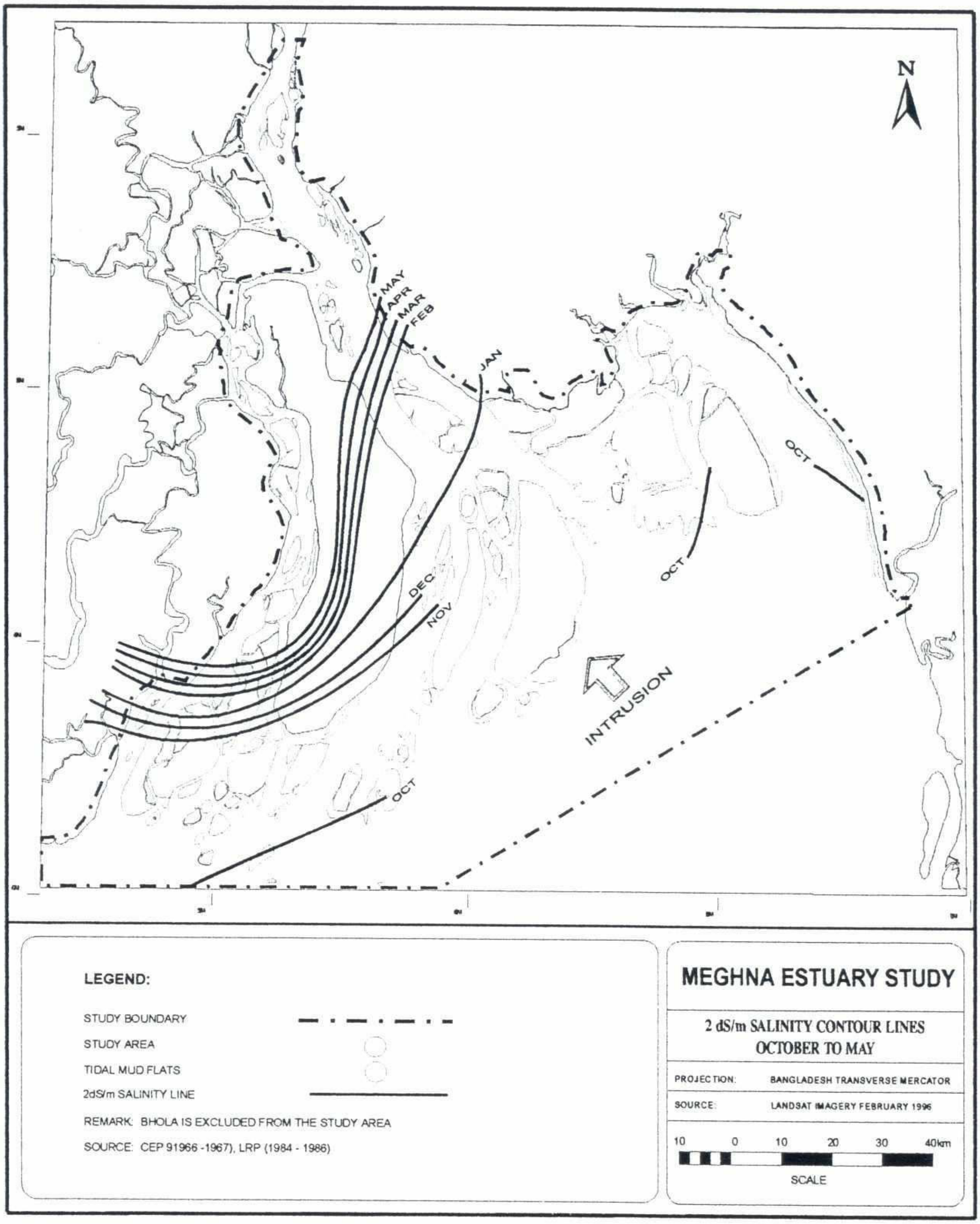


Figure 4.8 : Progress of salt Intrusion during October-May

Figure 4.8 Progress of Salt Intrusion during October-May



5. HYDROGRAPHIC CONDITIONS

5.1 Water level station statistics

Statistical analysis of long term water level series have been executed to compute frequency and duration curves of daily water levels and annual maximum and minimum high and low water levels. Since most of the gauge stations have no long term water level data (more than 5 years) extreme statistical value analysis in terms of extreme return periods are estimated only for 7 stations.

Frequency analysis requires homogenous data. All series have been checked for possible trends. Analysis of extremes revealed that all annual maximum water levels fitted well to the Extreme Value Type I (EVI) and Log-Pearson Type III distribution (Chow et. al., 1988). A convenient way of showing the variation of the high and low water levels throughout the year for a given water level station is by means of frequency curves where each frequency curve indicates the magnitude of the high and low water level for a selected specific probability of non-exceedance.
In all cases the 90%, 50% and the 10% probabilities were selected together with the maximum and minimum values in the years considered. The frequency curves presented are based directly on the corrected and updated time series for all the years available using a time step of one day. The corresponding exceedance curve gives the percentage that a given water level was not exceeded in the years considered.

The extreme water levels for selected return periods at different water level stations are presented in Table 5.1.

Table 5.1: Extreme water levels for selected return periods

Station	No. of Years	Method	Conversion Factor from CD to PWD	Return Period (years) of Water Levels (m.PWD)						
				1 : 2	1 : 5	1 : 10	1 : 20	1 : 25	1 : 30	1 : 50
Chandpur (m.CD)	7	GEVI	0,250	4,72	4,99	5,17	5,35	5,40	5,45	5,57
		LPTIII	0,250	4,80	4,92	4,97	4,99	4,99	5,00	5,00
Char Chenga (m.CD)	13	GEVI	-1,184	3,53	3,83	4,03	4,23	4,29	4,34	4,48
		LPTIII	-1,184	3,56	3,84	4,00	4,14	4,19	4,22	4,31
Chital Khali (m.CD)	7	GEVI	-1,350	3,80	4,41	4,80	5,18	5,31	5,40	5,68
		LPTIII	-1,350	3,94	4,39	4,59	4,74	4,78	4,81	4,89
Dashmina (m.PWD)	5	GEVI	-0,550	2,64	2,82	2,93	3,05	3,08	3,11	3,19
		LPTIII	-0,550	2,65	2,83	2,94	3,05	3,08	3,10	3,18
HWL at the D/S Site of Feni Regulator (m.SOB)	13	GEVI	0,460	5,84	6,31	6,62	6,92	7,01	7,09	7,30
		LPTIII	0,460	5,91	6,28	6,48	6,64	6,69	6,73	6,83
Khepupara (m.CD)	8	GEVI	-1,960	2,62	2,86	3,02	3,17	3,22	3,26	3,37
		LPTIII	-1,960	2,66	2,88	2,99	3,09	3,12	3,14	3,20
Ramdaspur (m.CD)	6	GEVI	-0,660	4,00	4,19	4,31	4,42	4,46	4,49	4,57
		LPTIII	-0,660	4,03	4,21	4,31	4,40	4,43	4,45	4,50

* Conversion Factors to PWD are derived from Geodetic Surveys and hydraulic model computations.
GEVI - Gumbel Extreme Value Type I Distribution.
LPTIII - Log Pearson Type III Distribution.

The difference between the Log-Pearson Type III distribution and Extreme Value Type I for the extreme water levels is within a few centimetres. The frequency curves and exceedance curves for high water level are presented in Appendix C and Appendix D.

Extreme value distributions of water level data have been widely used in civil engineering for the design of embankments. The crest level of the embankments in the coastal areas are commonly modelled by the Gumbel distribution (EVI) or Log-Pearson Type III extreme value distribution methods to calculate the event magnitudes for various values of return period T. The results of the extreme value distributions of water level data as presented in Table 5.1 give an indication of the spatial variation in extreme values of water level in the coastal area.

09

5.2 Spatial and temporal variation in water level characteristics

Tidal data from a large number of water level stations has been analysed by harmonic analysis to compute the major tidal constituents. The major tidal constituents, amplitudes and phases of the four tidal components M2, S2, K1, 01 and the two shallow water constituents M4 and M6 are listed in Table 5.2.

Table 5.2: Harmonic constituents of six water level stations

	CHANDPUR Jan-Dec 1996 PWD			CHAR CHENGA Jan-Jul 1997 PWD			KHEPUPARA Jan-Jun 1997 PWD		
Constituents Name	Amplitude (m)	Ampl./M2 (%)	Phase (deg)	Amplitude (m)	Ampl./M2 (%)	Phase (deg)	Amplitude (m)	Ampl./M2 (%)	Phase (deg)
M2	0.2879	100.00%	206.24	1.0276	100.00%	53.91	0.8200	100.00%	318.58
S2	0.1130	39.25%	238.23	0.5086	49.49%	100.79	0.3641	44.40%	4.11
M4	0.0674	23.41%	326.91	0.1425	13.87%	33.20	0.0689	8.40%	184.35
K1	0.0605	21.01%	116.91	0.0962	9.36%	54.93	0.1437	17.52%	15.65
O1	0.0436	15.14%	101.31	0.0287	2.79%	27.40	0.0554	6.76%	349.68
M6	0.0113	3.92%	58.73	0.0600	5.84%	239.62	0.0380	4.63%	346.14

	DHULIA Jan-Jul 1997 PWD			DASMONIA Jan-Jul 1997 PWD			KHAL No. 10 Jan-Dec 1996 PWD		
Constituents Name	Amplitude (m)	Ampl./M2 (%)	Phase (deg)	Amplitude (m)	Ampl./M2 (%)	Phase (deg)	Amplitude (m)	Ampl./M2 (%)	Phase (deg)
M2	0.4585	100.00%	105.38	0.5805	100.00%	20.76	1.5302	100.00%	19.46
S2	0.1874	40.87%	154.35	0.2483	42.77%	61.64	0.5215	34.08%	58.76
M4	0.0641	13.98%	69.88	0.0553	9.53%	312.91	0.0776	5.07%	275.87
K1	0.1373	29.95%	87.18	0.1223	21.07%	54.16	0.1656	10.82%	17.10
O1	0.0731	15.94%	59.89	0.0566	9.75%	27.08	0.0810	5.29%	2.94
M6	0.0236	5.15%	15.98	0.0191	3.29%	164.68	0.0278	1.82%	131.31

The spatial variability of the major components in the Study area in terms of amplitude and phase agrees with the results of MCSP (1993). 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 a southward direction. At Chandpur the seasonal variation of the mean high water level is about 2.7 metres while along the southern part of the Bangladesh coast, the seasonal variation of the mean high water level varies from about 0.7 metre to 1.7 metres. (Table 5.3).

Table 5.3: Seasonal variation of mean high and low water levels on 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	1.7 to 4.4	2.7	0.9 to 3.8	2.9
Chilalkhali	1.4 to 3.5	2.1	-0.8 to 0.8	1.6
Ramdaspur	1.3 to 3.4	2.1	-0.1 to 2.3	2.4
Char Chenga	1.3 to 2.9	1.6	-0.6 to 0.2	0.8
Khepurpara	0.9 to 2.0	1.1	-1.1 to -0.3	0.8
Dasmonia	1.0 to 2.3	1.3	-0.2 to 0.8	1.0
Dhulia	0.5 to 2.1	1.6	-0.6 to 0.9	1.5
Feni river	3.1 to 4.6	1.5	dry to 2.0	-

Figure 5.1 : 90%, 50% and 10% exceedance lows of the Jamuna, Ganges and Meghna for the period 1965-1995 (FAP 24)

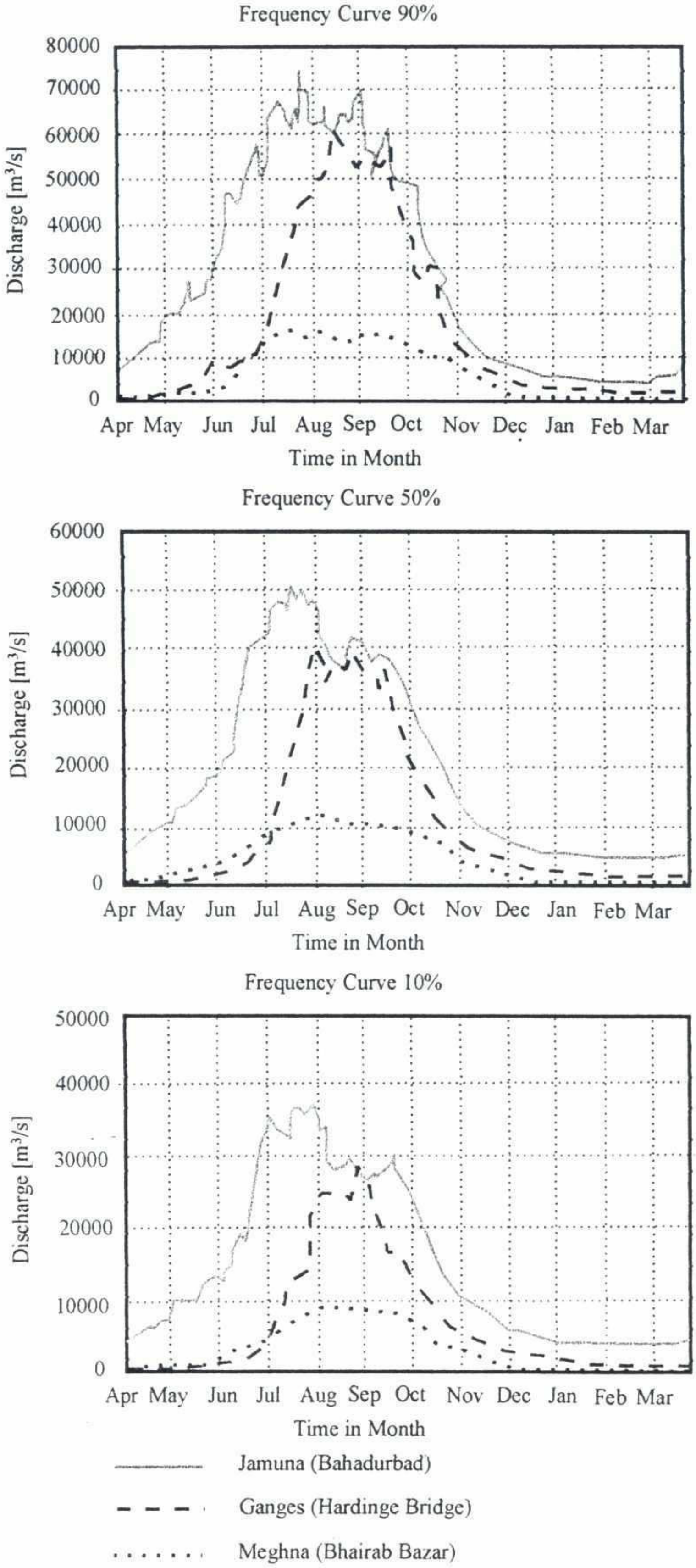
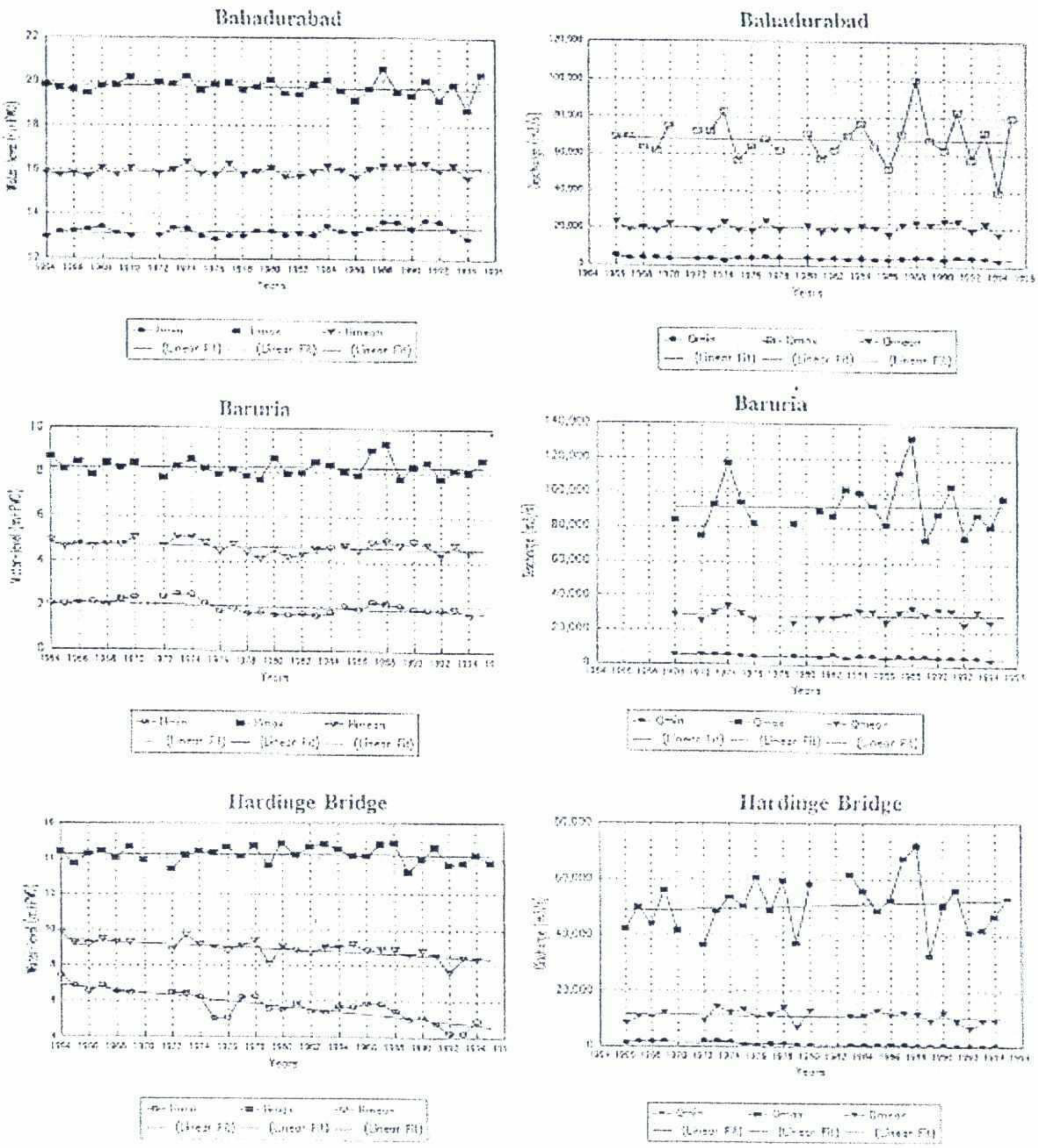


Figure 5.2a/f : Annual minimum, mean and maximum water level and discharge at Bahadurabad, at Baruria and at Hardinge Bridge (FAP 24)



5.3 Long term river flow characteristics

From Chandpur towards the Bay of Bengal the river is known as the Lower Meghna. The Lower Meghna river conveys the melt and rain water from the Ganges and the Jamuna basins, combined in the Padma river, and from the Upper Meghna basin to the sea. The river 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 the three main rivers of Bangladesh will be discussed 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 5.1, 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 one and a half to two months earlier than the Ganges, whereas flow recession in the Ganges begins somewhat earlier. During August and September the river flows are on average similar. The average discharge of the Jamuna river at Bahadurabad is approximately 21,000 m^3/s. Peak flows up to 100,000 m^3/s have been reported. The average discharge of the Ganges river at Hardinge Bridge of (1966-1995) is about 11,000 m^3/s. Since 1966 the highest peak flow amounted to 72,000 m^3/s. 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.

The annual minimum, mean and maximum water level and discharge time series at Bahadurabad, at Baruria and at Hardinge Bridge are presented in Figures 5.2a-5.2f (FAP 24). Figure 5.2e shows a slightly upward trend for the minimum water levels at Hardinge Bridge while the maximum water levels decline somewhat. Both trends are, however, insignificant. The annual minimum, mean and maximum discharges series at Bahadurabad show no trend. The minimum and mean water levels at Hardinge Bridge show a slightly downward trend whereas the maximum water levels do not show a trend (Figures 5.2e - 5.2f). The downward trend might be caused by the withdrawal of water at Farakka, beginning in the mid-seventies. The annual minimum and mean discharge series at Hardinge Bridge show a similar downward trend.

The annual characteristics of the water level and discharges illustrate the enormous river dynamics which influence the coastal area (Table 5.4).

Table 5.4: Calculated peak water levels and discharges for selected return periods

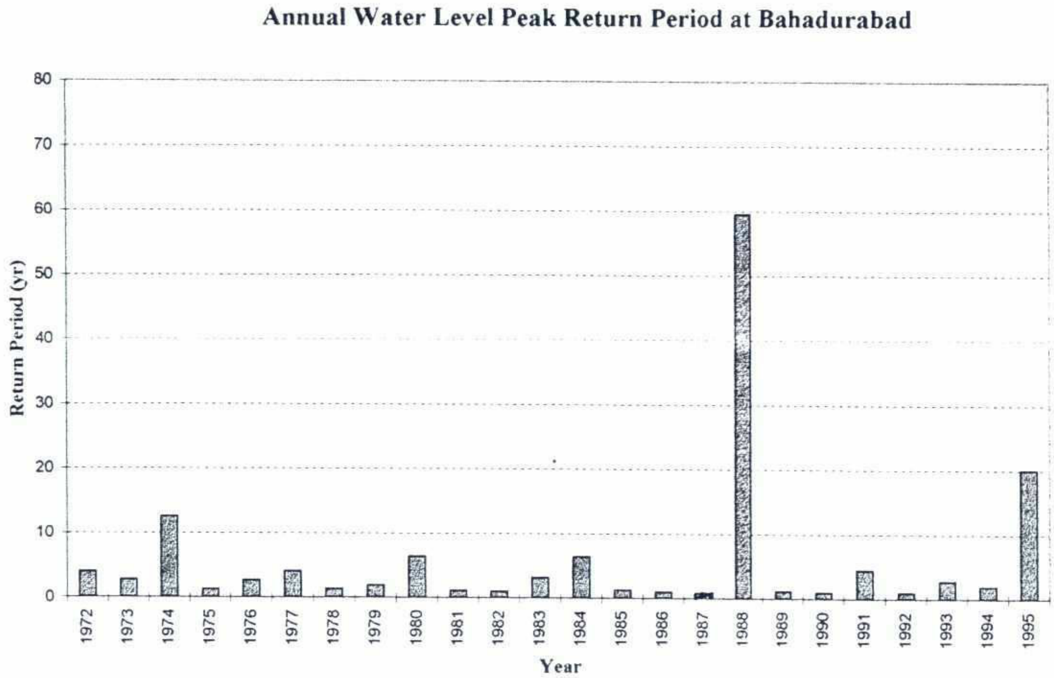
Station	(+ metre PWD) (m^3/s)	Return Period ($year^{-1}$) 1:2	1:5	1:10	1:25	1:50
Bahadurabad	Peak level	19.78	20.04	20.21	20.42	20.57
	Peak discharge	67,000	78,000	85,000	94,000	105,000
Hardinge Bridge	Peak level	14.72	14.80	14.85	14.92	14.97
	Peak discharge	49,000	59,500	66,500	76,000	82,500
Mawa	Peak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

Source: FAP 25

Figure 5.3 shows the annual water level peak return period at Bahadurabad over the period 1972-1995. This figure shows that the maximum peak water levels and thus the discharges over the period 1975-1983 and over the period 1989-1994 are relatively low. The 1988 and 1995, as well as the 1998, seasons were relatively very wet and can be characterised by extremely high water levels and river discharges. From this it might be expected that the overall river inflow characteristics at Chandpur will show the same trend.

Figure 5.3 : The annual water level peak return period at Bahadurabad over the period

Figure 5.3 : The annual water level peak return period at Bahadurabad over the period 1972-1995



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 at Chandpur for various return periods are shown in Table 5.5.

Table 5.5: Calculated peak water discharges and water level gradients at Chandpur

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

Source: FAP 9B

5.4 Long term cyclone events

The Multi-purpose Cyclone Shelter Preparatory Study (MCSP, 1993) has made a very thorough analysis of various aspects of the generation of cyclone surges and their penetration inland. The yearly maximum wind speed (anywhere in the Bay of Bengal) was analysed statistically revealing in a relationship between return period and wind speed (Table 5.6).

Estimation of the design surge heights due to cyclone (MCSP,1993) are shown in Table 5.7. The results indicate that the surge height in the area of Chittagong-Bhola due to a specific cyclone is higher than in the surrounding areas.

Table 5.6: Cyclone wind speeds

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

Source: MCSP, 1993

Table 5.7: Design surge heights

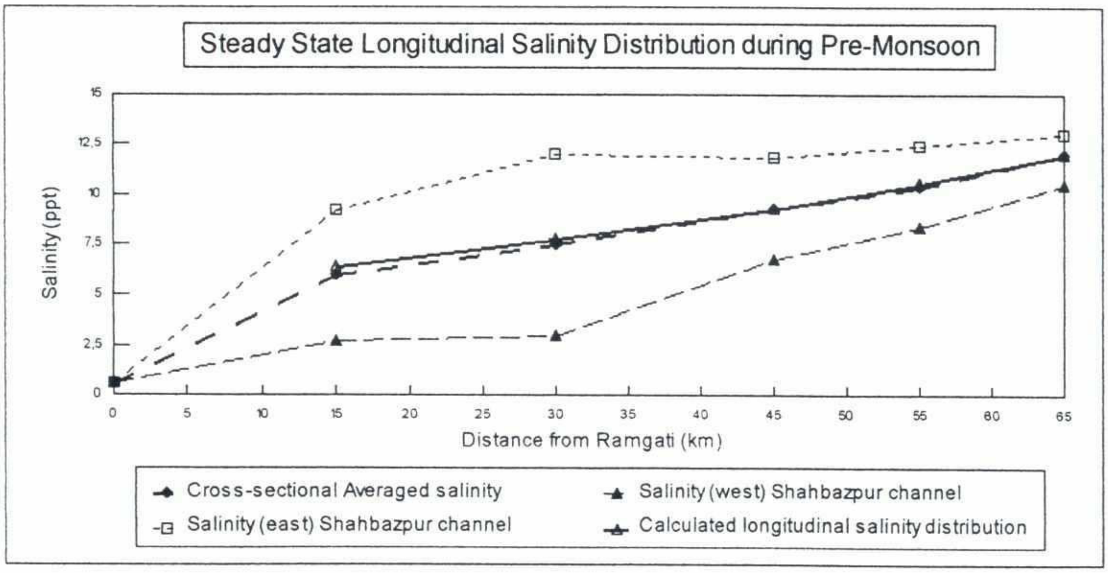
Return Period (years)		20	50	100
Wind Speed (km/h)		195	233	261
Region	Length of shelf (km)	Design Surge Heights (m) (as proposed by Reid, 1956)		
Teknaf-Cox's Bazar	140	2.7	3.7	4.5
Cox's Bazar-Chittagong	230	4.3	5.8	7.0
Chittagong-Bhola	260	4.8	6.5	7.8
Bhola-Barguna	200	3.8	5.1	6.2
Barguna-Khulna	160	3.1	4.3	5.2

Source: MCSP, 1993

5.5 Longitudinal salinity distribution and gravitational circulation

Gravitational circulation in the estuary depends on the rate of fresh water inflow from the river and the degree of tidal mixing. In particular, the resulting longitudinal salinity gradient is an important parameter; it causes the baroclinic pressure gradient that forces the gravitational circulation. The salinity during pre-monsoon (December-April) is about 0-1.0 ppt at Ramgati and 10.0-16.0 ppt near Nijhum Dwip (Figure 5.4).

Figure 5.4 : Steady state longitudinal salinity distribution along the Lower Meghna Estuary River



LRP based salinity measurements during pre-monsoon indicate that due to fresh water discharges salinities gradually increase when going from Ramgati in a seaward direction. Longitudinal salinity gradients are the largest at the landward end near north Hatia. The maximum value for the salinity gradient, ds/dx, vary from $1.0*10^{-4}$ to $4.0*10^{-4}$ ppt/metre. According to these observations the strength of the gravitational circulation in the main channel of the Meghna Estuary around north Hatia is estimated at 0 - 4 cm/s during pre- and post-monsoon, the exact value depending on fresh water discharge and location.

Generally, during the monsoon period the strength of the gravitational circulation is negligible in the main channel. Salinity measurements indicate that the salinity gradient in the areas near the Tetulia river, as well as in the Hatia channel, is steeper than in the surrounding waterways. For these areas the strength of the gravitational circulation might be more than 0 - 4 cm/s.

6. GEOMORPHOLOGICAL DEVELOPMENT OF THE COASTAL AREA

6.1 Introduction

Geomorphology is concerned with the study of earth surface forms and their evolution in time and space due to the physicochemical and biological factors acting on them. Most of the evolution is the product of a cyclic process based on erosion-transport-deposition of sediment particles. Added to this are the combinations that may occur from the meteorisation of a hard rock until the particle is permanently buried and becomes part of a new sedimentary rock. In particular, the coastal environments are subjected to the most energetic conditions on the earth surface. Modifications of geoforms and the characteristics of sediment distribution may occur in very short time periods. Nevertheless spatial and time scales may range from a few seconds and centimetres to centuries and thousands of kilometres (Table 6.1).

Table 6.1: Measurement units on the space-temporal scale

	Mega scale	Macro scale	Meso scale	Micro scale
Space	10^{9}-10^{3} km	10^{3} -1 km	1 - 10^{-3} km	10^{-3} - 10^{-9} km
Time	century	Decades/year	month/days/h	min/sec

The evolution of the Meghna Estuary Study area is subject to strong processes that fully cover the space-temporal scale. In this chapter the geomorphological development of the Meghna estuary will be discussed in detail for different spatial and time scales to assess long term changes in coastal morphology and to discern patterns and tendencies.

6.2 Geomorphological development due to relative sea level rise

One of the important controlling factors for the Meghna Estuary Study area is the change in relative sea level rise in the coastal area and the effect in the catchment areas of the rivers. The sediment transport capacity of the main rivers and tidal channels and the type of deposits are dependant, among others things, on the rise and the fall of the base level. The base level of the Meghna Estuary Study area is the sea level. In the deltaic reaches, the sea level variation has a far reaching effect, specially on a geologic time scale. During historic time, there have been changes in sea level, followed by periods of glaciation and anti-glaciation. Based upon the lithological structure of the deposits, Umitsu (1993) reconstructed the rise of the sea level in the case of Bangladesh coast over the last 12,000 years.

Figure 6.1 shows the sequence and position of the sea level over the last 12,000 years. This Figure indicates that the trend of sea level rise decreases in course of time. The amount of sediment inflow into the Lower Meghna estuary and coastal area seems to have been adequate to adjust to the rising sea level, so that they have preserved their characteristic properties (Figure 6.2).

For the coastal area another interesting factor in sea level variation is important. This involves seasonal variation in sea level following the monsoon. Analyses of long term time series of water level data indicate that the sea level rises by 0.8 - 3.0 metres due to the monsoon.

Figure 6.1 : Sea level rise over the last 12,000 years (Umitsu,1993)

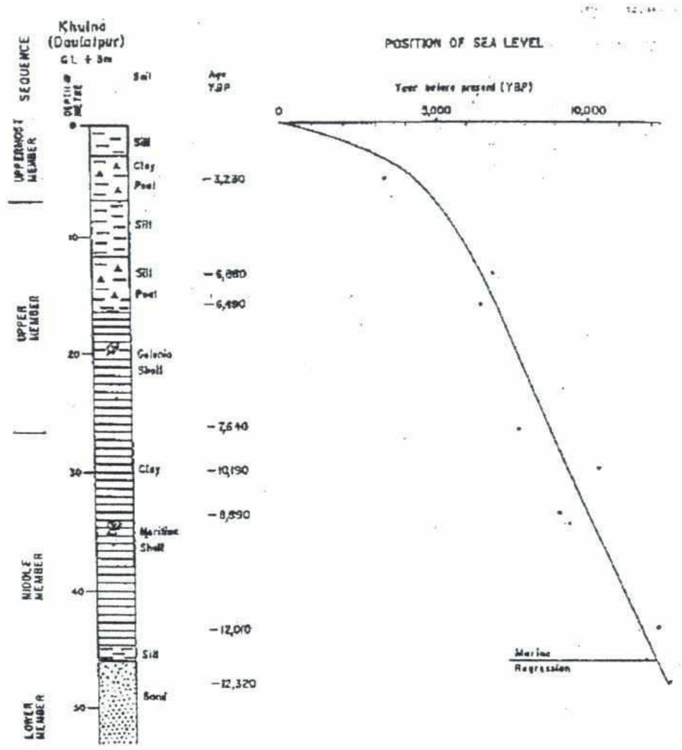


Figure 6.2 : Generalised geological reconstruction over the last 18,000 years (Umitsu,1993)

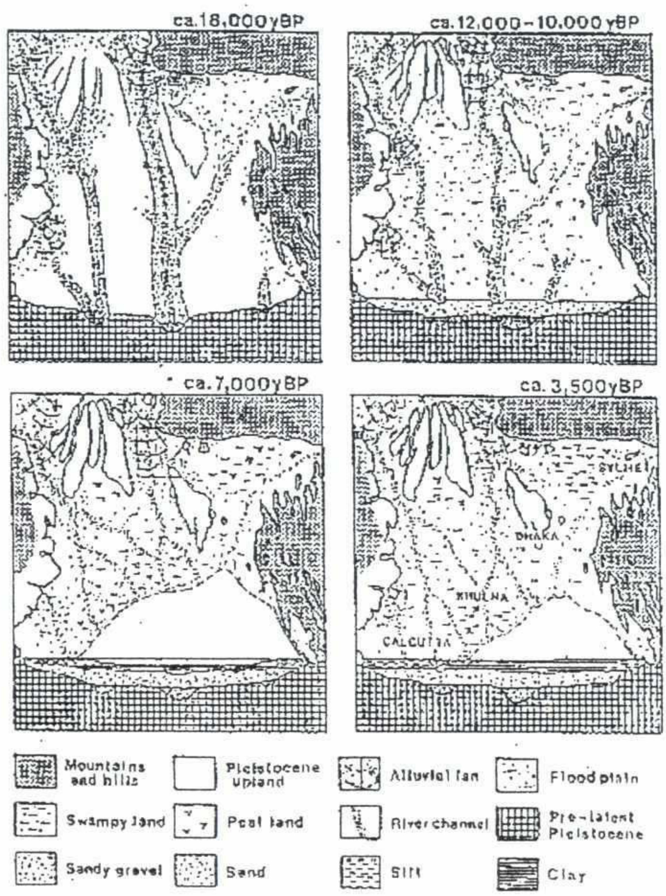


Figure 6.3a : Meghna Estuary Study area Anno 1776 (after J. Rennell)

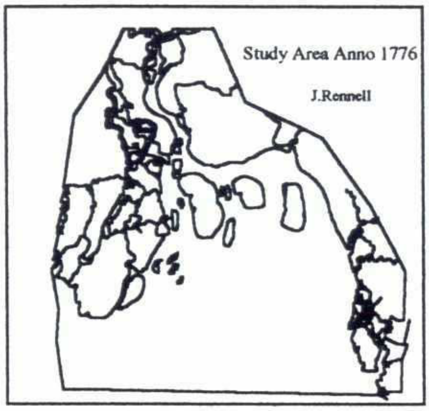
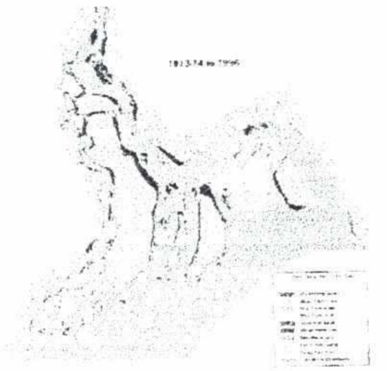
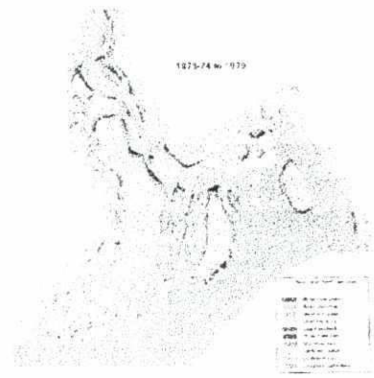


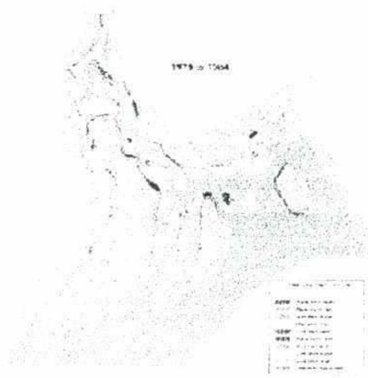
Figure 6.3b-g : Morphological changes in the period 1973/74-1996 derived from satellite imageries



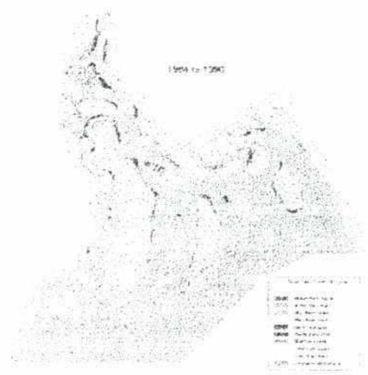
1973/74-96



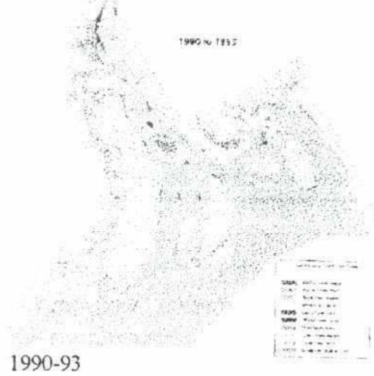
1973/74-79



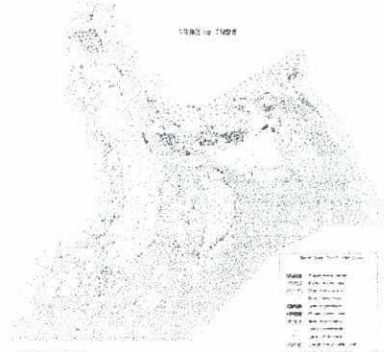
1979-84



1984-90



1990-93



1993-96

6.3 Geomorphological evolution during the last century

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

A comparison of the 1996 classified satellite image with the 1779 map of J.Rennell shows a completely changed system of channels and river courses but a more or less stable coastline west of the Tetulia River (Figure 6.3a/6.3g). 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 northwestern 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.

6.4 Long term net accretion rates

Several studies have examined the rates of change for coastal Bangladesh (Table 6.2). 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/year computed by MES for the period 1776-1996 compares closely with the 7.0 km^2/year computed by Allison (1998). Another, more reliable chart of 1840 prepared by Commander Lloyd was compared against a 1984 satellite image set where the rate of 4.4 km^2/year was computed. The range of net land gain over time periods ranging from 23 to 220 years varies from 4.4 km^2 per year to 16.4 km^2 per year.

A comparison of the rate of change for the period of 1973-1996 with the rate of change for the period 1940-1963 shows that natural processes have been speeded up to some extent by the construction of the two Meghna cross dams (1957 and 1964) in the old course of the Lower Meghna estuary.

Table 6.2: 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/year)	Reference
220	1776-1996	+2187	9.9	Present Study
192	1792-1984	+1346	7.0	Allison (1998)
187	1776-1963	--[1)]	--[1)]	Eysink (1983)
144	1840-1984	+638	4.4	Allison (1998)
23	1940-1963	+279	12.1	Eysink (1983)
23	1973-1996	+378	16.4	Present Study
7	1972-1979	+213	30.4[2)]	SPARRSO and ERIM (1981)

1) Accretion was not quantified, but was found "not extensive".
2) Area described as "mud flat" was considered as accreted; therefore rate of change is not comparable to the present study.

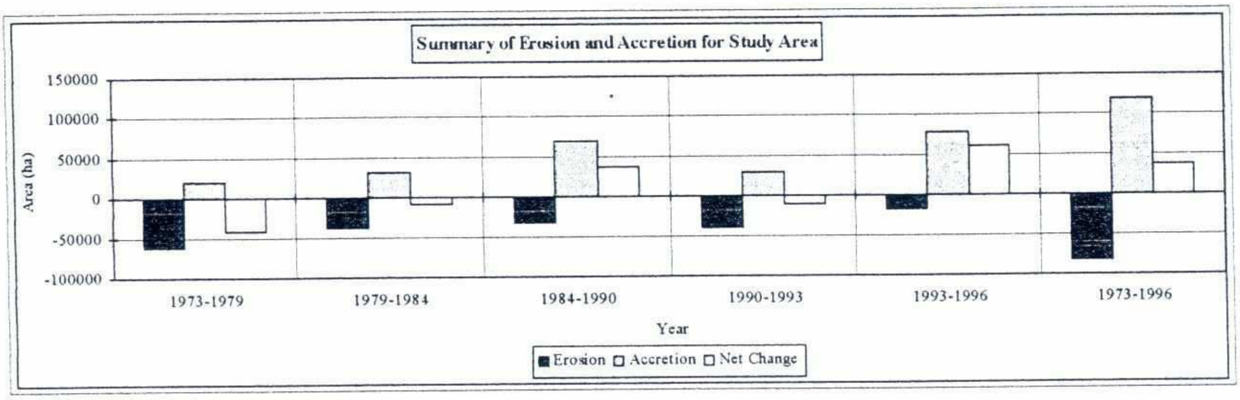
6.5 Long term trends of accretion and erosion over the last decades

6.5.1 Accretion and erosion of land

A time series of satellite images from the period 1973 to 1996 is used to examine the extent of land and intertidal area for each date and to assess the changes in the nine divided subareas, as defined in Figure 3.1. Summary statistics of land and intertidal area for each period in the time series and for each subarea are shown in Appendix E.

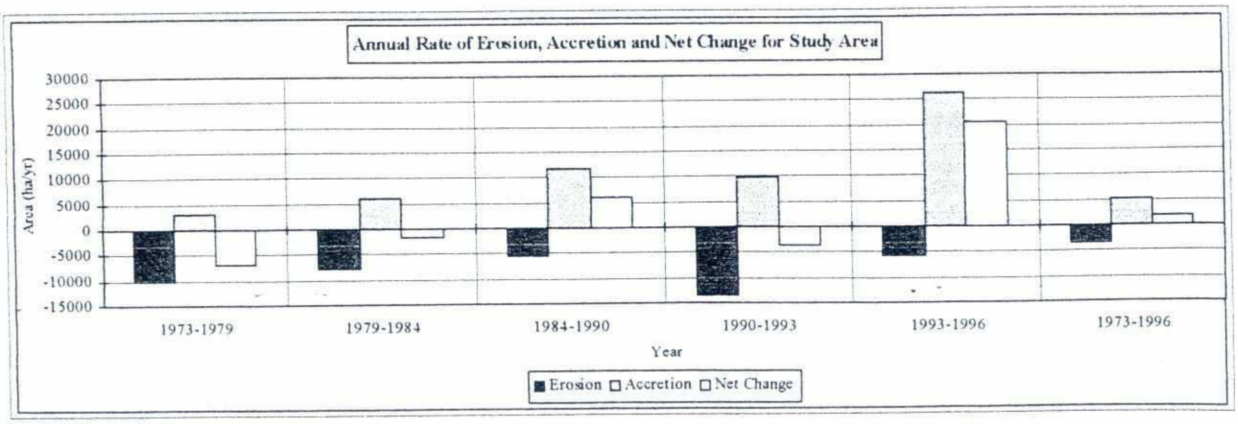
The net change over the period shows an overall land gain for the Meghna estuary system as a whole, for the period 1973-1996 of about 37,771 ha (Figure 6.4).

Figure 6.4 : Long term trend of accretion and erosion, 1973/74-1996



The net change over the period shows land loss up to 1984, with a period of gain during 1984 to 1990, followed by net land loss again during 1990 to 1993. During the period 1993 to 1996 a gain of land area of over 61,409 ha took place which accounts for much of the overall land gain for the period of study, 1973-74 to 1996. The annual rate of change for the entire study period ranged from a loss of nearly 7,000 ha per year during the 1973-74 to 1979 period to a gain of over 20,000 ha per year during the period 1993 to 1996 (Figure 6.5). The average annual gain for the entire study period is 1,642 ha/year.

Figure 6.5 : Annual rate of change of land in the period 1973/74 -1996



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 (see Figure 6.3).

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6.5.2 Accretion and erosion of intertidal area

The net change of intertidal area by period shows a net gain up to 1984, a period of loss during 1984 to 1990, followed by net gain during 1990-1996 (Figure 6.6). The net change of intertidal area for the period 1973-74 to 1996 is 70,589 ha. These results indicate an average long term annual rate of growth of the intertidal area of about 3,069 ha per year.

Figure 6.6 : Annual rate of change of intertidal area in the period 1973/74 -1996

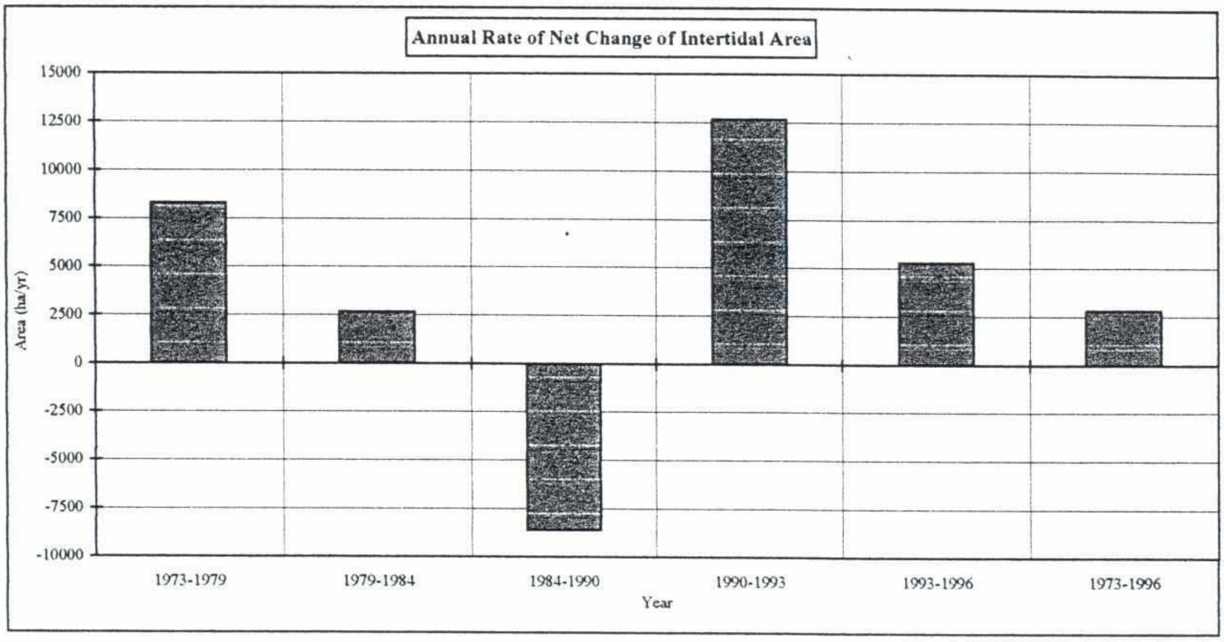
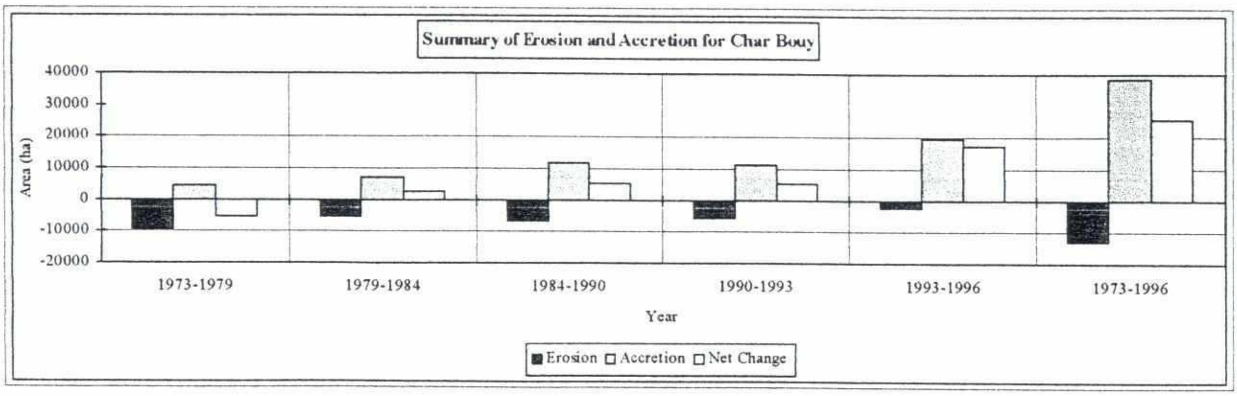


Figure 6.7 : Accretion and erosion of land area around char bouy in the period 1973/74-1996



6.5.3 Preferred areas of accretion and erosion

The changes for the period 1973-74 to 1996 show a vast area of new land off the Noahkali coast and Char Bouy which is associated with an even larger area of mud flat which appears to be emerging land. Figure 6.7 shows a distinct sedimentation trend around Char Bouy over the last two decades. There are new char areas and new areas of mud flat northwest of Sandwip island. Other large areas of accretion include the very large char in the Lower Meghna Channel which appears to be a consolidation and extension of Char Gazaria.

Extensive accretion has formed in the area north of the Tetulia off-take and the filling and enlargement of the chars in the extreme southwest of the study area, including Char Rangabali, Char Montaz and Char Kukri Mukri. With respect to the large areas of accretion in the southwest part of the Meghna Estuary Study area it can be 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 1987/88 and 1995 (see also Figure 5.3).

Most areas of erosion are associated with widening and migration of the main Lower Meghna and with the Shahbazpur and Hatia Channels. The north and east banks of Hatia and Bhola islands are particularly affected by erosion. It is believed that these areas are sensitive to changes in river and sediment discharges.

Figure 6.8 : Annual rate of change of land area in the period 1973/74 -1996 at middle estuary area

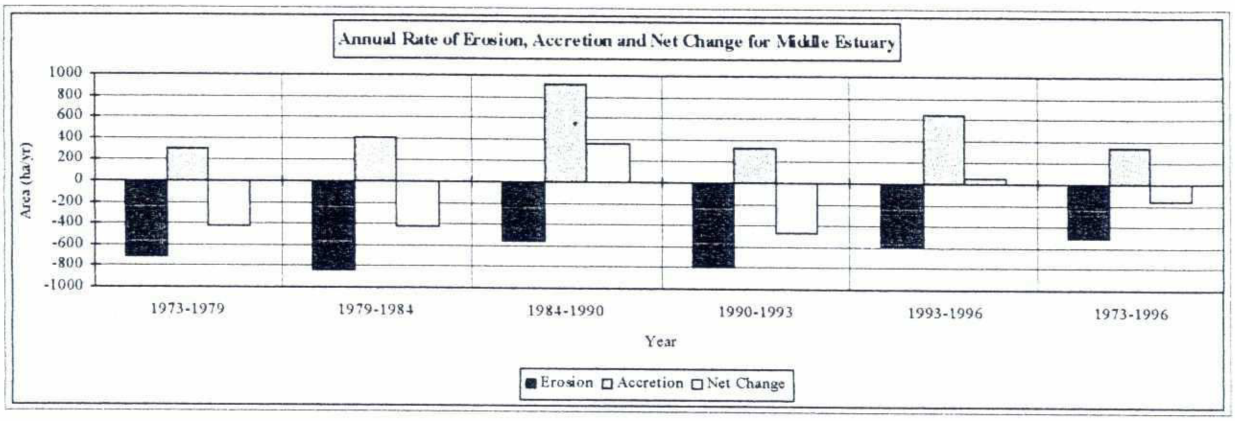
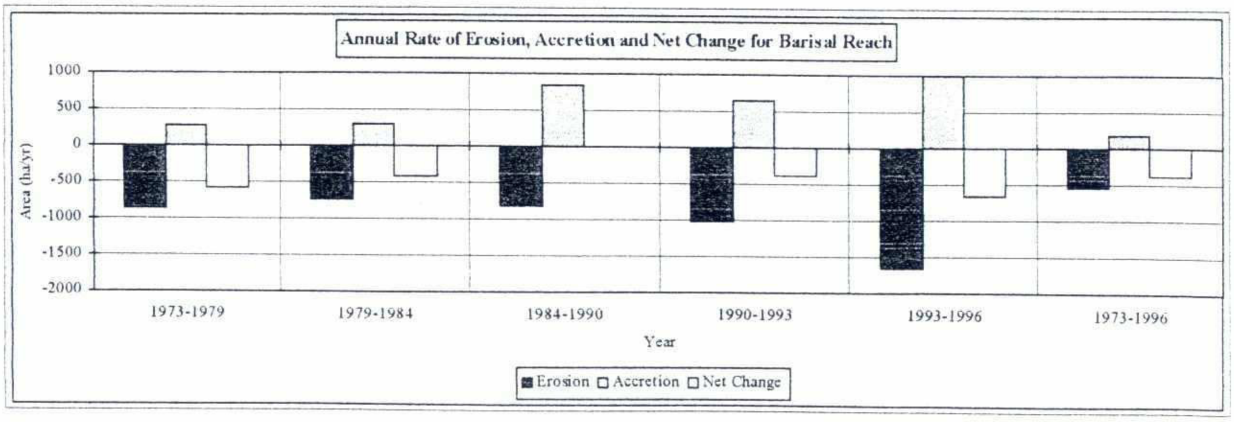


Figure 6.9 : Annual rate of change of land area in the period 1973/74 -1996 at Barisal area



Figures 6.8 (middle) and 6.9 (Barisal) illustrate the huge loss of land over the last 25 years due to widening and migration of the Shahbazpur and Hatia channel. Also the southwest coast of Sandwip island shows a distinct tendency of erosion over the last decade. During the same period Char Shahabani eroded completely and disappeared.

6.6 Shoreline migration

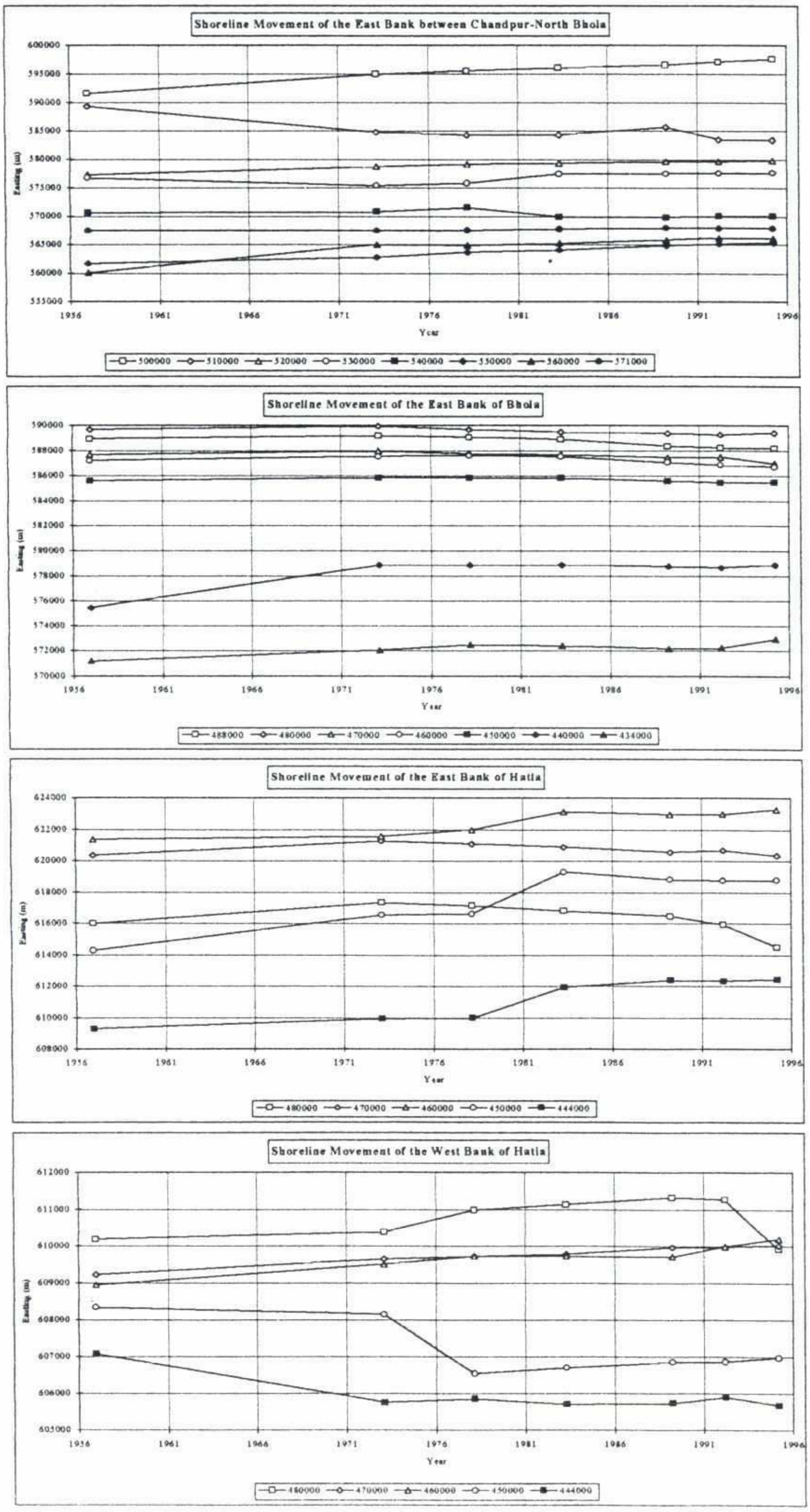
Studies of shoreline dynamics are used to establish the rate and distribution of shoreline erosion and accretion, trends of shoreline migration and patterns of overall shoreline movement. Areal photographs of 1956-1957 and satellite images from 1973 to 1996 were used to identify trends in the movement of the banklines. The following areas have been considered in detail:

- Chandpur and North Bhola
- Bhola - Manpura - Hatia
- Sandwip - Chittagong mainland

- Noahkali - Char Balua

To facilitate analysis, the positions for west and east banks were derived from about 200 transects spaced at 1,000 to 2,000 metre intervals as illustrated in Appendix F. The west and east bank positions of all transects were derived from the intersection of the transects with the banklines and stored in a spreadsheet. To identify trends in the movement of the shorelines, the eastings of the banklines were plotted against the years.

Figure 6.10 : Examples of the movement of the shoreline by year



In the area Noahkali - Char Balua, the trends in the movement of the shorelines were identified by plotting the northings of the banklines. The average rate of migration for each transect is estimated by linear regression of the bankline position over the period 1957-1996. On the east side of the Lower Meghna Estuary, retreat is indicated by a positive sign and accretion by a negative sign (see Appendix F). It is clear that for the west side the positive and negative signs refer to accretion and erosion, respectively.

6.6.1 Shoreline migration in the area Chandpur - North Bhola

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

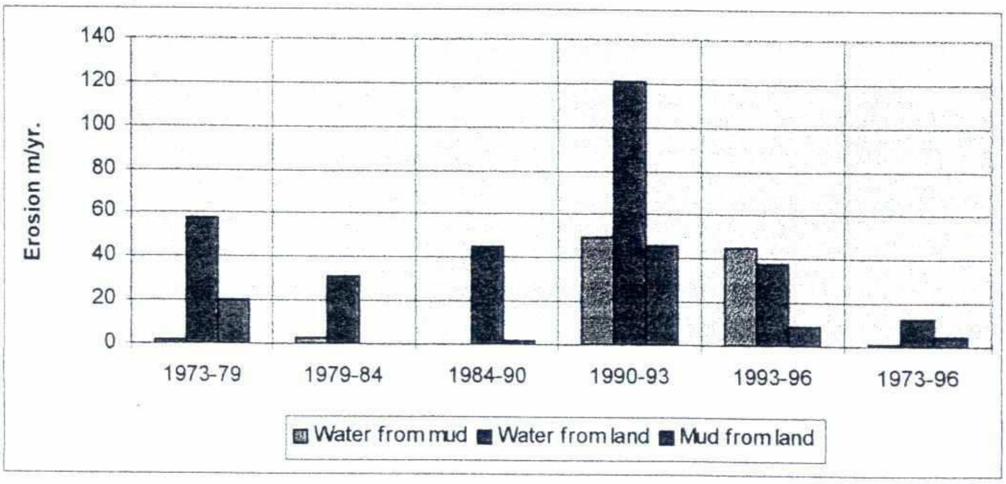
The average eastings for the west bankline moved about 4.8 km to the west between 1957 and 1996, while the east shoreline moved about 1.4 km to the east. Between 1974 and 1996 the east shoreline moved steadily eastward along the majority of its length. Only the areas between 508.000 N - 516.000 N and 533.000 N -545.000 N remained unchanged. Thus it might be concluded that these areas have been relatively stable over recent 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 220 metres per year. The areas correspond to embayments cut by flow deflected around growing bars and new island chars in the second order, east bank anabranch of the Lower Meghna river.

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 very rapid siltation. These peaks of rapid accretion corresponded with the shift of the main channel in an eastward direction which created new island chars on the west bank. The average accretion rate in the area between 533.000 N- 560.000 N) vary from 30 metres per year to more than 200 metres per year.

The history of shoreline shifting indicates that periods of slower than average retreat may abruptly end.

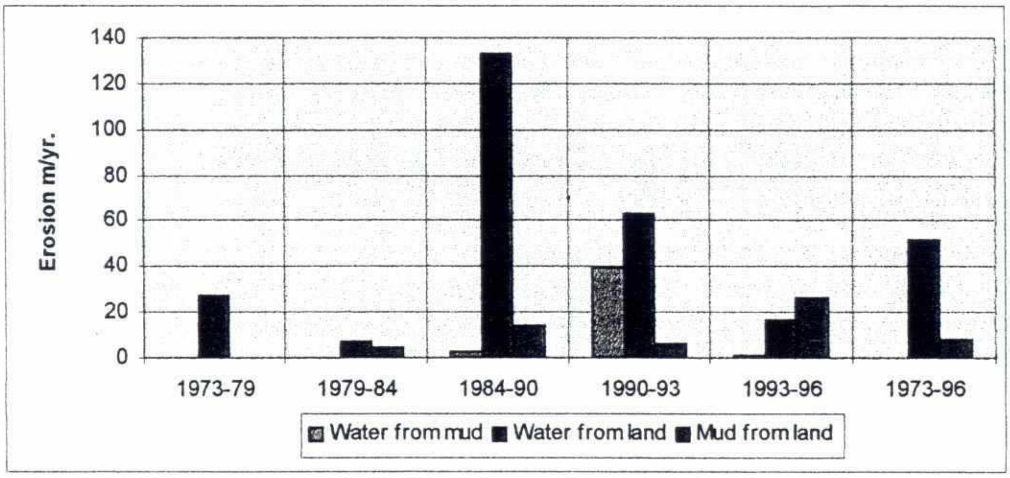
Figure 6.11 : Bankline movement rate near Haimchar



All data from the transects of the right shoreline indicate a net retreat of the shoreline to the west in the area between 488.000 N - 520.000 N. The rate and time trends differ in detail due to local influences such as changes in the growth or erosion of primary island-chars. The mean bankline movement rate in this area varies from 50 to 200 metres per year. The areas correspond to embayments cut by flow deflected around growing bars and new island chars near the west bank anabranch of the Lower Meghna river near Khorki. The rate of west bank erosion for northeast Bhola (around Khorki) is not uniform as shown in Figure 6.12 (see Appendix F).

The impact of high monsoon floods during 1987-1989 in generating accelerated shoreline retreat can be identified in nearly all transects. It can be concluded that the position of the shoreline is very moveable and sensitive to changes in hydraulic conditions.

Figure 6.12 : Bankline movement rate near Khorki



6.6.2 Shoreline migration in the Bhola - Manpura – Hatia area

The shoreline migration of the west bank of Hatia indicates a net retreat of the shoreline to the east. The rate of erosion varies between 5 to 35 metres per year. The east bank of Hatia is showing a long term trend of shifting in an eastward direction. The maximum bank erosion takes place at the northern head of the island. The average erosion rate is about 40 to 200 metres per year. All data from the transects indicate that the island migrates to the southeast.

The long term shoreline migration of Manpura shows a similar pattern to Hatia: erosion on the west bank and accretion on the east bank. The migration rate of the shoreline varies 1 to 30 metres per year at the west bank and from 2 to 20 metres per year the east bank. The movement of the island indicates a net long term shift to the southeast.

The small islands between Manpura and Hatia are relatively young islands which started to emerge during the 1970s and 1980s. These islands silted up very rapidly and extend in a southern direction. The dynamic behaviour of the shoreline of these islands over the last decades shows a natural tendency to shift to the south.

Nijhum Dwip is a relatively young island which started to emerge in the 1950s. During the 1970s and 1980s the higher parts of Nijhum Dwip silted up rapidly to about mean higher high water level. The coastline migration in recent decades shows a natural tendency to extend eastwards.

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

The shoreline migration of Bhola exhibits a long term trend of erosion. The long term bank erosion rate decreases slightly towards the south and varies from 10 to 150 metres per year.

The southern part of Bhola has a tendency to accretion with an accretion rate in the southern part of about 10 to 70 metres per year.

6.6.3 Shoreline migration in the Sandwip - Chittagong mainland area

The shoreline migration of the Chittagong mainland is showing a overall tendency to shift in westward direction. The migration rate increases towards the north. The rate varies form 10 to 200 metres per year. 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 been stopped due to coastal erosion protection measures.

The shoreline migration on the east and west banks of Sandwip exhibit a tendency to erode. The migration rate is about 10 to 150 metres per year. The shoreline development of the northern head of Sandwip showed a trend to erosion during the 1970s. During the 1980s and 1990s the movement of the shoreline has indicated a net trend of silting up rapidly to the northwards. Urir Char is a very dynamic island which tends to move to the northeast but whose southwestern part has a long term trend to erosion.

6.6.4 Shoreline migration in the Noahkali - Char Balua area

The shoreline development in the southern part of the Noahkali mainland over recent decades indicates a long term trend of accretion. The shoreline migration rates varies from 50 to 400 metres per year. Erosion of the shoreline can be recognised near Char Balua due to migration of the tidal channel northwards. The bank erosion rate varies from 200 to 500 metres per year.

