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RESIDUAL TIDAL AND SEDIMENT VOLUME, THEIR CIRCULATION PATTERNS AND LAND COVER CHANGES IN THE MEGHNA ESTUARY

Saifuddin Ahmed[1]

ABSTRACT : Tidal and sediment volume computed from hourly measurements and their residual direction in the estuary of the (Lower) Meghna River have been studied based upon an analysis of tidal velocity and sediment concentration measurements during full tidal cycles mostly at the time of premonsoon and postmonsoon for the period 1986-1994 during the 'influence period' of spring and neap tide. Residual volume and direction give the overall circulation pattern of water and sediment caused by asymmetry of tidal wave. Tidal environment along Bangladesh coastline is mostly mesotidal and tidal range decreases gradually going from east to west in the estuary. The overall trend of land cover changes between 1973 to 1996 shows a consistent increase in mudflat area and there is a net gain of land of about 37,770 ha, much of which is attributed to recent morphological changes. Suspended sediment concentrations are higher during spring tides and at the locations where tidal ranges are higher. Data shows that morphologically active areas have the highest concentration of sediment. During both spring and neap tides, some channels are inflow dominated and some are outflow dominated.

KEY WORDS : Tidal range, Residual tidal and sediment volume, Counterbalancing of tidal inflow and outflow, Accretion, Erosion, Sediment concentration.

INTRODUCTION

The combined flow of the Ganges-Brahmaputra-Meghna rivers is drained through the Lower Meghna river into the Bay of Bangal via the Lower Meghna Estuary (LME). Among the big rivers in the world, the combined flow the Ganges-Brahmaputra-Meghna rivers ranks third in terms of river flow (Coleman, 1967) and first in terms of total sediment discharge (Milliman, 1991).

1 Meghna Estuary Study Project; Road # 25, House # 34, Gulshan, Dhaka-1212, Bangladesh

The estuary (Fig. 1) is bounded at the eastern side by Chittagong main land, at the north by Noakhali main land, and at the west by the Tetulia river (located at the west of Bhola island). Based on interactions between the river discharge and tidal volume moving through the channels during the pre-monsoon and post-monsoon period in LME, the estuary can be divided into 3 sub-units (figure 1) i.e, the channels

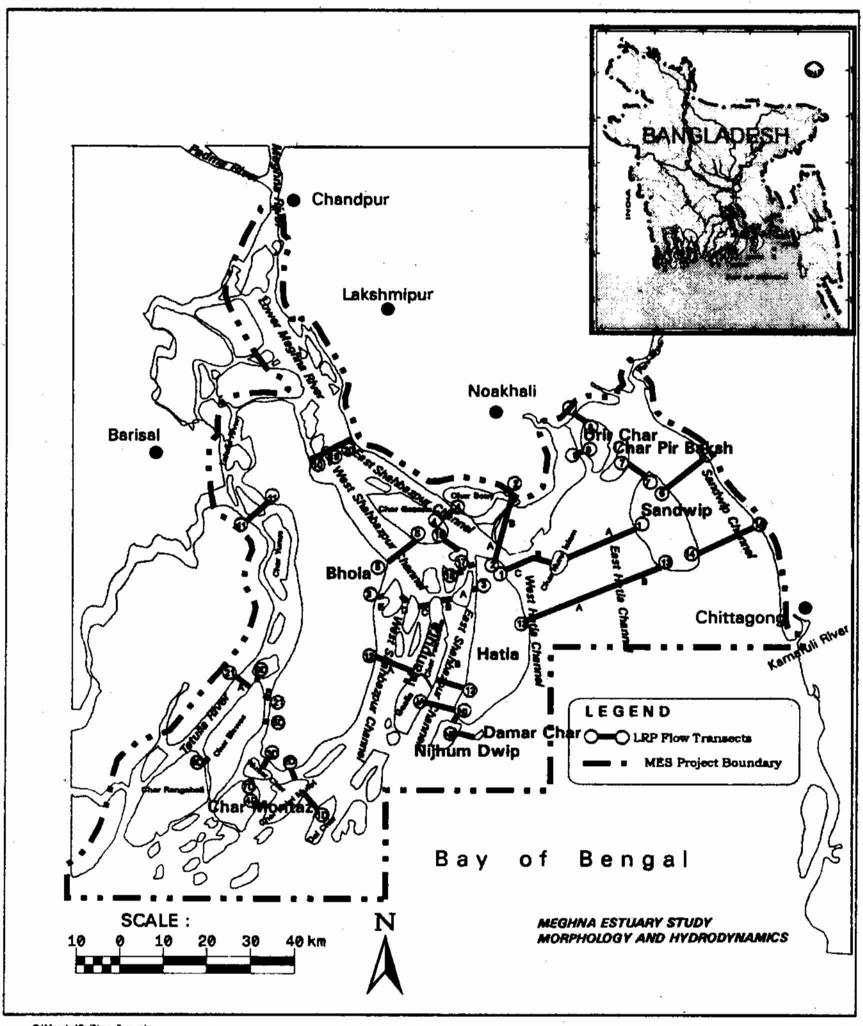

Fig 1. Location of flow transacts

are horizontally stratified in their plan view :

- The Tetulia and the west Shahbazpur channel can be termed as 'fluvial (in the sense that river outflow dominates over the tidal inflow)';
- The east Shahbazpur and the west Hatia channels can be termed as 'fluvio-tidal', and
- The east Hatia and the Sandwip channels can be termed as 'tidal'

Monpura island and Char Faizuddin divides the Shahbazpur channel into east and west. Char Nurul Islam divides the Hatia channel into east and west.

The major rivers that drain into the project area are the Lower Meghna and the Feni. Major channels in the LME disributary system are the Tetulia, east and west Shahbazpur, east and west Hatia and the Sandwip channel. The Sandwip channel carries negligible amount of fresh water flow when compared with tide-induced flow in this channel.

