VOL. 8, NO. 12, DECEMBER 2013 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

A STUDY ON THE EVER CHANGING PHYSICAL REGIME OF THE INNER ESTUARY OF THE RIVER HOOGHLY

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ABSTRACT

Unlike other estuaries in the world, Hooghly estuary in India, (study zone-$21^{o}44^{'}42^{''}/87^{o}56^{'}00^{''}$ to $22^{o}04^{'}50^{''}/88^{o}13^{'}25^{''}$) deserve special attention especially in regard of its seasonally varied movement, orientation of its submerged sand bodies i.e., bars and shoals and tortuous shipping route, which are typical of it's kind. However on account of insufficient data to study the estuarine tidal basin, quantitative analysis (vectorial approach) of the estuarine part vis-à-vis tidal part remains synoptic even till date. Nonetheless the estuarine part, below Diamond Harbour, was less problematic in the past compared to the upper tidal part from Diamond Harbour to Kolkata. But nowadays it is seen that the erratic behaviour of the shoals and bars of the upper part has gained stability to some extent, whereas the estuarine part comprising middle and upper estuary i.e., from Auckland to Diamond Harbour have developed some morphological changes in a rapid progressive manner. The aim of this paper is to set forth in a study on the basis of energy dissipation rate, along with other concomitant parameters like salinity, tide, flux etc associated with the changes of different shipping routes of the estuary (Sagor/sea face to up stream of Nayachara island) and the probable optimization of the length of that route which may be inflicted in future, if new routes are to be opened, as well as enlargement of submerged sand bodies.

Keywords: estuary, salinity effect, erosion, entropy, tide.

INTRODUCTION

The Bhagirathi-Hooghly river system is basically a tributary of the main stream of the river Ganga flowing southerly to meet the sea. Hooghly being the lower part of the Bhagirathi - Hooghly river system, the entire river stretch as a whole is christened as Ganga. The other branch of the main steam named Padma, flows easternly through Bangladesh and confluences with the River Brahmaputra at Gowalanda in Bangladesh and finally meets the Bay of Bengal. Even a few decade ago this southern branch of the river flowing through India named Ganga/Bhagirathi-Hooghly, was a spill channel of the eastern branch of the River named Padma- Brahmaputra and which form a vast and most economically important estuary in the world known as Hooghly estuary (Figure-1). But it should be noted from the literature that prior to sixteenth century this spill channel was the main water course of the river. This estuary is particularly important for the existence of the twin port, Kolkata and Haldia, which stand as the backbone of the trade and tourism of the eastern part of India. Basically it has a huge hinter and comprising several states of India and abroad. Thus necessity of the maintenance of shipping route connecting India and abroad becomes a prime concern of the Govt. of India. The upper part of the river, from Biswanathpur to Diamond Harbor has an average width of 0.5-1 km and average depth of 4m below dominant stage level. But from Diamond Harbor to the sea face the river flares abruptly from 3 km at Diamond Harbour to 20 km at Sagor (sea face) with a varied depth for navigation from 4 m to even 20 m below chart datum, with tortuous shipping channel comprising bars and shoals at places to places. A balance between the huge sea fluxes viz. high tide of the order of 45, 800 m^3/sec at Haldia and 50, 000 m^3/sec at Gangra and a little river flow (fresh water) of the order of 1, 100 m^3/sec (vide - Table-1), primarily plays the key role for governing the estuarine physical regime. To monitor and estimate the activity of this huge flood flow and river flows, data collection is very expensive as well as hazardous and thus synoptic and in most of the cases elicit unpredictable results in long run. Thus instead of vectorial approach which requires large volume of precise vectorial data collection, rather scalar approach considering the stream power may yield consistent result (Yang, 1971).

The salinity effect

When salt concentration in water exceeds 2 to 3 p.p.t. (Table-3), coagulation of major clay type i.e., Kaolinite, Illite and Montono villonite is complete (Hayter, 1983). However it is seen from field data collection, the river water and bed material is entirely composed of silty sand by nature (Table-5) and free from such effect. Typical salinity history of Hooghly River is depicted in Table-2 and Figure-4.

An analytical and empirical approach

Open channel flow is governed principally by the action of gravity upon the moving fluid. The dimension less parameter used to best describe and classify open channel flow is the Froud number (inertial force / gravity force). $F = \infty V / (gd)^{0.5}$; where V= flow velocity, d = flow depth, ∞ = kinetic energy correction factor and 'g' is Gravitational acceleration. The Froud number 'F' equals as under: F<1, flow is sub critical; F>1, flow is super critical; F = 1, flow is critical. Critical flow requires least energy for a given rate of discharge.

Erosion

Immediately following slack water a stationary suspension begins to erode or re-suspend rapidly as the flow speed picks up. This is often referred to as mass erosion or redispersion. A fully consolidated or a settled bed erodes by a slightly different process. At relatively low bed shear stress (or velocities); aggregates from the bed surface are entrained. At high shear stresses, or under rapidly accelerating flows erosion is much more rapid and relatively large chunks of sediment are entrained. The critical boundary shear or critical tractive force formula for quartz particle in water with substitution of appropriate specific weight is given by T_c (Psd) = 6.18 * d_s (in feet); d_s = diameter of sediment particle. Typical particle size distribution history of Bhagirathi/Hooghly River is depicted in Table-5 and Figure-3.