6.7 Channel migration and channel geometry

6.7.1 Channel migration

It is observed that over the course of some years, a few channels in the project area have 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 the thalweg has also shifted and this was the most significant change observed within the channel systems. The thalweg is defined by the position of the maximum depth below MSL. It is important to know the position of the thalweg in the sense that, for example, it may sometimes be used in conjunction with the coastline migration rate to ascertain the setback distance of embankments in coastal areas and also to locate a navigation route for vessels that have a large draft.

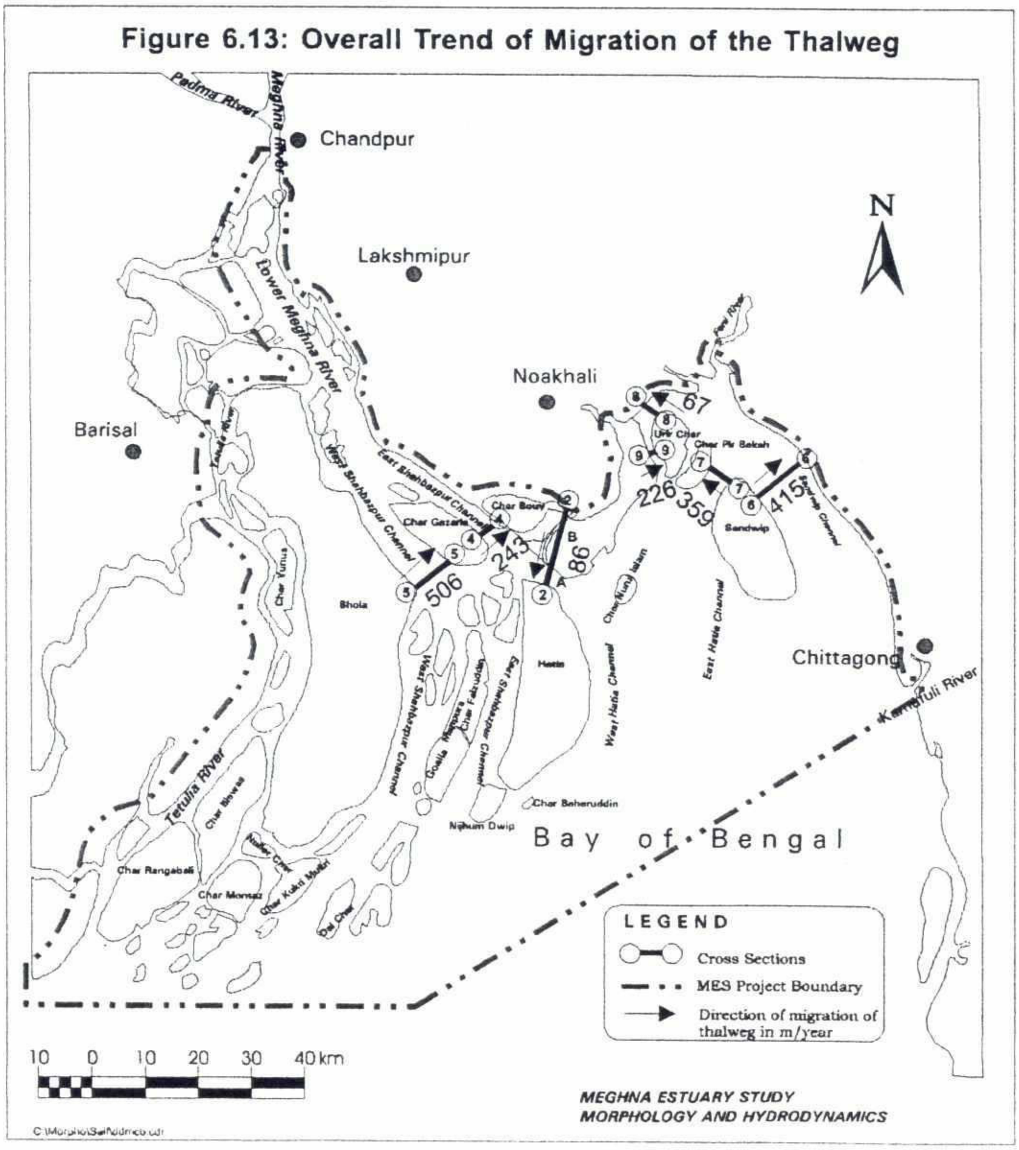
To identify trends and to estimate the migration rate of the thalweg, seven cross-sectional profiles in the project area were selected. These selected cross-sections which cover the area around Bhola-Hatia and the area around Urir Char-Sandwip have been profiled more than five times over the last 15 years. These two areas experience significant accretion and erosion due to the migration of the channels. The trend and migration rate of the thalweg for each cross-section is examined by plotting the position of the thalweg for each time period.

Figure 6.13 shows the overall trend of migration of the thalweg for the selected cross-section with arrows indicating the average rate and dominant direction of migration. The results of the analysis are presented in Table 6.3.

Table 6.3: Average migration rate of the thalweg

Cross-section	Period	No.	Average migration rate (metres/year)	Dominant direction
Bhola -Hatia				
2	1983-1990	7	86	towards Hatia
4	1983-1990	5	243	towards Char Bouy
5	1983-1990	6	506	towards Char Gazaria
Urir Char-Sandwip				
6	1981-1994	9	415	towards Chittagong mainland
7	1982-1994	11	359	towards Char Pir Baksh
8	1981-1994	8	67	towards Char Balua
9	1984-1994	9	226	towards Urir Char

Figure 6.13 : Overall trend of migration of the thalweg



The data of cross-section 2 over the period 1983-1990 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 86 metres per year. 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 243 metres per year.

The position of the thalweg in cross-section 5 indicates that the main channel has shifted from Bhola side towards Char Gazaria since 1985. The average rate of migration of thalweg towards Char Gazaria of about 506 metres per year indicating that the channel position is very unstable.

Cross-section 6, which connects Sandwip with the Chittagong mainland, has a regular shape and the bottom is nearly flat. Profiles show that the position of the thalweg is very moveable. The rate of migration of thalweg is about 226 metres per year towards the Chittagong coastline.

Since 1985 the thalweg of cross-section 7 shows a distinct migration north towards Char Pir Baksh. The rate of migration of thalweg towards Char Pir Baksh is 359 metres per year.

Data of cross-section 8 for the period shows the overall migration pattern of the thalweg is towards Char Balua but it shows a decreasing trend in its migration rate. The average rate of migration of thalweg is about 67 metres per year. The position of the thalweg on the Urir Char side (cross-section 9) indicates a net shift of the thalweg towards Urir Char. The average migration rate is about 226 metres per year. The analysis of the thalweg migration rates illustrate that the channel morphology and geometry in the selected areas are characterised by rapid and extensive changes over time and space. In general, it can be concluded that the position of the channel is very moveable and sensitive to changes in hydraulic and morphological conditions. Although the migration rates can differ a lot from year to year the long term migration rate will often indicate a more explicit trend.

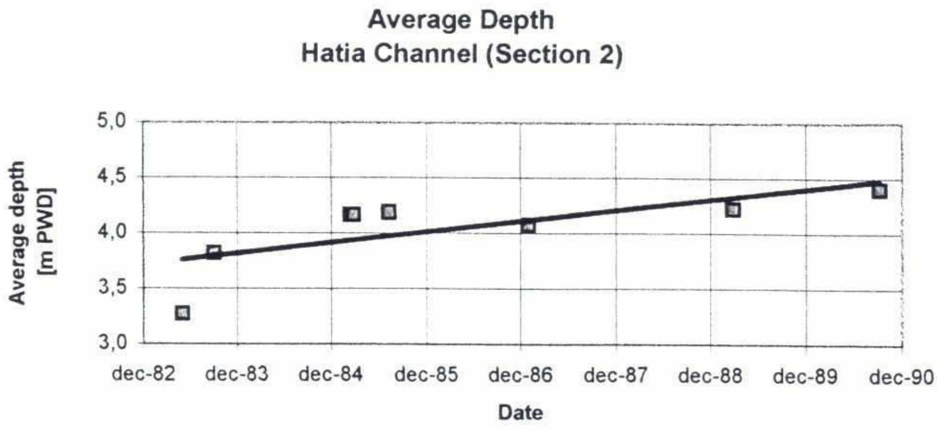
6.7.2 Channel geometry

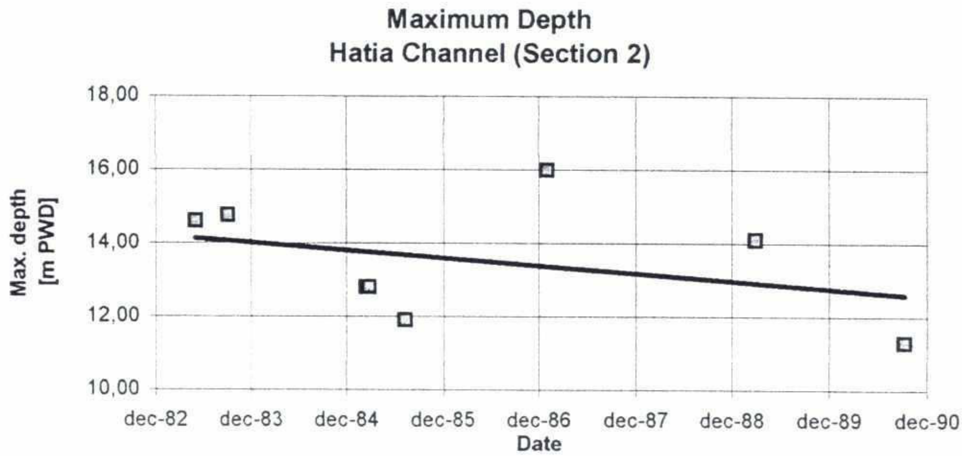
The cross-sectional data contain important information on channel characteristics and horizontal and vertical stability. In the present study seven cross-sections were selected for detailed analysis considering average and maximum depth and cross-sectional area. These selected cross-sections which cover the area around Bhola and Hatia and the area around Urir Char and Sandwip have been profiled more than five times over the last 15 years.

The cross-sectional area of the West Hatia channel at the tip of Hatia island shows a decreasing tendency during the last ten years (Figure 6.14). Over the same period the average channel depth has shown a tendency to increase slightly.

The cross-sectional area and the average channel depth of the East Shahbazpur channel between Char Gazaria and Noahkali mainland have shown a tendency to decrease slightly over the last two decades (Figure 6.15). The cross-sectional area of the West Shahbazpur channel shows a distinct trend to increase over the period 1981-1994. Over the same period the average channel depth decreases (Figure 6.16). The cross-sectional area between Sandwip and Chittagong mainland shows a distinct trend to increase over the period 1980-1994 (Figure 6.17). The cross-sectional area of the small channel between North Sandwip and Char Pir Baksh decreased slightly over the period 1981-1994 (Figure 6.18). The cross-sectional data for the channel between Urir Char and Noahkali mainland indicate that the maximum depth has increased from 2 metres in 1982 to 13 metres in 1994 (Figure 6.19). The cross-sectional area as well as the maximum depth of the cross-section Urir Char - Char Lakhi indicate a tendency to silt up rapidly (Figure 6.19).

Figure 6.14: Hatia Channel : Long term changes of the average and maximum channel depth and cross-sectional area over the period 1980-1994





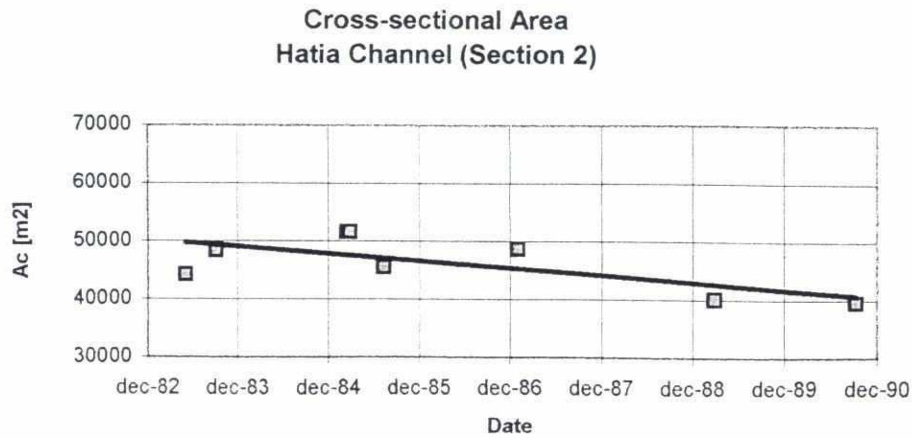
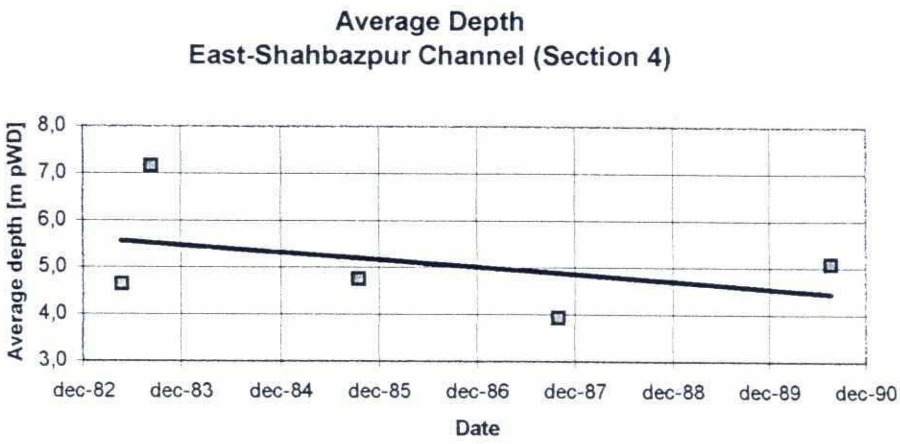
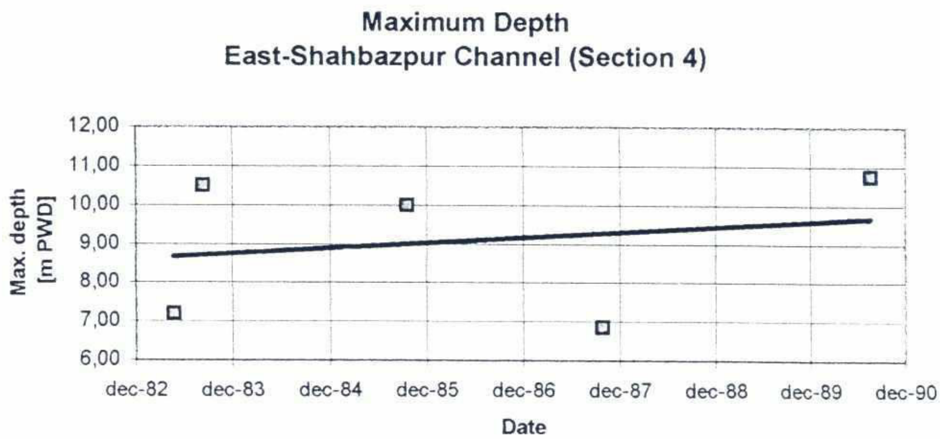


Figure 6.15 : East Shahbazpur Channel: Long term changes of the average and maximum channel depth and cross-sectional area over the period 1980-1994





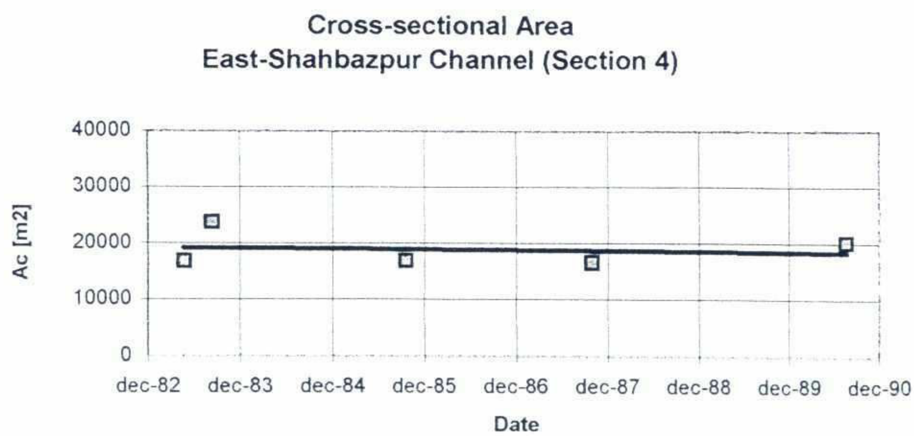
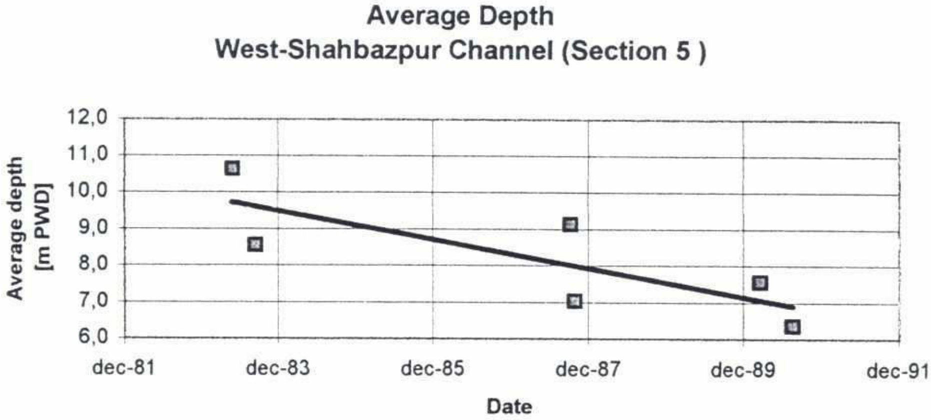
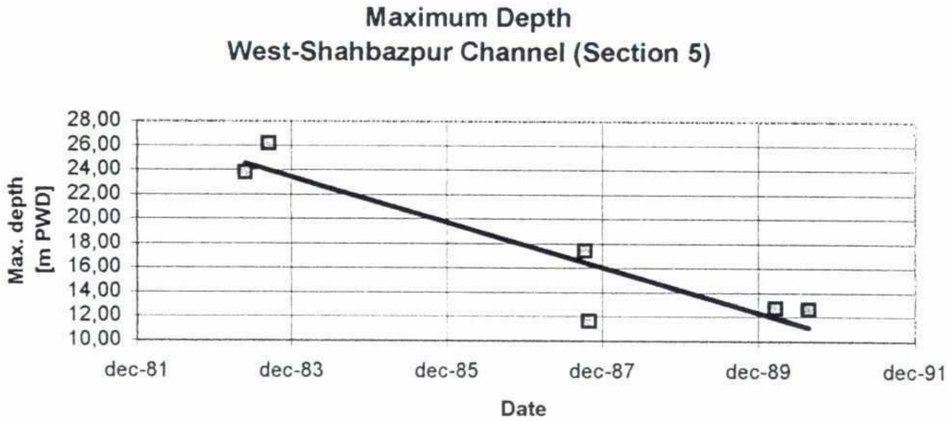


Figure 6.16 : West Shahbazpur Channel: Long term changes of the average and maximum channel depth and cross-sectional area over the period 1980-1994





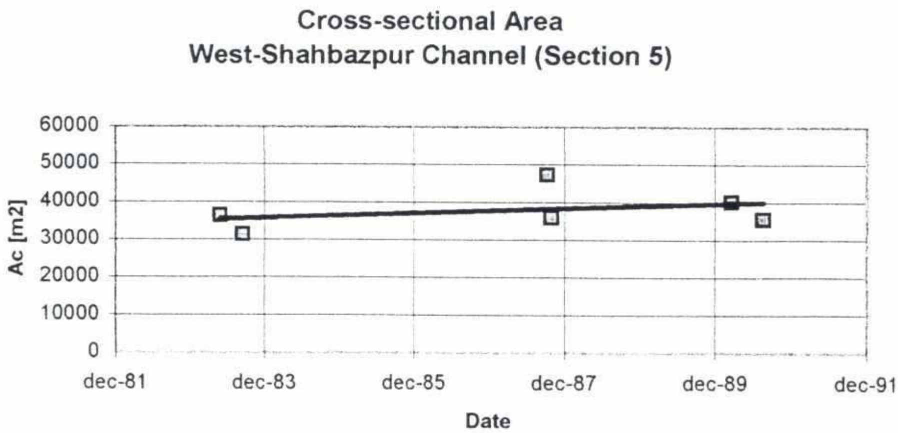
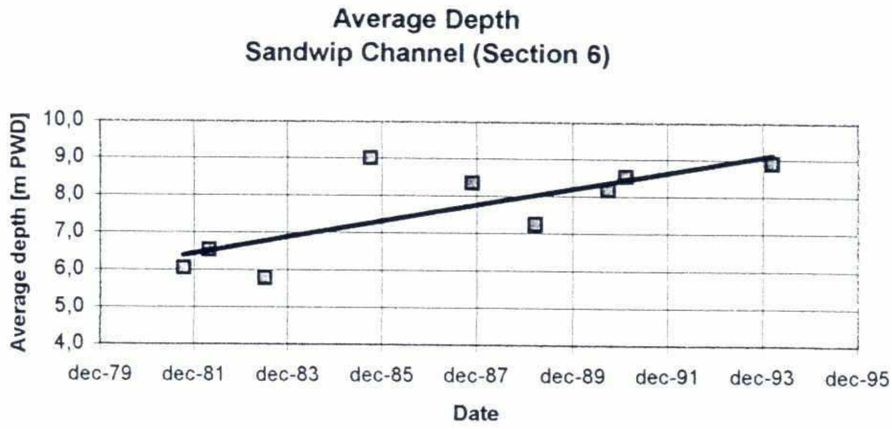
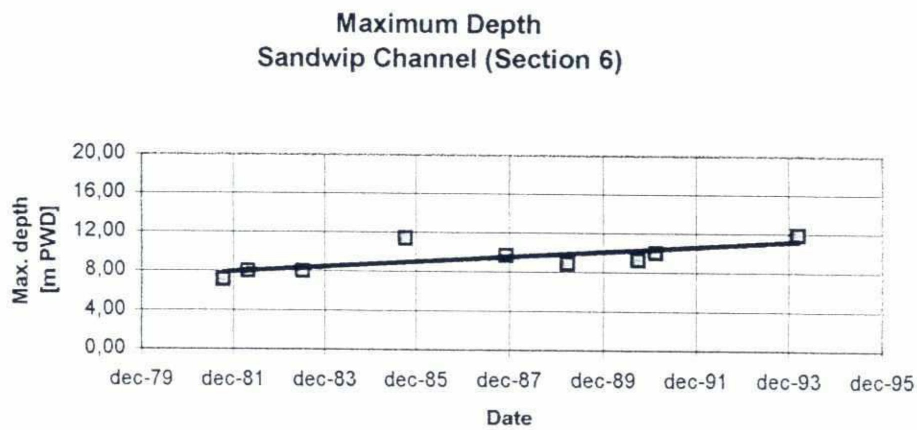


Figure 6.17: Sandwip Channel: Long term changes of the average and maximum channel depth and cross-sectional area over the period 1980-1994





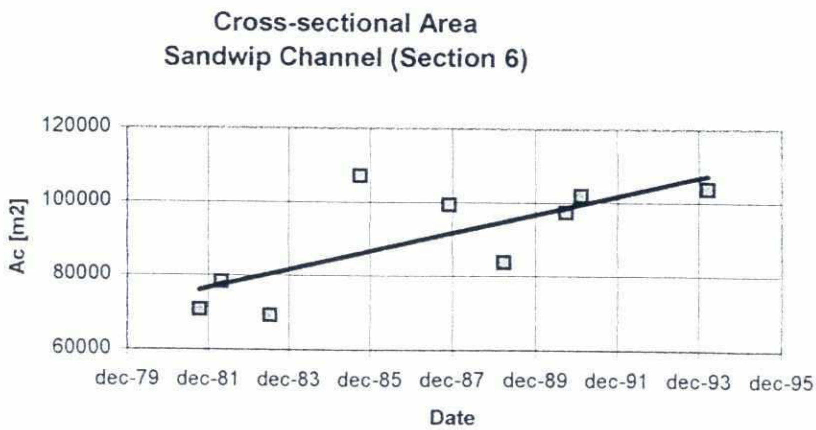
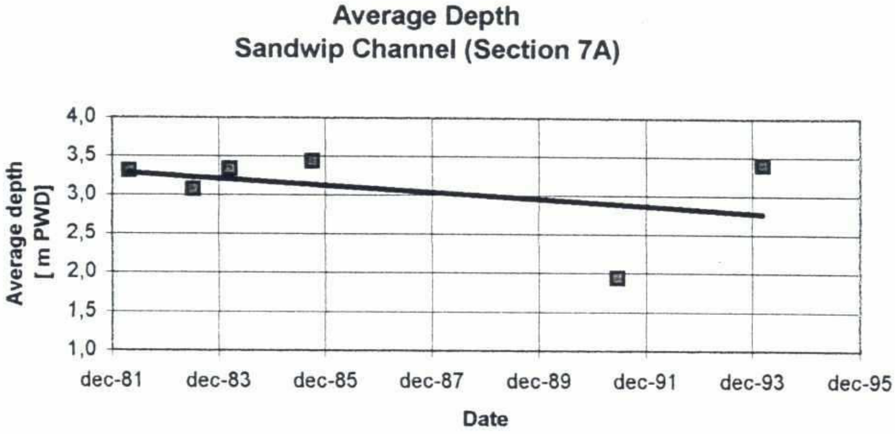
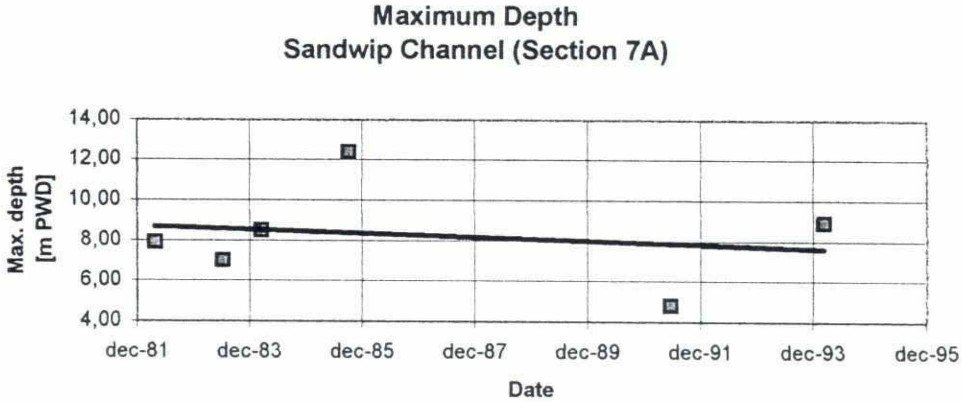


Figure 6.18 : Sandwip-Urir Char Channel: Long term changes of the average and maximum channel depth and cross-sectional area over the period 1980-1994





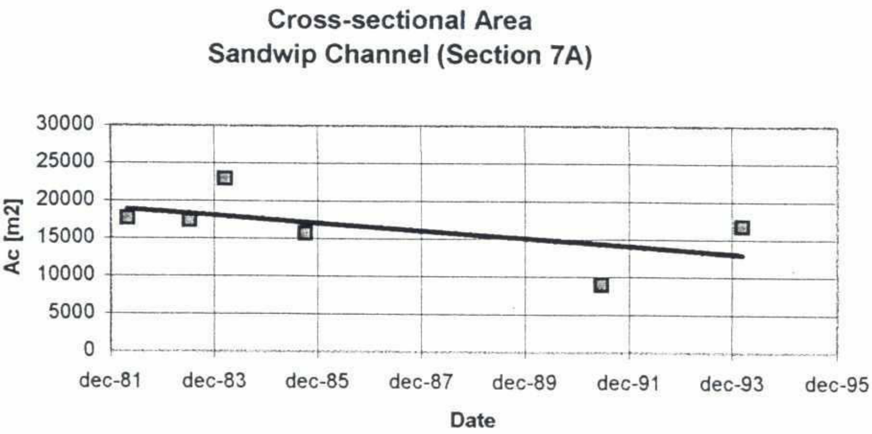


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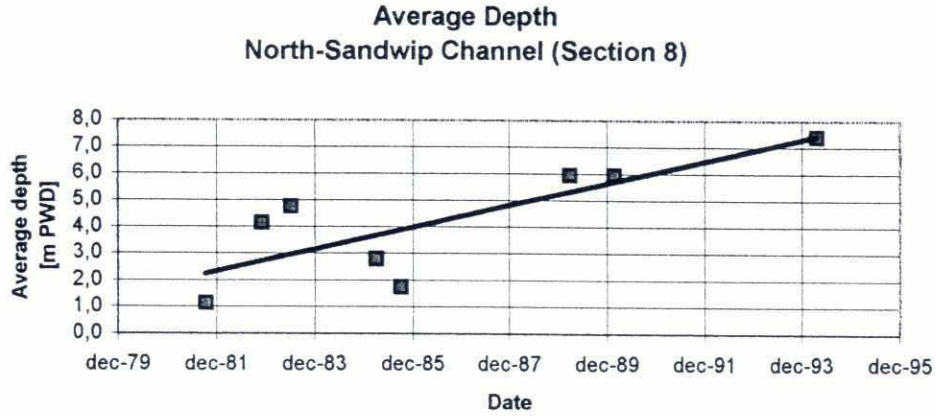
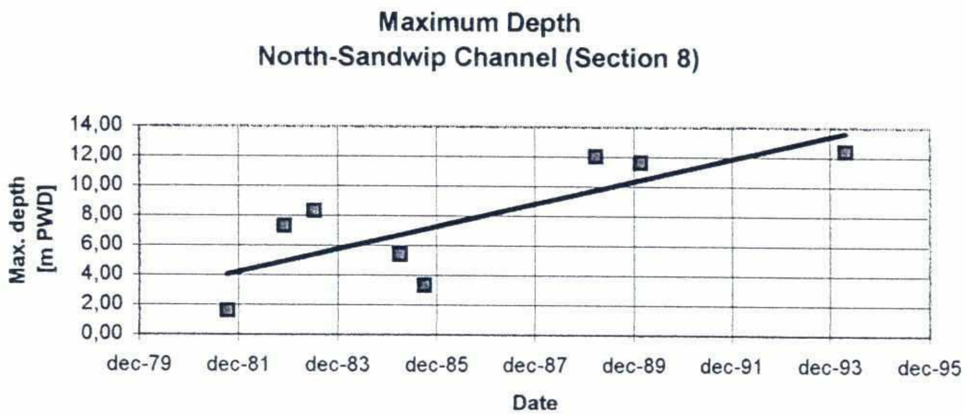
Figure 6.19: Urir Char - Noahkali mainland channel: Long term changes of the average and maximum channel depth and cross-sectional area over the period 1980-1994





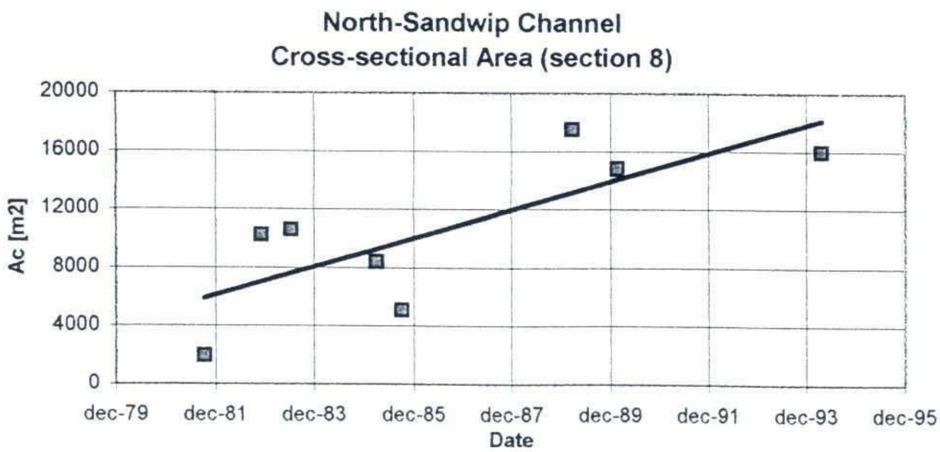
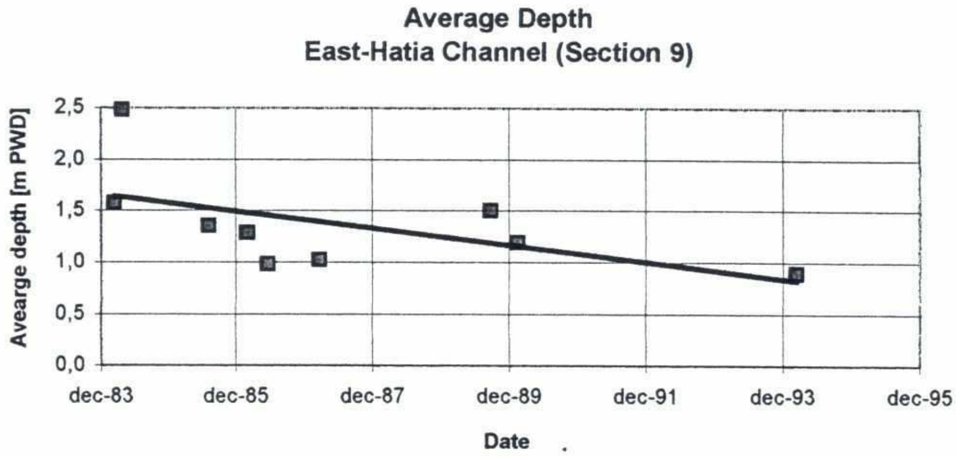
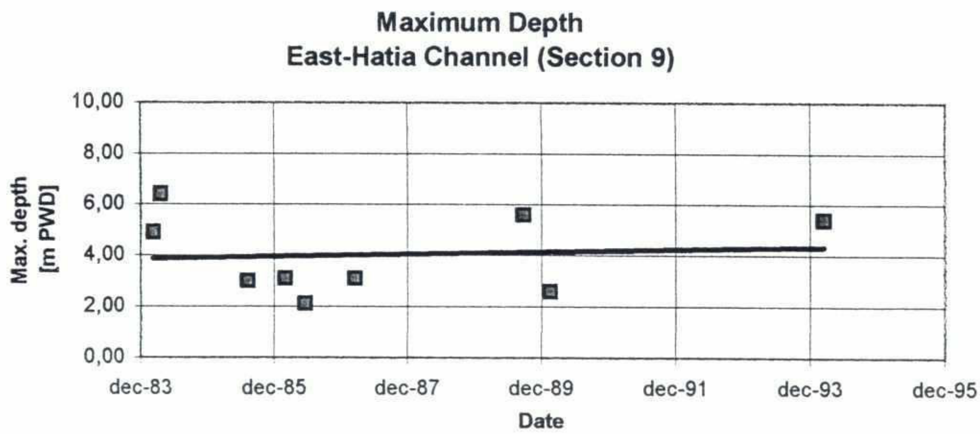
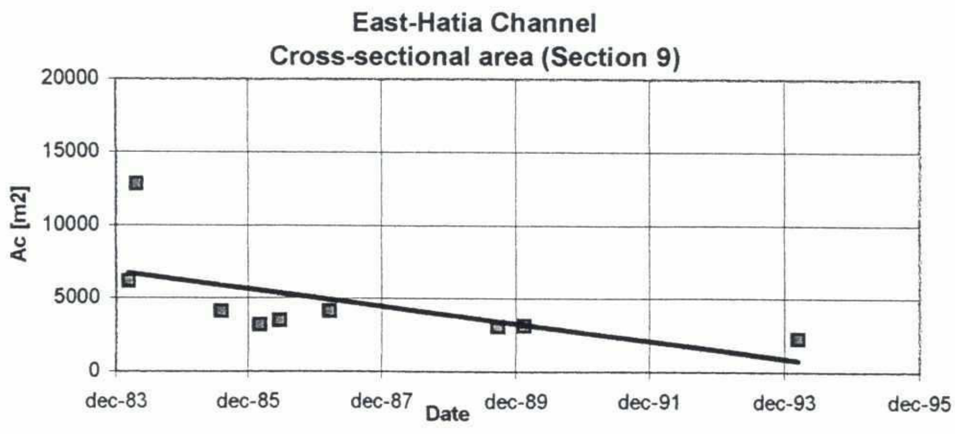


Figure 6.20 : East Hatia channel: Long term changes of the average and maximum channel depth and cross-sectional area over the period 1980-1994







7. SEDIMENT TRANSPORT AND SEDIMENT BUDGET

7.1 Long term fluvial sediment transport rates

The Lower Meghna estuary is the route by which sediment is transported from the major rivers to the Bay of Bengal. On the way down the rivers the grain size distribution of the sediment becomes altered by continual deposition, re-erosion and transport. Much of the coarser sediment becomes trapped on the flood plains 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.

Sediment forms a crucial control in the estuarine processes and evolution of the Lower Meghna Estuary. Within the Lower Meghna Estuary suspended sediment concentrations are generally high, the particles are fine, cohesive, and prone to flocculate and they are richly organic.

7.2 Sediment characteristics in the lower meghna estuary

To get insight in the sediment characteristics along the Lower Meghna Estuary area more than 450 samples of bed material were collected by MES. The sample locations are shown in Figure 7.1.

In the laboratory the granulometry of the samples was determined. The results of the MES survey shows that the bed consists of fine sand with considerable silts (e.g. silt 20-50%) and a median bed material grain size varying from 16-250 μm (Figure 7.2).

Figure 7.1 : Locations of the bed samples

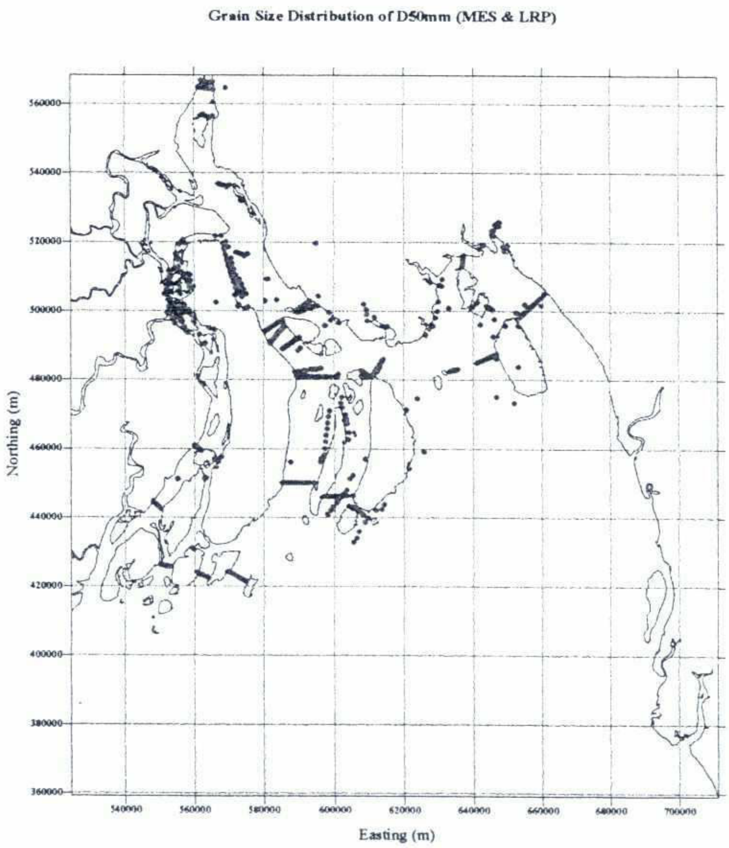
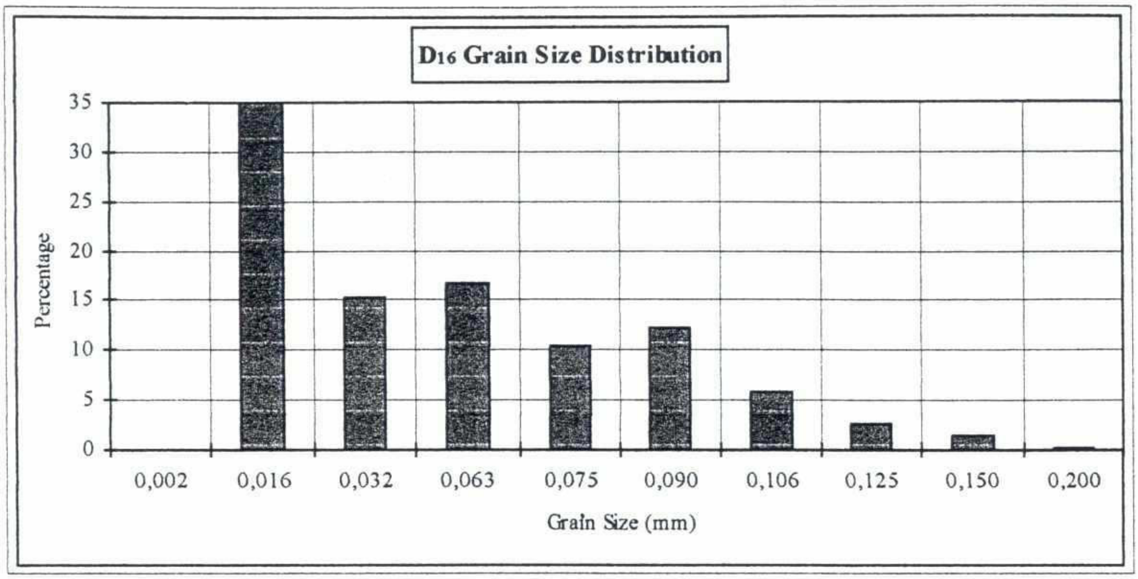
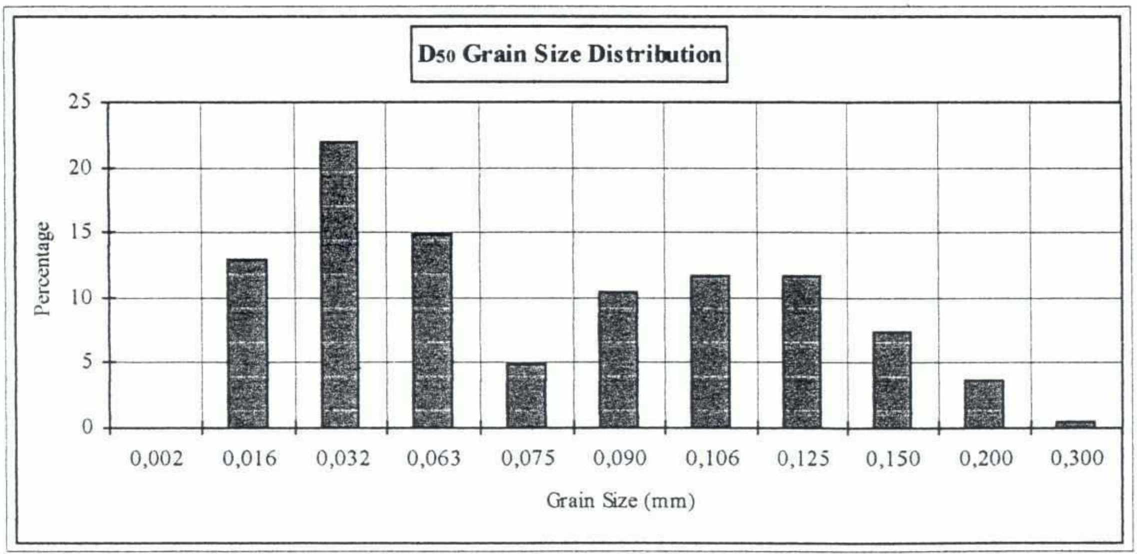


Figure 7.2 : Histogram of the D16, D50 and D84 characteristics of the bed material grain size





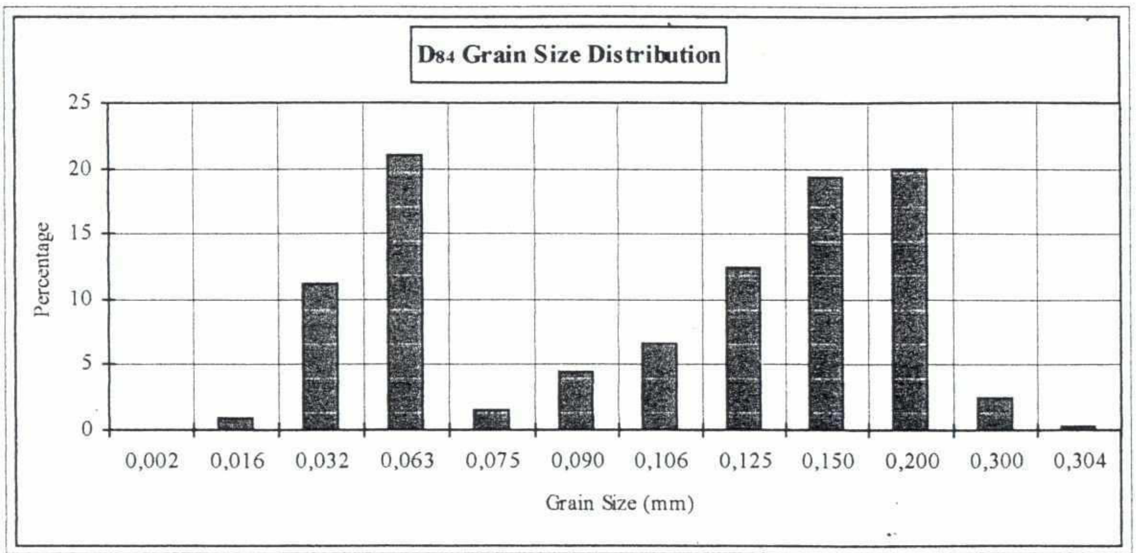
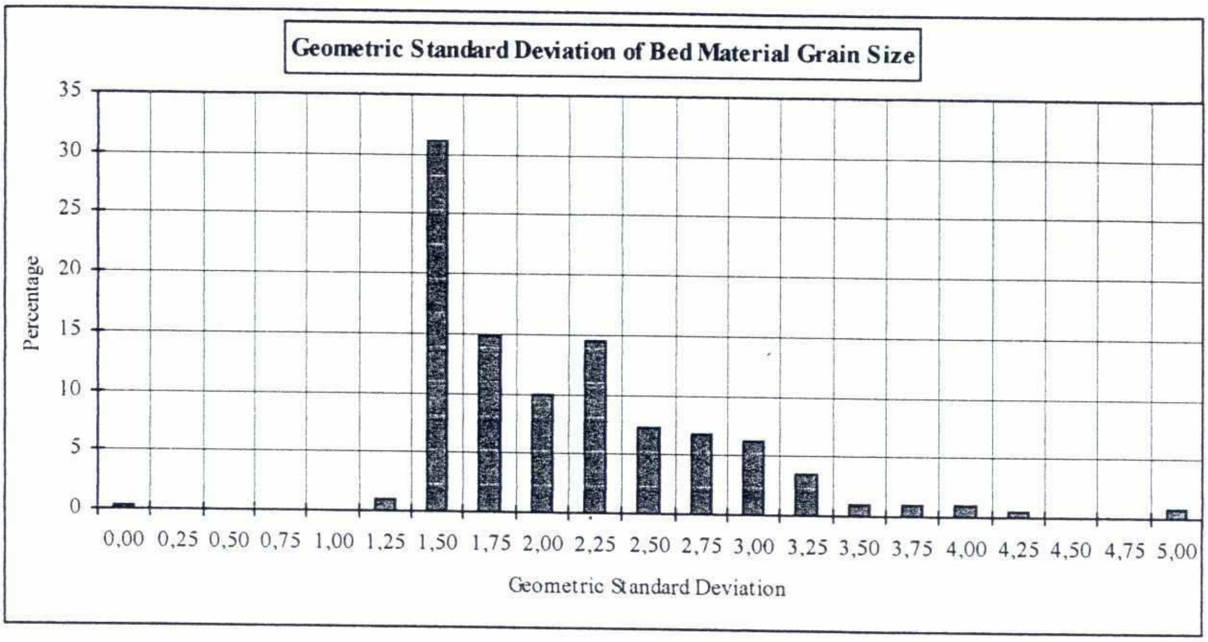


Figure 7.3 : Histogram of the geometric standard deviation of the bed material grain size



The geometric standard deviation varies form 1.50 to 3.25, indicating a rather uniform grain size distribution (Figure 7.3).

The results for the median bed material in the Lower Meghna Estuary 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.

The variation and geometric standard deviation of grain sizes in the downstream direction vary along the river. There is a trend to finer grain sizes in the downstream direction. Following Hack (1957, Leopold et al., (1964) described the exponential decrease of grain size along rivers that is due mainly to abrasion and to a less extent due to selective transport. The general form of this type of empirical equation is:

$$(D50)_x = (D50)_o * e^{-\beta x}$$

where,

$(D50)_x$ Characteristic grain size at a distance x (mm)
$(D50)_o$ Characteristic grain size at the origin (mm)
x Distance from the origin in a downstream direction (km)
β Downstream fining rate of the grain size (km^{-1})

Figure 7.4 shows the average grain size (D50) along the Jamuna and Lower Meghna Estuary in a downstream direction. The exponential regression line of the characteristic grain size indicate that the downstream fining rate coefficient (β value) along the Jamuna - Lower Meghna Estuary is about 0.0027 km^{-1}.

The results indicate that the bed samples with a high silt and clay content can be found in the shallow areas between Hatia and Sandwip (Figure 7.5).

Figure 7.4 : Downstream fining rate along the Jamuna and Lower Meghna Estuary.

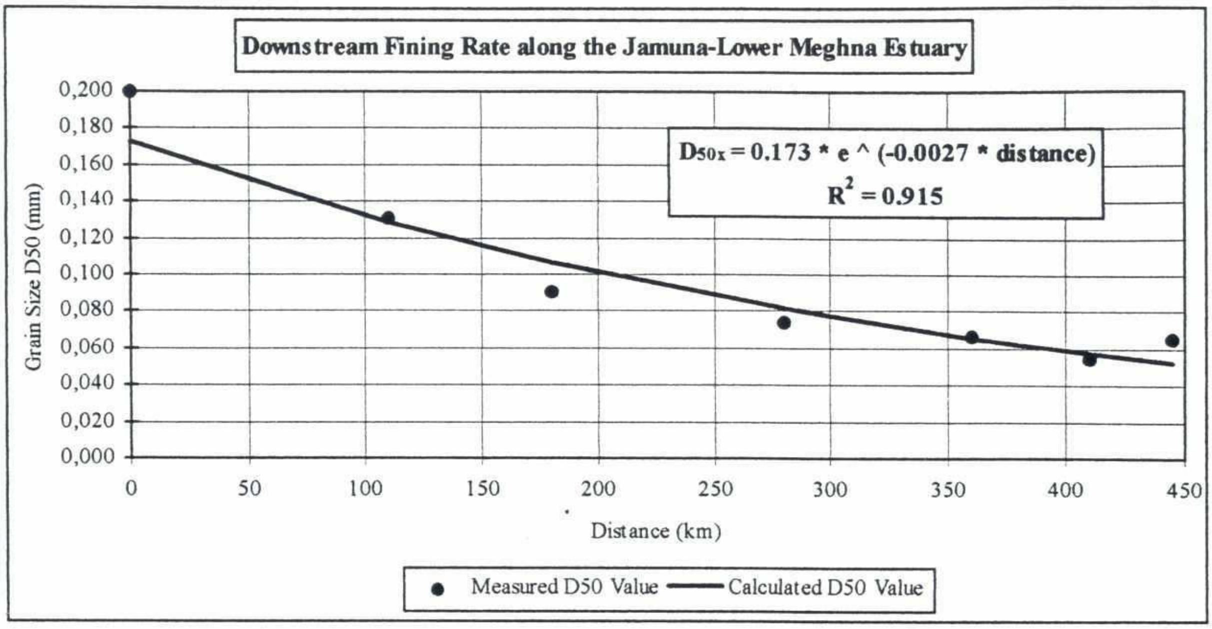
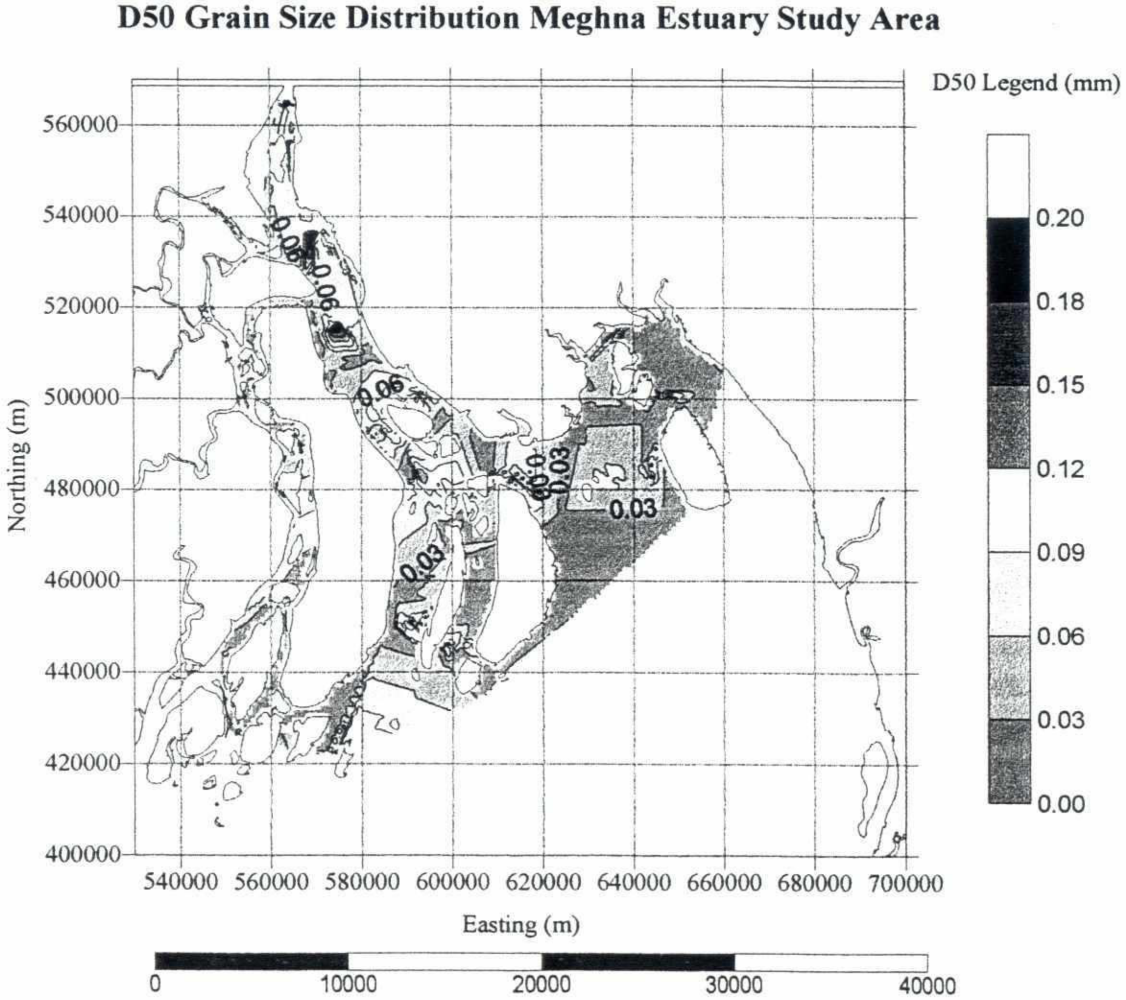


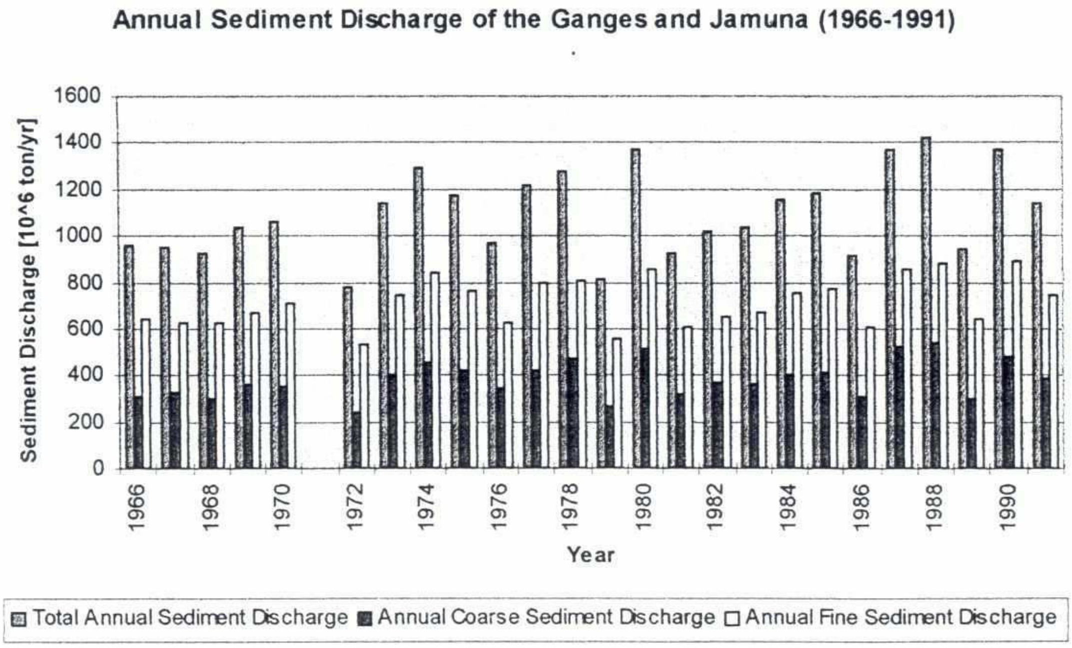
Figure 7.5 : Spatial distribution of the D50 grain size



7.3 Long term river borne sediment inflow

The long term 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. The sediment budgets of these major rivers dominate the river borne sediment inflow in the Study area at Chandpur. 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) were used to characterise the long term river borne sediment inflow at Chandpur. Figure 7.6 shows the annual sediment discharge at the stations Hardinge Bridge and Bahadurabad.

Figure 7.6 : Annual sediment discharge of fine and coarse material of the ganges and Jamuna (1966-1991)



Source: FAP 24

The averaged total annual sediment discharge of the Jamuna and Ganges over the period 1966-1991 is about 1,100 million tons per year (Figure 7.7). About 70% of the sediment discharge consists of fine sediment. The sediment discharge of the Meghna is negligible compared to the Jamuna and Ganges. The sediment discharge at the Hardinge Bridge and Bahadurabad stations is strongly related to the river discharge and the availability of the sediment. The morphological development of the Lower Meghna estuary will respond to the river borne sediment inflow.

The observed morphological changes derived from the time series of satellite images over the period 1973 to 1990 and the annual sediment discharge indicate qualitatively that the net gain of land is related to the amount of river borne sediment discharge. During periods of high river borne sediment discharge, the net gain of land and intertidal areas is higher than during periods of low river borne sediment discharge (see Figure 5.3).

Figure 7.7 also shows that during periods of relatively low river borne sediment discharge the dominant trend of land formation can reverse into an overall trend of erosion. More study is needed to verify this qualitative causal relationship and to understand the mechanisms behind it.

Figure 7.7a : Averaged annual sediment discharge and standard deviation of the ganges and Jamuna

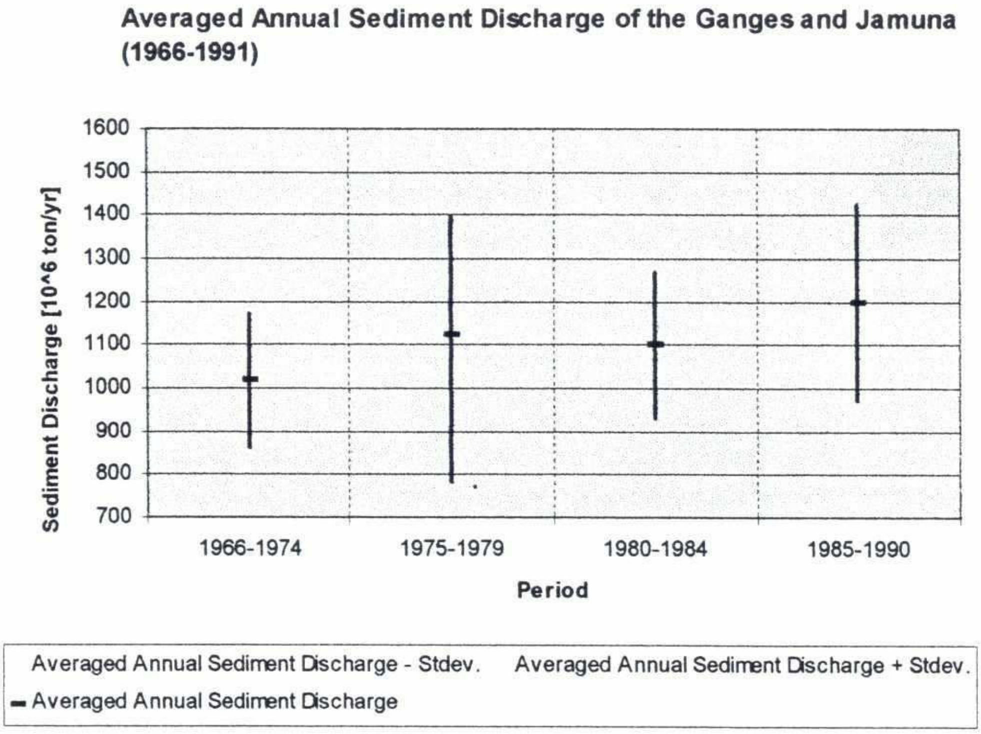
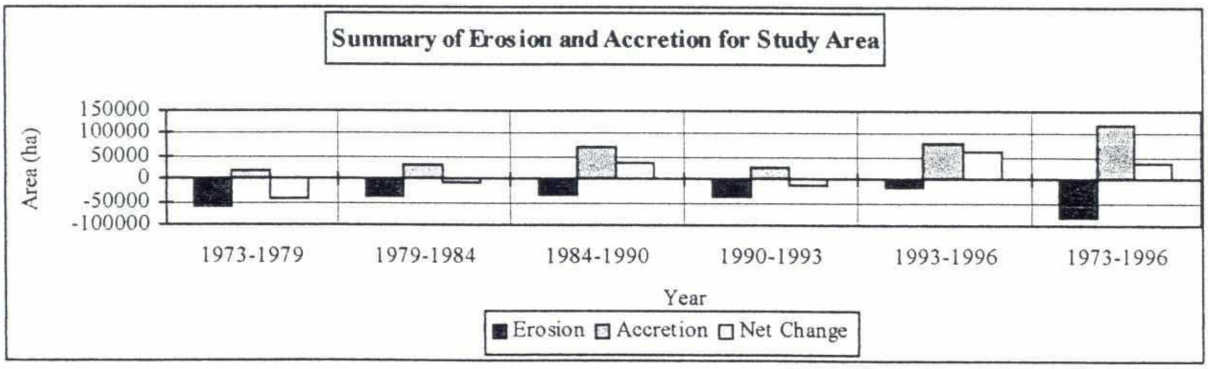


Figure 7.7b : Summary of erosion and accretion for the study area for selected satellite imageries



7.4 Sediment concentration

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.

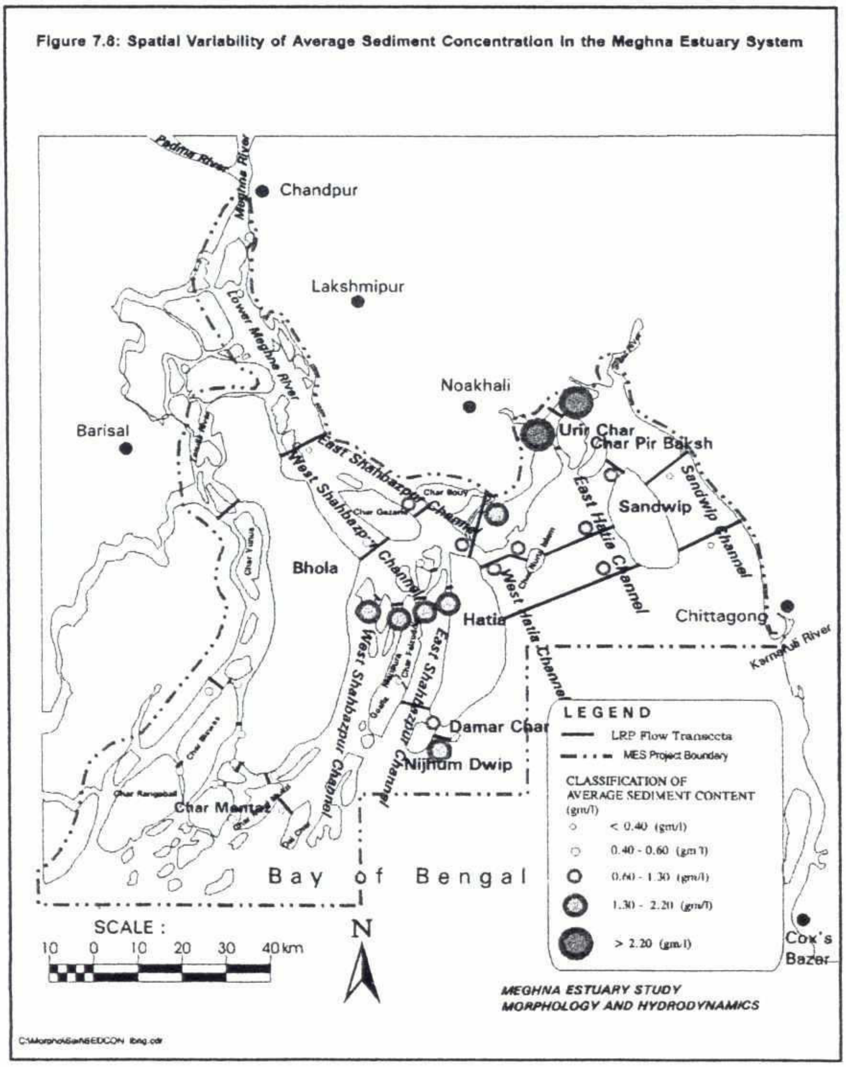
In order for the flow to transport fine sand and silt the velocities have to exceed critical values. The threshold for suspension of fine sandy grains from a flat be can be considered to occur at about $u_* \sim 0.8\ w_s$, where u_* is the friction velocity and w_s is the settling velocity (Perillo, 1995). Generally it can be said that grains less than about 150 μm will go into suspension immediately they begin to move. For grains above about 150 μm movement as bed load occurs first, and suspension does not take place until higher velocities. The threshold of bed load movement for a flat bed can be approximated by $u_*^2 \sim 40\ D$, where u_* is in cm/s, and D is the grain diameter (mm) (Perillo, 1995).

