RESEARCH ARTICLE

Sediment distribution and transport pattern in the nearshore region, southeast coast of India

Umakanta Pradhan[1]*, Subrat Naik[1], Pravakar Mishra[1], Uma Sankar Panda[1] and M. V. Ramana Murthy[1]

Abstract

The present paper aimed to assess the sediment distribution pattern, mode of transport, and its interaction with hydrodynamic and topographic conditions at different depths and regions along the east coast of India. About 900 surficial sediment samples were collected and analysed on a monthly basis for the Chennai coastal region at 32 stations from 2013 to 2015. The study region is classified into four types, such as beach, inlet, 5 m, and 10 m depth. Sediment textural and grain size trend analyses were conducted to achieve the objectives. Sediment characteristics for the region were recorded as sandy, equally dominated by unimodal and bimodal at the beach, while unimodal at shallow depths (5 and 15 m). The sediments were medium sand to coarse sand at the beach, mostly fine followed by medium at 5 and 15 m depths. The sediment sorting is dominated by moderately well-sorted sediments; the skewness of beach sediments was negative, while nearshore sediments were found positive; average kurtosis values of sediments were noticed to be mesokurtic. The CM plot depicts that the sediments were mostly derived by tractive current, and the modes of transport are "bottom suspension and rolling" and "graded suspension no rolling" at beach locations and shallow water depths, respectively. The GSTA analysis reveals the annual average sediment transport pattern is northerly. The numerical hydrodynamic study confirms the GSTA and CM plot analysis. The study reveals a stable sedimentary environment south of the Chennai port and instability in the northern part. The study includes large spatiotemporal nearshore sediment data with hydrodynamic conditions, immensely helpful to coastal stakeholders and researchers.

Keywords Sediment texture, Hydrodynamic modelling, Transport pattern, CM plot, GSTA, East coast of India

1 Introduction

Beach and near-shore sediments are more dynamic due to natural and human interference with the processes of erosion, accretion, and transportation. Grain size information is essential to understanding the sedimentary environment, which is the most fundamental property of sediment particles, affecting their entrainment, transport, and deposition. The grain size analysis provides important clues to the sediment provenance, transport history, and depositional conditions (Folk and Ward 1957; Friedman 1961; Bui et al. 1990). The sedimentary environments and their variation are controlled by the interaction between sediment availability and existing hydrodynamic processes by wave, tide, and current (Inman and Bagnold 1963; King 1975; Komar 1976), bottom morphology (Nichols and Biggs 1985), fluvial supplement (Millman and Made 1983; Carlin et al. 2019) and, more recently, by human intervention through sand mining, human settlement/tourism, and coastal construction. The sediment transport along the coast is highly complex and follows nonlinearity due to estuary/inlet, variation in nearshore slope, coastal orientation, existing hydrodynamics, groin, breakwater, sea wall, beach nourishment, and sand miming along the nearshore region. As a result, these sediments are composed of various sizes and

*Correspondence:
Umakanta Pradhan
uma22pradhan@gmail.com
[1] National Centre for Coastal Research, Ministry of Earth Sciences, NIOT Campus, Pallikaranai, Chennai 600100, India

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shapes, which are in a wide range of variations form of very coarser sand to clay and often rocky beds.

Several studies have been done along the Indian coast to evaluate the sediment distribution with beach profiles, whereas limited studies have been reported for the nearshore region. Along the east coast of India, the textural analysis and composition of beach sand were carried out (Chakrabarti 1977; Chauhan and Chaubey 1989; Pradhan et al. 2020), and sediment distributions and their seasonality variation were well studied along the Odisha coast (Chauhan et al. 1988; Chauhan and Chaubey 1989; Mishra 1992; Mohanty et al. 2012) similarly, for the Andhra Pradesh coast (Reddy and Prasad 1997) and Tamilnadu coast (Angusamy and Rajamanicikam 2006; Solai et al. 2013). Sediment textural studies for beaches and nearshore regions along the west coast of India were extensively conducted (Chaudhri et al. 1981; Nayak 1996; Dora et al. 2011, 2012; Narayana et al. 2008). The inner-shelf sediment for Gopalpur was studied by Murty et al. (2007), who found that dune-type sediments are at 15 m depth or below, while beach-type sediments are more than 15 m depth. Veerasingam et al. (2014) studied the Chennai nearshore clay mineral distribution, while the textural characteristics of nearshore sediment along Tamil Nadu were studied by Monokaran et al. (2014) through single-time observation. There is a dearth of studies on the sediment texture along the Chennai coast and also not been extensively studied in terms of temporal and spatial scale along the Indian coast. However, in the present study, the sediment texture analysis ($n = 900$) has been made with association of hydrodynamics modelling to understand the sedimentary environment, and its transport pattern.

Grain size trend analysis (GSTA) is a fundamental tool for determining the origin and history of sediment particles as well as the conditions of transport and deposition (Mc Laren 1981; McLaren and Teear 2014; McLaren et al. 2007; McCave and Syvitski 1991). Mc Laren (1981) was the first person to describe sediment trend analysis (STA) as a way to figure out the net path of sediment movement on the sea floor by using statistical measures of sediment texture, such as mean, sorting, and skewness (Mc Laren 1981; Gao and Collins 1992; Poizot et al. 2008). McLaren and Powys (1993), McLaren et al. (2007), and Mc Laren and Little (1987) conducted extensive research on the one-dimensional STA at the beginning. Gao and Collins (1991) modified McLaren's STA approach to allow for two-dimensional study, and many researchers used it as a result. In shallow marine environments around the world, the GSTA is used to study the movement of sediment. It is used in deltaic areas (Duc et al. 2007), estuaries (Mallet et al. 2000; Duc et al. 2016; Li and Li 2018),

beaches (Poizot et al. 2013; Liu et al. 2017), continental shelves and nearshore areas (Gao et al. 1994; Cheng et al. 2004; Duman et al. 2006; Liang et al. 2020; Wang et al. 2022), and lagoons (Gao and Collins 1992; Avramidis et al. 2008). In the nearshore regions, multiple sources of sediment are supplied, whereas in the urban coastal region, the sediments are more dynamic and the variability is greater.

The sediment grain size information is of utmost importance for understanding the sediment transport, and sedimentary environment, while spatiotemporal sediment grain size data provides the variation in sedimentary environment and its interaction with different geomorphic settings. Hence, the present study investigates the spatiotemporal sediment distributions, their variation, and sediment transport behavior along the Chennai nearshore region. The information sought in this study is immensely helpful further for the numerical modelling of sediment transport, port activity like dredging and dumping of sediment, maintaining the inlet opening, and understanding the erosion and accretion of the beach as well as the sea bed.

2 Study area

The Chennai coast is a wave-dominated sandy beach situated on the western boundary of the Bay of Bengal, which is influenced by seasonal reversal wind and current (Fig. 1). The study area has a humid and subtropical climate. The maximum temperature in this area for summer (April to May) varies from 35 °C to 42 °C, and the minimum temperature in winter (December to January) ranges from 20 °C to 34 °C, or about 20 °C. The annual rainfall is about 1250 mm, and the average relative humidity varies from a maximum of 84% in December to a minimum of 58% in May. Chennai metropolitan city is the fifth largest city in India, with a population of 8.24 million according to the 2011 census (Santhiya et al. 2011). Two rivers, viz., Cooum and Adyar, flow cress-crossing the city, carrying the major share of domestic sewage and urban effluents into the coastal water. On the northern extreme, Ennore Creek acts as a major effluent transporter, whereas on the southern end, the backwaters at Muttukudu connecting to the sea are used for recreational boating and surfing activities. Further, activities at Chennai and Ennore ports and fishing harbours, waste discharges from the thermal power plant, leather ternaries, and petroleum and tyre industries impoverish the adjacent coastal water. Three beaches, viz., Marina, Elliot, and Kottivakam (Thiruvanmiyur), act as major weekend resort destinations and fishing activities. The coast is characterised by the semidiurnal tide of a maximum ~ 1.2 m tidal prism. The average significant wave
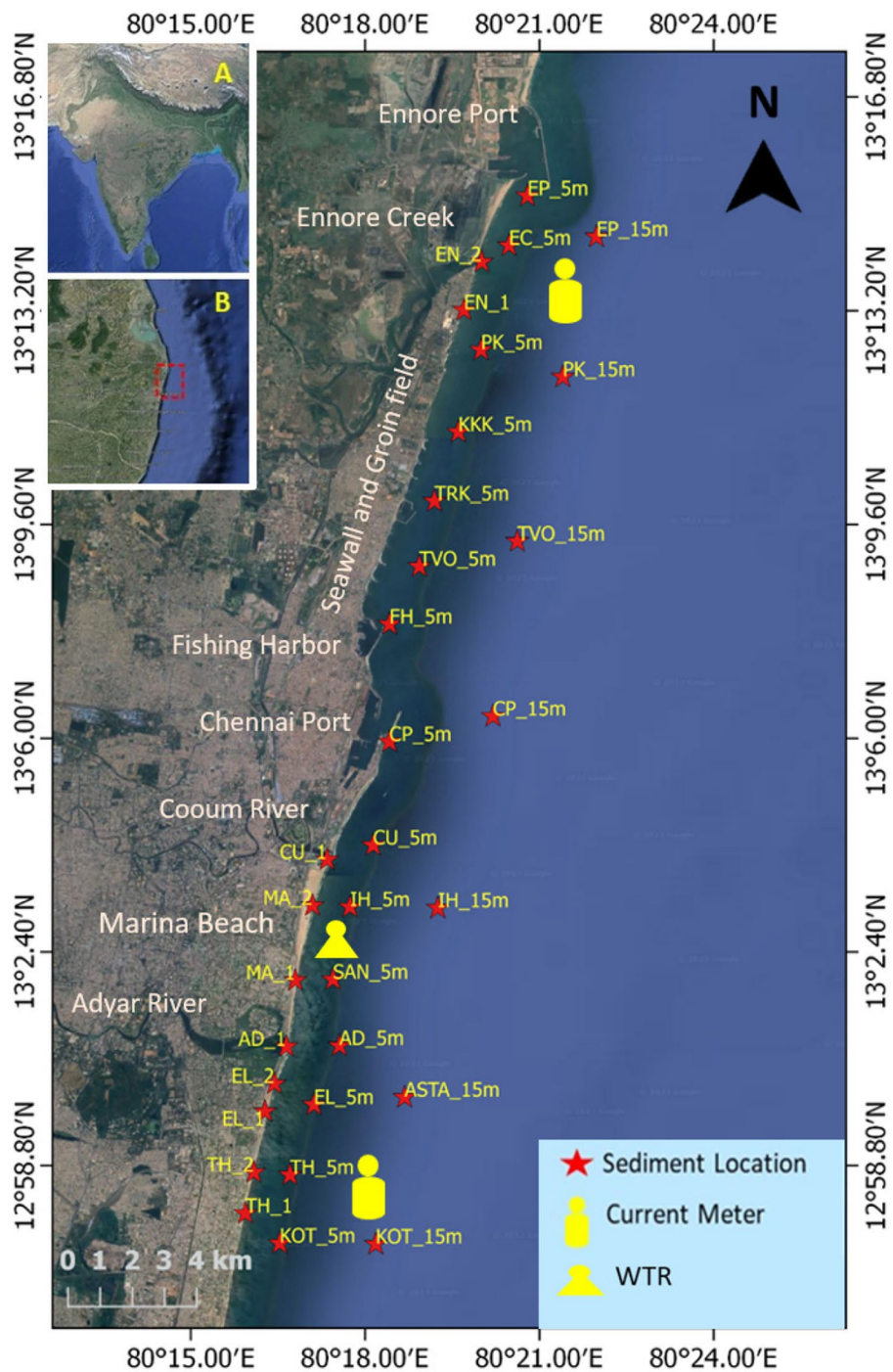
Fig. 1 Study area with deployment locations

