Evaluation of Textural Characteristics and their associated Environments in the Core Sediments of Muttukadu backwaters, Tamil Nadu, India

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Abstract: A core sample was taken from the Muttukadu backwaters to assess grain size variations, enabling the interpretation of sediment texture and inference of environmental conditions. Sedimentological parameters such as sand-silt-clay, calcium carbonate, and organic matter were analyzed in the samples. The core exhibited a high proportion of sand, suggesting a medium to high energy environment during sediment deposition. Over the course of the core, the calcium carbonate content increased due to the accumulation of shell fragments and dead oyster shells. The core displayed a low concentration of organic matter, likely due to limited vegetation, the flushing out of organic material by tidal fluctuations, or a higher percentage of sand. The granulometric study indicated the presence of medium to fine-grained sand, indicative of prevailing high energy conditions in the area during deposition. These sediments were likely transported by longshore currents and erosional activities during monsoonal conditions. Moreover, bivariate plots between statistical parameters proved valuable in interpreting energy conditions, transportation medium, mode of deposition, and other relevant factors.
Keywords: Textural analysis, Muttukadu, Backwaters, Grain size, Sand-silt-clay, Tamil Nadu.

Introduction

The sedimentation cycle comprises unique transportation and depositional parameters, distinguished by varying grain sizes and primary sedimentary structures. The grain-size parameters, together with sediment composition, clastic grain sphericity and roundness, diagenesis of deposited sediments, associated organic structures and substances, sedimentary structures, and clay minerals, all provide valuable insights into the deposition conditions of any sedimentary unit. A thorough analysis of these units yields information about the depositional history, including climatic conditions during deposition. Provenances significantly influence these aspects. The size distribution of sediments primarily reflects the conditions within the depositional environment, the prevailing processes, and the energy levels involved. Consequently, sediments deposited in different environments may exhibit distinct particle size distributions due to differential erosion, transportation, and deposition. By determining these particle size distributions, it becomes possible to hypothesize about the environment of deposition and use this technique as a tool for environmental reconstruction (Lario et al., 2002). Quantitative analysis of sediment size distributions is essential for detailed sample comparison and to identify meaningful relationships between sediment properties and geological processes or settings (Lewis, 1984).

The geomorphology of an estuary significantly influences its flows, circulation, and mixing dynamics. Researchers, such as Achythan et al. (2002), collected four sediment cores from water depths between 1.0 and 1.50 m in estuarine and tidal zones along the Tamil Nadu coast between Chennai and Pondicherry. Their analysis of these cores focused on major elements (Fe and Al), trace metals (Mn, Zn, Cr, Co, Pb, and Ni), as well as carbonate and organic carbon contents. The objective was to gain insights into the behavior of trace metals and identify their potential sources. Additionally, Achythan (2006) investigated the age and formation of Oyster beds in the Muttukadu tidal flat zones. In a separate study, Achythan et al. (2009) inferred the paleoenvironmental changes during the middle Holocene period from foraminifer and ostracod signatures at Muttukadu. Kumar et al. (2018) examined the characteristics of coastal waters along the Tamil Nadu coast on the East coast of India. Based on cluster analysis, they identified a polluted zone near Chennai and buffering zones at Kovalam and Kalpakkam. Kajal Kumari et al. (2020), investigated beach sediments between Besant Nagar and Sathurangapattinam, south of Chennai. They concluded that marine processes distributed sediments at various locations. Furthermore, sediment-rich in magnetic and heavy minerals was traced back to various source rock types, transported by rivers, and later influenced by longshore currents of the oceans from south to north and vice versa during different months. The SW–NE monsoon played a vital role in the distribution of beach placers. Building on the findings of previous research, the present study aims to assess grain size variations in core sediments. This analysis will aid in interpreting sediment texture and type, ultimately providing valuable insights into the depositional environment of the study area.

Study area: Muttukadu Backwater

The study area is located in the Muttukadu Backwater, situated (12.803512 N and 80.246777 E), approximately 36 km south of Chennai on the southeast coast of India (Fig. 1). The Muttukadu backwater stretches for about 20 km from its mouth. It runs perpendicular to the coastline for around 3 km and divides into southern and northern wings. Covering an area of 215.36 acres, the Muttukadu backwater forms a complex network of shallow estuaries, predominantly utilized for fishing and boating activities. The geological composition of the study area comprises Charnockite rocks as the basement, covered by a substantial layer of Quaternary alluvium. Overlying the alluvium, there are deposits from the Holocene tidal flats and coastal dunes. The backwater extends approximately 15 km in both the northern and southern directions, eventually opening into the Bay of Bengal at its eastern end. During the northeast monsoon period, floodwaters from the surrounding regions and the Buckingham Canal flow into the backwater. Between October and December, the water from the upper reaches causes inundation, leading to erosion of the sand bar, and subsequently, the connection with the sea is re-established.

