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Tidal impact leading to sedimentation at lower reach of Rupnarayan River, West Bengal, India

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During the last 20 years the lower reach of the Rupnarayan River has experienced a net shoaling of 26.57 million m^3 (survey made by Kolkata Port Trust, 1992-2012) with 42.04 million m^3 shoaling and 15.47 million m^3 scouring. Bathymetric close grid survey of the study area was made using Leveling instrument and Echo sounder interfaced with Position Fixing System (GPS). Simultaneous tidal observations were available at an interval of one hour, velocity of high tide and low tide, tidal asymmetry and discharge of water etc. are measured at different Gauge Stations in the field. Swifter and stronger high tide results more available energy during high tide than as low tide. The incoming high tide brings a lot of sediments from the downstream and deposits it on the bed of the studied river in absence of any upland discharge during the non-monsoon months. During the freshet (July, August and September) the impact of high tide is felt less due to the voluminous anti-directional flow of the upland discharge. Tidal range is more near Geonkhali (4.5m) and decreases towards upstream, being lowest near Kolaghat (2.9m). Tidal asymmetry increases from downstream (2 hours at Geonkhali) to upstream (6 hours at Kolaghat). Tidal prism (volume of water that enters a tidal region during flood flow) is very high in that region.

[Key words: Sedimentation, transport power, bathymetry, tidal asymmetry, shoaling and scouring, tidal prism.]

Introduction

Sedimentation is the main cause of deterioration of stream channels and navigation difficulties. The settling velocity of a particle of certain size is the threshold of deposition for that grain. Thus the flow velocity lowers than the threshold causes deposition of that particle[1]. Flow separation due to channel widening causes deceleration of flow and invites deposition. If a huge amount of sediment is discharged from upstream area, the river response by aggrading in order to steep the gradient and increase its velocity to become more competent[2-3, 1].

At present Rupnarayan river has been showing signs of rapid deterioration and incapacitation due to sedimentation. Rapid sedimentation and development of shoal area creates a variety of detrimental problems and impacts on society, economies and the environment including the shifting of river course and thalweg position, shortage of water during neap tide for utilization in different purposes, hindrance of easy discharge of water and upstream flood, navigation difficulties, river bank erosion and loss of settlements and properties. Being a tidal river Rupnarayan is affected by both riverine and maritime processes. That's why the causes and mechanism of sedimentation on that river bed is different from other normal streams. The landward intrusion of marine water and sediment during high tide is the main cause of rapid and continuous sedimentation at lower reach of the Rupnarayan River. In the present study attempts have been made to explain the causes

and mechanism of sedimentation in connection to the tidal mechanisms, i.e., the role of tidal range, tidal prism, tidal velocity and tidal asymmetry leading to sedimentation.

Materials and Methods

The Rupnarayan River with its network of sub-tributaries, including the Dwarakeswar, Silabati, Kangsabati and Damodar Rivers, is the most important tributary of the River Hoogly. River Silabati and Dwarakeswar meet at Bandar, and the combined flow is named as Rupnarayan, which joins river Hoogly at Geonkhali covering a distance of 78 km. The whole Trans- Damodar area is ultimately drained through this river. The entire Rupnarayan River has been divided into three reaches. Upper reach having 28 km length is extended between Bandar and Jasar. The middle reach is 10 km long extending between Jasar and Dainan (Kolaghat). The lower reach (study area) extends from Kolaghat to Geonkhali with a length of 40 km and is bounded by $22^0 12'$N to $22^0 26'$N and $87^0 53'$E to $88^0 03'$E (Fig 1), approximately 10930 km^2 catchment area of the Rupnarayan River. The study area has a typical tropical monsoonal type of climate with an average rainfall of 1320mm to 1630mm and annual temperature ranging from 11°C to 45°C. Lower reach is divided into four sub-reaches (Geonkhali to Dhanipur, Dhanipur to Anantapur, Anantapur to Gopinathpur and Gopinathpur to Dainan reach) based on the necessity of the study.

