



Beach and nearshore sediment textural characteristics of a monsoonal wave–dominated micro-tidal, human perturbed environment, Central East Coast of India

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Abstract

Beach and nearshore depth (4, 5, 7, and 10 m) sediment samples ($n = 111$) collected along a 40-km stretch of monsoonal wave–dominated, micro-tidal, human perturbed, exposed sandy coast in the Central East Coast of India are analyzed for textural characteristics, viz., mean (Φ), sorting (σ), skewness (S_k), and kurtosis (K_G) distribution. The objective of this study was to find the textural behavior from the beach to 10 m depth with different settings of a socio-economic coastal zone. The mean sand grain size varies from medium (1.22 Φ) to very fine (3.44 Φ), having predominantly unimodal oscillations, while sorting values changed from moderately well sorted to moderately sorted. The average of the mean grain size and sorting coefficient increases with increase in depth. Beach samples are symmetrical to fine skewed, dominantly leptokurtic; nearshore samples vary from symmetrical to coarse skewed and leptokurtic to very leptokurtic. The beach sand is transported by bottom suspension rolling, whereas, in the nearshore zone, the graded suspension mode of transport is active. It is concluded that the nearshore sediment is highly diverse in its distribution pattern with different depths, influenced by the variation of longshore drift, wave pattern, river influence, and the ongoing anthropogenic activities in the area. The numerical modeling for sediment transport and grain-size trend analysis confirms the sediment transport direction for the study period. The study concludes that the variation in sediment distribution is due to coastal settings and human interference. This study is beneficial for coastal management and port operations.

Keywords Sediment grain size · Nearshore environment · CM plot · GSTA · ST modeling · East Coast of India

Introduction

Sediment grain size plays a significant role in sediment transport processes; typically considered as a key parameter for the geomorphology by providing clues on sediment provenance, transport history, depositional conditions (Friedman, 1961; Masselink et al. 2008; Trindade and Ramos-Pereira,

2009; Dora et al. 2012, 2014; Lluís et al. 2011). Changes in sedimentary environments along the beaches and nearshore region are controlled by both natural and anthropogenic causative factors, i.e., cataclysmic events, local hydrodynamics, fluvial sand supply, sand mining, coastal constructions, beach nourishments, human settlements, and tourism. However, the continuous interplay of wind, waves, tides, and currents keeps the sand particles of the beach and nearshore zones in an incessant state of mobility; consequently, it alters the nearshore geomorphology and sediment characteristics and the distribution pattern in both cross-shore and long-shore directions (Komar 1976). In addition to natural causes, anthropogenic perturbations such as port construction, dunes mining, and river damming substantially affect the beach morphology, nearshore depth profiles, and sediment textural characteristics.

Total sediment load per year through the major river system from the Indian peninsula to the Bay of Bengal is about 1350 MT, which is ~8% of the total riverine sediment

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supply to the world ocean (Milliman 2001). Most of the annual sediment load entering the Bay of Bengal (BoB) during the southwest monsoon (SWM) period (Singh et al. 2007). The sediment load by the Ganges-Brahmaputra river system into the northern BoB is maximum (1×10^9 t/year) (Curry et al. 2003), while sediments are fed to the bay by several rivers, including the Godavari ($\sim 160 \times 10^6$ t/year), Mahanadi ($\sim 60 \times 10^6$ t/year), and Krishna rivers ($\sim 16 \times 10^6$ t/year); (Ahmad et al. 2009; Tripathy et al. 2011). The small river systems also contribute significant sediment influx to the nearshore region during the huge rainfall during SWM and cyclone (Chandramohan et al. 2001; Kumar et al. 2006). However, the BoB is influenced by the heavy influx of fresh water and sediment, which makes the coastal zone more dynamic. Frequent occurrence of depressions/cyclones and reversal monsoon over the BoB intensifies the sediment dynamics of the beach as well as the nearshore zone (Mishra et al. 2011).

Based on seasonal variation of wind and wave, the beaches along the east coast of India experienced erosion and deposition. Numbers of investigations related to the beach sediment texture were made along the east coast of India and reported, while, there is scanty reporting on nearshore sediment distribution and its transport. Chauhan et al. (1988) analyzed 550 beach sediments along Puri and Konark beaches and concluded that the variation of textural behavior could be used to determine the probable dynamic of the sediment. The sediments along the east coast of India are medium to fine sand, negatively skewed, and the high sand/silt ratio near the fluvial supply is prominent (Chauhan and Chaubey 1989), while they are polymodal, and the degree of polymodality varies spatially along the foreshore (Chakrabarti 1977). The seasonal variation of sediment textural characteristics along the east coast of India for the foreshore and backshore region was reported by Pradhan et al. (2020a). Inner shelf sediment off the Gopalpur region shows two types of depositional environment as beach and dune; and sediments at less than 15-m depths are characterized as dune type while more than 15 m is the beach type (Murty et al. 2007). In an earlier study, the sediment distribution at the inner shelf off Gopalpur is classified into two categories, as the surface sediment at below 15-m depth is dune type, where above 15 m is beach type, and reported the submergence of ancient beach and dune sediments by the holocene transgression (Rao et al. 1989). The surface sediment of the shelf region along Tamilnadu coast was investigated by Monokaran et al. (2014) and reported that the grain size decreased with increasing depth. A number of research have been made to evaluate the sediment transport through numerical modeling along the Indian coast.

In the simplest form, beach is the function of waves and sediment (Short 1999). The sediment size in concurrence with waves produces the longshore transport, which controls

the beach shape, size, and changes. The source of sediment (mostly fluvial), coastal settings (natural or manmade), forcings (oceanographic and meteorology) decide the nearshore sediment distribution pattern and its variation. Apart from these, the sediment textural study helps in evaluating the benthic diversity (Amar and Dattesh 2011), organic matter (Venkatramanan et al. 2010), and recently, micro-plastic interaction. Hence, the purpose of this paper is to examine the sediment characteristics, distribution, and transport pattern in the littoral and nearshore environment along a stretch of micro-tidal, wave-dominated exposed sandy coast located in the central east coast of India concerning the natural and ongoing man-made perturbations in the region. The study illustrates the impact of coastal features and depths on sediment distributions, which may help Gopalpur Port authorities to prepare better management strategies of sediment erosion, accretion of the navigational channel, and its peripheral.

Study area

The study area extends 30 km from Gopalpur lighthouse on the south ($19^\circ 14' 0''$ N $84^\circ 52' 0''$ E) to Kantiagada village on the north (to $19^\circ 25' 0''$ N $85^\circ 09' 0''$ E) in the north along south Odisha coast, India (Fig. 1). The study area is primarily depositional in nature backed by parallel ridges of the dune (~ 12 -m height), rich in six rare earth minerals: ilmenite, rutile, zircon, monazite sillimanite, and garnet. The study area has a unique importance in terms of socio-economic and ecology. The study area is well known for the nesting site of sea turtle (*Olive ridley*) at Rushikulya, Gopalpur Port near Aarjipalli with several groins, rare earth mineral mining by Indian Rare Earth Limited, tourism, fishing, and aquaculture activities along the coast.

The nearshore region of the study area is experienced by erosion/accretion along with the interaction of man-made construction and fluvial. The coastline orientation is 48° E to true north, which has significant interaction with the annual reversal wind and wave, which results from an effective sediment transport along the coast (Mishra et al. 2014). The study area setting has a significant variation with different geomorphological characteristics is represented in Table 1. The bathymetry is represented by cross-shore profiles at other regions (Fig. 2). The sediment properties are effective on the nearshore bottom topography and vice-versa. The sediments along the study area are continuously interacting with the high energy waves and mostly semidiurnal micro-tide and seasonal reversal current pattern, which makes transport alongshore as well as onshore and offshore movement.

The coastal process is responsible for sediment transport along the nearshore region, including the beach.