Depth effect

In deep estuaries, there can be a significant lag between near bed suspension response to depositions/ erosion and the corresponding response at the surface. This type of hysteresis effect is setup as a result of the time it takes for sediment to defuse upwards and the corresponding sediment settling time.

Tidal activity and sedimentation by water retention

Typical tidal activity of Hooghly estuary is depicted in Figures 8(a) and 8(b). During the falling or ebb tide, surface gradients are set up at the seaward end that is initially similar in magnitude to those occurring during the rising or flood tide, but opposite in direction. As water level falls, however the rate of wave propagation decreases and the influence of the rate of fall of the sea becomes weaker. Instead the ebb flow within an estuary becomes a process of drainage under gravity and where there are extensive areas of shallow water, there is a prolonged period of flow in the main deep channels, fed by surface drainage from the shoals on either side. Tidal behavior in an estuary can be observed by recording the rise and fall of water simultaneously at several stations spread along its length. Some typical observations are reproduced in above referred Figure-2. The River Hooghly in India (Figures 1, 8(a) and 8(b)) has a moderate tidal range (5.5 m during spring tides) and a considerable tidal length, with the result that when high water occurs at mouth, the previous high water has just reached the tidal limit. The Hooghly shown in plan (Figure-1), is tidal for a length of about 300 K.M. but in Amazon, which is tidal for over 850 km. and seven or eight successive high tides can occur simultaneously (Defant [3]).

A further effect of tidal propagation deserves comment. The mean tide level at sea-face (Sagor) shown in Figure-2 is about the same in each case, but at stations further inland the tide level during spring tides is higher than that observed during neaps. This effect can be so great that at some landward stations, low water during neap tides can be lower than low water during springs. For example, at 204 km from Sagor, low water, spring tide (LWS) is 2.8m above datum, whereas low water, neap tide (LWN) is only 2.2 m above datum. Evidently a large volume of water can accumulate in the upper part of an estuary during a spring tide cycle. This causes an increase of salinity during spring tides and a decrease during neaps. It also contributes to net landward movement of sediment during spring tides and net sea ward movement during neaps, with the peak of sediment concentration occurring latter than the highest spring tides. Here it should also be noted that the short duration of flood tide compared to relatively long duration of ebb tide causes lower amount of ebb discharge compared to flood tide thus enhancing the possibility of higher rate of sedimentation of the silt brought in the estuary by the action of flood tide.

Long term monitoring

Estuaries tend to be in a state of quasi equilibrium as far as the hydrodynamic and sedimentary processes are concerned. Superimposed on these processes of annual cycle of variation of tides, fresh water flows, salinity intrusion and sediment transport, longer period variation in the physical regime also occur. Slow filling up of the existing deep channel or thalweg coupled with scouring of a new channel elsewhere, may occur over a 10-20 year period (Calcutta Port Commissioners, 1973; M.C. Dowell and O'connor, 1977). It is therefore particularly important to understand the long-term estuarial behaviour through an adequate monitoring programme, particularly one involving extensive bathymetric surveys.

Entropy analogy and unit stream power

After Leopold and Langbein, Yang reintroduced the entropy concept to the study of natural stream system. He considered the only useful energy per unit mass of weight of water in a stream system is its potential energy. He further assumed that the potential energy and elevation of a stream system are equivalent of a thermal energy and absolute temperature, respectively of a heat system. Based on this analogy and the direct application of entropy concept in thermodynamics, it can be shown that

Dy/dt = a minimum

Where y = potential energy per unit weight of water in a stream system; and t = time. Thus, Yang concluded that during the evolution towards its equilibrium condition, a natural stream chooses its course of flow in such a manner that the rate of potential energy dissipation per unit weight of water along its course is a minimum. The minimum value depends on the constraints applied to the stream and he showed dy/dt = (dx/dt)*(dy/dx) = VS = a minimum.

Where X = distance along the course of flow; V = average flow velocity; and S = energy slope. Yang defined the VS product as the unit stream power.

Thus Young's theory states "For flow in an alluvial channel of a given width, where the rate of energy dissipation due to sediment transport is negligible, the channel will adjust its velocity, slope, depth, roughness in such a manner that a minimum amount of unit stream power is used to transport a given sediment and water discharge under equilibrium condition. The value of minimum unit stream power depends on the constraints applied to the channel. If the flow deviates from its equilibrium condition, it will adjust its velocity, slope, depth and roughness until the unit stream power is minimized and regains equilibrium."

Longitudinal profile

The velocity distribution, roughness, sediment transport rate, channel geometry, channel pattern, and the pool-riffle sequence are different means available to a river for the minimization of its rate of energy dissipation at a given station or within a given reach. It is a commonly observed phenomenon that a river generally has a concaved overall longitudinal bed profile and the slope decrease in the downstream direction. This concaved longitudinal river profile can be obtained by minimizing its rate of energy dissipation along its course of flow i.e.

$$\frac{d(QS)}{dx} = S\frac{dQ}{dx} + Q\frac{dS}{dx} = 0$$

Where x = longitudinal distance along the course of flow.

As the water discharge increases in the downstream direction, dQ/dx in above equation is positive. To satisfy the above equation, dS/dx must be negative and the slope must decrease in the downstream direction. Thus, the overall longitudinal bed profile adjustment of a river is also consistent with the theory of minimum rate of energy dissipation. Here one should note that in estuarine to and fro tidal flow, though tidal flux diminishes upstream, net flux is always higher during ebb flow as it is the combination of sea flux plus upland discharge Table-1.