Sediment concentration measurements at different heights in the water column show that the sediment concentration near the bottom is slightly higher than at the surface. This indicates that the major part of the sediment transport is suspended material and vertically well mixed. The spatial variability of the depth averaged sediment concentration in the Lower Meghna Estuary System at dry season is shown in Figure 7.8. The maximum depth averaged sediment concentration varies between 0.5 - 9 grams per litre. Data shows that the maximum concentration can be found near the Urir Char - Char Balua area and the 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 maximum sediment concentration coincides approximately with the zone of salinity intrusion. The lower limit lies at approximately the 10-20 metre 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 the turbidity maximum influences almost the entire estuary during the dry season.

Figure 7.8 : Spatial variability of average sediment concentration in the Meghna Estuary System



7.5 Sediment budget

For the long term development of the coastal area it is of utmost importance to know how big a 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 discharge can be deposited in the channels and on the tidal mudflats, mangroves and salt marshes, in this way reducing depth; on the other hand erosion of the bottom can also develop, whereby sediment is picked up and transported. Available bathymetric data over the last ten years have been used to calculate the change in sediment volume in four selected areas. The calculations are based upon interpolated depth values using 100x100 metre grid squares. The results are shown in Table 7.1

Table 7.1: Net accretion rate in four selected areas

Area	Period	Accretion (10^6 m^3)	Erosion (10^6 m^3)	Total area (km^2)	Net change (metres/year)
North Bhola- Char Gazaria	1986-1992	131	272	68	(0.3 – 0.4)
Manpura – South Hatia	1987-1997	197	115	139	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
Urir Char – Char Balua	1990-1994	302	157	247	0.1 - 0.2

Note: (....) = negative value

The sediment budget in the area around North Bhola - Char Gazaria is related to migration and widening process of the Shahbazpur channel. The channel is very moveable and sensitive to changes in hydro-morphological conditions. Over the period 1986 - 1992, the area shows a net total erosion of 141 million cubic meters. The net erosion rate is about 0.3 to 0.4 metres per year. The net quantities are small compared with the total erosion and accretion amounts.

The sediment budget in the area around Manpura - South Hatia shows a slight positive trend over the period 1987-1993. The net sedimentation rate is about 0 - 0.1 metres per year. The morphological development is influenced by migration of the main channel in eastward direction and erosion of the west bank of Hatia.

A distinct trend of sedimentation can be recognised in the area around Nijhum Dwip - Damar Char. The net sedimentation rate is about 0.1 to 0.3 metres per year.

The sediment budget in the area Urir Char - Char Balua shows a distinct trend of sedimentation. The net sedimentation rate is about 0.1 to 0.2 metres per year. The channel around Urir Char - Char Balua is very moveable. The channel tends to migrate to the north. The sediment concentration is very high (1-9 gram per litre) compared to the net sedimentation rate. A significant proportion of the sediment is suspended material. The relatively low net sedimentation rate might indicate that the local high energetic macro-tidal flow combined with high tidal velocities is capable of maintaining high concentrations in the water column.

7.6 Sediment transport rates

Erosion and deposition in estuarine and coastal areas are characterised by the spatial variation in sediment transport, in accordance with the non-linearity of the sediment transport formula which describes the relation between the flow characteristics and the quantities of the bed material being moved. For general application in morphological studies, either by numerical analysis or by scale modelling, it is effective to use a schematised sediment transport formula in a form which can be defined as the sediment transport per unit width as a function of the flow velocity to the power 'n'. The exponent 'n' depends on the Shield parameter, which is a d2

dimensionless shear stress parameter. In general, the power 'n' varies between 2 and 5 or even higher. The normal schematised sediment transport formula is:

$$s = f\,|u|^n$$

where

s is volumetric rate of sediment transport per unit width
f is function of sediment - and fluid characteristics
u is depth averaged velocity
n is number varying between 2 and 5.

In this study, the sediment rating curve produced from the relationship between the discharge and the sediment transport measured in a transect will be discussed. This curve is also an exponential function. The general equation is:

$$S = A \,.\, Q^B$$

where

S is suspended bed material transport in kg/s
Q is discharge in m^3/s
A and B are coefficients

The value and dimension of the constant A depends on the unit of the suspended sediment transport:

S in tons/day	: $A = 86.4\ 10^{+6}\ (m^3/s)^{1-B}$
S in kg/s	: $A = 1\ (m^3/s)^{1-B}$
S in m^3/s	: $A = 2.65\ 10^{+3}\ (m^3/s)^{1-B}$

To examine the magnitude of the exponent 'n' of the flow velocity in sediment transport prediction formulae more than 1300 sets of field data on sediment and discharge measurements were selected. These data were collected during pre- and post-monsoon for the period 1985-1994. The selected sets of field data cover the entire Meghna Estuary Area. The grain size of the sediment is limited to the suspended sediment i.e. greater than 10 micron.

The sediment rating curve for the Meghna Estuary study area has been estimated by a linear regression of log-transformed sediment transport and discharge data. The relationship obtained for the entire Meghna Estuary Study area is shown in Figure 7.9, and can be expressed as:

$$S = 0.9872\ Q^{1.007} \qquad r^2 = 0.703$$

where

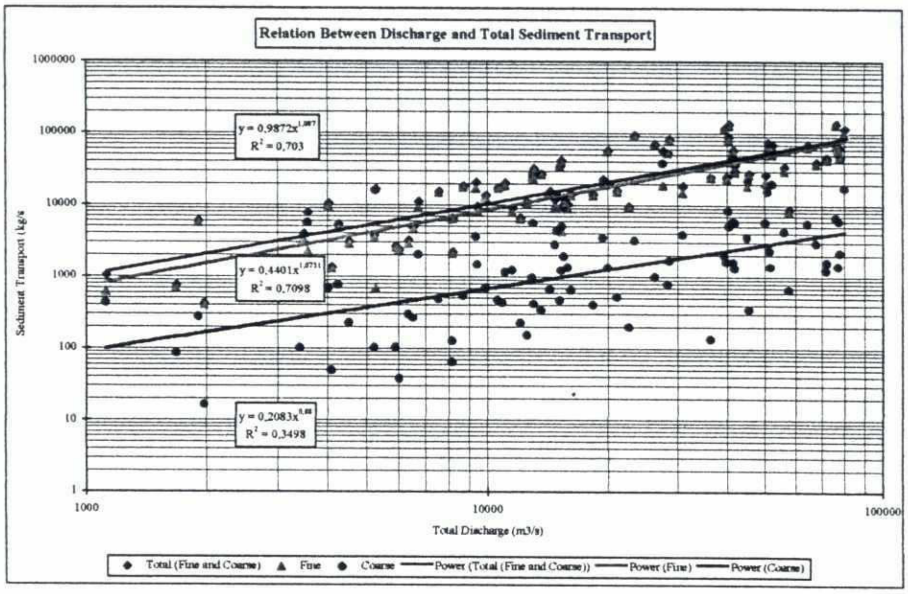
S = total (coarse) suspended sediment transport (kg/s)

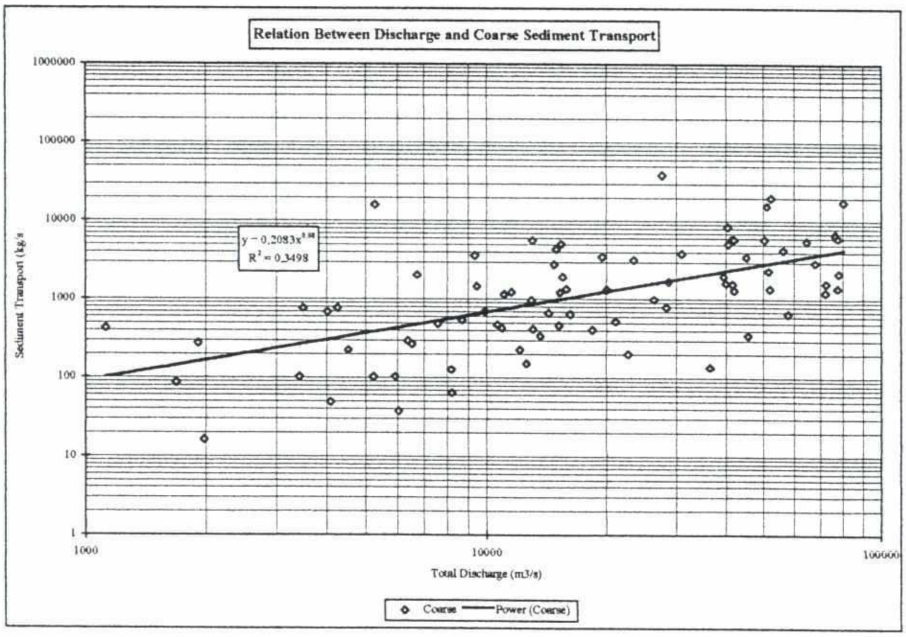
The coefficients A and B of the sediment rating equation for all transects were estimated. Figure 7.9 indicates that the sediment transport rating curve is independent of flood or ebb conditions. This might indicate that the sediment is very mobile.

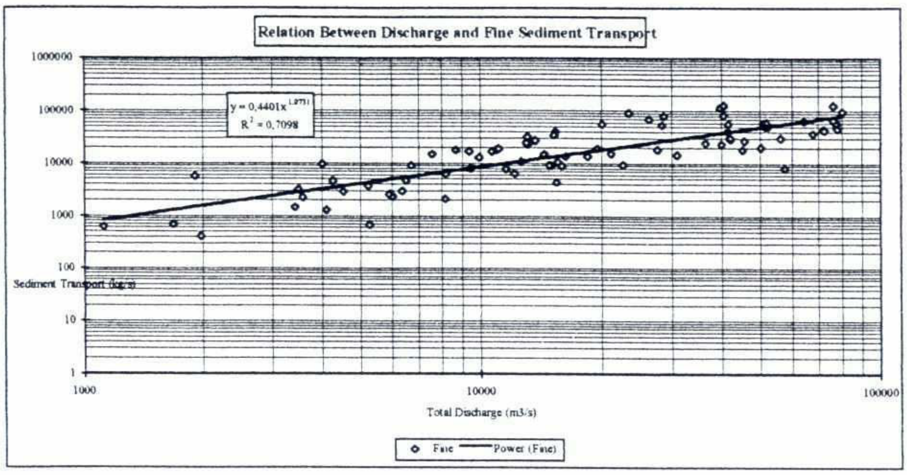
The results of the analysis show that the value of B for the transects varies between 0.9 and 1.5. The exponent found in the above formula is relatively low and indicates a small than expected increase in sediment transport with the increase of discharge. The low value of the exponent agrees with the values found for the rivers of Bangladesh (FAP 24).

A explanation for the low value in the sediment transport estimator is not yet found. One reason could be that during an ebb-flood tidal cycle a steady state situation between sediment transport and hydraulic conditions is not reached (or occurs only for a short while). Further investigations are needed to explain the low value of the exponent. Since most of the data are collected during the dry season it is also uncertain that these findings will be valid under monsoon conditions.

Figure 7.9 : Sediment rating curve





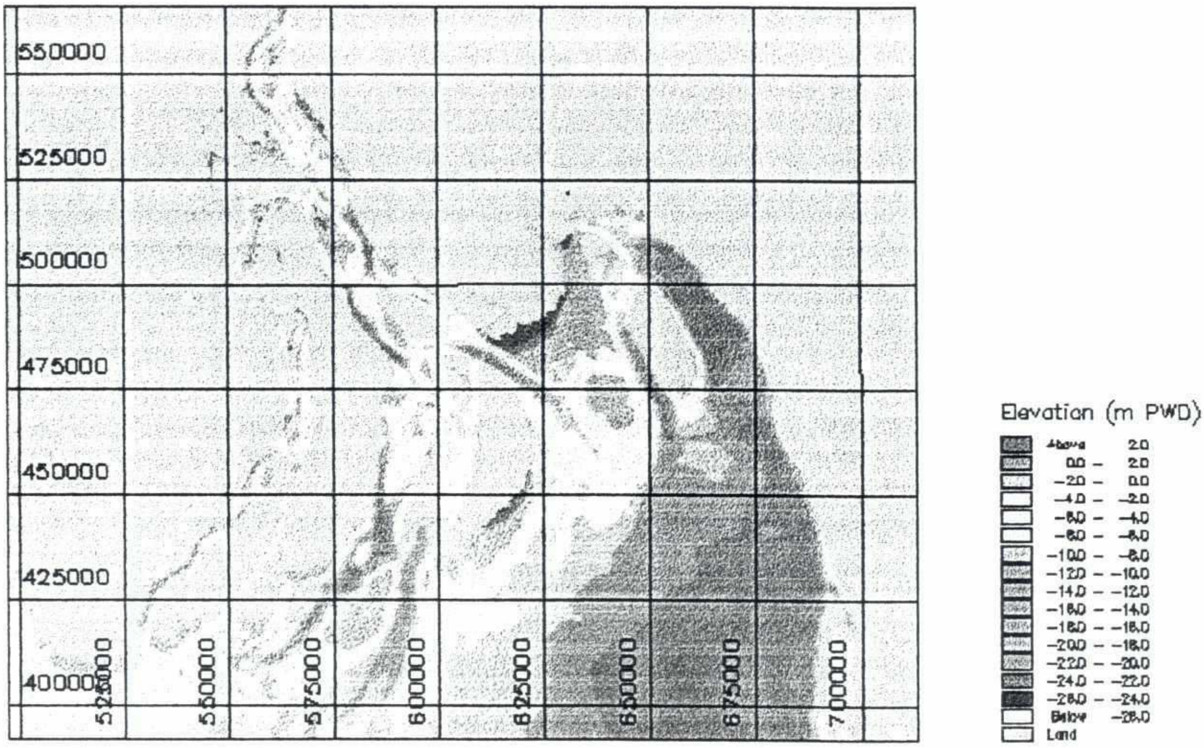

Relation Between Discharge and Fine Sediment Transport
y = 0,4401x
R² = 0,7098
1000000
100000
10000
1000
100
10
1
Sediment Transport (kg/s)
1000
10000
100000
Total Discharge (m3/s)
Fine
Power (Fine)

8. HYDRAULIC MODELLING

8.1 Introduction

As a part of MES, a numerical hydraulic model was set up (Figure 8.1). It is based on planform, bathymetry and calibration data from 1996-97, which have largely been produced by MES. The model can describe water levels, flow rates and current velocities, salinities, and mass budgets for solutes, as well as waves and erosive capacity.

Figure 8.1 : Model bathymetry



The model covers the estuary from Chandpur downstream, an area of 216 km (east-west) by 175 km (north-south), with a grid size of 600 metres. Its specifications, calibration and validation, and the basic applications are described in a separate report "Numerical modelling of hydrodynamics, salinity, waves and sediment transport in the Meghna Estuary" (June 1998). One additional fine grid (200 metre grid) model was set up and applied for Nijhum Dwip.

The model was established as a tool for description of the present and future hydraulic conditions in the study area. The results are required in connection with:

- assessment and comparison of development scenarios
- impact evaluation and design of various specific schemes.

For these purposes, a set of reference simulations (or baseline simulations) has been made for one dry season period and one monsoon period. These simulations serve as the evaluation basis for scenario simulations of different combinations of possible interventions. In this way, good consistency is obtained, and the relative evaluation of hydraulic impacts becomes robust with respect to uncertainties in the absolute description of present and future conditions.

In order to obtain a valid impact assessment, all simulations describe normal conditions, rather than extreme events.

Below, a summary is given of the different sets of simulations. A comprehensive description of the results is given in the report "Numerical modelling of hydrodynamics, salinity, waves and sediment transport in the Meghna Estuary" (June 1998).

8.2 Hydrodynamics during the dry season

The dry season is the calm season in the estuary. The wind is weak and the river discharge is much less than that in the monsoon, so the estuary is dominated by the tidal action. The dry season is critical with respect to salinity distribution.

A hydrodynamic reference simulation has been made for one fortnightly tidal period:
3 February 1996 0:00 - 20 February 1996 0:00

Spatial Velocity Pattern

Hydraulic computations under spring tide conditions indicate that during the dry season the maximum velocity can be found near Chandpur and in the Sandwip Channel in particular around Urir Char and the Noahkali mainland (Figures 8.2 and 8.3). The maximum flow velocity is about 2 to 3.5 m/s. The flow velocities in the shallow area are relatively low. The maximum velocity is less than 1.5 m/s most of the time. Near the southern edge of the delta the cross-sectional area of the channel is smaller due to sedimentation and consequently the current velocities increase. In the deeper part of the delta the current velocities reduce to about 0.5 to 2.0 m/s.

Figure 8.2 : Maximum Ebb velocity pattern in the Meghna Estuary Study area at spring tide during the dry season

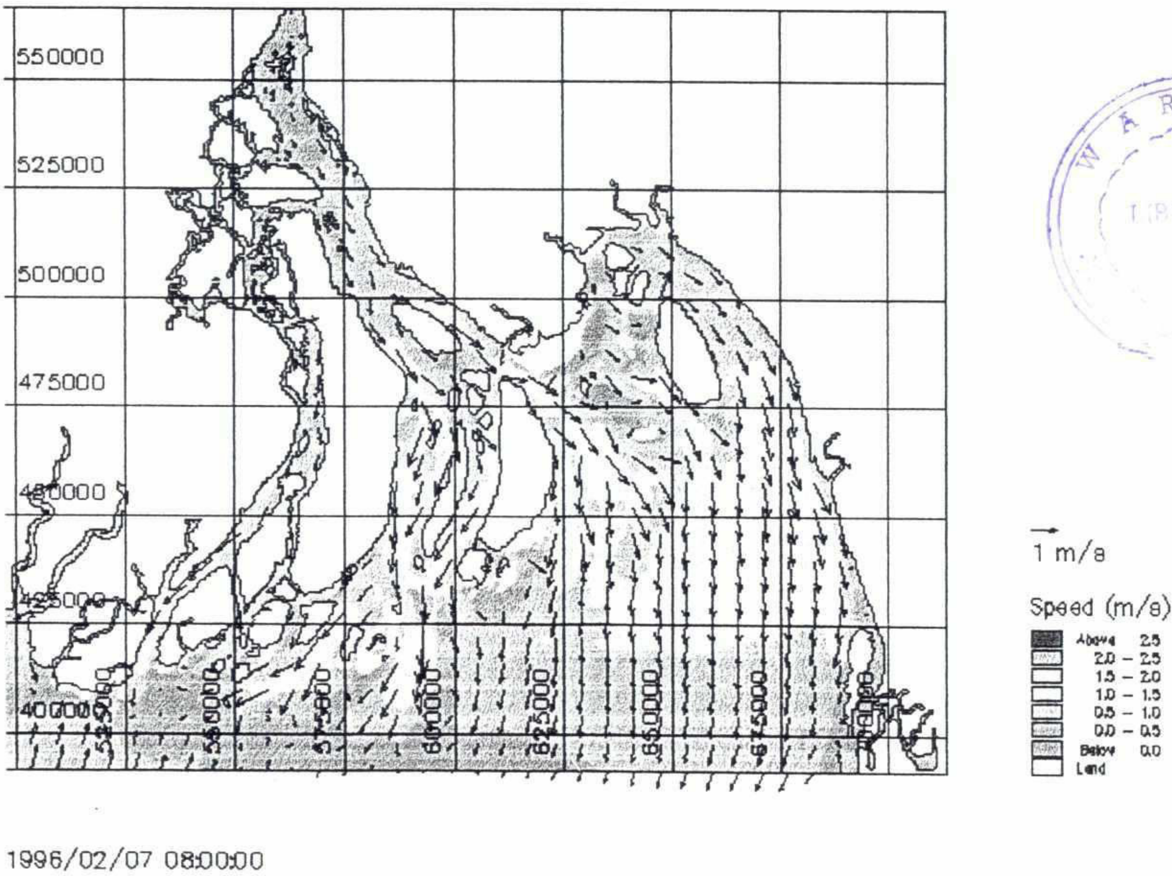
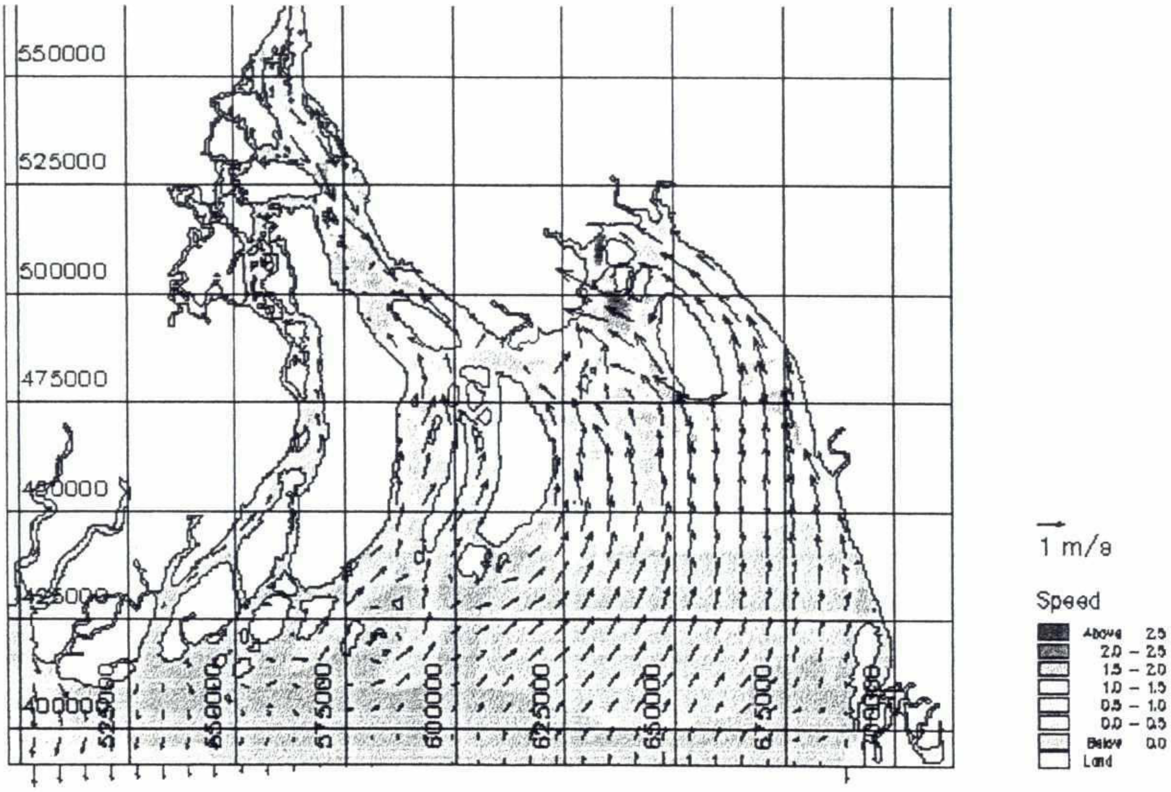
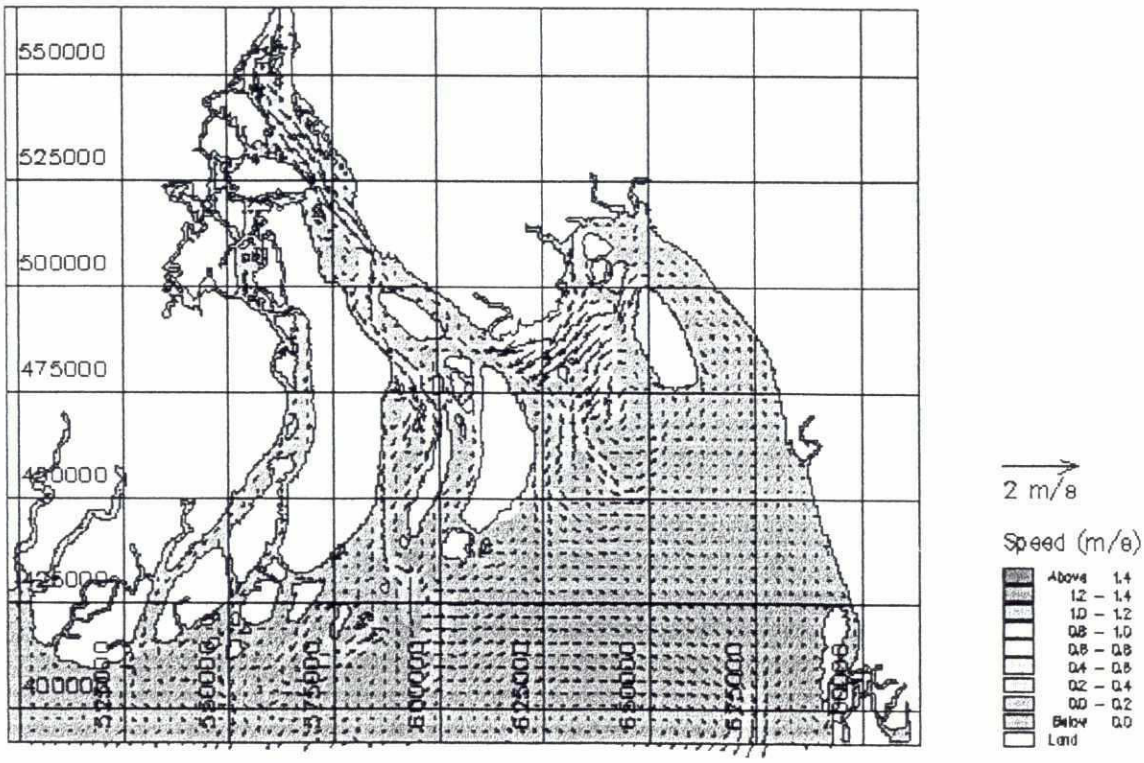


Figure 8.3 : Maximum flood velocity pattern in the Meghna Estuary Study area at spring tide during the dry season



1996/02/07 14:00:00

Figure 8.4 : Net flow pattern in the Meghna Estuary Study area at spring tide during dry season.



Net flow distribution pattern

The net flow pattern under spring tide conditions indicates that the outflow in the West Shahbazpur channel is dominant. A net circulation pattern can be observed around Sandwip. A net flow in a northward direction is dominant in the shallow areas seaward from the islands Nijhum Dwip Rangabali and Char Montaz. In the shallow areas between Hatia and Sandwip the net flow is dominant westwards. (Figure 8.4).

8.3 Hydrodynamics during the monsoon

The monsoon period is the dynamic season in the estuary. The southwesterly wind is steady, and the river discharge is high. Further, the general water level is higher than that in the dry season (Table 8.1). 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. In the Lower Meghna, the net flow and the maximum flow velocities are higher during neap tide than during spring tide, whereas in the Sandwip Channel, which is tide dominated, maximum velocities are higher during spring tide.

A hydrodynamic reference simulation has been made for one fortnightly tidal period:
8 September 1997 0:00 - 25 September 1997 0:00

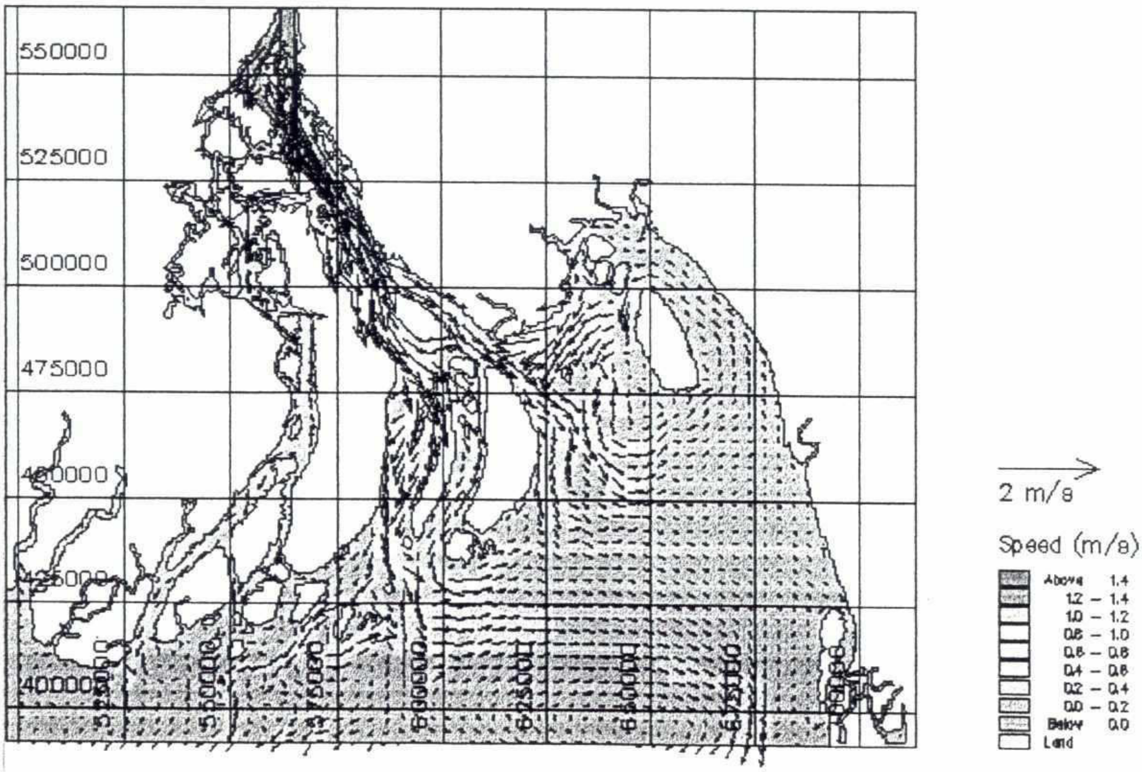
Table 8.1: Seasonal variation of water level in the estuary

	February	August	September
Chandpur	1.3 m+PWD	4.3 m+PWD	4.0 m+PWD
South model boundary	0.1 m+PWD	1.0 m+PWD	0.9 m+PWD

Note: PWD datum values are approximate

A typical example of the overall net flow distribution pattern under spring tide conditions is illustrated in Figure 8.5.

Figure 8.5: Net flow pattern in the Meghna Estuary study area at spring tide during monsoon



8.4 Salinity intrusion

A reference simulation of salinity distribution has been made for the selected dry season period: *3 February 1996 0:00 - 20 February 1996 0:00.*

The spatial salinity intrusion pattern showed that during the dry season the Lower Meghna Estuary between Chandpur and Gazaria is almost fresh water (Figure 8.6). South of Gazaria the salinity content increases up to 16 ppt at Nijhum Dwip. In the Bay of Bengal the salinity rises up to 30 ppt. The salinity in the Hatia Channel increases rapidly eastwards. The maximum salinity gradient can be found around North Hatia (Figure 8.7). The maximum salinity gradient is in the order of $1.0 * 10^{-4}$ to $1 * 10^{-3}$ ppt/m.

The salinity content around Sandwip indicate brackish to salty conditions.

The salinity content of the major part of Tetulia River is negligible. In the zone south of Rangabali-Kukri Mukri the maximum salinity gradient can be up to $1 * 10^{-3}$ ppt/m (Figure 8.7).

The results of the simulation of the salinity distribution shows that the zone of maximum gradient along the Estuary is sensitive to river discharge (dry season - monsoon) and tidal conditions (neap - spring tide conditions). During the monsoon period the salinity in the major part of the Lower Meghna Study area is fresh. The results of the simulation fit very well with the LRP and MES salinity measurements

Figure 8.6 : Minimum salinity intrusion pattern during dry season in the Meghna Estuary.

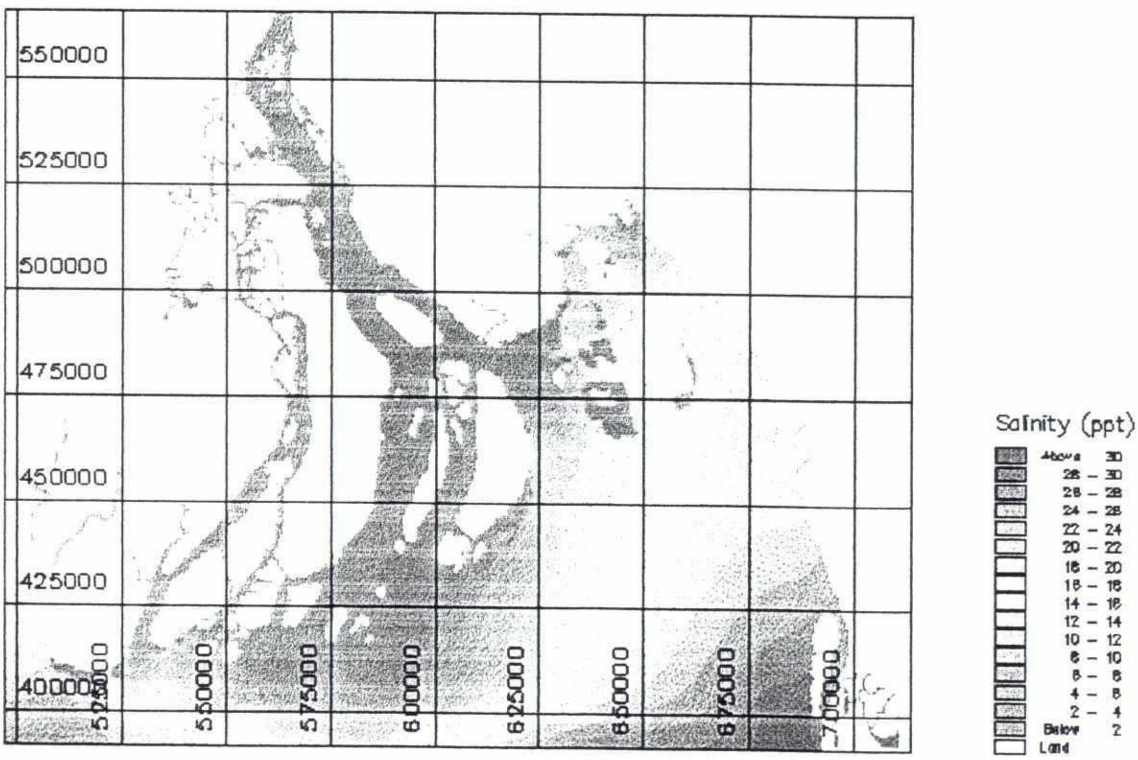


Figure 8.7 : Maximum salinity intrusion pattern during dry season in the Meghna Estuary

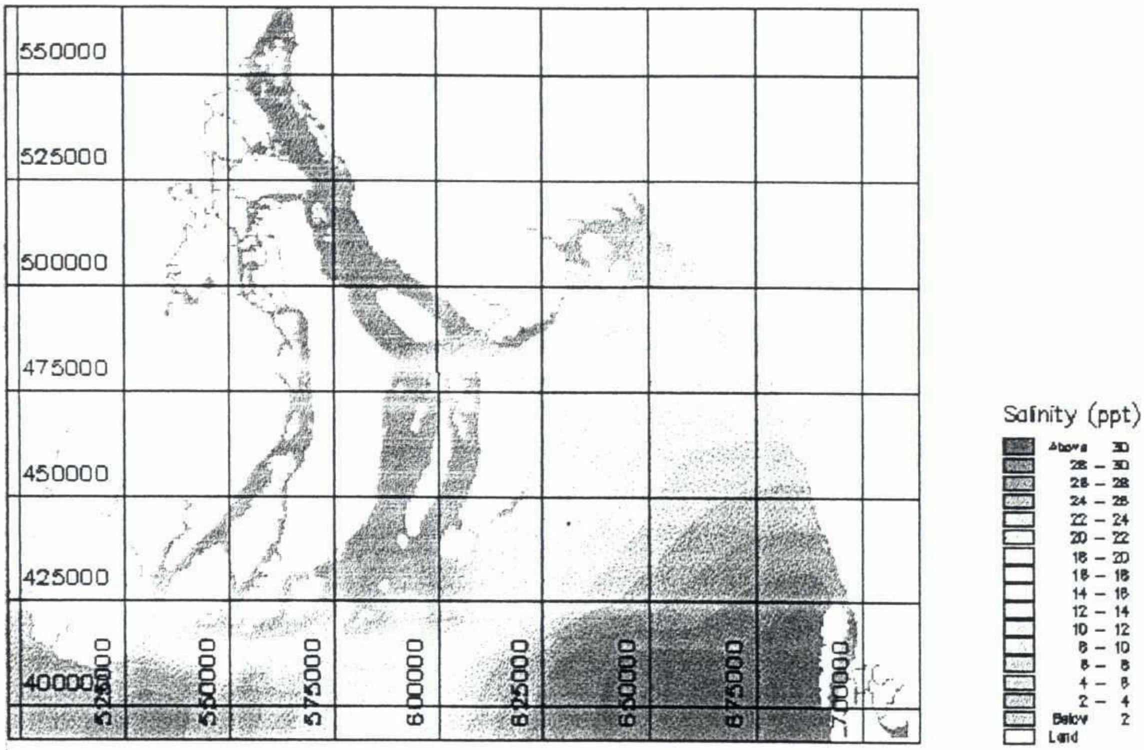
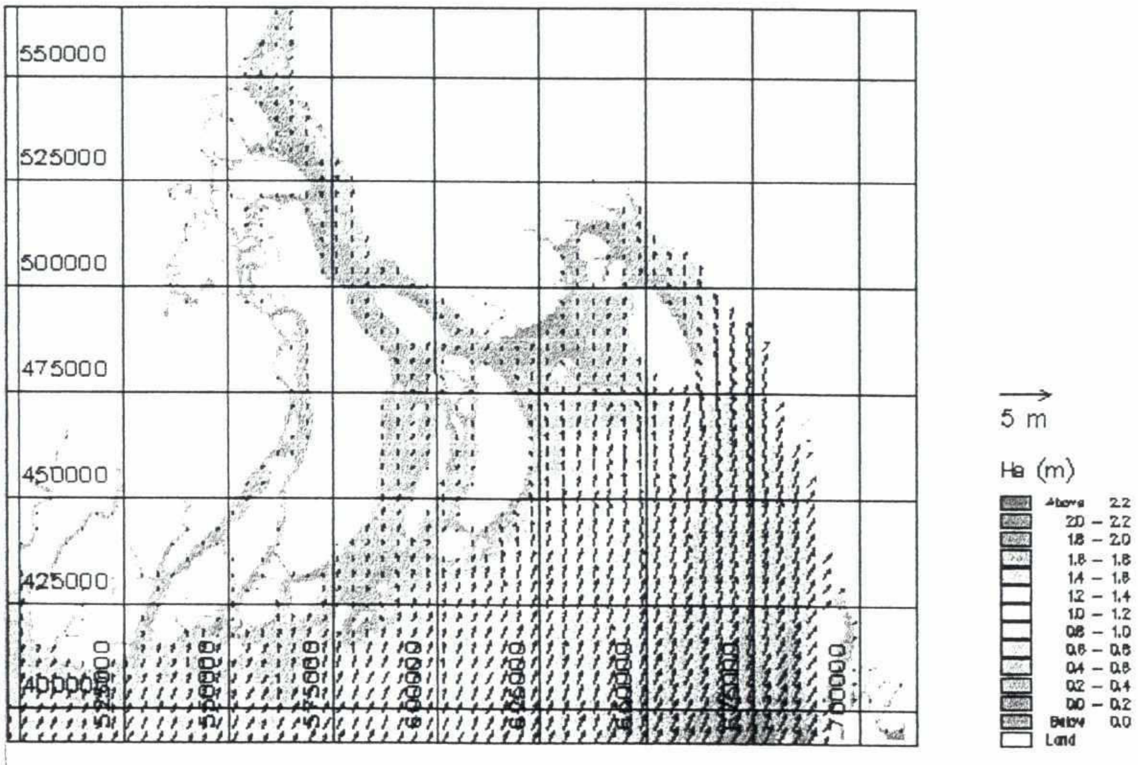


Figure 8.8 : Significant wave height in the Meghna Estuary Study area: Wind conditions SSW 8 m/s



8.5 Waves

Two wind-wave simulations have been made as a basis for the sediment transport modelling. They illustrate monsoon conditions, with steady winds of 8 m/s from SSE and from SSW respectively. The model simulations indicate that under moderate wind conditions the wave height is in the order of 0.6 to 1.5 metre in the nearshore zone and 0.1-0.6 metre in the landward part of the Meghna Study area (Figure 8.8). In the dry season the waves are generally less than 0.6 metre with peak periods of 3 - 4 seconds.

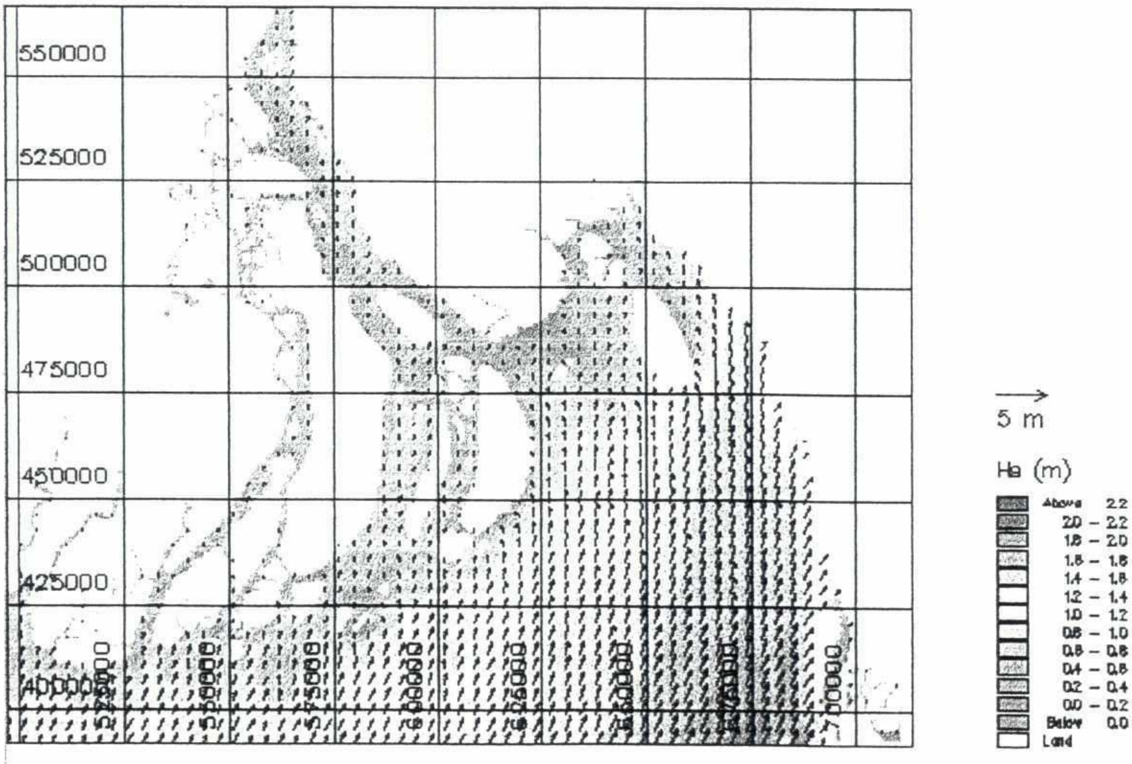
8.6 Interventions

Three different sets of intervention schemes were simulated with respect to:

- dry season and monsoon hydrodynamics
- dry season salinity distribution.

In the report "Numerical modelling of hydrodynamics, salinity, waves and sediment transport in the Meghna Estuary" (June 1998) detailed information is given about comparisons between these simulations and the reference simulations. In general, the hydrodynamic impact on the regional scale is small. On the local scale the flow velocity can reduce up to nearly 100 per cent which encourages the accretion process enormously (Figure 8.9). Further, the impact is inversely related to its significance: the dry season impact is more visible than the monsoon impact, and the net flow is more affected than the maximum velocities. One reason for this is that the overall flow resistance of the estuary as a whole is less in the monsoon, due to the higher water level. There are no indications of any effects in the Lower Meghna nor in the inland river system north of the study area.

Figure 8.9 : Net flow pattern in the Meghna Estuary Study area at spring tide during the monsoon after interventions 1-8



Hydraulic simulations indicate that the closing of the Nijhum Dwip - Hatia channel will create a water level difference between the east side and the west side of the cross dam by about 0.1-0.30 metre.

The water level differences in the case of closing of the Sandwip-Urir Char Channel would be in the range of 0.40 - 0.80 metre (Figure 8.10). The hydraulic simulations indicate also that the maximum water level in the Sandwip channel will increase by 0.40 to 0.80 metre (Figure 8.11). At the same time the maximum water level in the East Hatia channel near the cross dams will reduce by 0.2 to 0.5 metres. Implementation of the Sandwip cross dams without further measures to strengthen the embankments reduce the safety against flooding of the already embanked coastal areas around the Sandwip Channel. The water level, particularly in the Sandwip channel, seems to be very sensitive to tidal conditions and river discharge. To estimate the best closing strategy, more study is needed to define the optimal hydraulic conditions for closing the tidal channels.

The simulations of the future salinity distribution indicate unchanged levels in the major part of the estuary, including the Tetulia River (where the salinity is nil today, and should remain so). Salinity is most visibly affected by a cross dam (or a natural closure) across the channel north of Sandwip. For this scenario, the salinity is somewhat reduced around the mouth of Feni River and in Sandwip Channel, and is somewhat increased in the area between Sandwip and Hatia.

Figure 8.10 : Difference in water level between the east west sides of Urir Char cross dam (intervention 7 minus base run simulation)

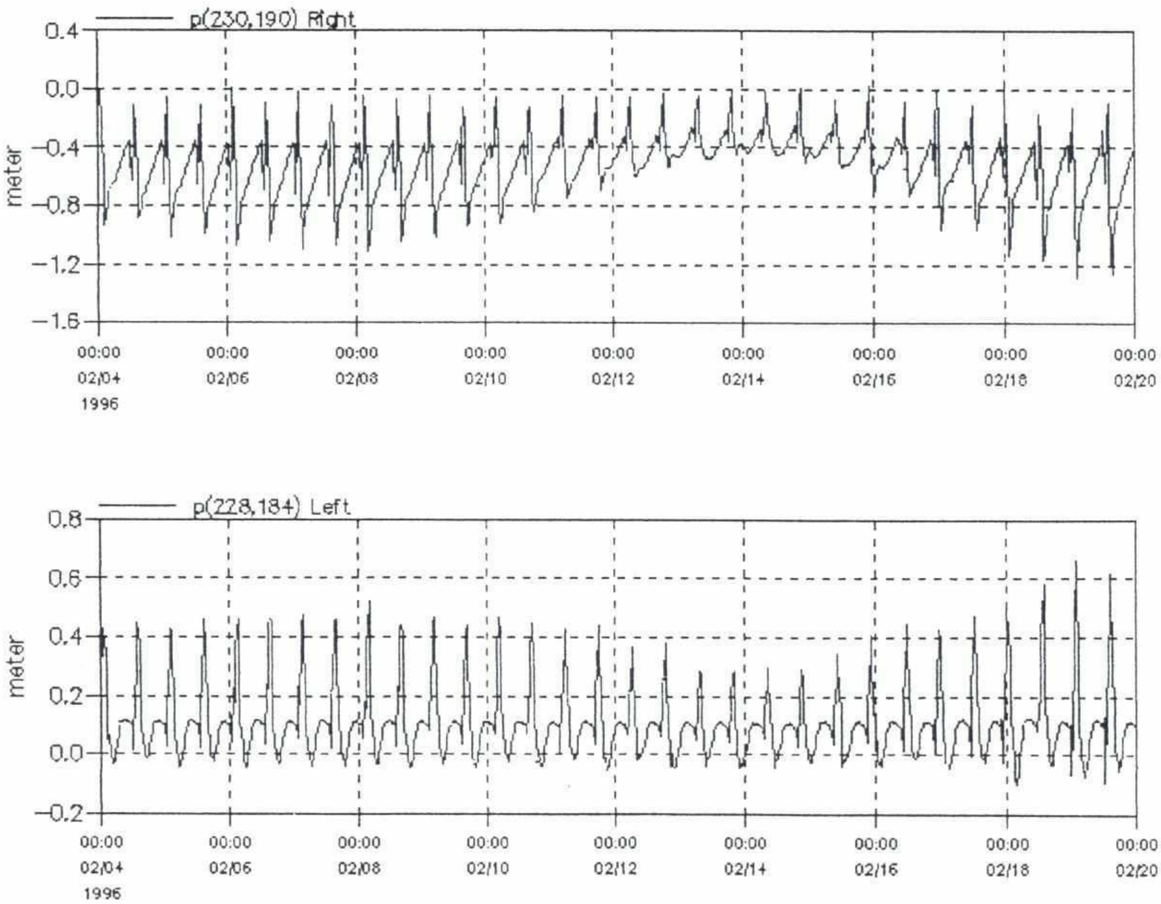
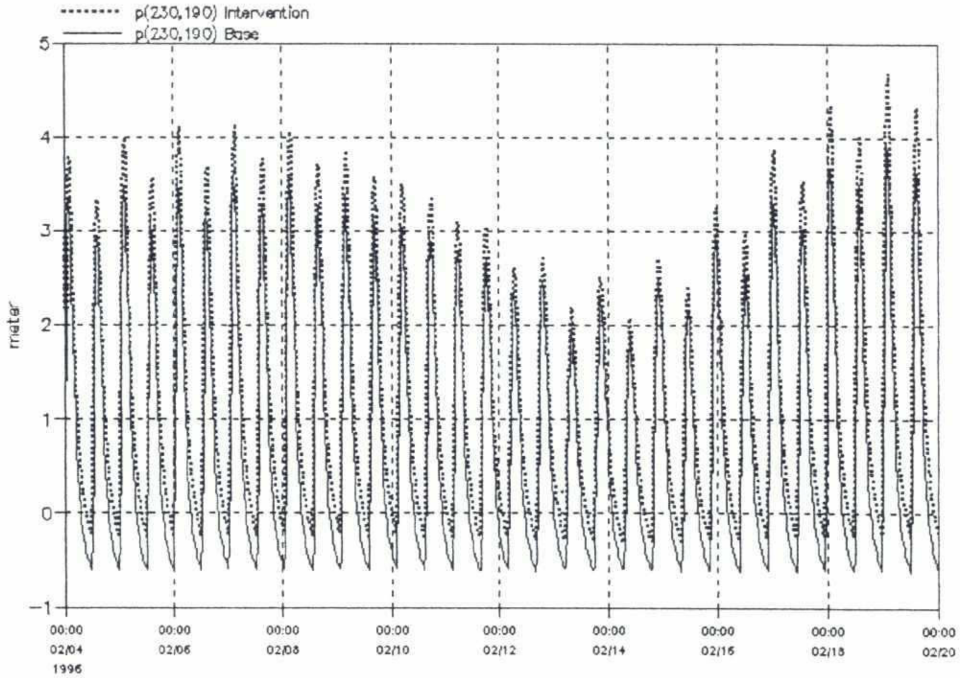


Figure 8.11 : Water level changes in the Sandwip channel near the Urir Char cross dam (intervention 7)



8.7 Overall flow distribution

The hydraulic simulations indicate that the major part of the river discharge flows through the West Shahbazpur Channel (55-70%) (Figure 8.12 and 8.13). About 5-35% of the river discharge flows through the Hatia Channel and about 10-20% through the East Shahbazpur Channel. The Tetulia River discharge is about 10 % of the river inflow at Chandpur.

Figure 8.12 : Net flow distribution in per cent of flow at Chandpur during dry season (Neap - Spring tide)

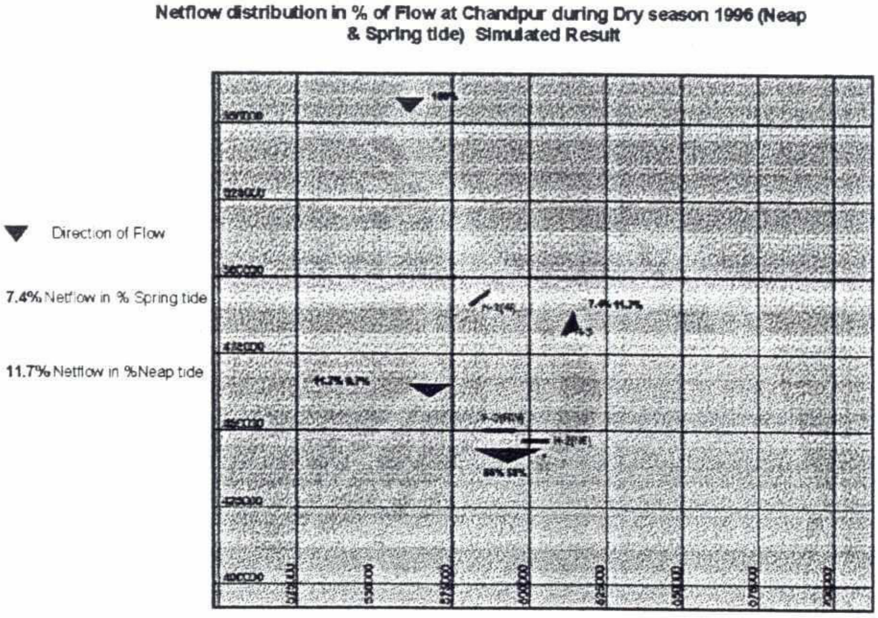
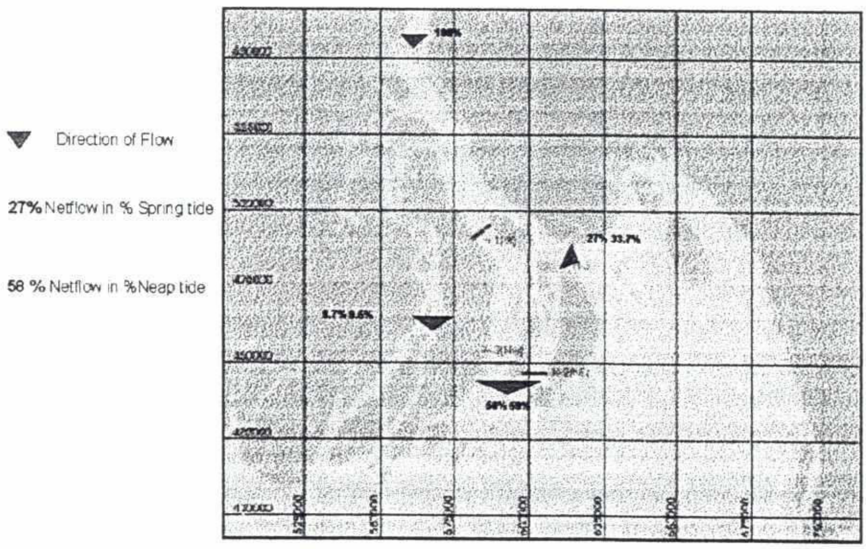


Figure 8.13 : Net flow distribution in per cent of flow at Chandpur during the monsoon (Neap-Spring tide)



9. MORPHO-DYNAMIC MODELLING

9.1 Sediment transport simulation

The interaction of different transport agents has been studied on the basis of a 2DH numerical model (Mike-21). The principal constituents of this model are:

- an (overall) regional 2DH tidal model, describing the tidal stages and boundary conditions for the flow model in the study area which solves the usual depth averaged shallow water equations;
- a wave field model describing the propagation and dissipation of wind waves in the study area;
- a sediment transport formula according to Bijker describing the bed load and suspended load transport due to waves (stirring) and currents;
- the sediment balance equation, yielding the sedimentation and erosion rate under the given conditions.

The two dimensional numerical model predicts the morphological changes during one neap-spring tidal cycle, based on the distribution of sediment transport rates computed at local grid points from wave and current conditions.

To support the morphological analysis, a series of indicative sediment transport simulations were made. A total of eight simulations were carried out, as follows:

- dry season - spring and neap tides, no waves
- monsoon - spring and neap tides, no waves, waves from SSE, and waves from SSW.

With the aim of illustrating transport rates, each of these simulations had a duration of one semi-diurnal tidal cycle.

This chapter focuses on the preliminary results of these indicative sediment transport simulations and will discuss the sediment transport patterns under various hydraulic conditions. Detailed information about the simulations and results is presented in a separate report "Numerical modelling of hydrodynamics, salinity, waves and sediment transport in the Meghna Estuary" (June 1998).

9.2 Sediment transport patterns during the dry season and monsoon

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, thereby further reducing the supply of sediments to the southern parts. In the southern part, where the flow is predominantly determined by the tide all 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 and the transport capacity of the main net flow channels are at their highest (while in the purely tidal channels, the transport capacity is more or less the same all year). In this season, the major erosion and accretion takes place.

As 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 lost 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.

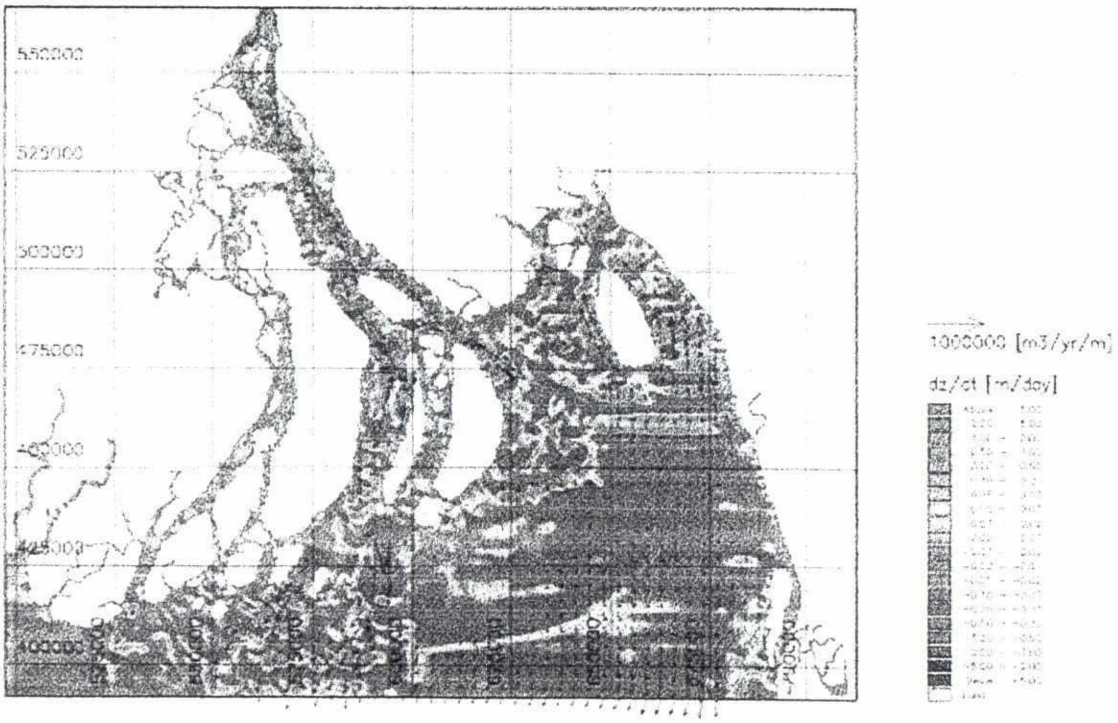
9.3 Waves and sediment transport pattern

According to the indicative model simulations of situations with and without waves, the overall sediment transport is clearly determined by the flow, rather than by the waves. This is the case even for the characteristic northward sediment transport through Sandwip Channel, which has supplied the material to the accretion that has occurred at Muhuri and in 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.

Also the erosion of cohesive banks can be enhanced by breaking waves, although the main erosion mechanism is the current, sometimes in a combination with a hydrostatic ground water pressure at low tide. In this respect, the sediment transport in the estuary resembles the pattern of the main river system, except for the regular and relatively fast changes in water level.

Figure 9.1 : Preliminary results of erosion and sedimentation patterns at spring tide during the monsoon



9.4 Preliminary results of erosion and sedimentation patterns

Preliminary results of erosion and sedimentation during the monsoon indicate an overall tendency of silting up of the Sandwip Channel and levelling up of the shallow areas between Hatia and Sandwip (Figure 9.1). An overall sedimentation trend can also be seen near the edge of the delta front where new islands and intertidal areas are formed and silt up. The results show a dominant erosion trend around north Hatia and north Bhola. The morphology of the Upper Tetulia River is relatively stable compared to the Lower Meghna Estuary. Alternation of erosion and sedimentation patterns along the Lower Meghna Estuary 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. The east and west sides of Hatia tend to silt up slowly. Sedimentation seems to be dominant in the shallow areas around Nijhum Dwip and the area around Rangabali - Kukri Mukri.

Although the physical knowledge of the hydro-morphological processes which shape the Lower Estuary Study area is low, the model results are fairly good: the simulated current and discharge show good agreement with hydraulic observations. The preliminary results of the overall sediment transport patterns show good agreement of the computed morphological changes with bathymetric observations and appear qualitatively reasonable.

The complex erosion and sedimentation patterns resulting in the general trends of geomorphological changes were calculated more or less satisfactorily in the study area. The results of the uncalibrated sediment transport model indicate an over-estimation of the initial rates of bed level changes and sediment transport discharge.

Quantitatively, the model results appear insufficient for prediction of future changes on an intermediate time scale. For this purpose additional field information is necessary to interpret the model generated forecast and to calibrate the sediment transport model. The model results are useful, however, to analyse the relative effects of different transport processes on the development of different geomorphological units.

10. EMPIRICAL RELATIONS

10.1 Characteristic equilibrium relationships

When in a state of morphological balance, relationships existing between the area's morphometric and hydrodynamic values present themselves. One of the key mechanisms behind morphological changes in a tidal area is the tidal prism. It should not come as a surprise that in the past various countries have conducted studies to determine the relationship between the morphological balance of the tidal inlets and the tidal prism.

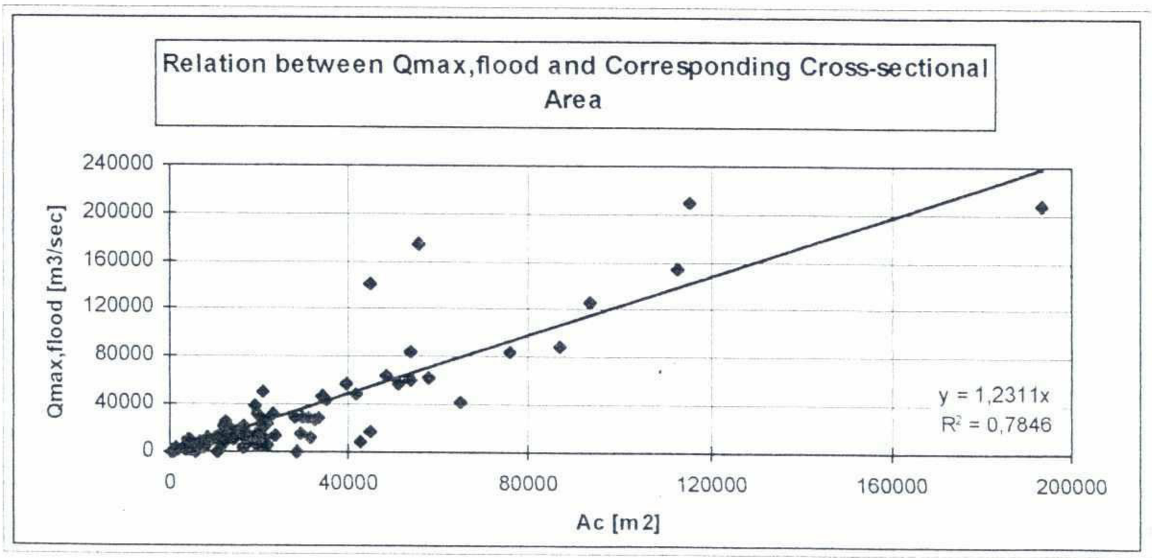
These relationships enable us to forecast morphological adjustment if changes occur in the Lower Meghna Estuary system, whether caused by human intervention or natural processes. The correlations are not universal and are influenced by site specific circumstances, such as waves, the size of sediment grains and the volume of sediment load transported through the inlet. When making general forecasts, these factors can be disregarded and the relationship can also be assumed to apply to an accelerated rise in sea level.

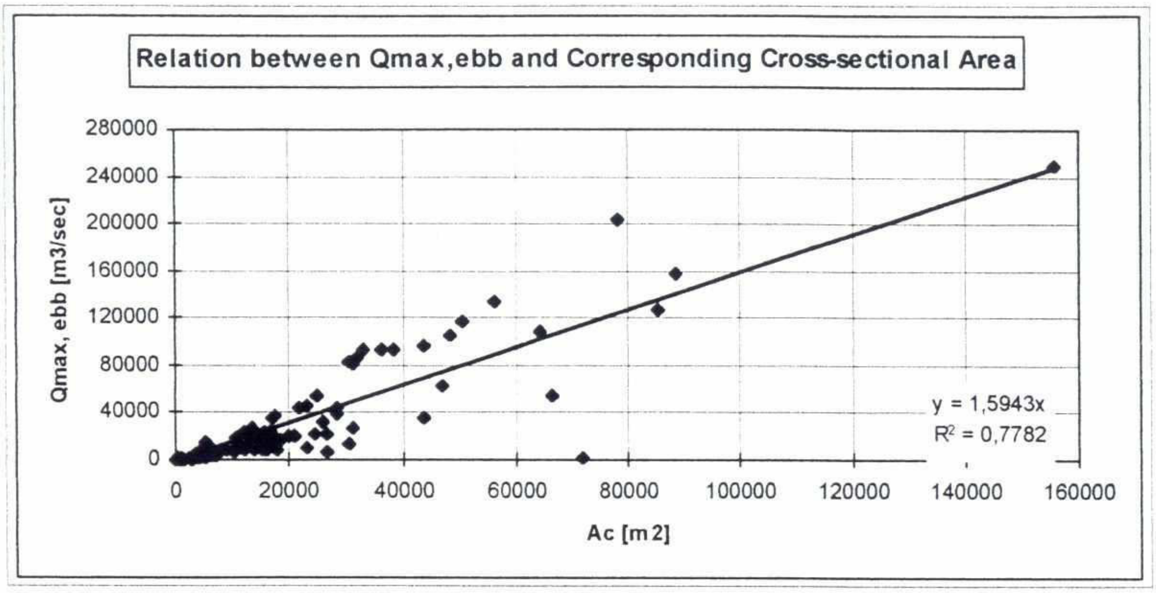
This study will briefly look at a number of characteristic empirical relationships between the tidal prism, on the one hand, and large scale geographical units such as delta, tidal inlet and tidal basin on the other.