height is 0.85, with a high wave field observed from May to September and a low from December to March (Kankara et al. 2013). Seasonal longshore current and littoral drift is active and reversal: it is northerly from March to September and southerly from November to February. This reversal current causes the siltation and formation of sand bars near the inlet. As a result, state government agencies regularly engage in dredging activities at the creek and river mouths to maintain the flushing.

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3 Data methodology

The sediment Grain characteristics such as central tendency (mean), sorting, kurtosis, and skewness are used to speculate on the sedimentary environments (Dora et al. 2011; Carranza-Edwards 2001; Friedman 1961, 1979) and their variation in spatial and temporal scale. About 900 sacrificial sediment samples were collected and analysed on a monthly basis for the Chennai coastal region at 32 stations from 2013 to 2015. The nearshore surface samples were collected by using Ven Veen grab of a 25×25 cm dredge area. For each field survey, the sampling locations are maintained by a handheld GPS. The sampling locations are classified into four types, such as beach, inlet, 5 m, and 10 m depth. First, the collected sediment samples were washed two to three times with Milli Q water. The samples were washed with 10% of acid (HCl) to remove the carbonates, and placed in at oven at 70 to 80 °C till the dry of samples. Amount of 100gm of dried sediment sample is sieved by using an automated sieve shaker (RESTEC-AS 200) and A.S.T.M. of 20 cm diameter sieves (63 μm, 90 μm, 125 μm, 180 μm, 250 μm, 355 μm, 500 μm, 710 μm and 1 mm) for 10 min.

Most sedimentologists used the logarithmic Udden-Wentworth grade scale (Udden 1914; Wentworth 1922) is adapted to calculate the textural parameters. The grain size of sediment was measured by Φ (phi) scale with the expression of logarithmic as $\Phi = -\log_2 D$, where D is the grain diameter in millimeters. The statistical parameters such as central tendency (mean), standard deviation (sorting), skewness, and kurtosis were calculated by the Folk and Ward (1957) method using GRADISTAT software (Blott and Pye 2001). GRADISTAT is a computer program written for the rapid analysis of grain size statistics from any of the standard measuring techniques, such as sieving and laser granulometry. In this study, the textural characteristics were estimated by the graphical method followed by Folk and Ward (1957).

The current information for two locations at the south and north of the study area (Fig. 1) was measured for the two major wind patterns (SWM: southwest monsoon and NEM: northeast monsoon) during the study period (2014 and 15). An interval of 15 min' time series current data was collected for 15 days by using the self-recording current meter (RCM 9 AANDERAA make). Similarly, water level and wave data were recorded by engaging WTR (Wave Tide Recorder) Valeport tide gauges at a depth of 8 m near Marinna Beach (Fig. 1) for two wind climates. The 14 days' time series data on water level elevation was collected for every 10 min interval at 2 Hz frequency corrected to chart datum (1.2 m) following NHO charts.

The total suspended material (TSM) is estimated by filtering 1 litter water sample collected from the surface through a pre-weighed filter paper. Millipore cellulose nitrate membrane, 47 mm diameter filter (porosity 0.45 μ) was used for gravimetric determination of TSM. The residue retained on the filter is dried for at least one hour at 103–105 °C in a drying oven. Allow it to cool in a desiccator and then weigh it. The amount of material retained in the filter paper is dry-weighted and expressed as mg/l.

3.1 GSTA

Sediment Trend Analysis (STA) is an empirical method that examines the relative changes in the complete grain size distribution of the mean, sorting, and skewness and evaluates the transport pathways together with their dynamicity (McLaren and Beveridge 2006). In terms of three statistical parameters, significant sediment grain size can be either fine (F) or coarser (C), the sorting may either be better (B) or poorer (P), and the skewness may be positive (+ve) or negative (-ve). As per Gao and Collins (1992), the two-dimensional GSTA considering the site-specific statistical parameters, i.e., mean, sorting, and skewness, is compared with the corresponding values of adjacent locations in all directions. In this work, the GSTA is used for the Chennai nearshore region developed by Poizot et al. (2006), Poizot and Méar (2010), and Dinesh (2009) after modification of the initial Gao and Collins (1992) approach. GSTA is a plug-in tool supported by QGIS, a geographical information system (GIS) software. To determine the trend vector field, three steps are followed: i) creation of a regular grid; ii) choice of a characteristic distance; and iii) choice of trend cases.

3.2 Numerical modelling

In this study, a cell-centred finite volume numerical method is adapted to understand the annual hydrodynamics of Chennai's nearshore region. The domain includes the three tidal inlets (Adyar, Cooum, and Ennore) and different coastal structures. The numerical model used accurate fine-resolution bathymetry (collected from observation and integrated from different sources like MIKE-C Map, and Gebco), forcing from atmospheric (time series wind, pressure, and temperature), tide from global tide model, and inlet discharge (Table 1). The model validations were made with the observations for two wind regimes. The hydrodynamic study is carried out by using MIKE 21, DHI software, which is working on the equation of continuity and Navier–Stokes momentum and temperature-salinity
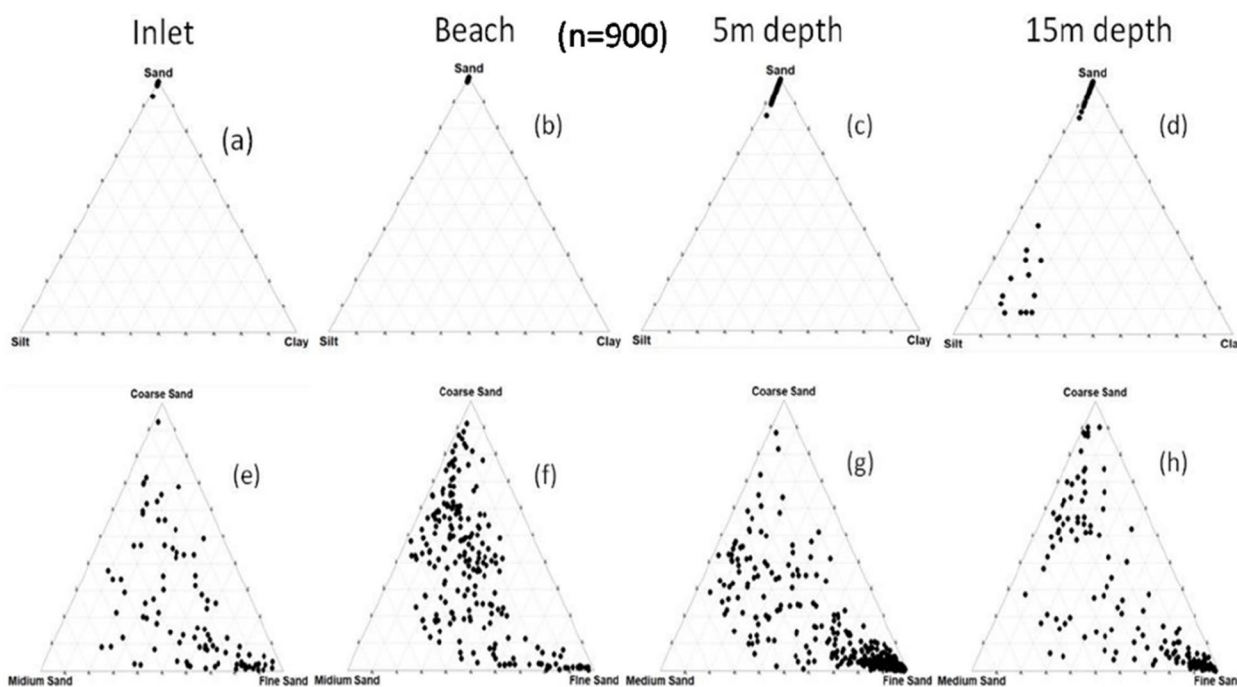
Fig. 2 Ternary plots for Sand-Silt–Clay (upper: **a** to **d**) and coarse-medium-fine sand (lower: **e** to **h**)

transport. The model is capable of accurate estimation of tide and flow field in the nearshore region to open seas (DHI Manual 2017).