Topographical maps from Survey of India, District Planning Maps from National Atlas and

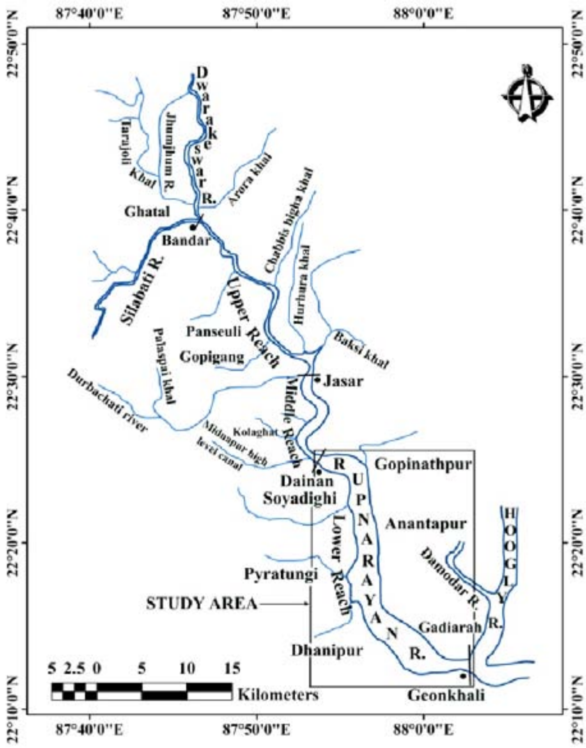

Fig.1- Study area

Thematic Mapping Organization (NATMO), Soil and Land use Maps from National Bureau of Soil Survey and Land Use planning have been collected. Bathymetric close grid survey of the study area was made using Leveling instrument and Echo sounder interfaced with Position Fixing System (GPS). Simultaneous tidal observations were available at an interval of one hour at different Gauge Stations in the river Rupnarayan and discharge of water is measured in the field. Tidal gauge and discharge related data were also collected from the Sectional Office at Ghatal and Tamluk, under the Irrigation and Waterways Department of Government of West Bengal. Bathymetric, tidal, sediment and discharge data have also been collected from the concerned authority of Kolaghat Thermal Power Project and Kolkata Port Trust. Velocity is measured by Digital water current meter and floating method at different sections along the river. Water samples during high and low tide were collected to measure the suspended load concentration. Rate of sedimentation was measured by keeping the wooden tray on river bed for few days. Some bed samples was collected and grain size analysis was done in the laboratory of Indian Institute of Technology, Kharagpur. Satellite data was procured from National Remote Sensing Agency (NRSA) and required analysis (digital image processing and visual image interpretation.) was made. ERDAS IMAGINE 8.5, ArcGIS 9.2 and Microsoft Office Excel etc. have been used for the preparation of maps and diagrams.

Amount of water discharge is calculated following Maddock[4]

$$Q = WDV \quad \ldots\ldots\ldots\ldots\ldots (1)$$

Where, Q = discharge, W= width of channel, D= depth, V= mean velocity.

Analysis of mean grain size is done following the equation of Folk and Ward[5]

$$\text{Graphic mean} = (\varphi 16 + \varphi 50 + \varphi 84)/3 \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Amount of energy required to transport the sediments of uniform size (critical shear stress) during all the seasons are calculated using Shield[6] formula

$$\tau_{cr} = \eta g(\rho_S - \rho)\pi/6\, D\tan\theta \ldots\ldots\ldots\ldots\ldots(3)$$

Where, ρ= fluid density, ρ_S= sediment density, g= gravity constant, D= grain diameter, η= nD^2, a measure of grain packing.

Fluid density (ρ) and sediment density (ρ_S) is measured in the laboratory by collecting water and sediment samples.

The available stream energy passing through open channel is expressed as energy equation following the equation-

$$H = Z + d\cos\theta + V^2/2g \ldots\ldots\ldots\ldots\ldots\ldots (4)$$

Where, d= depth, θ is the slope of river bed, Z= elevation above datum, v= mean velocity.