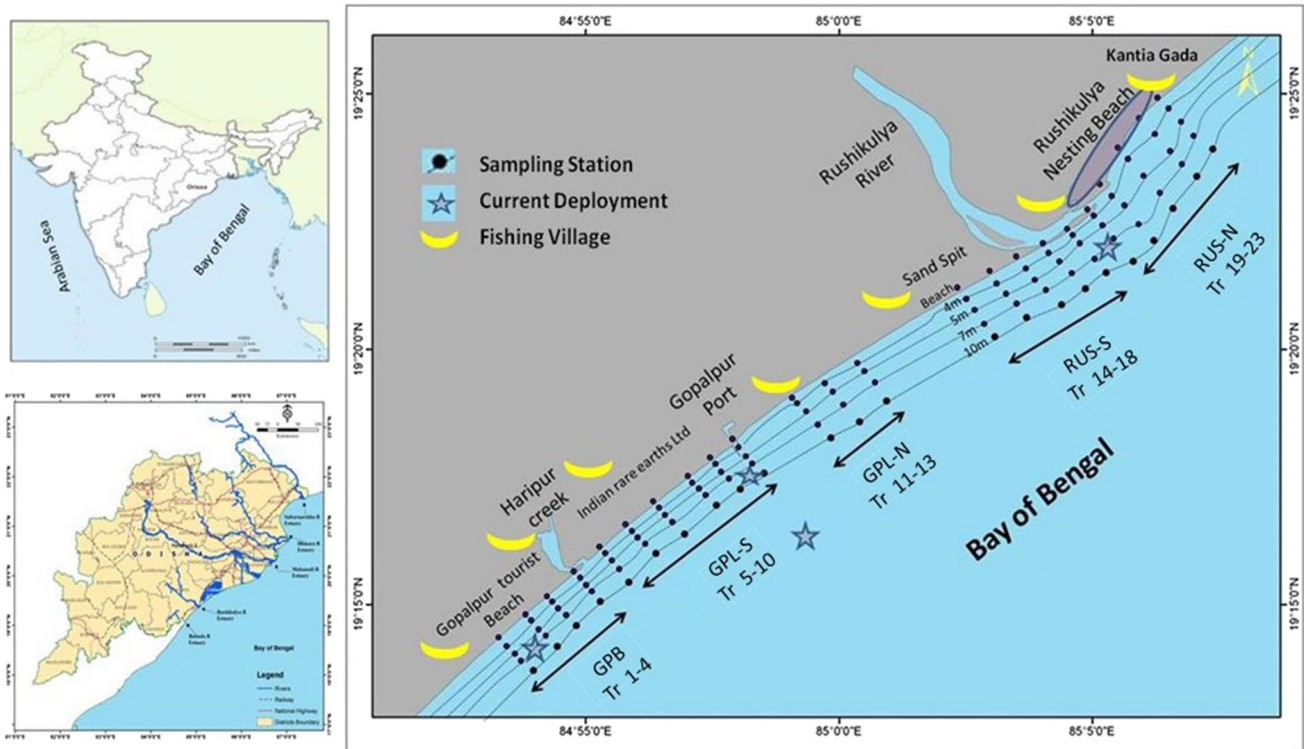


Fig. 1 Study area map showing locations of sediment, TSS sampling, and current meter deployments

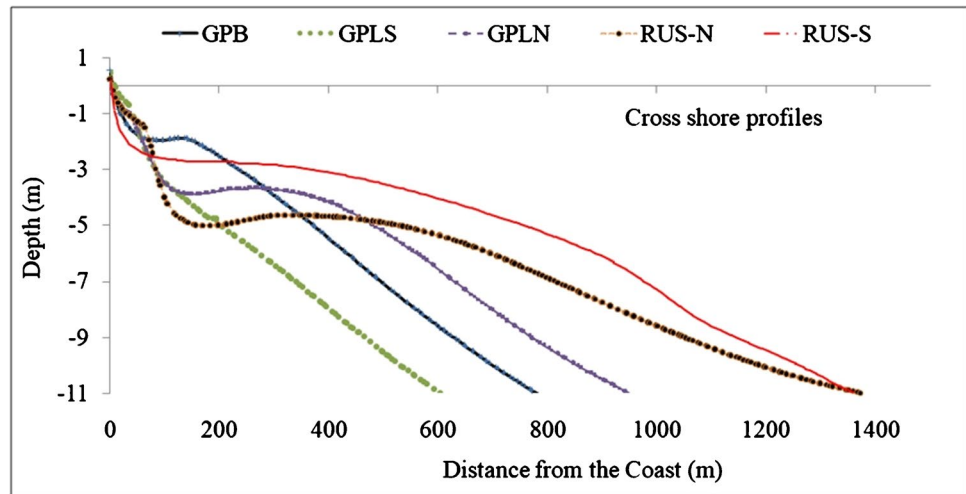
Table 1 Description of the study region and characteristics of the beach

Region	Transects	Description of the area	Beach slope (by RTK)	General characteristics of the beach
GPB	Tr-1 to 4	Gopalpur tourist beach	1:6	It is a recycling beach influenced by a seasonal creek, has a steeper foreshore, and the beach width varies from 25 to 50 m
GPL-S	Tr-5 to 10	South of Gopalpur Port	1:42	Accretion beach due to south groin of the port, backed by parallel sand dunes, and a wider beach length varying 150 to 240 m
GPL-N	Tr-11 to 13	Gopalpur Port north	1:3.5	This is eroding beach due to the north groin of the port, has steeper foreshore, backed by parallel sand dunes, and beach width varies from 15 to 35 m
RUS-S	Tr-14 to 18	Rushikulya River south (sand spit)	1:6	It is a recycling beach with growing sand spit, backed by parallel sand dunes, and beach width varies between 60 and 150 m
RUS-N	Tr-19 to 23	Rushikulya River north (nesting beach)	1:11	Eroding beach due to growth of sand spit, backed by parallel sand dunes, and beach width varies from 25 to 85 m

The coast is identified as wave-dominated with active longshore sediment transport. The coast is micro-tidal (within 2 m), semi-diurnal in nature, and predominated by the semi-diurnal constituents of lunar (M_2) followed by solar (S_2) (Pradhan et al. 2020a, 2020b; Mishra et al. 2014). Along the coast, sediment transportation is mostly through longshore current and annually reversal in nature (Kumar et al. 2006; Chandramohan and Nayak 1991). The annual variation of longshore transport is due to changes in wind and wave regime, as it is southerly during the

northeast monsoon (November to February) while it is northerly the rest of the time. Based on significant wave heights and energy distribution, the wave climate along this coast is grouped into four wave energy categories, i.e., high (H_s : 1.49 m and E_{max} : 2.56 m²/Hz) from June to September; moderate (H_s : 1.09 m and E_{max} : 1.24 m²/Hz) during March to May; low (H_s : 0.88 m and E_{max} : 1.26 m²/Hz) during October and November; very low (H_s : 0.53 m and E_{max} : 0.40 m²/Hz) from December to January (Mishra et al. 2011; Patra et al. 2016).

Fig. 2 Cross-shore profile for different locations



Materials and methods

The study area is classified into five regions based on physiographic settings (Table 1). The grain size analysis and statistics and their distributions are used to interpret sediment movement. The sediment texture data is used to compute the grain size trend analysis using GSTA software (Poizot et al. 2008, 2013), showing the sediment transport pathway up to 10-m depth. One hundred eleven (111) sediment samples were collected from 23 transects from the nearshore at varying depths during December 2008 (Fig. 1). Samples from the swash region are considered as 0 m, and the remaining samples were collected from varying depths (4 m, 5 m, 7 m, and 10 m) using a Van Veen grab sampler. Water samples are collected for total suspended solid (TSS) estimation.

Sediment samples were washed thoroughly with Milli Q water, subjected to 10% of acid wash (HCl) to remove the carbonates, and dried overnight at 70 to 80 °C. About 100 g of dried sediment sample is sieved at $1/2 \Phi$ (mesh size: 63, 90, 125, 180, 250, 355, 500 μm) interval using an automated sieve shaker (RESTEC-AS 200) and A.S.T.M. of 20-cm diameter sieves for 10 min. The logarithmic Udden-Wentworth grade scale (Udden 1914; Wentworth 1922) is used for sediment classification. The grain size of sediment is measured by Φ (phi) scale with the logarithmic expression here as $\Phi = -\log_2 D$, where D is the grain diameter (mm). The statistical parameters such as central tendency (mean), standard deviation (sorting), skewness, and kurtosis are enumerated (Folk and Ward 1957) and computed using GRADISTAT (Blott and Pye 2001).

The mean size of the sediment is a major statistical parameter and mathematically represented as $M = \frac{\Phi_{16} + \Phi_{50} + \Phi_{84}}{3}$. Shorting defines as the square root of the average of the squares of deviations about the mean of a set of data and mathematically expressed as $\sigma = \frac{\Phi_{84} - \Phi_{16}}{4} + \frac{\Phi_{95} - \Phi_5}{6.6}$. The smaller values indicate better sorting of sediment originated from different sources.

Skewness (S_k) describes the deviation of sediment distributions from the symmetry, either positive or negative skewed. The positive skewness characterizes the deposition, and negative skewness is the influence of the cyclic current pattern, indicative of the high energetic erosion environment. The skewness is calculated using the standard formula as $S_k = \frac{\Phi_{16} + \Phi_{84} - 2\Phi_{50}}{2(\Phi_{84} + \Phi_{16})} + \frac{\Phi_5 + \Phi_{95} - 2\Phi_{50}}{2(\Phi_{95} + \Phi_5)}$. Kurtosis (K_G) measures the degree of concentration of the grains relative to the average, whether they are peaked or flat relative to the normal distribution. Kurtosis is not a sensitive parameter to find out the deposition and erosion conditions of the sedimentary environment (Friedman 1961). However, it provides information about the quality, state, and condition of peakedness or flatness of the graphic representation of a statistical distribution. Mathematically, it is expressed as $K_G = \frac{\Phi_{95} - \Phi_5}{2.44(\Phi_{75} - \Phi_{25})}$. Sediment trend analysis (STA) is performed by GSTA software following Poizot et al. (2008).

The depth-averaged coastal current data is collected by deploying RCM-9, AANDERAA make current meters at 3 locations within 7 to 8 m water depths (Fig. 1). The beach profile data was measured using Leica make RTK GPS, and nearshore bathymetry is collected using ODUM make eco sounder, engaging a fishing trawler. The cross-shore profiles at selected transects are prepared from the corrected beach profile and nearshore bathymetry data. The average suspended sediment concentration (SSC) is estimated by filtering 1 L water sample using Millipore membrane filter paper (0.45 μm). The amount of sediment retained in the filter paper is dry weighed and expressed as mg/L.