4 Results and discussion

4.1 Sand-silt–clay distributions

Surface sediments were classified and plotted in ternary diagrams of sand (> 0.063 mm), silt (0.004–0.063 mm), clay (< 0.004 mm), and coarse sand, medium sand, and fine sand for the four different locations, such as inlet, beach, 5 m, and 15 m depths. Similarly, plots for coarse, medium, and fine sand are shown in Fig. 2.

4.2 Central tendency

The statistical parameters such as central tendency (mean), standard deviation (sorting), skewness, and kurtosis are calculated by the Folk and Ward (1957) method using GRADISTAT software (Blott and Pye 2001) and discussed. Nearshore sediment samples from the beach at 5 m and 15 m depths were collected on a monthly basis from April 2013 to January 2015, and the sampling locations are followed by the water quality stations given in the study map.

4.2.1 Mode

Mode is the most frequently occurring particle size or size class in the size distribution, which represents the highest point (peak) of the frequency curve. One

dominant peak in the frequency curve indicates unimodal, while two, three, and multiple peaks represent bimodal, trimodal, and polymodal, respectively. Unimodal is the most prevalent modality of the sediment, followed by bimodal, and finally trimodal (Fig. 3). The percentage of unimodal sediment is high in the nearshore region, at 65% at 5 m depth and 60% at 10 m depth, compared to the inlet (52%) and beach (49%). A higher percentage of bimodal sediment was observed at the beach (48%) and inlet (47%) as compared to the 5 m (26%) and 10 m (30%) depth stations. Similarly, trimodal sediments are more common in the nearshore region at 10% and 9% at 10 and 5 m depths, respectively. Whereas the trimodal sediments are less at inlet (1%) and beach (3%) stations. The result infers that the mostly trimodal sediments are poorly sorted and found near the offshore region of inlets and ports. The dominance of unimodal sediments in the nearshore region may be due to the supremacy of the northerly coastal current.

4.2.2 Mean

The spatiotemporal distribution of the mean diameter, minimum, and maximum of the surface sediments shows a significant variation with depths (Fig. 2A). The average mean size of sediment at inlets varies from 220 to 410 µm, with a minimum of 120 µm and a maximum of 620 µm. Similarly, the average mean size at beach stations varied from 260 to 600 µm, the minimum size was
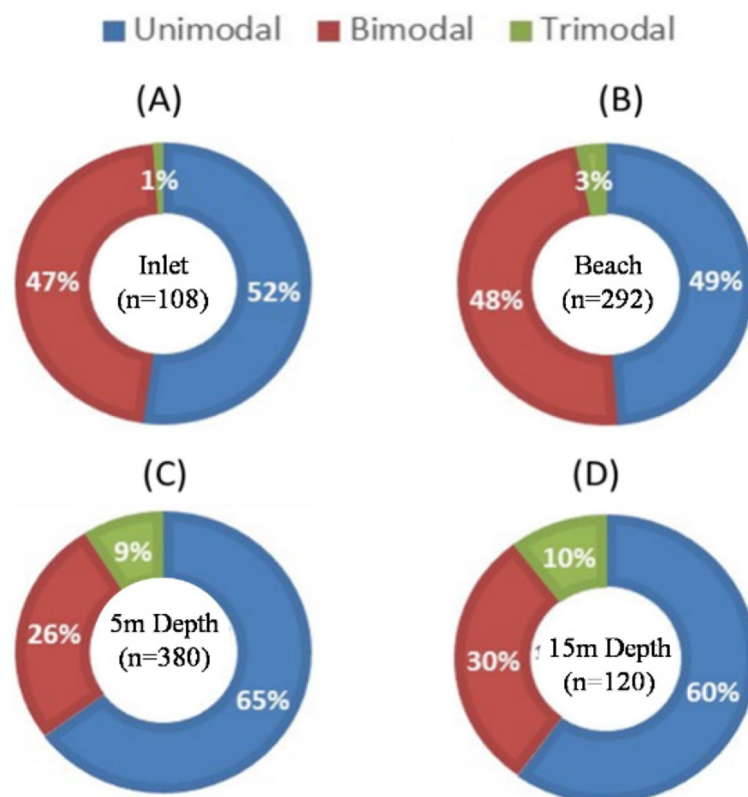
Fig. 3 Sediment modality at inlets (**A**), beach (**B**), 5 m depths (**C**) and 10 m depth (**D**)

120 μm, and a maximum of 850 μm was recorded. The mean sediment size at the beach and inlet stations along the coast is mostly medium sand, followed by coarse sand and occasionally fine sand. The mean size is higher at beach sediments as compared to near the stations of inlets, which is due to the supplies of finer material from the land side to the adjacent coast. The average sediment mean size at the 5 m depth counter clearly shows two types, such as being less in size in the southern part of Chennai port and quite higher in the northern part of Chennai port. The average sediment size at 5 m depth in the south part of the Chennai port varies from 140 to 220 μm, while on the northern part it is 140 to 300 μm. The minimum to maximum variation of mean size at 5 m depth stations is found between 80 to 600 μm, as the 5 m depth is just behind the wave breaking zone, which is the main settling zone for finer sediment driven from the beach (Pradhan et al. 2022a, b). The sediment at a 5 m depth counter is predominated by fine sand, followed by medium and then very fine sand. On the northern side of the Chennai port (CP_5m), the mean size is decreasing northward from FH to EP at 5 m depth. The above result depicts that the Chennai port and the navigational channel play a major role in sediment distributions. The Chennai port navigational channel depth is

mostly ≥ 15 m, which acts as a sediment-trapping barrier. As the study area is dominated by southerly longshore sediment in an annual cycle (Kankara et al. 2013; Rao et al. 2009), the sediment supply towards the north is arrested by the port channel. The wind and tide action immediately removes the finer particles from the area north of the Chennai port stations, moving them further north and depositing them south of the Ennore port (Station EC and EP). The average mean size at 15 m depth ranges from 180 to 400 μm, which shows a decreasing trend from the south (KOT to EP). The minimum and maximum mean grain size ranges from 30 μm to 800 μm, which is widely varied at 15 m depths, and its distribution behaves like beach sediment on the Gopalpur coast (Murty et al. 2007; Pradhan et al. 2022a, b). They are mostly medium sand, followed by fine, then coarse. Sometimes the very fine mud sediments are found near the port regions of Ennore and Chennai. All station is under the influence of a reversal current pattern, as the sediment mean size was found to be quite coarser during the southwest wind pattern (May to September) compared to the northeast monsoon (December to February) at coastal and 5 m depth stations. The strong winnowing process results in finer sediment at a 5 m depth counter. The settling of suspended sediment

and offshore sediment transport results in a wide variation of sediment size at 10 m depths.

4.2.3 Sorting

The sediment sorting is the most useful parameter to evaluate the distribution, sedimentary processes, and energy conditions of the transport medium. The average sorting values for the nearshore region and their variation are represented in Fig. 4b. The average sorting values for inlets and beaches are observed at 1.5 to 1.75 µm while varying by 1 µm (minimum 1.3 µm to maximum 2.3 µm). The sediment sorting of beaches and inlet stations is mostly moderately well sorted, followed by moderately sorted coarse sand and occasionally fine sand. The sorting values for the nearshore region significantly show two categories: low values on the port south and quite high values on the port north side. The average sorting values of 5 m depth sediments lies between 1.4 and 1.6 µm on the south and 1.6 and 1.8 µm on the northern side of the port. The maximum and minimum sorting values are recorded at 1.3 µm and 2.4 µm, respectively, for the 5 m depth locations. Sediment characteristics at 5 m depths are moderately well sorted, followed by moderately sorted, and sometimes poorly sorted. The average sorting values of 15 m depth sediments varied from 1.5 to 2.1 µm on the south side, while they varied from 1.5 to 3.0 µm on the northern side of the port. The sorting values vary from a minimum value of 1.3 to a maximum value of 3.5 µm at 15 m depth. The sediment sorting at 15 m depths is well sorted to moderately well sorted from April 2013 to June 2014, while sorting vale variations are in wide form well sorted to poorly sorted from July 2014 to January 2016, which may occur due to port activity, viz., dumping of dredged martial. The poorly sorted sediments are mostly found during southwest monsoon time, which may be due to high waves, during which most of the beaches are eroding.

4.2.4 Skewness

The skewness of sediment shows the depositional processes and energy conditions that are responsible for sediment transport. Figure 4C shows the average skewness values and their variation from minimum to maximum for the Chennai nearshore region. The average skewness values range from 0 to 0.2, while the minimum and maximum skewness are recorded at -0.5 and 0.5, respectively. The number of sediments is positively skewed and symmetrical. The average skewness value for the beach sediments fluctuated from -0.35 to 0.05, with a minimum value of -1.0 to a maximum of 0.5. The beach sediments are dominated by negatively skewed values. The sediments are mostly positively skewed at 5 m depth locations. The average skewness

values for 5 m depth sediments lie between -0.05 and 0.4, with a variation of -0.5 to 0.8. The skewness values at 5 m depth significantly show two categories, such as one is decreasing from the south station (Kot-5 m) to the Chennai port station (CP-5 m), while another is increasing from the Chennai port station (CP-5 m) to the station at the northern side of the study area and situated south of the Ennore creek and port. Similarly, the average skewness values of sediment at 15 m depths are between -0.15 and 0.25, with a variation from minimum to maximum of -1.0 to 0.6. Most of the sediments at 15 m depth are negatively skewed. The variations of skewness values at 15 m depths are greater during the northeast monsoon period compared to other periods. The sediments are characterised as symmetrical over the study area, followed by fine-skewed rather than coarse-skewed, but occasionally very fine-skewed and very coarse-skewed. The coastal current plays a major role in uniform sorting at 5 m depths, whereas Chennai port and its navigational channel significantly divide the sediment sorting distribution pattern. It has been noticed that beach sands commonly have a negative skewness since finer sediments like silt and clay are removed by the action of waves and tides. Due to the supply of finer materials by river discharge, sediments at beaches near rivers or inlets are typically positively skewed. Positive skewness is characterised as deposition, and negative skewness is due to the influence of the cyclic current pattern, indicative of the high-energy environment supposed to be an erosion environment. In general, fine sands have positive skewness and coarse sediments are negatively skewed.