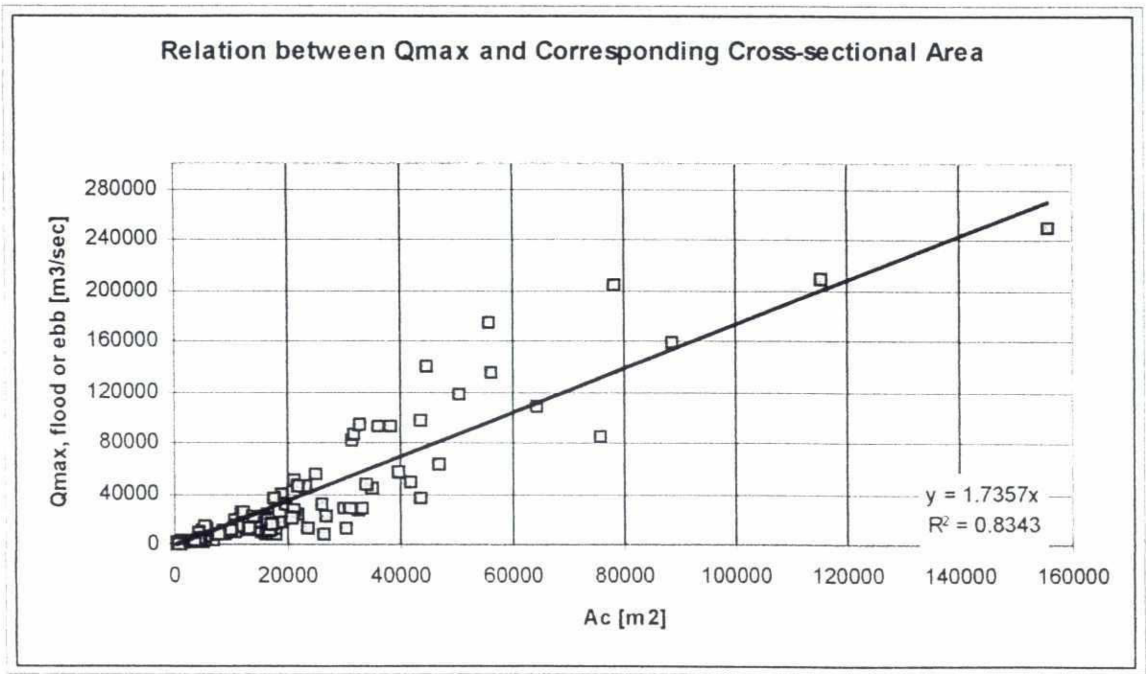
10.2 Relationship between cross-section and tidal prism

A typical unit of measure for an inlet is the narrowest cross-section at the opening. A clear connection has been established between the size of this cross-section and the tidal prism (as well as discharge). Although not universally equivalent, this correlation is probably the same for areas that form a morphological unit. Empirical study has shown that the cross-section of an inlet increases almost linearly with the tidal prism (and also with the discharge) (Figure 10.1). If we limit ourselves to the large inlets, a linear connection can safely be assumed between the average tidal prism and the cross-section at PWD-Level, or average sea level. The same type of relationship exists for cross-sections of channels in the basin and the tidal prism at the site of the cross-section.

Figure 10.1 : Relation between qmax and cross-sectional area in the Lower Meghna Estuary







10.3 Relationship between volume of sediment in the outer delta and the tidal prism

Tidal currents transport large quantities of sediment through the tidal inlets. Because the ebb flow spreads out beyond the inlet, sediment is deposited outside the inlet and a system of channels and banks is created: the outer delta. This outer delta is a 'storehouse' for a large quantity of sediment. According to Hayes (1975) there is a connection between the volume of the sediment in the outer delta (above the profile of the coastline) and the tidal prism.

Oertel (1988) and Walton et al. (1976) show a direct correlation between the sediment volume of an ebb tidal delta (Vd) and the tidal volume (Vt), which can be written as (see Table 10.1):

$$Vd = \alpha * Vt^{\beta}$$

where,

β = ca. 1.23 (Walton et al., 1976)
α = positive empirical constant.

This empirical model, which refers to equilibrium conditions, implies that in case of a tidal volume reduction, the sediment volume of the ebb delta is decreasing. The model also indicates that in the case of a migration of a delta in a seaward direction a huge amount of sediment is needed to reach a new state of equilibrium.

Table 10.1: Relation between sediment volume in the outer delta and the tidal prism

Tidal Prism	α	β
Micro-Tidal Delta	8,46E-03	1.23
Meso-Tidal Delta	6,44E-03	1.23
Macro-Tidal Delta	5,33E-03	1.23

Source: after Walton, 1976

10.4 Relationship between intertidal area and tidal prism

When the water level rises, a portion of the sediment carried in by the flood tide is deposited on the mudflats. The relationship between channels and flats is thus expected to relate to the inflow and outflow of sediment and, in turn, to the size of the tidal prism. The larger the tidal inlets (and tidal prism), the smaller the intertidal areas in proportion to the total surface of the basin. Eysink (1991)describe the relationship between intertidal area and tidal prism as follows:

$$P = (1 - a_f A_f/A_b)\ A_b\ Dh$$

$$A_f/A_b = 1 - a * (A_b)^b$$

where,

a and b are empirical coefficients
A_f is the surface area of the intertidal areas between MLW and MHW
A_b is basin area at MHW.

Empirical coefficients of a few tidal systems in the world are shown in Table 10.2. This type of relation might be useful and a handy tool to predict intertidal area in the near future. More study is needed to understand and to improve this type of causal relationship and physical background.

Table 10.2: Relationship between intertidal area and tidal prism

Estuarine/coastal Area	Author	Year	Basin Area Ab	A	b
American Coast	Renger and Partenscky	1974	5 - 200 km2	$2.5 * 10^{-5}$	0.50
American Coast	Renger et al.	1976	8 - 200 km2	$2.53 * 10^{-3}$	0.25
Netherlands	Eysink en Biegel (best fit all)	-	5 - 200 km2	$1.57 * 10^{-4}$	0.40
Wadden Sea	Eysink en Biegel	1992	-	$10.3 * 10^{-4}$	0.31

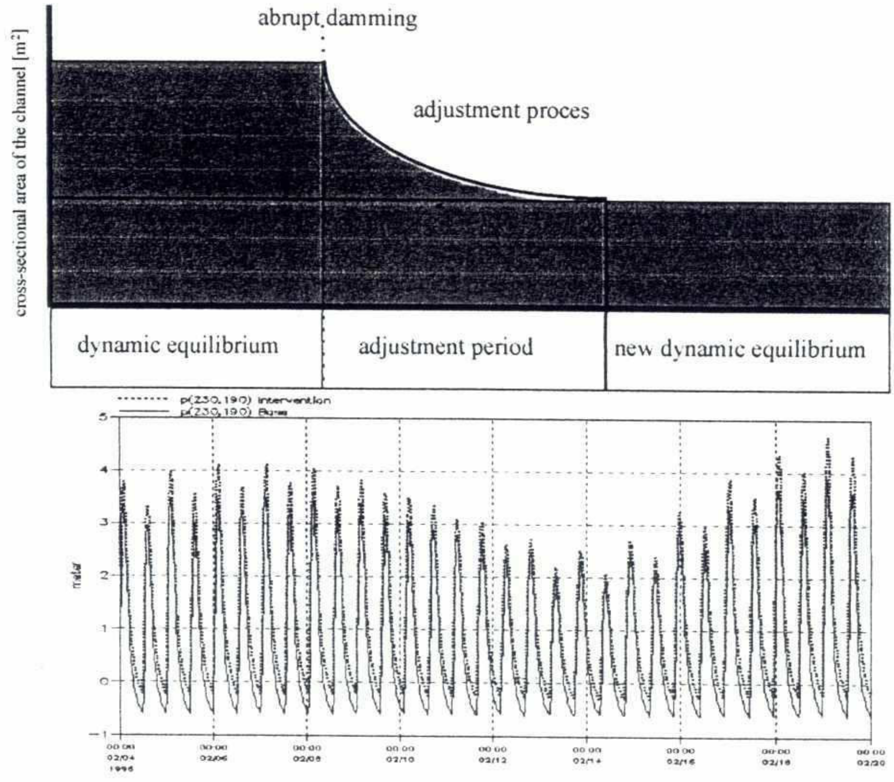
10.5 Adaptive behaviour of tidal basins

Morphological adjustments are not immediate; restoring dynamic equilibrium requires time. It has been observed that the rate of adjustment is usually proportional to the magnitude of the disruption. Some changes are abrupt, for instance, those caused by partial damming of a tidal basin, while others proceed more slowly, such as the rising sea level. Adjustment to these types of changes follows an exponential curve over time, with a certain lag effect (Figure 10.2).

Figure 10.2 : Concept of adaptive behaviour of tidal basins with (i) Abrupt changes and (ii) Changes varying over time

(i)

(ii)



10.6 Relationship between height of land level and water level

Knowledge on the morphology of tidal flats is rather limited. The tidal flat area or the intertidal zone, which is the area that normally inundates and dries twice a day, is of great importance as a feeding ground for many birds and benthic organisms. The tidal flat area A_f is the area between MLW and MHW. From a morphological point of view, the tidal flats reduce the tidal prism of the basin and, hence the size of the channels. The larger and the higher the intertidal zone, the smaller is the tidal prism.

Knowledge about the heights of tidal flats is also rather limited. Bathymetric and levelling data are seldom available. It is believed that the height of a mud flat is somehow related to Mean High Water Level Spring and the local flow and wave conditions. Evidence to support this hypothesis in Bangladesh is scarce and indicative only.

The firmest support is found in the rapid adaptation of he tidal flats in the Muhuri accreted area after closure of the Feni dam. The accretion process of tidal flats in the Muhuri accreted area after closure of the Feni dam follows an exponential curve over time; as land elevation rises by continuing siltation, the frequency of inundation reduces. As a result the siltation process slows down (Figure 10.3). As the sedimentation process depends on water depositing sediments on the

22

char, the maximum sedimentation level depends on the maximum water level to occur at a certain location. For practical reasons the maximum water level to occur is taken to be Mean High Water Spring (MHWs), even though water levels may occasionally exceed this level during exceptional conditions. The accretion process can be described as follows:

$$h_t = h_o \exp[-q(t - t_o)]$$

where,

$t - t_o$ = time in years after closure (1985)
h_o = initial depth of water before closure (m)
h_t = depth of water after a period t (m)
q = a coefficient describing the average accretion rate.

In order to determine the average accretion rate in the Muhuri area after closure of the dam, land elevation measurements from the years 1986, 1987, 1988 and 1990 have been analysed. Land elevation data were used from five locations, three from the initial gully locations (point A, B and C) and two from initial flat locations (point D and E). These measurements showed that the accretion took place up to about 4.25 metre +PWD in 1990 (Table 10.3).

Table 10.3: Land level development downstream of the Feni Closure Dam, 1982-1990

Year	Location A		Location B		Location C		Location D		Location E	
	PWD (m)	4.5m +PWD	PWD (m)	4.5m +PWD	PWD (m)	4.5m +PWD	PWD(m)	4.5m +PWD	PWD (m)	4.5m +PWD
1985*	-1.85	6.35	-1.50	6.00	-1.20	5.70	1.85	2.65	0.30	4.20
1986	3.00	1.50	3.25	1.25	3.75	0.75	3.00	1.50	3.75	0.75
1987	3.50	1.00	3.96	0.54	4.17	0.33	3.50	1.00	3.80	0.70
1988	3.62	0.88	4.20	0.30	4.34	0.16	3.60	0.90	3.85	0.65
1990	4.05	0.45	4.25	0.25	4.24	0.26	4.15	0.35	4.15	0.35

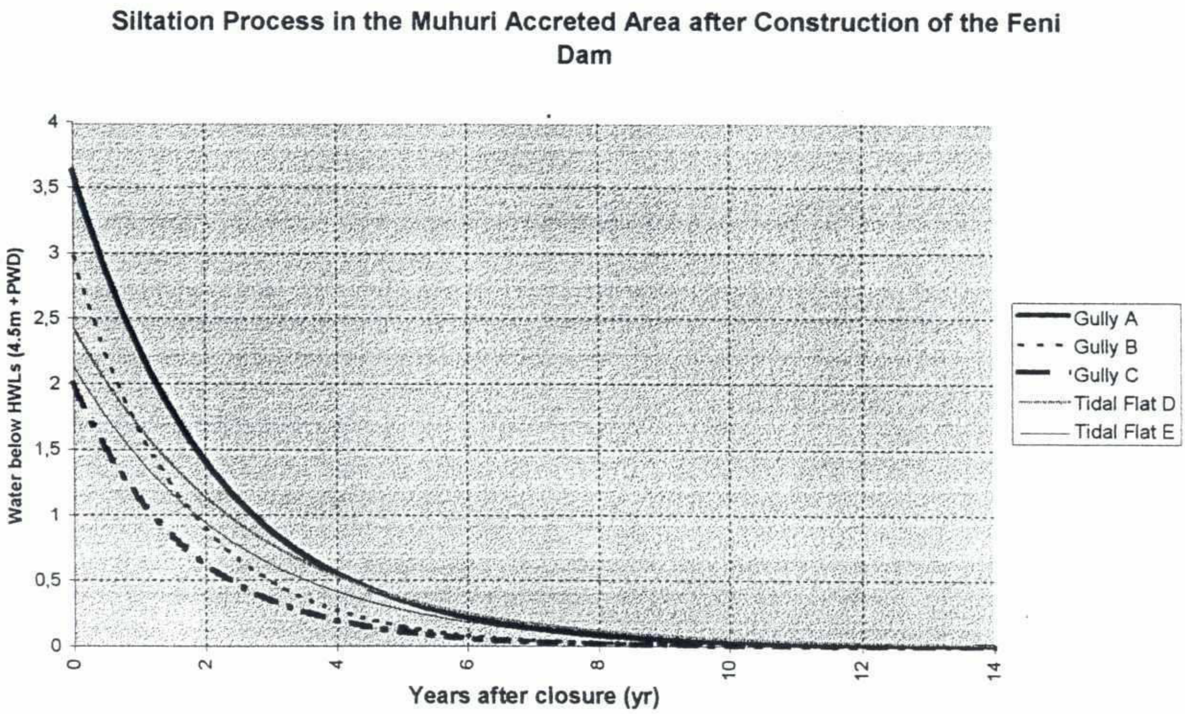
Source: Modified after Barua, 1990
Note: * The actual survey, by the dam directorate, represents 1982. The dam was completed in 1985.

Table 10.4 shows the result of an exponential regression analysis of the accretions process at the five representative accretion plots. The HWLs is about 4.3 to 4.5 metre + PWD. Here h_t is the new depth of water below HWLs in meter after siltation and Δt is the time in years after the closure dam. As can be expected, the coefficient q is higher at the initial gully locations A, B and C representing faster accretion (Figure 10.4). At the initial tidal flat locations D and E, the accretion rate is slower (a lower value of q). The average value of the accretion factor q is about -0.49. From the examination of the average value of the accretion factor it can be concluded that the siltation rate in 1998 at the selected locations is less than 0.02 m. This means that the elevation height increases slowly during this time. Furthermore, it can be concluded that the siltation rate of the higher parts of the accreted area is more or less homogenous.

Table 10.4: Exponential regression analysis of accretions up to 4.5m+PWD at selected locations downstream of the Feni Closure Dam

A	$h_t = 3.63 \exp(-0.47*\Delta t)$	$r^2 = 0.83$;	former gully
B	$h_t = 2.97 \exp(-0.60*\Delta t)$	$r^2 = 0.80$;	former gully
C	$h_t = 2.00 \exp(-0.58*\Delta t)$	$r^2 = 0.62$;	former gully
D	$h_t = 2.42 \exp(-0.38*\Delta t)$	$r^2 = 0.97$;	tidal flat
E	$h_t = 2.13 \exp(-0.41*\Delta t)$	$r^2 = 0.71$;	tidal flat

Figure 10.3 : Siltation process in the muhuri accreted area after construction of the Feni dam



11. ANALYSIS OF DOMINANT PROCESSES OF MORPHOLOGICAL DEVELOPMENT

11.1 Introduction

Important factors that shape the Lower Meghna Estuary area are the hydrodynamic factors, namely 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 Eastside 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 following paragraphs all these aspects are treated in detail.

11.2 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 towards the head of the estuary and the river influence becomes progressively larger. The tidal effect reaches about as far as the Ganges-Jamuna confluence and at Baruria there is still some tidal influence felt in winter.

The degree of salt intrusion depends on season and climate. Salt intrusion is an important factor which affects the sediment transport dynamics and hydro-morphological conditions in major portions of the coastal area, in particular during the 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.

The velocities in the Lower Meghna river usually decelerate in a 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 is encountered and it may mix with salt water; sediment transporting ability diminishes and sediments are deposited. The periodic rise and fall of the 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 the tide is known as the tidal prism. Generally, 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 effect of the tide produces bi-directional currents and high shear stresses during peak flows. Although residual flow will be 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 a 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 axis of an estuary is governed by the equation for propagation of shallow water waves, and is therefore a direct function of water depth. Because of this depth dependence, estuarine tides in the Lower Meghna Estuary are deformed during upstream propagation as flood crests overtake ebb troughs.

The results of this are 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, thereby magnifying the differences between ebb and flood velocities and slack water duration.

Figure 11.1 illustrates the effect of deformation of the tides along the Lower Meghna Estuary. This Figure illustrates the effect that tides also tend to increase in amplitude from upstream convergence. Decreases in depth and width resulting from the characteristic funnel-shaped geometry force the tidal wave through progressively smaller cross-sectional areas. However, frictional dissipation from the bottom and banks of the estuary occurs with convergence, and tends to counteract it, thus decreasing the amplitude. If the effects of convergence exceed frictional dissipation, which is the case in the Lower Meghna Estuary, then the system is referred as hyper-synchronous (Figure 11.2). 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.

Figure 11.1 : The magnitude of the major tidal constituents (M2, S1) along the Lower Meghna Estuary

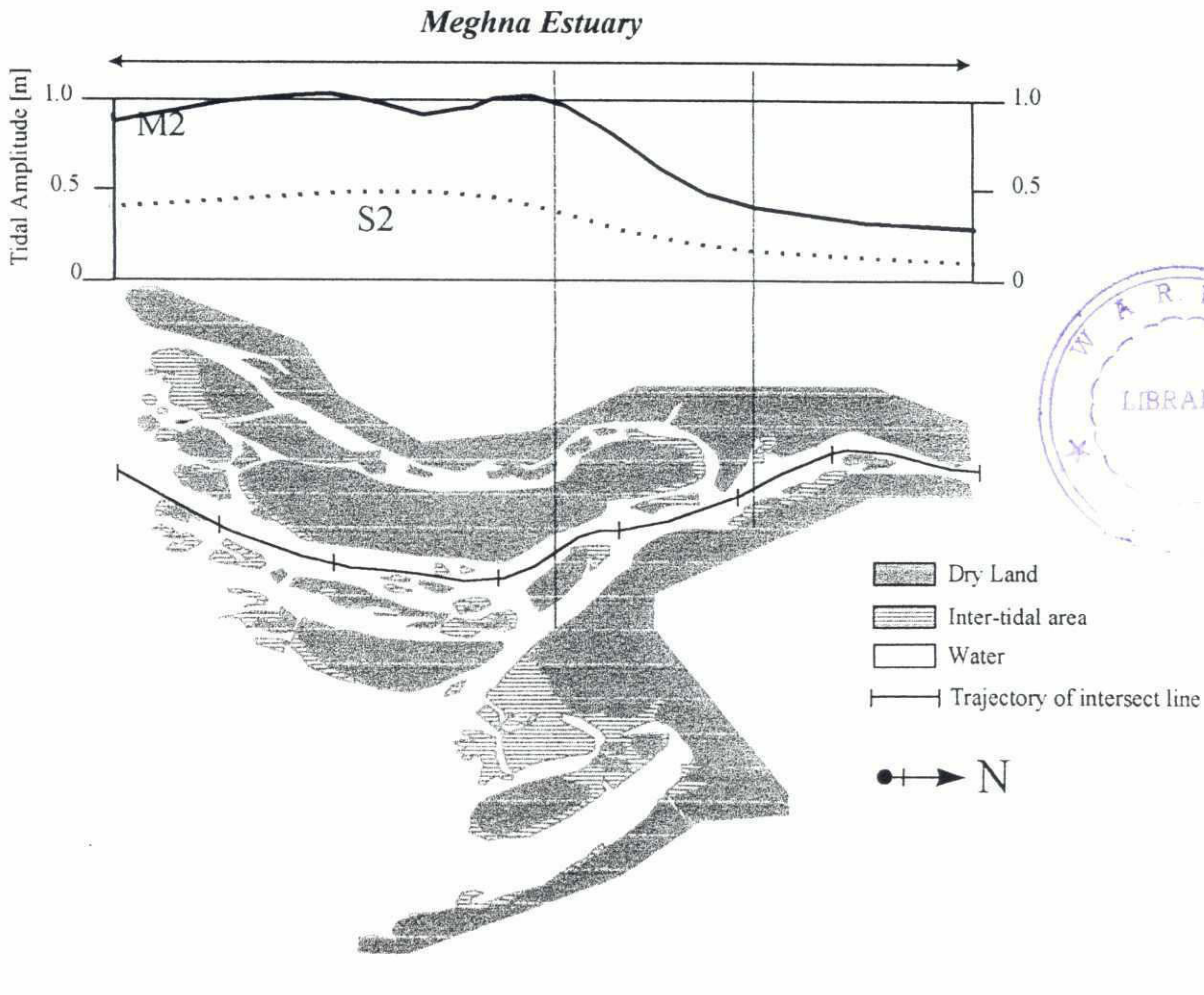


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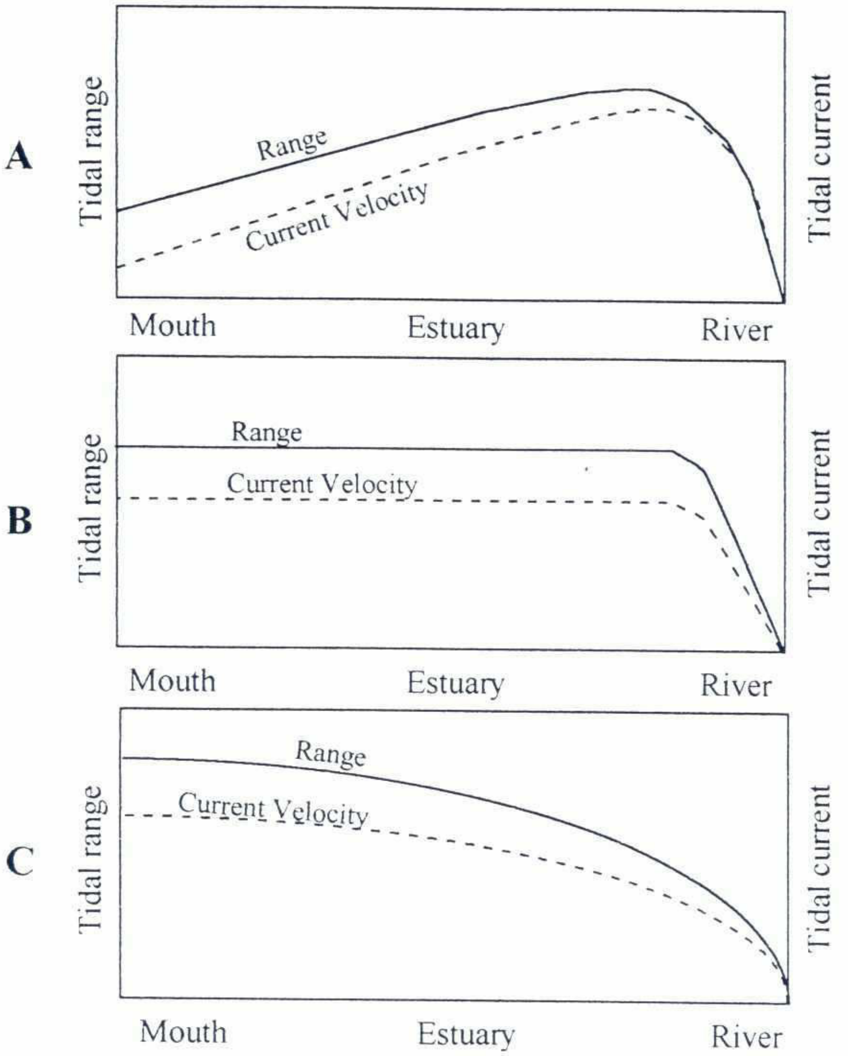
Figure 11.2: Tidal response in estuaries. A) Hypersynchronous, B) Synchronous, and C) Hyposynchronous



Source: after Nichols and Biggs, 1985

11.3 Estuarine sediment dynamics

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 area 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 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 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. 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:

a) 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
b) 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.

The above concepts referred to as settling lag and scour lag have been applied to tidal flat sediments.

11.4 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 0.1-0.5%.

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 within wide limits. Despite the differences due to sediment availability in the Shahbazpur channel and Char Balua and Char Pir Baksh areas, they have maxima with concentrations of the order of 1-9 grams 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 be redistributed down the estuary during the 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.

The estuary may be partially mixed at neap tides, but during the increasing tides there can be a change to well mixed conditions.

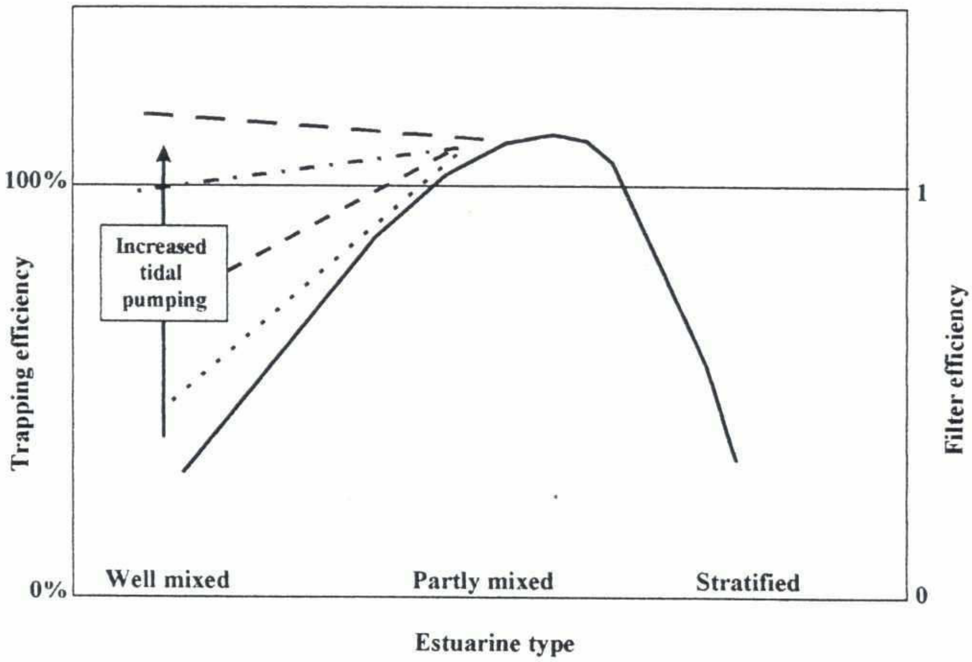
At spring tide the turbidity maximum has its highest concentration, as the currents are able to erode and sustain more sediment in suspension and it will be located further up the estuary. This is due to the fact that there is a higher mean sea level in the upper estuary at springs than at neap tides, 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.

11.5 Residual circulation and estuarine trapping

Within the Lower Meghna Estuary the river borne sediments become trapped by the tidal pumping and residual circulation, and mixes 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 the 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 11.3).

Figure 11.3 : Variation of trapping and filter efficiency of various estuary types (after K.R.Dyer, 1988)



From the 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 11.3, it can be assumed that the trapping characteristics of the Lower Meghna Estuary are 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 affects the stratification and the gravitational circulation.

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 metres per year.

Seasonal effects in river discharge also have an influence on the trapping efficiency of the estuary. The zone of the turbidity maximum changes with the variations in river discharge, which influences 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 an upstream instead of a 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. 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.

11.6 Waves

In general the influence of the waves in the Lower Meghna Estuary is limited to the shallow nearshore zone and the intertidal areas. The wind induced waves often have an important influence on the erosion and deposition processes. Waves generate an orbital velocity which is superimposed on the normal velocities in an area 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 on to 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.

11.7 Bank erosion processes

The bank erosion rate along the Lower Meghna Estuary is mostly related to bank failure. Two types of bank failure generally occur: liquefaction and flowage of material, i.e. the shearing away of bank materials. The former type of bank failure occurs below the low water level or in the zone between low and high water level. Generally they occur during the recession of the flood hydrograph. The 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 are also important for how quickly 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 banklines are very sensitive to bank erosion.

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

The average bank erosion rate on the right and left banks in the area between Chandpur and 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 1984-1996. 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 from recent decades shows that maximum bank erosion can be found on the outer banks of 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 concluded 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 on the right bank near Haimchar. The ratio between river width and bend radius in this area is about 2.5 - 2.6. It appears that the concept of Hickin and Nanson might work in the study area.

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11.8 A conceptual model of driving 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 the 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 being marine dominated, mixed energy processes or 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.

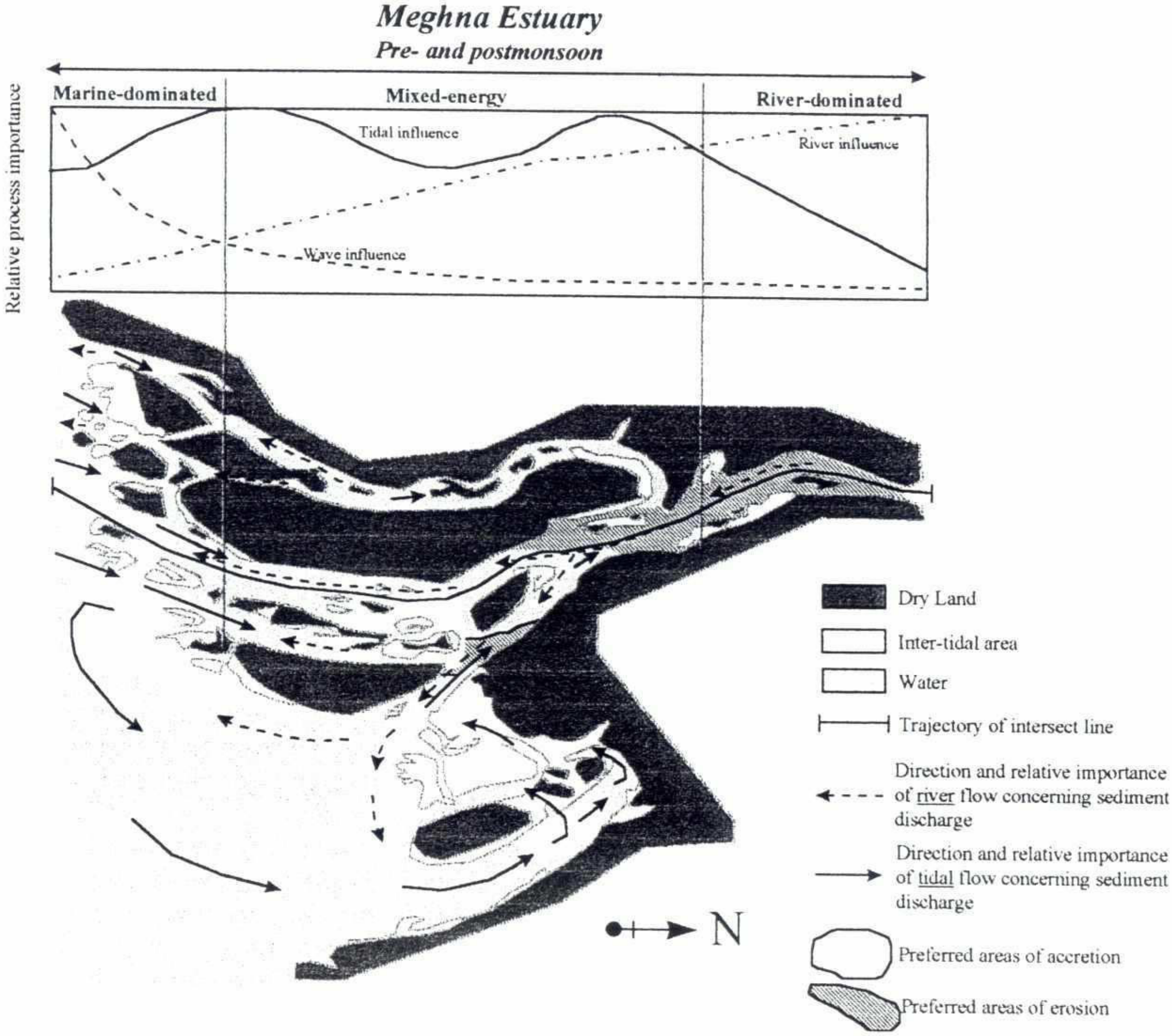
Dry season period

During the dry season a relatively large part of the estuary can be described as a well mixed to a partly mixed system (Figure 11.3). 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 result in a spatially varying pattern of energy conditions, which have their reflection in erosion and sedimentation (Figure 11.4).

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

Interaction between tidal currents and river currents forms a net circulation pattern in the vicinity of the Sandwip area. This net circulation pattern 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 11.4: Conceptual model of dominant geomorphological processes during the dry season



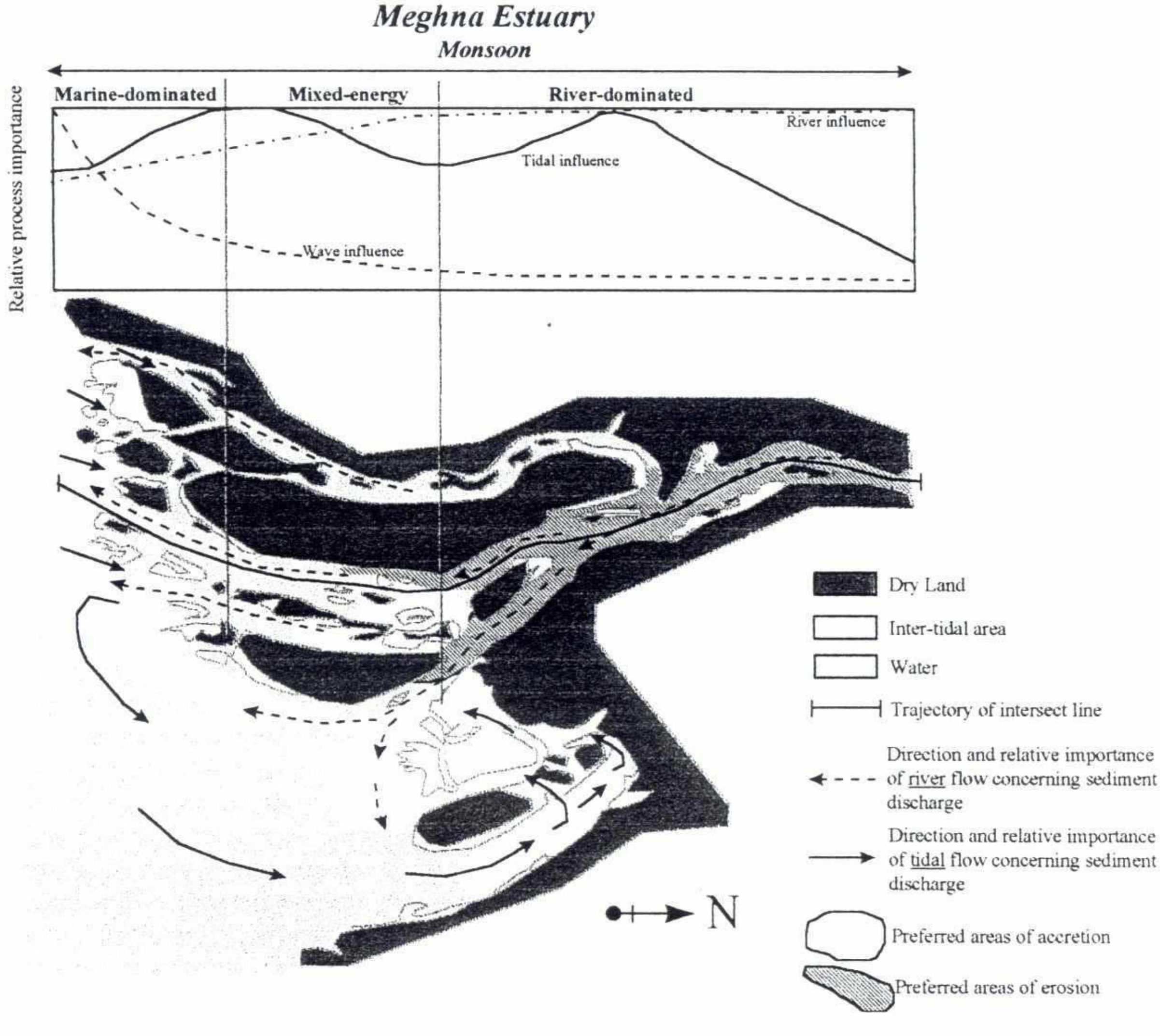
Monsoon period

In a large part of the estuary, the processes during the monsoon can be classified as river dominated (Figure 11.5). 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 and 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 of 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 11.5 : Conceptual model of dominant geomorphological processes during the monsoon

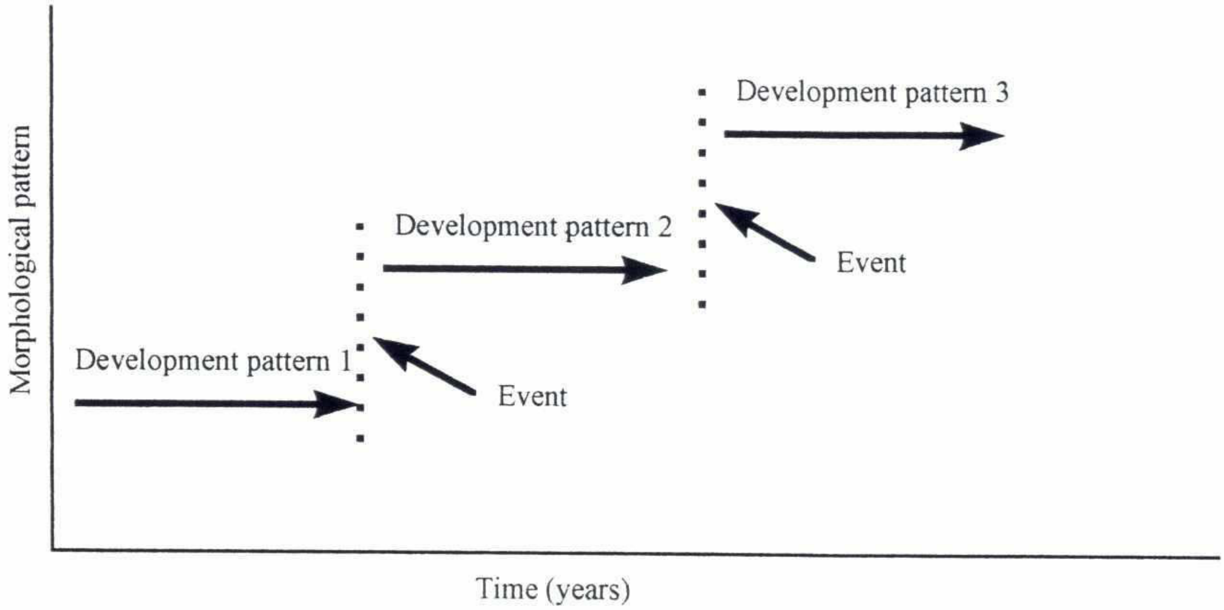


12. EXPECTED MORPHOLOGICAL DEVELOPMENT

12.1 Extrapolation of present planform evolution trends in the intermediate time scale

The historical development of the 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 12.1)

Figure 12.1 : The historical development of Meghna Estuary as a series of periods of continuous development interrupted by catastrophic events



Within each pattern, the morphological processes can be mapped empirically, or even by their cause and 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.

Little is known 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.

Here, an extrapolation of the present planform evolution trends over a time scale of 25 years is presented based upon the long term analysis of the geomorphological development and patterns over recent decades (Figure 12.2). Catastrophic events which might trigger a shift in morphological development and patterns are not taken into account. Figure 12.2 shows the expected position of the coastline in 2025. The expected position of the coastline is mapped by linear extrapolation of the coastline trends over period 1957-1996 (see also chapter 6) and morphological expertise.

The morphological trends indicate that the process of erosion and widening of the Lower Meghna River in the area between Chandpur and Bhola will continue in the coming 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 qualitatively in the map. It may be expected that new chars will develop in the braided river and migrate westward. 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 a southeast direction. The main islands Manpura and Hatia will also shift to the southeast. The heads of these islands will be exposed to erosion if no preservation measures are taken. Without further embankment and erosion protection measures, the erosion process and retreat of the north and east coastlines of Bhola towards the west will continue during the coming decades. The coastline along the Tetulia river is relatively stable and will not change much.

The areas around Nijhum Dwip, Rangabali and Kukri Mukri will extend eastward and new islands will develop. The position of the new islands is indicated on the map qualitatively. The coastline of Noahkali mainland area will extend to the south.

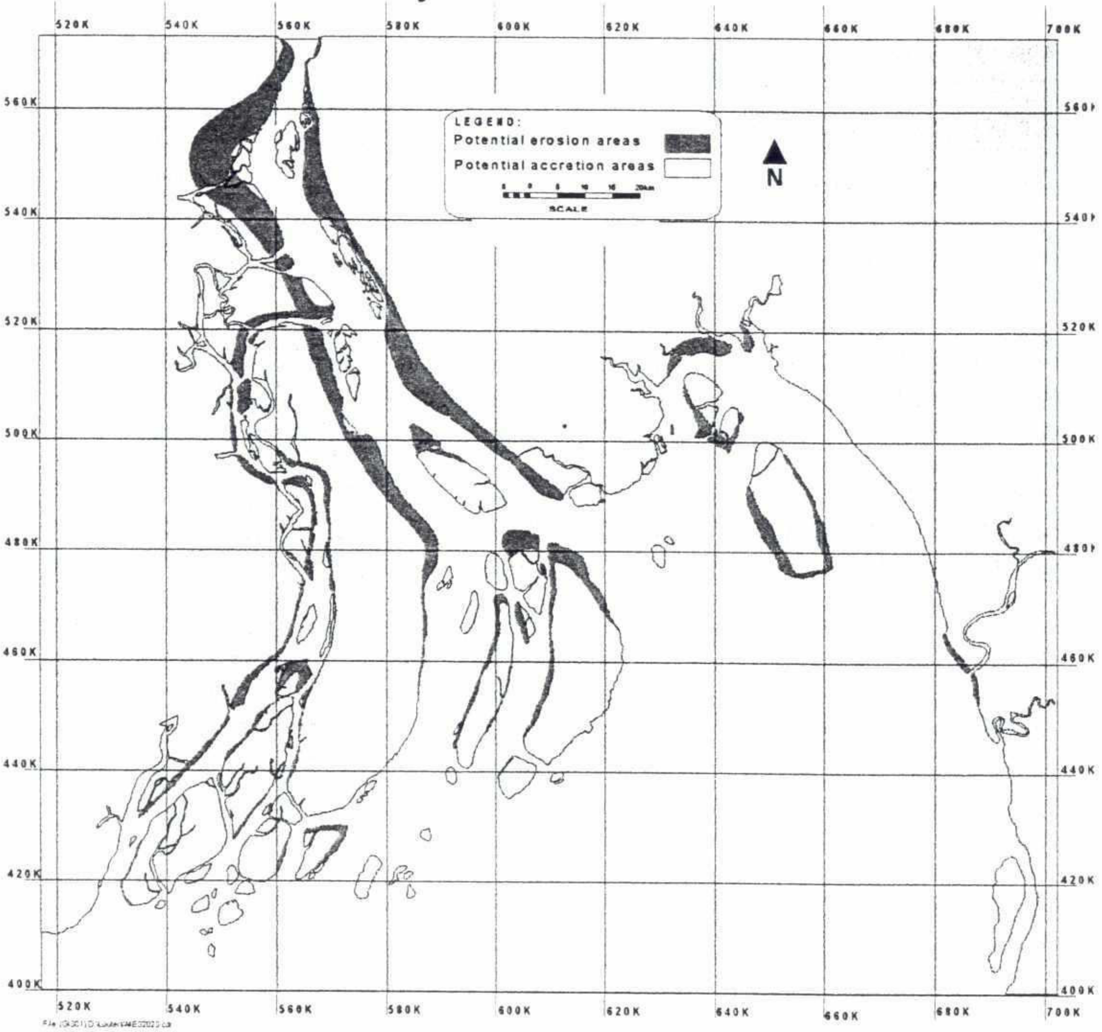
The long term morphological trend around Sandwip-Urir Char indicates net sedimentation. In this highly dynamic environment, zones with strong sedimentation will alternate with zones with strong erosion, both spatially and temporally: The tendency of the Sandwip Channel to silt up will continue but the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

The net natural gain of land will be in order of 10 km^2/year.

It is to be noted that the rate of land formation is relatively slow compared with the potentially 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.

Figure 12.2 : Extrapolation of present planform evolution trends over a time scale of 25 years

Figure 12.2: Extrapolation of Present Planform Evolution Trends over a Time Scale of 25 years



12.2 Potential land reclamation areas and land levels

In view of the expected morphological development due to interventions in the five pre-feasibility and feasibility development projects (Table 1.1), an analysis has been made 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 12.1 gives a qualitative synthesis for each development project of the importance of several hydrodynamic and morphological factors and the risk sensitivity to major events. In this synthesis an idea is given about the empoldering suitability of each area and the time span before which it 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 salt content 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 metres). The most easterly chars (Urir Char, Sandwip) are subjected to relative 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 rates (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 but 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. Mode studies indicate that the East Shahbazpur Channel will silt up rapidly and encourage the erosion process on the east side of Bhola. Around Urir Char - Sandwip the negative morphological side effects might also be significant. These morphological side effects should be studied in detail.

When the interventions are implemented, the time that is needed by emerging land area to become suitable for empoldering is speeded up by an order of 2 to 3. The older chars with a higher actual land level (Rangabali-Char Biswas, Char Montaz-Kukri Mukri, Nijhum Dwip) can be reclaimed within 5 to 15 years. The favourable hydrologic conditions, lower 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 the order of 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 12.1: Qualitative synthesis of the empoldering suitability of feasibility and pre-feasibility study areas

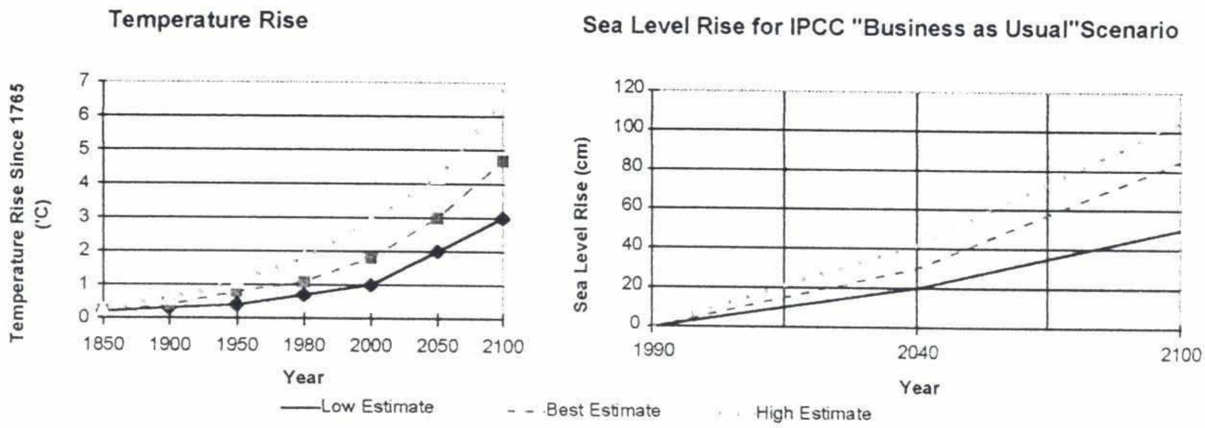
	Rangabali-Char Biswas	Char Montaz-Kukri Mukri	Nijhum Dwip	North Hatia-Manpura	Noakhali intertidal area	Urir Char-Sandwip
Potential for development						
Hydrodynamic aspects						
Overall energetic conditions	low-moderate	low-moderate	moderate	moderate-high	moderate-high	very high
Water level range (river)	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 before which area is unsuitable for empoldering (years)	15-30	15-30	10-30	20-40	20-40	20-40
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 which area is unsuitable for empoldering (years)	5-15	5-10	5-10	10-20	20-40	10-20

12.3 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. 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 especially vulnerable to changes.

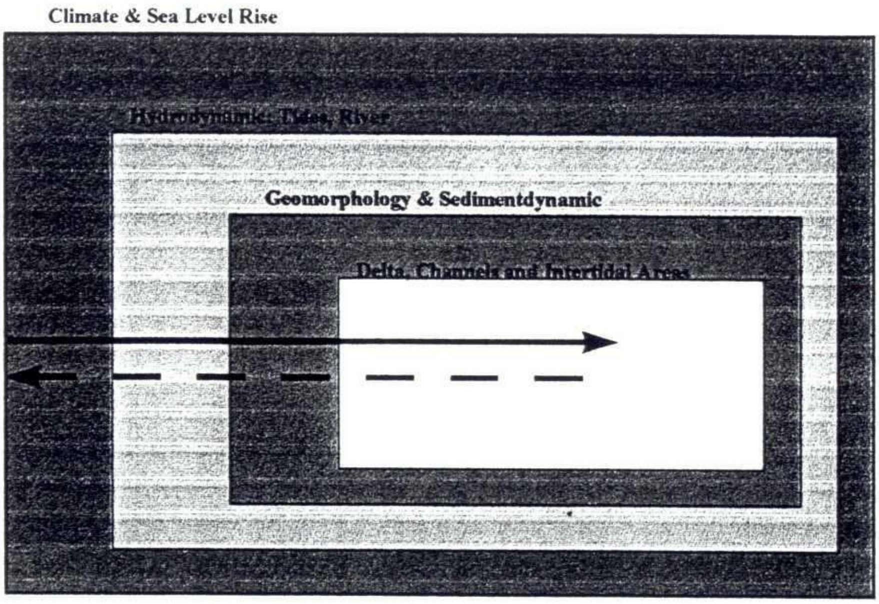
An increase of the greenhouse effect may imply a shift in radiation budget, a general temperature increase, changes in wind and cyclone characteristics and in global circulation (IPCC, 1990). A potential effect of a general increase of temperature is an increased sea level rise (SLR). Predictions in this respect however show large uncertainties especially in relation to the timing, the extent and regional patterns (IPCC, 1990). For Bangladesh this increase has been estimated to amount to an average value of 0.60 to 1.0 metre for the next century. Little is known about potential changes in wind and wave characteristics and related cyclones and storm surges. The results, in terms of anticipated temperature rise and accelerated sea level rise, for a "business as usual" scenario is shown on Figure 12.3.

Figure 12.3 : Temperature rise and sea level rise for PPC "Business as Usual" scenario



The ecosystem is affected by climatic change through a complex of interrelated processes. These processes may be ordered according to an hierarchical model (Figure 12.4). In this model outer compartments dominate inner compartments; feed-back is of secondary importance. Climatic changes induce changes in hydraulics, which in turn influence geomorphological developments. These changes in abiotic boundary conditions dominate changes in flora and fauna. This hierarchical model shows that due to an accumulation of uncertainties in estimates of the respective processes, any prognosis of ecological effects is bound to be only indicative.

Figure 12.4 : Hierarchical model of ecosystem interrelations



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 for many of these areas due to increased risk of flooding. 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 main three rivers Ganges, Jamuna and Meghna contributes to the elevation of the coastal area of Bangladesh. The Lower Meghna Estuary system consisting of the coast of the 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 has shown 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 in the coming decades, limiting the Lower Meghna Estuary system's freedom of movement. In the upstream river catchment areas, rapid human population growth accelerates the exploitation of the resources and consequently, the river hydro-morphology will change in response.

Fixing larger portions of the island 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. The increased incidence of floods is likely to flush these sediments 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 is 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 more 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 among disciplines and combined field, laboratory and modelling work is essential. This should be anchored at the institutional level.

12.4 Anthropogenic controls and integration of coastal and river zone management

In the coastal area, as well as in the upstream river catchment areas, rapid human population growth accelerates the exploitation of the resources and consequently the coastal and river hydro-morphology changes in response. 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 construction, etc. Whilst the influence of these factors on the river and estuarine system is often only known qualitatively, they can 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 that it 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.

13. SYNOPSIS AND CONCLUSION

13.1 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. The results presented in this report are based upon an analysis of remote sensing imageries, bathymetric data and historical coastline maps, and field surveys and numerical modelling. It outlines the well documented changes in the system's geomorphology over the last centuries and recent decades. Special attention is paid to the geomorphological development of pilot areas for executing pre-feasibility and feasibility studies.

The hydraulic and morphological conditions and processes that shape the morphology were studied through regional and detailed local 2D-numerical models. Simulations were carried out under different hydrodynamic conditions during dry and monsoon season to determine the behaviour of the entire estuary system and to quantify the consequences of different intervention options.

Based upon the findings of the field data and numerical model simulations, hypothesises 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 (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.

13.2 Hydraulic and morphological characteristics

The Meghna Estuary system is a very dynamic estuarine and coastal system. The Meghna Estuary system forms the northern end of the Bay of Bengal where some of the world's largest rivers, the Ganges, Brahmaputra and Meghna join and flow via the Lower Meghna river into 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 river borne sediment load of Lower Meghna river amounts to more than a billion tons annually and is dominated by silt to fine sand. The river discharge varies between approximately 20,000 m^3/s during the dry season to more than 100,000 m^3/s during the monsoon.

The changes in tidal flow direction and channel topography, the occurrence of new channels and newly accreted land and abandonment of old ones are the rapid building and destroying processes that exist in the estuary. These processes trigger changes in sedimentation and erosion rates which are directly related to the change in discharge and sediment content. The Meghna Estuary Study area is characterised by extensive shallow (mud)flats, numerous small and large islands (e.g. Hatia, Bhola and Sandwip) and chars. The major distributary system of the Lower Meghna include 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, we can say that the overall sediment budget is determined by the continuous redistribution process of the 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 the continuously changing tide flows.

From braided river to tide dominated morphology

The Upper Tetulia river and Lower Meghna river between Chandpur and North Bhola show a braided river dominated morphology. The area around Char Gazaria forms a transitional zone between the braided river dominated morphology and the southern area, which is more micro-tide and meso-tide dominated. 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 Meghna Estuary system exhibits a funnel shape. The river influence becomes progressively larger in an upstream direction as friction drains tidal energy. Tidal influence extends substantially farther upstream than salt intrusion and deltaic sedimentation occurs only in the subaqueous environment. There is appreciable upstream transport of bed load and suspended load sediment as a result of deformation of tide 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.

13.3 Hydraulic aspects

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 major tidal constituents are M2, S2, K1 and O1. The area around Sandwip island is macro-tidal with variation in tidal range of about 3 to 8 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 wet season) decreases significantly along the Lower Meghna Estuary in a southward direction. The seasonal variation of the mean high water level at Chandpur is about 2.7 m. The variation in the southern part of the Bangladesh coast is about 0.7 to 1.7 m.

Extreme value distributions of water level data indicate 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 varies from 3.2 metre at Khepupara to about 6.7 metre on the downstream side of the Feni Regulator.

Salinity

Salinity data indicate an enormous seasonal effect on salinity in the coastal area due to the influence of the huge fresh water discharge from the Lower Meghna river. Approximately during the period from mid August to mid October the salinity in the Meghna Estuary Study area drops considerably and the water becomes almost completely fresh. After the monsoon the salinities rises again and the sea water intrudes into the Study area. However, even during the period with low river discharges the salinities in the area never approach normal sea water salinity (34.5 ppt) but always remain distinctly lower. The steepness of the salinity gradient during the dry season is at a 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.

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13.4 Morphological changes over recent centuries and decades

Morphological changes over the last two centuries

Comparison of present configuration of the Meghna Estuary with that prepared by James Rennell (1776) shows that the net gain of land area is about 2,187 km^2, i.e., 9.9 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 different 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 of Bhola and Hatia islands 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 northwestern part of Study area (North Bhola-Chandpur), on Sandwip and the mainland of Chittagong.

Morphological changes during the last three decades

Gain of Intertidal Area

A time series of satellite images for the period 1973 to 1996 were used to examine the extent of land and intertidal area (i.e., mudflats) for each date and to assess the changes in the project area and in the nine subareas. Analysis of satellite images regarding the emergence of mudflats in the estuary (project area) indicates that about 3,100 ha of mudflats emerged each year during 1973-96.

The net change by period shows a net gain of intertidal area (i.e., mudflats) up to 1984, with a period of loss during 1984 to 1990, followed by net gain of mudflats during 1990-1996. The net change of mudflats for the period 1973-74 to 1996 is 70,589 ha. These results indicate an average long term annual rate of growth of mudflats of about 3,069 ha per year.

Gain of Land

The net change by period shows an overall land gain in the Meghna estuary system as a whole, for the period 1973-1996 of about 37,771 ha. The net change by period shows land loss up to 1984, with a period of gain during 1984 to 1990, followed by net land loss again during 1990 to 1993. During the period 1993 to 1996, a gain of land area of about 61,000 ha took place which accounts for much of the overall land gain for the period of study, 1973-74 to 1996. The annual rate of change for the entire study period ranged from a loss of nearly 7,000 ha/year during 1973-74 to 1979 period to a gain of over 20,000 ha/year during the period 1993 to 1996. The average annual gain for the entire study period is 1,642 ha/year.

Areas dominated by natural accretion

The changes for the period 1973-74 to 1996 show a vast area of new land off the southern coast of Noahkali. This land is associated with an even larger area of mudflat. These mudflats appear to be an extensive area of emerging land. A distinct sedimentation trend can be observed around the southern coast of Noahkali over the last 30 years. There are new char areas and new areas of mudflat northwest of Sandwip island. Other large areas of accretion include the very large char at the head of Shahbazpur Channel, which appears to be a 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 southwest of the study area, including Char Rangabali, Char Biswas, Char Montaz and Char Kukri Mukri. With respect to the large areas of accretion in the southwest 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. Erosion of the east bank of the Lower Meghna around Haimchar is about to engulf the already retired embankment of the Chandpur Irrigation Project. The retreat of the west and east banks of the Lower Meghna varies from 50 metres to more than 200 metres per year. The north and northeast banks of Hatia and Bhola up to a point downstream of Tazumuddin are affected by erosion. The northwest coast of Bhola is experiencing erosion. Land on the east bank of the Lower Meghna River around Ludua opposite to Char Ramdaspur and on the west bank of the East Shahbazpur channel opposite to the Char Gazaria are also eroding. The entire west coast of the Hatia island is experiencing erosion except the small extreme southwest coast of Hatia located at the north of the entrance of the Nijhum Dwip channel from the Shahbazpur channel.

Figure 13.1 illustrates the huge loss of land over the last decades due to widening and migration of the Shahbazpur channel and the net gain of land to the seaward.

The southeast, south and the entire west coast of Sandwip are erosion affected areas. The retreat of the west and east sides of Sandwip is in the order of 10 to 150 metres per year.

The natural developments in the past, as shown by the historical maps, clearly indicate that most of the land gains and losses can be explained by the migration of the main conveyance channels or by migration of islands, with old land eroded in one place being replaced elsewhere in due course. Therefore, the preservation of old land with its villages and infrastructure is considered at least equally important as the reclamation of new land in the master plan.

Channel Geometry

The cross-sectional area of the West Hatia channel at the northern tip of Hatia island shows a decreasing tendency during the last ten years. Over the same period the average channel depth is showing a tendency to increase slightly.

The cross-sectional area and the average channel depth of the East Shahbazpur channel between Char Gazaria and the Noahkali mainland have shown a tendency to decrease slightly over recent decades. The cross-sectional area of the West Shahbazpur channel has shown a distinct trend to increase over the period 1981-1994. Over the same period the average channel depth decreases. 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.

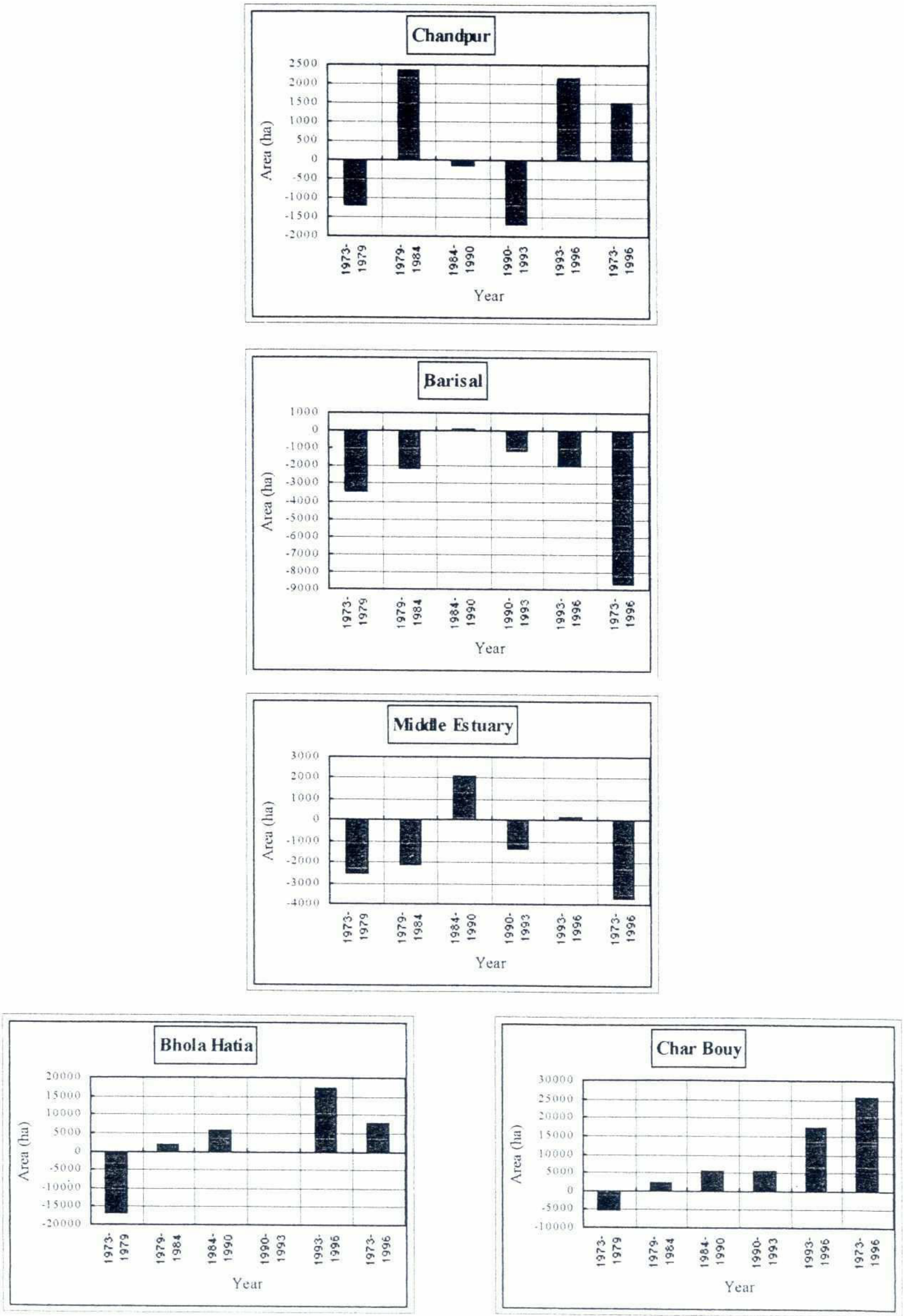
13.5 Sediment transport and sediment budget

Sediment characteristics

The bed of the Lower Meghna river consists of silt to fine sand with a median bed material grain size varying from 16-200 μm. The bed material size varies in both the transverse and downstream directions of the river. A major part of the bed material (70%) has a median grain size less than 75 μm.

The maximum depth average sediment concentration varies between 0.5 and 9 grams per litre. During spring tide the concentration is about 2-5 times higher than during neap tide. The maximum concentration can be found near the Urir Char - Char Balua area and Manpura - North Hatia area.

Figure 13.1 : Net Change of land along the Lower Meghna



Sediment budget

An overall sediment budget is not available. Over the period 1986-1992 a maximum net erosion rate of 0.3-0.4 metres per year occurs in the area of North Bhola - Char Gazaria. This amounts to net erosion of 141 million cubic meters. The sediment budgets around Manpura-South Hatia, Nijhum Dwip-Damar Char and Urir Char - Char Balua all show positive trends with an average rate of about 0.2 metres per year.

The sediment concentration near Urir Char - Char Balua is very high (1-9 grams per litre) compared to the net sedimentation rate. The local high energetic macro-tidal flow is assumed to be responsible for the high sediment concentrations.

Sediment transport

The average total annual sediment discharge of the Jamuna and Ganges over the period 1966-1991 is about 1,100 million tons per year. The sediment discharge of the 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.

The sediment rating curve is given by an exponential equation that describes the sediment transport in relation to discharge. The results show that the sediment rate curve is independent of flood or ebb conditions. The exponent varies between 0.9 and 1.5. This is a relatively low value and indicates a smaller than expected increase in sediment transport with the increase of discharge. Further investigations are needed to explain the low value of the exponent.

13.6 Dominant hydraulic and morphological processes

Numerical modelling

As a part of MES, a numerical hydraulic model was set up. It is based on planform, bathymetry and calibration data from 1996-97, which have largely been produced by MES. The model can describe water levels, flow rates and current velocities, salinities, and mass budgets for solutes, as well as waves and erosive capacity. Calibration and validation of the model was based upon field survey data of the water level of several gauge stations and transect measurements. The model covers the estuary from Chandpur and downstream, an area of 216 km (east-west) by 175 km (north-south), with a grid size of 600 metres.

To support the morphological analysis, a series of indicative sediment transport simulations were carried out under different hydraulic conditions during dry season and monsoon.

Waves

According to the indicative model simulations of situations with and without waves, the overall 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

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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, thereby 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 and the transport capacity of the main net flow channels are at their highest (while, in the purely tidal channels, the transport capacity is more or less the same all year). In this season, the major erosion and accretion takes place.

As 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 lost 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 grams 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 seasonal changes in river flow suggest that sediment can accumulate in the upper estuary during the pre-monsoon and post-monsoon and be redistributed down the estuary during monsoon.

Residual circulation and estuarine trapping

Within the Lower Meghna Estuary 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.