It has been shown that a natural river can adjust its velocity distribution, roughness, channel geometry, channel pattern, and longitudinal bed profile, either individually or collectively, to minimize its rate of energy dissipation in accordance with the general theory of minimum rate of energy dissipation or its simplified versions. More detailed discussion on the application of this theory to the study of river morphology was given recently by Yang, 1971. Sediment concentration variation with respect to season and tide gives insight on deposition and accretion and thus affecting the river morphology vis-à-vis a changed energy dissipation rate of the river course following a creation of new route of water course so that to keep the energy dissipation rate minimum. This deposition is dependent on sediment carrying capacity of flood or ebb flow. As sediment load becomes a major concern in this issue, it is seen that Brahmaputra, Ganga and Bhagirathi carry 900, 500 and 20 million tons per year[6] respectively. The amount of sediment brought in by the major rivers and their tributaries in the past and present, with relative vertical movements of the surrounding area, are the major factors affecting the types and sizes of the delta. Both the Ganga and Brahmaputra bring in a large amount of sediments per year - about 500, 000, 000 and 900, 000, 000 tones, respectively. The annual sediment load brought in by the tributaries of the Ganga is of the order of 20, 000, 000 tons, i.e., about 4% of the annual sediment load of Ganga. Sediment contribution for delta building activity by the Bhagirathi - Hooghly river system therefore is not very significant (Bhattacharia S. K., 1976). The bulk of the sediment load finds its way into Meghna estuary in Bangladesh. Because of the preferred slope of the Ganga towards the east, the flow into the Bhagirathi progressively decreased. The source of the sediment of Bhagirathi is the bed of the river itself, where deposition occurred in the preceding freshets. This cycle sets in a progressive state of instability in the Hooghly.

Long term monitoring

Estuaries tend to be in a quasi equilibrium as far as the hydrodynamic and sedimentary processes are concerned. Superimposed on these processes of annual cycle of variation of tides, freshwater flows, salinity intrusion, and sediment transport, longer period variations in the physical regime also occur. As the preferred slope is east ward so equilibrium sets in accordingly east ward. The rate of supply of new sediment from the river varies widely from one estuary to another and in a given estuary, there is usually a strong seasonal dependence as well (Krone, 1979). Normally, however, the oscillatory, 'to and fro' tide controlled transport is higher than the net (incoming minus outgoing) input of sediment. In the long term, such factors as changes in the upstream discharge hydrograph and sediment supply rates, morphologic changes within the estuary, sea level changes, eustatic effects will alter the sediment transport regime (Dyer, 1973; McDowell and O' Connor, 1977). Closure of estuarine mouth is not likely to happen so long dredging and river training works will be beneficial for navigation. Although estuarine mouth closure or tidal chocking is a potential problem in the sandy entrance in which the strength of flow is insufficient to scour the bed, with the result that littoral drift is deposited in the mouth, the depth becomes shallow and the entrance closes eventually (Bruun, 1978). Training walls or jetties and dredging between the jetties could sometimes be a system for bypassing sand from the updrift beach to the downdrift beach and can be used to keep entrance open (Bruun, 1978).

Formula application: the application of sediment transport formulas developed for unidirectional flows is usually suitable to tide-dominated oscillatory flows because the tidal frequency is low, and tidal currents may be considered to be 'piecewise' steady. Differences tend to arise due mainly to three causes:

a) The complexity of flow distribution resulting from salinity effects.
b) The condition of slack water and flow reversal following the slack.
c) The dependence of bed forms and associate bed resistance on the stage of tide and the direction of flow (Ippen, 1966).

The study

It appears from the shape of the estuary from its inner end (i.e., Diamond Harbour) to its sea face, the entire system maintain an over all balance of its morphological stability. On account of the nature of the wind, orientation of co-tidal lines and river morphology the right bank, i.e., Haldia side, becomes the flood dominated channel, where as the left bank, i.e., Rangafalla side, becomes the ebb dominated channel, as is evident from the presence of coarser sand in the left bank channel (Table-5).

The huge curvature of about 18 km diameter at Diamond Harbour site, comprising the confluence of river Rupnarain, directs the ebb flow towards the western channel crossing over the Auckland area. However the huge flood flows entering through eastern channel crosses over Auckland area to enter the Jellingham channel at Haldia side (right bank). Thus crossing over these two flows, ebb and flood, over Auckland area makes it sensitive to create problems in regard of its depth availability. This may be attributed that highly stratified estuary causes zones of rapid shoaling. Increased up land flow for a given set of tidal condition, tends to stratify the estuary thus creating zone of rapid shoaling. Thus shoaling in river depends on peak upland flow having high sediment supply. Increased channel dimension results in lower transport capacity and thus shoaling becomes high when sediment supply is high.

As is evident from the contour superimposition study at the up-stream of Nayachara Island (Figure-9), right bank of the diamond harbor reaches has exhibited a prominent example of this type of shoaling, especially during last five years, 2000 - 2010. Closure of the Balari region, just upstream of Nayachara Island has played a key role by diminishing the flood flow through its passage.

Oceanic tide being the impetus of the maintenance of the estuarine morphology, onslaught of the upland discharge veer the river contours manyatimes. This makes the alluvial river bed - morphology prediction a crux and thus become a trawl ground. Nonetheless we have to depend on pragmatic ways to discernible the way out. Augmentation of ‘o’ contour into the trans thalweg /deeper contours may be conjoining to the onset of the Balari passage closure.