Result and Discussion

The lower reach, from Dainan to Geonkhali (40km) of the Rupnarayan River has been deteriorated and has lost its carrying capacity due to continuous sedimentation and development and shifting of shoal area. Throughout this stretch the river is interspaced with inter tidal flats which keeps on shifting, decaying and growing, contributing to the frequent changes of the river morphology. During the last 20 years net shoaling area is 26.57 million m^3 (survey made by Kolkata Port Trust, 1992-2012) in this region with 42.04 million m^3 shoaling and 15.47 million m^3 scouring (Fig 2 and Table 1). Four cross-sections have been drawn at different stretches to analyze the shoaling and scouring pattern in that region and in shown in Fig 3.

In Geonkhali to Dhanipur stretch of 10 km 75% of the area has been shoaled up. Maximum shoaling of around of 5 m is observed near the confluence at Geonkhali reach. During the period of last 20 years the right bank between confluence and 3 km upstream has encroached in to the river to the tune of 200-500 m. The incidence of local scour area is observed to be restricted within the lower half of this reach. It is observed that a deep pocket area just downstream of Dhanipur ($22^0 13^{'}$N and $87^0 59^{'}$ to 88^0E) has not only survived but also improved with a maximum scour of 307m during the last 20 years. The upper half of the reach has been shoaled up almost completely with a maximum deposition of 2.1m.

During the last 20 years, Dhanipur to Anantapur stretch of about 12 km has narrowed down to the extent of 45% of its width prevailing in the year 1992. Though the right bank at the lower stretch of around 5 km has got eroded to the extent of about 500m, the remaining 7 km lengths has encroached into the river to the tune of 750m. However this stretch could manage to maintain a narrow scouring channel in its entire length.

Anantapur to Gopinathpur stretch of about 10 km has undergone severe transformation with respect to the year of 1992. Main channel, which used to flow hugging the left bank in its upper part in 1992, has completely shifted towards right bank to the extent of around 1.5 km. Severe deposition along the left bank in the upper part of the reach has induced sedimentation in the central portion of the lower part also.

