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Bed sediment characteristics and transport processes along the inlet channel of Chilika Lagoon (INDIA)

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Bed sediment samples were collected along the 9.5 km long inlet channel of Chilika lagoon, east coast of India during low freshwater discharge and low rainfall condition. Distributions of bed sediment along with its texture were studied in detail. Bivariate plots between mean, sorting, skewness and kurtosis of sediments revealed definite grouping pattern. The study, through C-M plot, indicates that the prime factors for transportation of sediment within inlet channel of Chilika lagoon are rolling and bottom suspension during period of low discharge and low rainfall (November-June). Sustainable conservation and management of wetlands require information on its past, present and future.

[Keyword: Inlet channel, Bed sediment texture, Transport processes, Chilika Lagoon]

Introduction

In coastal lagoons and estuaries, increased accretion rate often alter water renewal, and therefore hinders the functioning of local ecosystems. Over the period of time, most of the inlets exhibit seasonal variation in their morphology, which in turn control the exchange of water and sediments within the sea and lagoon. In micro/macro tidal coast, tidal inlets exhibit variable geomorphology owing to nonlinear interaction of inlets with its environmental drivers such as low period and high energy waves, tide, current and fresh water discharges[1-3]. Inlet geomorphology along east coast of India exhibits significant spatio-temporal variability and controls the freshwater discharge, sediment influx and saline water intrusion[4-5]. The processes mentioned above are primarily responsible for inlet shifting, sedimentation along the inlet channel[6] and act as drivers for deterioration of water quality, proliferation of macrophytes[5], reduction of tidal influx[7] and salinity gradient[4]. Chilika lagoon, due to changing geomorphology of its inlet(s), has experienced most of the stated problems in the past and some are still persistent at present. To resolve some of the issues and to save the pristine environment of the lagoon from a foreseeable danger, Chilika Development Authority (CDA), Government of Odisha dredged open an inlet at Sipakuda in September 2000. After opening of the inlet at Sipakuda, the lagoon environment significantly improved and the lagoon was removed from the Montreux record and was enlisted as a Ramsar site in 2002, a wetland of international importance[1]. However, the restored ecology of the lagoon could not be sustained due to subsequent geomorphological changes of inlet(s)[1]. Among countless studies around the world coastline, few investigations have suggested that bed sediment characteristics have definite control on hydraulics of inlet[8], locational inlet stability[9] and also on bed load transport[10]. Besides, knowledge on bed sediment characteristics of an inlet channel is of great importance in differentiating various depositional/erosional micro environments. Therefore, it is crucial to investigate the sediment characteristics of tidal inlet of Chilika lagoon.

Perusal of literature reveals that most of the sediment research is limited to beaches and tidal inlet(s) along the Indian coast[11-29] and provide information on sediment texture and mineralogy. However, information on sediment characteristics such as texture, sediment statistics and the transport processes within the inlet channel and also at the inlet are very sparse.

Studies on circulation and salinity structure of Chilika lagoon and its impact on lagoon ecosystem [1, 4, 5, 7, 30] clearly indicate the impacts of inlet(s) closing/opening and shifting on lagoon hydrodynamics. Studies on sediment texture in and around Chilika lagoon including the outer channel have been conducted by many sedimentologists[31-34] revealed that sediments are highly variable in spatial mode than seasonal mode except for the northern sector due to higher rate of seasonal fresh water discharge. Geomrphological changes of inlet(s) and their impacts on lagoon biodiversity are very significant, which has been described in a recent study[35]. However, the present study on bed sediment characteristics including transport mechanism within inlet channel of Chilika assumes importance as prior information on these aspects is not available and more so this information is vital to understand the sedimentation processes and the future geomorphological changes of inlet(s). Both qualitative and quantitative information on sediment characteristics and transport mechanism within the inlet channel shall supplement the management plan for sustainable restoration of Chilika ecosystem.