Hence marginally noted above observation, following conclusions, unless otherwise any major perturbation happening in respect of River morphology (man made or natural), are that: i. this site is free from sever bank erosion as inferred from thalweg time history for last fifteen years as well as from the image of the ruins of the fort on river bank ii. River thalweg is very near to the bank and it’s lateral movement is very low iii. River thalweg depth is considerably high of the order of twenty meters at least for last fifteen years iv. Reduction in volume of the River stretch is due to the fact that the stretch has turned into a repository place as the ‘o’ contours has swerved towards the deep contours of the down stream end of the left bank on account of ebb dominance thus by inducing upland detritus and suffering from the weak flood flow to push them back ward.

The average grain diameters of the material which constitutes these sands and shoals is 0.10 mm. they are theoretically transportable by the tidal currents, over these regions which often reach and exceeds two meter per seconds. It is apparently not clear why the sands and shoals should maintain their geographical location at the particular region of the estuary. Normally they should gradually be washed out by the currents and that too when there is high turbulences, particularly at the estuary proper, from June to October when south-west monsoon is prevalent. Thus existence of short term mobility and long term persistence of sands and shoals is rather paradoxical. There are two suggestions viz. - a) the sands and shoals are being fed with detritus from various ends at the same rate as the material are removed from the other ends b) there is a delicate balance between the amount being removed by the flood and that deposited by the end.

Transverse centrifugal forces acting as a result of reversible flow in curved reaches of the estuary coupled with the carioles forces induced by earth’s rotation, especially which is active in wide estuary (A.P. Banerjee, 2008), just after and prior to the commencement of slack water, both of which in combination produce helical motion and are thus responsible for transverse mass transport. However in the Hooghly estuary (Diamond Harbour / Hospital point to Sagore), the upland discharge has very little effect on water levels as that constitute a small fraction of the total mass of tidal water which moves in and out of the estuary during a tidal cycle. However the upland discharge along with the tide sets the stability in the upper reaches of the estuary. Now the striking feature of the study zone viz ranging from upstream and down stream of the Nayachara Island i.e., Balari reach(up stream of Nayachara Island) to Auckland reach (down stream of Nayachara Island) and even further downstream up to Maragolia reach (adjacent to Sagor Island (Figures 9 and 10) it is seen that siltation has been enhanced almost simultaneously all along the entire reach as mentioned above mentioned Balari reach, as well as up to Auckland reach as evidenced from the veer of ‘o’ contour line. Also it has been shown that the water course of the river has adopted several new courses time to time viz. A, B, and C (Figures 5, 6, and 7). But it can be discerned that the course length for each path has almost a fixed path length of the order of 61.87 km (Figure-5).

Moreover, the change of path length not only occurs over a wide stretch of the river but also to a short zone of the river stretch (Figure-7). The second group of path changes may be due to the local adjustment by the river for minimization of its stream power. Moreover overall adjustment of the channel path, for an almost fixed path length over several years, shows that the river is keen to conserve its stream power minimum, for a given set of constraints, not for a temporal basis but thus establishing the theory of minimum stream power as the process of natural rule. These constraints are like tidal range (5.5m), water retention amount in different reaches in the upstream, depending up on the different physical morphology of the respective reaches. Practical field data

(Figures 8(a) and 8(b) shows that low water level of the spring tide at Haldia though distorted as a natural rule is comparable to the low water level of the neap tide. But at sea face, such difference is not noticed. This situation creates greater amount of sea water retention at higher reaches and thus forming greater siltation during spring tide. Higher salinity of sea water also augments the process of siltation of the finer particles.

From the study of flux and discharge distribution (Table-1) of the estuary at Gangra reach and further land ward of it i.e., at Haldia / Rangafallah reach where the river suffers bifurcation on account of the existence of the Nayachara Island, it shows that sea flux is 75% higher than the flux coming from river discharge alone. Although as a whole it appears that ebb flux is always greater than flood flux, because of the addition of upland discharge. But it can be noticed that on account of greater length of ebb period than flood period, ebb discharge of the estuary becomes less than the flood discharge of the estuary (Table-1). Hence sediment carrying capacity of the river also becomes less in the ebb period than the flood period. As a result sedimentation /accumulation of silt in the estuary mouth becomes favoured as a natural way. Higher upland discharge can push up the upland sediment from the mouth of the estuary further downwards to the sea face. This sediment accumulation thus consequent change of river morphology creates change in energy dissipation rate of the river water during its passage of flow.

Table-6 and Figure-10 shows that in 1993 there was no island at the down Stream of Nayachara Island. At that time, area of the island was 46.512 Sq. km. Thereafter the island not only spatially expanded progressively at least up to the year 2005 but gave birth to a new island at its just down stream. After the year 2005, the downstream island took its highest spatial area of 26.266 Sq. km. and got detached from the main island Nayachara. Afterwards it is seen that the spatial area of both the island i.e. Nayachara as well as down stream island began to reduce at least up to 2010 and the area of the Nayachara island assumed the same value i.e. 47.5 Sq. km. as that was in the year 1968, i.e. 46.512 Sq. km. Hence it may be inferred that the huge sand mass accumulated at this locality finally got dislodged and dispersed downstream.