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.

Preliminary results of erosion and sedimentation during monsoon indicate an overall tendency of silting up of the Sandwip Channel and levelling up of the shallow areas between Hatia and Sandwip. An overall sedimentation trend can also be seen near the edge of the delta front where new islands and intertidal areas are formed and silted up. The results show a dominant erosion trend around north Hatia and north Bhola. 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 only slowly.

The east and southeast sides of Hatia also tend to silt up slowly. Sedimentation seems to be dominant in the shallow areas around Nijhum Dwip and the area around Rangabali-Kukri Mukri.

The erosion of cohesive banks can also be enhanced by breaking waves, although the main erosion mechanism is the current, sometimes in combination with a hydrostatic ground water pressure at low tide. In this respect, the sediment transport in the estuary resembles the pattern of the main river system, except for the regular and relatively fast water level changes.

Although the physical knowledge of the hydro-morphological processes which shape the Lower Estuary Study area is narrow, the model results are fairly good: the simulated current and discharge show good agreement with hydraulic observations. The preliminary results of the overall sediment transport patterns show good agreement with the computed morphological changes and also with bathymetric observations and appear qualitatively reasonable.

The complex erosion and sedimentation patterns resulting in the general trends of geomorphological changes were calculated more or less satisfactorily in the study area. The results of the uncalibrated sediment transport model indicate an overestimation of the initial rates of bed level changes and sediment transport discharge.

Quantitatively, the model results appear insufficient for prediction of future changes on an intermediate time scale. For this purpose additional field information is necessary to interpret the model generated forecast and to calibrate the sediment transport model. The model results are useful, however, to analyse the relative effects of different transport processes on the development of different geomorphological units.

13.7 Interventions

In general, the hydrodynamic impact on regional scale of the proposed interventions is small. On the local scale the flow velocity can reduce up to nearly 100 per cent which encourage the accretion process enormously. Further, the impact is inversely related to its significance: the dry season impact is more visible than the monsoon impact, and the net flow is more affected

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than the maximum velocities. One reason for this is that the overall flow resistance of the estuary as a whole is less in the monsoon, due to the higher water level. There are no indications of any effects in the Lower Meghna nor in the inland river system north of the study area.

Hydraulic simulations indicate that closing of the Nijhum Dwip-Hatia Channel will create a water level difference between the east side and the west side of the cross dam of about 0.10 - 0.30 metres.

The water level differences in the case of the closing of the Sandwip-Urir Char Channel will be in the order of 0.40 - 0.80 metres. The hydraulic simulations indicate also that the maximum water level in the Sandwip channel will increase by about 0.40-0.80 metres. At the same time the maximum water level in the East Hatia channel near the cross dams will fall by about 0.2-0.5 metres. Implementation of the Sandwip cross dams without further measures to strengthen the embankments reduce the safety against flooding of the embanked coastal areas around the Sandwip Channel.

The water level, particularly in the Sandwip channel, seems to be very sensitive to tidal conditions and river discharge. To estimate the best closing strategy more study is needed to define the optimal hydraulic conditions for closing the tidal channels.

The simulations of the future salinity distribution indicate unchanged levels in the major part of the estuary, including Tetulia River (where the salinity is nil today, and should remain so). The salinity is most visibly affected by a cross dam (or a natural closure) of the passage north of Sandwip. For this scenario, the salinity is somewhat reduced around the mouth of Feni River and in Sandwip Channel and is somewhat increased in the area between Sandwip and Hatia.

14. RECOMMENDATIONS

14.1 Field survey

LRP and MES experience shows that the project area has complex hydraulic and morphological characteristics. Bathymetry (affecting navigation, flooding, erosion and sedimentation, etc.) and flow distribution and sediment transport distribution data of priority project areas as well as selected areas of the estuary (as the primary variables of the physical system) are to 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 which can in turn induce i) loss of land, and ii) damage to coastal structures, such as embankments. The zero levels of established water level gauges should be verified and tied to PWD or SOB.

More bathymetric data and levelling data are needed to enhance the knowledge about the dominant process in shallow areas and their sediment budget characteristics.

The zero levels must be checked during gauge shifts. Future morphological studies could benefit from referring to the same datum. Automatic water level gauges should be installed at remote stations.

14.2 Numerical modelling

The shallow areas will be surveyed by hovercraft and shallow area model bathymetry should be updated. A limited calibration of the existing model of the MES should be done. The bathymetry of the whole Meghna Estuary should be updated with new data and the 1998 coastline. Hydrodynamic, salinity, wave and sediment transport simulations as carried out during MES should be rerun.

In order to suitably upgrade the present MES model, it must be nested with a bigger model having the boundary in the deep sea. A boundary in the deep sea is required because the outer boundary conditions must be unaffected by the impact to be described by different simulations (especially salinity and wave simulations). After combining the calibrated MES model with the latest bathymetry (specially shallow areas) and the latest land level from FINNMAP surveys, the nested model will be used for running different development scenarios and undertaking impact analysis.

14.3 Integrated coastal zone management

Through surveys and studies, an understanding has been obtained of the forces that control the ever changing pattern of land in coastal zone and sea areas in the project area. From this understanding, a phased long term Master Plan with a planning horizon of 25 years and a short term Development Plan describing the priority interventions that are recommended for implementation within next 10-15 years were developed. An integrated and multidisciplinary approach was adopted in developing the Master Plan and Development Plan.

Coastal zone management aims at solving present and future problems in the coastal zone, by finding a balance between economic welfare and environmental well-being. At MES, this was achieved by careful analysis, planning and interpretation of the natural processes and socio-economic developments. There will be a need for controlled development of the Bangladesh coastal zone in an integrated manner because population growth and associated economic development and the erosion of existing valuable agricultural land will place demands on coastal areas and resources, posing threats to the sustainability of the areas. Excepting natural erosion of channel banks, resource use conflicts are often the primary underlying cause of problems as they result in the unsustainable use and unrestricted development of coastal areas and resources. For example, there is evidence of over-exploitation of fishery resources in MES area. The demand of settlers for more land for agriculture, livestock and aqua-culture by cutting foreshore mangrove belts which are used as safety belts during cyclones in islands like Nijhum Dwip is in conflict with the interest of stakeholders in forestry resources. When mangroves are logged and cleared in an unsustainable way or are polluted beyond their filtering capacity, this will be at the expense of functions that enable fish to breed and be caught in the same area, and hence of those depending on fisheries. MES formulated its Development and Master Plans in such a way that the maintenance of all functions at a sustainable level would provide higher economic returns over a longer period of time.

Integrated Coastal Zone Management (ICZM) provides a framework and practical tools to assist policy makers, planners, and resource managers to meet the challenges of sustainable development in the coastal areas. MES, based on its experience in developing a sustainable and integrated coastal zone management plan for the Meghna Estuary of Bangladesh, recommends the following for the successful implementation of its Development Plan and Master Plan:

- An organisation should be mandated to plan, adopt and implement ICZM programmes or projects with appropriate and adequate legal and institutional framework. Planning measures and strategies is useless if they cannot be implemented and enforced by laws and regulations and if there is no clear organisational infrastructure to manage the coastal zone system.

- Adopt a systematic, incremental approach in developing and implementing ICZM projects and programmes. ICZM plan was developed in a systematic manner which allows time for soliciting financial resources and building local managerial and technical capacities to support the identification and implementation of appropriate technological interventions; promoting interagency and stakeholders co-operation and co-ordination. It is appropriate to apply ICZM on a local level and proceed to more ambitious district and national levels after sufficient expertise has been developed.

- Involve the public in ICZM process. Involve the interested and affected parties at all phases and levels of an ICZM programme development and implementation. The public and private stakeholders can contribute to the identification of use conflicts and environmental management problems, determination of their causes and effects, and to their resolution.

- Integrate environmental, economic, and social information from the very beginning of the ICZM process. Due to the complex and dynamic nature of the Meghna Estuary, it is very important to integrate hydrologic, hydraulic, morphologic, environmental, economic, and social information at the very start of the coastal development projects and programmes. Information gathering is a continuous process in the ICZM cycle, enriching our knowledge as the process progresses.

- Develop institutional mechanisms which facilitate integration and co-ordination. Integration brings about the harmonisation of policies and legislation between national and local organisations. Co-ordination plays a central role in fostering understanding and co-operation among stakeholders, line agencies, researchers, policy-makers, and resource managers.

- Establish sustainable financing mechanisms within the ICZM programme to ensure programme continuity. Sources of finance which can be used to sustain management activities should be explored before finalising the ICZM project or programme plan.

- Develop ICZM capacity at all levels. Strengthen the capacity of stakeholders to effectively contribute to the ICZM programme. Integration of professional skills of different disciplines are required to support the formulation, design and implementation of successful ICZM programme. These are, e.g., ecology, geomorphology, marine biology, economics, sociology, engineering, political science (institutions) and law.

- Monitor the effectiveness of ICZM projects and programmes. Monitor the social, environmental and economic impacts throughout the life of the ICZM programme. Monitoring provides a powerful tool for assessing the performance of projects and gives early warning of adverse effects so that corrective action can be taken to modify the design and management of projects to avoid irreversible impacts.

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APPENDICES

Chronology of major cyclonic storms and tidal surges in Bangladesh

Year of occurrence	Month and date of occurence	Affected area	Nature of the phenomena	Approximate loss/damage
1797	May-June	Chittagong	Most severe	Every hut levelled to ground and 2 vessels sunk in Chittagong port
1822	May	Barisal	Most severe	Collectorate records were swept away. 40,000 people killed and 1,00,000 cattle lost
1831	October	Barisal	Storm wave	Damage report not available
1872	October	Cox's Bazar	Storm	Many lives lost and cattle destroyed.
1876	October	Meghna estuary	Most severe storm wave 10-45 ft.	Hatiya, Noakhali, Patuakhali, Chittagong coast affected. A great number of population lost and enormous properties lost by tidal bore.
1895	October	Sundarban	Cyclone accompanied by storm wave	Bagerhat sub-division affected.
1897	October	Chittagong	Hurricane reached maximum intensity with series of storm waves	Kutubdia Island and villages on mainland near coast were swept away. 14,000 people were killed and 18,000 died subsequently in epidemic.
1898	May	Teknaf	Cyclonic and storm waves	Damage report not available
1901	November	Western Sundarbans	Ditto	Ditto
1909	October	-	Ditto	Ditto
1909	December	Cox's Bazar	Ditto	Ditto
1911	April	Teknaf	Ditto	Ditto
1917	May	Sundarbans	Ditto	Ditto
1919	September	Barisal	Ditto	Ditto
1922	April	Teknaf	Ditto	Ditto
1923	May	Teknaf	Ditto	Ditto
1926	May	Cox's Bazar	Storm wave	Ditto
1941	May	Eastern Meghna estuary	Cyclonic with storm wave	Eastern Meghna coast, and adjacent islands affected
1942	October	Sundarban	Servere cyclonic storm	Damage report not available
1948	May 17-19	Between Chittagong and Noakhali	Cyclonic storm	Ditto
1950	Nov. 15-20	Patuakhali	Ditto	Ditto
1958	May 16-19 Oct. 21-24	East Meghna estuary, east of Barisal, Noakhali and West Meghna estuary	Ditto	Ditto
1960	May 25-29	Sundarban coast	Ditto	Ditto
1960	Oct. 9-10	Eastern Meghna	Severe cyclonic storm 125 miles per hour, maximum storm wave 10 ft.	Considerable damage to Char Jabbar, Char Amina, Char Bhati, Ramgati, hatiya and Noakhali. 3000 people reported killed.
1960	Oct. 30-31	Chittagong	Severe cyclonic storm maximum speed 130 miles per hour, surge height 20 ft.	70 percent, building in Hatiya blown off, 2 large ocean liners washed ashore, 5-7 vessels capsized in Karnaphully river and 8149 people killed.
1961	May 9	West Meghna estuary	Severe cyclonic storm, speed 90-92 mile per hour, wave 8-10 ft.	Rail track between Noakhali and Harinarayanpur damaged. Heavy loss of life in Char Alexander and 11468 people killed.
1961	May 30	Chittagong Noakhali coast and off-shore island	Cyclonic storm 59 miles per hour at Chittagong.	Damage report not available.

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Year of occurrence	Month and date of occurence	Affected area	Nature of the phenomena	Approximate loss/damage
1962	Oct. 26-30	Near Feni	Ditto	Ditto
1963	May 28-29	Chittagong, Cox's Bazar	Severe cyclonic storm with storm wave 8-12 ft. in Chittagong. Maximum speed 125 miles per hour and Cox's Bazar 102.	Chittagong, Noakhali, Cox's Bazar and off-shore Islands badly affected, 11520 people killed.
1963	June 5-8	Near Jessore	Cyclonic storm	Damage report not available
1663	October 25-29	Near Teknaf	Ditto	Faridpur, Khulna, Jessore, Chittagong & Noakhali affected.
1965	May 11-12	Barisal	Most severe cyclonic storm, maximum speed 100 miles per hour, with storm wave 12 ft.	Total loss of life 19,270. In Barisal alone 14,193 people were killed.
1965	December 14-15	Cox's Bazar	Severe cyclonic storm with storm wave 8-10 ft. Maximum speed 130 miles per hour in Cox's Bazar.	40,000 salt beds in Cox's Bazar inundated, 873 people were killed.
1966	October 01	Sandwip	Severe cyclonic storm with storm wave 20 to 22 ft.	Chittagong district affected, 850 people, killed.
1966	December 12	Near Cox's Bazar	Cyclonic storm	Damage report not available.
1967	October 11	Khulna and Sundarban coast	Ditto	Ditto
1967	October 23-24	Near Cox's Bazar	Ditto	Ditto
1969	April 14	Dhaka (Demra)	Tnado locally known as Kalbaishakhi wind speed was 400 M. P. H.	922 people killed & injured 16511, estimated loss 40 to 50 Million Taka.
1969	October 11	Khulna coast	Cyclone storm	Damage report not available
1970	May 7	Chittagong coast south of Cox's Bazar	Ditto	Ditto
1970	October 23	Khulna, Patuakhali	Severe cyclonic storm with storm surge.	No heavy damage report received.
1970	November 12-13	Meghna estuary	Most severe cyclonic storm accompanied by storm surge 10-33 ft. Reported speed 138 miles per hour.	Wind speed damage to crops and property. About three lakh lives were lost. A great number of animals were also killed.
1971	May 7-8	Meghna estuary	Cyclonic storm 50 m. p. h.	
1971	November 5-6	Chittagong coast	Severe cyclonic storm	
1971	November 28-29	Sundarban coast	Low lying areas of Khulna town inundated. The district of Khulna experienced stormy weather and wind reaching a speed of 60-70 m. p.h. Storm surge 2 ft.	
1973	November 16-18	Chittagong coast	-	
1973	December 6-7	Sundarban coast	Severe cyclonic storm, low-lying coastal areas of Patuakhali and offshore islands inundated any storm surge.	-
1974	August 13-15	Khulna coast	Severe cyclonic storm 50 mph.	

Year of occurrence	Month and date of occurence	Affected area	Nature of the phenomena	Approximate loss/damage
	November 24-28	Coastal belt from Cox's Bazar to Chittagong and offshore islands	Severe cyclonic storm 100 mph 9-17 ft. storm surge.	20 persons killed 1000 cattle killed 2300 dwelling houses perished.
1975	May 9-12	Bhola Cox's Bazar and Khulna	Severe cyclonic storm 60-70 mph	5 persons killed 36 fishermen missing.
1976	October 19-20	Meghna estuary	-	-
1977	May 9-12	Khulna, Noakhali, Patuakhali, Barisal, Chittagong and off-shore islands.	Cyclonic storm 70 m.p..h.	-
1978	September 30 to October 3	Khulna and Sundarban Coastal	Cyclonic storm 46 m.p.h. (40 kts)	
1979 1980 1981 1982		No major cyclonic stroms reported		
1983	Oct. 15	Chittagong coast near the Feni River	Cyclonic storm with a speed of 122 k.p.h.	43 persons killed, 6 fishing boats and a trawler drowned, more than 1000 fishermen and 100 fishing boats reportedly missing and 20% aman crops destroyed.
	Nov. 9	Chittagong Cox's Bazar coast near Kutubdia and the low lying areas of St. Martin, Teknaf, Ukhya Moheshkhali and Sonadia	Severe cyclonic storm (Hurricane) with a speed of 136 k.p.h and a storm surge of 5 feet height.	300 fishermen with 50 boasts reportedly missing, 2000 kutcha houses destroyed.
1985	May 24-25	Chittagong, Noakhali coast	Severe cyclonic storm of 154 km/hr. and surge of 14 ft.	Cox's Bazar, Chittagong, Sandwip, Haiya, Noakhali and Urir char affected. 11069 persons killed, houses damaged : 94379 Livestock lost 135033, Road damaged 40 miles, Embankment damaged.
1986	Nov. 09	Chittagong, Patuakhali & Barguna	Cyclonic storm hit 110 km/hr. at Chittagong & 90 at Khulna	14 persons killed, crop damage 240000 acres of paddy, Huge damage to schools, Mosques, Godowns Hospitals, houses and buildings at Amtali upazila in Barguna.
1988	Nov. 19	Khulna coast near river Raimangal	Severe Cyclonic storm with core wind speed 160 km. per hour storm surge 14.5 ft. at Mongla Point	People killed 5708 Deer killed 15000 Royal Bengal 09 Cattle killed 65000 Crops damaged : Tk. 9410 million
1989	April 26	Shaturia	Tornado, 210-260 mph	
1991	April 29	Ctg. Cox's Bazar Noakhali, Patuakhali, Barguna & Kutubdia etc.	Cyclonic storm hits 120 mph, Tidal bore	People killed 150,000 Cattle heads 70,000 crops damaged Tk. 4,200 crores.
1991	June 2	Ctg. Cox's Bazar Barisal, Patuakhali Barguna & Kutubdia	Tidal bore and thunderstorm	
1992	May 17-19	Chittagong, Cox's Bazar	Cyclonic storm	
1992	Nov. 17-21	Saver	Cyclonic storm weaken into depression.	
1993				

Source: Bangladesh Meteorological Department.

Wind Statistics of Nine Meteorological Stations

Table-1 : Monthly Wind Statistics of Bhola BMD Station

BHOLA Wind (knots)								
1996 Month	Mode (Degree)	Prevailing Speed	Prevailing Direction	Maximum Speed	Maximum Direction	Min	Ave. Speed	Std (Speed)
Jan	360	2.42	N	4	N	0	0.47	1.02
Feb	360	2.33	N	4	N	0	0.73	1.22
March	225	4.70	SW	10	SW	0	2.43	2.32
April	180	2.95	S	6	SSW	0	1.68	1.67
May	180	4.55	S	16	S	0	3.00	3.32
June	180	3.41	S	10	SW	0	1.83	2.13
July	180	2.78	S	8	S	0	1.52	1.66
August	180	2.43	S	10	SW	0	1.25	1.51
Sept	180	2.75	S	6	SE	0	0.72	1.28
October	270	3.17	W	24	SE	0	0.85	2.46
Nov	360	2.15	N	4	SW	0	0.26	0.72
Dec	360	2.00	N	3	N	0	0.27	0.69
Annual		3.14	S	24	SE	0	1.25	2.01

BHOLA Wind (knots)								
1997 Month	Mode (Degree)	Prevailing Speed	Prevailing Direction	Maximum Speed	Maximum Direction	Min	Ave. Speed	Std (Speed)
Jan	360	2.14	N	4	W	0	0.36	0.92
Feb	230	2.46	SW	4	NW	0	0.62	1.11
March	180	3.58	S	12	NW	0	1.60	2.29
April	180	3.06	S	10	SE	0	1.24	1.82
May	180	3.26	S	26	N	0	2.35	2.96
June	180	3.13	S	10	SE	0	2.45	2.23
Jan-June		3.26	S	26	N	0	1.45	2.17

Wind Statistics of Nine Meteorological Stations

Table-2 : Monthly Wind Statistics of Chandpur BMD Station

CHANDPUR								
Wind (knots)								
1996	Mode	Prevailing		Maximum		Min	Ave. Speed	Std (Speed)
Month	(Degree)	Speed	Direction	Speed	Direction			
Jan	360	2.00	N	6	NW	0	0.67	1.18
Feb	315	2.62	NW	8	NW	0	1.11	1.65
March	180	3.09	S	6	S	0	1.53	1.70
April	180	2.28	S	25	NW	0	1.24	2.05
May	180	3.98	S	12	S	0	2.13	2.39
June	135	3.10	SSE	10	SE	0	1.85	2.18
July	135	2.38	SSE	6	S	0	1.22	1.35
August	135	2.31	SSE	6	E	0	1.15	1.34
Sept	315	1.93	NW	5	SW	0	0.80	1.10
October	315	2.52	NW	12	SE	0	1.02	1.80
Nov	315	2.00	NW	4	NW	0	0.77	1.02
Dec	315	2.29	NW	8	NW	0	1.11	1.29
Annual		2.27	NW	25	NW	0	1.22	1.69

CHANDPUR								
Wind (knots)								
1997	Mode	Prevailing		Maximum		Min	Ave. Speed	Std (Speed)
Month	(Degree)	Speed	Direction	Speed	Direction			
Jan	310	2.17	NW	6	N	0	0.77	1.19
Feb	180	2.07	S	5	NW	0	0.86	1.24
March	230	2.51	SW	6	SW	0	1.04	1.28
April	180	2.09	S	11	SE	0	1.26	1.55
May	180	3.35	S	15	NE	0	2.06	2.34
June	180	2.64	S	15	SE	0	2.15	2.57
Jan-June		2.54	S	15	SE	0	1.36	1.87

Wind Statistics of Nine Meteorological Stations

Table-3 : Monthly Wind Statistics of Chittagong BMD Station

CHITTAGONG WIND (knots)								
1996	Mode	Prevailing		Maximum		Min	Ave. Speed	Std (Speed)
Month	(Degree)	Speed	Direction	Speed	Direction			
Jan	22	4.59	NNE	12	SSW	0	1.81	2.74
Feb	22	4.29	NNE	15	SSW	0	2.12	2.98
March	180	14.47	S	35	S	0	8.02	7.80
April	180	8.55	S	25	NNW	0	5.63	5.06
May	157	11.45	SSE	35	S	0	9.06	6.87
June	180	14.86	S	46	S	0	10.78	7.45
July	180	9.70	S	24	SSE	0	9.30	5.81
August	157	9.07	SSE	30	SSW	0	7.86	5.90
Sept	180	10.46	S	27	NE	0	4.10	5.42
October	360	5.68	N	35	E	0	4.94	6.08
Nov	360	4.00	N	9	W	0	1.24	2.29
Dec	360	5.36	N	14	NW	0	2.07	2.91
Annual		8.54	S	46	S	0	5.60	6.31

CHITTAGONG Wind (knots)								
1997	Mode	Prevailing		Maximum		Min	Ave. Speed	Std (Speed)
Month	(Degree)	Speed	Direction	Speed	Direction			
Jan	350	4.46	N	12	W	0	1.94	2.89
Feb	180	8.44	S	17	S	0	2.71	3.50
March	180	10.23	S	22	S	0	5.10	5.84
April	180	5.88	S	23	NE	0	4.08	4.26
May	180	10.38	S	25	S	0	6.82	5.57
June	180	11.06	S	50	SE	0	9.10	6.01
Jan-June		9.20	S	50	SE	0	4.98	5.42

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Wind Statistics of Nine Meteorological Stations

Table-4 : Monthly Wind Statistics of Cox's Bazar BMD Station

COX'S BAZAR Wind (knots)								
1996	Mode	Prevailing		Maximum		Min	Ave. Speed	Std (Speed)
Month	(Degree)	Speed	Direction	Speed	Direction			
Jan	360	6.56	N	20	N	0	3.46	3.79
Feb	22	5.48	NNE	14	NE	0	3.36	3.39
March	180	6.90	S	23	NE	0	5.15	4.91
April	202	5.54	SSW	24	N	0	3.22	3.56
May	180	8.71	S	35	N	0	6.19	4.82
June	180	7.58	S	22	SW	0	5.86	4.81
July	180	7.78	S	16	SSW	0	5.23	3.81
August	180	6.55	S	17	SSW	0	4.13	3.66
Sept	202	6.56	SSW	12	S	0	2.76	3.17
October	360	5.33	N	14	S	0	2.95	3.27
Nov	360	4.86	N	10	NNW	0	1.98	2.62
Dec	360	5.29	N	12	NE	0	1.95	2.84
Annual		7.51	S	35	N	0	3.86	4.04

COX'S BAZAR Wind (knots)								
1997	Mode	Prevailing		Maximum		Min	Ave. Speed	Std (Speed)
Month	(Degree)	Speed	Direction	Speed	Direction			
Jan	30	5.94	NNE	14	NNW	0	2.48	3.38
Feb	330	6.30	NNW	13	N	0	2.08	3.12
March	210	7.26	SSW	22	S	0	3.24	3.89
April	210	5.91	SSW	18	NW	0	2.57	3.80
May	180	7.53	S	95	SSW	0	5.52	9.05
June	180	7.05	S	19	NNE	0	5.42	4.18
Jan-June		7.29	S	95	SSW	0	3.57	5.22

Wind Statistics of Nine Meteorological Stations

Table-5 : Monthly Wind Statistics of Hatia BMD Station

HATIA								
Wind (knots)								
1996 Month	Mode (Degree)	Prevailing		Maximum		Min	Ave. Speed	Std (Speed)
		Speed	Direction	Speed	Direction			
Jan	360	2.82	N	13	N	0	0.68	1.34
Feb	180	4.19	S	6	SE	0	0.98	1.65
March	180	6.38	S	25	N	0	3.49	4.67
April	180	4.82	S	16	SW	0	3.24	3.47
May	180	6.23	S	20	NNE	0	4.81	4.24
June	180	5.79	S	28	SE	0	4.25	4.81
July	180	4.69	S	16	SE	0	3.44	3.32
August	180	3.69	S	15	SE	0	2.48	3.02
Sept	157	4.03	SSE	15	E	0	1.46	2.21
October	45	2.28	NE	20	SE	0	1.53	3.13
Nov	360	2.89	N	6	SSW	0	0.68	1.28
Dec	360	2.42	N	8	NE	0	0.99	1.35
Annual		5.11	S	28	SE	0	2.35	3.44

HATIA								
Wind (knots)								
1997 Month	Mode (Degree)	Prevailing		Maximum		Min	Ave. Speed	Std (Speed)
		Speed	Direction	Speed	Direction			
Jan	50	3.54	NE	17	NE	0	0.86	1.96
Feb	130	3.46	SE	20	SW	0	1.44	2.78
March	130	4.27	SE	60	ENE	0	2.39	5.42
April	180	4.06	S	30	SSE	0	2.63	3.92
May	180	7.88	S	118	NW	0	5.29	10.40
June	180	7.59	S	50	S	0	6.96	7.36
Jan-June		6.51	S	118	NW	0	3.28	6.44

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Wind Statistics of Nine Meteorological Stations

Table-6 : Monthly Wind Statistics of Khepupara BMD Station

KHEPUPARA Wind (knots)								
1996	Mode	Prevailing		Maximum		Min	Ave. Speed	Std (Speed)
Month	(Degree)	Speed	Direction	Speed	Direction			
Jan	360	4.45	N	15	NW	0	1.48	2.72
Feb	360	4.17	N	31	NW	0	2.71	3.64
March	180	7.47	S	21	S	0	5.63	4.63
April	180	6.08	S	16	S	0	4.67	3.89
May	180	8.04	S	20	S	0	7.79	5.28
June	180	8.13	S	29	S	0	6.40	5.55
July	180	6.34	S	19	SSW	0	6.34	3.88
August	180	5.22	S	21	WNW	0	5.17	3.84
Sept	180	3.27	S	14	NE	0	2.52	2.78
October	360	2.57	N	28	SE	0	2.03	4.16
Nov	360	2.95	N	6	N	0	0.90	1.45
Dec	360	2.59	N	10	NNW	0	1.25	1.73
Annual		6.36	S	31	NW	0	3.92	4.44

KHEPUPARA Wind (knots)								
1997	Mode	Prevailing		Maximum		Min	Ave. Speed	Std (Speed)
Month	(Degree)	Speed	Direction	Speed	Direction			
Jan	360	3.31	N	12	NW	0	1.52	2.19
Feb	180	3.73	S	12	S	0	1.54	2.30
March	180	4.40	S	25	N	0	3.08	3.53
April	180	3.86	S	45	N	0	2.82	4.30
May	180	6.36	S	32	NNW	0	5.02	4.78
June	180	6.35	S	30	ESE	0	5.65	5.10
Jan-June		4.94	S	45	N	0	3.29	4.18

Wind Statistics of Nine Meteorological Stations

Table-7 : Monthly Wind Statistics of Kutubdia BMD Station

KUTUBDIA								
Wind (knots)								
1996	Mode	Prevailing		Maximum		Min	Ave. Speed	Std (Speed)
Month	(Degree)	Speed	Direction	Speed	Direction			
Jan	360	4.75	N	11	NNE	0	4.08	2.41
Feb	360	3.81	N	16	SE	0	3.92	2.74
March	180	7.85	S	26	S	0	6.02	5.04
April	180	3.81	S	18	S	0	3.35	2.99
May	180	6.32	S	26	N	0	4.96	3.87
June	180	5.55	S	24	S	0	5.14	3.94
July	180	3.78	S	12	SE	0	3.51	2.02
August	180	3.89	S	12	S	0	3.66	1.95
Sept	180	2.58	S	7	SSE	0	2.20	1.55
October	360	2.34	N	23	E	0	2.53	3.33
Nov	360	2.53	N	6	N	0	1.63	1.47
Dec	360	2.67	N	7	NW	0	2.25	1.47
Annual		4.82	S	26	S	0	3.61	3.20

KUTUBDIA								
Wind (knots)								
1997	Mode	Prevailing		Maximum		Min	Ave. Speed	Std (Speed)
Month	(Degree)	Speed	Direction	Speed	Direction			
Jan	360	2.56	N	7	N	0	2.38	1.25
Feb	360	2.64	N	13	WNW	0	2.60	1.36
March	360	2.56	N	15	SE	0	3.01	2.62
April	180	2.84	S	19	NW	0	2.53	2.13
May	130	3.17	SE	92	SW	0	3.90	7.37
June	180	6.23	S	24	S	0	5.35	4.34
Jan-June		2.59	N	92	SW	0	3.30	3.97

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Wind Statistics of Nine Meteorological Stations

Table-8 : Monthly Wind Statistics of Sandwip BMD Station

SANDWIP								
Wind (knots)								
1996	Mode	Prevailing		Maximum		Min	Ave. Speed	Std (Speed)
Month	(Degree)	Speed	Direction	Speed	Direction			
Jan	360	1.91	N	5	N	0	1.33	1.13
Feb	315	1.84	NW	4	E	0	1.38	1.14
March	180	4.48	S	13	SSW	0	3.52	2.94
April	180	3.37	S	18	NW	0	3.25	2.77
May	180	5.69	S	18	SE	0	4.40	3.93
June	180	4.99	S	25	SE	0	5.11	4.60
July	180	4.99	S	15	SSW	0	5.46	3.24
August	180	4.38	S	16	SW	0	4.23	2.92
Sept	180	2.70	S	15	NE	0	2.13	1.85
October	360	2.53	N	24	SE	0	2.48	3.78
Nov	360	2.00	N	6	S	0	1.09	1.21
Dec	360	2.46	N	7	ENE	0	1.55	1.47
Annual		4.37	S	25	SE	0	3.01	3.19

SANDWIP								
Wind (knots)								
1997	Mode	Prevailing		Maximum		Min	Ave. Speed	Std (Speed)
Month	(Degree)	Speed	Direction	Speed	Direction			
Jan	360	2.00	N	8	NW	0	1.51	1.48
Feb	180	4.82	S	12	SE	0	2.22	2.70
March	180	4.94	S	20	NW	0	3.48	3.42
April	180	2.54	S	15	E	0	2.40	2.46
May	180	5.03	S	100	NNW	0	4.58	7.05
June	180	5.01	S	18	SE	0	4.76	2.94
Jan-June		4.47	S	100	NNW	0	3.17	3.99

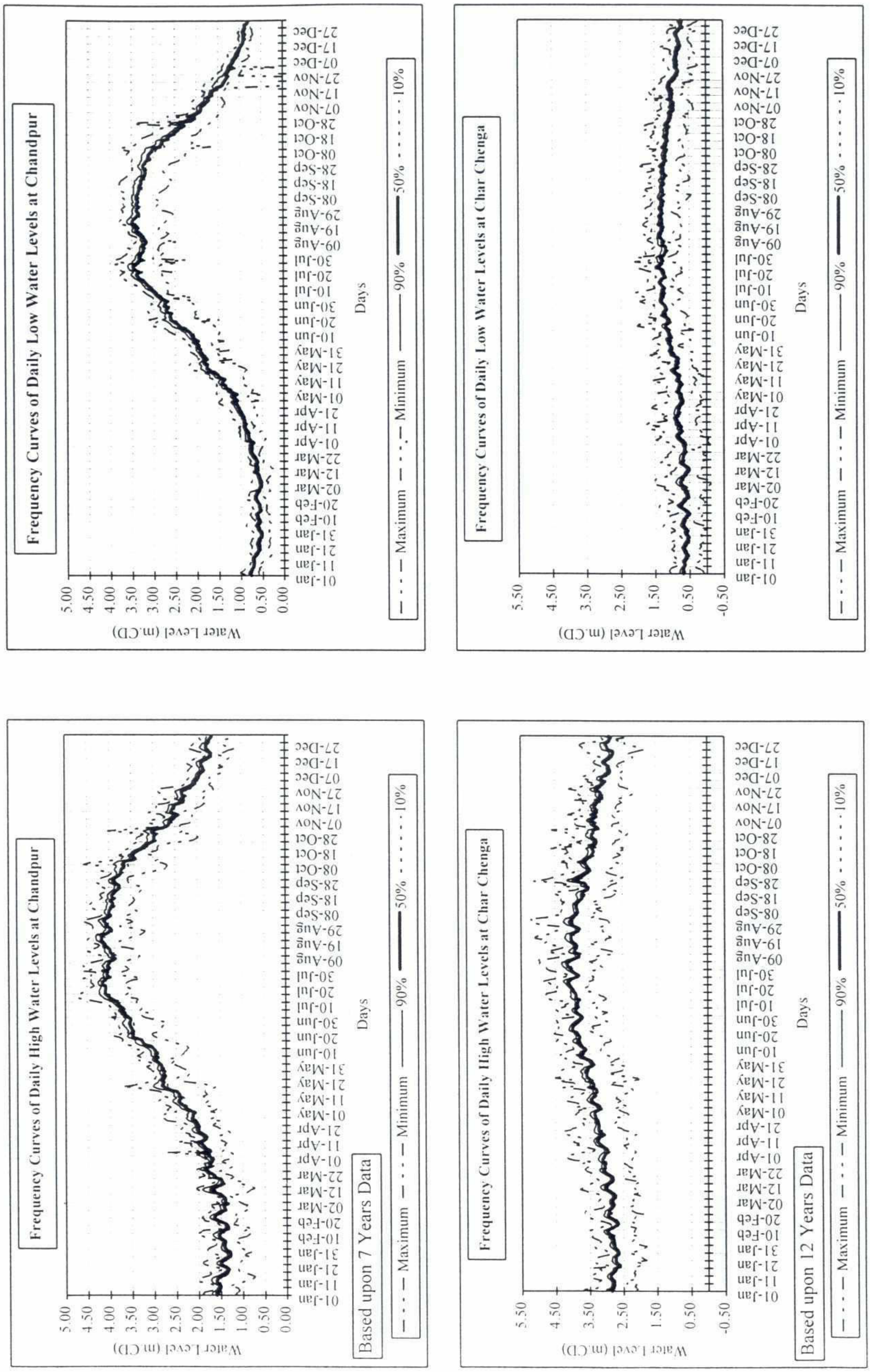
Wind Statistics of Nine Meteorological Stations

Table-9 : Monthly Wind Statistics of Patuakhali BMD Station

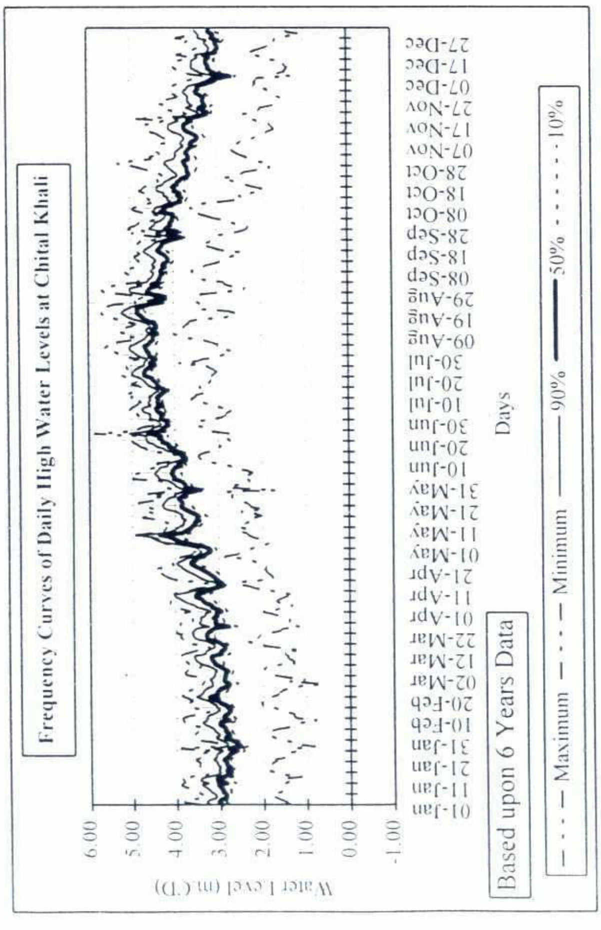
PATUAKHALI Wind (knots)								
1996	Mode	Prevailing		Maximum		Min	Ave. Speed	Std (Speed)
Month	(Degree)	Speed	Direction	Speed	Direction			
Jan	360	2.42	N	4	N	0	0.47	1.02
Feb	360	2.33	N	4	N	0	0.73	1.22
March	255	4.70	SW	10	SW	0	2.43	2.32
April	180	2.95	S	6	SSW	0	1.68	1.67
May	180	4.55	S	16	S	0	3.00	3.32
June	180	3.41	S	10	SW	0	1.83	2.13
July	180	2.78	S	8	S	0	1.52	1.66
August	180	2.43	S	10	SW	0	1.25	1.51
Sept	180	2.75	S	6	SE	0	0.72	1.28
October	270	3.17	W	24	SE	0	0.85	2.46
Nov	360	2.15	N	4	SW	0	0.26	0.72
Dec	360	2.00	N	3	N	0	0.27	0.69
Annual		3.14	S	24	SE	0	1.25	2.01

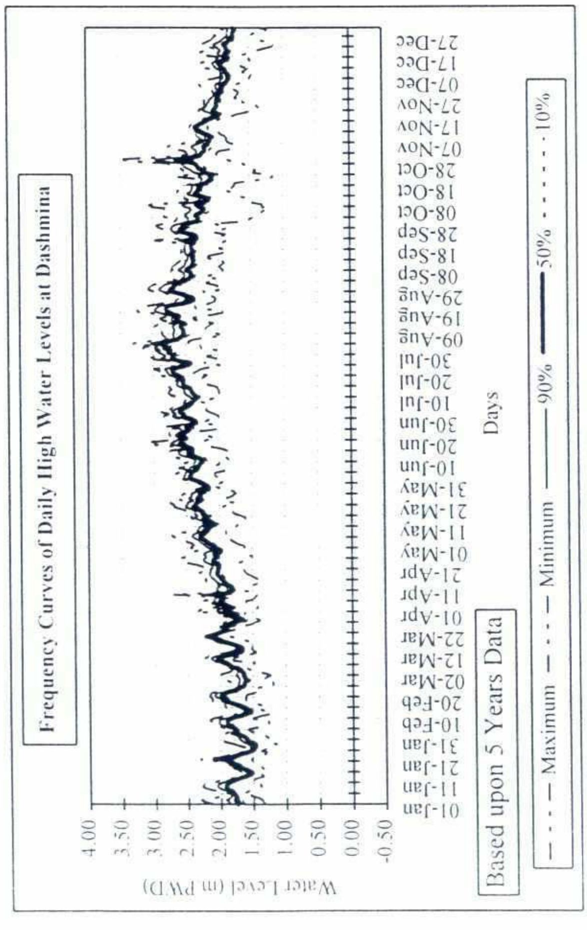
PATUAKHALI Wind (knots)								
1997	Mode	Prevailing		Maximum		Min	Ave. Speed	Std (Speed)
Month	(Degree)	Speed	Direction	Speed	Direction			
Jan	360	3.00	N	10	W	0	1.17	1.90
Feb	50	2.87	NE	8	SSW	0	1.23	1.82
March	180	3.61	S	14	SSW	0	2.19	2.33
April	180	3.18	S	20	NNE	0	2.18	2.56
May	180	4.84	S	30	N	0	3.38	3.82
June	180	4.62	S	15	E	0	3.23	3.17
Jan-June		4.06	S	30	N	0	2.24	2.83

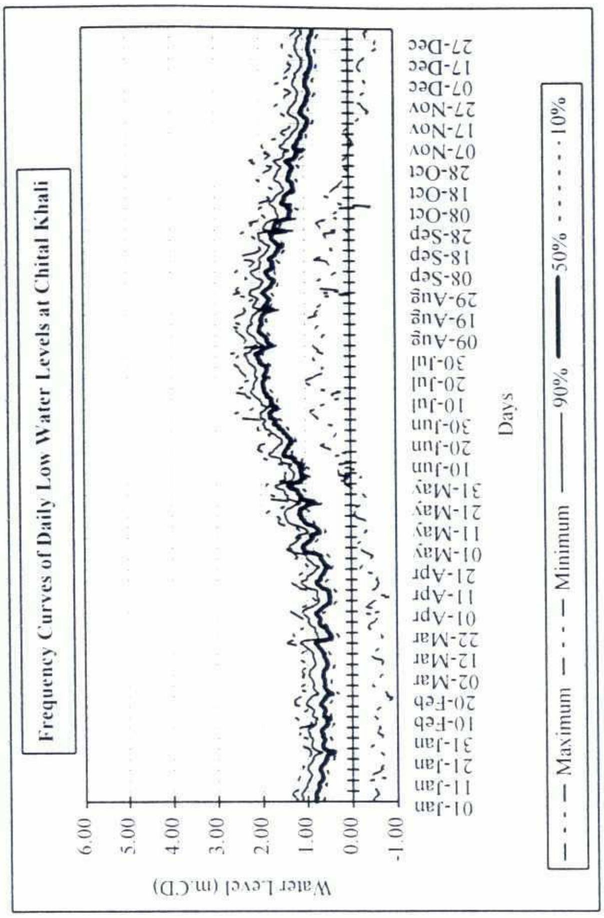
Frequency Curves of High and Low Water Level

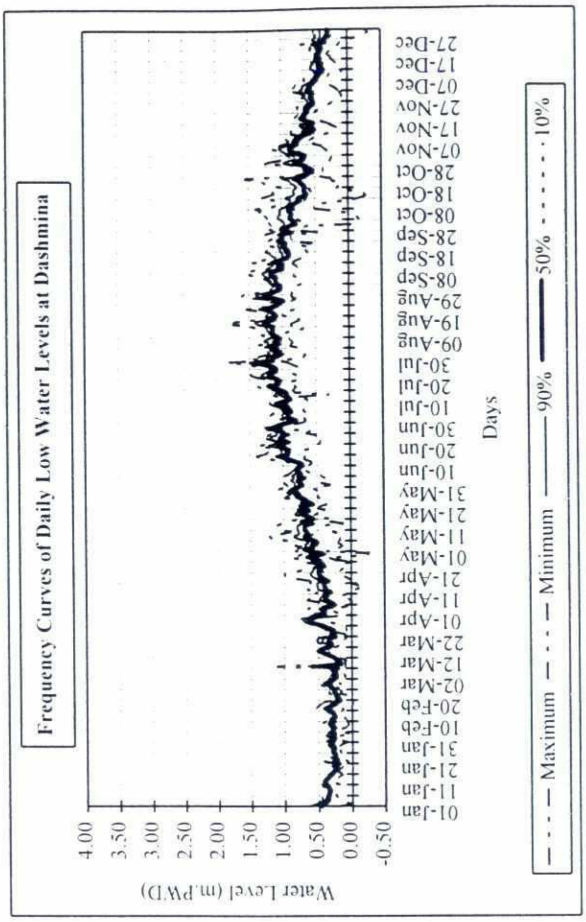


Frequency Curves of High and Low Water Level

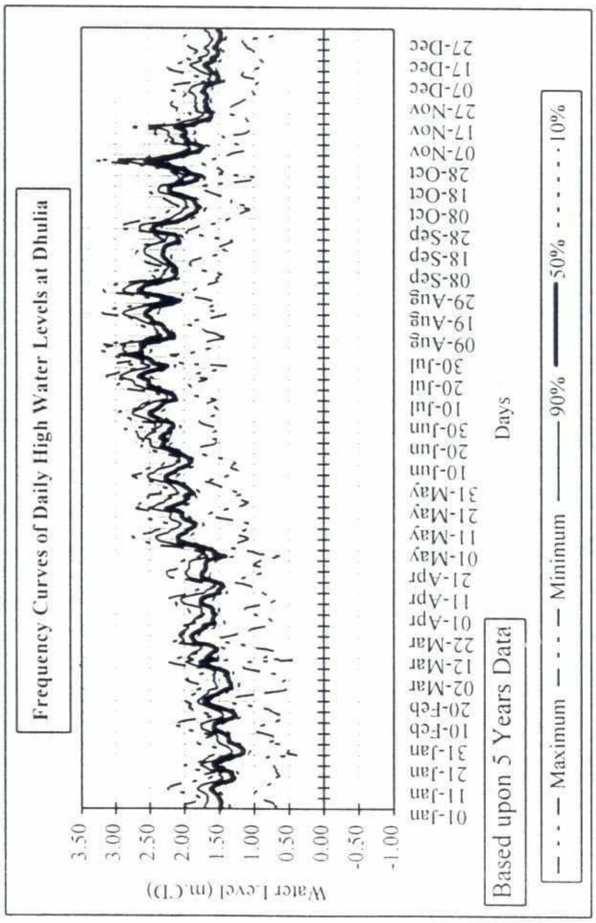


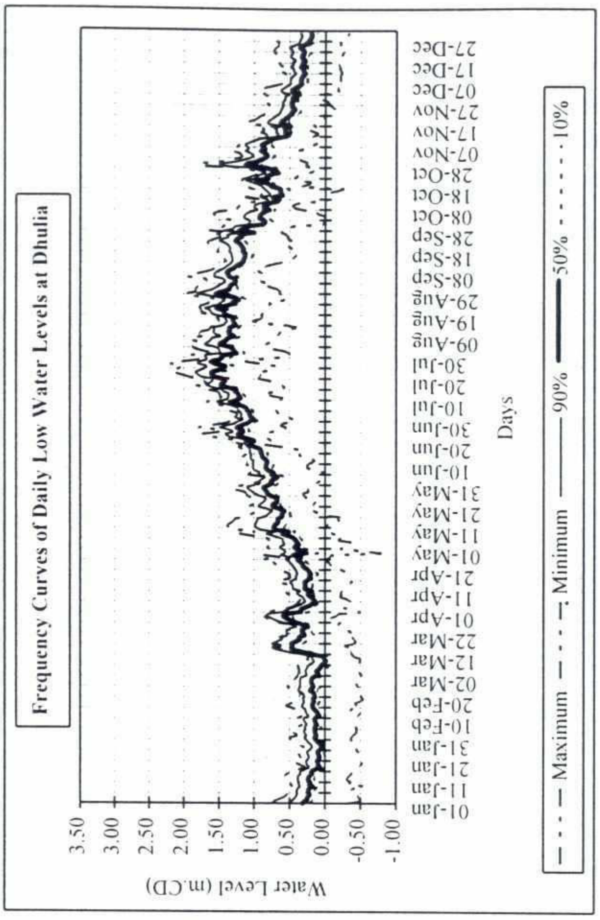


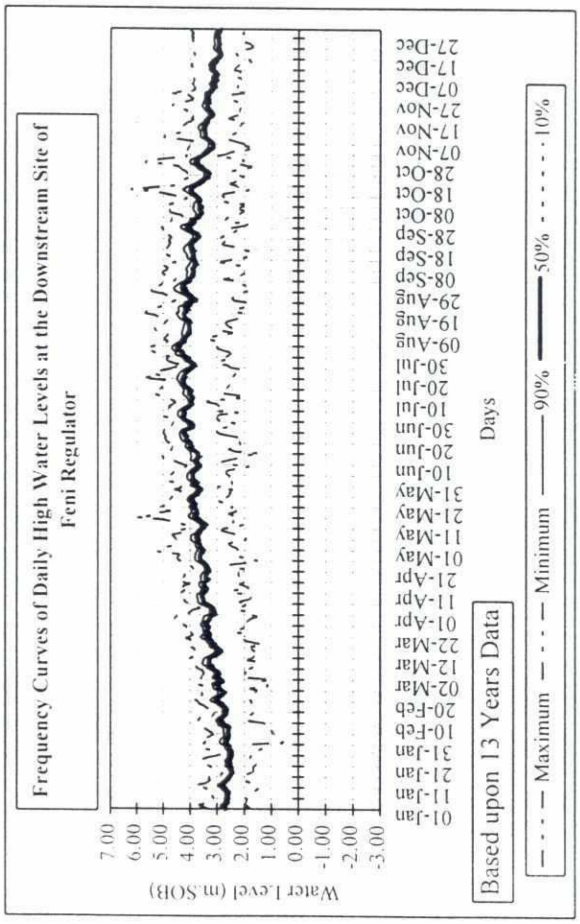


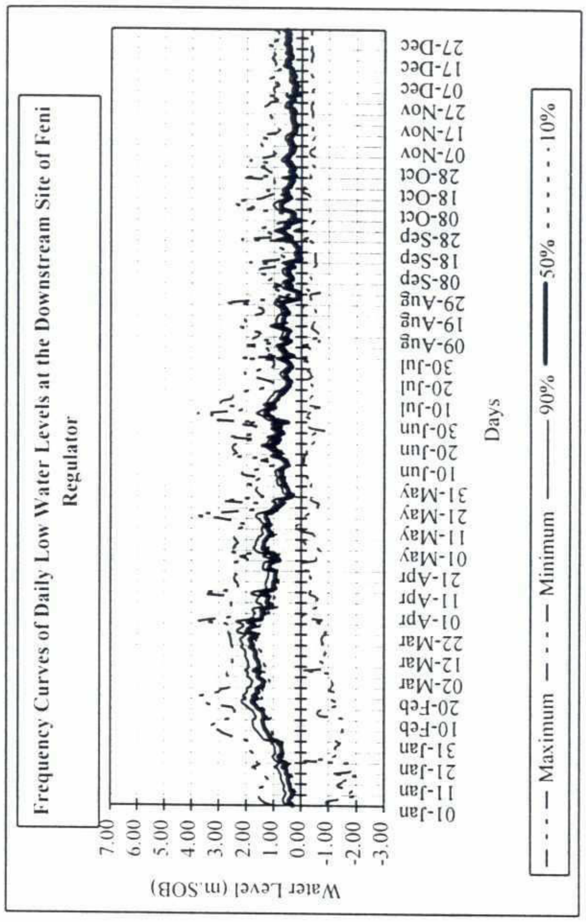


Frequency Curves of High and Low Water Level

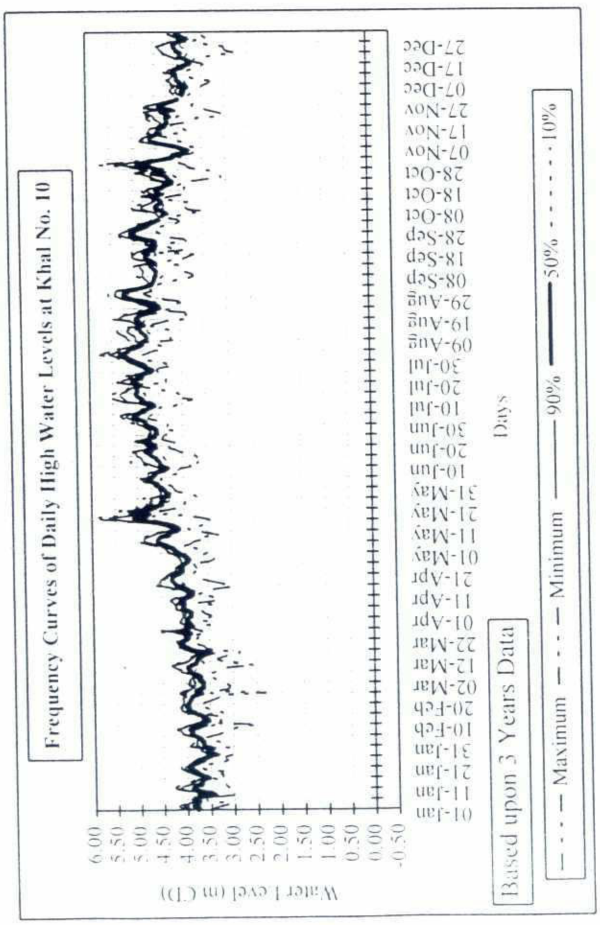


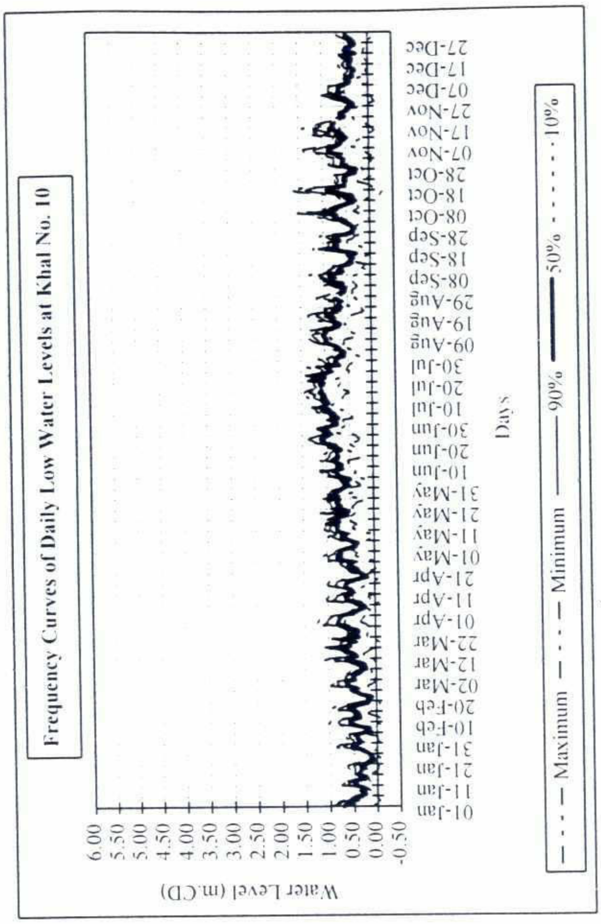


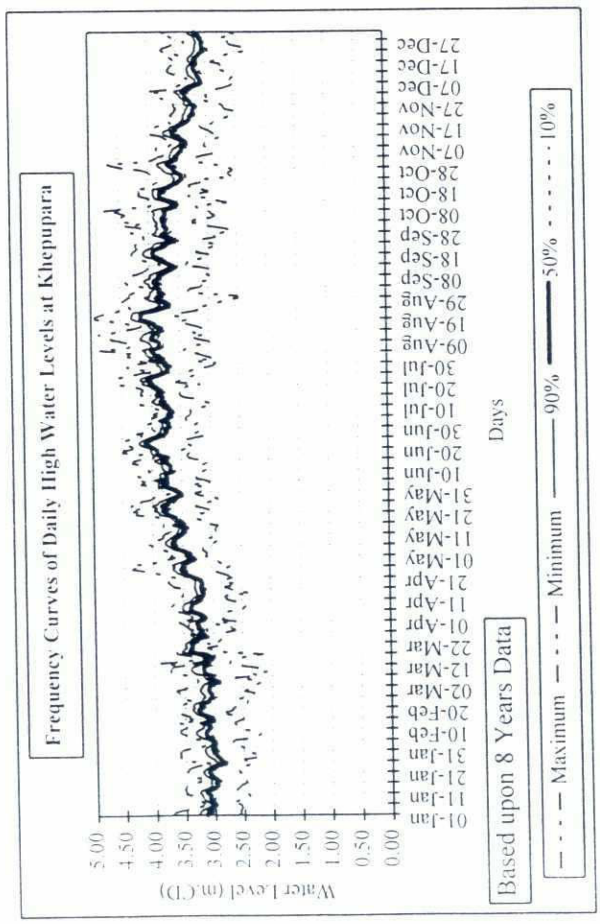


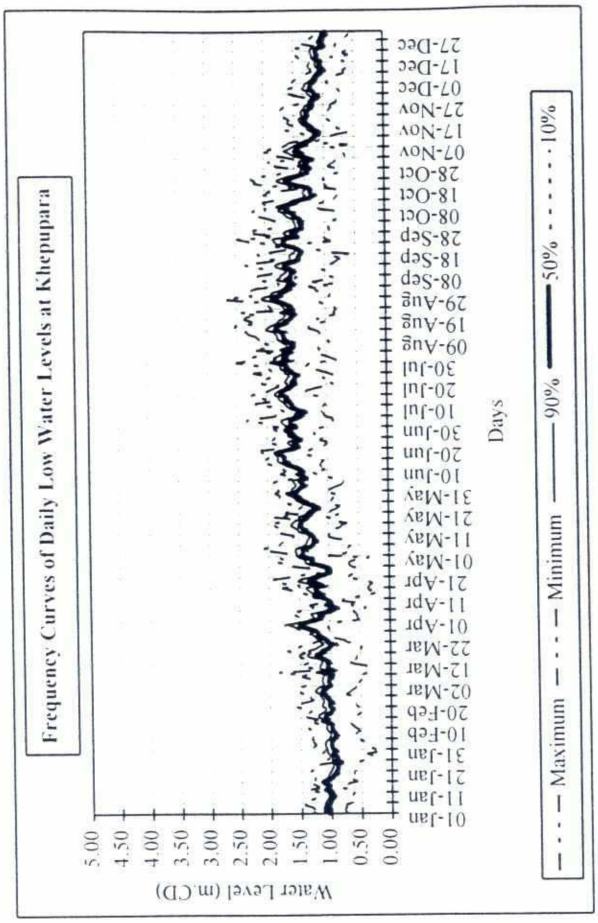


Frequency Curves of High and Low Water Level

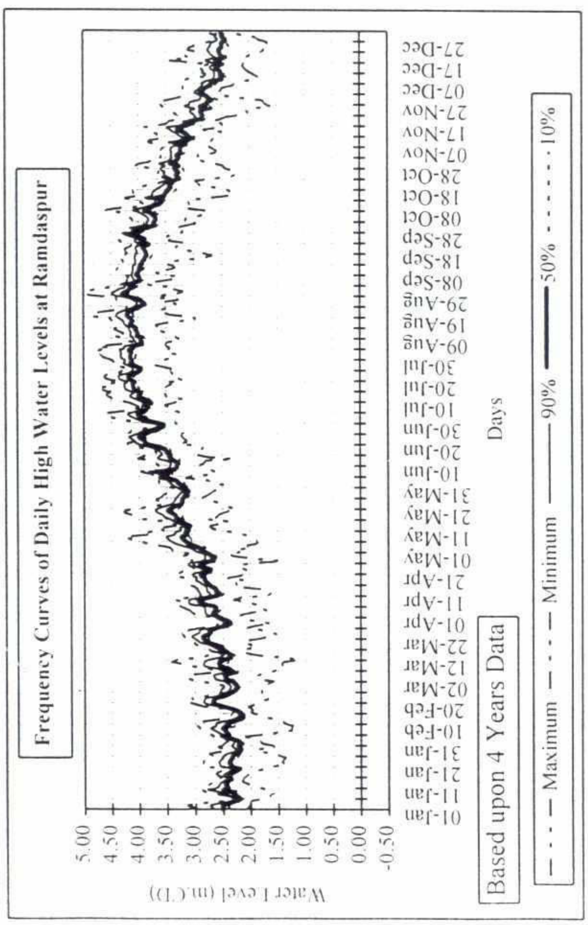


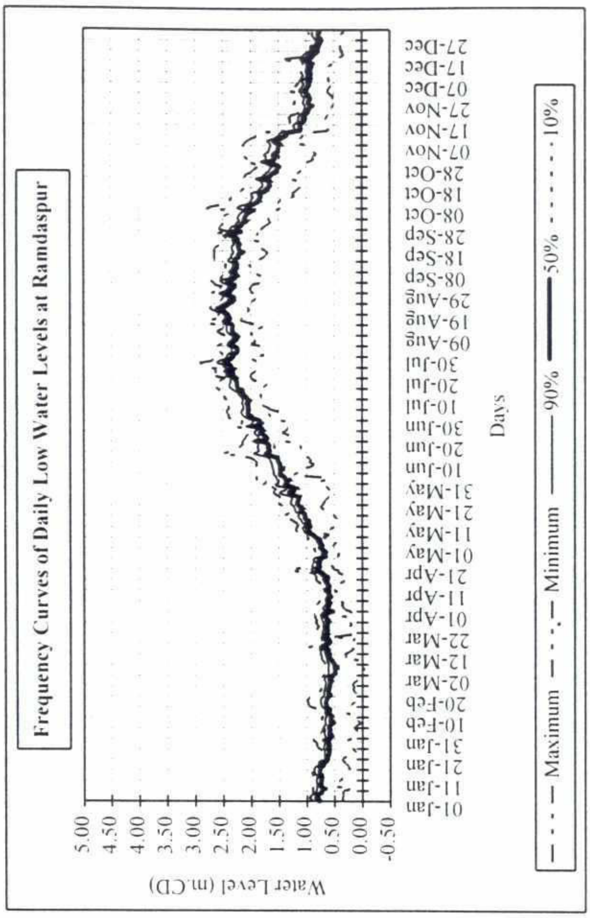


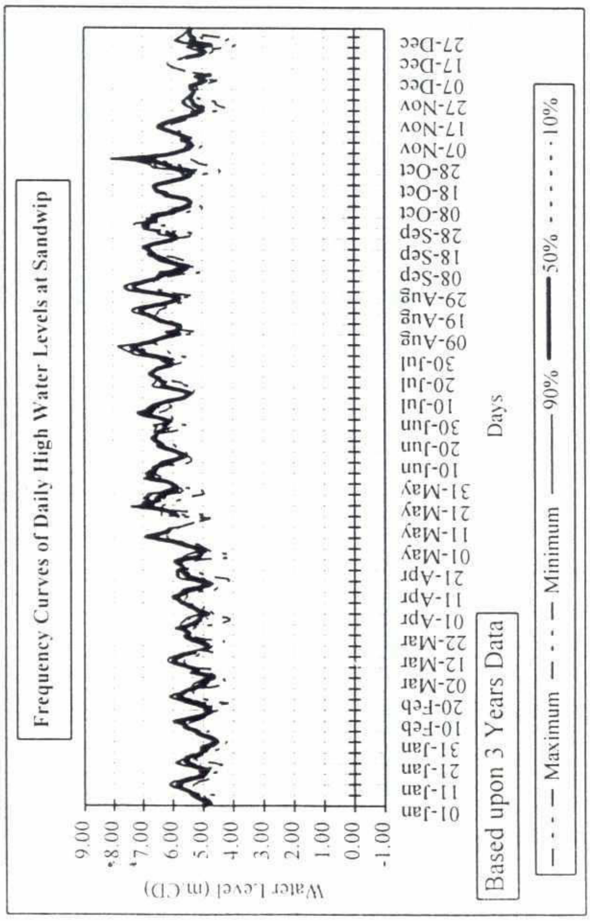


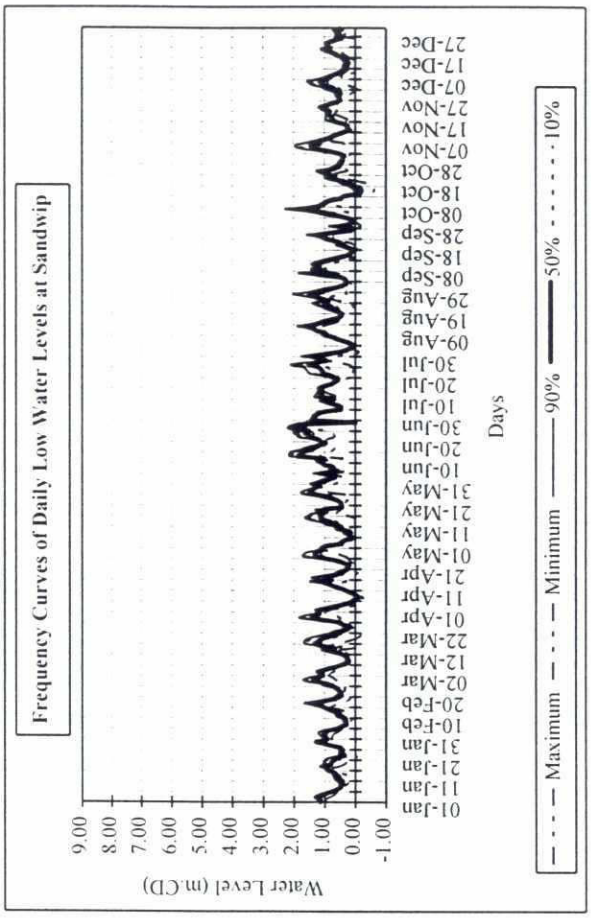


Frequency Curves of High and Low Water Level









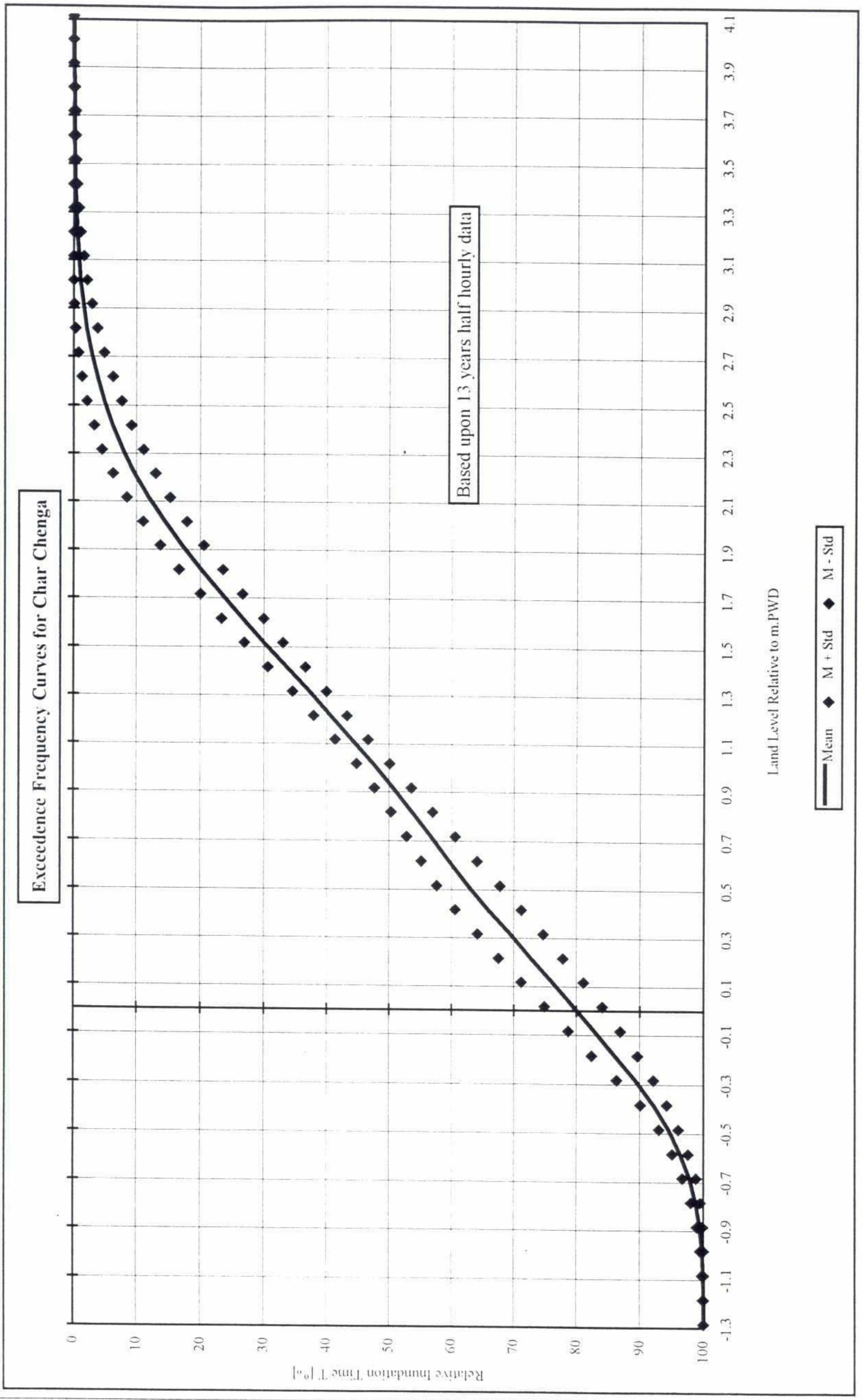
Analysis of Extreme Values of Different Water Level Stations