There are many islands and *chars* in the project area. Notable ones are the Bhola, Hatia, Sandwip, Gazaria, Char Pir Baksh and Urir Char, Manpura and the Nijhum Dwip.

The 'fluvial' and the 'fluvio-tidal' sub-units as described above act as a tidal river with very high river discharges in the monsoon whereas the 'tidal' unit behaves as a tidal estuary without significant fresh water discharge from the Feni river. The interaction between the tidal river and the tidal estuary is induced by the open sea connection with the Bay of Bengal south of the Sandwip island and by the two channels between the north of Sandwip island and the Noakhali main land. The flow in these two channels is induced by the tide level and phase difference between tidal river and tidal estuary as mentioned above.

Elevations of channel bottoms in the estuary indicate a pronounced pattern of channels and tidal flats. Due to sedimentation and erosion induced by tidal flow, and river discharge, the location and geometry of channels strongly change even within a few years. Comparison of satellite images taken during several years available at MES support this argument. Tidal mudflats (land which emerge around low tide when a relatively small part of tidal area is covered with water) are concentrated in the Shahbazpur and in the west Hatia channels indicating interaction of river sediment and the sediments brought in by tidal currents from the Bay of Bengal.

OBJECTIVES

The main objective of this paper are :

- to determine the tidal flow characteristics and sediment transport patterns during spring and neap tide conditions in the Lower Meghna Estuary that prevailed during 1986-1994
- to classify the tides along the Bangladesh coastlines
- to assess erosion-accretion areas in the estuary
- to determine the spatial variability of average sediment concentrations in the estuary

COMPUTATIONAL METHODS

The interaction of a turbulent and oscillating unsteady tidal flow, the characteristics of which are empirical, and a boundary consisting of loose sediments is not very easy to perceive. This is because the combined transport of water and sediment is a 3 dimensional time dependent phenomena and the relationship between water movement and sediment transport is strongly non-linear. The result is complex. However, the observed data, i.e., velocity and sediment concentration in a vertical was depth averaged to make our analysis simple and practical without loosing accuracy.

In this chapter, some simple relations for computing flow and sediment transport are mentioned.

TIDAL VOLUME DURING OUTFLOW (EBB TIDE) AND INFLOW (FLOOD TIDE)

Computation of tidal discharge is made by using the velocity area method as described by Barua and Koch (1986). In this method, the total cross-sectional area is divided into representative subareas. In each of these subareas current velocity is measured or is estimated from data of the adjacent vertical. The total discharge is found by the summation of all these subareas according to :

$$Q = \sum_{i=1}^{i=n} (b_i * d_i * V_i * \sin\phi_i)_t \qquad \text{Eq (1)}$$

Where i = subscript representing subarea, total number of subarea being 'n'

Q = total discharge representing the total cross-sectional area [m^3/sec]

V = depth averaged velocity over a vertical representing a subarea [m/s]

b = width of a representing subarea [m]

d = water depth of a representing subarea [m]

ϕ = angle between the current direction and cross-sectional direction in a vertical representing a subarea.

Depth averaged velocity is computed from individual velocity sampled at 'n' number of points in the vertical, according to :

$$V_i = \frac{1}{d_j} \sum_{i=1}^{i=n} (d_j - d_{j-1}) \frac{(V_j - V_{j-1})}{2}$$

Where j = subscript representing measuring location in a vertical

V_j = measured current velocity at depth d_j ([m/s)]

d_j = sampling depth [m]

Inflowing and outlawing tidal volume are calculated by integrating hourly discharges computed from depth averaged hourly velocity measurements over a tidal cycle of 12 hours 25 minutes.

QUANTITY OF SEDIMENT TRANSPORT DURING OUTFLOW AND INFLOW

The main objectives of sediment transport computations in the large area of turbidity maximam (entrapment of suspended sediment at the mouth of the Lower Meghna river along with fine sediments brought by tide from the Bay of Bengal result in formation of more turbid areas i.e., areas of turbidity maxima) in the LME are :

1. -whether an equilibrium condition, erosion, or deposition exist and
2. - to determine the quantities of tidal water and sediment.

Achievement of these objective is important in designing river training and bank protection works, enhancing accretion for land reclamation (the direction of residual (i.e., net) flow and sediment transport over a tidal cycle at locations of interest will help in designing layout of cost-effective sand catching curtains with an opening towards the tidal current transporting the largest quantities of sediment for making sills for cross-dams), etc.

Total sediment transport during outflow and inflow is calculated for each of the representative subareas by multiplying the depth averaged sediment concentration with the depth averaged current velocity. The total sediment transport volume is found by the summation of sediment transport through all these subareas according to :

$$Sed_t = \sum_{i=1}^{i=n} (bi * d_i * C * V_i * \sin\phi_i)_t \qquad \text{Eq (3)}$$

where	i	=	subscript representing subarea, total number of subarea being 'n'
	Sed	=	Sediment transport through the total cross-sectional area (kg/sec)
	C	=	depth averaged sediment concentration in a vertical representing a subarea per tidal cycle [kg/m^3]
	V	=	depth averaged velocity in a vertical representing a subarea [m/s]
	b	=	width of a subarea [m]
	d	=	water depth of a subarea [m]
	ϕ	=	angle between the current direction and cross-sectional direction in a vertical representing a subarea.