4.2.5 Kurtosis

The kurtosis of the sediment shows a departure from the normal frequency curve. The variation of kurtosis values for the study area is shown in Fig. 4D. The average kurtosis values are 1, 0.95, 1.1, and 1.2 for the sediment at inlets, beaches, and 5 m and 10 m depth locations, respectively. Mostly, the minimum kurtosis values are the same (0.6) for all, while these are 2.9, 2.1, 2.7, and 3.8 for inlets, beaches, and 5 m and 10 m depth locations, respectively. It is noticed that the average kurtosis values are increasing from the beach to 15 m depth. The average kurtosis of beach sediment along Chennai is mostly platykurtic, followed by mesokurtic, and then occasionally leptokurtic. Sediments at 5 m depth are observed to be mesokurtic in nature, while they have been leptokurtic for some time. At 15 m depths, sediments varied from mesokurtic to very leptokurtic and were dominated by mesokurtic, followed by leptokurtic. The variation of kurtosis values is greater in the northern part of the nearshore region (5 and 15 m depth).
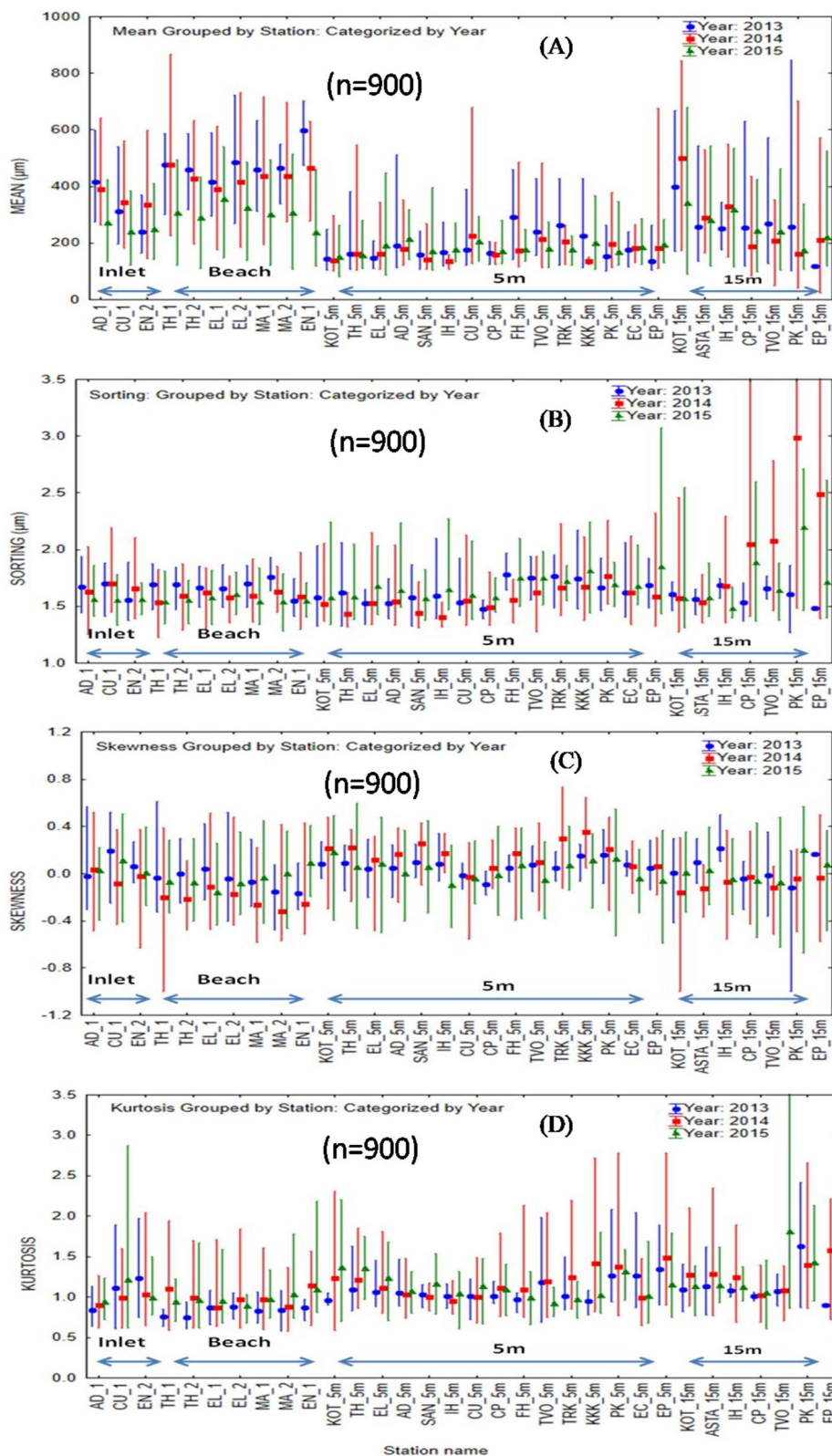
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Fig. 4 Textural parameters for nearshore sediment; mean grain size (**A**), sorting (**B**), skewness (**C**) and kurtosis (**D**)
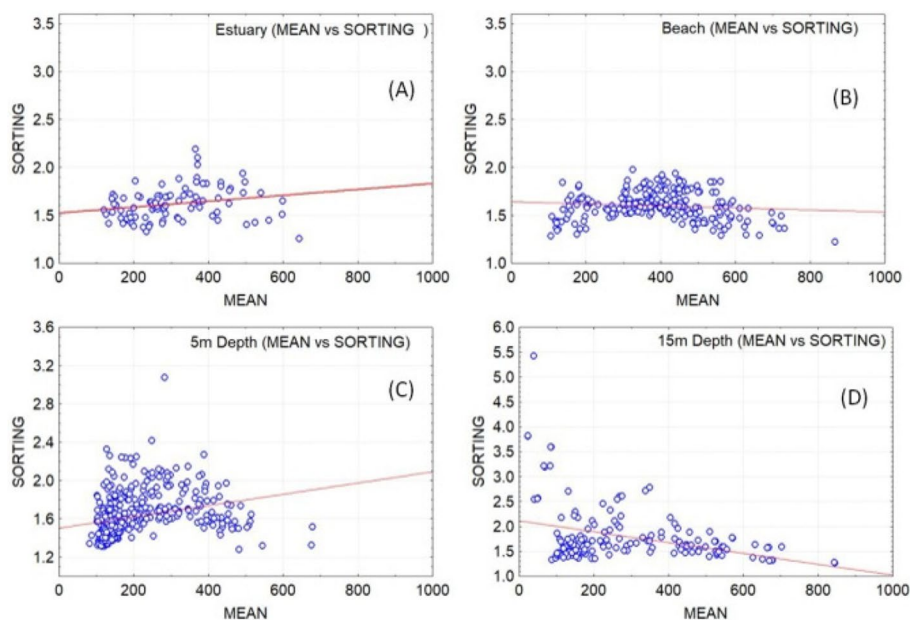
Fig. 5 Bivariate plot between mean and sorting at inlet/estuary (**A**), beach (**B**), 5 m depth (**C**) and 15 m depth (**D**)

4.3 Bivariate plot

The bivariate plot (scatter) between the textural parameters provides important information about the energy conditions, transportation, and erosion/deposition (Folk and Ward 1957; Passega 1957; Friedman 1979). The bivariate plots between mean versus sorting, mean versus skewness, and mean versus kurtosis were executed for different regions of inlet, beach, 5 m, and 15 m depths.

4.3.1 Mean size vs sorting

The scatter plot between mean grain size vs. sorting for the different environments (inlet, beach, 5 and 10 m depths) for the nearshore region is shown in Fig. 5. The bivariate plots between sediment mean size and sorting for the estuary and 5 m depth show similar behavior. A positive correlation was found as the mean size increased with the increase in sorting value, while a negative correlation was found for the beach and 15 m depth as the sediment mean size increased with a decrease in sorting value. Sediment over the study area depicts that the finer sands are accomplished with a wider sorting value, while the coarser sands are bound with a limited sorting value. The above results show that coarse sediment with better sorting (less) values shows erosion or a cycle of accretion and erosion environment at beach locations, while finer sediment with a wide range of sorting values shows depositional sedimentary facies at inlets and 5 m depth. The increase of mean size with the increase of sorting value at the inlet system and the decrease of mean size with a decrease of sorting value at beaches shows the

dynamicity of sediment. The increase in mean and sorting value represents the energy dissipation zone which makes settling of sediment and observed quite finer sediment at inlets and 5 m depths. The decrease in mean size with sorting value shows the high energy conditions with less settling of sediment, which results in a wider range of sediment from fine to coarse and noticed at the beach locations.