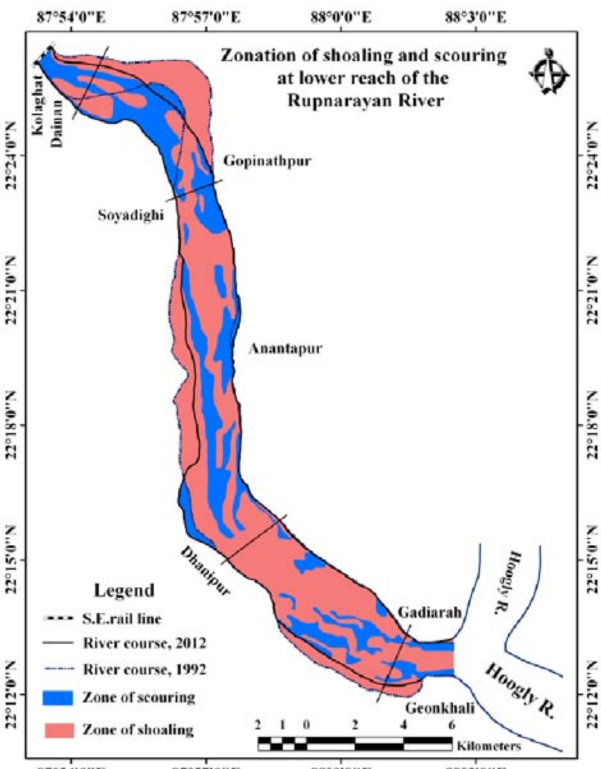

Fig.2- Zonation of shoaling and scouring area

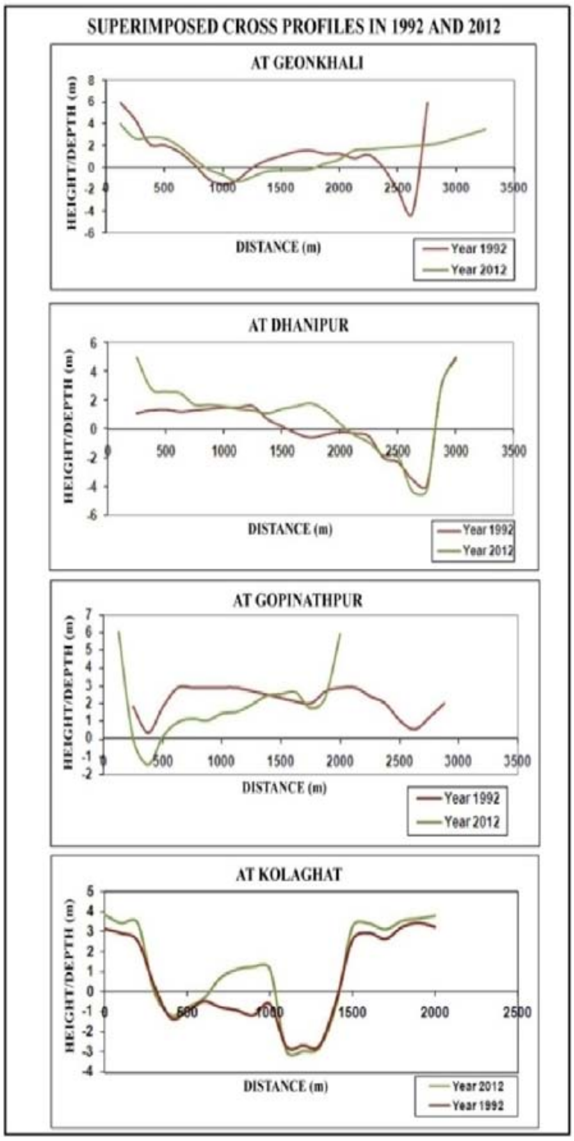

Fig.3- Superimposed cross-sections in the study area

Total shoaling and scouring in Gopinathpur to Dainan reach region are 6.21 million m^3 and 3.92 million m^3 respectively during the last 20 years. Shifting of river course is an important phenomenon in this stretch. During 1992, the main channel used to flow hugging the left bank but now a large portion of the left bank has shoaled up pushing the main flow towards the right bank. Diversion of flow due to obstruction and sudden widening of channel is very common feature here.

The entire stretch, from Geonkhali to Dainan has been incapacitated to such an extent that after Dhanipur area, existing bed levels prevents the flood water to propagate in the up-stream till the level of flood water reaches a height of around 2.5 m in Gopinathpur reach and 3.5 m in Kolaghat reach on an average (project report of Kolkata Port Trust, 1992-2012). Development of the new shoal area, expansion and shifting of the existing shoal area continuously modifying the river be

Table.1- Quantification of shoaling and scouring at different reaches

Reach	Length (km)	Total shoaling (million m^3)	Total scouring (million m^3)	Net shoaling (million m^3)
Geonkhali to Dhanipur	10	12.18	3.85	8.33
Dhanipur to Anantapur	12	18.17	4.66	13.51
Anantapur to Gopinathpur	10	5.48	3.04	2.44
Gopinathpur to Dainan	8	6.21	3.92	2.29
Total	40	42.04	15.47	26.57

Table.2- Spatial and temporal variation of sedimentation rate

Reach	Geonkhali			Dhanipur			Anantapur			Gopinathpur			Dainan		
Season	Pre-monsoon	Monsoon	Post-monsoon	Pre-monsoon	Monsoon	Post-monsoon	Pre-monsoon	Monsoon	Post-monsoon	Pre-monsoon	Monsoon	Post-monsoon	Pre-monsoon	Monsoon	Post-monsoon
Sedimentation rate (mm/hr)	2.84	2.14	3.05	3.12	2.98	3.54	2.56	1.29	2.37	2.22	1.54	2.66	2.36	1.81	3.18


Plate 1: Sedimentation near Geonkhali
Plate 2: Sedimentation near Dhanipur
Plate 3: Sedimentation near Gopinathpur
Plate 4: Sedimentation near Kolaghat

morphology in this regime. This mechanism is the result of the interaction between tidal influence and upland riverine discharge. More over the change of bed morphology is affected by number of engineering structures; like four bridges built over piers within the waterways, cluster of piles built for power transmission lines etc. The velocity of water during high and low tide, concentration of suspended load and mean grain size have been analyzed during pre-monsoon, monsoon and post-monsoon to explain the available energy in stream during high and low tide and the energy required to transport the sediment (Table 3 and Table 4).