Depth averaged suspended sediment concentration is computed from individual sediment concentration sampled at 3 points in a vertical, as per

$$C_i = \frac{1}{3} \sum_{i=1}^{j=n} (C_{0.5m\ below\ surface} + C_{0.5depth} + C_{0.5m\ above\ bottom}) \qquad \text{Eq (4)}$$

where C_i = Sediment concentration averaged at 0.5m below water surface, 0.5 m above the bottom, and at mid-depth

Inflowing and outflowing sediment transport in kg/tidal cycle are calculated by integrating the individual discharges over a tidal cycle as per :

$$Sed_{outflow} = \sum_{t=0}^{t=Toutflow} Sed_t * \blacktriangle t$$

$$Sed_{inflow} = \sum_{t=Toutflow}^{t=Tinflow} Sed_t * \blacktriangle t$$

$$Sed_{tot} = Sed_{outflow} + Sed_{inflow}$$

ANALYSIS OF FLOW TRANSECT MEASUREMENTS

Tidal Discharge and Sediment Transport Measurements

Tidal volume calculated from hourly discharges and sediment volume and their residual direction in the Lower Meghna Estuary have been studied based upon an analysis of tidal velocity and sediment concentration measurements by the survey vessel 'Anwesha' during full tidal cycles in about 33 flow transacts i.e., cross sections (fig 1) mostly at the time of premonsoon and postmonsoon for the period 1986-1994. Velocity and concentrations were measured in one vertical and at many points in a vertical in a flow transact during the 'influence periods' of spring and neap tides.

LRP usually measured the cross sections with the help of echosounder before the measurement of tidal velocity and sediment concentration in vertical (s) of the cross sections.

Dates of most of LRP tidal velocity and sediment concentration measurements in cross sections located at different parts of the estuary fall in the 'influence period' of spring and neap tides (influence period has a duration of 7 days and this duration is counted from the 3rd day before up to the 3rd day after the occurrence of spring and neap tides) and not exactly on the date of occurrence of spring and neap tides. Locations of these cross-sections give a coverage of the estuary, at least the areas close to tidal flats and islands were covered. Dates of remaining few measurements coincide with the occurrence of spring and neap tides as published in BIWTA Tide Table.

Simultaneous tidal flow measurements were not possible in more than one vertical (the reference vertical) in a cross-section during a tidal cycle due to the non-availability of more than one sea-worthy measurement vessel. To compute the missing flow data in the remaining vertical (s) of a cross-section where measurements of flow parameters were not possible on the same day, LRP referenced (Barua and Koch, 1986) the unmeasured verticals (s) to the measured vertical by using Chezy's roughness equation (valid for steady flow) and assuming that water surface across a cross-section is horizontal. As flow in the Lower Meghna Estuary is never in steady state, specially there are wind, wave, transitional shelf width, and tidal effects in addition to the riverine flow, this method of computing missing flow data has drawbacks. Probably LRP used this due to the non-availability of more sophisticated instruments like ADCP(Acoustic Doppler Current Profiler) and GPS (Global Positioning System) and advanced methods of measurement during LRP period.

In LRP measurements, there were combined effects of river outflow, tide, wave, and wind although it is not yet known to what extent these parameters dominate the circulation process and drive sediment dispersal mechanisms. Moreover, the main cause may change from season to season and in a few cases from measurement to measurement. In the Lower Meghna Estuary, usually the measurements are related to a set of hydromorphologic conditions. So, an analysis that is suitable for one season or for a specific set of hydromorphologic conditions, may not be suitable for another season or for another set of conditions. Again, the Lower Meghna Estuary is hardly ever in steady state. Despite that, it is helpful and essential to at least conceptualize the dominant tidal flow and sediment transport mechanisms and trends.

It can be inferred from the analysis of tidal flow that ratio between outflow and the total tidal volume during a tidal cycle remains considerably more than 50% through cross-section (cross-sections 11, 21A and 21B, 10,19 and 20,5 and 12A) in fluvial channels which means that river outflow dominates over the tidal inflow from the Bay of Bengal except in a few cases, more than but close to 50% through cross sections (3A,3B, 12B, JA, 2A, 1B, 1C, and 13A) in fluvio-tidal channels and remain always less than 50% through cross sections (1A, 13B, 6 and 14) in tidal channels which means that tidal inflow from the Bay of Bengal dominates over the river outflow.

It is to be noted that flow data of 1987 only is available for cross sections 3A, 3B, 3C, and 3D which are comparatively old and seems to be inconsistent also probably due to the presence of many intertidal areas and islands along the alignment of cross-section 3. The sub-division of distributary channels in the estuary into three sub-units as narrated in "introduction" of this paper is also supported by bed material distribution, which is fine sand in fluvial channels, becomes gradually finer as tide becomes significant, and in tidal channels in the east the median diameter (D50) represents fine to medium silt. The subdivision is also an indication of the horizontal stratification of distributary channels and has been recognized by Barua and Koch (1986) and Barua (1990).

TIDAL ENVIRONMENT

The tide is semidiurnal in nature with two successive tidal cycles per lunar day of 24 hours 50 minutes duration - each cycle having a period of 12 hours 25 minutes.

The tide originates in the India Ocean and propagates faster along the eastern side than along the western side of the Bay of Bengal. In general, the tidal range decreases gradually going from east to west in the estuary.

Tidal waves approaching the coastal belt and coastal islands of Bangladesh are affected at least by four factors causing amplification and deformation of the waves. They are the Coriolis acceleration, the width of the transitional continental shelf, the coastal geometry (e.g., the funnelling shape of coastline around north of Sandwip island) and the frictional effects due to fresh water flow and bottom topography. Table 1 shows the mean spring tidal ranges at different locations along the coast in 1990 (Barua 1991).

Table 1. Mean Spring Tidal Ranges in Meter at Different Locations Along Bangladesh Coast in 1990 (Barua 991).

Name of Location	Mean Tidal Range in Meter
Hiron Point	2.95
Tiger Point	3.15
Khepupara	2.28
Galachipa	2.96
Char Chenga	3.56
Sandwip	6.01
Chittagong Khal No. 10	4.81
Cox's Bazar	3.58
Shahpuri Island	3.37

Tidal range is an important control on coastal ecology and geomorphology, determining the width of coast subjected to alternate wetting and drying and the impact of waves (Viles and Spencer, 1995).