CONCLUSIONS

Though the estuary is well mixed in respect of its salinity structure and its sediment load is mostly silt dominated but in case of the huge sediment deposition to its up stream as well as downstream region of Nayachara Island and finally dispersement of the huge sand body accumulated at Nayachara Island gets dislodged and dispersed downstream to minimize the river's energy dissipation rate. Conversely the high flood discharge carries huge amount of silt from sea face to the upstream direction. This imbalance of flood and ebb discharge, latter being the smaller one, finally hinders the sediment load to be washed out to the deep sea and augments the creation of sand bodies all along the estuary in a sporadic manner. Nonetheless it is seen that over a long distance the estuary is maintaining its deep contour's path length nearly a constant for the sake of maintaining its energy dissipation rate a minimum, and which may be considered as the characteristic path length of this estuary for these set of constraints.

Table-1. Flux and discharge distribution of Hooghly estuary.

Parameter nature	**Place**	**Date**	**Haldia channel**		**Rangafalla channel**		**Total flux**	
			Flood	**Ebb**	**Flood**	**Ebb**	**Flood** (Flood hour = 5.078 at c/s-174A, 5.076 at c/s-181)	**Ebb** (Ebb hour = 7.162 at c/s-174A, 7.164 at c/s-181)
Tidal Flux in *$10^6 m^3$ (Sagor range = 3.58 and 3.16 respectively)	Along Nayachara island (c/s-74A)	27th and 29th Dec. 2011	247.5	163.75	706.25	1042.5	953.75	1206.25
Tidal Discharge in*$10^6 m^3$	At downstream of Nayachara (c/s-181)	27th and 29th Dec. 2011	1.27	0.65	4.04	3.84	5.22	4.58
Tidal Flux in *$10^6 m^3$ (Sagor range = 3.34 and 3.96 respectively)	Along Nayachara island (c/s-174A)	23rd and 25th Nov. 2011	336.25	327.5	602.5	1026	938.75	1353.75
Tidal Discharge in *$10^6 m^3$	At downstream of Nayachara (c/s-181)	23rd and 25th Nov. 2011	1.83	1.25	3.56	3.70	5.32	5.01

Table-2. Variation of salinity in the Hooghly river.

Year	**Place**	**Salinity in ppt.**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
2010	Haldia	Salinity from collected sample		11.7 to 11.9	10.44 to 17.10	10.6 to 11.34	10.44 to 12.80	8.10						
		Salinity from Obsn. site												
	Diamond Harbour	Salinity from collected sample		0.54 to 1.15	0.63 to 3.49	2.16 to 4.05	3.24 to 3.96	1.62						
		Obs sal												
	Hoogly Point	Salinity from collected sample		0.18 to 0.54	0.43 to 1.26	1.35 to 2.52	1.17 to 2.97	0.54						
		Salinity from Obs. site				1.26 to 3.96								
	Phalta	Salinity from collected sample		0.072 to 0.32	0.163 to 2.09	0.27 to 1.26	0.63							
		Sal. from Obs. site					0.10 to 2.21							
	Moyapur	Salinity from collected sample		0.027 to 0.036	0.027 to 1.032	0.072 to 0.43	0.054 to 0.36	0.072						
		Salinity from Obs. site						0.018 to 0.15						
2011	Haldia	Salinity from collected sample		9.10 to 10.10	10.40 to 12.30	11.34 to 12.78	11.30 to 13.90	9.8 to 10.4						
		Salinity from Obs. site												
	D/Harbour	Salinity from collected sample												
		Salinity from Obs. site												
	Hoogly Point	Salinity from collected sample	0.50 to 0.77	0.70	1.80 to 2.60	2.60 to 3.60	2.5	0.90 to 1.70						
		Salinity from Obs. site												
	Phalta	Salinity from collected sample	0.072 to 0.20	0.36 to 1.36	0.77 to 1.58	1.136 to 1.952	0.162 to 1.62	0.132						
		Obs sal												
	Moyapur	Salinity from collected sample	0.054 to 0.20	0.036	0.36	0.126 to 0.63	0.072 to 0.558							
		Salinity from Obs. Site												

Table-3. As per ISO 14688, grain size characterization.

Sand unit (mm)	**Silt unit** (mm)	**Clay unit** (mm)
0.063 - 2.0	0.002 - 0.063	< 0.002

Table-4. Variation of cross sectional areas under 'o' contour of Nayachara Island.

Year	Area in Sq. Km
1968	46.5
1995	60.63
2000	74.61
2005	76.39
2010	59.17

Table-5. Sediment characters of the Jellingham - Auckland study reach.

Date of observation	Name of place/position	D_{50}	**Silt Conc.** (gm/C.C.)						
2006			10 Hrs.	12 Hrs.	14 Hrs.	16 Hrs.	18 Hrs.	20 Hrs	22 Hrs
16.1.'06	Gangra/c/s-181-'A'	0.08	0.12	0.14	0.13	0.34	0.1	0.17	0.14
16.1.'06	Gangra/c/s-181-'B'	0.13	0.7	0.23	0.1	0.77	0.69		
15.2.'06	Haldia/c/s-174A-'F'	0.1	0.36	0.6	0.23	0.41	1.34	0.97	0.59
15.2.'06	Haldia/c/s-174A-'G'	0.11	1.38	0.48	0.51	0.94	1.93	0.11	
1.3.'06	Upper Auckland	0.15							
2.3.'06	Lower Auckland	0.13							
16.3.'06	Jellingham	0.14							
16.3.'06	Upper Jellingham Shoal	0.13							
2008									
9.2.'08	Gangra/c/s-181-'B'	0.14	0.55	0.51	0.37	0.32	0.43	0.15	
9.2.'08	Gangra/c/s-181-'A'	0.11	1.35	1.02	1.27	0.37	0.39		
22.2.'08	Haldia/c/s-174A-'F'	0.08							
22.2.'08	Haldia/c/s-174A-'G'	0.08							
13.3.'08	Lower Auckland Bar	0.11							
24.7.'08	Lower Auckland	0.12							
21.8.'08	Auckland Spur	0.12							
22.8.'08	Auckland Spur	0.08							
13.11.'08	Haldia/c/s-174A-'G'	0.11							

Table-6. Spatial area of Nayachara Island and down Stream Island.