In tidal river the process of sediment deposition is the result of balance of quantum of head water flow on one hand and the tides on the other. River discharge is impounded during flood period and released during ebb period. When the material carried by littoral drift reaches a river mouth, it is picked up by the tidal current and is carried into the river channel by the flood current. Regular influxes of tidal water through the river

Rupnarayan visit this area twice a day. The incoming high tide brings a lot of sediments from the seaward and deposits it on the bed of Rupnarayan River in absence of any upland discharge during the non-monsoon months. During the freshet (July, August and September) the impact of high tide is felt less due to the voluminous anti-directional flow of the upland discharge of the Rupnarayan River. Apart from such a direct effect of the tides interrupting the

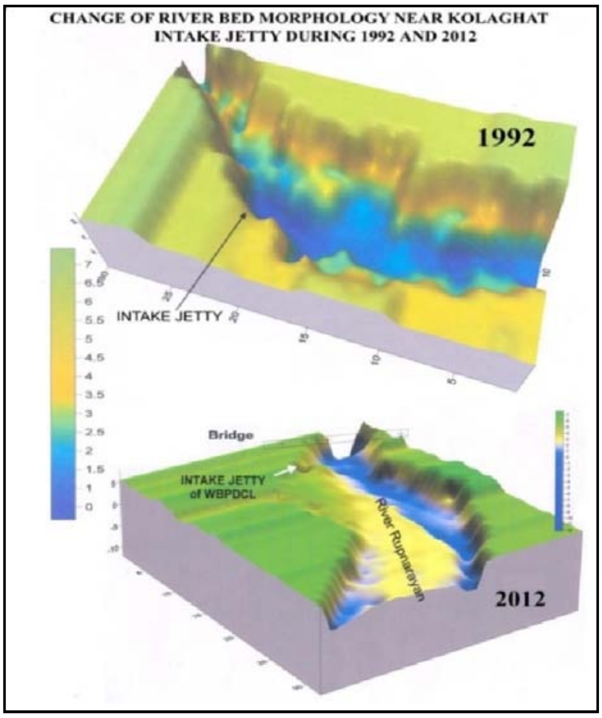

Fig.4- Previous and present condition of Kolaghat region

load transport behavior of Rupnarayan River, the injection of saline water by tides into the sweet water has an indirect impact to control sediment deposition. Considering a specific reach of the river, as the salt water wedge approaches this reach from downstream, the river flow, upon meeting this salt water wedge, loses its velocity. Materials carried as bed load will cease to move and coarse particles of the suspended load will also settle down in accordance with Stoke's law. Very fine of colloidal sediment in suspension will settle down very slowly, while particles subject to electro-chemical reaction will flocculate upon contact with the salt water[7].

As a tidal current is essentially non-steady and non-uniform in character and as sediments behave quite differently as bed, suspended and colloidal loads, a correct expression to define the sediment transportation power of a tidal current has not yet been determined. As an approximation, it may be assumed that the transportation power is proportional to the square, cube or any higher power of mean velocity of flow (V^m with m>1) and that the mean velocity is approximately proportional to the discharge, Q. Transportation power will then be proportional to Q^m, m being greater than unity. The instantaneous discharge of the tidal current and its sediment transportation power Q^m at any point can be plotted against time over a complete tidal period. Areas under the Q curves give the total quantity of flow while the areas under the Q^m curves give the work done in transporting sediment. The difference in the area enclosed by the Q^m curve for the flood and ebb currents respectively indicates the net result of sediment movement, either upstream or downstream as the case may be. When a tidal wave runs into the river Rupnarayan having a certain discharge Q_o, a symmetrical Q curve will also experience a deformation. This is due to the fact that the crest of every tidal wave partly overtakes the trough preceding it. As a result of which, the Q curve at some distance upstream shows a sharper rise in discharge with a corresponding shorter period for the flood flow and a slower outflow and consequently a longer period for the ebb flow. In such a case the area under the Q^m curve for the flood current movement is usually greater than that for the ebb current and the net result will be a movement of sediment towards upstream which indicates deposition (Fig 5). But this condition is reversed when the river gets an upland discharge during freshets between the month of July and September. River gets an upland discharge which causes a good amount of flushing of the river bed. The sediment supplied from the feeder rivers moves down and initially causes sporadic shoaling in the Rupnarayan but as the ebb current is stronger than flood due to the voluminous upland discharge, it does not allow the sediments to settle down but instead scours and keeps the sediment moving down seaward. As a result the general depth of the river attains the best possible condition and the net result can be represented by the difference between the areas enclosed by the Q^m curve of the flood current and the $(Q+Q_o)^m$ curve of the ebb current as shown in Fig 5.