Sediment grain size trend analysis (GSTA) is a widely used coastal management tool which determines the net sediment transport pathways. The present work follows the workflow of Poizot and Mear (2008, 2010) to evaluate the sediment trend analysis for the nearshore region along the south Odisha coast. The statistical parameters of

sediment texture (mean, sorting, and skewness) are used in the grain size trend analysis (McLaren 1981; Poizot and Méar, 2008). Freely available GiSedTrend (http://www.geoceano.fr/accueil/la_recherche/item_1_/gisedtrend), a plug-in of QGIS (Quantum GIS Development Team 2012) geographical information system software is used for evaluating the sediment pathway. Mainly three steps are followed to make sediment trend analysis such as (1) generation of a regular grid, (2) choice of a characteristics distance, and (3) choice of trend cases (Poizot et al. 2013). Present sediment trend analysis was set up with regular grids of each statistical parameter in the original grid; characteristic distance is defined by the neighboring observations and mostly occurring trend along the study region.

A two-dimensional depth-averaged numerical model of sediment transport was used to estimate the sediment transport rate and the direction. The details of the numerical model for hydrodynamic, wave, and sediment transport were as followed by Mishra et al. (2014). The sediment transport direction evaluated from the sediment grain size trend analysis (GSTA) and numerical model is verified with available literature for this area.

Results

Cross-shore profiles representing five distinct physiographic zones, i.e., the non-disturbing environment at the normal beach (GPB), depositional environment at the south side of the Gopalpur Port (GPL-S), active erosion environment at the north side of Gopalpur Port (GPL-N), and sand spit growth due to alongshore sediment entrapment and shifting of inlet towards the north at the south of Rushikulya River (RUS-S) and, North of Rushikulya River inlet, identified as highly eroding and direct fluvial sand supply region (RUS-N) are shown (Fig. 2). The cross-shore profiles are steeper at GPL-S followed by GPB but a quite gentle slope up to 2 m depth, while GPL-N profile is gentle and higher steeper up to 4 m depth. Both profiles at RUS-S and RUS-N are gentle as compared to others as the estuarine effect and indicating the depositional environment at nearshore region.

The current speed and direction during the study period at 8-m water depth off Gopalpur beach, south of the port, south of the Rushikulya River and 18-m depth off the port is given in Table 2. The measured average current speed is higher (22.6 cm/s) at GPL-18, and minimum at GPL-8 (11.7 cm/s) during the study period, while the current direction is predominantly south-westerly and parallel to the shore.

TSS concentration

Total suspended solids (TSS in mg/L) distribute the finer sediment in the nearshore region (Aagaard and Hughes 2006) and depend upon the coastal currents, physiographical setting, artificial constructions, and modifications in the coastal front and, more importantly, the quantity brought by fluvial supply. The TSS concentrations at different depths (4, 7, and 10 m) ranged from 3.8 to 7.2 mg/L along GPB and GPL-S, while significant changes were observed in the northern part of the study area (Fig. 3). TSS concentration near the river mouth is almost 2 to 3 times higher at the nearshore region of Rushikulya River inlet region than the undisturbed Gopalpur area (GPB).

Sand-silt-clay distributions

Usually, in a sandy environment like the present study area, the presence of silt and clay is either too meager or absent. There was a minor variation in the sand percentage distribution, and gradually decreased with depth and the order is beach (99.2 %) > 4 m (98.2 %) > 5 m (98.1 %) > 7 m (97 %) > 10 m (95.7 %) depth. Similarly, the average silt + clay percentage followed an opposite trend, i.e., 10 m (4.3%) > 7 m (3%) > 5 m (1.9 %) > 4 m (1.8%) depth > beach (0.8%). Clay percentage is highest in the region off the sand spit (Tr-17 and Tr-18), south of the Rushikulya estuary. Maximum percentage of silt + clay is observed at Tr-12 and Tr-13 located off the northern side of the port where the coast is under constant phases of erosion frequently and the order is at 10 m (10.5%), 7 m (6.5%), 5 m (6.1%), and 4 m (4.9%) depth. For a better representation of the sand-silt-clay distribution and their contribution in the sedimentary environment, a tri-plot analysis for three major groups as medium, fine, and very fine, is shown (Fig. 4). The beach sediments

Table 2 Current summaries at different locations shown at study map

Locations (depth in m)	Minimum current speed (cm/s)	Maximum current speed (cm/s)	Average current speed (cm/s)	Current direction (deg)
GPB-8 (8 m)	0.3	58.1	15.6	206
GPL-8 (8 m)	0.3	44	11.7	217
GPL-18 (18 m)	0.3	48.7	22.6	208
RUS-S-8 (8 m)	0	70.1	20.7	199

Fig. 3 Total suspended solids (mg/L) concentration for different transects at 4-, 7-, and 10-m depths

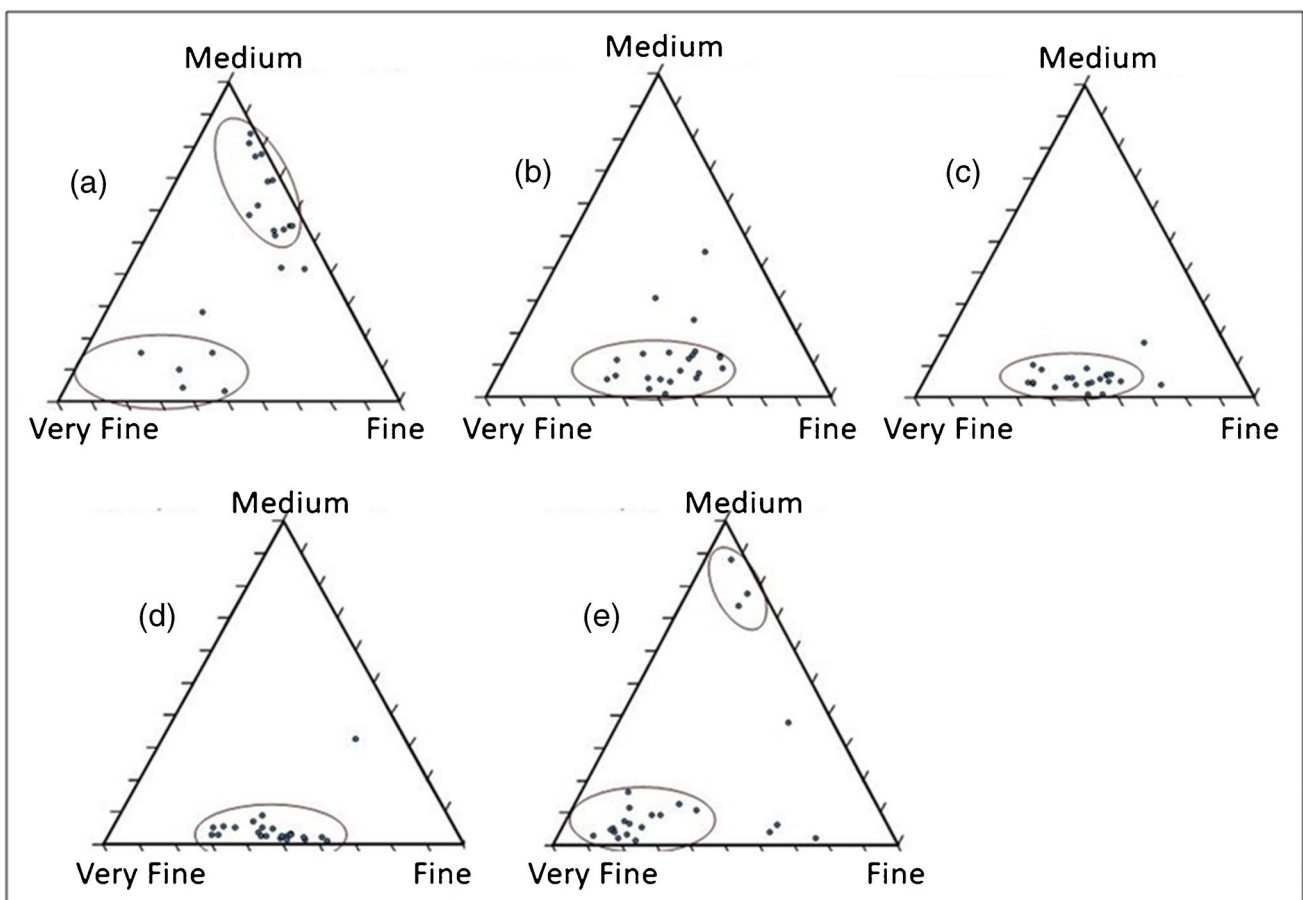
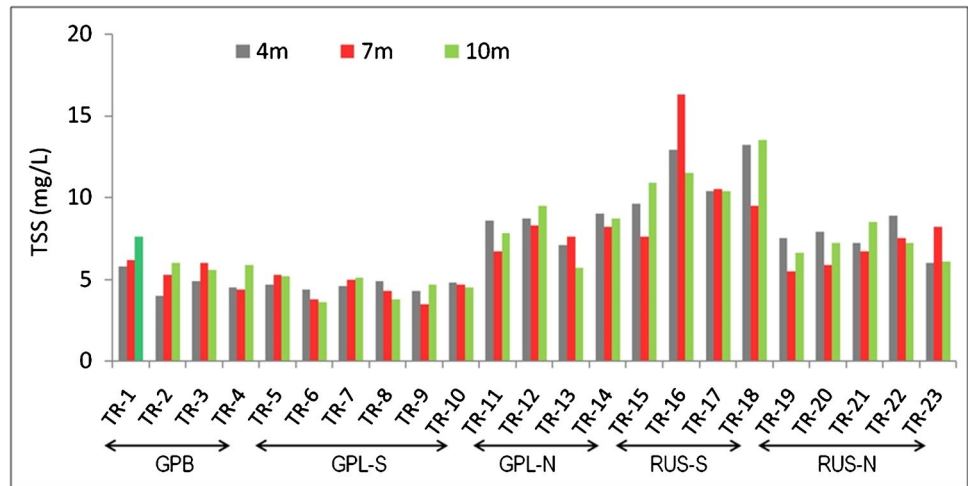


Fig. 4 Sand triplot at different depths (a: beach, b: 4 m, c: 5 m, d: 7 m, and e: 10 m)

fall mostly in two clusters as medium and very fine sands at depositional areas namely south of Rushikulya River, Haripur creek, and south of the Gopalpur groin. Mostly the 4 m and 5 m depth areas of sand are fine and very fine with little variation in distribution. All 7 m depth sediments are unique as between fine and very fine, while sediments at a depth of 10 m are mostly very fine, but some of them are medium and fine.