Year	Area in Sq. Km.		
	Main Island (Nayachara) (A)	Downstream Island of Nayachara (B)	Total (A+B)
1968	46.512	-	46.512
2000	62.938	11.672	74.61
2005	50.125	26.266	76.391
2010	47.5	11.67	59.17

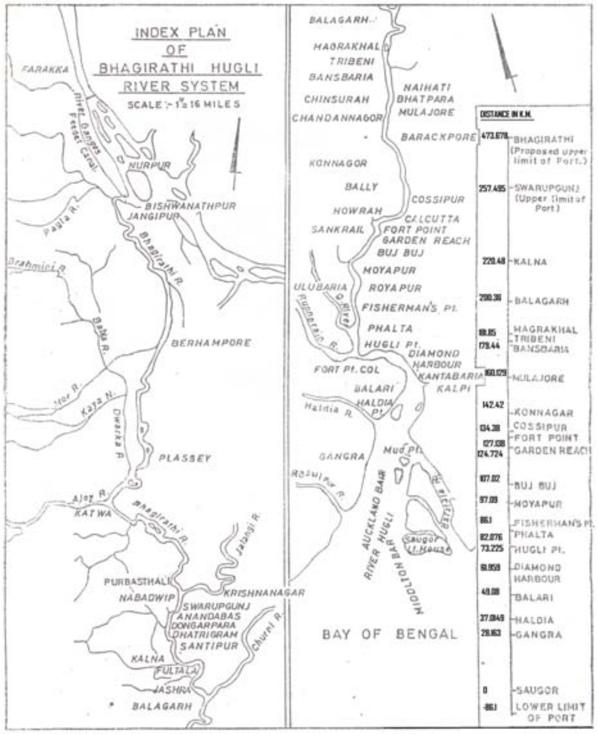


Figure-1.

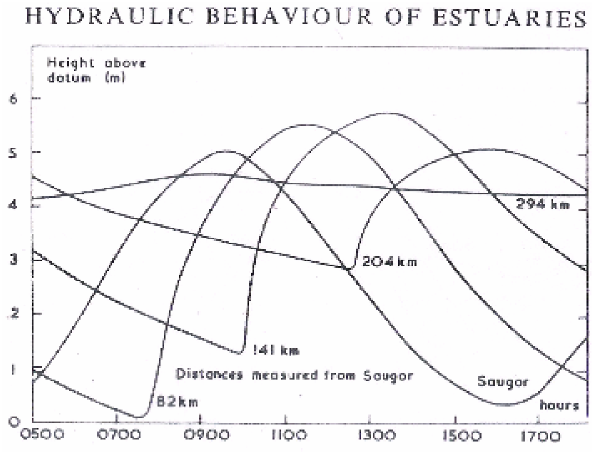
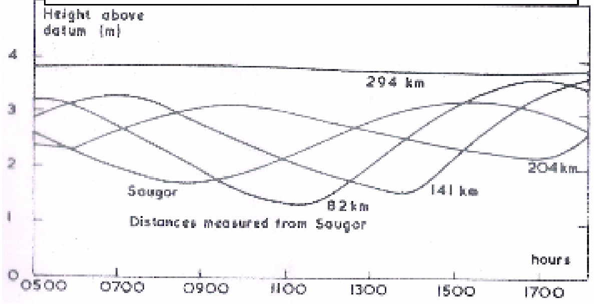


Figure 1.2. Spring tide recorded in the River Hooghly

Spring tide recorded in the River Hooghly



Neap tide recorded in the River Hooghly

Figure-2.

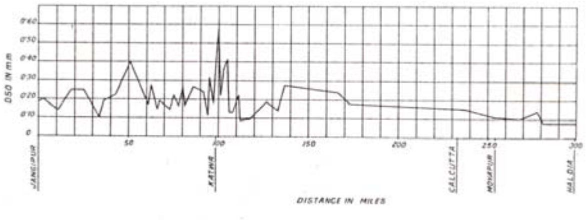


Figure-3. Longitudinal variation of d50 of bed sediment of Bhagirathi-Hooghly River.

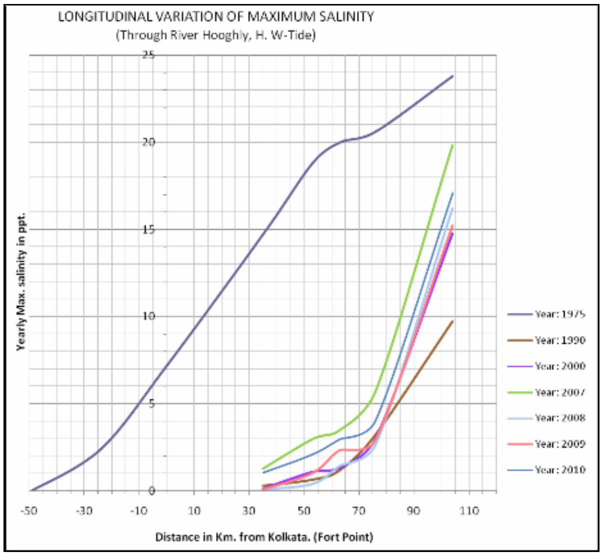


Figure-4.