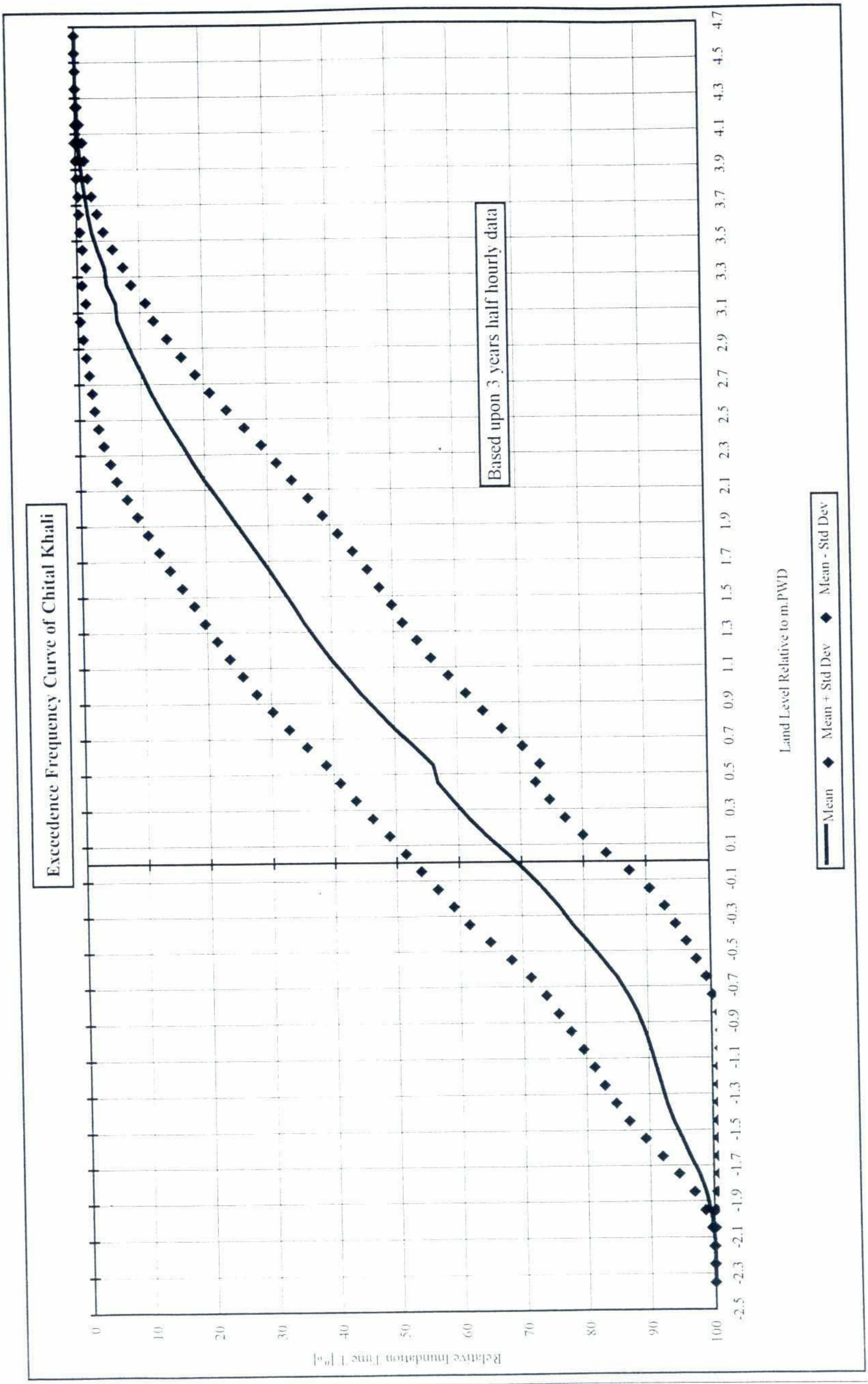
Station	No. of Years	Method	Conversion Factor from CD to PWD	Return Period (years) of Water Levels (m.PWD)						
				1 : 2	1 : 5	1 : 10	1 : 20	1 : 25	1 : 30	1 : 50
Chandpur (m.CD)	7	GEVI	0.250	4.72	4.99	5.17	5.35	5.40	5.45	5.57
		LPTIII	0.250	4.80	4.92	4.97	4.99	4.99	5.00	5.00
Char Chenga (m.CD)	13	GEVI	-1.184	3.53	3.83	4.03	4.23	4.29	4.34	4.48
		LPTIII	-1.184	3.56	3.84	4.00	4.14	4.19	4.22	4.31
Chital Khali (m.CD)	7	GEVI	-1.350	3.80	4.41	4.80	5.18	5.31	5.40	5.68
		LPTIII	-1.350	3.94	4.39	4.59	4.74	4.78	4.81	4.89
Dashmina (m.PWD)	5	GEVI	-0.550	2.64	2.82	2.93	3.05	3.08	3.11	3.19
		LPTIII	-0.550	2.65	2.83	2.94	3.05	3.08	3.10	3.18
HWL at the D/S Site of Feni Regulator (m.SOB)	13	GEVI	0.460	5.84	6.31	6.62	6.92	7.01	7.09	7.30
		LPTIII	0.460	5.91	6.28	6.48	6.64	6.69	6.73	6.83
Khepupara (m.CD)	8	GEVI	-1.960	2.62	2.86	3.02	3.17	3.22	3.26	3.37
		LPTIII	-1.960	2.66	2.88	2.99	3.09	3.12	3.14	3.20
Ramdaspur (m.CD)	6	GEVI	-0.660	4.00	4.19	4.31	4.42	4.46	4.49	4.57
		LPTIII	-0.660	4.03	4.21	4.31	4.40	4.43	4.45	4.50

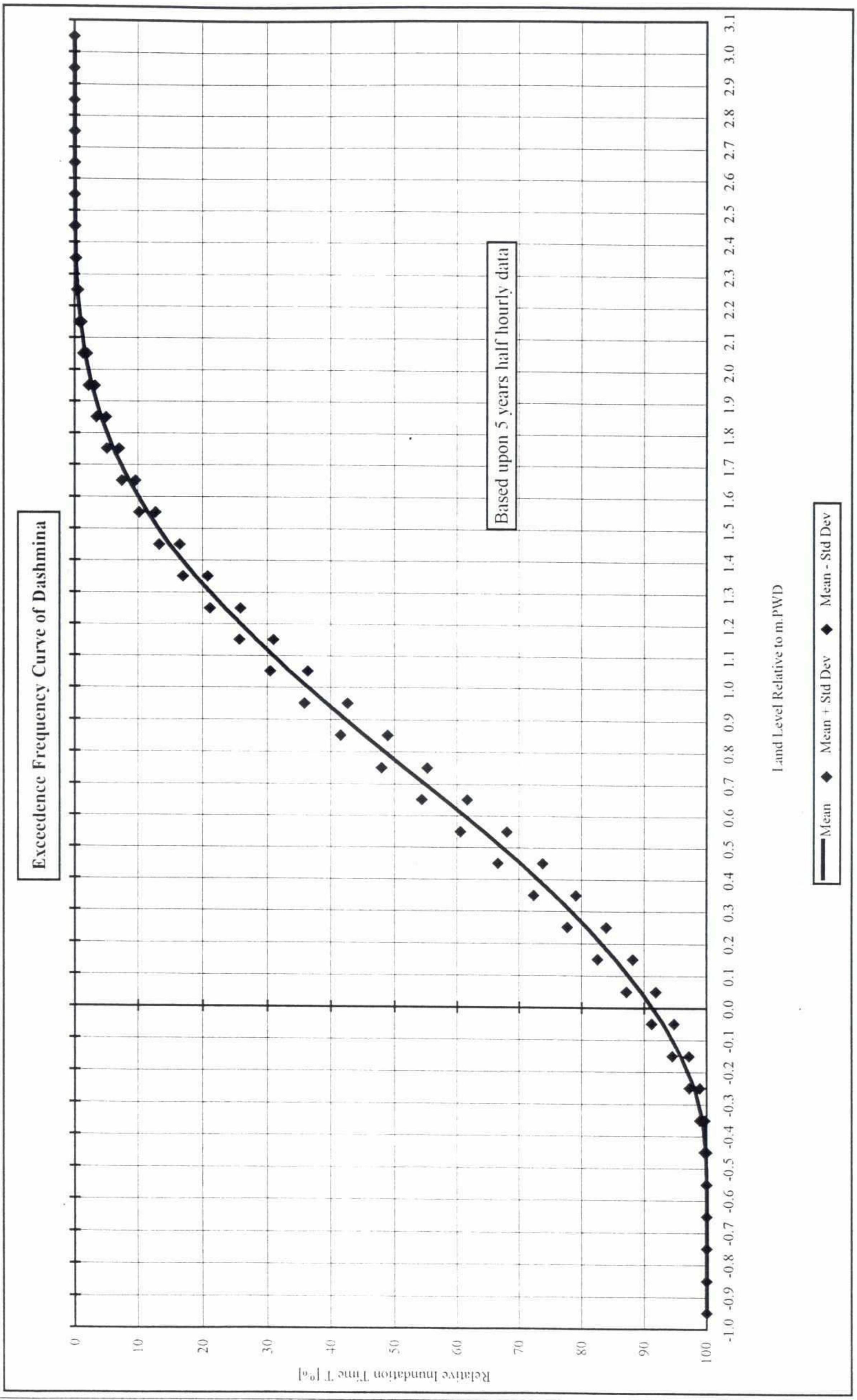
* Conversion Factors to PWD are derived from Geodetic Surveys and hydraulic model computations.

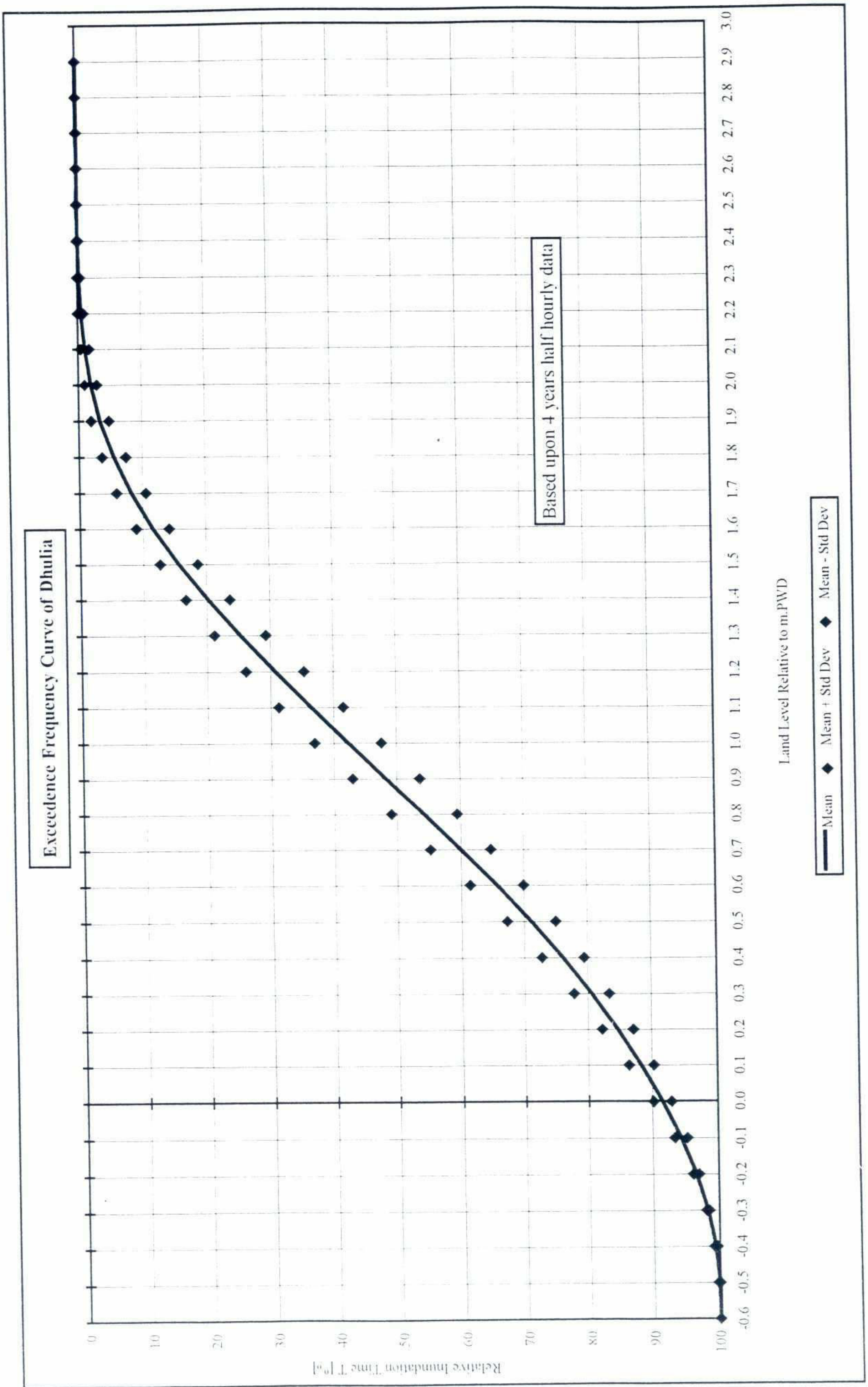
GEVI - Gumbel Extreme Value Type I Distribution.

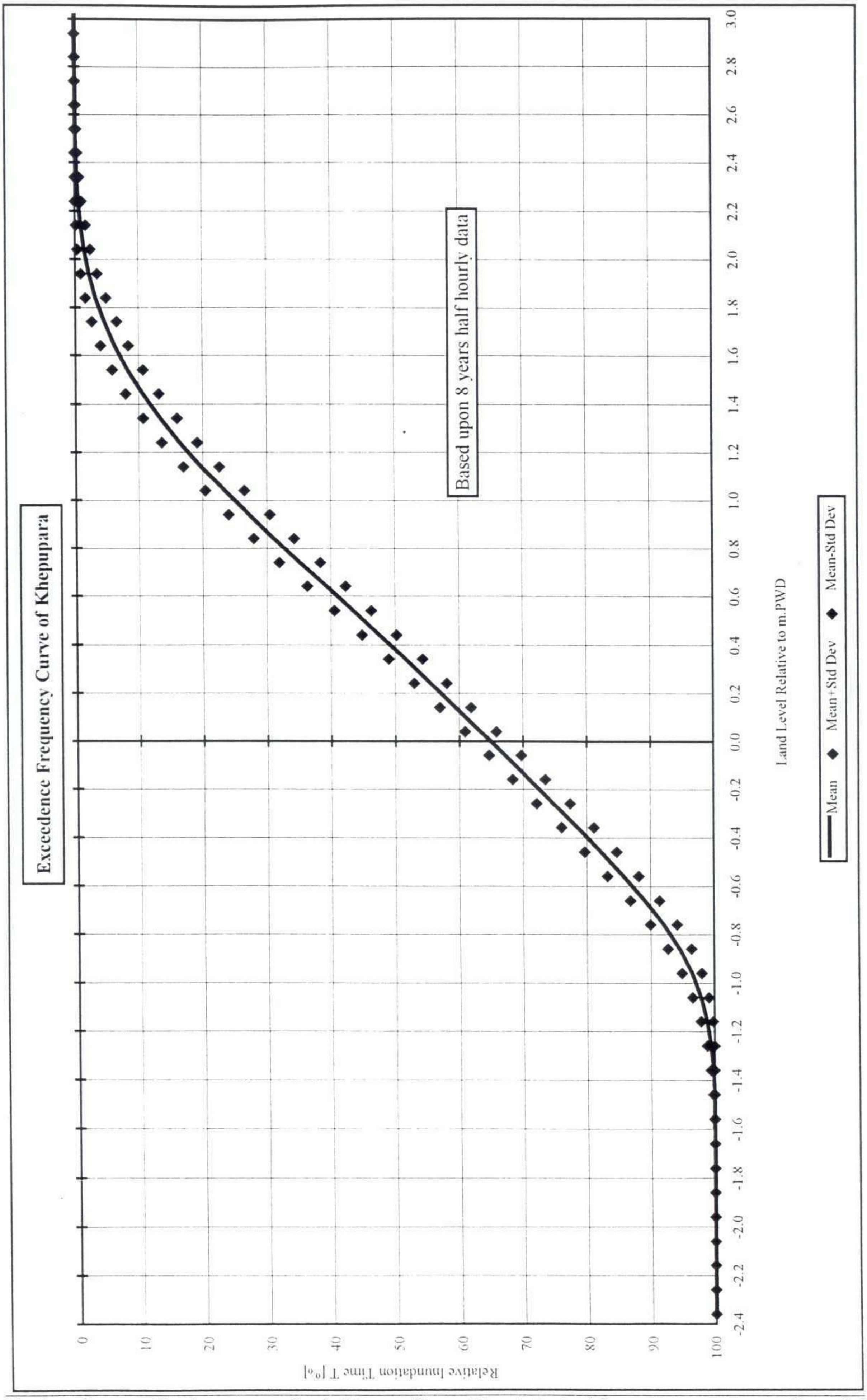
LPTIII - Log Pearson Type III Distribution.

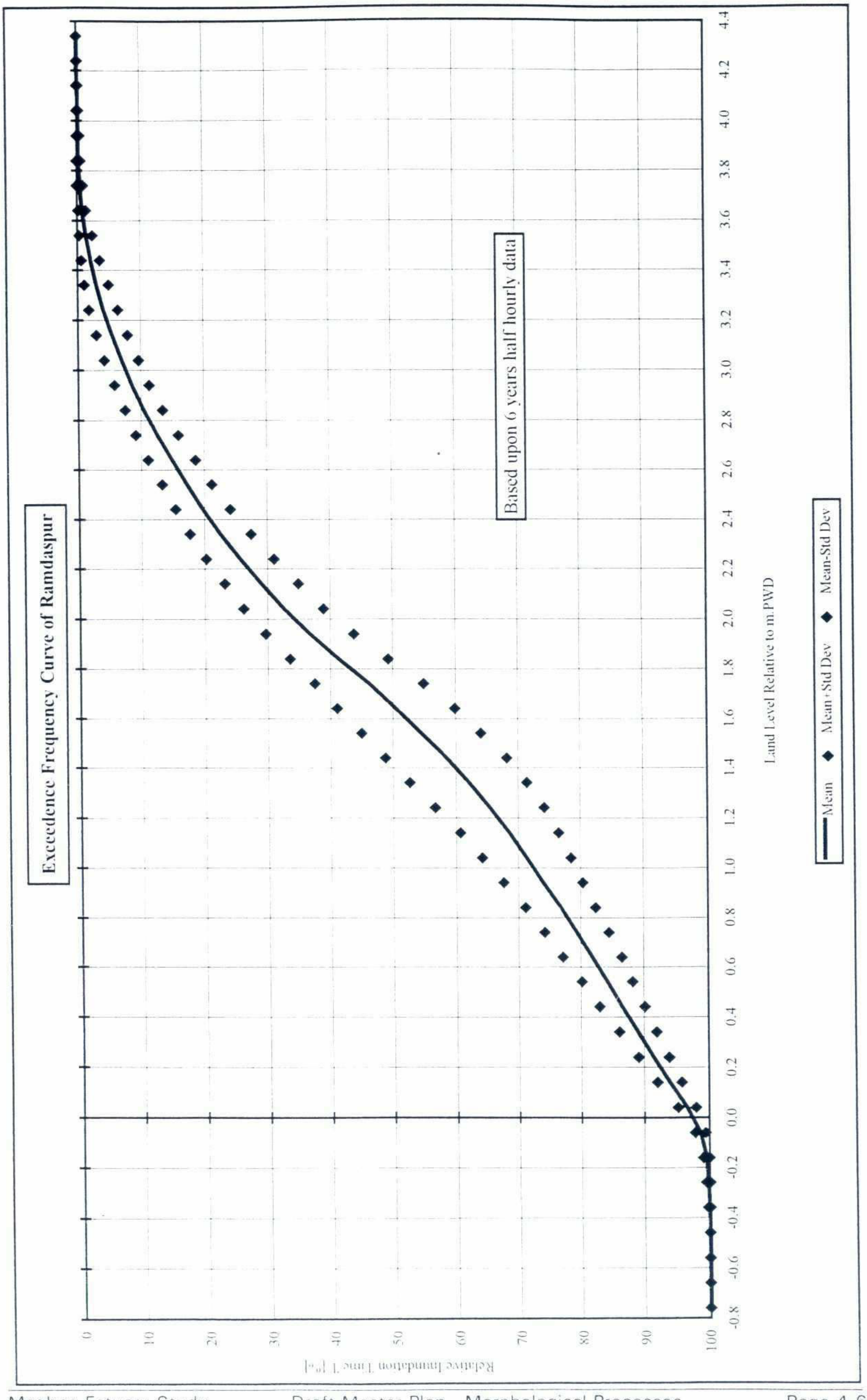

Exceedence Frequency Curves for Char Chenga
Based upon 13 years half hourly data
Land Level Relative to m.PWD
Relative Inundation Time 'I' [%]
Mean
M + Std
M - Std
-1.3
-1.1
-0.9
-0.7
-0.5
-0.3
-0.1
0.1
0.3
0.5
0.7
0.9
1.1
1.3
1.5
1.7
1.9
2.1
2.3
2.5
2.7
2.9
3.1
3.3
3.5
3.7
3.9
4.1
0
10
20
30
40
50
60
70
80
90
100

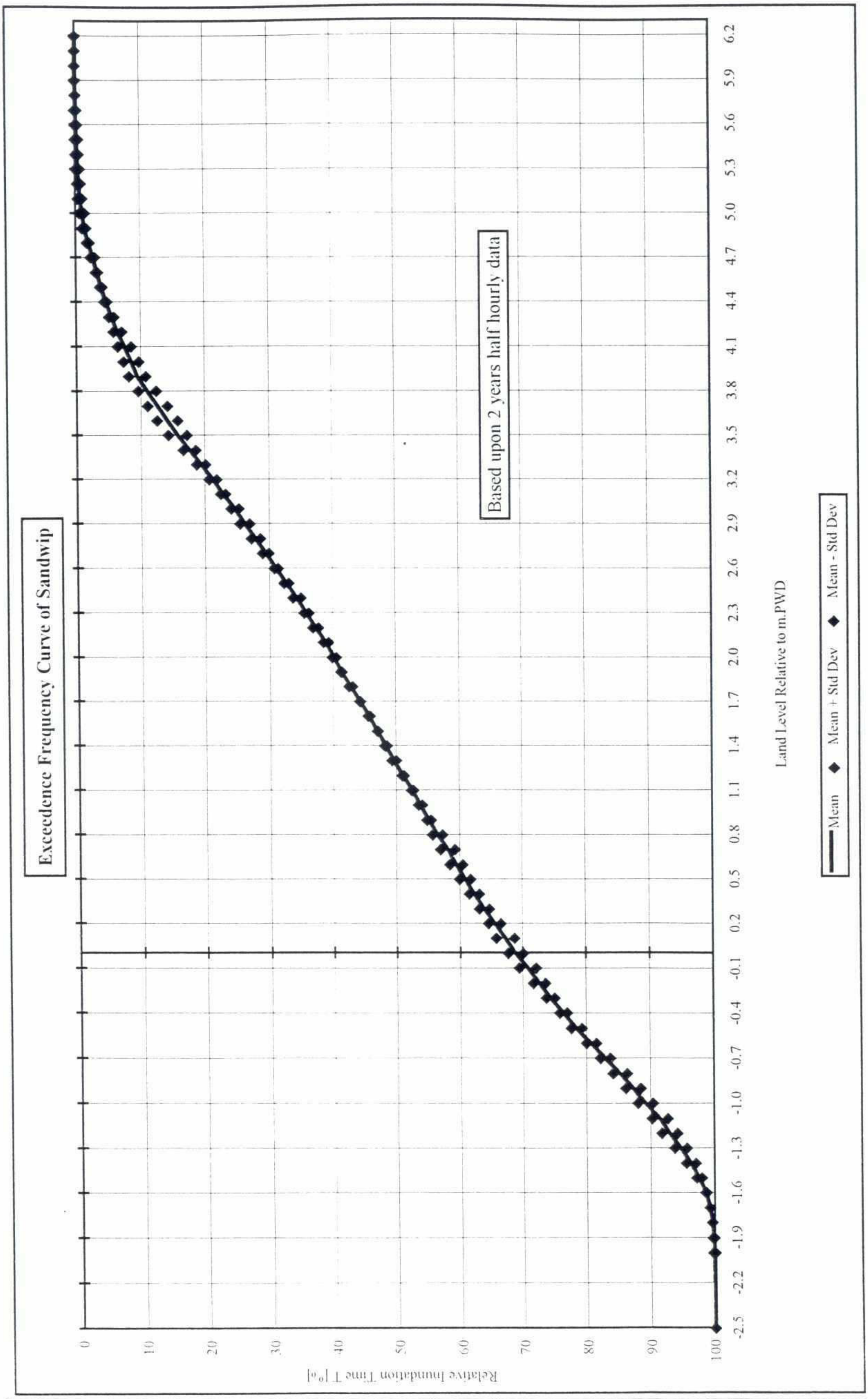

Exceedence Frequency Curve of Chital Khali
Based upon 3 years half hourly data
Relative Inundation Time T [%]
0
10
20
30
40
50
60
70
80
90
100
Land Level Relative to m.PWD
-2.5 -2.3 -2.1 -1.9 -1.7 -1.5 -1.3 -1.1 -0.9 -0.7 -0.5 -0.3 -0.1 0.1 0.3 0.5 0.7 0.9 1.1 1.3 1.5 1.7 1.9 2.1 2.3 2.5 2.7 2.9 3.1 3.3 3.5 3.7 3.9 4.1 4.3 4.5 4.7
Mean
Mean + Std Dev
Mean - Std Dev


Exceedence Frequency Curve of Dashmina
Based upon 5 years half hourly data
Relative Inundation Time T [%]
0
10
20
30
40
50
60
70
80
90
100
Land Level Relative to m.PWD
-1.0 -0.9 -0.8 -0.7 -0.6 -0.5 -0.4 -0.3 -0.2 -0.1 0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9 2.0 2.1 2.2 2.3 2.4 2.5 2.6 2.7 2.8 2.9 3.0 3.1
Mean
Mean + Std Dev
Mean - Std Dev


Exceedence Frequency Curve of Dhulia
Based upon 4 years half hourly data
Relative Inundation Time T [%]
0
10
20
30
40
50
60
70
80
90
100
Land Level Relative to m.PWD
-0.6 -0.5 -0.4 -0.3 -0.2 -0.1 0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9 2.0 2.1 2.2 2.3 2.4 2.5 2.6 2.7 2.8 2.9 3.0
Mean
Mean + Std Dev
Mean - Std Dev


Exceedence Frequency Curve of Khepupara
Based upon 8 years half hourly data
Land Level Relative to m.PWD
Relative Inundation Time T [%]
Mean
Mean+Std Dev
Mean-Std Dev


Exceedence Frequency Curve of Ramdaspur
Based upon 6 years half hourly data
Land Level Relative to m.PWD
Relative Inundation Time T [%]
Mean
Mean+Std Dev
Mean-Std Dev
-0.8 -0.6 -0.4 -0.2 0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0 2.2 2.4 2.6 2.8 3.0 3.2 3.4 3.6 3.8 4.0 4.2 4.4
0 10 20 30 40 50 60 70 80 90 100


Exceedence Frequency Curve of Sandwip
Based upon 2 years half hourly data
Relative Inundation Time T [%]
0
10
20
30
40
50
60
70
80
90
100
Land Level Relative to m.PWD
-2.5
-2.2
-1.9
-1.6
-1.3
-1.0
-0.7
-0.4
-0.1
0.2
0.5
0.8
1.1
1.4
1.7
2.0
2.3
2.6
2.9
3.2
3.5
3.8
4.1
4.4
4.7
5.0
5.3
5.6
5.9
6.2
Mean
Mean + Std Dev
Mean - Std Dev

Summary Statistics of Land and Intertidal Area

Table-1a : Change Classes for Barisal Reach by Period

Change Classes		Interpretation	1973-1979	1979-1984	1984-1990	1990-1993	1993-1996	1973-1996
New	Old							
Water	Water	No Change	18287	22331	20793	23867	24162	13821
			22%	26%	25%	28%	29%	16%
Water	Mud Flat	Erosion	2479	1060	928	2078	569	2524
			3%	1%	1%	2%	1%	3%
Mud Flat	Water	Accretion	1705	1895	3303	1345	2276	3878
			2%	2%	4%	2%	3%	5%
Mud Flat	Mud Flat	No Change	1122	1967	899	1638	1979	1194
			1%	2%	1%	2%	2%	1%
Land	Land	No Change	9352	7430	4042	5977	2924	2007
			11%	9%	5%	7%	3%	2%
Water	Land	Erosion	3959	2717	3654	1685	1170	9555
			5%	3%	4%	2%	1%	11%
Mud Flat	Land	Erosion	1244	943	1277	1370	3810	2993
			1%	1%	2%	2%	5%	4%
Land	Water	Accretion	456	498	2011	164	1191	2749
			1%	1%	2%	0%	1%	3%
Land	Mud Flat	Accretion	1282	1044	2979	1763	1805	1165
			2%	1%	4%	2%	2%	1%
Stable Land	Stable Land	No Change	44727	44727	44727	44727	44727	44727
			53%	53%	53%	53%	53%	53%
Total			84613	84613	84613	84613	84613	84613
			100%	100%	100%	100%	100%	100%

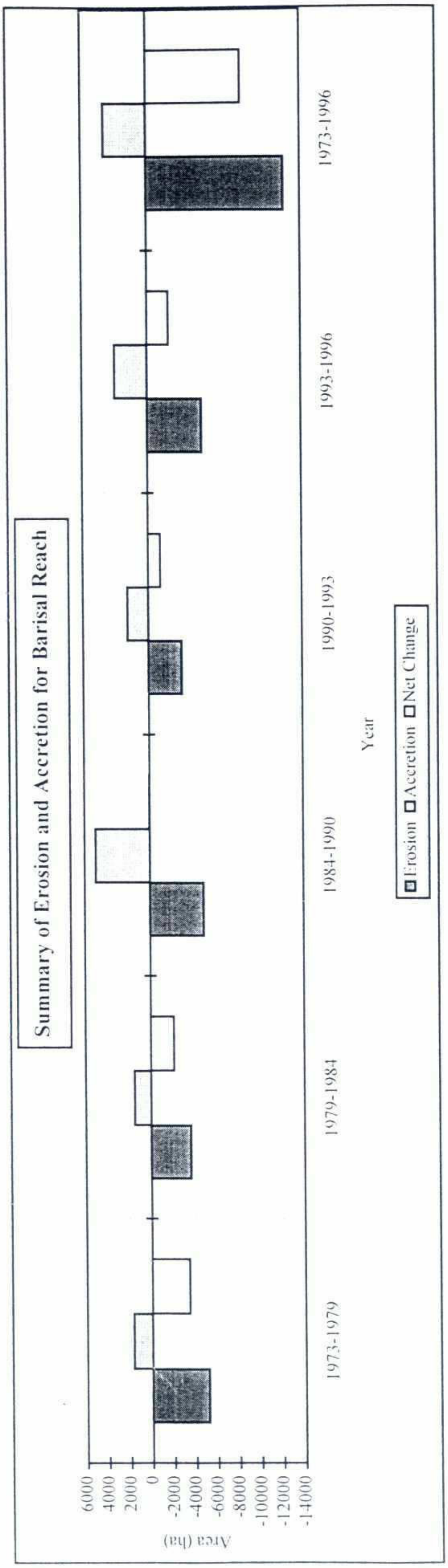
Table-1b : Annual Rates of Change Classes for Barisal Reach by Period

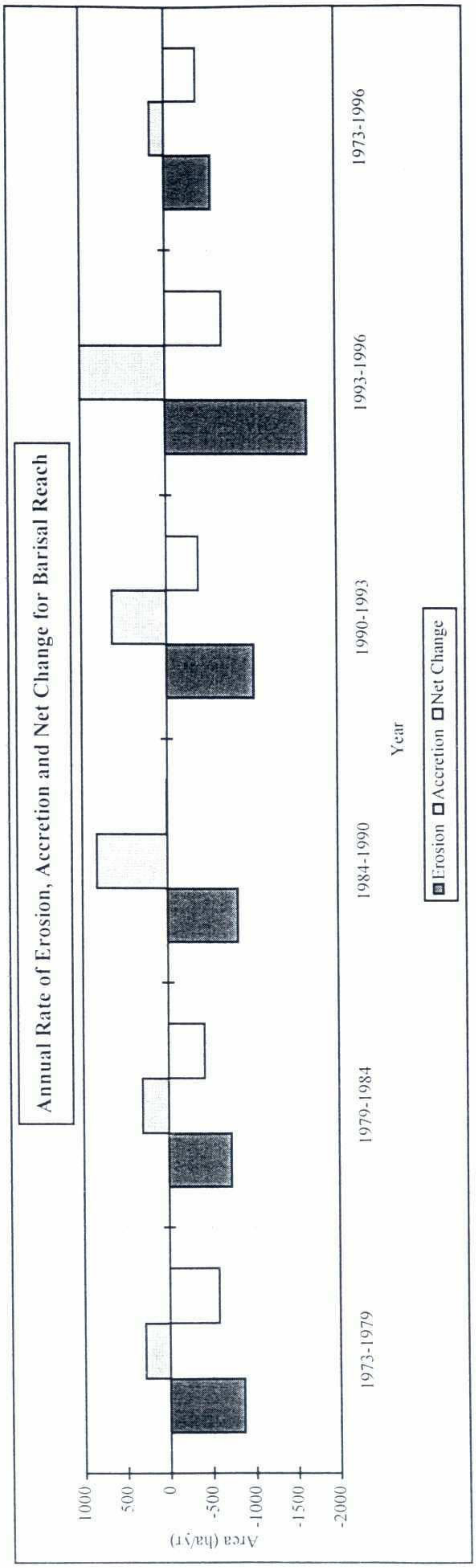
Change Classes		Interpretation	1973-1979	1979-1984	1984-1990	1990-1993	1993-1996	1973-1996
New	Old							
Water	Mud Flat	Erosion	413	265	155	693	190	110
Mud Flat	Water	Accretion	284	379	551	448	759	169
Water	Land	Erosion	660	543	609	562	390	415
Mud Flat	Land	Erosion	207	189	213	457	1270	130
Land	Water	Accretion	76	100	335	55	397	120
Land	Mud Flat	Accretion	214	209	497	588	602	51

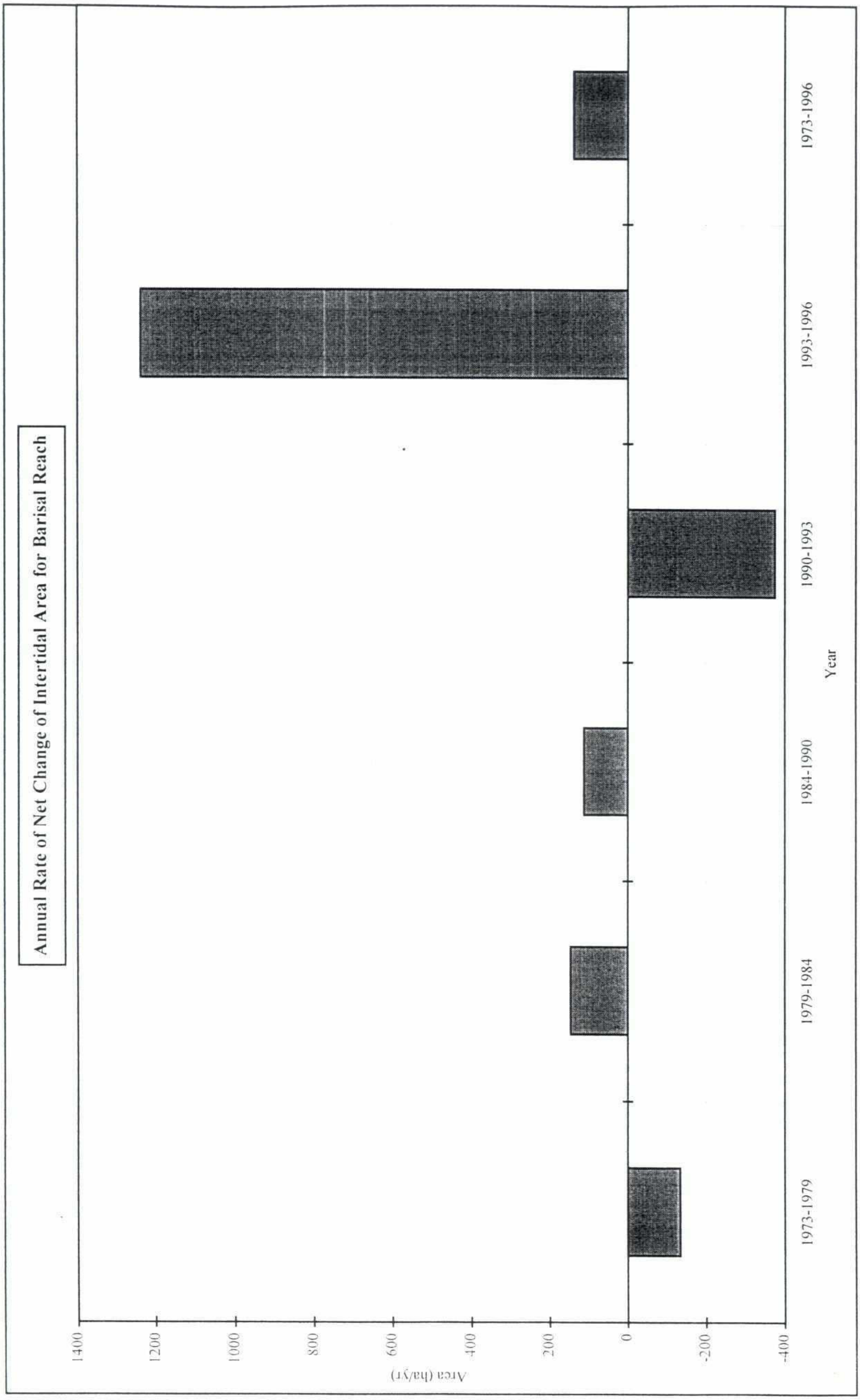
Table-1c : Summary of Erosion and Accretion for Barisal Reach

Land Cover Change	1973-1979	1979-1984	1984-1990	1990-1993	1993-1996	1973-1996
Erosion for Period (ha)	-5203	-3660	-4931	-3055	-4980	-12548
Accretion for Period (ha)	1738	1542	4990	1927	2996	3914
Net Change for Period (ha)	-3465	-2118	60	-1128	-1984	-8635
Annual Rate of Erosion (ha/yr)	-867	-732	-822	-1018	-1660	-546
Annual Rate of Accretion (ha/yr)	290	308	832	642	999	170
Annual Rate of Net Change (ha/yr)	-578	-424	10	-376	-661	-375
% of Erosion	-6%	-4%	-6%	-4%	-6%	-15%
% of Accretion	2%	2%	6%	2%	4%	5%
% of Net Change	-4%	-3%	0%	-1%	-2%	-10%
Erosion, Water from Mud (ha)	-3760	-2104	-3907	-3840	-2374	-3689
Accretion, Mud from Water (ha)	2949	2839	4580	2715	6086	6871
Net Change	-811	734	672	-1126	3712	3182
Annual Rate of Net Change	-135	147	112	-375	1237	138
General Tide Levels						

Summary Statistics of Land Area






Annual Rate of Net Change of Intertidal Area for Barisal Reach
Area (ha/yr)
1400
1200
1000
800
600
400
200
0
-200
-400
1973-1979
1979-1984
1984-1990
1990-1993
1993-1996
1973-1996
Year

286

Summary Statistics of Land and Intertidal Area

Table-2a : Change Classes for Bhola-Hatia by Period

Change Classes		Interpreta-	1973-1979	1979-1984	1984-1990	1990-1993	1993-1996	1973-1996
New	Old	tion						
Water	Water	No Change	314900 70%	314464 70%	318440 71%	319810 71%	301837 67%	292991 65%
Water	Mud Flat	Erosion	5133 1%	10062 2%	10847 2%	2433 1%	5068 1%	4029 1%
Mud Flat	Water	Accretion	17259 4%	11572 3%	6660 1%	11501 3%	18007 4%	21940 5%
Mud Flat	Mud Flat	No Change	2627 1%	14803 3%	10198 2%	11793 3%	7099 2%	1278 0%
Land	Land	No Change	8648 2%	4683 1%	7609 2%	12439 3%	15829 4%	13566 3%
Water	Land	Erosion	6891 2%	1735 0%	2503 1%	1377 0%	720 0%	10604 2%
Mud Flat	Land	Erosion	10690 2%	3001 1%	1169 0%	3285 1%	170 0%	2058 0%
Land	Water	Accretion	538 0%	888 0%	1161 0%	479 0%	3777 1%	17766 4%
Land	Mud Flat	Accretion	233 0%	5711 1%	8331 2%	3802 1%	14412 3%	2686 1%
Stable Land	Stable Land	No Change	83258 18%	83258 18%	83258 18%	83258 18%	83258 18%	83258 18%
Total			450176 100%	450176 100%	450176 100%	450176 100%	450176 100%	450176 100%

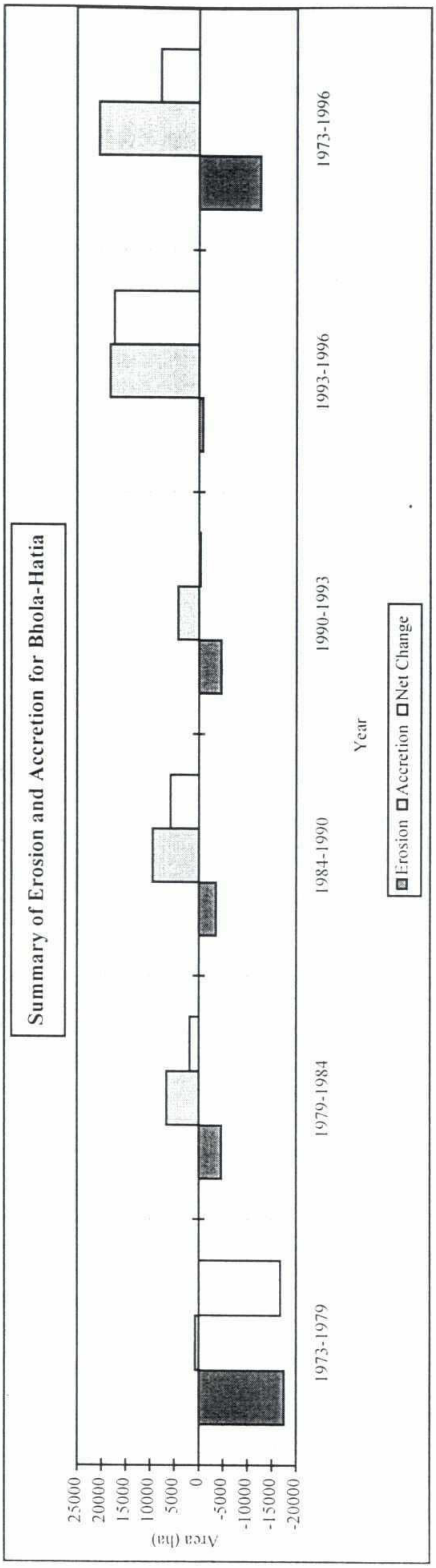
Table-2b : Annual Rates of Change Classes for Bhola-Hatia by Period

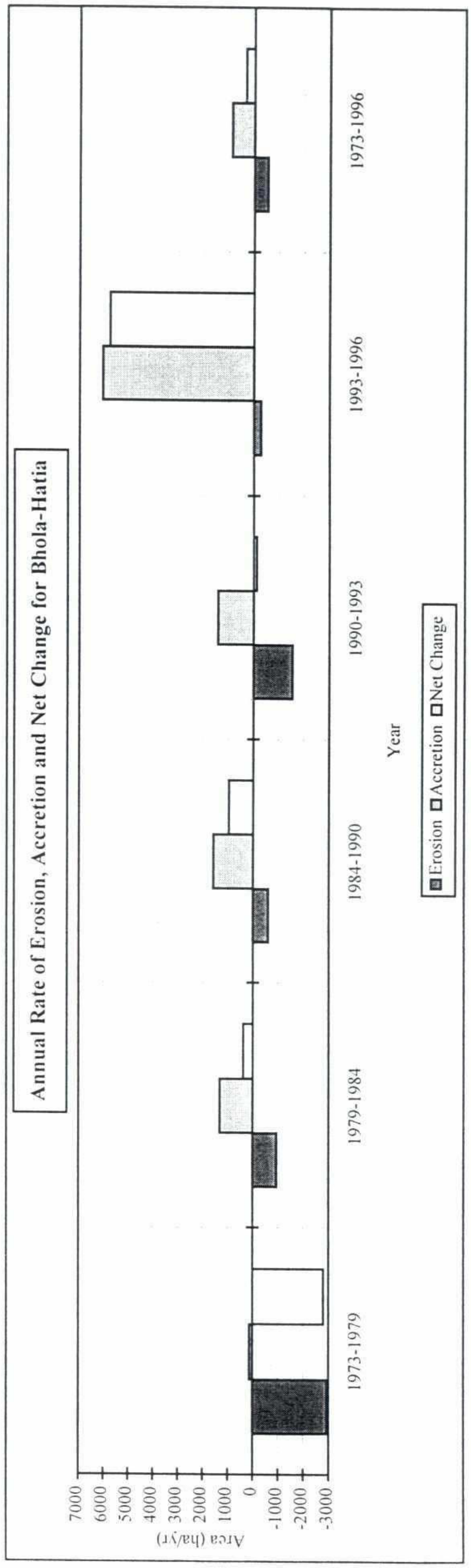
Change Classes		Interpre-	1973-1979	1979-1984	1984-1990	1990-1993	1993-1996	1973-1996
New	Old	tation						
Water	Mud Flat	Erosion	856	2516	1808	811	1689	175
Mud Flat	Water	Accretion	2877	2314	1110	3834	6002	954
Water	Land	Erosion	1149	347	417	459	240	461
Mud Flat	Land	Erosion	1782	600	195	1095	57	89
Land	Water	Accretion	90	178	194	160	1259	772
Land	Mud Flat	Accretion	39	1142	1388	1267	4804	117

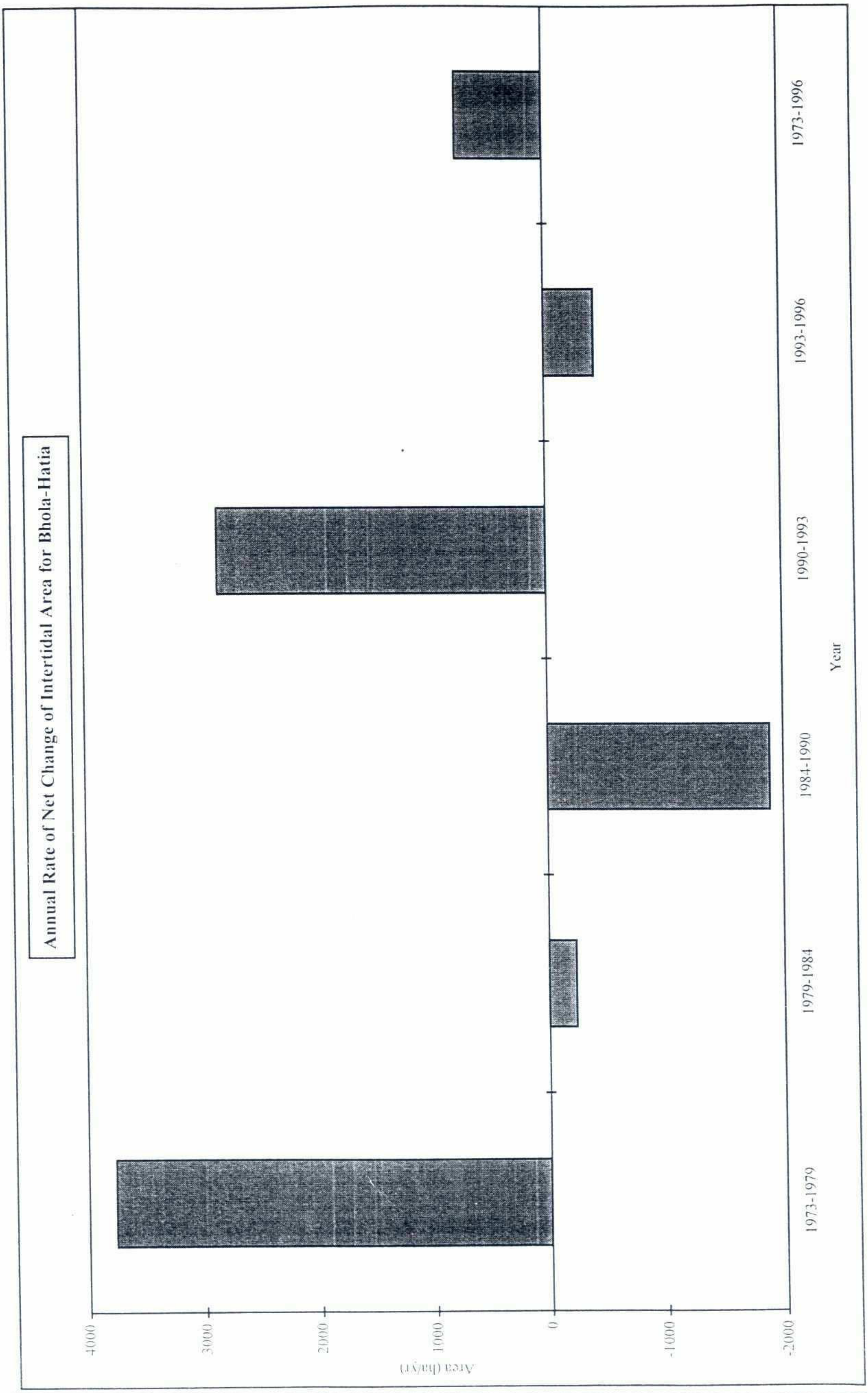
Table-2c : Summary of Erosion and Accretion for Bhola-Hatia

Land Cover Change	1973-1979	1979-1984	1984-1990	1990-1993	1993-1996	1973-1996
Erosion for Period (ha)	-17581	-4736	-3673	-4662	-890	-12663
Accretion for Period (ha)	771	6599	9492	4281	18189	20452
Net Change for Period (ha)	-16810	1863	5819	-381	17299	7790
Annual Rate of Erosion (ha/yr)	-2930	-947	-612	-1554	-297	-551
Annual Rate of Accretion (ha/yr)	129	1320	1582	1427	6063	889
Annual Rate of Net Change (ha/yr)	-2802	373	970	-127	5766	339
% of Erosion	-4%	-1%	-1%	-1%	0%	-3%
% of Accretion	0%	1%	2%	1%	4%	5%
% of Net Change	-4%	0%	1%	0%	4%	2%
Erosion, Water from Mud (ha)	-5366	-15773	-19178	-6234	-19480	-6715
Accretion, Mud from Water (ha)	27949	14573	7829	14786	18177	23998
Net Change	22583	-1200	-11349	8551	-1303	17283
Annual Rate of Net Change	3764	-240	-1891	2850	-434	751
General Tide Levels						

Summary Statistics of Land Area






Annual Rate of Net Change of Intertidal Area for Bhola-Hatia
4000
3000
2000
1000
0
-1000
-2000
Area (ha/yr)
1973-1979
1979-1984
1984-1990
1990-1993
1993-1996
1973-1996
Year

Summary Statistics of Land and Intertidal Area

Table-3a : Change Classes for Char Bouy by Period

Change Classes New	Change Classes Old	Interpretation	1973-1979	1979-1984	1984-1990	1990-1993	1993-1996	1973-1996
Water	Water	No Change	177541 55%	175500 55%	177524 55%	174009 54%	129959 41%	120741 38%
Water	Mud Flat	Erosion	12587 4%	7458 2%	10641 3%	2642 1%	2101 1%	5481 2%
Mud Flat	Water	Accretion	15563 5%	19627 6%	7736 2%	17478 5%	45675 14%	43939 14%
Mud Flat	Mud Flat	No Change	7832 2%	13012 4%	12871 4%	9728 3%	12286 4%	9065 3%
Land	Land	No Change	8445 3%	7781 2%	8646 3%	14639 5%	23725 7%	4761 1%
Water	Land	Erosion	6534 2%	3526 1%	3698 1%	1266 0%	1489 0%	7326 2%
Mud Flat	Land	Erosion	2927 1%	1474 0%	2819 1%	4566 1%	860 0%	5818 2%
Land	Water	Accretion	2528 1%	1535 0%	1224 0%	375 0%	2283 1%	30949 10%
Land	Mud Flat	Accretion	1809 1%	5852 2%	10599 3%	11056 3%	17384 5%	7682 2%
Stable Land	Stable Land	No Change	84349 26%	84349 26%	84349 26%	84349 26%	84349 26%	84349 26%
Total			320114 100%	320114 100%	320108 100%	320108 100%	320112 100%	320112 100%

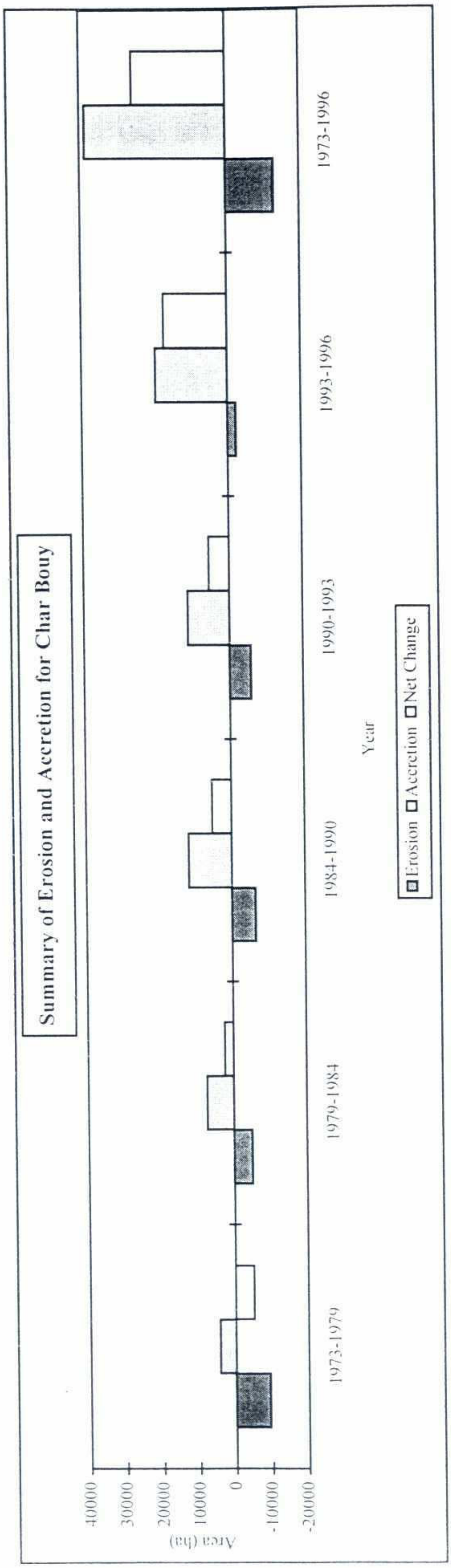
Table-3b : Annual Rates of Change Classes for Char Bouy by Period

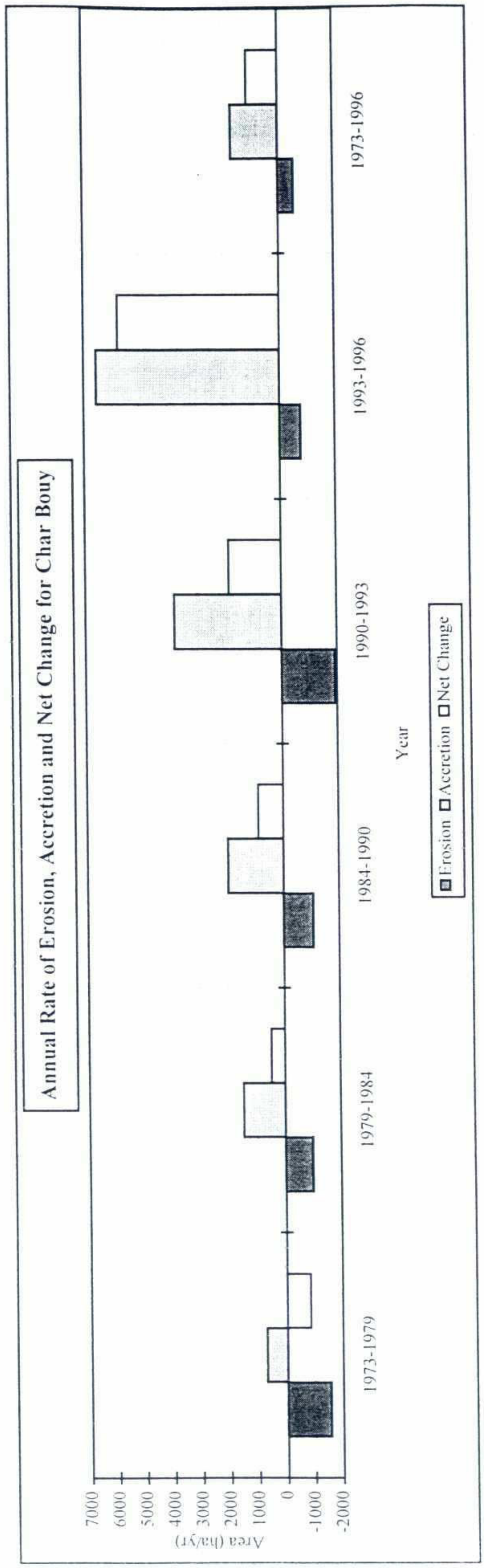
Change Classes New	Change Classes Old	Interpretation	1973-1979	1979-1984	1984-1990	1990-1993	1993-1996	1973-1996
Water	Mud Flat	Erosion	2098	1864	1773	881	700	238
Mud Flat	Water	Accretion	2594	3925	1289	5826	15225	1910
Water	Land	Erosion	1089	705	616	422	496	319
Mud Flat	Land	Erosion	488	295	470	1522	287	253
Land	Water	Accretion	421	307	204	125	761	1346
Land	Mud Flat	Accretion	302	1170	1767	3685	5795	334

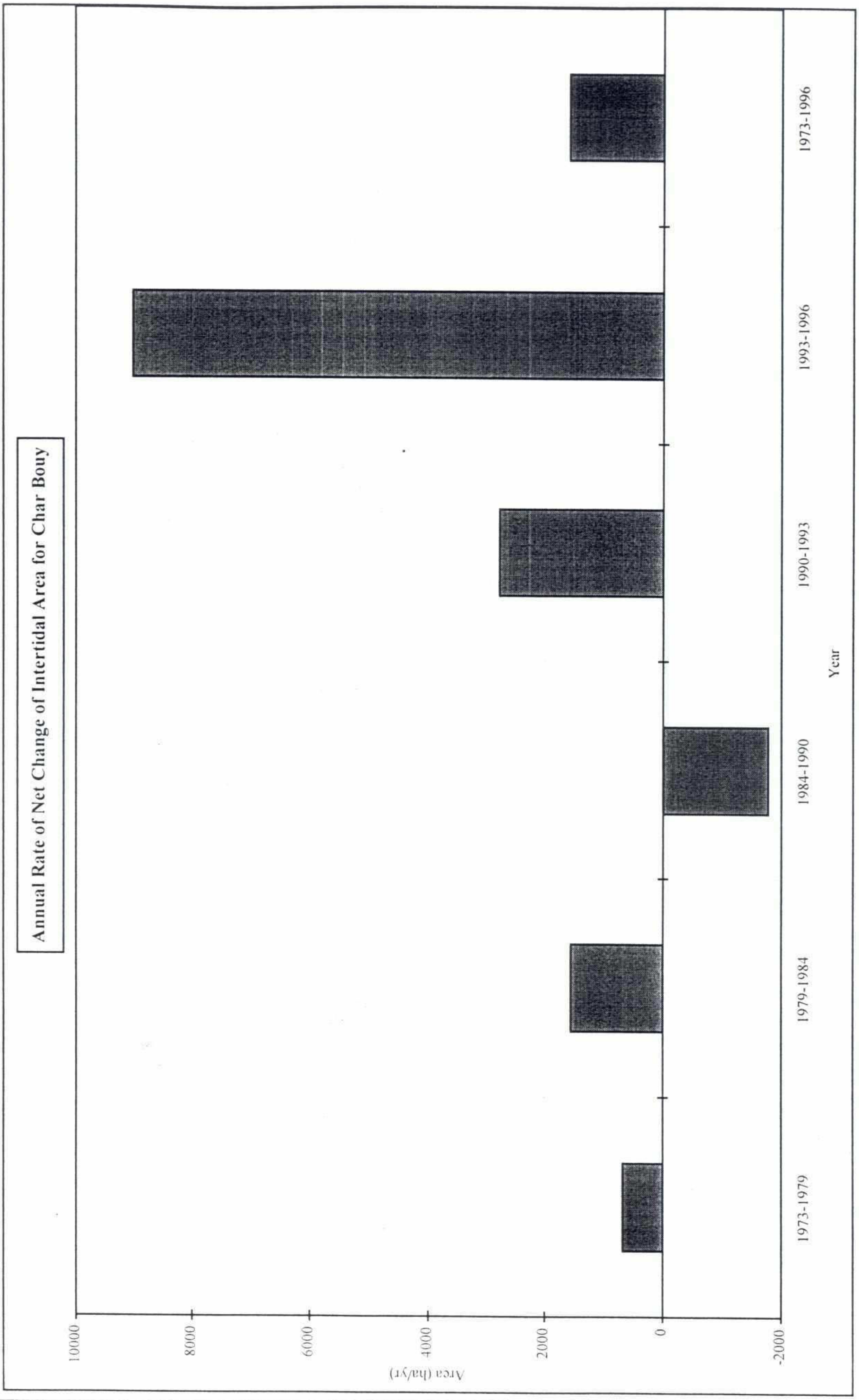
Table-3c : Summary of Erosion and Accretion for Char Bouy

Land Cover Change	1973-1979	1979-1984	1984-1990	1990-1993	1993-1996	1973-1996
Erosion for Period (ha)	-9461	-5000	-6517	-5832	-2348	-13144
Accretion for Period (ha)	4337	7387	11824	11431	19668	38631
Net Change for Period (ha)	-5124	2386	5306	5599	17319	25487
Annual Rate of Erosion (ha/yr)	-1577	-1000	-1086	-1944	-783	-571
Annual Rate of Accretion (ha/yr)	723	1477	1971	3810	6556	1680
Annual Rate of Net Change (ha/yr)	-854	477	884	1866	5773	1108
% of Erosion	-3%	-2%	-2%	-2%	-1%	-4%
% of Accretion	1%	2%	4%	4%	6%	12%
% of Net Change	-2%	1%	2%	2%	5%	8%
Erosion, Water from Mud (ha)	-14396	-13310	-21240	-13698	-19485	-13163
Accretion, Mud from Water (ha)	18490	21101	10555	22044	46535	49756
Net Change	4094	7791	-10685	8346	27050	36594
Annual Rate of Net Change	682	1558	-1781	2782	9017	1591
General Tide Levels						

Summary Statistics of Land Area






Annual Rate of Net Change of Intertidal Area for Char Bouy
10000
8000
6000
4000
2000
0
-2000
Area (ha/yr)
1973-1979
1979-1984
1984-1990
1990-1993
1993-1996
1973-1996
Year