According o the classification of spring tidal ranges proposed by Davies (1964), the tidal range in the study area can be classified as follows (Figure 2) :

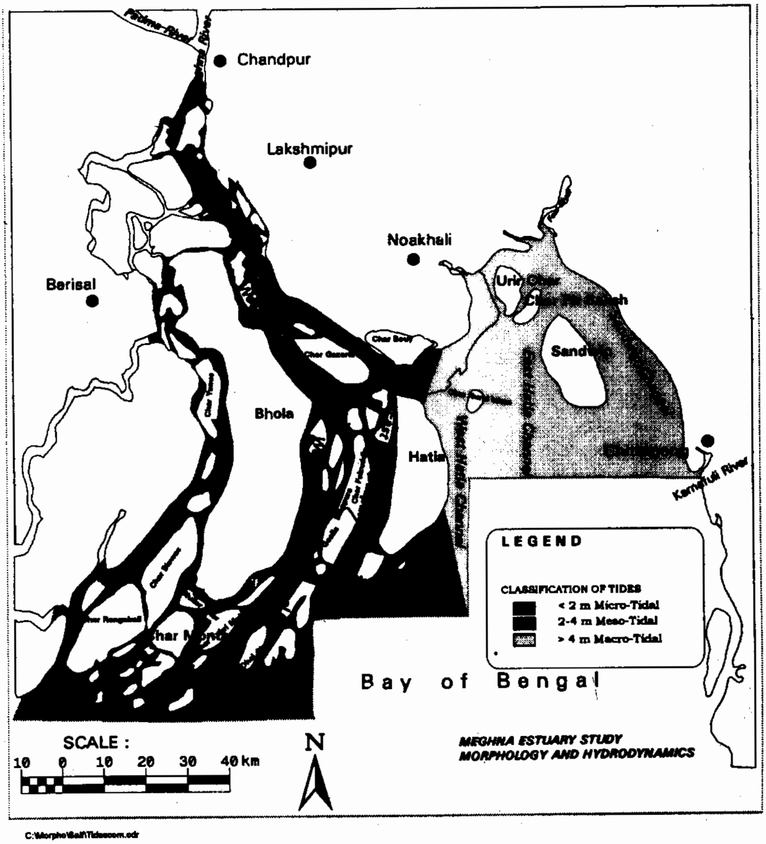

Fig 2. Classification of tides in the Lower Meghna estuary and coastal area

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

Table 1 shows that tidal environment of Bangladesh along its coastline is mostly mesotidal.

Available data shows that recorded maximum tidal range was 9 m during a spring tide on 31.03.94 at Urir Char (West) which most probably was a tidal bore. Water level observations of may 1983, February 1984, and of March and July 1985 in the estuary and around the east and west coasts of Sandwip island in the Sandwip and Hatia channels show that some reflection of the tidal wave occurs contributing to the increase of tidal range around the northeast and northwest of Sandwip island. This means that if any human intervention is planned or implemented in this area like Noakhali-Sandwip cross-dam, the tidal range will increase as a result and this should be kept in mind.

LRP study (Barua and Koch, 1987) shows that the mean tidal range increases up to Sandwip (amplification) after which it gradually gets damped up the estuary through the west Hatia and Shahbazpur channels towards the Lower Meghna river due to friction from river flow and bed topography.

The tidal range at Cox's Bazar is higher than that at Hiron Point partly due to the changes in the transitional shelf width and partly due to Coriolis acceleration which provides higher tidal ranges along the eastern coast than along the western coast in the northern hemisphere.

In the estuary, M2 and S2 constituents of tide are dominant. Char Chenga tidal water level gauge is located few kilometers north of south-west coast of the Hatia island in the east Hatia channel. Analysis of January through July, '86 water level data of Char Chenga shows that M2 and S2 are 1.0103 m and 0.4127 m respectively. The magnitudes of these constituents show seasonal variation also, e.g., monsoon values of M2 and S2 are greater than premonsoon values.

Hiron Point is situated at the entrance of the Pussur river and Cox's Bazar is situated at the south of Chittagong coast along Bangladesh coastline. Hiron Point and Cox's Bazar are located at about the same latitude. BIWTA water level data of January and August, 1996 for these two stations show that the tide reaches at Cox's Bazar earlier than it reaches at Hiron Point and the time lag varies between 0 minutes to about 45 minutes.

LAND COVER CHANGE CLASS

Erosion and accretion in the Meghna estuary was assessed with the help of satellite images for the period 1973 to 1996 (MES, 1997b). GIS was used in the analysis. A digital classification scheme was developed which categorized major land and water cover types. These cover types are associated with erosion and accretion process. The class changes are summarised in Table 2. In this analysis, mudflat category was taken as an intertidal feature and was considered to be most related to water. Thus, for an area to be considered accreted or eroded, it had to change either to or from the land category. Areas that went from mudflat to or from water were not considered either eroded or accreted. This interpretation is considered more representative of the processes observed and, because the mudflat category was interpreted similarly to the water category, the effect of tide levels on the erosion and accretion mapping was minimised.

In Table 2, 'land' is defined as the area above high spring tide water surface.

Table 2. Summary of Erosion and Accretion in the Meghna Estuary During 1973-1996 (MES, 1997b); Erosion is shown in ( )

Land Cover Change	1973-74 to 1979	1979-74 to 1984	1984 to 1990	1990 to 1993	1993 to 1996	1973-74 to 1996
Erosion (ha)	(60,791)	(38,832)	(33,383)	(40,636)	(17,152)	80,933)
Accretion (ha)	19,849	30,686	70,274	29,195	78,561	118,704
Net Change (ha)	(40,942)	(8,146)	36,891	(11,441)	61,409	37,771
Annual rate of Change of land (ha/yr)	(6,823)	(1,629)	6,149	(3,814)	20,470	1,642
Net change (mudflat), water to/from mud (ha)	34,007	19,753	(6,113)	34,613	71,566	70,589
Annual rate of change of mudflat (ha/yr)	5,668	3,951	(1,019)	11,538	23,855	3,069
General Tide Levels	low/mid to mid	mid to mid/high	mid/high to low/mid	mid/high to low/mid	low/mid to low/mid	low/mid to low/mid

The net change by period actually 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 (figure 3). There was huge gain of land are during the 1993 to 1996 period, which accounted for much of the overall land gain shown for 1973-1996. Also notable, with one exception during 1984 to 1990, substainally more water changed to mud than the reverse of mud to changing to water in each of the time periods.