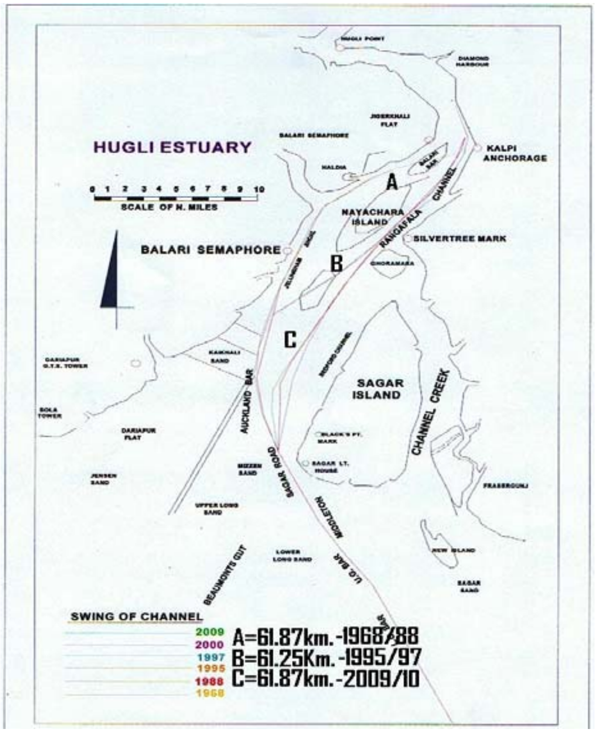


Figure-5. Channel swing of present Hooghly river.

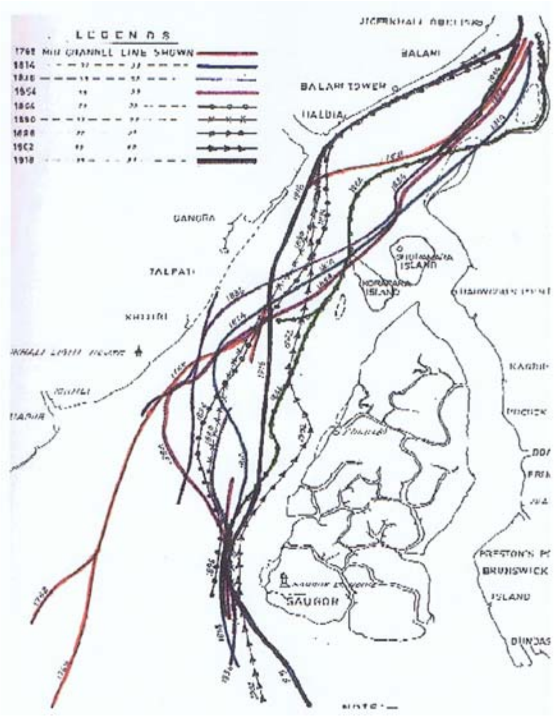


Figure-6. Long term channel swing of old Hooghly river.

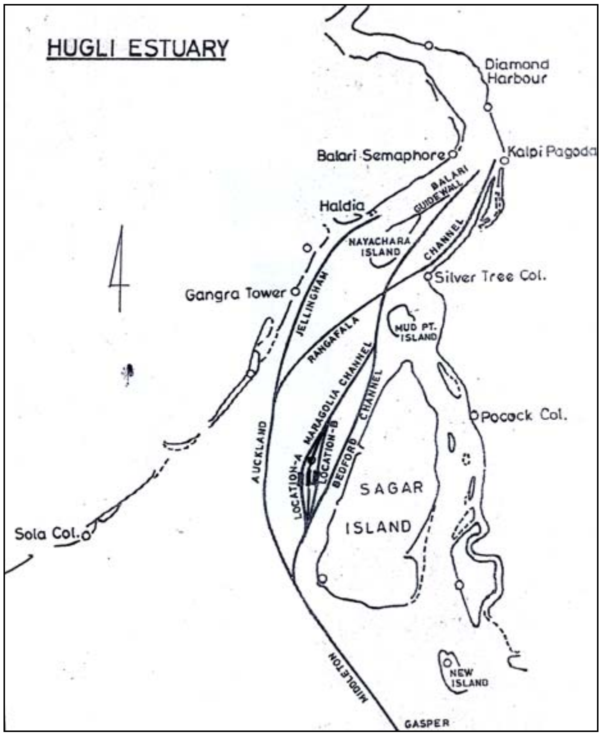


Figure-7. Local channel swing at down stream of Hooghly.

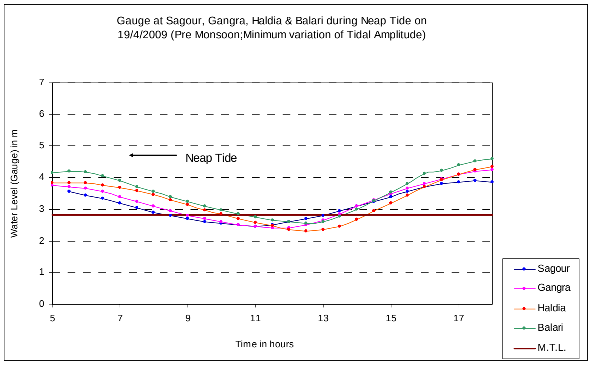


Figure-8(a).