Summary Statistics of Land and Intertidal Area

Table-4a : Change Classes for Chandpur by Period

Change Classes New	Change Classes Old	Interpretation	1973-1979	1979-1984	1984-1990	1990-1993	1993-1996	1973-1996
Water	Water	No Change	21596 18%	25716 22%	22663 19%	26032 22%	27613 23%	14353 12%
Water	Mud Flat	Erosion	2992 3%	1411 1%	1650 1%	1824 2%	1217 1%	4663 4%
Mud Flat	Water	Accretion	4752 4%	3266 3%	4384 4%	2284 2%	1916 2%	3762 3%
Mud Flat	Mud Flat	No Change	2277 2%	2174 2%	1533 1%	2404 2%	2373 2%	868 1%
Land	Land	No Change	9299 8%	11419 10%	11306 10%	11800 10%	12858 11%	4037 3%
Water	Land	Erosion	7110 6%	4445 4%	6003 5%	4090 3%	1579 1%	11393 10%
Mud Flat	Land	Erosion	1202 1%	553 0%	1471 1%	2753 2%	2521 2%	2180 2%
Land	Water	Accretion	4369 4%	2715 2%	4526 4%	1999 2%	2417 2%	12601 11%
Land	Mud Flat	Accretion	2749 2%	4646 4%	2811 2%	3158 3%	3851 3%	2488 2%
Stable Land	Stable Land	No Change	61991 52%	61991 52%	61991 52%	61991 52%	61991 52%	61991 52%
Total			118337 100%	118336 100%	118338 100%	118335 100%	118336 100%	118336 100%

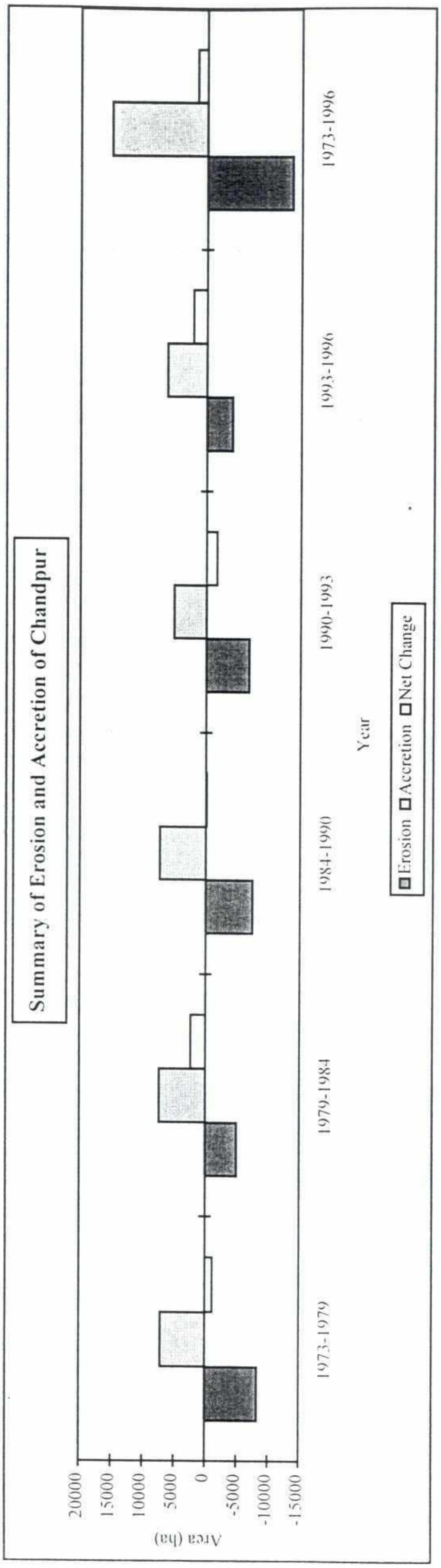
Table-4b : Annual Rates of Change Classes for Chandpur by Period

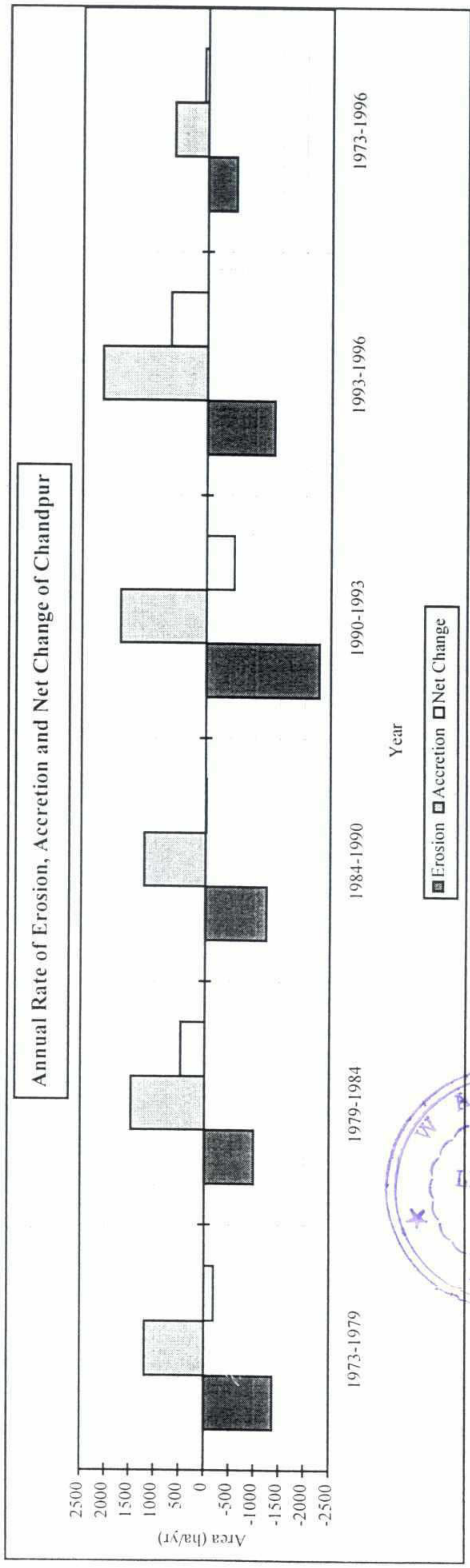
Change Classes New	Change Classes Old	Interpretation	1973-1979	1979-1984	1984-1990	1990-1993	1993-1996	1973-1996
Water	Mud Flat	Erosion	499	353	275	608	406	203
Mud Flat	Water	Accretion	792	653	731	761	639	164
Water	Land	Erosion	1185	889	1001	1363	526	495
Mud Flat	Land	Erosion	200	111	245	918	840	95
Land	Water	Accretion	728	543	754	666	806	548
Land	Mud Flat	Accretion	458	929	469	1053	1284	108

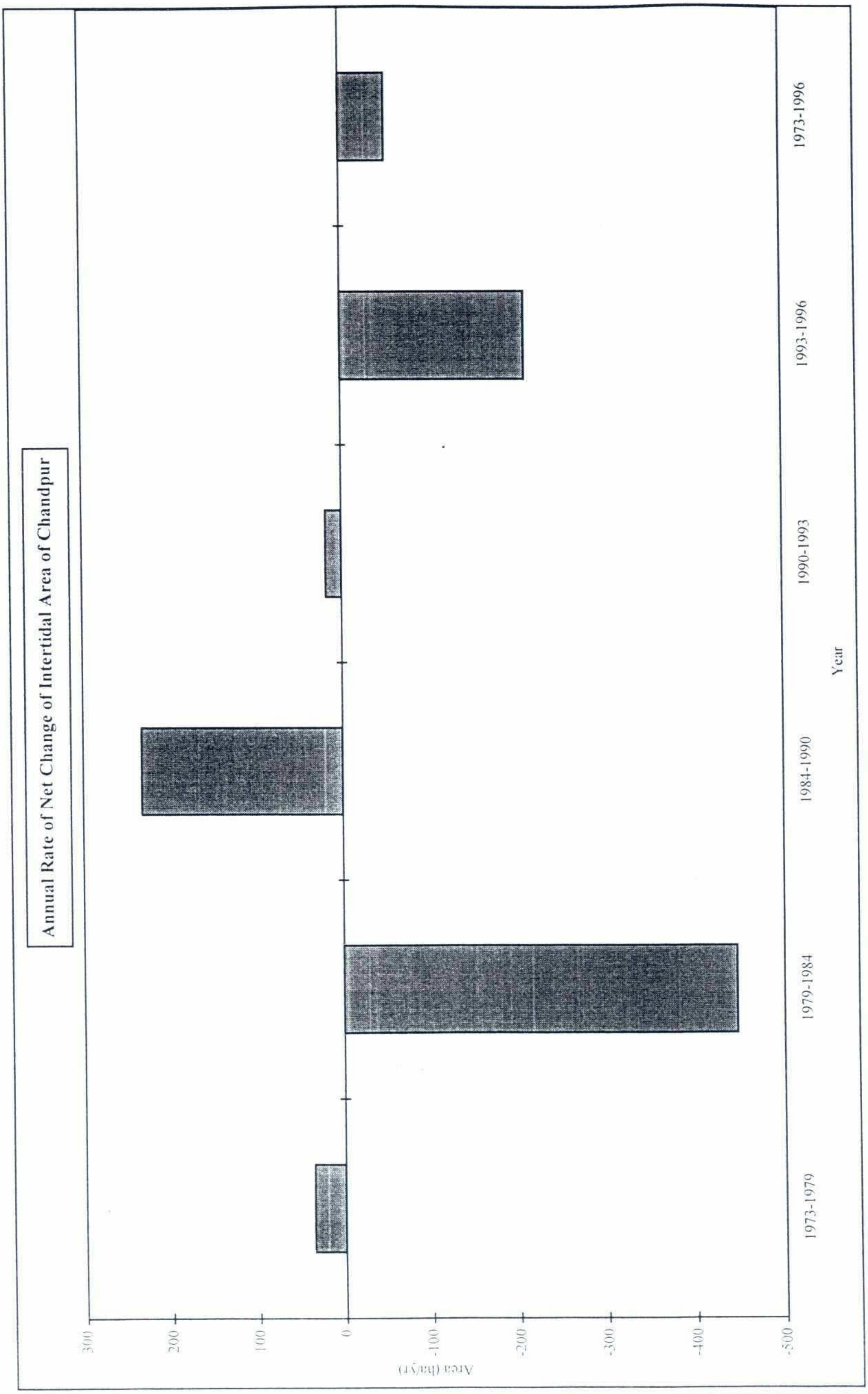
Table-4c : Summary of Erosion and Accretion for Chandpur

Land Cover Change	1973-1979	1979-1984	1984-1990	1990-1993	1993-1996	1973-1996
Erosion for Period (ha)	-8312	-4998	-7474	-6843	-4100	-13573
Accretion for Period (ha)	7118	7361	7337	5157	6268	15089
Net Change for Period (ha)	-1194	2363	-137	-1686	2168	1516
Annual Rate of Erosion (ha/yr)	-1385	-1000	-1246	-2281	-1367	-590
Annual Rate of Accretion (ha/yr)	1186	1472	1223	1719	2089	656
Annual Rate of Net Change (ha/yr)	-199	473	-23	-562	723	66
% of Erosion	-7%	-4%	-6%	-6%	-3%	-11%
% of Accretion	6%	6%	6%	4%	5%	13%
% of Net Change	-1%	2%	0%	-1%	2%	1%
Erosion, Water from Mud (ha)	-5741	-6057	-4461	-4982	-5068	-7151
Accretion, Mud from Water (ha)	5954	3819	5855	5037	4437	5942
Net Change	213	-2238	1394	55	-631	-1209
Annual Rate of Net Change	36	-448	232	18	-210	-53
General Tide Levels						

Summary Statistics of Land Area






Annual Rate of Net Change of Intertidal Area of Chandpur
300
200
100
0
-100
-200
-300
-400
-500
Area (ha/yr)
1973-1979
1979-1984
1984-1990
1990-1993
1993-1996
1973-1996
Year

Summary Statistics of Land and Intertidal Area

Table-5a : Change Classes for Chittagong by Period

Change Classes New	Change Classes Old	Interpretation	1973-1979	1979-1984	1984-1990	1990-1993	1993-1996	1973-1996
Water	Water	No Change	94494 68%	94630 68%	94809 68%	93965 67%	91323 65%	91220 65%
Water	Mud Flat	Erosion	764 1%	176 0%	1180 1%	82 0%	561 0%	186 0%
Mud Flat	Water	Accretion	747 1%	1198 1%	99 0%	2221 2%	2710 2%	3057 2%
Mud Flat	Mud Flat	No Change	1653 1%	2179 2%	2477 2%	2020 1%	2105 2%	992 1%
Land	Land	No Change	1203 1%	858 1%	1507 1%	1821 1%	3796 3%	2833 2%
Water	Land	Erosion	668 0%	107 0%	260 0%	5 0%	43 0%	521 0%
Mud Flat	Land	Erosion	2343 2%	750 1%	1576 1%	157 0%	93 0%	860 1%
Land	Water	Accretion	81 0%	98 0%	5 0%	62 0%	19 0%	1044 1%
Land	Mud Flat	Accretion	431 0%	2387 2%	471 0%	2049 1%	1732 1%	1671 1%
Stable Land	Stable Land	No Change	37271 27%	37271 27%	37273 27%	37273 27%	37272 27%	37271 27%
Total			139655 100%	139655 100%	139655 100%	139655 100%	139655 100%	139655 100%

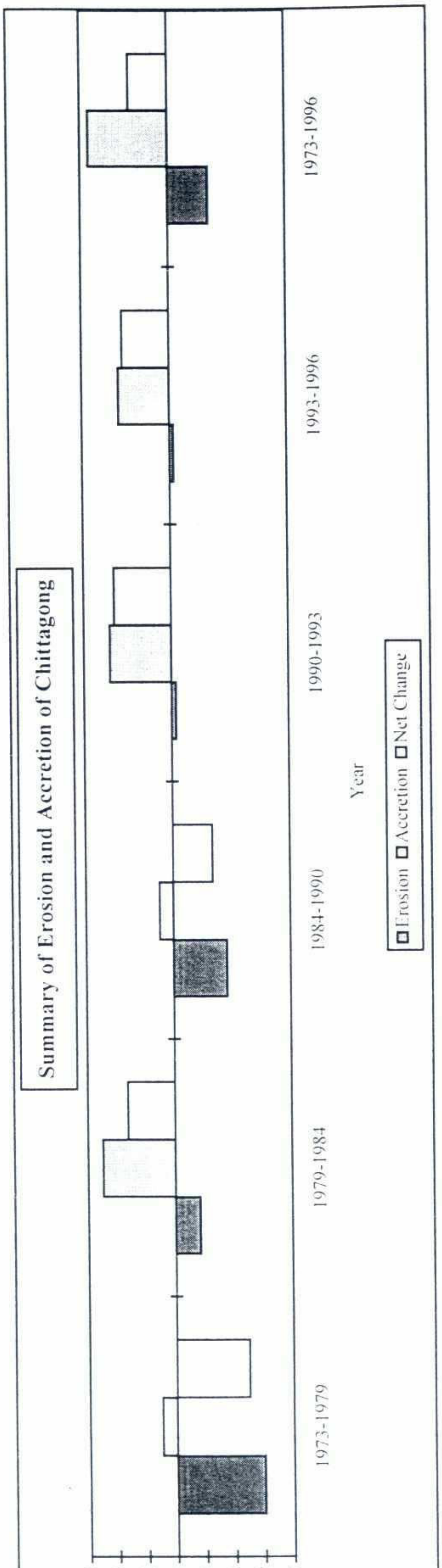
Table-5b : Annual Rates of Change Classes for Chittagong by Period

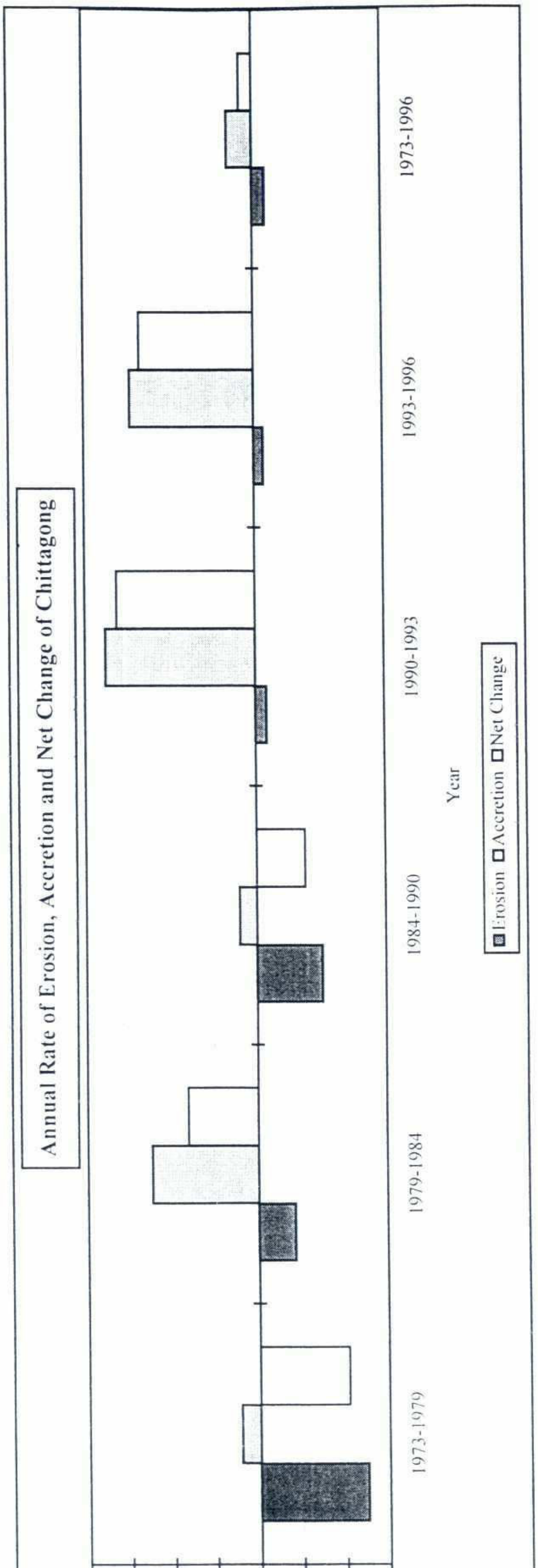
Change Classes New	Change Classes Old	Interpretation	1973-1979	1979-1984	1984-1990	1990-1993	1993-1996	1973-1996
Water	Mud Flat	Erosion	127	44	197	27	187	8
Mud Flat	Water	Accretion	124	240	16	740	903	133
Water	Land	Erosion	111	21	43	2	14	23
Mud Flat	Land	Erosion	390	150	263	52	31	37
Land	Water	Accretion	14	20	1	21	6	45
Land	Mud Flat	Accretion	72	477	79	683	577	73

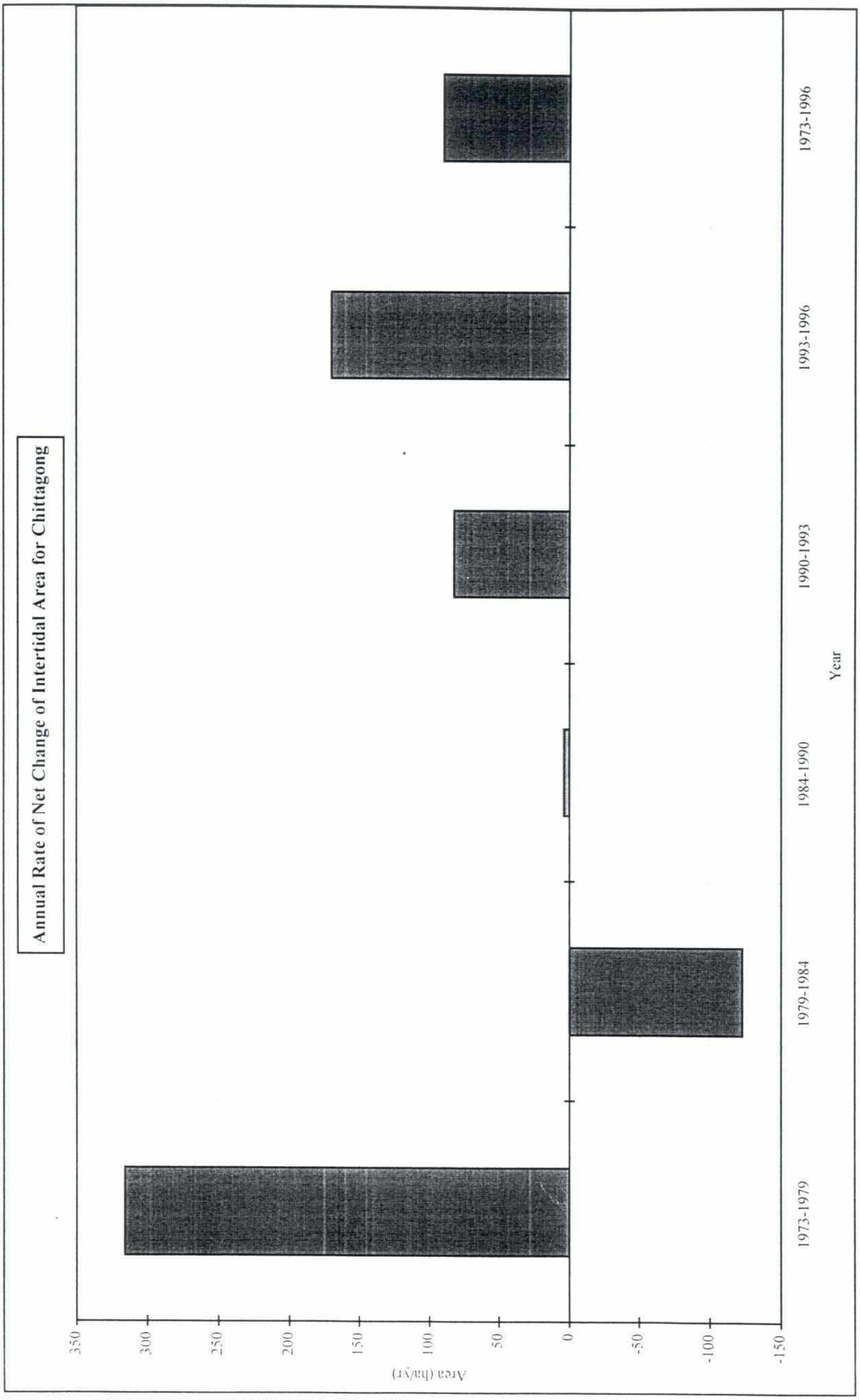
Table-5c : Summary of Erosion and Accretion for Chittagong

Land Cover Change	1973-1979	1979-1984	1984-1990	1990-1993	1993-1996	1973-1996
Erosion for Period (ha)	-3011	-857	-1836	-162	-136	-1381
Accretion for Period (ha)	512	2485	477	2111	1751	2715
Net Change for Period (ha)	-2498	1628	-1359	1949	1615	1335
Annual Rate of Erosion (ha/yr)	-502	-171	-306	-54	-45	-60
Annual Rate of Accretion (ha/yr)	85	497	79	704	584	118
Annual Rate of Net Change (ha/yr)	-416	326	-227	650	538	58
% of Erosion	-2%	-1%	-1%	0%	0%	-1%
% of Accretion	0%	2%	0%	2%	1%	2%
% of Net Change	-2%	1%	-1%	1%	1%	1%
Erosion, Water from Mud (ha)	-1195	-2563	-1651	-2132	-2293	-1857
Accretion, Mud from Water (ha)	3090	1949	1674	2379	2803	3917
Net Change	1894	-615	23	247	510	2060
Annual Rate of Net Change	316	-123	4	82	170	90
General Tide Levels						

Summary Statistics of Land Area






Annual Rate of Net Change of Intertidal Area for Chittagong
Area (ha/yr)
350
300
250
200
150
100
50
0
-50
-100
-150
1973-1979
1979-1984
1984-1990
1990-1993
1993-1996
1973-1996
Year

Summary Statistics of Land and Intertidal Area

Table-6a : Change Classes for Lower Tetulia by Period

Change Classes		Interpretation	1973-1979	1979-1984	1984-1990	1990-1993	1993-1996	1973-1996
New	Old							
Water	Water	No Change	105700	104845	108791	103906	100669	97330
			42%	42%	43%	42%	40%	39%
Water	Mud Flat	Erosion	627	5621	4757	492	2368	941
			0%	2%	2%	0%	1%	0%
Mud Flat	Water	Accretion	18067	3826	1094	10064	3439	7521
			7%	2%	0%	4%	1%	3%
Mud Flat	Mud Flat	No Change	1344	16681	3887	4128	4342	82
			1%	7%	2%	2%	2%	0%
Land	Land	No Change	11808	3914	4234	13833	15157	13808
			5%	2%	2%	6%	6%	6%
Water	Land	Erosion	2733	1849	1536	839	521	5290
			1%	1%	1%	0%	0%	2%
Mud Flat	Land	Erosion	4919	8408	561	12261	184	361
			2%	. 3%	0%	5%	0%	0%
Land	Water	Accretion	2125	389	2427	1108	1129	21038
			1%	0%	1%	0%	0%	8%
Land	Mud Flat	Accretion	237	2028	20272	922	19743	1185
			0%	1%	8%	0%	8%	0%
Stable Land	Stable Land	No Change	102726	102726	102726	102726	102726	102726
			41%	41%	41%	41%	41%	41%
Total			250286	250286	250284	250278	250278	250283
			100%	100%	100%	100%	100%	100%

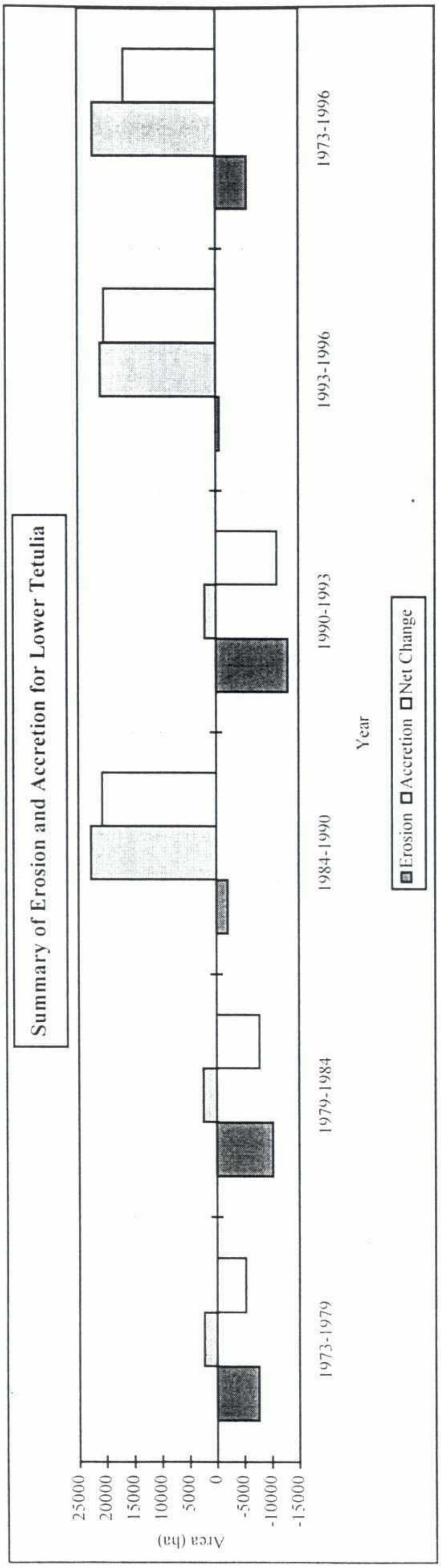
Table-6b : Annual Rates of Change Classes for Lower Tetulia by Period

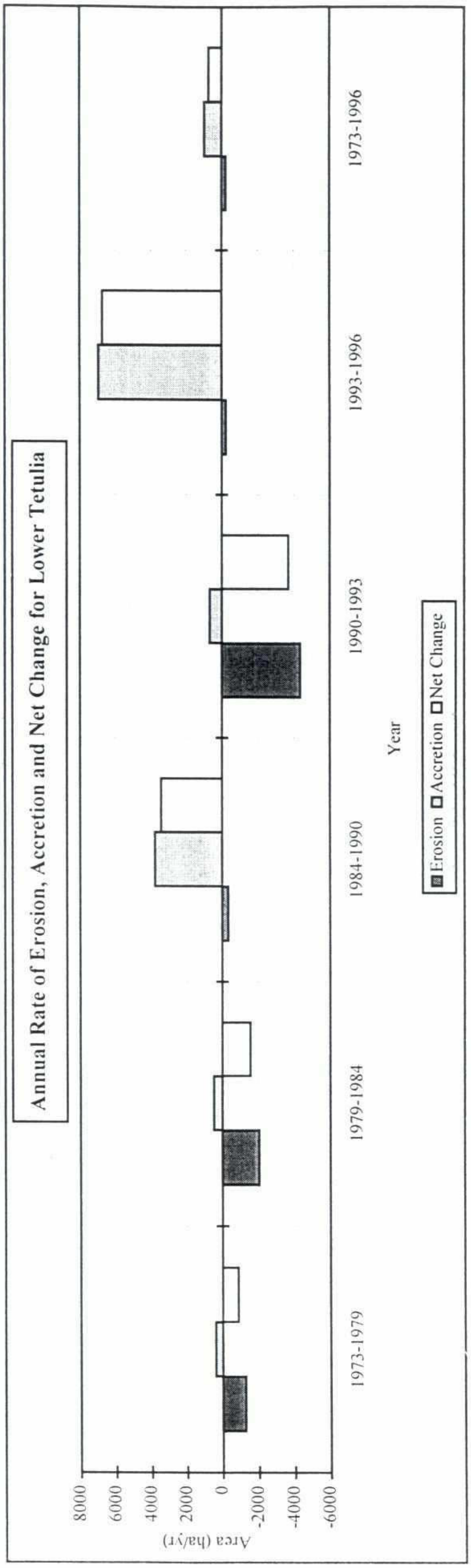
Change Classes		Interpretation	1973-1979	1979-1984	1984-1990	1990-1993	1993-1996	1973-1996
New	Old							
Water	Mud Flat	Erosion	105	1405	793	164	789	41
Mud Flat	Water	Accretion	3011	765	182	3355	1146	327
Water	Land	Erosion	456	370	256	280	174	230
Mud Flat	Land	Erosion	820	1682	93	4087	61	16
Land	Water	Accretion	354	78	405	369	376	915
Land	Mud Flat	Accretion	39	406	3379	307	6581	52

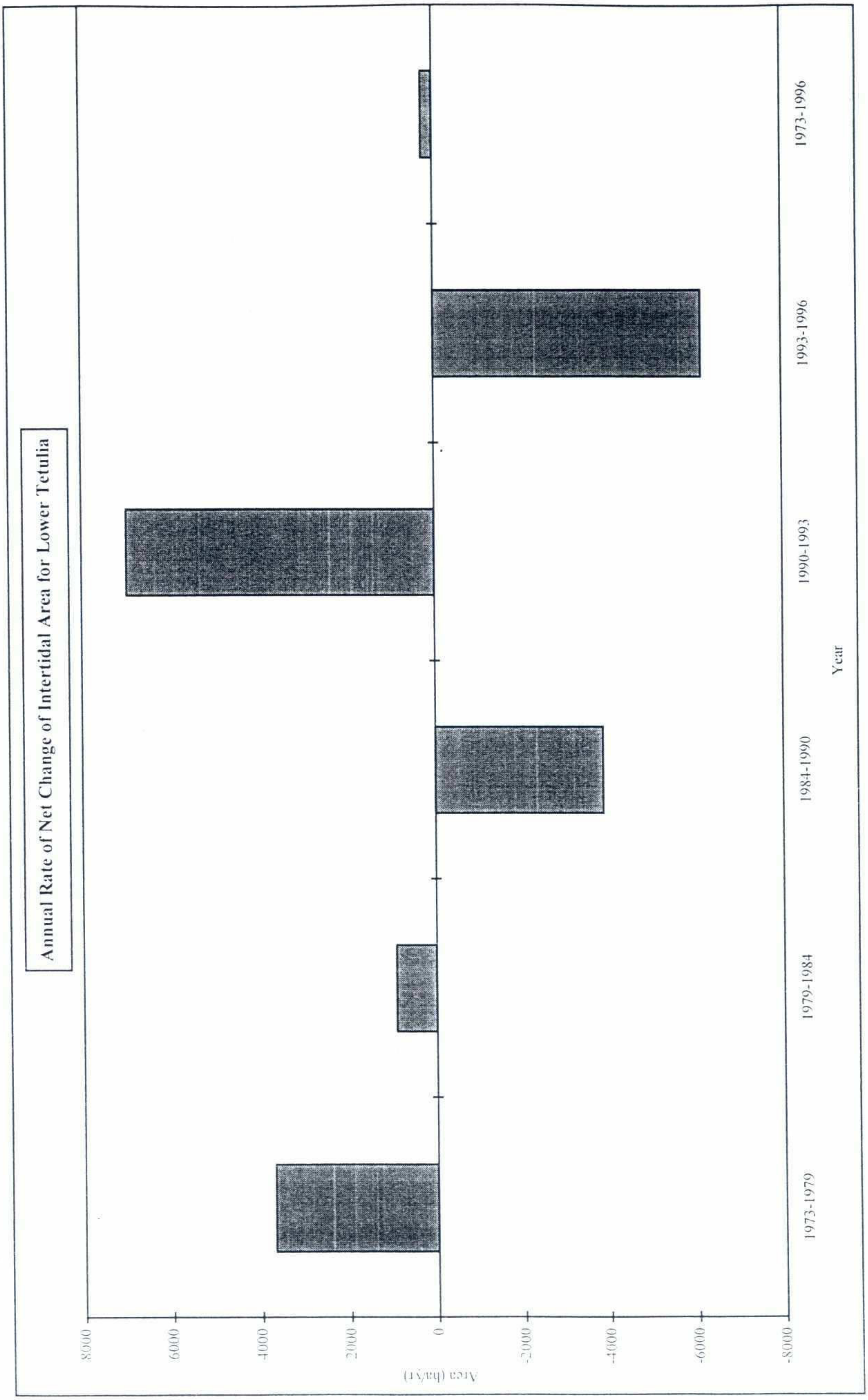
Table-6c : Summary of Erosion and Accretion for Lower Tetulia

Land Cover Change	1973-1979	1979-1984	1984-1990	1990-1993	1993-1996	1973-1996
Erosion for Period (ha)	-7652	-10256	-2097	-13100	-705	-5651
Accretion for Period (ha)	2362	2417	22699	2029	20872	22223
Net Change for Period (ha)	-5290	-7839	20602	-11071	20168	16572
Annual Rate of Erosion (ha/yr)	-1275	-2051	-349	-4367	-235	-246
Annual Rate of Accretion (ha/yr)	394	483	3783	676	6957	966
Annual Rate of Net Change (ha/yr)	-882	-1568	3434	-3690	6723	721
% of Erosion	-3%	-4%	-1%	-5%	0%	-2%
% of Accretion	1%	1%	9%	1%	8%	9%
% of Net Change	-2%	-3%	8%	-4%	8%	7%
Erosion, Water from Mud (ha)	-864	-7649	-25028	-1414	-22111	-2126
Accretion, Mud from Water (ha)	22986	12234	1655	22325	3623	7883
Net Change	22122	4585	-23373	20911	-18488	5756
Annual Rate of Net Change	3687	917	-3896	6970	-6163	250
General Tide Levels						

Summary Statistics of Land Area






Annual Rate of Net Change of Intertidal Area for Lower Tetulia
Area (ha/yr)
8000
6000
4000
2000
0
-2000
-4000
-6000
-8000
1973-1979
1979-1984
1984-1990
1990-1993
1993-1996
1973-1996
Year

Summary Statistics of Land and Intertidal Area

Table-7a : Change Classes for Middle Estuary by Period

Change Classes New	Change Classes Old	Interpretation	1973-1979	1979-1984	1984-1990	1990-1993	1993-1996	1973-1996
Water	Water	No Change	23753	28100	28985	34181	35127	22041
			27%	32%	33%	38%	39%	25%
Water	Mud Flat	Erosion	3976	2222	3155	3117	514	4185
			4%	2%	4%	3%	1%	5%
Mud Flat	Water	Accretion	5657	3703	3855	542	3413	2399
			6%	4%	4%	1%	4%	3%
Mud Flat	Mud Flat	No Change	2474	4079	789	1368	575	1150
			3%	5%	1%	2%	1%	1%
Land	Land	No Change	7993	5596	4262	7402	6600	672
			9%	6%	5%	8%	7%	1%
Water	Land	Erosion	4101	3730	2798	1691	1282	10697
			5%	4%	3%	2%	1%	12%
Mud Flat	Land	Erosion	204	459	597	680	491	930
			0%	1%	1%	1%	1%	1%
Land	Water	Accretion	159	27	1212	215	449	5129
			0%	0%	1%	0%	1%	6%
Land	Mud Flat	Accretion	1632	2035	4298	755	1500	2748
			2%	2%	5%	1%	2%	3%
Stable Land	Stable Land	No Change	39140	39140	39140	39140	39140	39140
			44%	44%	44%	44%	44%	44%
Total			89091	89091	89091	89091	89091	89091
			100%	100%	100%	100%	100%	100%

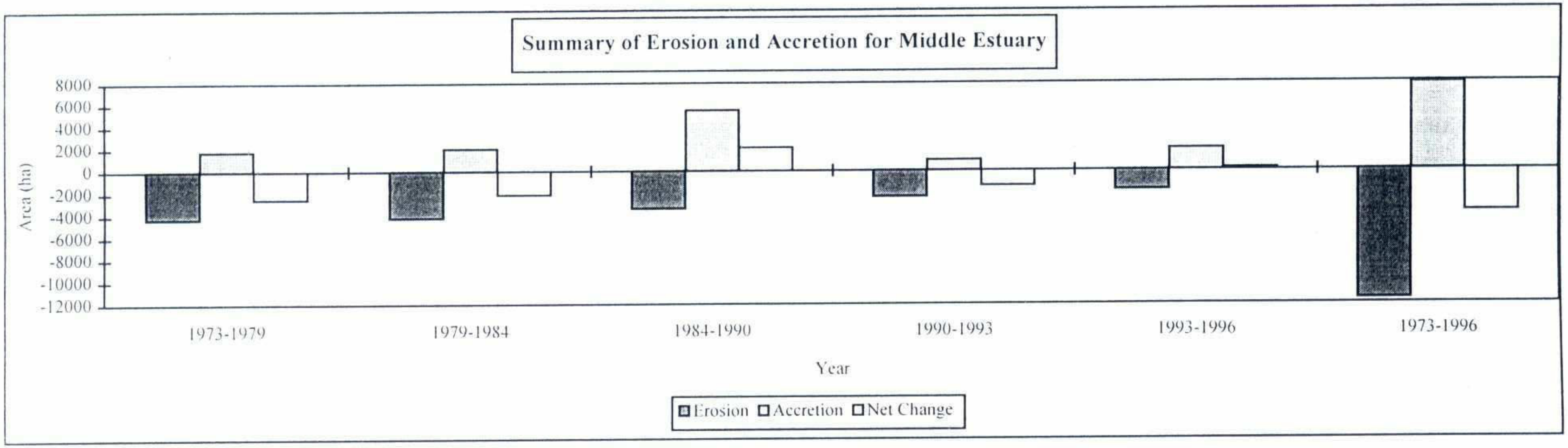
Table-7b : Annual Rates of Change Classes for Middle Estuary by Period

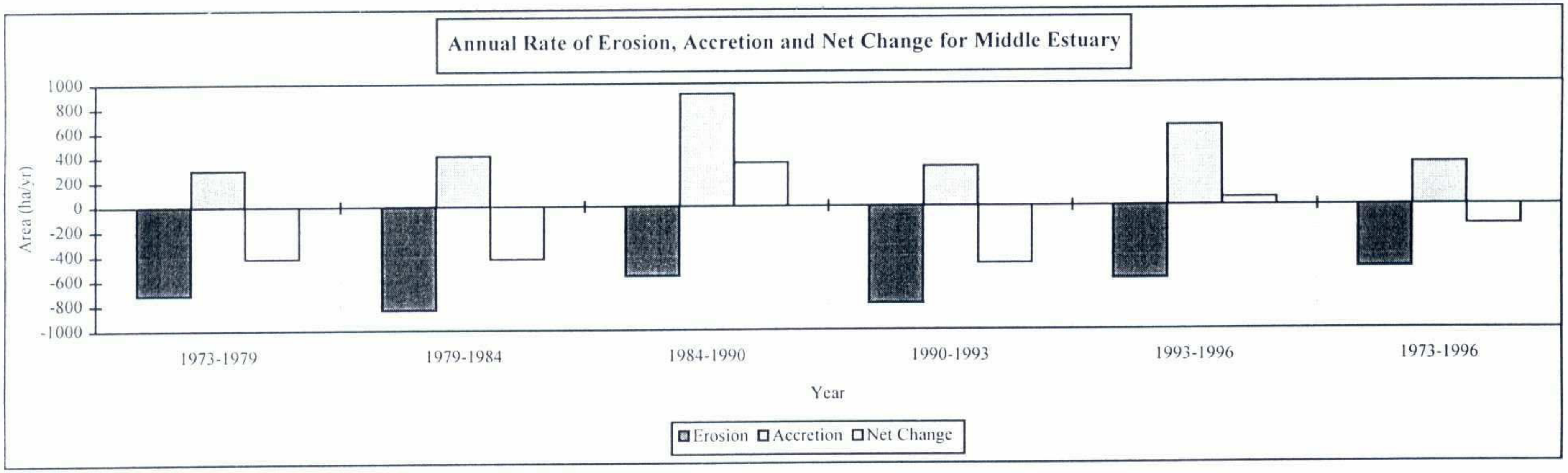
Change Classes New	Change Classes Old	Interpretation	1973-1979	1979-1984	1984-1990	1990-1993	1993-1996	1973-1996
Water	Mud Flat	Erosion	663	556	526	1039	171	182
Mud Flat	Water	Accretion	943	741	642	181	1138	104
Water	Land	Erosion	684	746	466	564	427	465
Mud Flat	Land	Erosion	34	92	99	227	164	40
Land	Water	Accretion	27	5	202	72	150	223
Land	Mud Flat	Accretion	272	407	716	252	500	119

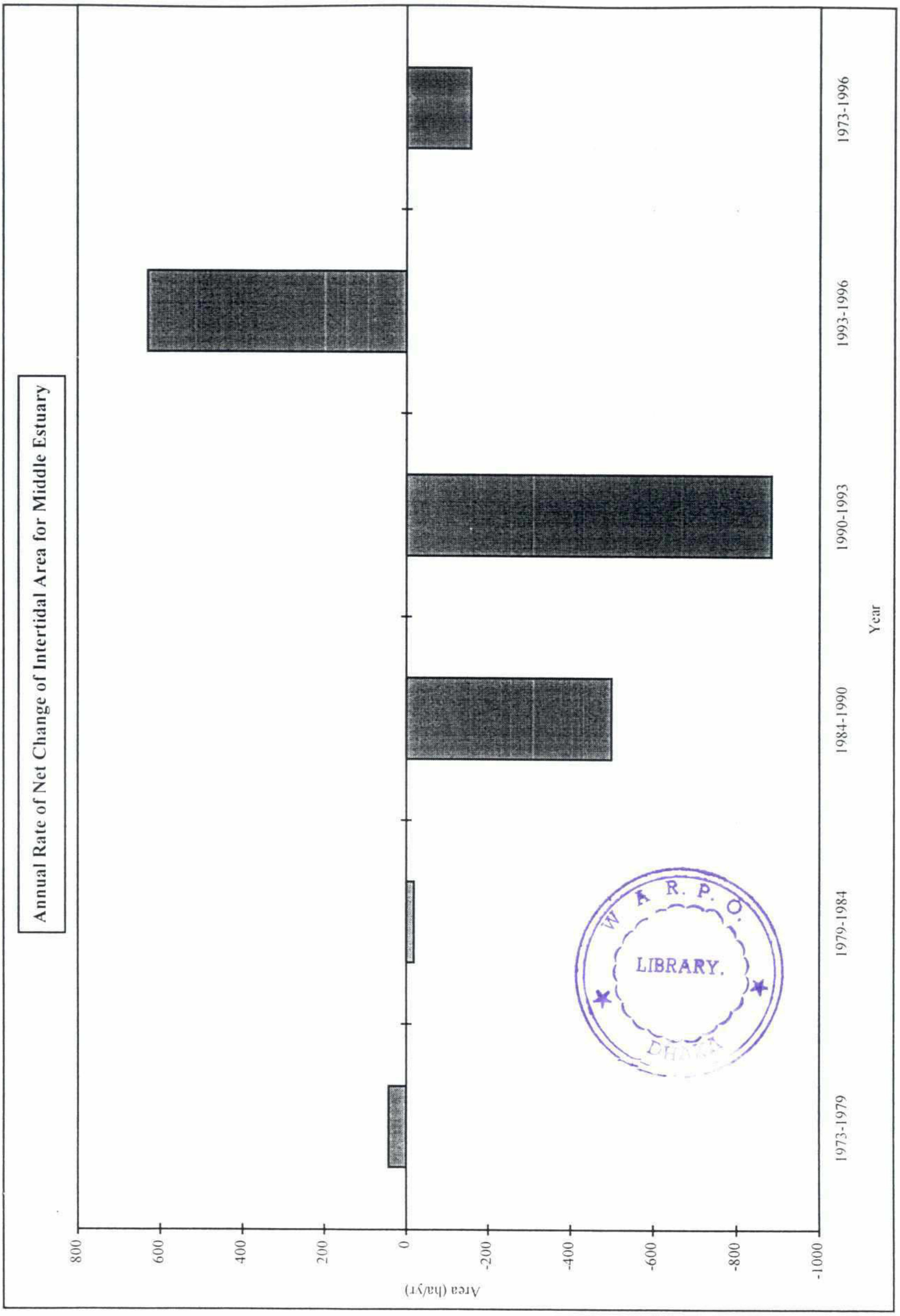
Table-7c : Summary of Erosion and Accretion for Middle Estuary

Land Cover Change	1973-1979	1979-1984	1984-1990	1990-1993	1993-1996	1973-1996
Erosion for Period (ha)	-4306	-4189	-3395	-2371	-1773	-11627
Accretion for Period (ha)	1791	2062	5510	971	1949	7877
Net Change for Period (ha)	-2514	-2127	2115	-1400	176	-3750
Annual Rate of Erosion (ha/yr)	-718	-838	-566	-790	-591	-506
Annual Rate of Accretion (ha/yr)	299	412	918	324	650	342
Annual Rate of Net Change (ha/yr)	-419	-425	353	-467	59	-163
% of Erosion	-5%	-5%	-4%	-3%	-2%	-13%
% of Accretion	2%	2%	6%	1%	2%	9%
% of Net Change	-3%	-2%	2%	-2%	0%	-4%
Erosion, Water from Mud (ha)	-5608	-4257	-7452	-3872	-2015	-6933
Accretion, Mud from Water (ha)	5862	4162	4451	1221	3903	3329
Net Change	253	-95	-3001	-2650	1889	-3604
Annual Rate of Net Change	42	-19	-500	-883	630	-157
General Tide Levels						

Summary Statistics of Land Area






Annual Rate of Net Change of Intertidal Area for Middle Estuary
800
600
400
200
0
-200
-400
-600
-800
-1000
Area (ha/yr)
1973-1979
1979-1984
1984-1990
1990-1993
1993-1996
1973-1996
Year

Summary Statistics of Land and Intertidal Area

Table-8a : Change Classes for Sandwip by Period

Change Classes: New	Change Classes: Old	Interpretation	1973-1979	1979-1984	1984-1990	1990-1993	1993-1996	1973-1996
Water	Water	No Change	31335 53%	33042 56%	34568 59%	33714 57%	27701 47%	24498 42%
Water	Mud Flat	Erosion	464 1%	127 0%	804 1%	129 0%	329 1%	208 0%
Mud Flat	Water	Accretion	116 0%	180 0%	224 0%	2999 5%	6118 10%	5992 10%
Mud Flat	Mud Flat	No Change	207 0%	628 1%	120 0%	407 1%	1416 2%	534 1%
Land	Land	No Change	4765 8%	2873 5%	1385 2%	539 1%	47 0%	1842 3%
Water	Land	Erosion	1433 2%	1628 3%	1341 2%	447 1%	69 0%	3392 6%
Mud Flat	Land	Erosion	480 1%	425 1%	204 0%	714 1%	435 1%	1443 2%
Land	Water	Accretion	15 0%	10 0%	5 0%	0 0%	471 1%	975 2%
Land	Mud Flat	Accretion	147 0%	47 0%	309 1%	12 0%	2375 4%	76 0%
Stable Land	Stable Land	No Change	19791 34%	19791 34%	19791 34%	19791 34%	19791 34%	19791 34%
Total			58751 100%	58751 100%	58751 100%	58751 100%	58751 100%	58751 100%

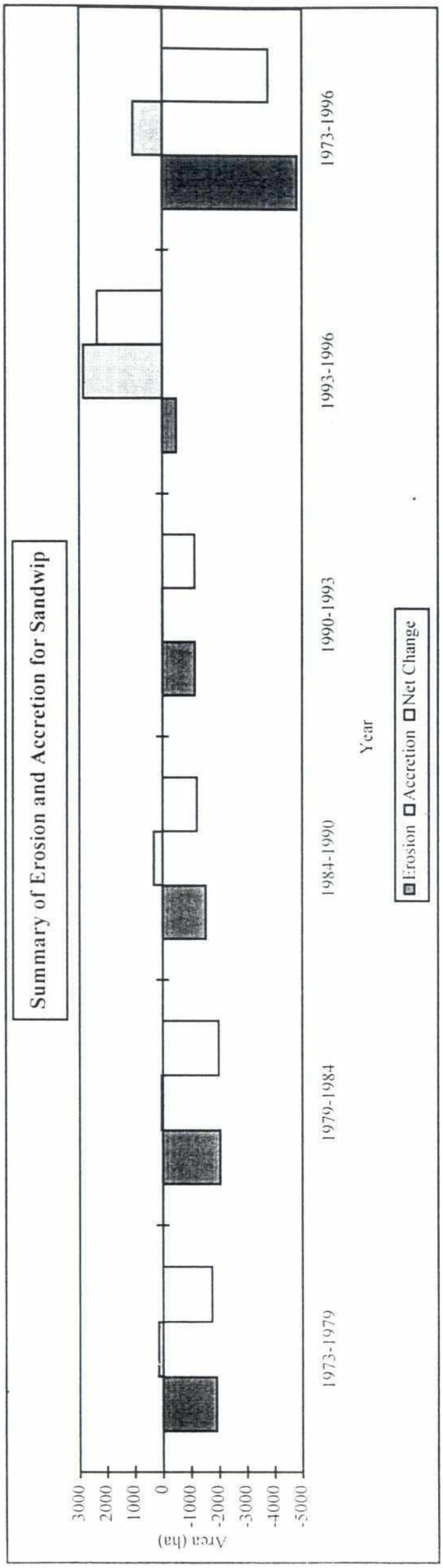
Table-8b : Annual Rates of Change Classes for Sandwip by Period

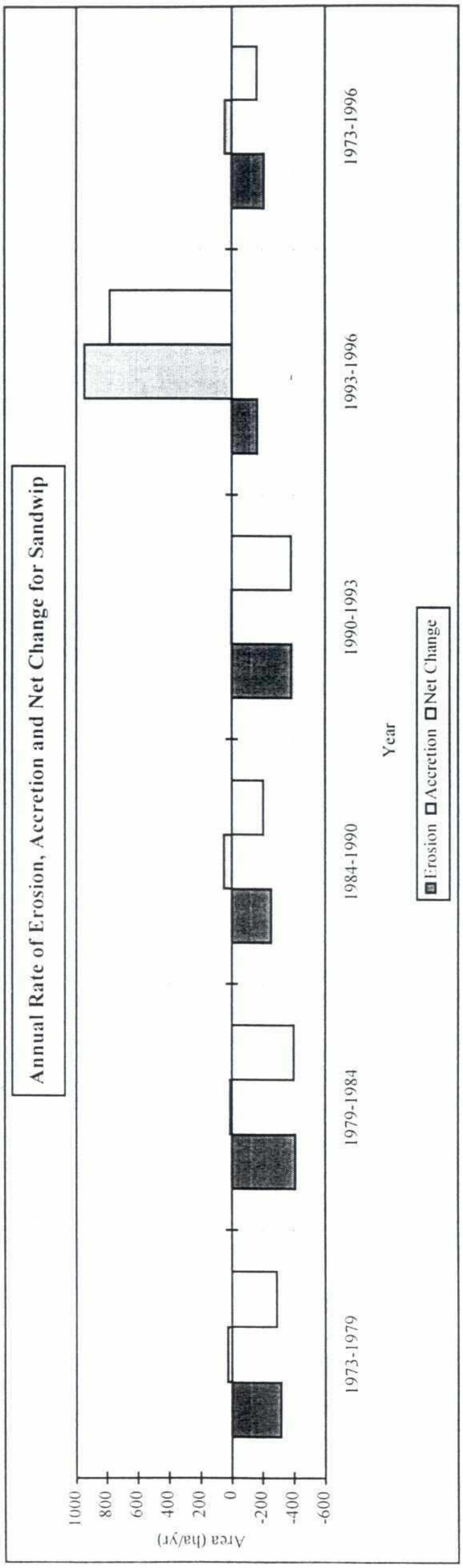
Change Classes: New	Change Classes: Old	Interpretation	1973-1979	1979-1984	1984-1990	1990-1993	1993-1996	1973-1996
Water	Mud Flat	Erosion	77	32	134	43	110	9
Mud Flat	Water	Accretion	19	36	37	1000	2039	261
Water	Land	Erosion	239	326	224	149	23	147
Mud Flat	Land	Erosion	80	85	34	238	145	63
Land	Water	Accretion	2	2	1	0	157	42
Land	Mud Flat	Accretion	24	9	51	4	792	3

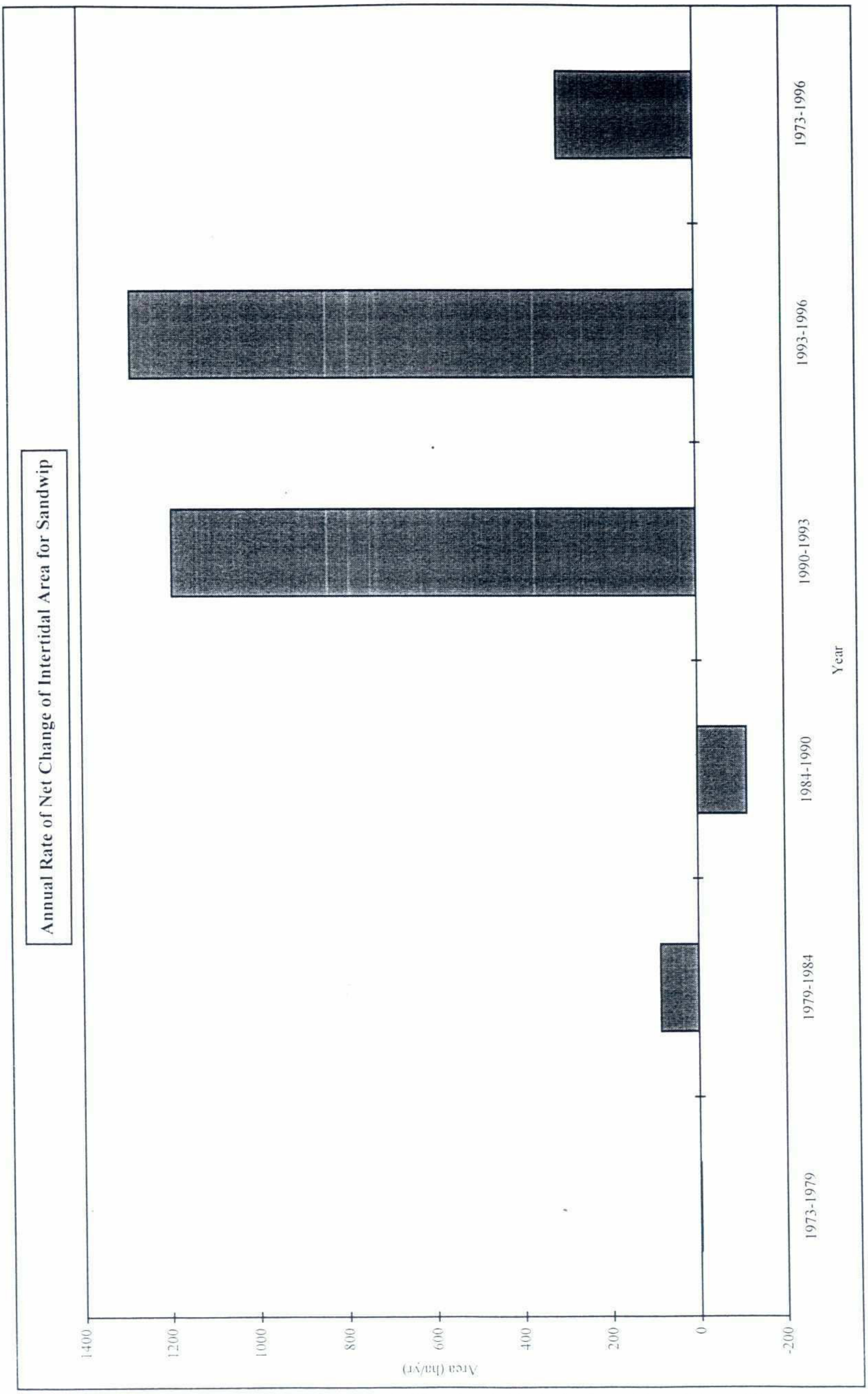
Table-8c : Summary of Erosion and Accretion for Sandwip

Land Cover Change	1973-1979	1979-1984	1984-1990	1990-1993	1993-1996	1973-1996
Erosion for Period (ha)	-1912	-2053	-1545	-1160	-504	-4835
Accretion for Period (ha)	162	57	314	12	2846	1050
Net Change for Period (ha)	-1751	-1996	-1231	-1149	2342	-3784
Annual Rate of Erosion (ha/yr)	-319	-411	-258	-387	-168	-210
Annual Rate of Accretion (ha/yr)	27	11	52	4	949	46
Annual Rate of Net Change (ha/yr)	-292	-399	-205	-383	781	-165
% of Erosion	-3%	-3%	-3%	-2%	-1%	-8%
% of Accretion	0%	0%	1%	0%	5%	2%
% of Net Change	-3%	-3%	-2%	-2%	4%	-6%
Erosion, Water from Mud (ha)	-611	-174	-1113	-141	-2704	-283
Accretion, Mud from Water (ha)	595	604	428	3713	6553	7435
Net Change	-16	431	-685	3572	3849	7151
Annual Rate of Net Change	-3	86	-114	1191	1283	311
General Tide Levels						

Summary Statistics of Land Area







Annual Rate of Net Change of Intertidal Area for Sandwip
Area (ha/yr)
1400
1200
1000
800
600
400
200
0
-200
1973-1979
1979-1984
1984-1990
1990-1993
1993-1996
1973-1996
Year

Summary Statistics of Land and Intertidal Area

Table-9a : Change Classes for Upper Tetulia by Period

Change Classes		Interpretation	1973-1979	1979-1984	1984-1990	1990-1993	1993-1996	1973-1996
New	Old							
Water	Water	No Change	14297	14815	13423	15918	16235	9829
			15%	16%	14%	17%	17%	10%
Water	Mud Flat	Erosion	2272	941	1405	1256	162	2025
			2%	1%	1%	1%	0%	2%
Mud Flat	Water	Accretion	1436	3563	1899	233	899	2342
			2%	4%	2%	0%	1%	2%
Mud Flat	Mud Flat	No Change	3177	4443	2484	2443	1986	1290
			3%	5%	3%	3%	2%	1%
Land	Land	No Change	4248	2222	1082	5261	4822	2090
			5%	2%	1%	6%	5%	2%
Water	Land	Erosion	2266	1413	1396	1135	363	4906
			2%	2%	1%	1%	0%	5%
Mud Flat	Land	Erosion	1088	1669	519	2317	1352	606
			1%	2%	1%	2%	1%	1%
Land	Water	Accretion	182	458	1846	73	1175	3743
			0%	0%	2%	0%	1%	4%
Land	Mud Flat	Accretion	875	317	5785	1203	2845	3010
			1%	0%	6%	1%	3%	3%
Stable Land	Stable Land	No Change	64149	64149	64149	64149	64149	64149
			68%	68%	68%	68%	68%	68%
Total			93990	93990	93988	93988	93988	93988
			100%	100%	100%	100%	100%	100%

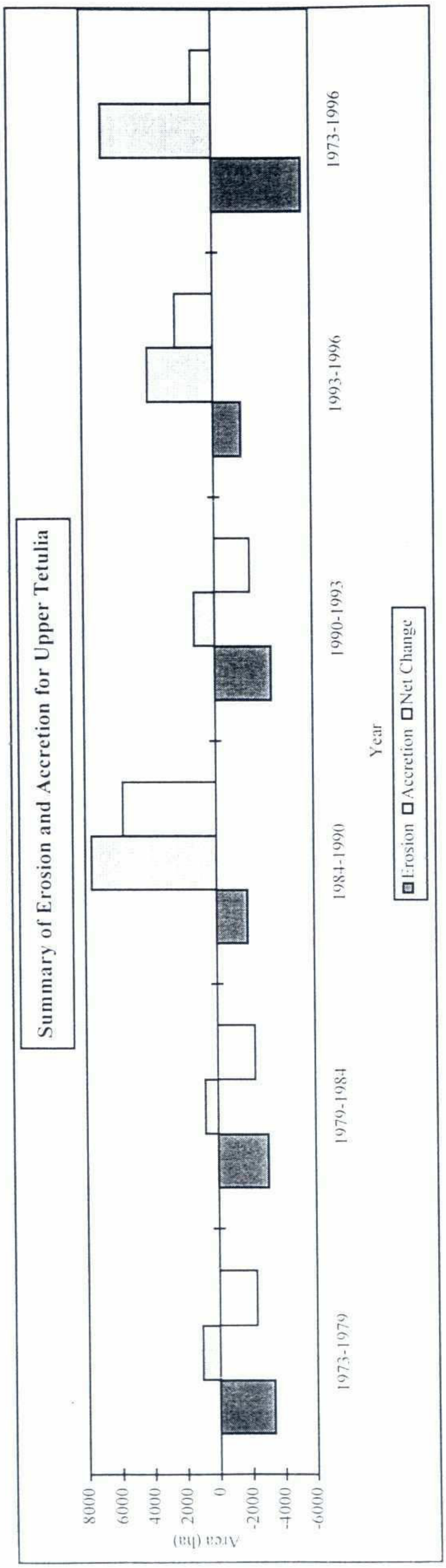
Table-9b : Annual Rates of Change Classes for Upper Tetulia by Period

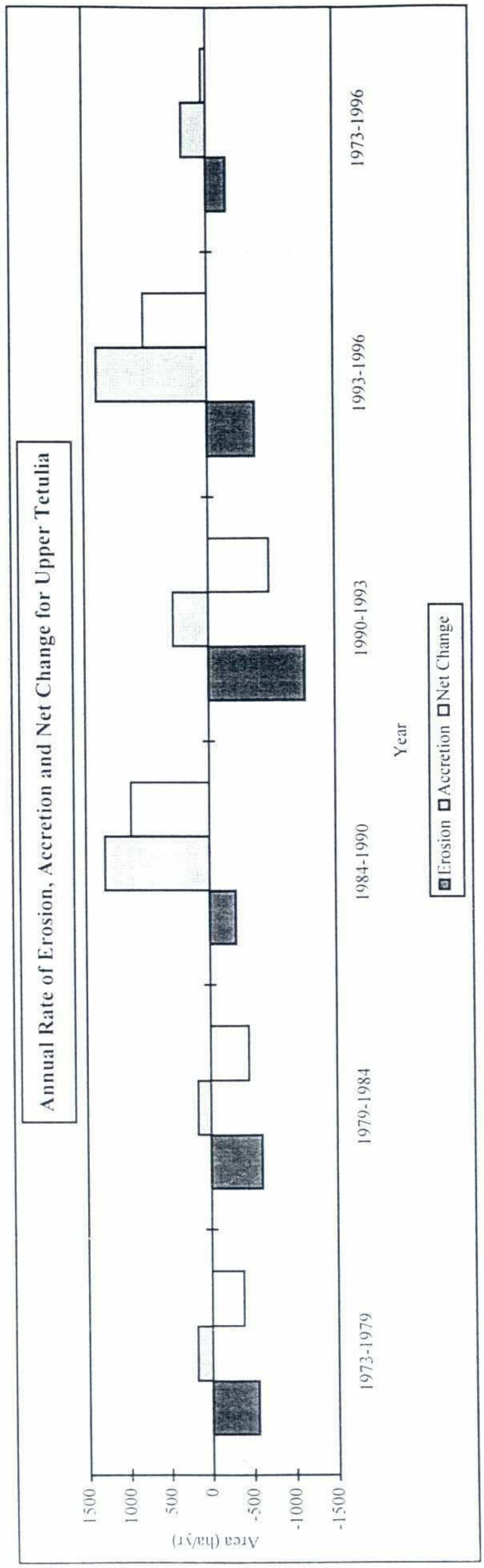
Change Classes		Interpretation	1973-1979	1979-1984	1984-1990	1990-1993	1993-1996	1973-1996
New	Old							
Water	Mud Flat	Erosion	379	235	234	419	54	88
Mud Flat	Water	Accretion	239	713	316	78	300	102
Water	Land	Erosion	378	283	233	378	121	213
Mud Flat	Land	Erosion	181	334	87	772	451	26
Land	Water	Accretion	30	92	308	24	392	163
Land	Mud Flat	Accretion	146	63	964	401	948	131