Material and Methods

The Chilka Lagoon, along Odisha coast, east coast of India (19^0 28'- 19^0 54' N , 85^0 06'- 85^0 35' E) is about 64 km long and oriented in NE- SW direction with an average width of 13.5 km (Figure 1) The catchment area of the lagoon experiences both southwest and northeast monsoon. Hence, the lagoon receives huge amount of fresh water and suspended solids during monsoon period. The lagoon acts as a sink to a large fraction of the sediments coming from the western catchment and Mahanadi river system while rests of the sediments are discharged into the sea through the inlet. Due to this huge sediment load into the lagoon system, decrease in depth of the lagoon, particularly in the northern sector, is alarming and ebb shoals are also observed[1]. Therefore, emphasis of the present study is to understand the sediment characteristics and transport processes within the inlet channel. This inlet communicates to the Bay of Bengal (BOB) at Sipakuda and also to the central lagoon at Magarmukh near station 16 (Figure 1). The length of tidal inlet is approximately 8Km with variable width. The depth of outer channel varies from 2- 6.5 m. The tidal characteristic near the shore front of Chilika lagoon is semidiurnal with an average spring and neap tide of 1.60 m and 0.50 m respectively[1]. Wave climate near inlet entrance may be characterized as high energy and low period waves approaching from south-south-east, south-east direction with a maximum wave height up to five meter[36]. Maximum flood (ebb) current near the inlet entrance is about 0.81 m/s (0.92 m/s)[1]. Lagoon and its outer channel accommodate rare species of Dolphin and hence is considered as a tourist site. Besides, this inlet acts as a major navigational channel for most of the recreational activities and fishing practices. It has been noticed that inlet entrances and associated island exhibit significant geomorphological changes due to influence of both longshore sediment transport and alluvial sediment deposits[1,37,38]. Geomorphological changes of inlet(s) brought significant transformation in water quality, biodiversity and hydrographic characteristics of the lagoon[4]. Keeping in view the geomorphological changes of inlet, inlet channel and the associated processes, study on sediment characteristics and transport processes within inlet channel bears importance.

The bottom sediments were collected along 9.5 km long tidal inlet channel starting from inlet entrance to Magarmukh (station 16) during June, 2014. June corresponds to the period of low rainfall in the locality as well as low freshwater discharge into the lagoon[7]. Hence, the freshwater discharge from the lagoon to the sea through the inlet channel is minimal and the flood dominates over ebb. However, the present sampling was under taken during ebb condition which provides a conducive environment for sampling due to lower current speed and depth compared to flood. A Van Veen grab sampler was used to collect bottom sediments. The sediment sampling stations were selected using Global Positioning System (GPS) and each station was chosen at midpoint of the channel width. The detail station locations are shown in Figure 1. After collection of bottom sediments, samples were treated primarily for isolation of impurity and purification. Soon after isolation of impurity, samples were brought to the laboratory in a polythene container. Sediments were oven dried with temperature of 100^0C following the prescribed method[39].