Griffths (1967) explained that the fine and best-sorted sediments are hydraulically controlled; while in present study, the dominance of fine and better sorted sediment at estuary, 5 m and 15 m depths controlled by hydrodynamic. In all situations, two clusters of sediment may be noticed. The first kind is composed of fine sediment, which is moderately to moderately well sorted. The second group consists of medium-sized sediment, also moderately to moderately well sorted. The prevalence of the first category is predominant. The thorough investigations reveal that the distribution of sediment exhibited a notable seasonal pattern. Specifically, medium sand with a moderate to well-organized arrangement was observed at beach locations, while fine sand with a moderately sorted to moderately well-sorted arrangement was found at inlets, as well as at depths of 5 m and 10 m during the period of high waves (southwest monsoon). Similarly, the beach exhibited finer sand that was moderately to fairly well sorted, whereas other situations during the low wave period (northeast monsoon) showed medium sand that was moderately sorted to moderately well sorted.
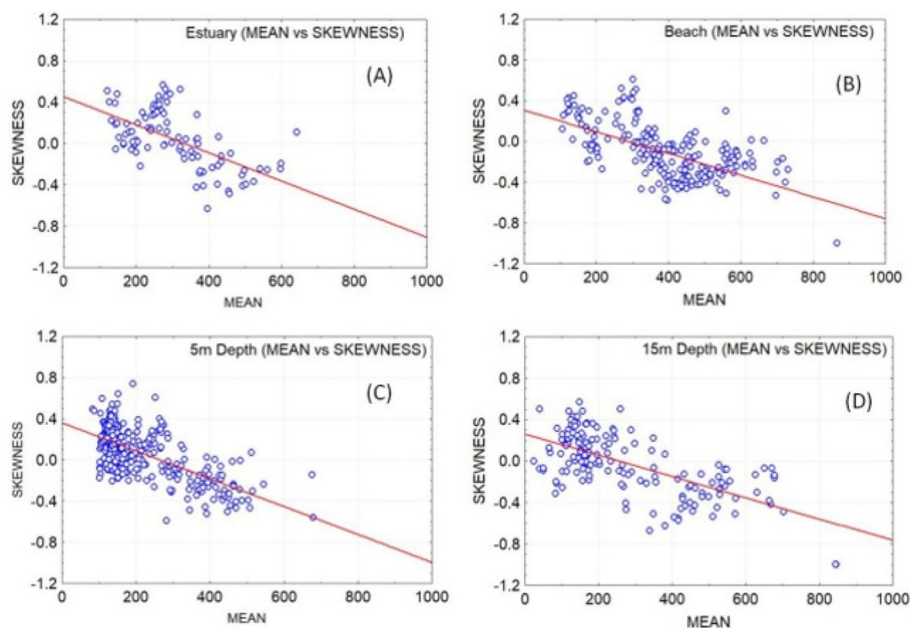
Fig. 6 Bivariate plot between mean and skewness at inlet/estuary (**A**), beach (**B**), 5 m depth (**C**) and 15 m depth (**D**)

4.3.2 *Mean size vs. skewness*
The scatter plot between sediment mean grain size and skewness reveals a negative relationship in all environments for the study region (Fig. 6). The study observed the general sedimentary processes as follows: An increase in mean size (coarser sediment) value exhibits negative skewness at beach stations, while finer sediments exhibit coagulation-positive skewness at inlets and 5 m depth locations. The skewness value at the beach shows a negative value, which means that sediments were subjected to high energy conditions (both wave breaking and tide). Figure 6 displays two predominant types of sediments at all depths: finer sediments exhibit a positive skewness, whereas coarser sediments display a negative skewness. The predominance of fine sediment with a positive skewness indicates a depositional environment during a low-energy period, specifically the northeast monsoon. Conversely, the presence of medium to coarse sand with a negative skewness suggests erosion or the presence of more suspended sediment in the water column, which is characteristic of a high-energy period, such as the southwest monsoon.

4.3.3 *Mean size vs. kurtosis*
The bivariate plots between mean grain size Vs kurtosis values reveal a negative correlation for estuary/inlets, 5 m, and 10 m depth sediments, while the beach sediments are almost unchanged with an increase or decrease in mean and kurtosis values (Fig. 7). The sediments in nearshore regions show the scatterings are wider due to

the multiple processes of human interventions such as port activity and material discharged through flash floods from urban areas.

4.4 CM plot
The CM plot is defined as a scatter plot between the 1% coarsest (C) and median (d_{50}) of grain size on a logarithmic scale. The transport of sediment depends on environmental forces such as wind, wave, tide, current, and river runoff, as well as availability, type, size, sources of sediment, and geographical settings. The plotting and interpretation of the CM plot are adopted from Passega (1957, 1964) and the plot clears the sediment types, sources, and modes of transport. The CM plots for different geographical settings such as rivers, beaches, and at 5, and 10 m depths are shown in Figs. 8 and 9. The sediment source for the study region is dominated by a tractive current, and few are under beach processes (Fig. 8). Though the northerly current pattern is dominant (Kankara et al. 2013) and the beaches are cyclic in nature, they undergo erosion during the southwest monsoon and accretion during the northeast monsoon on an annual basis. The CM plot showed that the transport patterns for different environmental scenarios are significant (Fig. 9). Sediments at inlets and beaches were transported by bottom suspension and rolling, followed by rolling. The mode of sediment transport at 5 m depth is dominated by graded suspension with no rolling, followed by bottom suspension and rolling, while few are transported by rolling. Similarly, the sediments at 15 m depth were transported
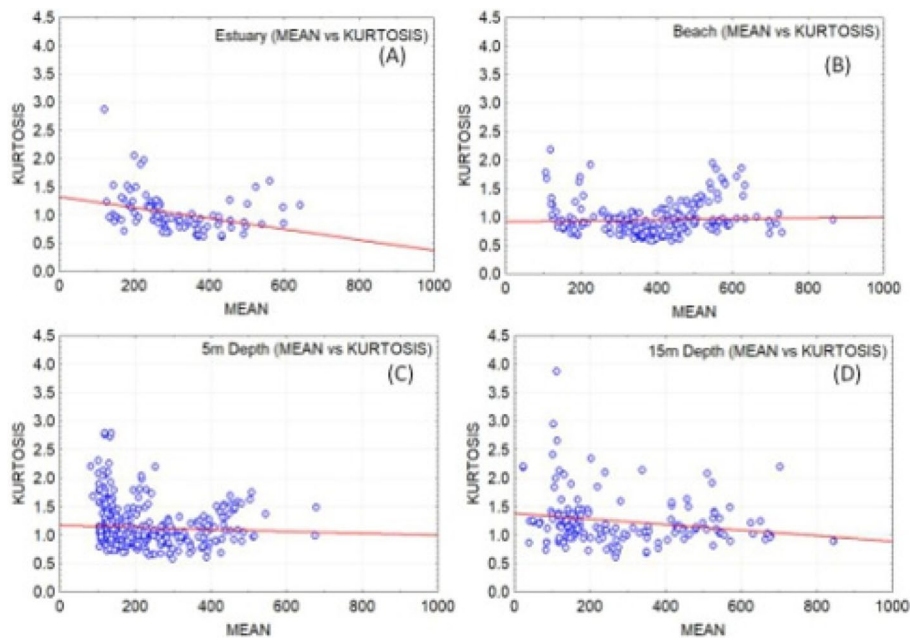
Fig. 7 Bivariate plot between mean and kurtosis at inlet/estuary (**A**), beach (**B**), 5 m depth (**C**) and 15 m depth (**D**)
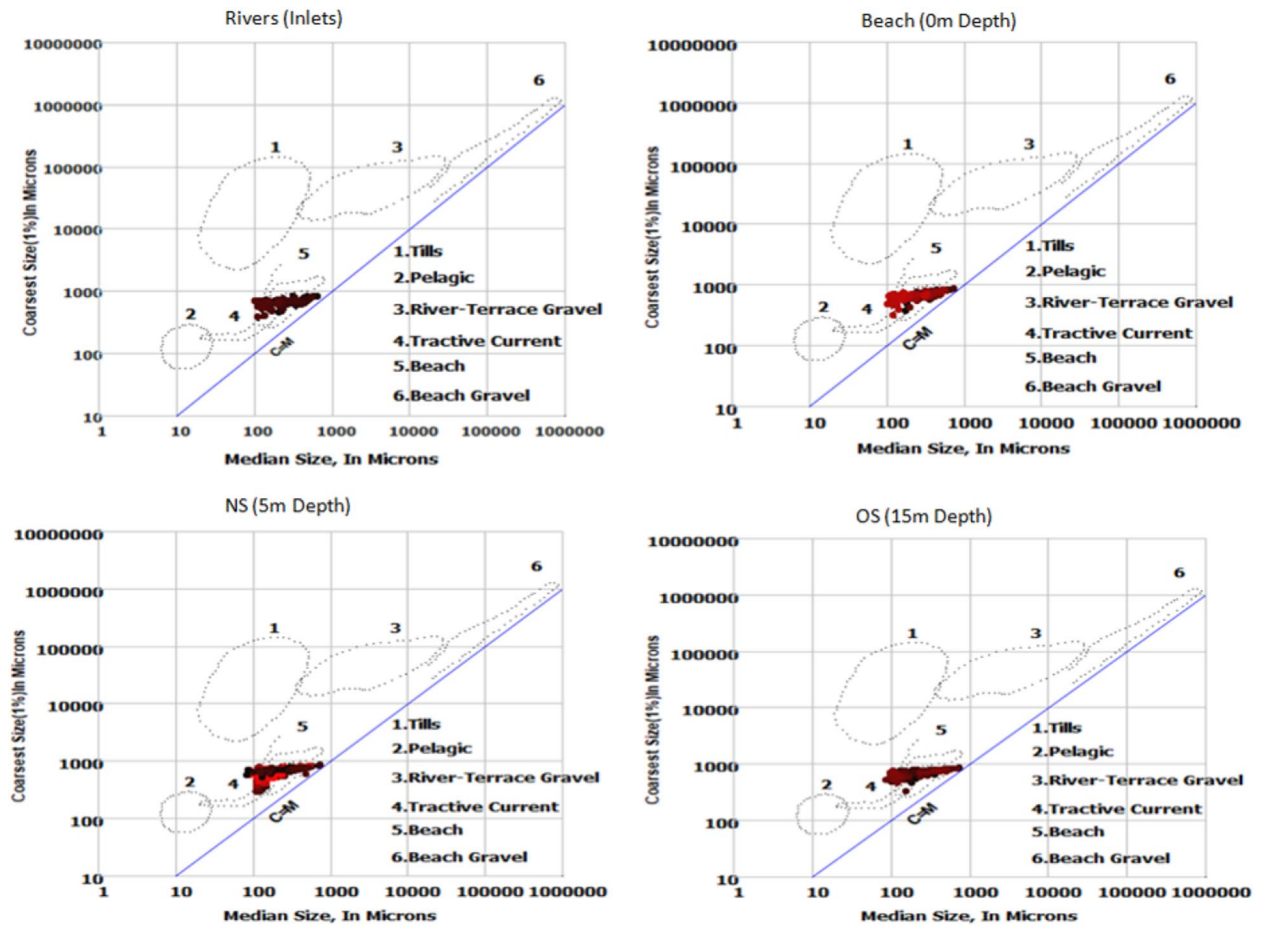