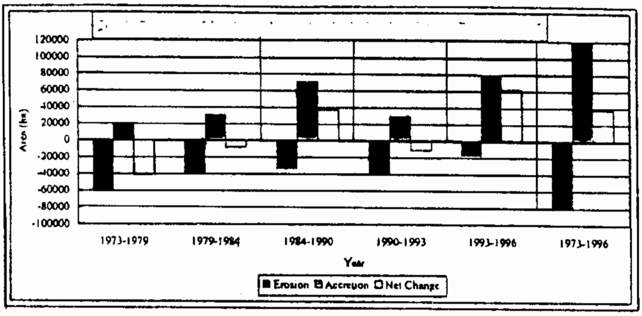

Fig 3. Summary of Erosion and Accretion in the Meghna Estuary During 1973-96

The changes for the total period of study of satellite images, 1973 to 1996, show a vast area of new land off the Noakhali coast.

FINDINGS

To understand the morphological behaviour of chammels, islands and tidal flats in the Meghna Estuary for improving the safety situation, it is necessary to study the hydraulic parameters such as tidal velocity and morphologic parameters such as cross-sectional area.

Hydraulic parameters represent the hydraulic energy that shape morphologic parameters and the morphologic parameters are related to the sediment transport. Also the directions of residual tidal volume and sediment volume (calculated from sediment transport) at different parts of the estuary are important because these give the overall circulation pattern of water and sediment.

Tidal velocity and sediment concentrations were measured mostly during post-monsoon and per-monsoon seasons (October to April) in the course of LRP.

Monsoon data (May to September) are few except some measurements conducted in September, 1990 in sections 1, 2, 4, 5 and

6 (Fig. 1) and also in September, '87 in the channel between South Hatia and Nijihum Dwip and a few in July and August.

TIDAL VELOCITY

The Lower Meghna River

Cross-sections 10, 19 and 20 are parts of one cross-sections.

Recorded maximum velocity through cross-sections 10, 19 and 20 is 1.14 m/sec (outflow).

The Tetulia River

In the Tetulia reiver, through cross section 11 at Dhulia-Gangapur, the recorded maximum velocity varied between 1.07 m/sec (outflow) and 1.42 m/sec (outflow).

Only one measurement is available for cross-section 21A and the maximum velocity was 1.57 m/sec (outflow). No data for cross-section 21B is available.

Also the cross-sections 9D, 5D, and 8D are situated in the Tetulia river. Maximum velocities in cross-sections 9D, 5D, and 8 D were 1.09 m/sec (outflow), 1.54 m/sec (outflow), and 1.18 m/sec (outflow).

The Shahbazpur Channel

There are four cross-sections in the east Shahbazpur river, namely 3A and 3B (part of cross-section 3), 4, 12B ad JA. Four cross-sections are available in the west Shahbazpur river, namely, 3C, 3D and 3E (all are part of cross-section 3), 5, 12B and JA. No. measurements are available for cross-section 3E.

At cross-sections 3C and 3D, 5 and 12A, maximum recorded velocities were 1.74 m/s (inflow), 1.62 m/sec (inflow), 3.2 m/sec, and 2.66 m/sec (outflow) respectively.

Maximum recorded velocities at cross-sections 3A, 3B, 4, 12B and JA were 2.33 m/sec (inflow), 1.4 m/sec (outflow), 2.3 m/sec, 1.24 m/sec, and 1.38 m/sec (inflow) respectively. Measurements for cross-sections 3A, 3B, 3C and 3D are available for March, 1987 only which are old in the context of MES.

The Hatia Channel

There are 3 cross-sections in the west Hatia channel, namely, 2 (2A and 2B) 1B and 1C (parts of cross-section 1) and 13A. The cross-sections 13A, 1A and 9 are located in the east Hatia channel.

Recorded maximum velocities through cross-sections 2A and 2B were 3.13 m/sec (inflow) and 2.55 m/sec ((outflow) respectively. Maximum velocity in cross-sections 1B and 1C were 3.6 m/sec (outflow) and 1.94 m/sec (outflow) respectively.

Recorded maximum velocities through cross-sections 9, 1A and 13B were 1.73 m/sec (inflow), 3.23 m/sec (inflow) and 1.63 m/sec (outflow) respectively.

The Sandwip Channel

Cross-sections 6 and 14 fall in the Sandwip channel. Cross-sections 7 and 8 can also be assigned to the Sandwip Channel. Maximum velocities through cross-sections 14, 6, 7 and 8 were 1.13 m/sec (inflow), 1.79 m/sec (inflow), 1.82 m/sec (north-eastward),and 2.07 m/sec (south-westward) respectively.

South and southeast Bhola Area

Maximum recorded velocities through cross-sections 1D, 2D, 3D, 4D, and 7D which are located in this area were 2.41 m/sec (inflow),1.82 m/sec (inflow), 0.96 m/sec (outflow), 2.59 m/sec (inflow), and 1.12 m/sec respectively. All these velocities were measured in September, 1989.

Nijhum Dwip Area

There are 2 cross-sections in this area, namely, NI and NB. Maximum velocities in NI and NB were 2.1 m/sec (inflow) and 2.2 m/sec (outflow) respectively.

Typical velocity of 1 to 3 m/sec in the Meghna Estuary is sufficient to keep sediment in motion for much of the tidal cycle.