Textural characteristics

Textural characteristics, such as mean, sorting, skewness, and kurtosis at different depths are described (Fig. 5a–d). The average mean size for a beach station was 2.26 Φ , while it varied from 1.5 Φ at the north of Gopalpur Port to 3.25 Φ at the south of the Rushikulya River. Along the beach stations, sediments are varied from medium to very

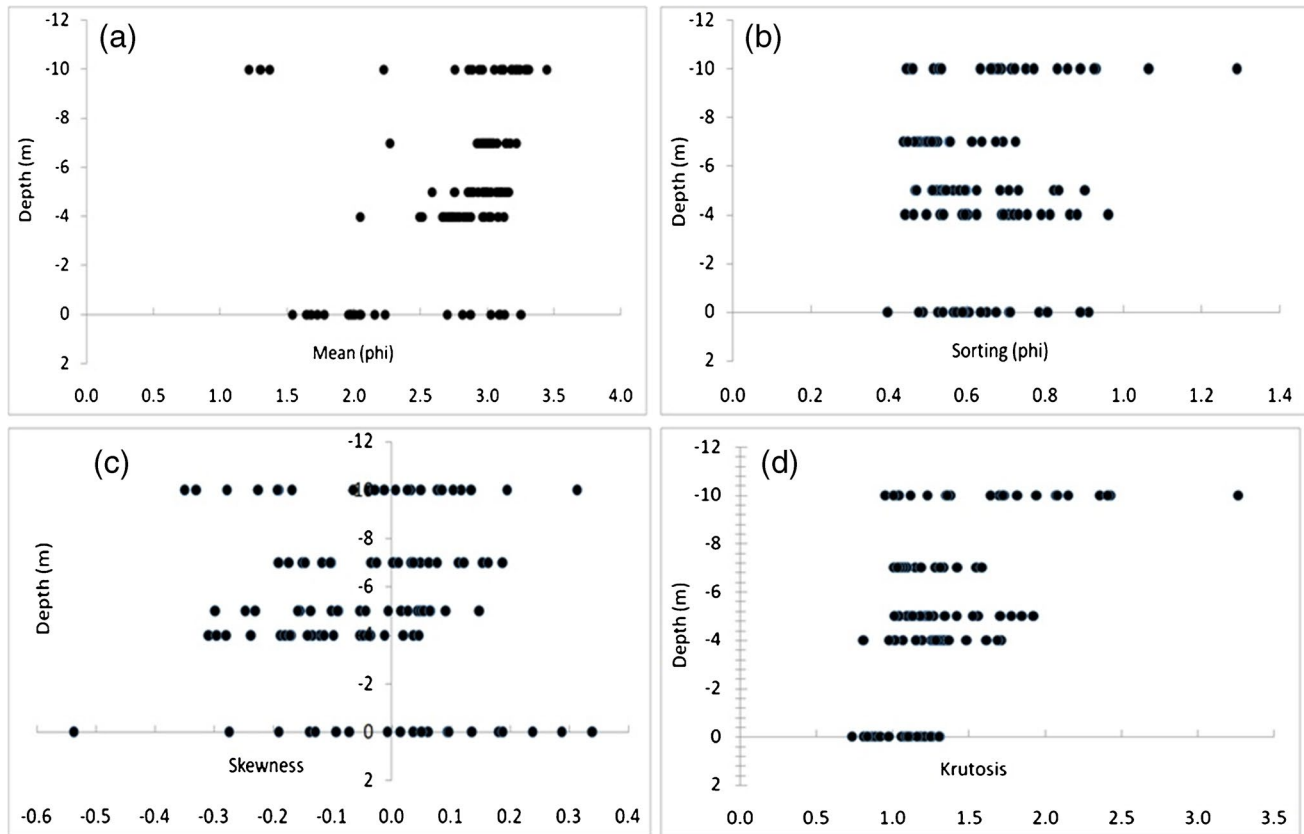


Fig. 5 Textural parameters (a) mean, (b) sorting, (c) skewness, and (d) kurtosis at different depths

fine while they were fine and very fine at all inlets, viz. Rushikulya River, Haripur creek, and south of the Gopalpur Port and medium at the northern part of the port. The beach sediments were found as both unimodal and bimodal nature, which characterized as the beach was mixed in nature during the survey period. The average mean at 4 m depth was 2.8 Φ and minimum (2.05 Φ) at the south of Rushikulya River and maximum (3.12 Φ) at the north of the port (Tr-12). Sediments were unimodal with fine to very fine in nature at 4 m depth. At a depth of 5 m, the average mean size was 2.95 Φ , while it was maximum (3.2 Φ) at port north and minimum (2.6 Φ) at the front of the Rushikulya River inlet due to estuarine circulation. Mostly the sediment at a depth of 5 m, same as the 4 m depth, varies from finer to very finer. The average mean size at a depth of 7 m was 2.93 Φ with a minimum (1.12 Φ) at Kantiagada and maximum (3.2 Φ) at the north of the Rushikulya River. Similarly, at 10 m depth, the average mean size was 2.84 Φ and minimum (1.21 Φ) at the northern part of the port; maximum (3.44 Φ) at the south of the port. Coarser sediments (three samples) were found at 10 m depth near the port region may be occurring due to the port structures.

The average sorting value at beach stations was 0.65 Φ and varied from 0.4 to 0.94 Φ . Beach sediments were mostly moderately well sorted (57%) followed by moderately sorted (29%) and well sorted (14%). The well-sorted sediment was found at the south of the Rushikulya region, which area was reported as a continuous growing sand spit (Pradhan et al. 2015). At a depth of 4 m, the average sorting value was almost the same (0.66 Φ) as beach sediment and varied from 0.44 to 0.96 Φ . Sediments at 4 m were mostly moderately well sorted (45%) followed by moderately sorted (41%), and the rest of the 14% are well sorted. At 5 m depth, average sorting was found as 0.61 Φ and ranged between 0.48 and 0.9 Φ , while they were moderately well sorted (64%) followed by moderately sorted (23%) than well sorted (14%). The south port region (Tr-7, 8, 9) experienced better sorting values as compared to other 5 m stations. Better sorting was found at 7 m depth as their average sorting value was 0.55 Φ , and variation was comparatively narrow (0.44 to 0.85 Φ). At 7 m depth, 57% of the sediments were observed to be moderately well sorted, 39% were well sorted, and the rest was moderately sorted. The average sorting value of 10 m depth sediments was quite higher (0.71 Φ) as compared to other locations and varied from 0.45 to 1.3 Φ . At

10 m depth, sediments were moderately well sorted (44%) followed by moderately sorted (36%), well sorted (12%), and poorly sorted (8%). The poorly sorted sediment was found only at the port north region because of the high erosion of dune by constructing the groins at Gopalpur Port (Mohanty et al. 2012).

In general, the sediment composed with fine sands is positively skewed and that with coarse sands represents negatively skewed. The beach sediments varied from very coarse skewed to very fine skewed, and most of them were symmetrical (43%) followed by fine skewed (33%). The sediments at 4 m depth varied from very coarse skewed to symmetrical. Half of the total sediment samples were found coarse skewed, and the rest were symmetrical (45%) and very coarse skewed (5%). Similarly, the sediments at 5 m depth were found mostly symmetrical (64%), and the remaining were coarse skewed (32%) and fine skewed (5%). Maximum fine skewed (22%) sediments were found at a depth of 7 m counter, whereas they were mostly symmetrical (48%) followed by coarse skewed (30%). Most of the sediments at 5 m and 7 m depth were negatively skewed. Like the beach sediments, the skewness of the sediment at the 10-m depth was a wider range and varied from very coarse skewed to very fine skewed. Most of the sediments were symmetrical (48%), whereas 22% was coarse skewed. The skewness values of the beach and 10-m depths were of similar characteristics.