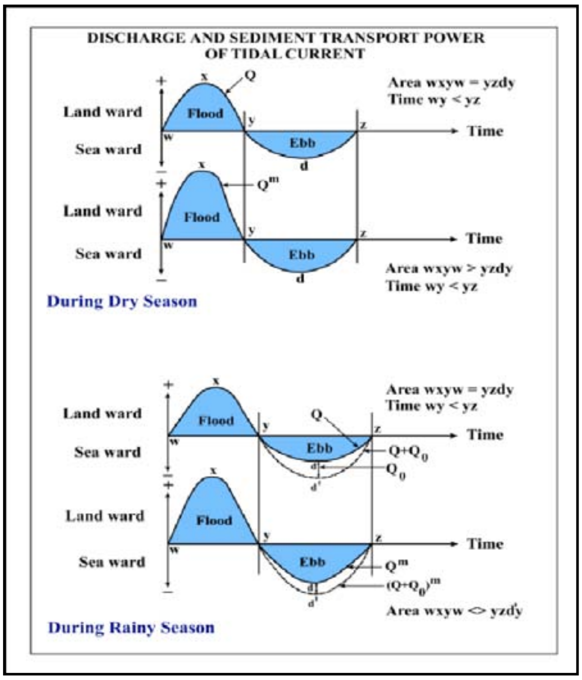

Fig.5- Discharge and sediment transport power of tidal current

Table.3- Concentration of suspended load in water, surface water velocity and grain size analysis

Season	Concentration of suspended load (gm/liter)		Water velocity (m/sec)		Mean grain size (mm)
	High tide	Low tide	High tide	Low tide	
Pre- monsoon	4.10	3.21	1.81	0.95	0.106
Monsoon	7.16	6.58	2.01	1.90	0.168
Post-monsoon	5.28	4.18	1.95	1.10	0.122

Table.4- Threshold energy and available stream energy during high and low tide

Season	Threshold energy ($\eta g(\rho_S-\rho)\pi/6\ D\tan\theta$)	Stream energy during high tide ($H=d+Z+V^2/2g$)	Stream energy during low tide ($H=d+Z+V^2/2g$)
Pre- monsoon	14.84 Joule	16.267 Joule	13.146 Joule
Monsoon	15.86 Joule	17.306 Joule	17.186 Joule
Post- monsoon	15.12 Joule	16.693 Joule	13.561 Joule

Tidal range, tidal asymmetry and tidal prism are the prime factors to control the rate of sedimentation and spatial variation of development and shifting of shoal area. Tidal range is the difference in elevation between high and low water marks and is divided into three classes[8] (i) Micro-tidal: <2m (ii) Meso-tidal: 2-4 m (iii) Macro-tidal: >4m. Tidal range is very significant because the extension of intertidal areas that receives water during tide depends on it. A greater tidal range is responsible to the movement of greater volume of water and more possibility of fluctuation. At the lower reach of the Rupnarayan River the tidal range continue to decrease from downstream (Geonkhali) to upstream (Dainan). So, extensive intertidal areas towards upstream receive more water and sediment during high tide than areas towards upstream. Based on the tidal range Dainan and Gopinathpur reaches are under meso-tidal (2-4m) range whereas Dhanipur and Geonkhali reaches are under macro-tidal (>4m) range. That's why the sedimentation rate is different at different reaches, though it is affected by other terrestrial and tidal factors. The values of tidal range of all the stretches are shown in Table 5.