SEDIMENT CONCENTRATION

Concentration of materials held in water in suspension by turbulence (suspended sediment) is measured with a view to computing the amount of sediment present in water column at a particular moment. Sediment is eroded, transported, and deposited by water. This erosion, transportation, and deposition of sediment by flowing water is important on both long and short-term time scale in terms of land form development and also on shorter engineering time scale because of its impact on, e.g., navigation channels, on hydraulic structures and, on agricultural resources.

Depth-mean suspended sediment concentration averaged over whole tidal cycle during discharge measurements in cross sections located at different parts of the estuary are calculated. Figure 4 shows the spatial variability of the average sediment concentration in the Meghna Estuary area.

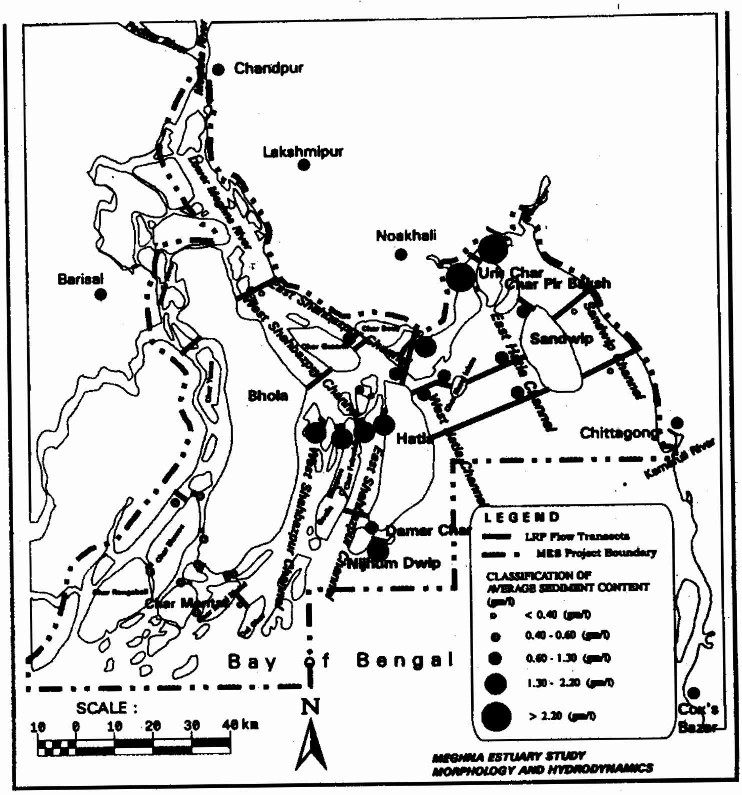

Fig 4. Spatial variability of average sediment concentration in the Lower Meghna estuary system

Data shows that in general, concentration of sediment at 0.5 m above the channel bed is slightly higher than that at 0.5 m below surface.

Except in a few cases, concentration at the surface was close to that at the bottom.

Also, suspended sediment concentrations are higher where tidal ranges are higher. Maximum tidal range of 9 m during spring tide was recorded around Urir Char on 31.03.94 which was probably a tidal bore. Tidal bores occur during spring tide conditions around Urir Char.

Data shows that the area of recorded maximum concentration in the whole project area is the Urir Char area.

A tendency of higher sediment concentrations during spring tides was observed. Maximum sediment concentration of 9.74 gm/1 at 0.5 meter above channel bed during spring tide was recorded at the north of Urir Char.

RESIDUAL CIRCULATION OF WATER AND SEDIMENT

An important characteristics of tidal flows is that superimposed on the back-and-forth flow is a net steady circulation, often called the 'residual circulation'. The residual circulation is generally said to be the velocity field obtained by integrating the velocity at measurement vertical (s) taking into account the flow direction in cross section (s) in the estuary over the tidal cycle.

In large estuaries like the Lower Meghna estuary, one cause of the residual circulation is the earth's rotation which deflects currents to the right in the northern hemisphere and to the left in the southern hemisphere. Therefore, in the northern hemisphere flood tide currents are deflected towards the left bank (looking seaward) and ebb tide currents toward the right bank, resulting in net counter-clockwise circulation. A second cause of this residual circulation is interaction of tidal flow with the irregular bathymetry found in the estuary. This residual circulation is additional to, and superimposed on, circulations driven by wind and the river.

Data was collected mostly during dry season (October to April) and some data were also collected during monsoon.

At the time of calculation of residual water and sediment volume during a tidal cycle of 12 hours and 25 minutes, it was found that river flow dominates over the tidal inflow from the Bay of Bengal during monsoon in the Lower Meghna, Shahbazpur and the Tetulia rivers irrespective of the effects of spring and neap tides, i.e., in monsoon, the direction of residual water and sediment volume during a tidal cycle is towards the sea in these rivers.

Figures 5 & 6 show direction of residual tidal volume and sediment volume respectively. In Figures 5 and 6, two symbols were used- the arrow was used to denote the direction of residual water and sediment volume and '●' was used when ratio of inflow and outflow as a function of total volume of water and sediment integrated over a tidal cycle varies between 47% to 54%. The band of 47% to 54% was chosen arbitrarily to account for assumptions and errors in calculation and measurements. From the analysis of available data, '●' means that the tidal flow and sediment volume is counterbalanced during outflow and inflow.

In general, from Figure 5, it is concluded that there is a residual circulation of water in the counter-clockwise direction in the Sandwip, east and west Hatia channels. The same can be concluded for the residual i.e., net circulation of sediment in the same area per tidal cycle except for the cross sections 8 and 13 (B) during neap tides keeping in mind that few data are available for cross-section 13 (B).

The direction of residual water and sediment volume per tidal cycle through cross-sections 1D, 2D, 4D and 7D is towards southwest during both spring and neap tides. The same through cross-sections 5D and 3D is towards southeast during spring and neap tides.