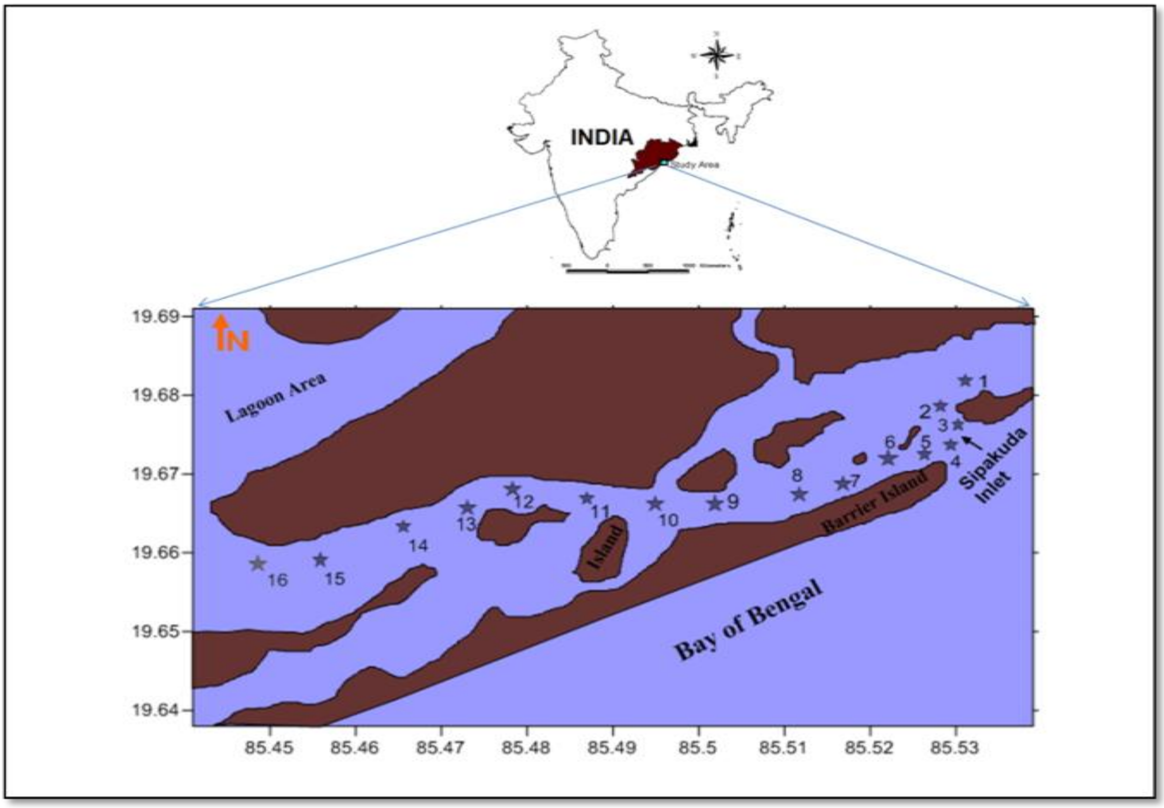

Fig. 1- Study area and station locations (marked with *)

Thereafter, 100gm of oven dried sediment was sieved for five minutes using Retsch-AS200 sieve shaker having interval of 0.5Φ from 0 to 4 Φ. After sieving for five minutes, the weight of sediments retained in each sieve was measured with precision electronic weight balance of 0.1gm accuracy. The statistical parameters such as mean, median, mode, sorting, skewness and kurtosis of grain size distribution were determined using GRADISTAT software. Besides, percentage distribution of sediments at each station was determined. The bottom sediment transport processes, erosion and accretion trends were investigated adopting established method[10]. Based on the above statistical parameters, bivariate plots and CM diagrams were prepared and the data analyzed. CM plot takes into account different modes of transportation by plotting coarsest first percentile grain size(C) and the median size (M) of the sediment samples on a double log paper[40]. The CM plot of sedimentary environment helps in analyzing transport mechanism, depositional/erosional environment with respect to size, range and energy level of transportation.

Results and Discussion

Grain Size Distribution

In general, the sediment distribution is largely dependent on the efficiency of transportation processes. When the energy of transportation medium is high (low), it helps in withdrawal (addition) of finer sediments from (to) a sediment bed. The percentage distributions of sediment type based on mean grain size (Φ) at the sixteen selected stations are presented in Table-1. It is observed that the sediment composition at station-1 is different from other stations with maximum percentage (45%) of very fine sands. Also, the percentage of very coarse silt (7%) is highest in station-1. The nature of sediment composition is linked to its position near the inlet (Figure 1). It is a sheltered environment and favours deposition.