Fig. 8 CM plot for sediment derived sourceat inlet/estuary (**A**), beach (**B**), 5 m depth (**C**) and 15 m depth (**D**)
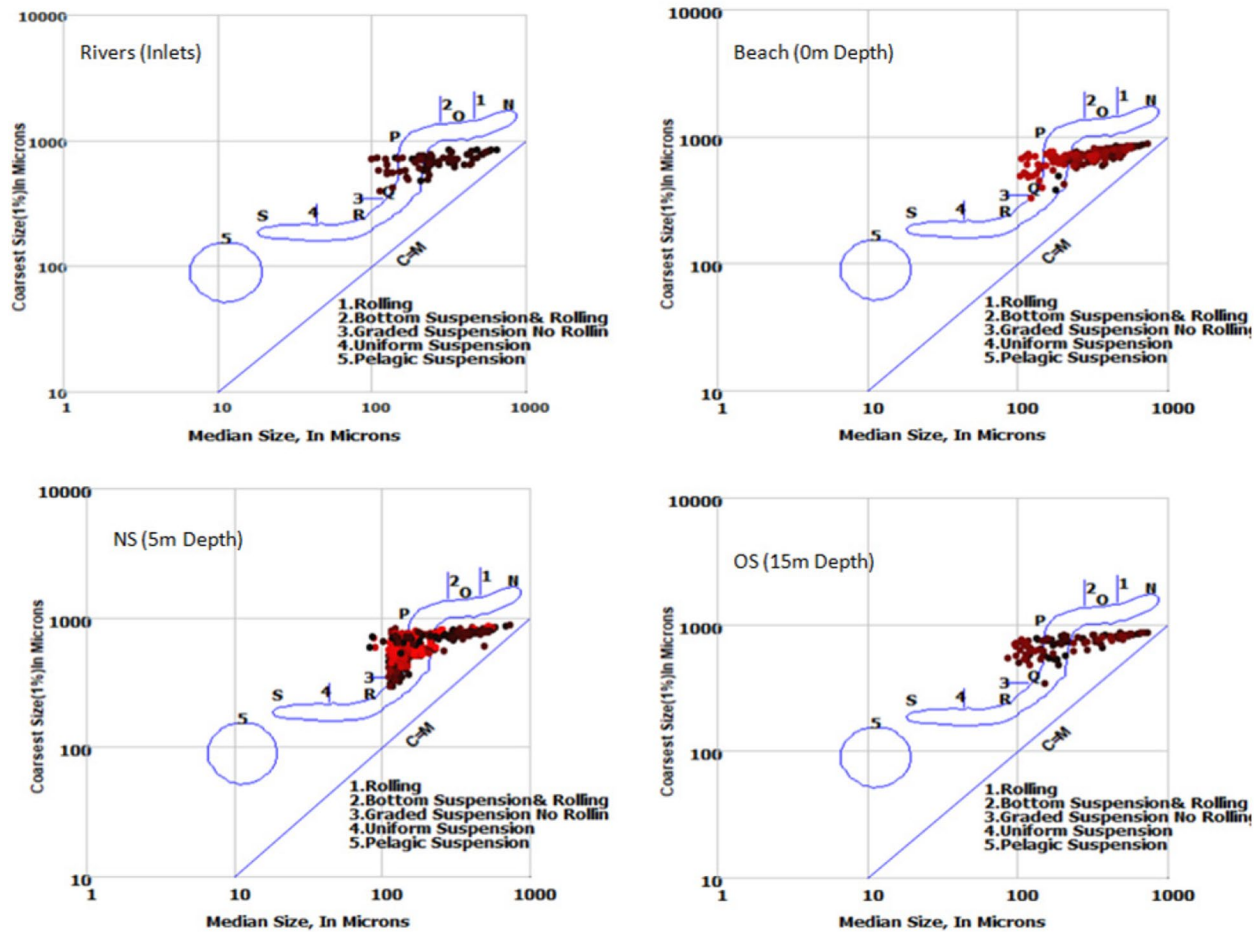
Fig. 9 CM plot for transport mode at inlet/estuary (**A**), beach (**B**), 5 m depth (**C**) and 15 m depth (**D**)

by bottom suspension and rolling, followed by graded suspension with no rolling and few rolling. The study area's transport is not uniform because of anthropogenic activities like the construction of ports, harbours, groins, and seawalls; dredging of ports and inlets; land runoff with a high load of suspended material; and coastal erosion/accretion due to monsoons and cyclonic events.

4.5 Grain size trend analysis (GSTA)

Grain Size Trend Analysis (GSTA) is a technique that provides the net sediment patterns to be determined by relative changes in grain size distributions of naturally occurring sediments. It shows the bottom sediment dynamics concerning erosion, accretion, and transport direction. The theory is based on relative changes in sediment textural parameters such as mean size, sorting, and skewness value, with concern for geographic positions such as latitude and longitude (McLaren and Bowles 1985a, b; Mc Laren 1993; McLaren and Beveridge 2005). The practical case study for GSTA was carried out on the Chennai coast for two scenarios. The two cases are

considered for the present study (Fig. 10). One generally occurring condition is CB+ (coarse: C, better sort: B, and positive skewness: +) and FB- (finer: F, better sort: B, and negative skewness: -). Another case is decided from the three years' data set and mostly occurred sediment environment, which is CB- (coarse: C, better sort: B and negative skewness: -) and FB+ (finer: F, better sort: B and positive skewness: +). To assess a better vector field of sediment transport, the observed data was interpolated in the GIS platform through the "Neighbour Kriging" method. The variogram study provides the "r "value for the GSTA analysis as 0.02.

The result of grain size trend analysis for the first case (CB+ and FB-) shows the sediment movement is seaward, and it shows that the most of sediments in the study area are uni-directional (Fig. 10 A). In the second case, sediment transport direction is uniformly northward on the south of the port region, while it is northeast and east (seaward) on the northern part of the Chennai port (Fig. 10 B). The sediment dynamics on the northern side of the port are observed in four local cells, which may
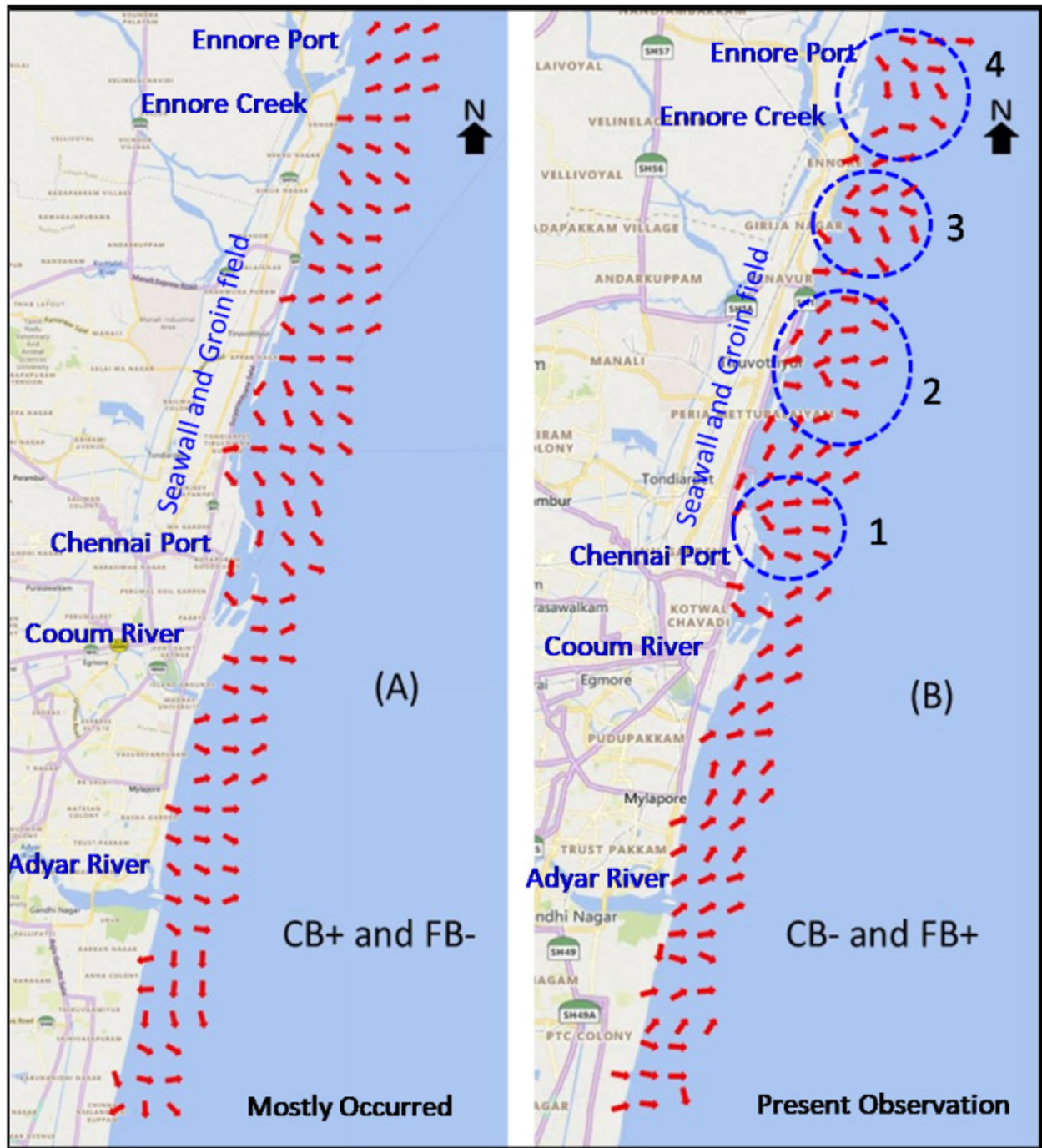
Fig. 10 Grain size trend analysis (GSTA) for two case: (**A**) CB + & FB- and (**B**) CB- & FB+