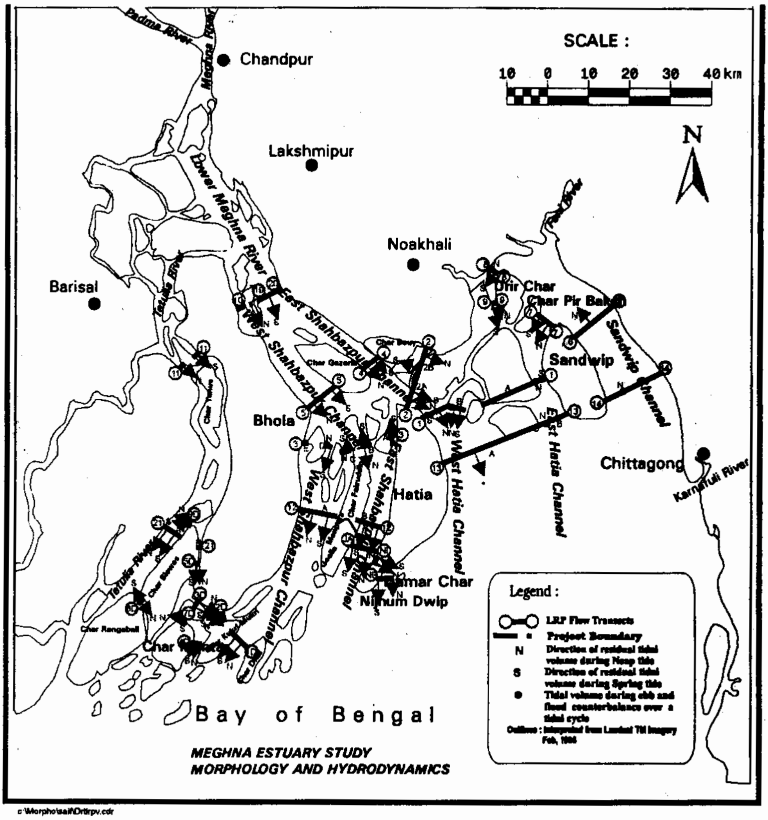

Fig 5. Direction of residual tidal volume during pre-monsoon and post-monsoon in Lower Meghna estuary

During neap tidal cycles, the direction of residual water and sediment volume through the cross-sections 4, 5, 2A, 2B, 1B, 1C, and 13A is towards the sea when integrated over a tidal cycle.

The direction of residual water and sediment volume per tidal cycle in the channel between south Hatia and Nijhum Dwip is towards south-east during spring and neap tides and the same for the channel between eastern Nijhum Dwip and Damar Char is towards south i.e., seaward.

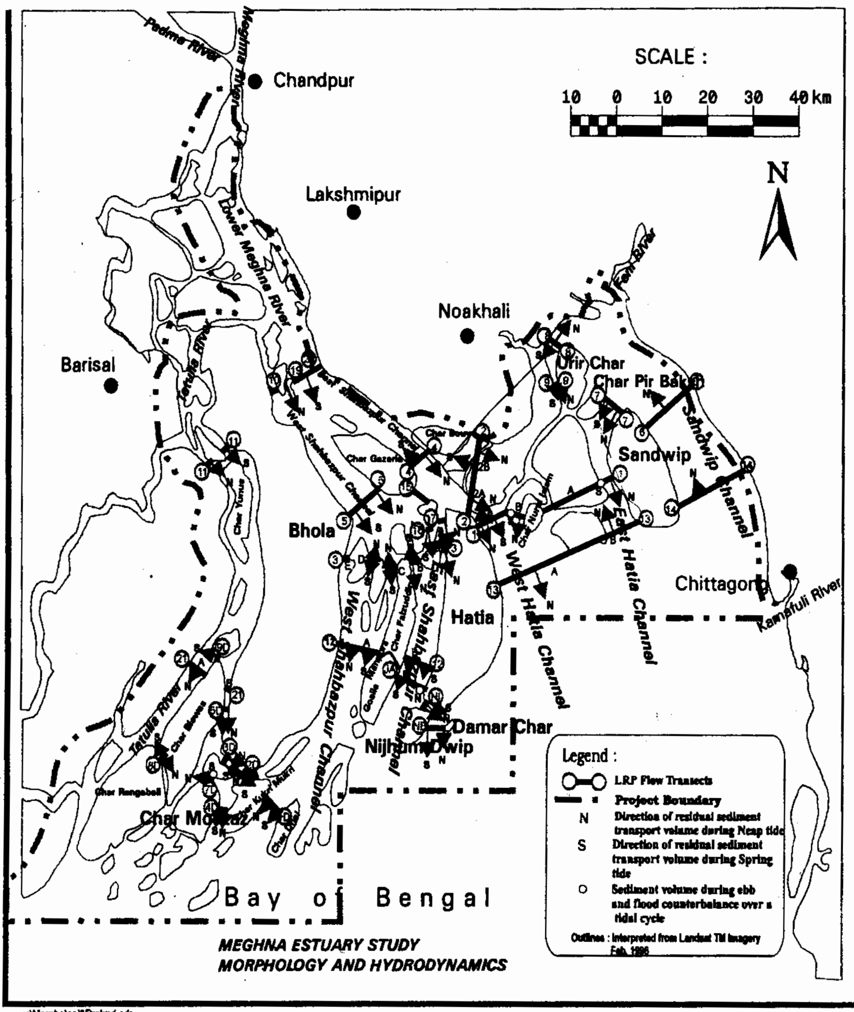

Fig 6. Direction of residual sediment volume during pre-monsoon and post-monsoon in the Lower Meghna estuary

Barua (1990) tried to define dominant flood and ebb channels in cross sections separated by islands in the Lower Meghna river, and in the Shahbazpur and Hatia channels. Based on data of spring and neap tides of the high and low river discharges between 1983 and 1985, Barua (1990) concluded that cross sections 1A, 2B, and 4 had net landward water flow and cross sections 5, 2A, 1B, and 1C had net seaward water flow.