Stations 2 and 3 are on the north of the inlet, while station 4 and 5 are on the south of the inlet and hence exhibit different sediment composition. Compared to south of the inlet, stronger hydrodynamic conditions exist at the north of the inlet and hence the geomorphological changes on the north and south of the inlet are quite different[37]. The study showed that during 2008-2010, the inlet has migrated 919 m northward and the southern side of the inlet moved towards the Bay of Bengal, while northern side moved towards the interior of Chilika lagoon. The particular pattern of geomorphological changes clearly indicates the prevalence of erosional environment on the north and depositional environment on the south. Because, the grain size distribution on the north of the inlet

(Station 2 & 3) is dominated by medium sand followed by coarse and fine sand while on the south of the inlet (Station 4 & 5), fine sand dominates followed by medium or coarse sand. Station 6 is located at an approximate distance of 765 m from the inlet mouth (Station 4) and its sediment composition is almost similar to those at station 7 and 8, located within a distance of 1.4 km from Station 6. Dominance of medium sand is observed at Station 6 & 8, while coarse sand dominates at Station 7. Pattern of sediment composition at the Stations 9 to 13 is similar. Mostly percentage of coarse sand is dominant in these stations followed by medium sand. Thus, it is evident that from Station 6 to Station 13 either coarse sand or medium sand dominates, which constitute the major portion of the inlet channel. The flow in this area is restricted to limited width due to the presence of small islands (Figure 1). As a result, the flow in these portions of the inlet channel is relatively stronger, which helps in settling of medium/coarse sediments and removal of finer sediments. On the other hand, the width of the inlet channel from Station 14-16 is relatively wider and hence the flow in this area is relatively weaker, which helps in the settling of fine sand.

Table 1 - Percentage distribution of sediments (station wise)

Station	Coarse Sand (%)	Medium Sand (%)	Fine Sand (%)	Very Fine Sand (%)	Very Coarse Silt (%)
S1	17.5	19.5	11	45	7
S2	39	51	9.5	0.5	0
S3	18.5	69	12.5	0	0
S4	4.5	11.5	75	9	0
S5	29	22	39	9.5	0.5
S6	32	51	13.5	3.5	0
S7	41.5	32.5	23	3	0
S8	8.5	48	42	1.5	0
S9	47.5	49.5	3	0	0
S10	55.5	39.5	5	0	0
S11	57.5	38	4.5	0	0
S12	42	41	15	2	0
S13	51	39	9.5	0.5	0
S14	13	28	55.5	3.5	0
S15	26.9	38.3	30.3	4	0.5
S16	7.5	29	50	11.5	2

Bed Sediment Texture

The textural characteristics of sedimentary environment can be assessed from statistical properties such as mean, standard deviation, skewness and kurtosis, which help to understand the process of deposition and erosion in a sedimentary environment. Besides, information on textural characteristics is helpful in a vicinity of constructional, geotechnical and developmental activities along the coastal regions. Sediment texture and energy conditions associated with the transportation medium have significant influence on sediment deposition/erosion pattern[10,41]. The statistical analysis of bottom sediment (Table 2) indicated that the mean grain size of bottom sediment varies from 0.81 Φ to 2.58 Φ with average value of 1.50 Φ. The highest of mean sediment size (Φ) is observed at S1 while lowest value is observed at S11. Mean grain size of the sediments (Table 2) agrees with percentage distribution and the grouping pattern. The grouping, based on mean grain size, observed for the different stations are; fine at S1, medium at S2 and S3, fine or medium at S4 and S5, medium at S6-S8, coarse at S9-S13 and medium or fine at S14-S16. Sediment sorting observed are mainly of three types; moderately sorted sediments from S10-S16, moderately well sorted sediments at S3-S4 and S8-S9 and poorly sorted sediment at S1, S5 and S7. The variations in the sorting values are likely due to continuous addition of finer/coarser materials in varying proportions [27]. Similar to sorting, skewness are of three types; symmetrical skewed from S10-S16, except at S14 and S15, coarse skewed at S2-S3, S5, S8-S9 and S15 and very coarse skewed at S1 and S14. Skewness variation also indicates both depositional and erosional environment under varying energy conditions. Kurtosis of the sediment indicates predominantly platykurtic to very platykurtic followed by leptokurtic and occasionally mesokurtic. The variation in the kurtosis values is a reflection of flow characteristics in the inlet channel[42]. Grouping pattern which emerge between different sediment characteristics are; fine sediments present at the north of the inlet (S1) are poorly sorted with very coarse skewed and mesokurtic in characteristics. Medium sand mostly present at S2 to S8 and at S14-S15 are predominantly moderately sorted and occasionally MWS or PRS with coarse skewed and leptokurtic characteristics and represent an erosional environment.