The beach sediments varied from leptokurtic to platykurtic. Mostly, they were leptokurtic (52%) followed by platykurtic (24%) and mesokurtic (22%) (Table 3). The sediments at a depth of 4 m were ranged from very leptokurtic to platykurtic and dominated by leptokurtic (64%) than mesokurtic (18%) and very leptokurtic (14%), respectively. At 5 m depth, half of the sediment samples were leptokurtic, where 27% were identified as very leptokurtic and 23% as mesokurtic, respectively. It was found as mesokurtic (65%) followed by leptokurtic (26%) at 7 m depth. Similarly, at a depth of 10 m, the sediments were observed mostly very

leptokurtic (52%) and varied from extreme leptokurtic to mesokurtic. The kurtosis value at 7 and 5 m were observed within a narrow range and having unique settings, whereas the sediments in the beach, 4 m, and 10 m depth showed a wider nature (Fig. 5d)

Bivariate plot

The bivariate plots are used to interpret various aspects such as energy conditions, the medium of transportation, deposition of any region (Folk and Ward 1957; Passega 1957), as the textural parameters of the sediment are often environmentally sensitive (Friedman 1961). The bivariate plots of the mean versus sorting (Fig. 6) indicate that sediments along the coast were mainly two clusters, as all the beaches and port regions were mostly medium sand to coarse sand with well sorted to moderately well sorted, while another cluster of sediments at 4 to 10 m depths, and beaches adjacent to inlets (Rushikulya and Haripur creek) were identified as medium sand to very fine sand and well sorted to moderately sorted. The sediment characteristics at 5 and 7 m were similar and close due to the quick settling of similar types of sediments associated with low energy levels just behind the surf zone, as the northeast monsoon period is reported as low wave energy. While at 4 m depth, the sediments were distributed quite widely because of longshore current and wave breaking. The sediments were mostly positively skewed at the beach station and off port region while negatively skewed near the inlets and port region while they were predominantly negatively skewed and symmetrical at all depths (Fig. 7). The positively skewed sediment at the beach indicates the deposition, and similar results were reported for the Gopalpur and Rushikulya for the northeast monsoon period (Mohanty et al. 2011; Pradhan et al. 2020a, b). The symmetrical sediment nearshore shows the uniformity of sediment of a similar source and mode of transport. Along the beach, the sediments varied from very platykurtic to platykurtic

Table 3 Percentages of skewness and kurtosis at different depths

	Type	Beach	4 m	5 m	7 m	10 m
Skewness (% of total collected samples on specific depth)	Very fine skewed	5	0	0	0	4
	Fine skewed	33	0	5	22	17
	Symmetrical	43	45	64	48	48
	Coarse skewed	14	50	32	30	22
	Very coarse skewed	5	5	0	0	9
Kurtosis (% of total collected samples on specific depth)	Very platykurtic	0	0	0	0	0
	Platykurtic	24	5	0	0	0
	Mesokurtic	24	18	23	65	17
	Leptokurtic	52	64	50	26	26
	Very Leptokurtic	0	14	27	9	52
	Extreme Leptokurtic	0	0	0	0	4

while having a wide range variation in the mean size (1.3 to 3.3). The sediments at different depths varied from fine to very fine, whereas the values of kurtosis were wide, from platykurtic (0.8) to very leptokurtic (2.6), which shows the impact of coastal settings and local hydrodynamics

on sediment distribution (Fig. 8). The beach sediments were platykurtic in nature, while nearshore (all depths) sediments were found from mesokurtic to very leptokurtic. Three bivariate plots clarify the beach sediments were different from the nearshore sediments.

Fig. 6 Bivariate plot between mean and sorting at different depths

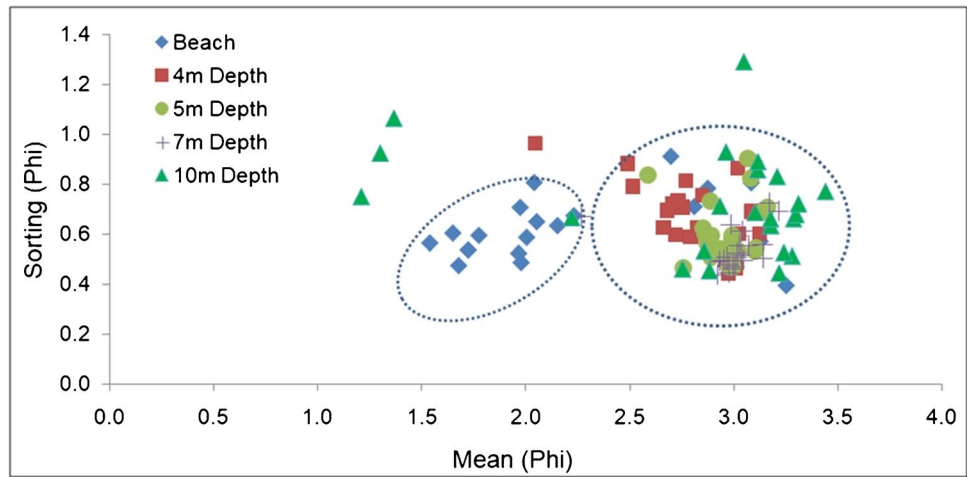


Fig. 7 Bivariate plot between mean and skewness at different depths

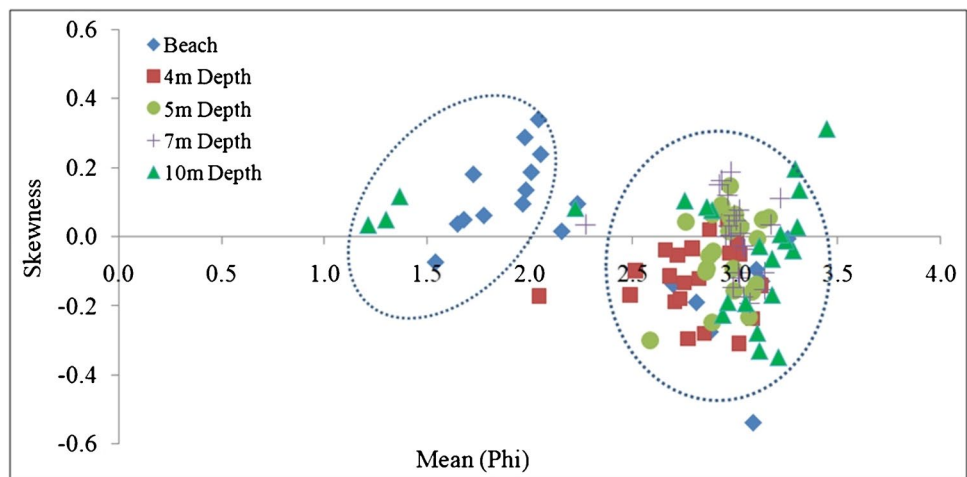
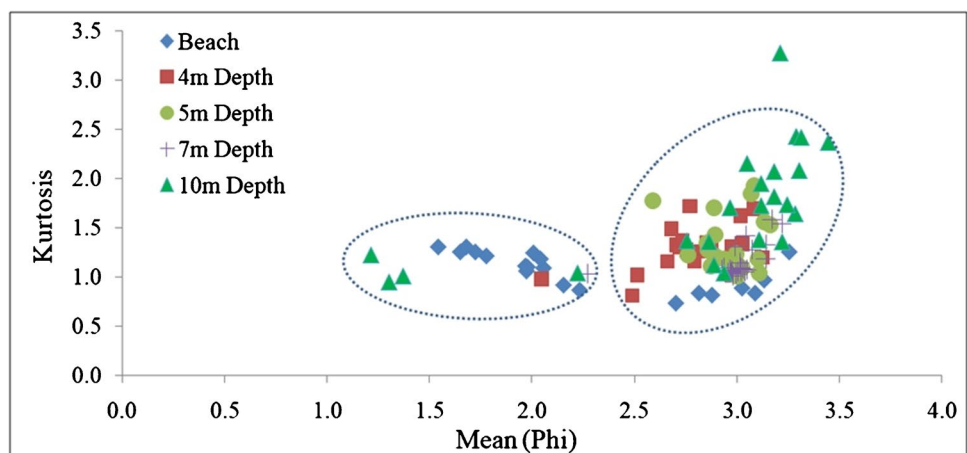


Fig. 8 Bivariate plot between mean and kurtosis at different depths



CM plot

The sediment transport mode depends upon the sediment type, size, source, and environmental forces acting on it. The sediment transport is mainly two modes as defined: rolling and suspension. The CM plot provides information about the sediment types, sources, and mode of transport (Passega 1964). The CM plot is represented by 1% of coarsest (C) and median (d_{50}) of grain size in a logarithmic scale. Earlier, researchers have suggested that the nearshore sediment is more dynamic due to current, wave breaking, fluvial activity, and coastal constructions. The settling velocity plays a major role in nearshore sediment distribution. Figure 9 represents the CM pattern at different depths, which are plotted using GSTA software developed by visual basic programming (Dinesh 2009) followed by Passega (1964).

The beach sediments were moving as both bottom suspension and rolling, whereas near port south and Rushikyla River, both side beaches are followed by graded suspension and no rolling (Fig. 9). Most of the shallow sediments were transported as graded suspension and no rolling, whereas the sediments at the port front at a depth of 10 m were moved by bottom suspension and rolling. The sediments off Rushikyla River and port south were found to have uniform

suspension movement at 7 m and 10 m depths. All sediment sources are identified as tractive current and beach (Passega 1964).