This paragraph pertains to the analysis of 1990 and 1994 LRP and sediment volume data (most recent available LRP data). After analysing data of cross sections 1A, 2B, and 4, the author could not conclude what Barua (1990) concluded (as mentioned in the previous paragraph) for these same cross sections. This is evident from Figure 5. This disagreement is most probably due to the morphological changes (e.g., sedimentation) that took place around these cross sections between the years 1983-85 to 1994. Comparison of satellite images of 1984 and 1993 support this conclusion.

For spring and neap tidal cycles, the residual direction of tidal volume for the cross sections 5, 2A, and 1B is seaward. Barua (1990) concluded the same for these cross sections. Cross-section 1 (C) showed net seaward tidal flow during neap tide but inflow and outflow counterbalance during spring tide.

Cross-section 2B showed net landward flow during spring tides but net seaward flow during a neap tide (24.09.90).

Barua (1990) did not report such notable features in flow data of 1983, 1994, and 1985. One of the reasons of such features is that flows were not measured simultaneously on the same date at all these cross sections due to the availability of only one sea-worthy measurement vessel which means that during a tidal cycle, flow was measured in one vertical only in a cross section and the flow parameters of other verticals were derived from this vertical. Then the vessel was moved to other cross sections and it took several days to complete the measurements in a part of the estuary.

Two salient features of some of the tidal flow and sediment data of cross-sections 1A, 1B, 4 8 and JA are that i) tidal inflow and outflow counterbalances but there is residual sediment volume (x-sections 1A, 4 & 8) and ii) Tidal sediment inflow and outflow counterbalances but there is residual tidal volume (x-sections 1B and JA). In other words, we can say that residual direction of tidal volume is opposite to the direction of residual sediment volume on a date during a tidal cycle.

Barua (1990) did not report such event. Incidentally, all these cross sections are located in and around the Sandwip island except the cross sections 4 and JA. One the probable reasons is that there may be significant longshore and/or wave driven transport through cross sections 4, 8 and JA in addition to the suspended sediment carried by the flow. Waves mainly loosen material on the bottom and stir up, while currents transport material to another place. 2D model studies by LRP showed that tides coming from the sea through the Hatia and Sandwip channels meet somewhere around the northern edge of Sandwip island. The location of this point may vary by few kilometers due to the effects of seasonal climatic events and hydraulic factors. This may be another reason.

Residual directions of water (tidal) volume of the data collected by MES in the whole estuary during August through November, '97 are almost the same those shown by LRP data.

CONCLUSION

The data used in the analysis cover a range of flow conditions measured mainly during premonsoon and postmonsoon but they are in no way synoptic of the physical processes in the whole estuary. Any interpretation of there results should, therefore, be considered tentative because of practical limitations of data collection and available logistics and also due to rapid morphological changes in some parts of the estuary.

However, the following conclusions can be drawn :

The channels are horizontally stratified in their plan view on the basis of the upland flow and tidal volume moving through the channels. During both spring and neap tides, some channels are inflow dominated (residual direction is landward) and some are outflow dominated (residual direction is seaward) and in some channels (e.g., section 2B and 8D) residual direction during spring is opposite to the residual direction during neap.

As ocean tide propagates into the shallow parts (depth less than 10 m) of the estuary, tidal wave is deformed by frictional damping on the estuary floor with short flooding period and extended ebbing period.

Most of the Bangladesh coastline experiences average tidal range of 2 to 4 m i.e., mesotidal. Sandwip channel along Chittagong coast is mostly macrodidal (tidal range > 4 m).

Erosion-accretion study by GIS shows land loss up to 1994, with a period of gain during 1984 to 1990, followed by net land loss again during 1990 to 1993. There was huge gain of land area during the 1993 to 1996 period, which accounted for much of the overall land gain shown for 1973-1996. Also notable, with one exception during 1984 to 1990, substantially more water changed to mud than the reverse of mud changing to water in each of the time periods.

Recorded maximum velocities in the Lower Meghna, Tetulia, Shahbazpur, Hatia, and Sandwip channels were 3.2, 1.57, 3.20, 3.6, and 2.07 m/sec respectively. The same for Nijhum Dwip area was 2.2 m/sec. This gives an idea about the exposure of erosion protection structures to the flow.

In general, concentration of sediment at 0.5 m above the channel bed is slightly higher than that at 0.5 m below surface. Except in a few cases, concentration at surface was close to that at the bottom. Usually suspended sediment concentrations are higher where tidal rages are higher. A tendency of higher sediment concentrations at the places where tidal ranges are higher and also during spring tides was observed. Morphologically active areas were found to have higher sediment concentrations.

Data shows that there is a residual circulation of water in the counter-clockwise direction in the Sandwip, east and west Hatia Channels. The direction of residual water and sediment volume in the Nijhum Dwip channel is towards southeast.

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NOTATIONS

b	=	width of a subarea [m]
C	=	depth averaged sediment concentration in a vertical representing a subarea [kg/m^3]
d	=	water depth of a subarea [m]
i	=	subscript representing subarea, total number of subarea being 'n'
j	=	subscript representing measuring location in a vertical
Q	=	total discharge representing the total cross-sectional area [m^3/sec]
Sed	=	Sediment transport through a cross-section (kg/sec) per tidal cycle
V	=	current velocity [m/s]
ϕ	=	angle between the current direction and cross-sectional direction in a vertical representing a subarea.

ABBREVIATIONS

BWDB	Bangladesh Water Development Board
BIWTA	Bangladesh Inland Water Transport Authority
LME	Lower Meghna Estuary
LRP	Land Reclamation Project
MES	Meghna Estuary Study Project
SSC	Suspended Sediment Concentration
SSD	Survey and Study Division