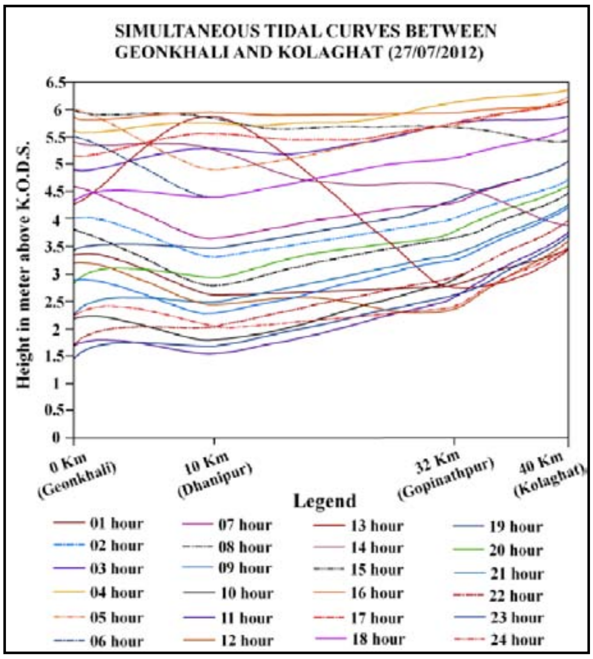

Fig.6- Simultaneous tidal curves between Geonkhali and Kolaghat

If the flood and ebb tides are of unequal length (tidal asymmetry), then on the shorter, the fixed volume of water and sediment has to move faster than on the longer. The only way that these can be achieved by variations in velocity and, therefore, energy[8]. If, as in the situation above, flood periods are shorter, and energy greater, more sediment can be carried in on the flood tide than can be moved on the ebb (assuming adequate sediment supply).

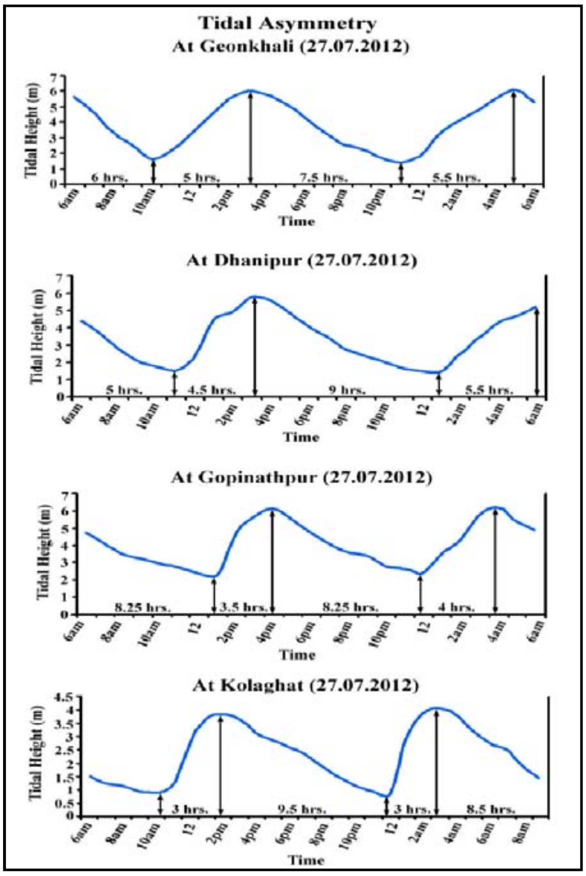

Fig.7- Tidal asymmetry at different gauge stations

Hence, the region will experience a net input of sediment. Tidal asymmetry at different stretches of the lower reach of Rupnarayan river is calculated and shown in Table 5. The data reveals that though the tidal asymmetry is lowest at Geonkhali (2 hour), but increases continuously and attains highest at Dainan/Kolaghat (6 hours). So, tidal asymmetry is another important cause for increasing sedimentation at lower reach of the Rupnarayan River.