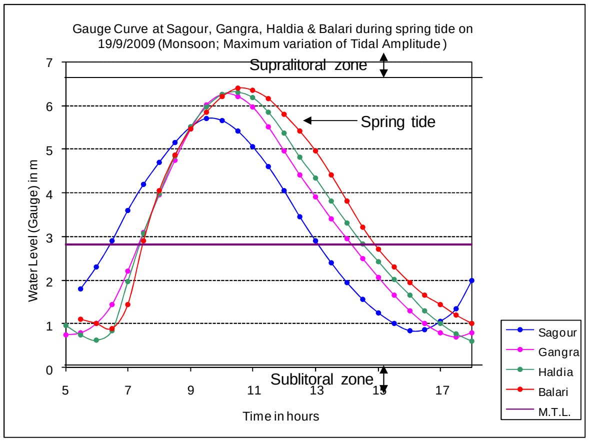


Figure-8(b).

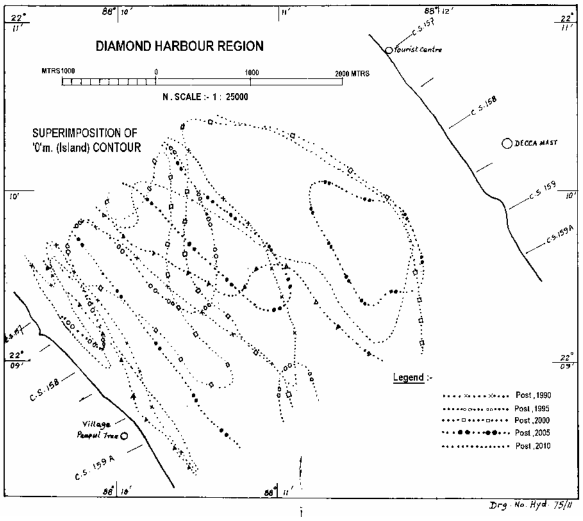


Figure-9. 'O' mt. contour superimposition at upstream of Nayachara.

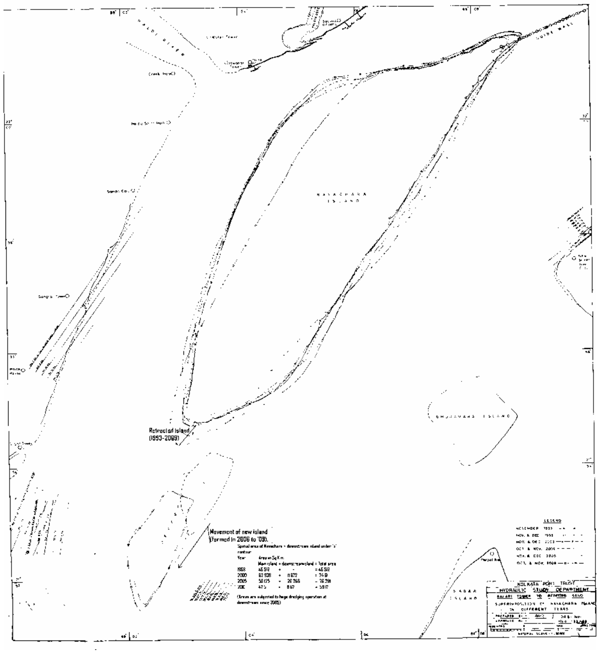


Figure-10. Superimposition of Nayachara Island over different years.

Limitation

It is a crux that, how the major sand bodies like 'Lower Long Sand' 'Mizen sand', 'Kaukhali Sand', 'Auckland Sand bar', "Jellingham Shoal" etc. (Figure-5) maintain their position more or less the same over several years. Only orientation, shape and volume changes with season, which might be the zones of trawl ground of sediment accumulation for the particular set of constraints of this estuary viz. flood and ebb discharge prevalence, salinity, wind, tidal range and wave etc. which makes these zones favourable for ultimate deposition ground so long river flow energy dissipation rate does not exceed it's minimum value.

Scope of further study

River contour superimposition of entire estuary over last few decades may reveal the detail path of the deep contours, thus estimating the energy dissipation pattern of this estuary.

ACKNOWLEDGEMENT

In particular I wish to thank Sri C. M. Rout, Dy. Director of KoPT for his thoughtful suggestion.

REFERENCES

Yang C.T. 1971. Potential Energy and Stream Morphology. American Geophysical Union, Water Resource Research. 7(2): 311-322.

Nicholas P. Cheremisinoff. Encyclopedia of Fluid Mechanics. Golf Publishing Company; Book Division; Houston, USA.

Victor L. Streeter. Hand book of fluid dynamics.

George J. Klir / Bo Yuan. Fuzzy sets and fuzzy logic. Prentice Hall of India Ltd.

Davis –sorensen. Hand book of applied hydraulics.

A.P. Banerjee. 2008. A Case Study on Some Aspect of the Hooghly Estuary and Concomitant Changes of Its Morphology. Indian National Conference on Advances in Hydraulic Engineering with special emphasis on Model-Prototype Conformity; INCAHE, The Indian Society for Hydraulics.

Bhattacharia Sunil K. 1976. Deltaic activity of Bhagirathi-Hooghly River System. Journal of the waterways, Harbour and Coastal Engineering Division, ASCE. 99(WWI, Proc. Paper 9538): 69-87.