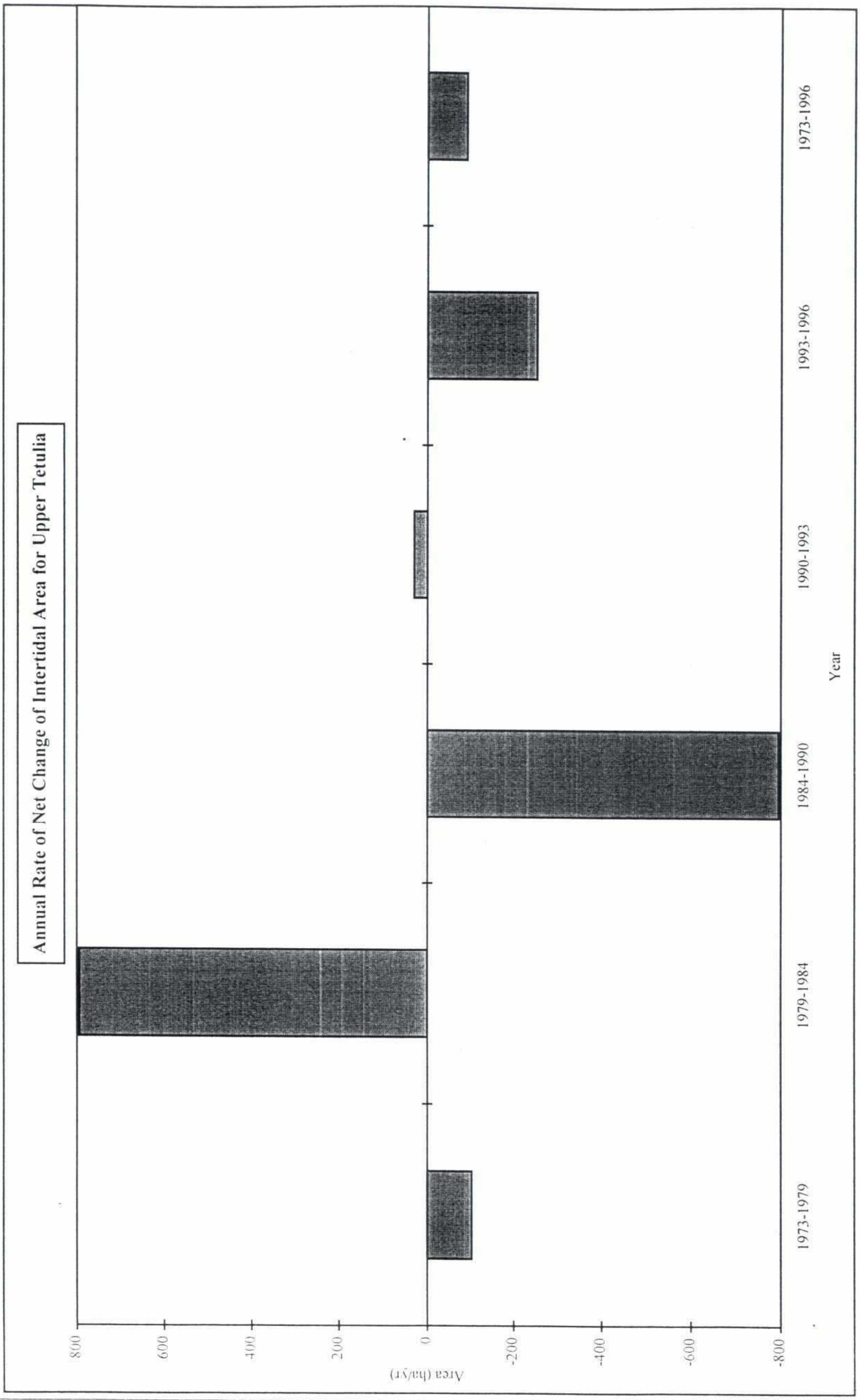
Table-9c : Summary of Erosion and Accretion for Upper Tetulia

Land Cover Change	1973-1979	1979-1984	1984-1990	1990-1993	1993-1996	1973-1996
Erosion for Period (ha)	-3354	-3083	-1916	-3452	-1715	-5512
Accretion for Period (ha)	1057	775	7631	1276	4020	6753
Net Change for Period (ha)	-2297	-2307	5715	-2176	2305	1241
Annual Rate of Erosion (ha/yr)	-559	-617	-319	-1151	-572	-240
Annual Rate of Accretion (ha/yr)	176	155	1272	425	1340	294
Annual Rate of Net Change (ha/yr)	-383	-461	953	-725	768	54
% of Erosion	-4%	-3%	-2%	-4%	-2%	-6%
% of Accretion	1%	1%	8%	1%	4%	7%
% of Net Change	-2%	-2%	6%	-2%	2%	1%
Erosion, Water from Mud (ha)	-3147	-1258	-7190	-2460	-3007	-5035
Accretion, Mud from Water (ha)	2524	5232	2418	2550	2251	2947
Net Change	-624	3974	-4772	90	-756	-2087
Annual Rate of Net Change	-104	795	-795	30	-252	-91
General Tide Levels						

Summary Statistics of Land Area






Annual Rate of Net Change of Intertidal Area for Upper Tetulia
Area (ha/yr)
800
600
400
200
0
-200
-400
-600
-800
1973-1979
1979-1984
1984-1990
1990-1993
1993-1996
1973-1996
Year

Summary Statistics of Land and Intertidal Area

Table-10a : Change Classes for Study Area by Period

Change Classes		Interpretation	1973-1979	1979-1984	1984-1990	1990-1993	1993-1996	1973-1996
New	Old							
Water	Water	No Change	801901 50%	813442 51%	819995 51%	825403 51%	754625 47%	686826 43%
Water	Mud Flat	Erosion	31295 2%	29077 2%	35365 2%	14054 1%	12888 1%	24241 2%
Mud Flat	Water	Accretion	65302 4%	48830 3%	29252 2%	48667 3%	84454 5%	94830 6%
Mud Flat	Mud Flat	No Change	22713 1%	59967 4%	35256 2%	35929 2%	34161 2%	16453 1%
Land	Land	No Change	65760 4%	46776 3%	44073 3%	73711 5%	85757 5%	45617 3%
Water	Land	Erosion	35695 2%	21150 1%	23190 1%	12534 1%	7236 0%	63685 4%
Mud Flat	Land	Erosion	25096 2%	17682 1%	10193 1%	28102 2%	9916 1%	17248 1%
Land	Water	Accretion	10454 1%	6619 0%	14419 1%	4476 0%	12912 1%	95996 6%
Land	Mud Flat	Accretion	9395 1%	24067 1%	55855 3%	24719 2%	65649 4%	22708 1%
Stable Land	Stable Land	No Change	537402 33%	537402 33%	537403 33%	537403 33%	537403 33%	537402 33%
Total			1605012 100%	1605012 100%	1605002 100%	1604997 100%	1605001 100%	1605006 100%

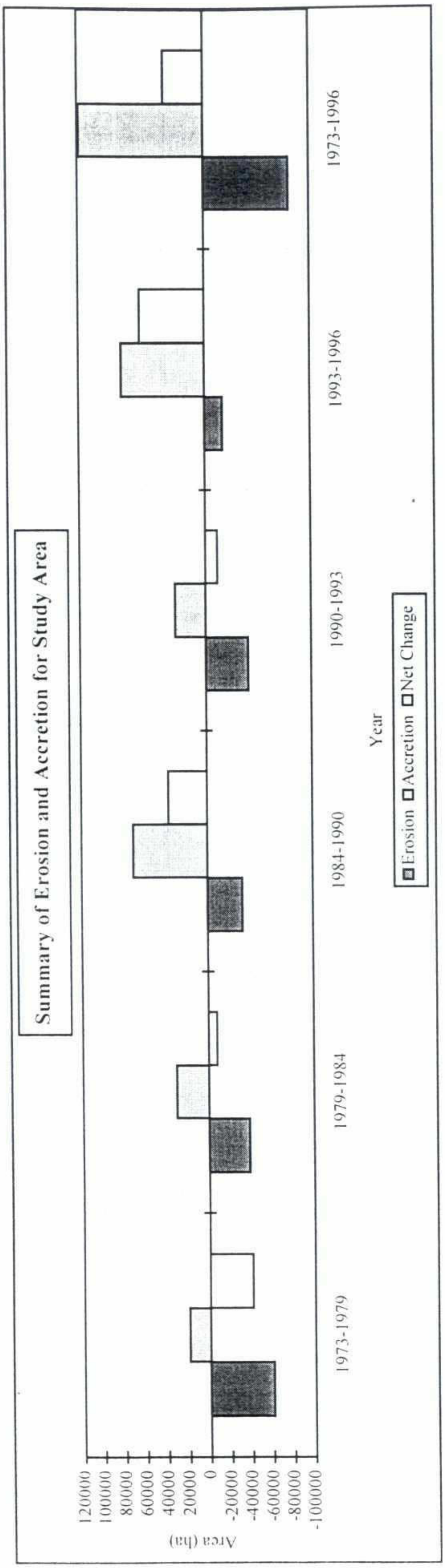
Table-10b : Annual Rates of Change Classes for Study Area by Period

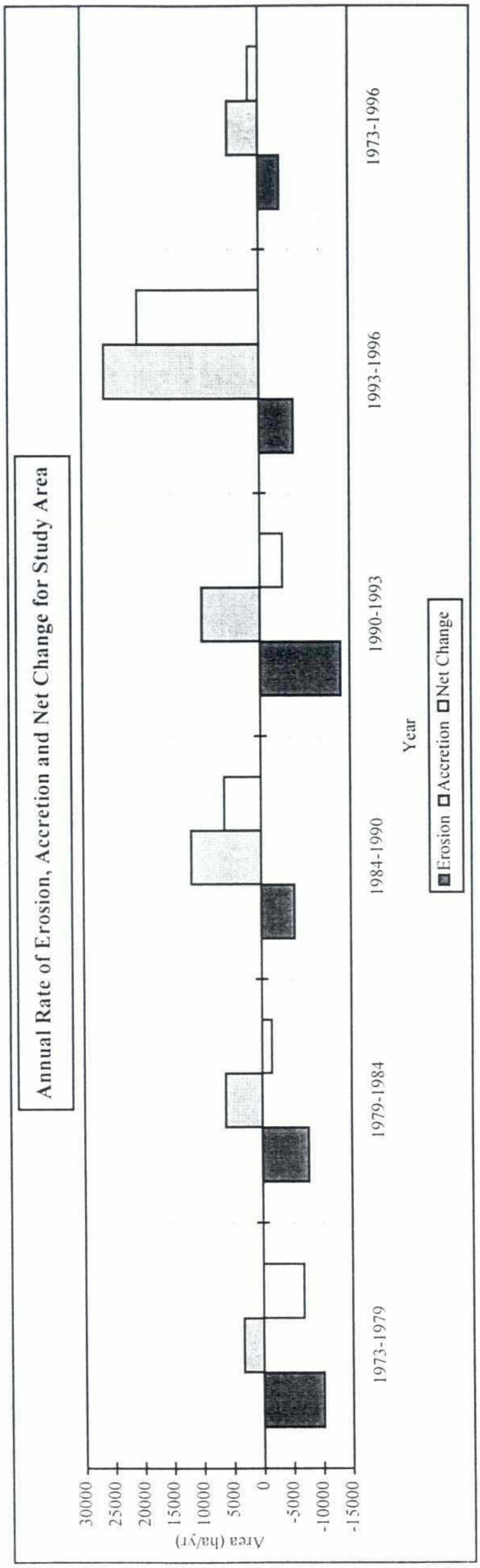
Change Classes		Interpretation	1973-1979	1979-1984	1984-1990	1990-1993	1993-1996	1973-1996
New	Old							
Water	Mud Flat	Erosion	5216	7269	5894	4685	4296	1054
Mud Flat	Water	Accretion	10884	9766	4875	16222	28151	4123
Water	Land	Erosion	5949	4230	3865	4178	2412	2769
Mud Flat	Land	Erosion	4183	3536	1699	9367	3305	750
Land	Water	Accretion	1742	1324	2403	1492	4304	4174
Land	Mud Flat	Accretion	1566	4813	9309	8240	21883	987

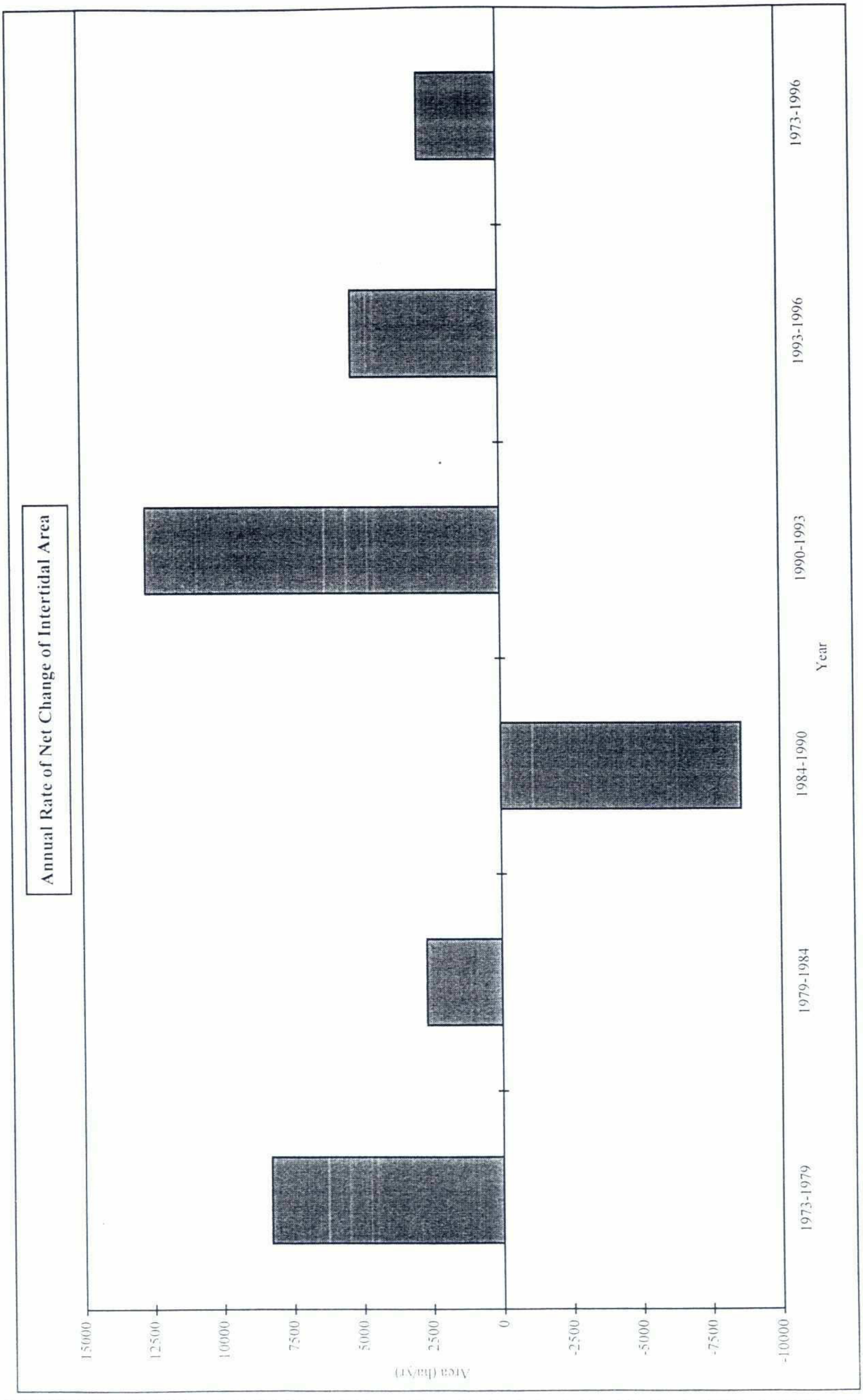
Table-10c : Summary of Erosion and Accretion for Study Area

Land Cover Change	1973-1979	1979-1984	1984-1990	1990-1993	1993-1996	1973-1996
Erosion for Period (ha)	-60791	-38832	-33383	-40636	-17151	-80933
Accretion for Period (ha)	19848	30686	70274	29195	78561	118704
Net Change for Period (ha)	-40943	-8146	36891	-11441	61409	37772
Annual Rate of Erosion (ha/yr)	-10132	-7766	-5564	-13545	-5717	-3519
Annual Rate of Accretion (ha/yr)	3308	6137	11712	9732	26187	5161
Annual Rate of Net Change (ha/yr)	-6824	-1629	6148	-3814	20470	1642
% of Erosion	-4%	-2%	-2%	-3%	-1%	-5%
% of Accretion	1%	2%	4%	2%	5%	7%
% of Net Change	-3%	-1%	2%	-1%	4%	2%
Erosion, Water from Mud (ha)	-40689	-53144	-91220	-38773	-78537	-46950
Accretion, Mud from Water (ha)	90398	66513	39446	76768	94370	112078
Net Change	49709	13369	-51775	37995	15833	65128
Annual Rate of Net Change	8285	2674	-8629	12665	5278	2832
General Tide Levels						

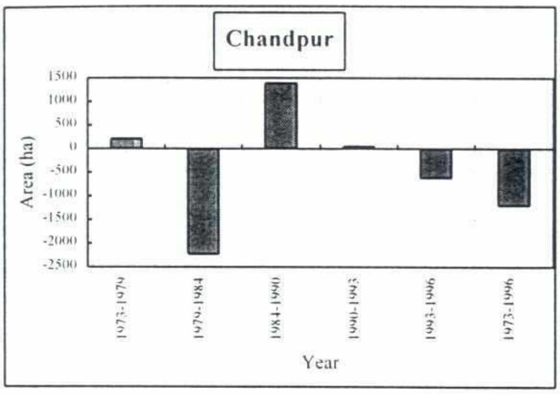
Summary Statistics of Land Area

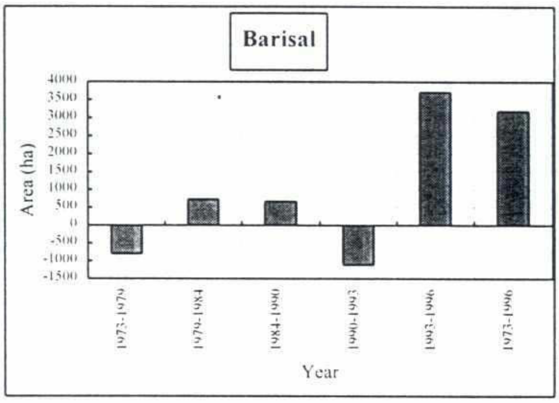


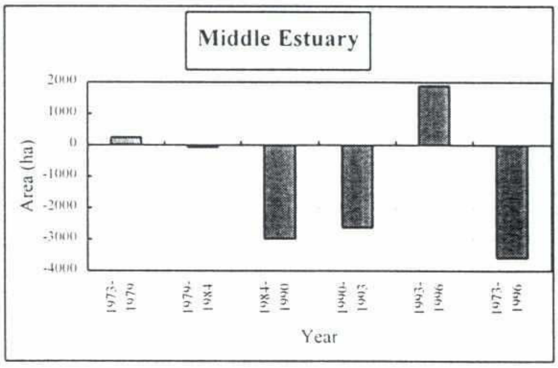


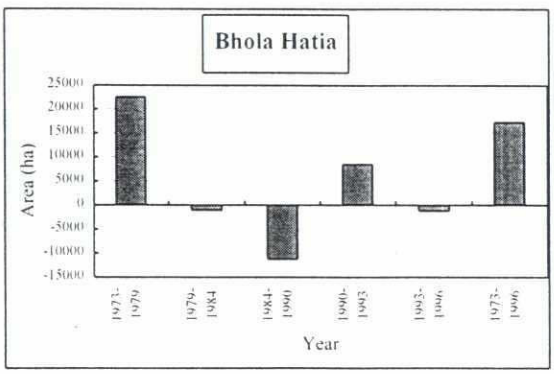

Annual Rate of Net Change of Intertidal Area
Area (ha/yr)
15000
12500
10000
7500
5000
2500
0
-2500
-5000
-7500
-10000
1973-1979
1979-1984
1984-1990
1990-1993
1993-1996
1973-1996
Year

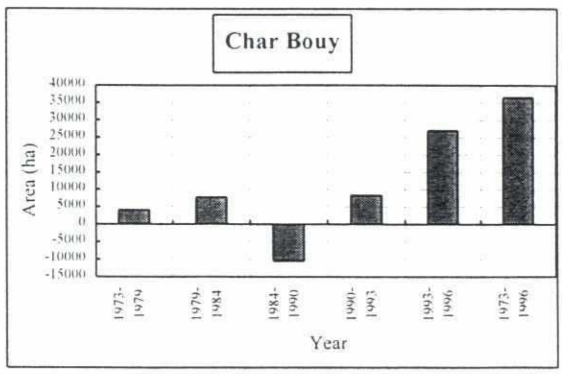
Net Change of Intertidal Area along the Lower Meghna



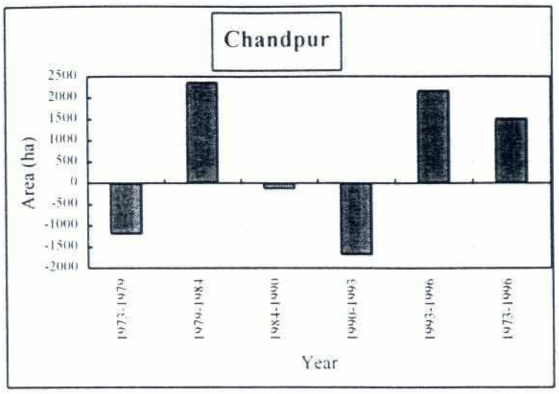


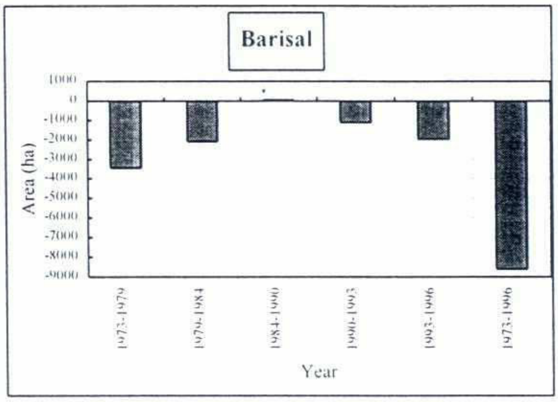


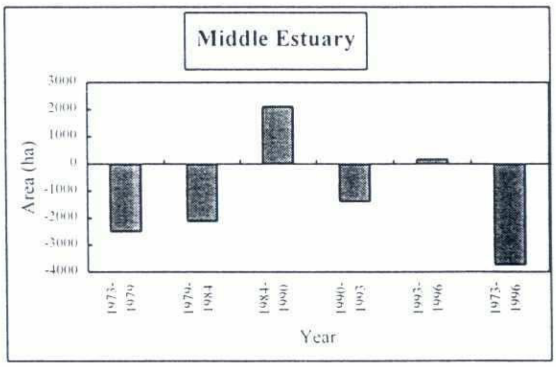


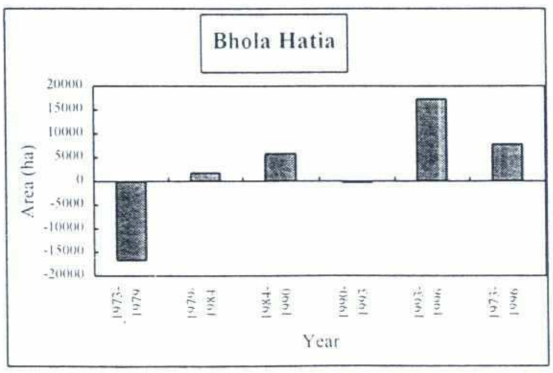


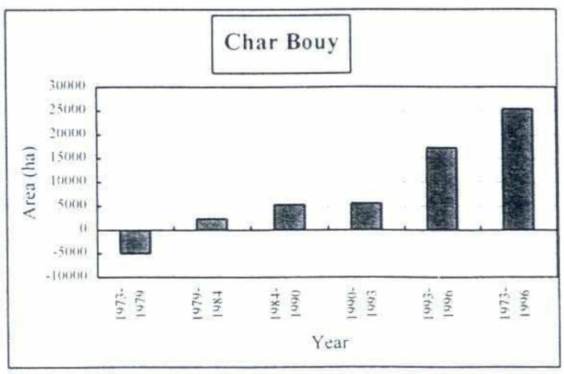
Net Change of Land Area along the Lower Meghna











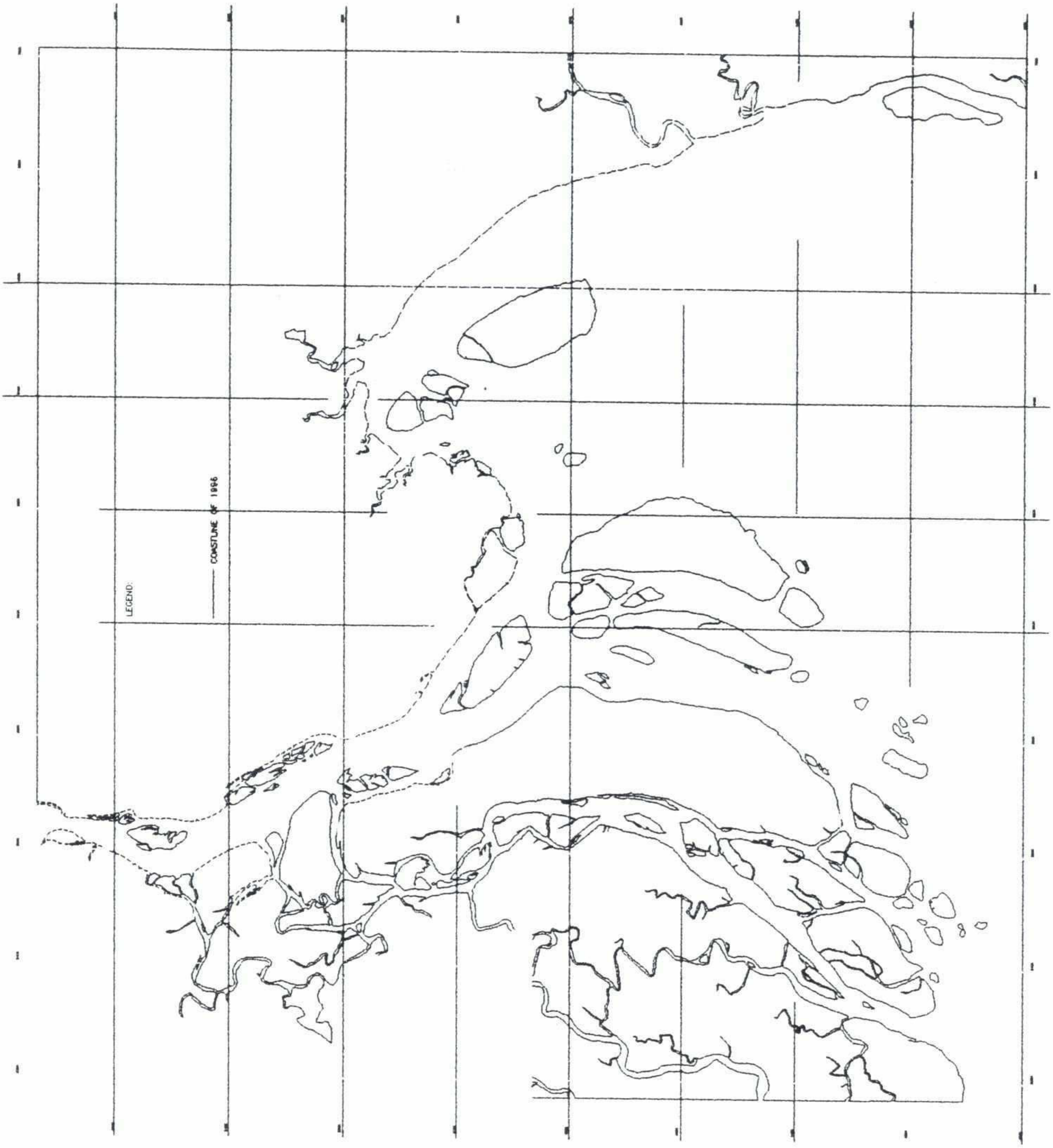

LEGEND:
COASTLINE OF 1996

Table 1 : Longterm Shoreline Migration Rate (from 1957 to 1996) of West and East Banks between Chandpur and North Bhola

Northing	West Bank		East Bank	
	Migration Rate (m/yr)	R^2	Migration Rate (m/yr)	R^2
571000	44.33	0.162	-4.04	0.457
570000	34.40	0.122	23.92	0.069
569000	21.07	0.058	-2.20	0.604
568000	-2.84	0.001	-11.74	0.811
567000	25.87	0.153	-36.22	0.952
566000	15.96	0.036	-52.97	0.971
565000	-28.34	0.094	12.55	0.115
564000	-41.30	0.203	40.05	0.861
563000	-39.08	0.119	33.76	0.785
562000	-54.63	0.894	2.09	0.460
561000	-106.51	0.915	28.83	0.991
560000	-124.98	0.908	58.61	0.721
559000	-148.91	0.917	83.36	0.898
558000	-243.26	0.966	100.21	0.832
557000	-270.78	0.950	102.73	0.839
556000	-280.22	0.911	73.56	0.942
555000	-289.39	0.881	83.34	0.942
554000	-260.03	0.841	103.89	0.957
553000	-212.00	1.000	121.55	0.969
552000	-413.00	1.000	133.71	0.967
551000	-334.00	1.000	93.85	0.990
550000	-324.00	1.000	87.72	0.995
549000	-389.00	1.000	64.66	0.975
548000	-346.00	1.000	2.15	0.002
547000	34.33	1.000	-45.30	0.636
546000	-336.25	1.000	-69.80	0.841
545000	-249.58	1.000	-104.42	0.806
544000	-231.45	1.000	-140.05	0.756
543000	-126.64	1.000	-148.05	0.753
542000	-129.52	1.000	-167.99	0.782
541000	-167.18	1.000	-111.66	0.606
540000	-162.67	1.000	-52.99	0.466
539000	-144.44	1.000	-53.78	0.522
538000	-61.25	1.000	-28.44	0.357
537000	-101.44	1.000	-119.91	0.437
536000	-93.48	1.000	39.16	0.523
535000	-22.28	1.000	52.10	0.531
534000	-70.66	1.000	83.15	0.687
533000	141.33	1.000	92.79	0.657
532000	-125.06	1.000	121.88	0.746
531000	-67.69	0.860	116.70	0.839
530000	-180.01	0.912	107.37	0.817
529000	-133.18	0.994	59.59	0.363
528000	-132.73	0.919	85.12	0.827
527000	-113.78	0.865	123.10	0.829
526000	-90.65	0.848	159.64	0.909
525000	-63.21	0.860	163.64	0.929

Table 1 : Longterm Shoreline Migration Rate (from 1957 to 1996) of West and East Banks between Chandpur and North Bhola

Northing	West Bank		East Bank	
	Migration Rate (m/yr)	R^2	Migration Rate (m/yr)	R^2
524000	-32.43	0.835	153.05	0.960
523000	5.59	0.028	137.29	0.970
522000	-100.45	0.673	114.12	0.962
521000	72.56	0.045	75.62	0.931
520000	-75.90	0.933	48.12	0.970
519000	-87.35	0.982	33.25	0.818
518000	-97.37	0.977	30.34	0.545
517000	-98.06	0.968	-22.06	0.373
516000	-94.60	0.963	-31.24	0.389
515000	-87.95	0.976	-30.53	0.352
514000	-92.14	0.908	-29.89	0.301
513000	-99.36	0.873	-53.14	0.404
512000	-89.41	0.891	-56.29	0.442
511000	-68.51	0.896	-52.31	0.744
510000	-55.27	0.860	-35.65	0.137
509000	-45.61	0.859	2.88	0.000
508000	-29.36	0.823	-13.82	0.003
507000	-16.54	0.920	-78.06	0.113
506000	-38.53	0.920	-7.79	0.003
505000	-72.68	0.864	39.01	0.153
504000	-128.59	0.796	51.12	0.693
503000	-201.24	0.738	68.26	0.696
502000	-339.90	0.873	84.07	0.831
501000	-181.68	0.850	97.60	0.943
500000	-136.25	0.827	114.77	0.989
499000	-115.59	0.867	120.55	0.997
498000	-99.62	0.898	143.41	0.981
497000	-93.82	0.955	147.26	0.990
496000	-90.65	0.877	204.65	0.675
495000	-104.42	0.898	75.63	0.994
494000	-114.43	0.800	72.08	0.935
493000	-124.56	0.768	63.87	0.746
492000	-138.34	0.814	57.97	0.831
491000	-153.67	0.844		
490000	-172.20	0.865		
489000	-209.83	0.867		
488000	-223.85	0.801		
	positive = sedimentation negative = erosion		positive = erosion negative = sedimentation	

Table 2: Longterm Shoreline Migration Rate (from 1957 to 1996) of West and East Banks of Hatia and Manpura

Northing	West Bank of Hatia		East Bank of Hatia		Northing	West Bank of Manpura		East Bank of Manpura	
	Migration Rate (m/yr)	R^2	Migration Rate (m/yr)	R^2		Migration Rate (m/yr)	R^2	Migration Rate (m/yr)	R^2
482000	75.88	0.882	-201.26	0.794					
480000	-1.23	0.000	-108.21	0.790					
478000	15.61	0.250	-74.15	0.957					
476000	33.17	0.990	-70.83	0.962					
474000	30.77	0.971	-47.93	0.957					
472000	29.28	0.916	-33.96	0.942	472000	21.51	0.613	-12.48	0.657
470000	17.46	0.959	-39.36	0.949	470000	5.35	0.733	-4.86	0.344
468000	12.45	0.857	-9.62	0.328	468000	14.32	0.898	4.49	0.022
466000	10.73	0.696	48.33	0.543	466000	27.00	0.867	27.93	0.487
464000	5.62	0.253	49.70	0.737	464000	24.94	0.879	47.26	0.632
462000	14.97	0.674	63.92	0.841	462000	17.91	0.826	30.65	0.541
460000	25.52	0.778	73.77	0.796	460000	25.72	0.899	-2.17	0.017
458000	24.12	0.845	76.49	0.614	458000	1.34	0.056	-14.79	0.745
456000	24.59	0.975	32.16	0.385	456000	6.97	0.555	-6.87	0.326
454000	23.88	0.913	34.74	0.442	454000	1.49	0.008	-3.64	0.037
452000	23.08	0.994	63.49	0.318	452000	-1.25	0.007	8.27	0.310
450000	24.58	0.977	113.44	0.624	450000	0.27	0.000	-7.37	0.248
448000	18.44	0.947	201.68	0.916	448000	2.73	0.143	-17.17	0.736
446000	-14.17	0.426	110.23	0.696	446000	5.86	0.069	4.41	0.191
444000	-9.83	0.074	130.23	0.848	444000	-15.30	0.874	38.17	0.665
442000	44.33	0.801	72.20	0.753	442000	-7.78	0.850	34.64	0.628
	positive = erosion negative = sedimentation		positive = sedimentation negative = erosion			positive = erosion negative = sedimentation		positive = sedimentation negative = erosion	

Table 3: Longterm Shoreline Migration Rate
(from 1957 to 1996) of East Bank of Bhola

Northing	East Bank	
	Migration Rate (m/yr)	R^2
488000	-133.40	0.683
486000	-100.54	0.702
484000	-50.01	0.577
482000	-15.44	0.537
480000	-11.74	0.475
478000	-10.05	0.481
476000	-23.04	0.561
474000	-32.01	0.553
472000	-19.07	0.498
470000	-15.33	0.420
468000	-16.24	0.614
466000	-9.86	0.227
464000	-10.99	0.225
462000	-15.58	0.443
460000	-13.96	0.272
458000	-7.50	0.264
456000	-7.54	0.363
454000	8.48	0.202
452000	2.58	0.027
450000	-4.39	0.134
448000	16.60	0.475
446000	41.91	0.739
444000	36.08	0.776
442000	11.71	0.287
440000	76.23	0.642
438000	66.11	0.792
436000	39.23	0.685
434000	34.40	0.721
432000	89.82	0.665
	positive = sedimentation negative = erosion	

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Table 4: Longterm Shoreline Migration Rate (from 1957 to 1996) of Chittagong

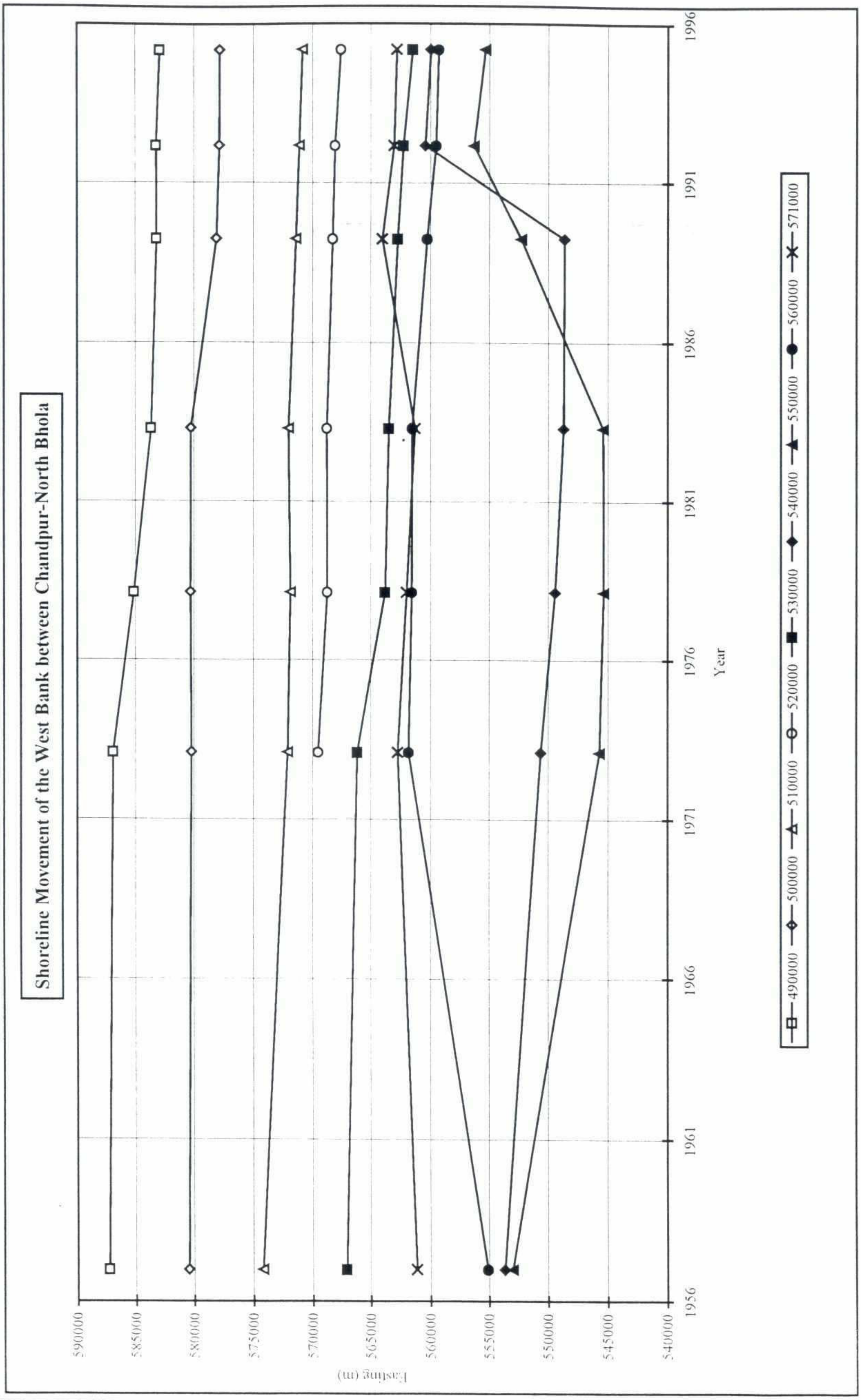
Northing	East Bank	
	Migration Rate (m/yr)	R^2
526000	-205.13	0.595
524000	-228.54	0.617
522000	-140.98	0.849
520000	-52.90	0.752
518000	-103.67	0.898
516000	-131.70	0.951
514000	-206.11	0.924
512000	-210.47	0.910
510000	-105.00	0.772
508000	16.87	0.425
506000	17.51	0.625
504000	13.88	0.807
502000	-9.46	0.147
500000	-57.76	0.436
498000	-32.39	0.406
496000	-27.38	0.385
494000	-24.13	0.443
492000	-14.74	0.130
490000	-7.68	0.301
488000	-9.96	0.300
486000	-15.20	0.643
484000	-16.74	0.535
482000	-15.07	0.430
480000	-18.06	0.273
478000	-32.83	0.680
476000	-52.03	0.586
474000	-44.50	0.515
472000	-17.64	0.141
470000	-19.51	0.156
468000	-16.28	0.253
466000	-29.59	0.767
464000	17.16	0.699
462000	32.84	0.524
460000	-6.25	0.091
458000	17.79	0.314
456000	22.58	0.998
454000	13.50	0.974
	positive = erosion negative = sedimentation	

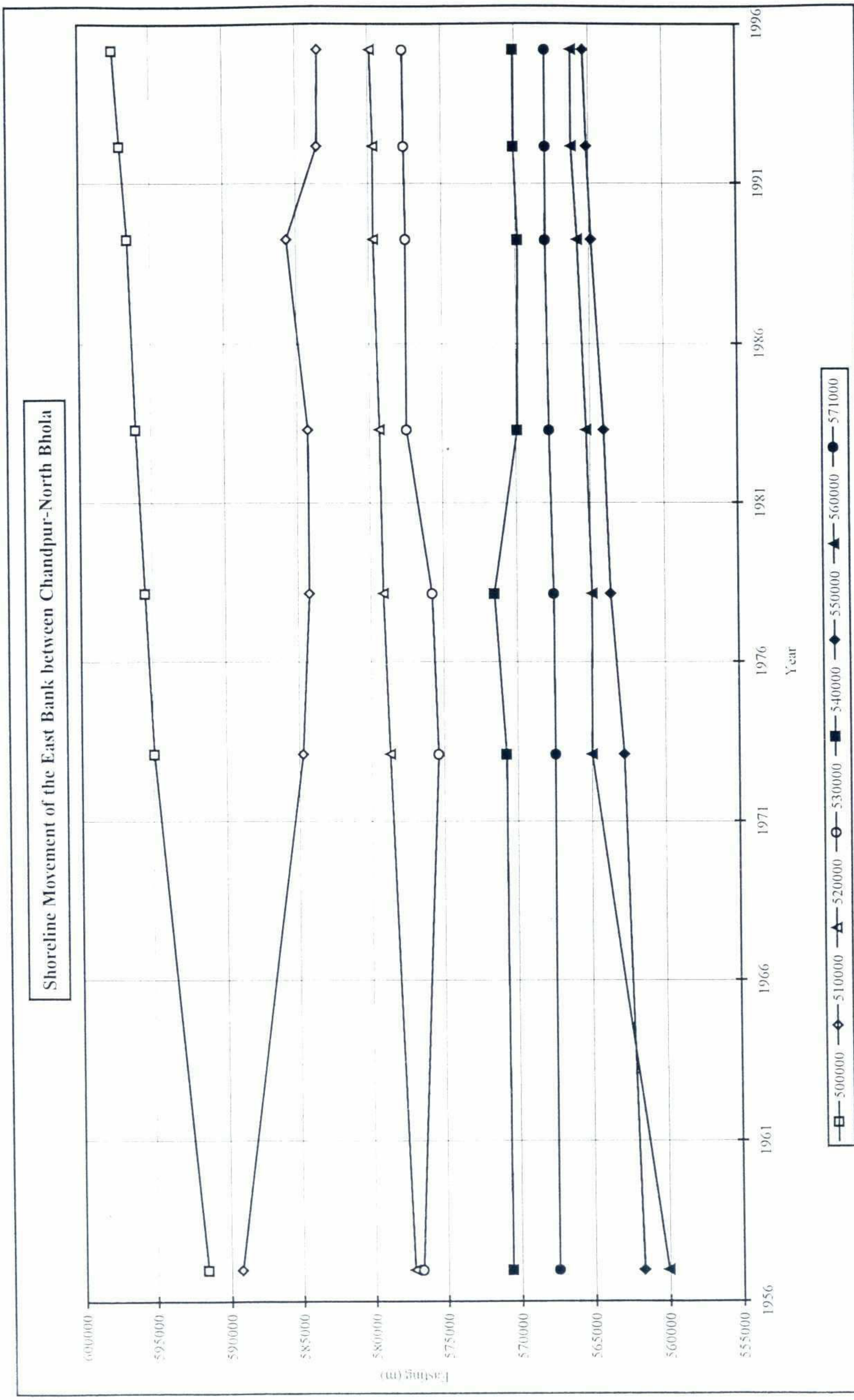
Table 5: Longterm Shoreline Migration Rate
(from 1957 to 1996) of Sandwip

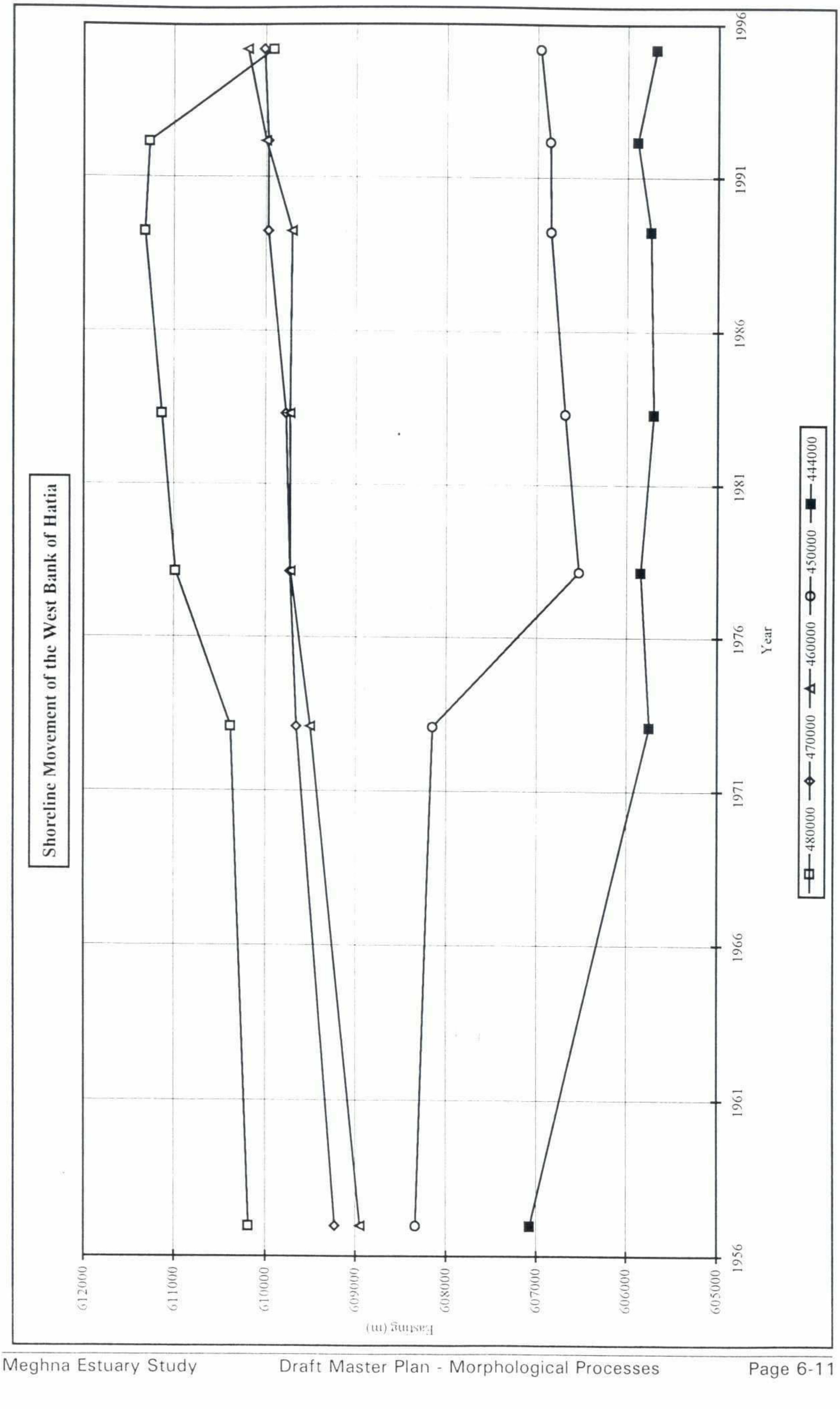
Northing	West Bank		East Bank	
	Migration Rate (m/yr)	R^2	Migration Rate (m/yr)	R^2
498000	103.70	0.960	9.96	0.045
496000	100.94	0.920	5.24	0.025
494000	42.94	0.257	-11.00	0.095
492000	38.34	0.351	-7.65	0.048
490000	45.27	0.867	-9.04	0.083
488000	59.03	0.988	-20.46	0.910
486000	82.52	0.972	-34.61	0.973
484000	83.39	0.985	-47.67	0.984
482000	71.01	0.917	-57.20	0.919
480000	74.08	0.945	-38.47	0.776
478000	62.80	0.954	-14.61	0.385
476000	108.49	0.957	-151.77	0.796
474000	176.20	0.972	-123.90	0.941
	positive = erosion negative = sedimentation		positive = sedimentation negative = erosion	

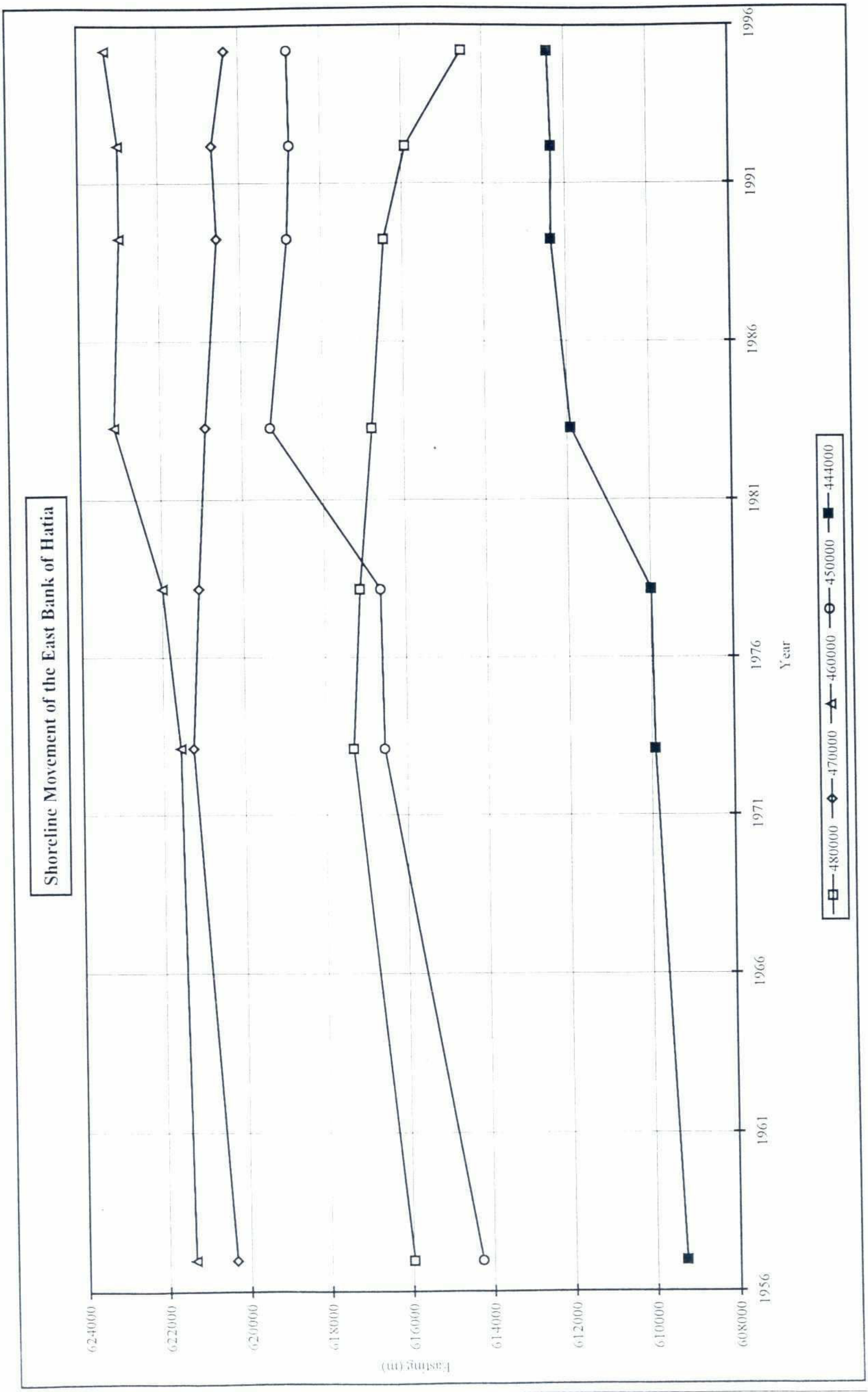
Table 6: Longterm Shoreline Migration Rate
(from 1957 to 1996) of Noakhali

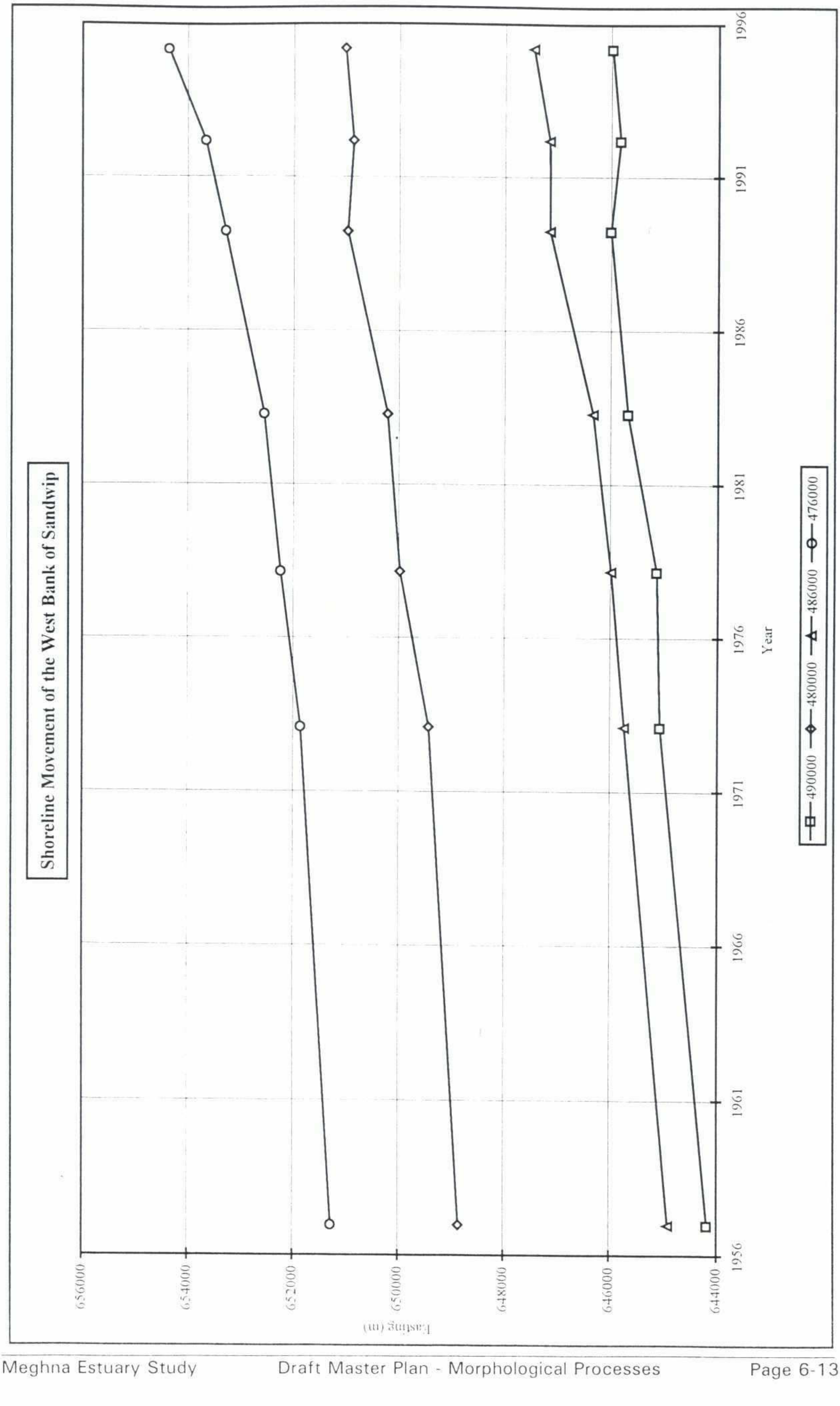
Northing	South Bank	
	Migration Rate (m/yr)	R^2
600000	107.61	0.986
602000	20.97	0.411
604000	-124.53	0.560
606000	-271.05	0.646
608000	-409.44	0.689
610000	-485.02	0.804
612000	-538.91	0.921
614000	-363.51	0.933
616000	-376.14	0.814
618000	-378.14	0.931
620000	-276.34	0.870
622000	-327.93	0.961
624000	-367.77	0.945
626000	-348.93	0.878
628000	-282.51	0.660
630000	25.27	0.231
632000	36.81	0.061
634000	292.91	0.974
636000	71.83	0.987
638000	93.00	0.937
640000	48.67	0.865
642000	87.00	0.891
644000	-236.50	0.945
646000	-1229.00	0.716
648000	-880.00	0.736
650000	-524.67	0.750
	positive = erosion negative = sedimentation	


Shoreline Movement of the West Bank between Chandpur-North Bhola
Easting (m)
590000
585000
580000
575000
570000
565000
560000
555000
550000
545000
540000
Year
1956
1961
1966
1971
1976
1981
1986
1991
1996
490000
500000
510000
520000
530000
540000
550000
560000
571000

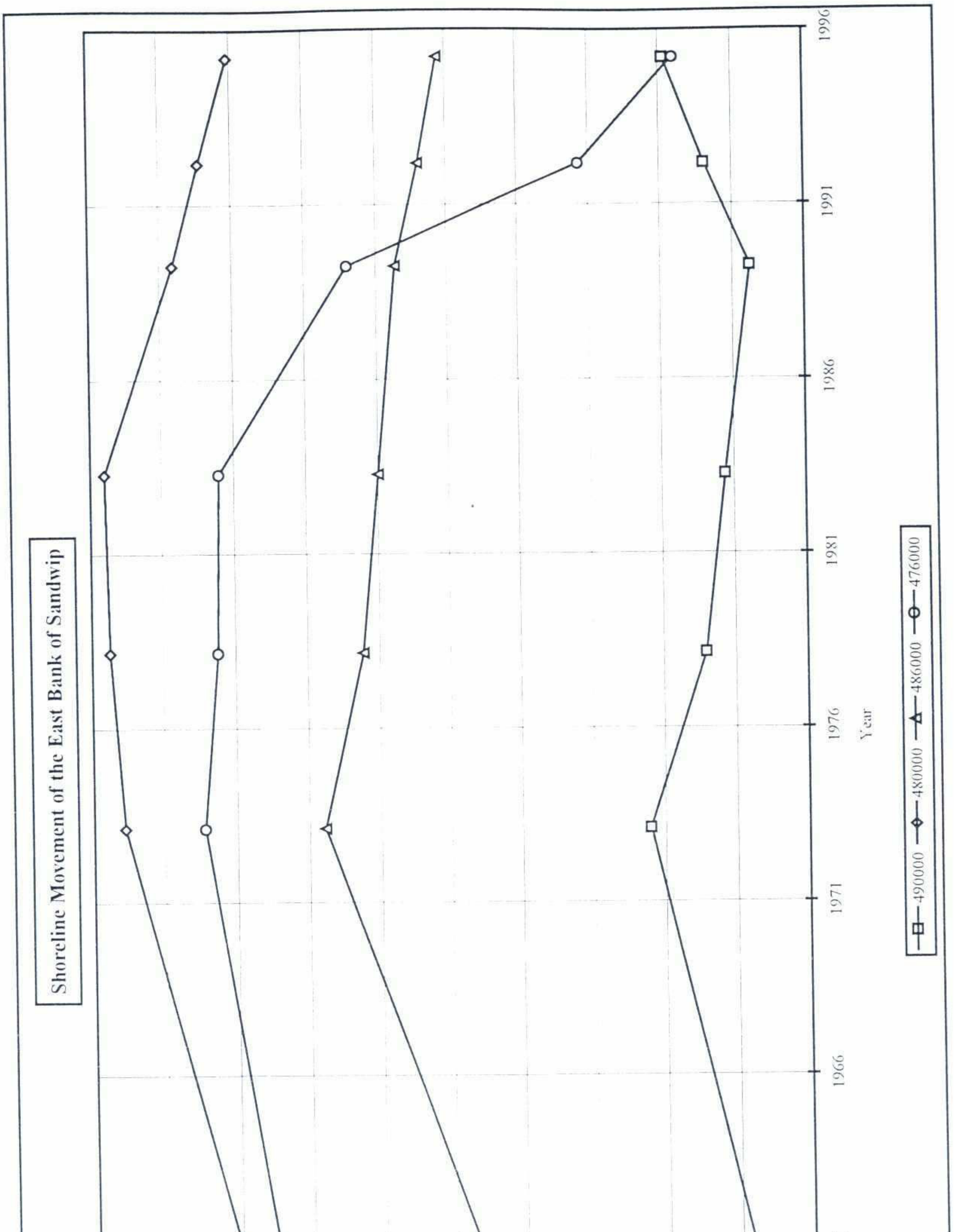

Shoreline Movement of the East Bank between Chandpur-North Bhola
Easting (m)
600000
595000
590000
585000
580000
575000
570000
565000
560000
555000
1956
1961
1966
1971
1976
1981
1986
1991
1996
Year
500000
510000
520000
530000
540000
550000
560000
571000

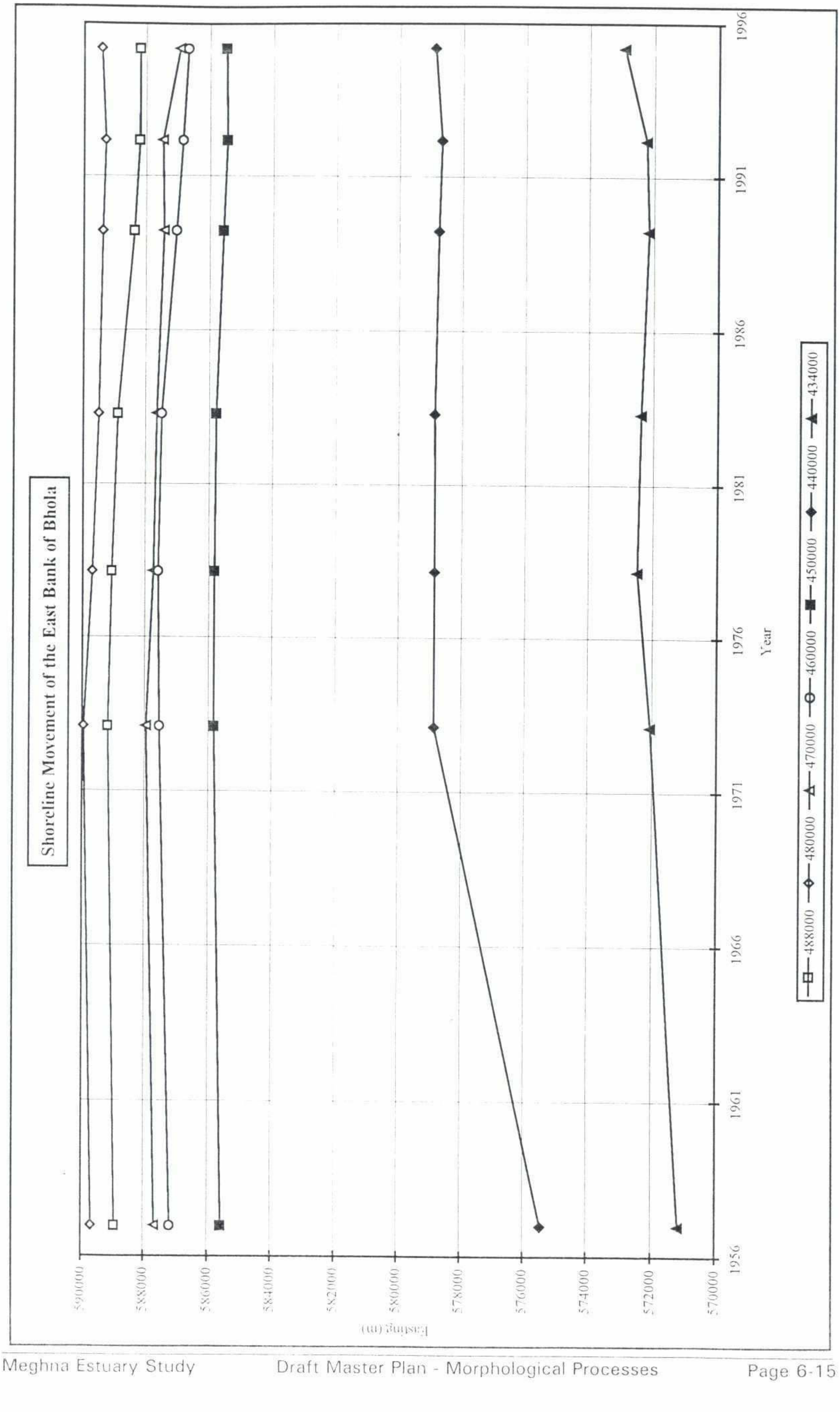

Shoreline Movement of the West Bank of Hatia
Easting (m)
612000
611000
610000
609000
608000
607000
606000
605000
Year
1956
1961
1966
1971
1976
1981
1986
1991
1996
480000
470000
460000
450000
444000


Shoreline Movement of the East Bank of Hatia
Easting (m)
624000
622000
620000
618000
616000
614000
612000
610000
608000
Year
1956
1961
1966
1971
1976
1981
1986
1991
1996
480000
470000
460000
450000
444000



Shoreline Movement of the West Bank of Sandwip
Easting (m)
656000
654000
652000
650000
648000
646000
644000
Year
1956
1961
1966
1971
1976
1981
1986
1991
1996
490000
480000
486000
476000


Shoreline Movement of the East Bank of Sandwip
662000
661500
661000
660500
660000
659500
659000
658500
658000
657500
657000
1956
1961
1966
1971
1976
1981
1986
1991
1996
Year
490000
480000
486000
476000


Shoreline Movement of the East Bank of Bhola
Easting (m)
590000
588000
586000
584000
582000
580000
578000
576000
574000
572000
570000
1956
1961
1966
1971
1976
1981
1986
1991
1996
Year
488000
480000
470000
460000
450000
440000
434000