Table.5- Tidal range and tidal asymmetry at the lower reach

Stretch	Geonkhali	Dhanipur	Gopinathpur	Dainan/Kolaghat
Tidal range (m)	4.5	4.4	3.85	2.9
Tidal asymmetry (hour)	2	3	4.5	6

Tidal prism is defined as a volume of water that enters a tidal region during flood flow. Jarrett[9] developed a relationship for tidal prism, P, as a function of cross-sectional area. Carter[10] suggest that a crude way of estimating this volume is by measuring the surface area of the water at high tide, and multiplying by the tidal range. The volume water exchanged during a tidal cycle occur through flood and ebb tides, leading to the streams being classified as either flood dominant, ebb dominant, or co dominant, where the flood and ebb are of equal magnitude. As the lower reach of the Rupnarayan River is largely affected by tidal phenomenon, thus the volume of water penetrating inward is very high. Tidal prism of all the stretches have been calculated and shown in Table 6 and Figure 8. At all the stretches the volume of water penetrating inward is very high than the flow of water downstream during lean period, when upland riverine discharge is meager. So, there is the possibility of penetrating more sediment upstream and increases the rate of sedimentation. But during freshet (rainy season) the voluminous increase of upland discharge make the condition reverse and sedimentation rate decreases.

Table.6- Tidal prism at the lower reach

Stretch		Geonkhali	Dhanipur	Pyratungi	Soyadighi	Dainan
Water discharge (thousand m^3/sec)	Flood tide	-9.5	-6	-3.75	-2	-1.25
	Ebb tide	4.75	2.75	1.75	1.25	0.85

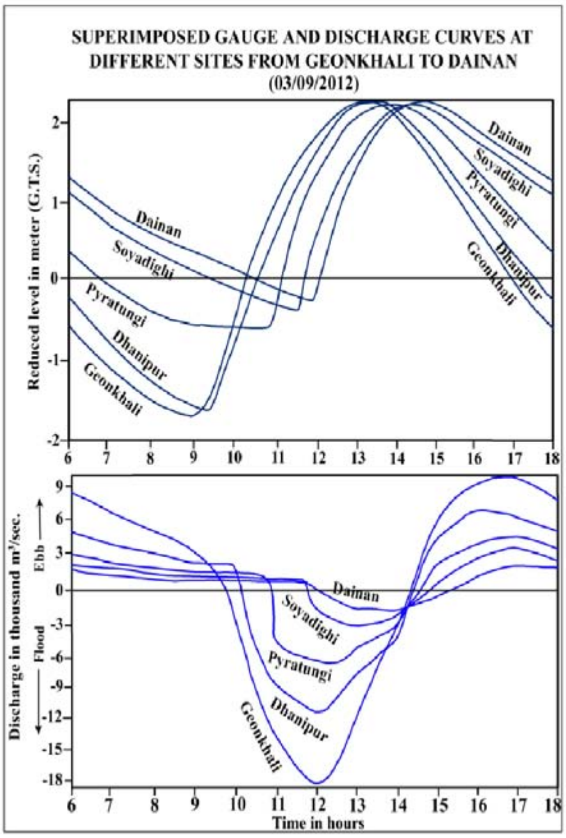

Fig.8- Superimposed gauge and discharge curves

Sluggish low tide discharge over longer duration allows sufficient opportunity for settling the sediment. Low energy availability during low tide causes sedimentation that makes the river incapacitated day by day. The problem has been engaging the attention of the Hydraulic Engineers, Geologists, Hydrologists and the Government. Most approaches followed by the concerned authority are still firmly empirical, but mathematical modeling is becoming more important as understanding of drainage systems improves[11]. So, proper understanding of stream hydraulics and interaction between fluvial and marine processes will help to suggest suitable remedial measures for the reduction of sedimentation rate and improvement of capacity and navigation of the Rupnarayan River.

Conclusion

Present study reveals that tidal asymmetry leads to swifter flow and greater energy during high tide leading to inland transport of sediment.

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