be influenced by the existence of groins with sea walls, the same scenarios were computed through the numerical approach. The hydrodynamic flow field is similar to GSTA analysis and confirms the qualitative approach of the sediment pathway for this study area. The sediment of the inlets was moving seaward in both cases, clearing the finer material at the off-inlet location, which is derived from the higher suspended material from river discharge on both sides of the port. However, the current along the east coast of India is a reversal in nature but dominated by the northerly in an annual phase; hence, the general sediment pattern also shows the northerly.
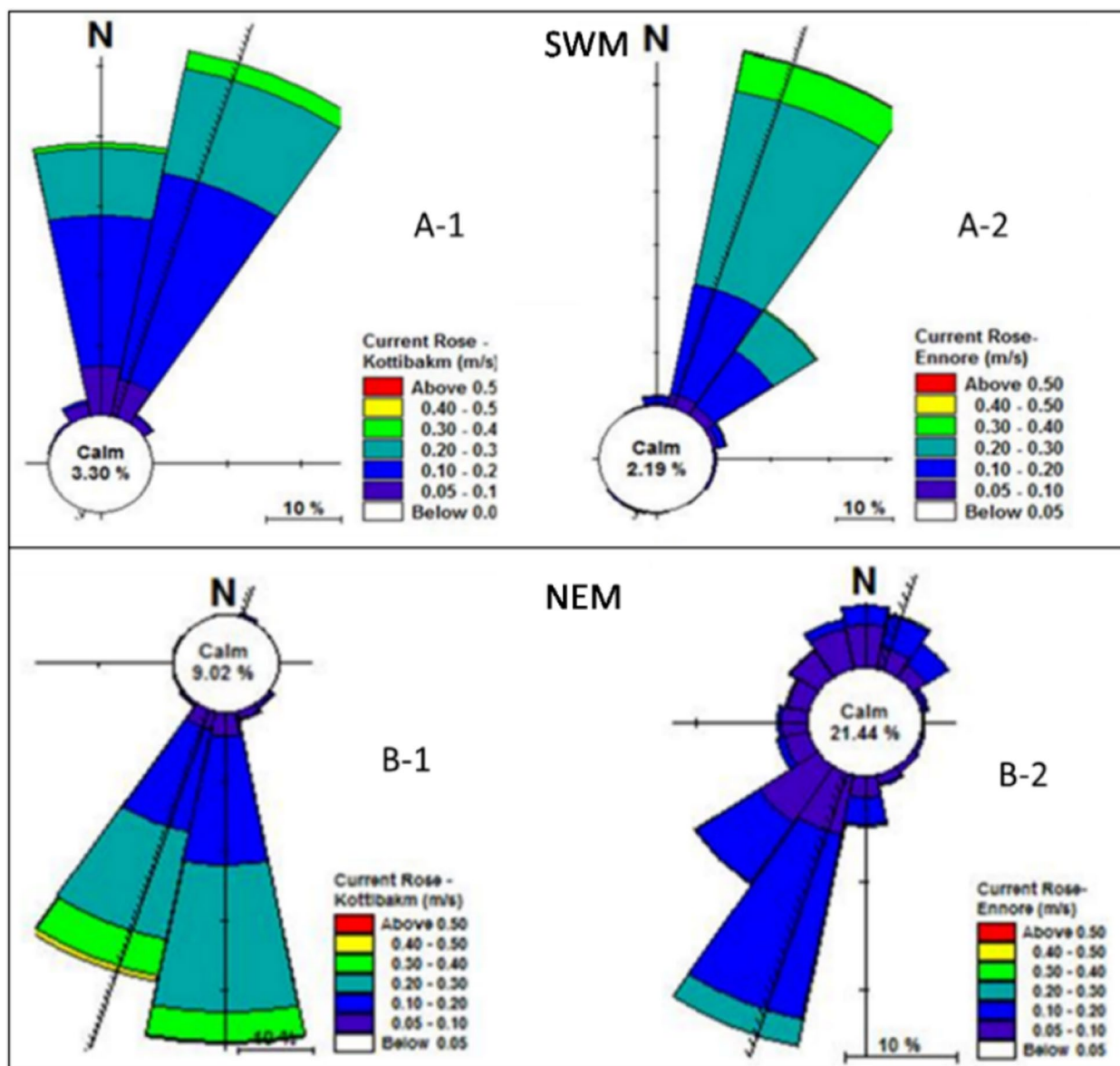
Fig. 11 Observed coastal current during southwest monsoon (upper: A-1 and A-2) and northeast monsoon (lower: B-1 and B-2)

4.6 Oceanographic/ environmental conditions

4.6.1 Coastal oceanography

The coast is characterised by micro-tidal and semi-diurnal features, as the tidal range is ~1.2 m and the form number falls below 0.25. Monsoonal high waves (Hs > 1.5–2.0 m) with a predominant period Tp of 9–12 s is dominant. Low wave heights (Hs) of 0.5–1.0 m and (Tp) of 12–18 s are characteristics of northeast monsoons. The coastal current plays a key role in sediment transport; hence, current data is immensely helpful to understand the sediment dynamic. Figure 11 shows the current information for two locations south and north of the study area measured for the two major wind patterns (southwest and northeast) during the study period (2014 and 15). During September 2015 (SW monsoon), the current direction is predominantly north-northeast at all locations, with varying speeds. The average current speed is 0.16 m/s and 0.20 m/s at Kottivakkam and Ennore, respectively. Similarly, during November 2014, the average current speed at Kottivakkam was 0.16 m/s m/s with a predominantly direction of south and southwest, while it was 0.1 m/s at off Ennore with a predominantly south-westerly direction. The current is swifter during the SWM period as compared to NEM.

Table 1 Configuration of hydrodynamic model

Parameter	Value
Method	Cell-centred finite volume numerical method
Mesh and Bathymetry	Unstructured mesh with 3524 numbers of nodes and 5946 elements Measured bathymetry and C-map data
Simulation Period	1st January to 30th December 2015 (Annual Basis)
No. of Time Steps	Time step: 300 s
Solution Technique	High order, slow algorithm, Minimum time step: 0.01 s, Maximum time step: 120 s, Critical CFL number: 0.8
Formulation	Function of barotropic
Eddy viscosity	Smagorinsky formulation (constant ~ 0.5)
Bottom Resistance	Chezy number ($C = 40$ m^1/3/s)
Enable Flood and Dry	Drying depth 0.01 m, Flooding depth 0.05 m, Wetting depth 0.1 m
Wind Friction	AWS, IMD, wind friction parameters with $fw = 0.0016$ for < 8 m/s and $fw = 0.0026$ for > 10 m/s are used
Wave	Wave height, period and direction (ECMWF)
Sources (Point Source)	Adyar, Cooum and Ennore River discharge data (literature and estimated)
Boundary	Tide from Global reanalysis data (MIKE Tide)
Heat Exchange coefficient TS	Latent heat (Constant $= 0.5$, wind coefficient $= 0.9$, Critical wind speed $= 2$ m/s) Sensible heat: Transferred coefficient 0.0011, Sun constant $a = 0.295$, $b = 0.371$ Light extinction coefficient $= 1.1$

4.6.2 Numerical modelling-hydrodynamics

The hydrodynamic modelling and seasonal transport were well studied by several researchers for the Chennai nearshore region (Rao et al. 2009; Kankara et al. 2013; Mishra et al. 2015; Panda et al. 2020). Our earlier study for the numerical modelling of hydrodynamics for the same period and study domain reported that the dominated northerly current causes the sediment transport as well as pollutant driven through the inlets such as Adyar, Cooum, and Ennore towards north during southwest wind climate while it is southerly during the northeast wind regime (Pradhan et al. 2022a, b). As the nearshore sediment transport is purely dependent on coastal current and the water flux. The present numerical study depicts the annual current pattern and water flux. The detailed hydrodynamic setup, input, and outputs are given in Table 1, while other model calibration and validation techniques are discussed by our earlier study by Panda et al. (2020) and Pradhan et al. (2022a, b) for the same.