On the other hand, coarse sand mostly present at S9 to S13 are either moderately sorted or MWS with symmetrical skewed and platykurtic characteristics and also represent an erosional environment albeit with higher intensity than with medium sand. Bivariate plots of mean grain size with different sediment statistics (Figure 2) also corroborates the grouping pattern mentioned above.

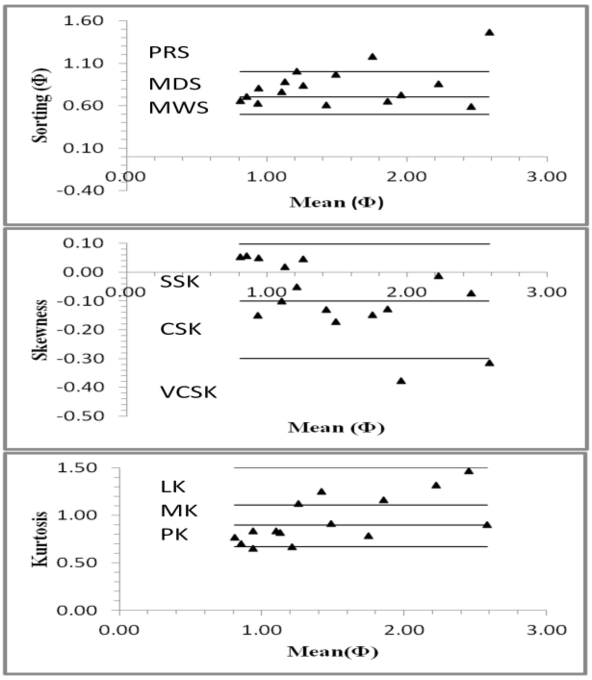

Fig. 2- Bivariate plots of mean *grain size with a)* Sorting b) Skewness c) Kurtosis, where abbreviations are mentioned in Table 2

Table 2 - Bed sediment characteristics (station wise)

Station	Mean(Φ)	Sorting(Φ)	Skewness	Kurtosis
S1	FS	PRS	VCSK	MK
S2	MS	MDS	CSK	PK
S3	MS	MWS	CSK	LK
S4	FS	MWS	SSK	LK
S5	MS	PRS	CSK	PK
S6	MS	MDS	SSK	LK
S7	MS	PRS	SSK	VPK
S8	MS	MWS	CSK	LK
S9	CS	MWS	CSK	PK
S10	CS	MDS	SSK	PK
S11	CS	MWS	SSK	PK
S12	MS	MDS	SSK	PK
S13	CS	MDS	SSK	VPK
S14	MS	MDS	VCSK	VLK
S15	MS	MDS	CSK	MK
S16	FS	MDS	SSK	LK

Note: FS-Fine sand, MS-Medium sand, CS-Coarse Sand, PRS-Poorly sorted, MDS-Moderately Sorted, MWS-Moderately Well Sorted, CSK-Coarse Skewed, VCSK-Very Coarse Skewed, SSK-Symmetrical Skewed, MK-Mesokurtic, PK-Platykurtic, LK-Leptokurtic, VPK-Very Platykurtic, VLK-Very Leptokurtic

From the distribution of grain size and the grain size statistics, it is evident that the bed sediment of the 9.5 km long inlet channel comprises of medium size sediments at two extreme ends and coarse sediments in the middle. Depositional environment with finer sediment at S1 could be due to its location at a sheltered region while at S16, it could be due to low energy environment associated with wider channel width[43]. Further, finer sediment distribution indicating depositional environment at S1 and S16 could be attributed to the spring-neap inversion of tidal asymmetry[44]. While mean grain size and their statistical analysis provide deeper insight on sediment distribution and the depositional/erosion environment, it does not provide sufficient clue on transport processes and the associated energy conditions. In order to have a better understanding of transport processes, we have examined C-M plot.