GSTA

Figure 10 depicts the sediment trend for the study area with current rose plots at four locations. It is observed that the sediment transport pathway was southerly as per the current directions. This figure clearly shows two segments as per sampling distribution and identified as port and river regions. The transport pathway on the north side of the river inlet was mostly moved seaward due to tidal flow by the river, while the pathway was southerly on the south part of the river. Similarly, the sediment moves seaward on the north side of the port due to the impact of port structures. Mostly, the transport pathway was southerly in the nearshore region at the southern part of the port, while the beach sediments were landward, clearly indicating depositional environment as the previous researcher suggested during the post-monsoon period along the same region (Mohanty et al. 2012). In the present sediment trend analysis, the sediment transport is agreed with the observed current pattern.

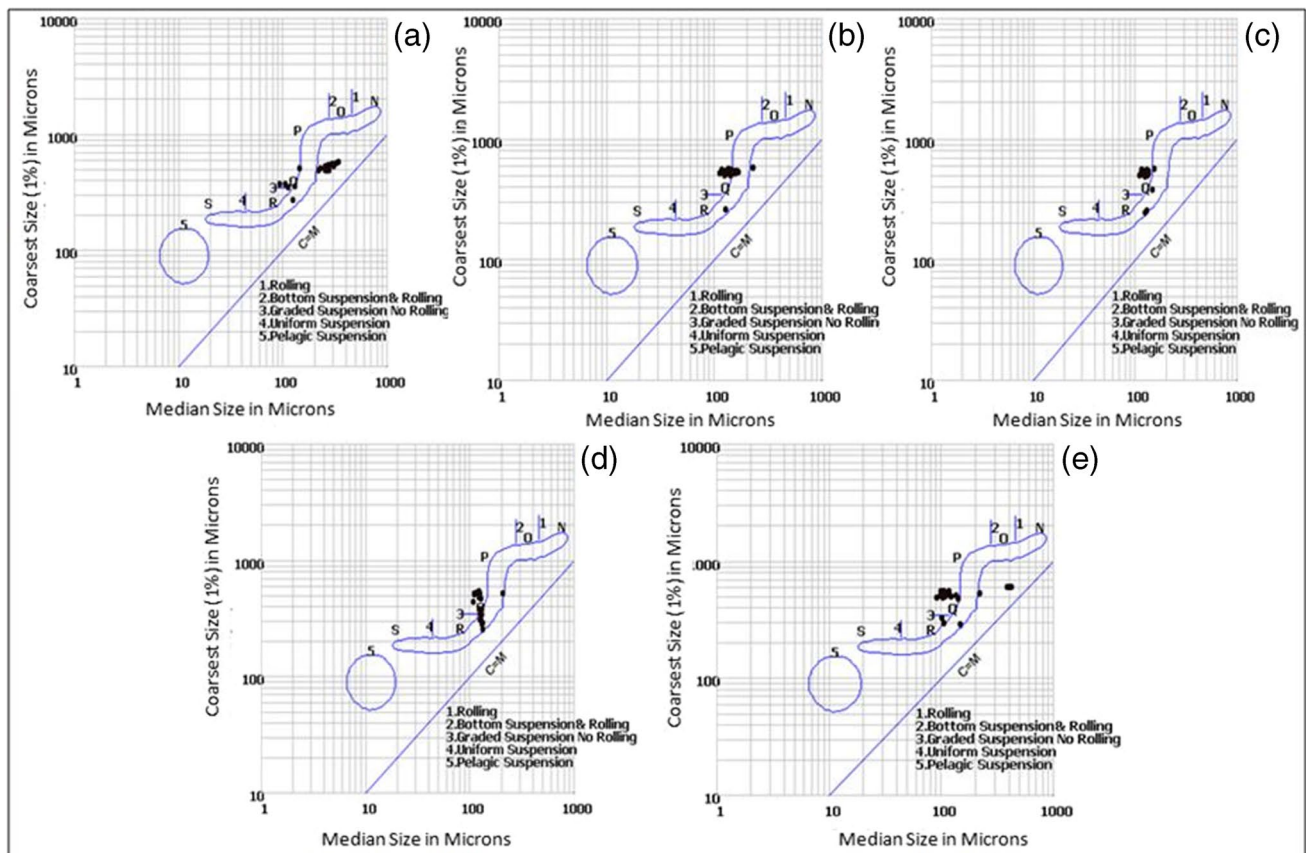
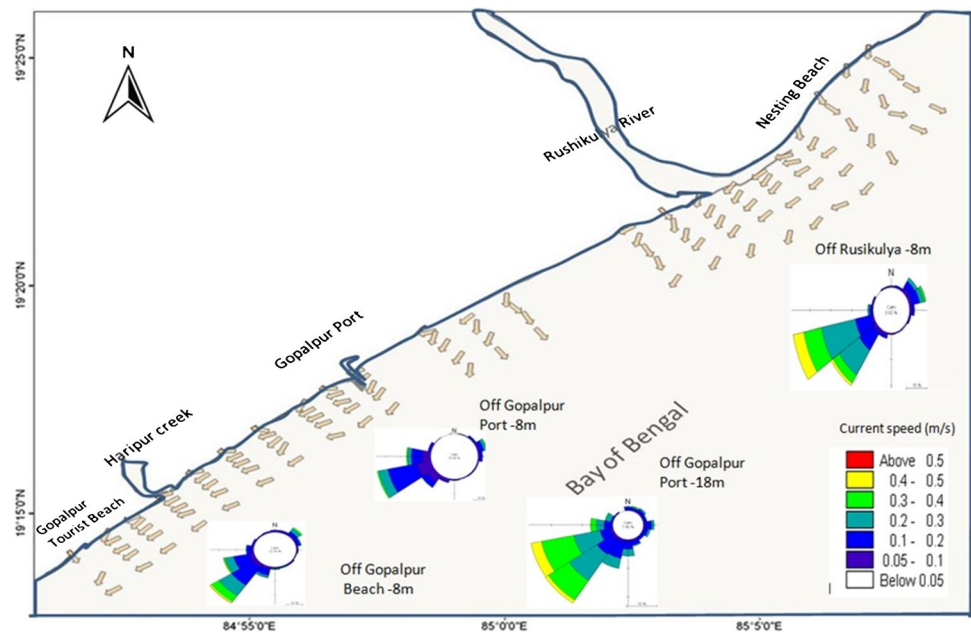


Fig. 9 CM plot for different depth (a: beach, b: 4 m, c: 5 m, d: 7 m, e: 10 m) sediments

Fig. 10 Sediment trend analyses with a current rose plot along the study area



Sediment transport modeling

The sediment transport (ST) model simulates the non-cohesive sediment transport and its directions by using the fluxes and wave radiation stresses resulting from the hydrodynamic and PMS (parabolic mild slope) wave model, respectively. The hydrodynamic (HD) flow module of MIKE 21, DHI was used to simulate the flow fields (tide, current, and fluxes), while surface wave parameters and energy for the same domain were simulated by engaging the MIKE PMS wave model. The PMS wave model works with parabolic approximation to the elliptic mild slope equation, which considers the wave refraction, diffraction, and shoaling with the variation of depths (DHI, 2007). For all simulations (HD, PMS, and ST), the model domain (28 km × 8 km) is set up with a grid resolution of 100 m × 100 m. The observed tide, current, wind, wave, and sediment textural information were used in model simulation and validation. Detailed studies of model set-up, simulation, calibration, and validation for the same model domain and period were discussed in our earlier studies (Mishra et al. 2014). With the discussed model set up (Table 4), the sediment transport modeling was carried out for 16 days during December 2008. The model results show good agreement with the grain size trend analysis, as the sediment moves southerly. Similar studies also reported by earlier researchers that the longshore sediment transport is southerly during the northeast wind pattern along the east coast of India (Chandramohan and Nayak 1990; Mishra et al. 2001; Pradhan et al. 2017). The sediment transport rate for the northeast monsoon period was estimated in terms of X and Y components. The result “Ps” stands for the sediment

transport in X-direction (east-west), while “Qs” stands for the transport in Y-direction (North-south). As the south Odisha coast orientation is 48° with the true north, hence the sediment transport direction is southwesterly, and the transport rate for the Ps varies from -6×10^{-6} to 6×10^{-6} m³/s/m (Fig. 11A), whereas the Qs varies from 0 to -16×10^{-6} m³/s/m; the -ve Qs value stands southerly transport (Fig. 11B). Based on Littoral Environment Observation (LEO) data, the northerly transport (0.96×10^6 m³/year) is observed during the southwest monsoon period and southerly drift (0.26×10^6 m³/year) during the northeast monsoon (Chandramohan and Nayak 1991). Similarly, based on the beach profile data, Mishra et al. (2001) reported that the northerly sediment transport is 1.1×10^6 m³/year, while it is southerly with a magnitude of 0.51×10^6 m³/year during the SWM and NEM, respectively, for the Gopalpur region.