As the sediment texture and its trend analysis are done for the year starting from 2013 to 2015, hence the numerical modelling study for hydrodynamics is done for the year 2015. The different season flow fields for the study region (Fig. 12A & B) and the water flux rate, current speed, and direction at 6 m depth off Marinna beach (Fig. 13A, B & C) are discussed with relevance to sediment transport pathway. Figure 12A shows the mostly occurred flow pattern during the southwest monsoon period, while Fig. 12B shows for northeast monsoon. Generally, the

coastal current occurs along the south of Chennai port is parallel to the coast, and is northerly during the southwest monsoon period, while it is southerly during the northeast monsoon. The flow fields at the northern part of the Chennai Port show overall northward with three eddies in the nearshore region during southwest monsoon and southward during northeast monsoon with four dynamic circulations at nearshore. The major variation in the flow field at the northern part of Chennai port is due to the existence of a fishing harbour, jetties seawall, and a series of groins. The modelled coastal current (speed and direction) at 6 m depth off Marinna beach is northerly (4 to 8 cm/sec) from February 2nd week to September 3rd week, while it is southerly (0 to 7 cm/sec) from October to January (Fig. 13A & B). The first two weeks of February and the last week of September show the shifting of the current direction. To understand the true water flux along Marinna off is chosen. Both P and Q flux at 7 m depth for the year 2015 is shown in the Fig. 13C. The P flux represents the eastward (+ve) and westward (-ve) movement of water mass, while the Q flux is northward (+ve) and southward (-ve). Modelled flux is positive from March to September, which reveals the eastward and northward water mass movement. The maximum positive rate of flux is occurred during May month. Similarly, the maximum negative rate of flux is computed in November. The model study concludes that the intensity of the Q flux is higher than the P flux, always for this coast. Interestingly, the flux rate is very minimal during the last week of January to the third week of February.
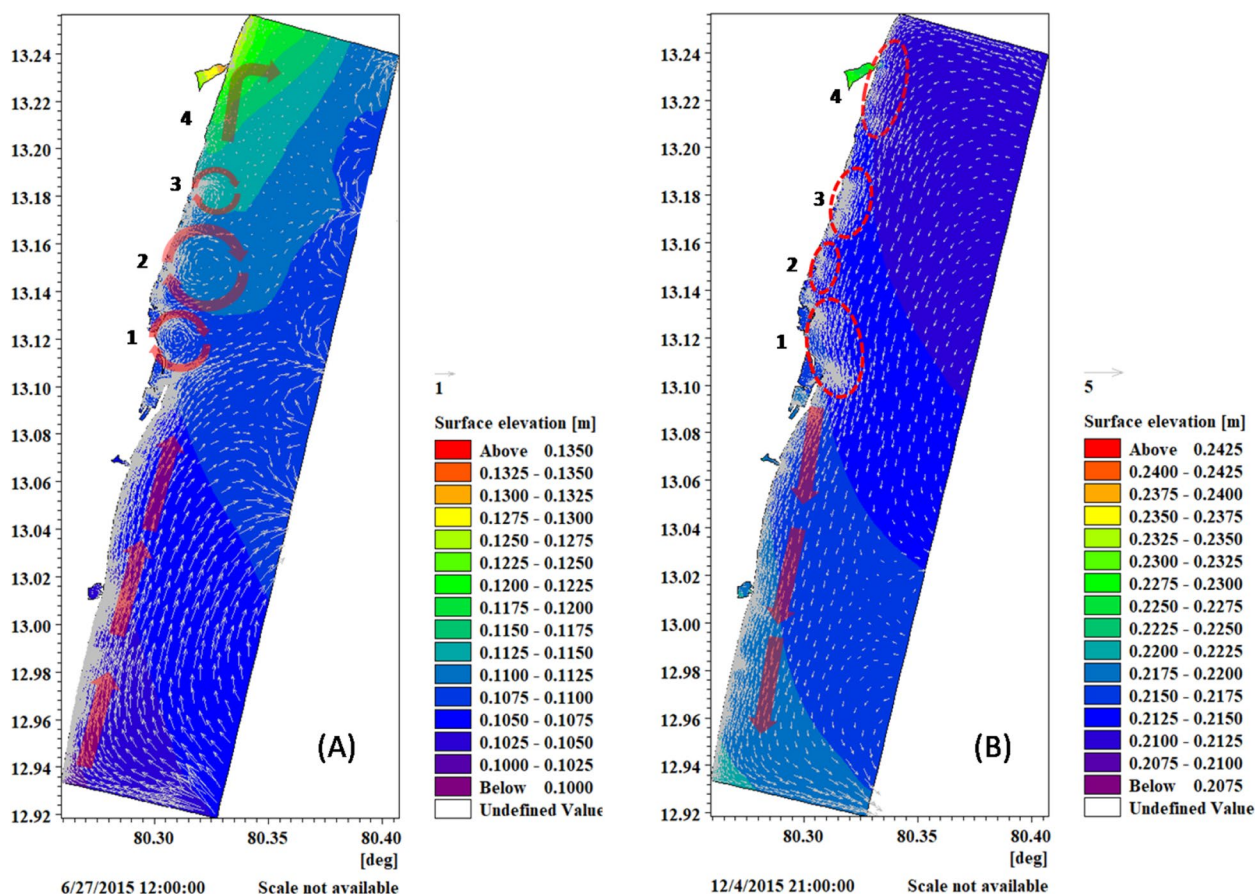
Fig. 12 Hydrodynamic (circulation pattern) during southwest monsoon (**A**) and northeast monsoon (**B**) at Chennai nearshore region

4.6.3 Total suspended material (TSM)

The sediments are classified into two types: i) cohesive and ii) non-cohesive. Mostly, cohesive sediments are transported through suspension mode in the water column, while non-cohesive sediments are transported through bed transport, such as rolling and bottom suspension. The suspended sediment is transported by current from the inlet to the adjacent side as well as the offshore region with the mutual interaction of the wind, wave, and tide. The TSM concentration is higher near the inlets, followed by the surf zone water, 5 m, and 15 m depth contours. The higher order of TSM values were encountered during the rainy period (November and December) and the high wind period during May and June, due to the land discharge and churning process in shallow water, respectively. The churning processes and the settling of TSM cause variations in mud and clay components in a nearshore environment.

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5 Conclusion

The surface sediment of the Chennai nearshore region was analysed to understand the distributions of the sediment textural characteristics, mode, and pathway of transport with the associated local hydrodynamic conditions. The average grain size of beach and inlet sediments
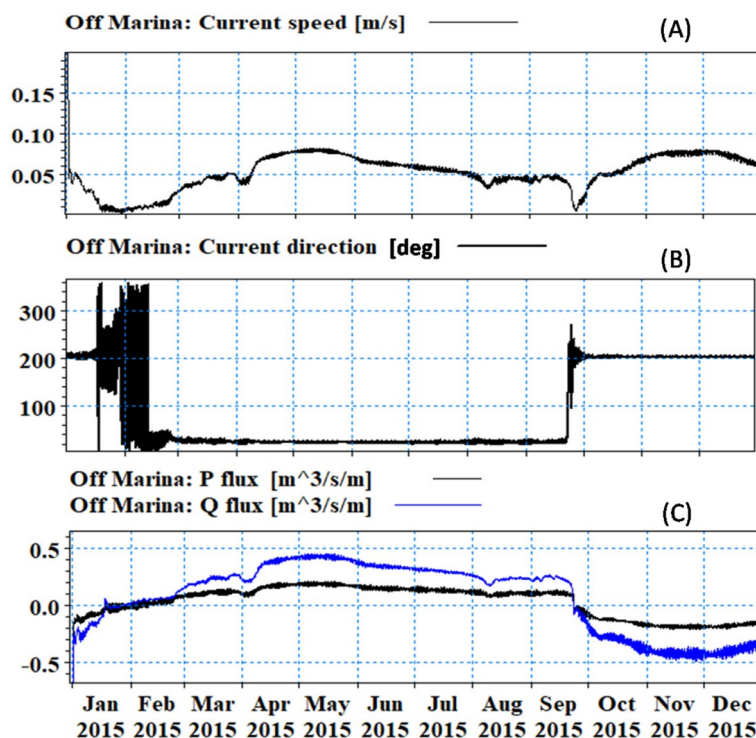
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Fig. 13 Time series information of current speed (**A**), current direction (**B**) and rate of water flux (**C**) at 6 m depth off Marinna

is medium sand, while inlet sediments are comparatively finer than beaches. The sediments at 5 m and 15 m depth are fine sand, but more finer sediments were observed at 5 m depth. The mean grain size on the southern part of the port is quite finer than the northern part of the port. The average sorting of sediment is moderately well sorted, while it is widely varying in the northern part of the Chennai port at 15 m depths. Most of the beach sediments were negatively skewed, while other nearshore sediments were found positive. The average kurtosis values of sediments were noticed to be mesokurtic, while a significant variation in kurtosis values was observed on the northern part of Chennai port. The impact of port structure, navigational channel, and groins with seawall on the northern side makes more vagary sediment distributions and transport patterns. The Chennai port plays a major role in creation of sediment environment of two types, as the southern part of the port region is stable while the northern part of the port region is unstable with different local sediment transport patterns. The CM diagram shows sediment transport is predominantly driven by a tractive current with a northerly direction throughout the study domain. The sediments at beaches and inlets were transported through "bottom suspension and rolling," while the shallow water sediments were mostly transported through "graded suspension and no rolling." The numerical study of local hydrodynamics confirms the transport pattern by the GSTA and CM plot analysis. This type of study is of utmost importance for port channel operation and erosion accretion in the nearshore region including the inlets.

Authors' contributions
Umakanta Pradhan: Fieldwork, literature review, data analysis, writing – original draft. Subrat Naik: Fieldwork, data analysis, and interpretation. Pravakar Mishra: Final draft and supervision. Uma Sankar Panda: Review, literature review. M. V. Ramana Murthy: Project administration.

Availability of data and materials
The datasets generated during and/or analyzed during this study are available from the corresponding author on realistic request.Code availability (software application or custom code) The software used for this study is purely commercial and tools used for this study are publicly available.

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Declarations

Competing interests
The authors declare no competing interests.

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