Transport Process along Inlet Channel

C-M plot (Figure 3) delineates the different transport processes (1-5) prevalent in the inlet channel. CM plot is subdivided into five segments (1-5) representing different transport processes. Corresponding to the five segments, the segments NO, OP, PQ, QR and RS respectively represents rolling, bottom suspension and rolling, graded suspension and no rolling, uniform suspension and pelagic suspension during the transport of sediments[45,46]. CM plot shows that most of the sediment samples occupy positions between NO and OP. The results indicate that the dominant modes of transport processes prevalent in the inlet channel during ebb condition are rolling and bottom suspension. Due to rolling of the sediments, the samples attain coarser size and are moderately well sorted to moderately sorted at the stations S9-S13 and also at S2, S3 and S6. Sediments at S1, S4, S8, S14-S16 are relatively finer in size and either moderately or poorly sorted and are subjected to bottom suspension and rolling. Sediments at S5 and S7 are medium in size with poor sorting and hence are subjected to graded suspension and no rolling. The study reveals that the prime factors for transportation of sediment within the inlet channel of Chilika lagoon are rolling and bottom suspension during the period of low discharge and low rainfall (November-June).

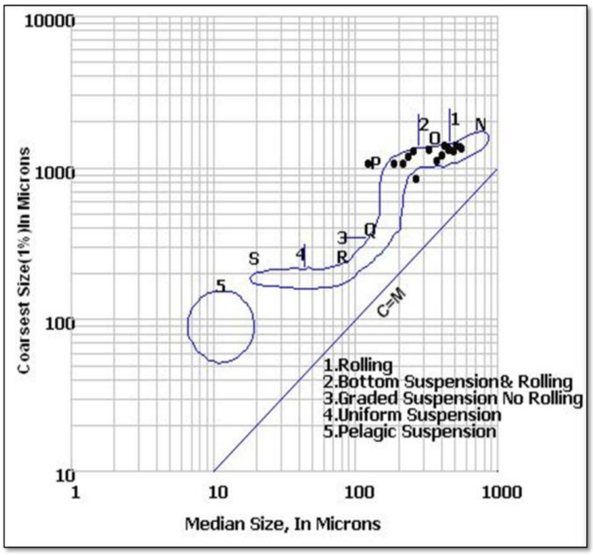

Fig. 3- C-M plot of sediment samples indicating transport processes along the tidal inlet (dots represent the 16 stations through their median and coarsest first percentile grain size.

Conclusion

Sediment samples were collected along the inlet channel of Chilika lagoon during low discharge and low rainfall period**.** Percentage distribution of sediment types based on mean grain size (Φ) indicate that out of the sixteen stations, either coarse or medium sand dominates over 11 stations which constitute the bulk of the inlet channel (S2, S3, S6-S13, S15). In the rest of the stations (S1, S4-S5, S14 and S16) the sediment composition is mostly dominated by fine sand. Bed sediment texture was studied anlysing the sediment statistics such as sorting, skewness and kurtosis. The study reveals definite grouping pattern; fine sediments at the north of the inlet are poorly sorted with very coarse skewed and mesokurtic in characteristics, medium sand representing an erosional environment at S2 to S8 and at S14-S15 are predominantly moderately sorted with coarse skewed and leptokurtic characteristics, and coarse sand mostly present at S9 to S13 are either moderately sorted or moderately well sorted with symmetrical skewed and platykurtic, and also represent an erosional environment albeit with higher intensity than with medium sand. Bivariate plots of mean grain size with different sediment statistics also corroborate the grouping pattern. Prime factors for transportation of sediment within the inlet channel of Chilika lagoon are rolling and bottom suspension during the period of low discharge and low rainfall (November-June). This information is vital while formulating the sediment transport model.

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