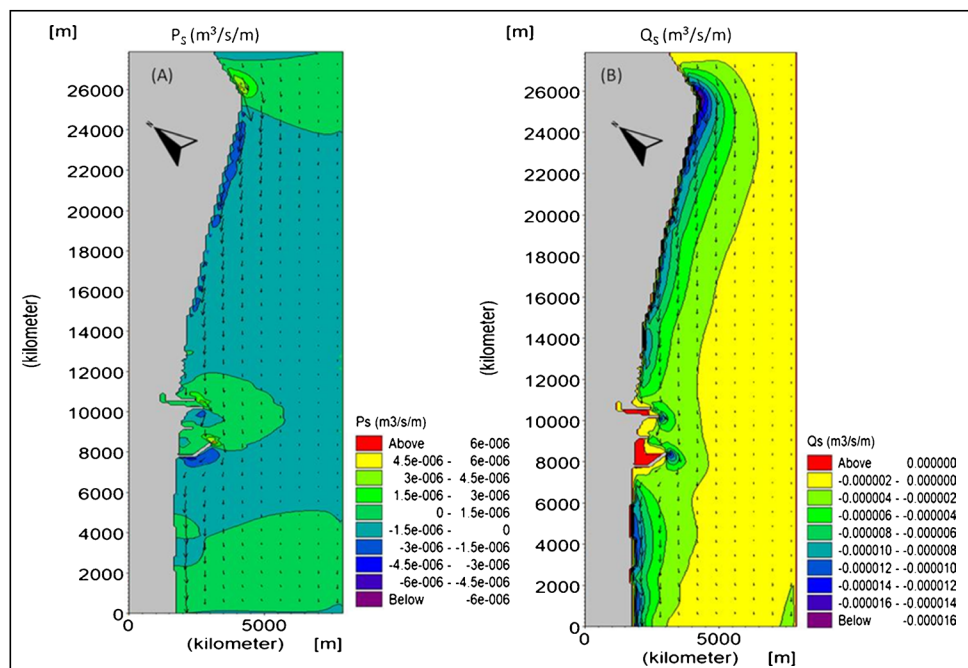
Discussion

Littoral sediment transport plays a major role in the development of certain shoreline features like sand spit and bars and also causes considerable coastal erosion and accretion (King 1975). Three factors are mainly influencing the littoral sediment transport such as (i) nature of the material (sediment) existing in the environment for transport, (ii) coastal setup (orientation, feature, bathymetry), (iii) wave approaching angle (King, 1975; Swift, 1976). As the study area is characterized by micro-tidal, semidiurnal, and in the monsoonal climatic zone, hence waves show the seasonal variation with the wind (Mishra et al. 2014). The wind waves are stronger during the southwest monsoon compared to the northeast monsoon along the study area

Table 4 Details of model type, input, and output information

Types of modeling	Input to model	Output from model
Hydrodynamic (HD)	<ul style="list-style-type: none"> •Basic data: <ul style="list-style-type: none"> Bathymetry Time step and length of the simulation Boundary forcing (tide, wind, and current) •Calibration parameter: <ul style="list-style-type: none"> Initial conditions Boundary data type Friction coefficient (Chezy number = $40 \text{ m}^{1/3}/\text{s}$) Eddy viscosity (0.5) Wind friction coefficient 	<ul style="list-style-type: none"> Sea level changes Current speed Current direction P Flux Q flux
Parabolic mild slope (PMS) wave	<ul style="list-style-type: none"> •Basic data: <ul style="list-style-type: none"> Bathymetry (same used in HD model) Time step and length of the simulation Boundary forcing (tide, wind, and wave) •Calibration parameter: <ul style="list-style-type: none"> Initial conditions Boundary data type Friction coefficient (Chezy number = $40 \text{ m}^{1/3}/\text{s}$) Eddy viscosity (0.5) Wind friction coefficient Wave breaking White capping 	<ul style="list-style-type: none"> Significant wave height Root mean square wave height Wave period Wave direction Wave radiation stresses (S_{xx}, S_{xy}, and S_{yy})
Sediment transport (ST)	<ul style="list-style-type: none"> •Basic data: <ul style="list-style-type: none"> HD output: P and Q fluxes Time step and length of the simulation Forcing Wave output: wave parameters and wave radiation stresses (S_{xx}, S_{xy}, and S_{yy}) Sediment grain size •Calibration parameter: <ul style="list-style-type: none"> Initial conditions Boundary data type 	<ul style="list-style-type: none"> Sediment transport, direction (transport on X and Y direction), bed level changes

Fig. 11 Snapshot of sediment transport modeling; **(a)** P_s and **(b)** Q_s in $\text{m}^3/\text{s}/\text{m}$



(Patra et al. 2016). Sediment dispersal in the coastal region is the cumulative movement of beach and nearshore material by the combined action of coastal oceanography and meteorology forces (Sinha et al. 2021).

The sediment along the littoral zone was observed as unimodal in nature, which describes the nearshore bathymetry slope as gentle. The bimodal beach sediments confirm the multiple sources like dune, fluvial, and transported from adjacent beaches. But, in the present study, the observed cross-shore profile depicts that the nearshore deposition is more at Rushikulya southern part (off the sand spit) due to the trapping of longshore sediment transport and followed by the northern side (off the nesting beach). Pradhan et al. (2020a, 2020b) identified the clockwise eddy formed off the river assumes importance in the development of special geomorphologic features and sustains the sand spit and its northward elongation. Though the estuary is semidiurnal with a tidal range of ≤ 2 m, the flood and ebb current near the estuary and fluvial supplies cause the nearshore deposition off Rushikulya River and causes the availability of finer sediment. Similarly, the cross-shore profile at the northern part of the Gopalpur Port shows nearshore deposition, which may be the heavy erosion on beach and dune due to the construction of groin reported by Mohanty et al. (2012). The profile at the southern side of the port (GPL-S) and Gopalpur beach has no signature of nearshore deposition, while the beaches on the southern side of the port got accretion. This study confirms the construction of the groin, and the influence of the river is prominent on nearshore bathymetry and sediment distribution. The total sediment concentration along the coast is higher-order, where the erosion and accretion were noticed as compared to the other undisturbed region. The littoral zone was mostly sandy in nature, while the mean grain size was varying from medium to very fine at the beach and 10 m depth locations. The textural behavior of the beach and 10 m depth was mostly similar as reported by Murty et al. (2007). The occurrence of medium sand at the beach (foreshore) was due to the removal of fine particles from the intertidal region by swash action and which might be settled behind the breaker zone. The sediments at 4, 5, and 7 m depths are fine to very fine sand as these reside behind the surf zone. During the northeast monsoon, the significant wave height is from 0.26 to 2.18 m with a mean value of 0.71 m (Mishra et al. 2014), so the wave-breaking depth is limited up to 0.63 m. Hence, the sediment is mostly disturbed up to the wave-breaking zone, and beyond this depth, the sediment starts moving onshore-offshore. Thereafter, the finer sediment started settling in the seaward direction, and hence, fine to very fine sediment is observed at the nearshore region. The littoral sediment transport is northward from March to September, and it is southward from October to February along the east coast (Chandramohan and Nayak. 1991; Kumar et al. 2006). Similar results of the

sediment transport are evaluated for the northeast monsoon period by using the grain size trend analysis tool and also numerical modeling of non-cohesive sediment transport.

Conclusion

The study area is sandy in nature, with significant settings of sediments at different depths. The percentage of mud/clay order followed as $10\text{ m} > 7\text{ m} > 5\text{ m} > 4\text{ m} > 0\text{ m}$ (beach). Beach sediments are mostly medium and very fine at Rushikulya south and identified as a depositional sector that is forming northerly growing sand spit. With an increase in depth from 4 m to 10 m, the mean size and sorting value increased. The sediment at a depth of 4 m is unimodal moderately sorted fine sand to well-sorted fine sand, while the sediments at 5 m depth are moderately well-sorted fine sand to moderately sorted very fine sand. While, at 7 m depth, the sediments are well-sorted fine sand to moderately well sorted very fine sand, and at 10 m depth, the sediments are moderately well-sorted fine sand to well-sorted very fine sand. The high suspended matter is observed at off Rushikulya region due to the estuarine circulation. The sediments at the beach were moving by bottom suspension and rolling, but at the estuarine region and all shallow water region, the sediments (4 m, 5 m, 7 m, and 10 m) were through graded suspension and no rolling mode. The beach and nearshore sediments are derived from tractive current and some are from the beach. The present sediment trend analysis and numerical model results are reasonable with the field observations. The sediment transport was southerly while it is seaward at north of the river and port during the study period. The most important result is that the grain size distribution at different depths shows the integrated response of the sediment through morphological settings, fluvial supply, and local hydrodynamics. This type of study is important for the port operations and detection of erosion/accretion of nearshore regions.

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Declarations

Conflict of interest The authors declare no competing interests.

Disclaimer This is extensive work done by the authors during the “Shoreline management Plan for Gopalpur” project tenure.

References

- Aagaard T, Hughes MG (2006) Sediment suspension and turbulence in the swash zone of dissipative beaches. *Mar Geol* 228(1–4):117–135
- Ahmad SM, Padmakumari VM, Babu GA (2009) Strontium and neodymium isotopic compositions in sediments from Godavari, Krishna, and Pennar rivers. *Curr Sci* 97(12):1766–1769
- Amar SM, Dattesh VD (2011) Distribution and Abundance of Macrobenthic Polychaetes along the South Indian Coast. *Environmental Monitoring and Assessment* 178(1–4):423–436. <https://doi.org/10.1007/s10661-010-1701-3>
- Blott SJ, Pye K (2001) GRADISTAT: a grain size distribution and statistics package for the analysis of unconsolidated sediments. *Earth Surf Proc Land* 26(11):1237–1248
- Chakrabarti A (1977) Polymodal composition of beach sands from the east coast of India. *J Sediment Petrol* 47(2):634–641. <https://doi.org/10.1306/212F7202-2B24-11D7-8648000102C1865D>
- Chandramohan P, Nayak BU (1991) Longshore sediment transport along the Indian coast. *Indian Jour Geo-Marine Sci* 20(2):110–114
- Chandramohan P, Jena BK, Kumar VS (2001) Littoral drift sources and sinks along the Indian coast. *Current. Science* 81:292–297
- Chauhan OS, Chaubey AK (1989) Comparative studies of moment, graphic and phi measures of the sands of the East coast beaches, India. *Sediment Geol* 65:183–189
- Chauhan OS, Verma VK, Prasad C (1988) Variations in mean grain size as indicators of beach sediment movement at Puri and Konark beaches, Orissa, India. *J Coastal Res* 4:27–35
- Curray JR, Emmel FJ, Moore DG (2003) The Bengal Fan: morphology, geometry, stratigraphy, history and processes. *Mar Pet Geol* 19:1191–1223. [https://doi.org/10.1016/S0264-8172\(03\)00035-7](https://doi.org/10.1016/S0264-8172(03)00035-7)
- Dinesh AC (2009) GStat- A software for grain size statistical analyses, CM Diagrams and Sediment Trend Maps. International Seminar on Prospects of Marine Sediment as Resource Base for the Growth of Mankind. 5–7 October, 2009, Dept. of Geology, Andhra University, Visakhapatnam. PP.23–25.
- Dora GU, Kumar VS, Johnson G, Philip CS, Vinayaraj P (2012) Short-term observation of beach dynamics using cross-shore profiles and foreshore sediment. *Ocean Coast Manag* 67:101–112
- Dora GU, Kumar VS, Vinayaraj P, Philip CS, Johnson G (2014) Quantitative estimation of sediment erosion and accretion processes in a micro-tidal coast. *Int J Sediment Res* 29(2):218–231
- Folk RL, Ward WC (1957) Brazos River bar: a study in the significance of grain size parameters. *J Sediment Petrol* 27:3–26
- Friedman GM (1961) Distinction between dune, beach and river sands from their textural characteristics. *J Sediment Petrol* 31:514–529
- King CAM (1975) Introduction to marine geology and geomorphology. Engl. Long. Soc. And Edn. Arn, Lond., ix + 309 p.
- Komar PD (1976) Beach processes and sedimentation. Prentice-Hall, New Jersey, pp 1–429
- Kumar VS, Pathak KC, Pednekar P, Raju NSN, Gowthaman R (2006) Coastal processes along the Indian Coastline. *Curr Sci* 91(4):530–536
- Lluis G, Orfila A, Álvarez-Ellacuría A, Tintoré J (2011) Controls on sediment dynamics and medium-term morphological change in a barred microtidal beach (Cala Millor, Mallorca, Western Mediterranean). *Geomorphology* 132:87–98
- Masselink G, Austin M, Tinker J, O'Hare T, Russell P (2008) Cross-shore sediment transport and morphological response on a macrotidal beach with intertidal bar morphology, Truc Vert. *France Mar Geol* 251:141–155
- McLaren P (1981) An interpretation of trends in grain size measures. *J Sediment Petrol* 51(2):611–624
- Milliman JD (2001) River inputs In J. H. Steele, S. A. Thorpe, & K. K. Turekian (Eds.) *Encyclopedia of Ocean Sciences*, pp. 754–761. Academic Press: San Diego
- Mishra P, Patra SK, Ramana Murthy MV, Mohanty PK, Panda US (2011) Interaction of monsoonal wave, current and tide near Gopalpur, east coast of India and their impact on beach profile; a case study. *Nat Hazards* 59(2):1145–1159. <https://doi.org/10.1007/s11069-011-9826-4>
- Mishra P, Pradhan UK, Panda US, Patra SK, Ramana Murthy MV, Seth B, Mohanty PK (2014) Field measurements & numerical modelling of nearshore processes at an open coast port on the east coast of India. *Indian Journal of Geo-Marine Sciences* 43:1277–1285
- Mohanty PK, Patra SK, Bramha S, Seth B, Pradhan U, Behera B, Mishra P, Panda US (2012) Impact of groins on beach morphology: a case study near Gopalpur Port, east coast of India. *J Coast Res* 28(1):132–142
- Monokaran S, Mishra P, Ajmal SK, Lyla PS, Ansari KGMT, Raja S (2014) Textural characteristics of shelf surface sediments of southeast coast of India. *Indian Journal of Geo-Marine Sciences* 43(6):967–976
- Murty TVR, Rao KM, Rao MMM, Lakshminarayana S, Murthy KSR (2007) Sediment-size distribution of innershelf off Gopalpur, Orissa Coast using EOF analysis. *J Geol Soc India* 69(1):133–138 (<http://drs.nio.org/drs/handle/2264/554>)
- Passega R (1957) Texture as a characteristic of clastic deposition. *American Association of Petroleum Geology* 41:1952–1984
- Passega R (1964) Grain size representation by C-M pattern as a geological tool. *J Sediment Petrol* 34:830–847
- Patra SK, Mishra P, Mohanty PK, Pradhan UK, Panda US, Murthy MVR, Sanil Kumar V, Nair TMB (2016) Cyclone and monsoonal wave characteristics of northwestern Bay of Bengal: long-term observation and Modeling. *Nat Hazards* 82:1051–1073. <https://doi.org/10.1007/S11069-016-2233-0>
- Poizot E, Méar Y (2008) ECSedtrend: a new software to improve sediment trend analysis. *Comput Geosci* 34(7):827–837. <https://doi.org/10.1016/j.cageo.2007.05.022>
- Poizot E, Anfuso G, Méar Y, Bellido C (2013) Confirmation of beach accretion by grain-size trend analysis: Camosoto beach, Cádiz. SW Spain *Geo-Marine Letters* 33:263. <https://doi.org/10.1007/s00367-013-0325-3>
- Poizot E, Méar Y (2010) Using a GIS to enhance grain size trend analysis. *Environ Model Softw* 25(4):513–525. <https://doi.org/10.1016/j.envsoft.2009.10.002>
- Poizot E, Méar Y, Biscara L (2008) Sediment trend analysis through the variation of granulometric parameters: a review of theories and applications. *Earth Sci Rev* 86:15–41. <https://doi.org/10.1016/j.jearesc.2007.07.004>
- Pradhan S, Mishra S, Baral R, Samal RN, Mohanty PK (2017) Along-shore sediment transport near tidal inlets of Chilika Lagoon; East Coast of India. *Mar Geodesy* 1–17. <https://doi.org/10.1080/01490419.2017.1299059>
- Pradhan UK, Mishra P, Mohanty PK, Behera B (2015) Formation, growth and variability of sand spit at Rushikulya River mouth, South Odisha coast, India. *Procidia Engineering* 116:963–970. <https://doi.org/10.1016/j.proeng.2015.08.387>
- Pradhan UK, Mishra P, Mohanty PK, Panda US, Ramanamurthy MV (2020a) Modeling of tidal circulation and sediment transport near tropical estuary, East coast of India. *Regional Studies in Marine Science* 37:10135. <https://doi.org/10.1016/j.rsma.2020.101351>
- Pradhan UK, Sahoo RK, Pradhan S, Mohanty PK, Mishra P (2020) Textural analysis of coastal sediments along East Coast of India. *Journal Geological Society Of India* 95(January 2020b):67–74
- Rao M, Rajamanickam KGV, Rao TCS (1989) Holocene marine transgression as interpreted from bathymetry and sand grain size parameters off Gopalpur, East Coast of India. *Proc. Indian Acad. Sci. (Earth Planet Sci)* 98:173–181
- Short AD (1999) *Handbook of beach and shoreface morphodynamics*. John Wiley and Sons, Chichester, p 379p

- Singh M, Singh IB, Müller G (2007) Sediment characteristics and transportation dynamics of the Ganga River. *Geomorphology* 86:144–175. <https://doi.org/10.1016/j.geomorph.2006.08.011>
- Sinha S, Mondal SK, Mondal S, & Patra UK (2021) Sediment characterization and dispersal analysis along a part of the meso- to microtidal coast: a case study from the east coast of India. *Arab J Geosci*, 14(1). doi:<https://doi.org/10.1007/s12517-020-06249-y>.
- Swift DJP, (1976) Coastal sedimentation. In : Marine sediment transport and environmental management, Stanley DJ and Swift DJP (Eds), John Wiley and Sons, New York, pp-255–310.
- Trindade J, Ramos-Pereira A (2009) Sediment textural distribution on beach profile in a rocky coast. (Estremadura - Portugal. *Journal of Coastal Research*, SI-56, pp- 138–142 ISSN 0749–0258
- Tripathy GR, Singh SK, Bhushan R, Ramaswamy V (2011) Sr-Nd isotope composition of the Bay of Bengal sediments: impact of climate on erosion in the Himalaya. *Geochem J* 45:175–186. <https://doi.org/10.2343/geochemj.1.0112>
- Udden JA (1914) Mechanical composition of clastic sediments. *Geol Soc Amer Bull* 25:655–744
- Venkatramanan S, Ramkumar T, Anitha Mary I (2010) Textural characteristics and organic matter distribution patterns in Tirumalairajanar river Estuary, Tamilnadu, east coast of India. *International Journal of Geomatics and Geosciences* 1(3):552–562
- Wentworth CK (1922) A scale of grade and class terms for clastic sediments. *J Geol* 30:377–392