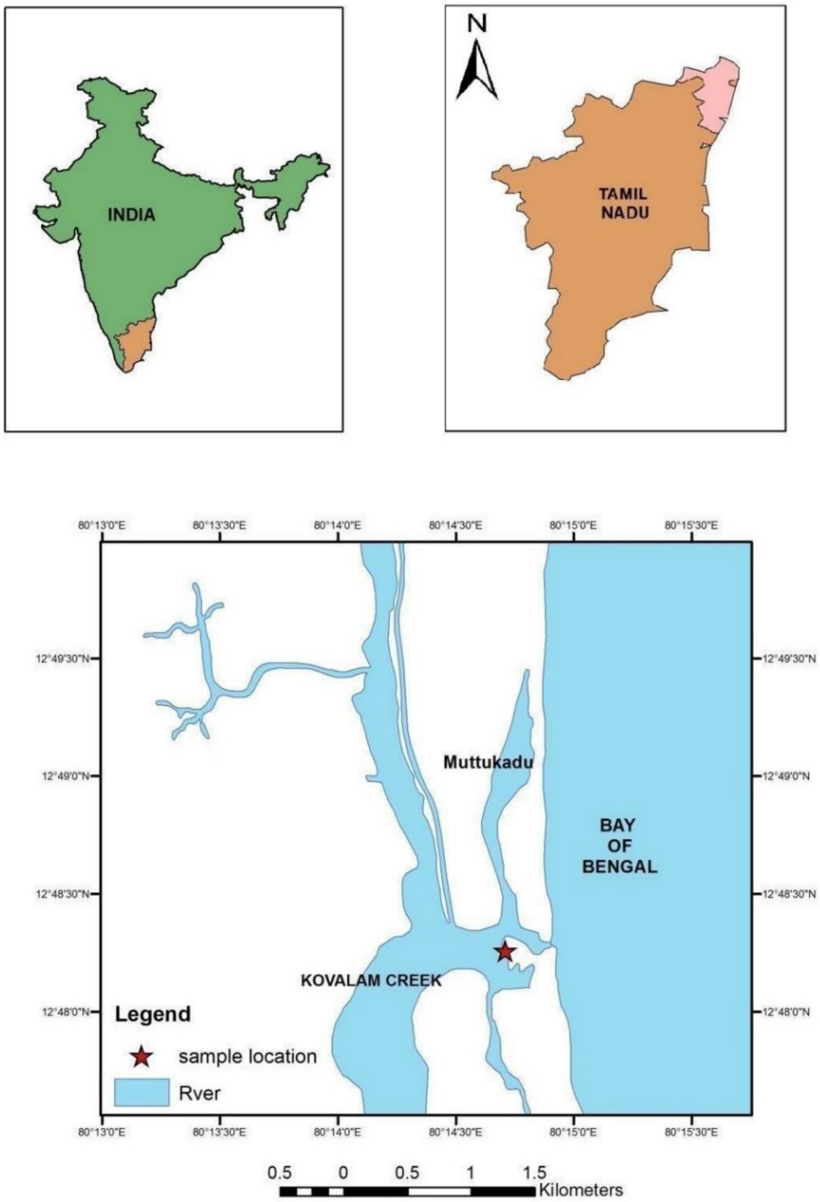


Fig. 1. Location map of the study area.

Materials and methods

In October 2018, fieldwork and core sampling were conducted in the Muttukadu backwaters to investigate the variations of granulometric and sedimentological parameters down the core sample, which had a length of 1.11 meters. The core sediments were sub-sampled at 3 cm intervals, resulting in a total of 37 samples for analysis. To determine the fine fraction silt and clay in the sediments, the pipette method was employed, following the procedure established by Krumbein and Pettijohn (1938). The textural classification of the sediments in this study was based on Trefethen (1950) nomenclature. Calcium carbonate content was determined using the rapid titration method as described by Piper (1947). Organic matter content was measured using the titration method of Gaudette et al. (1974). Granulometric studies of all sediment samples were conducted using standard sieving methods (Ingram, 1971) and pipetting techniques (Galehouse, 1971). Understanding the granulometric properties is vital in discerning the mode of sediment transportation and depositional environments. The weight percentage data from the 37 samples were processed using graphic methods (Folk and Ward, 1957) and moment methods (Friedman, 1961, 1967, 1979) on a personal computer, employing a modified version of Schlee and Webster (1967) procedure. Various statistical parameters, CM diagrams, and bivariate plots were generated from the analysis to gain further insights into the sediment characteristics.

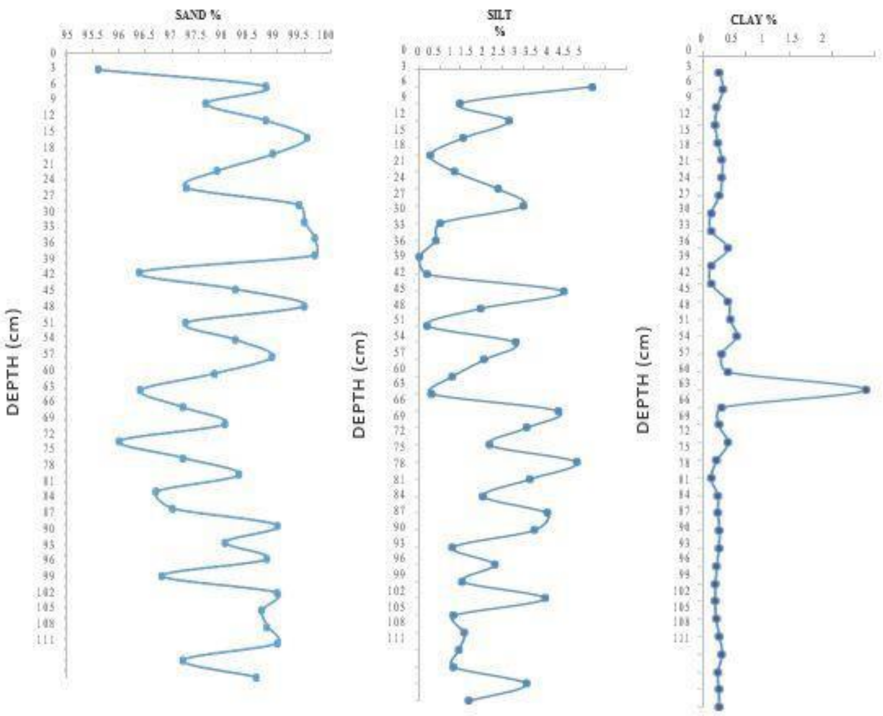


Fig. 2. Down core variation of Sand-Silt-Clay at Muttukadu Backwaters.

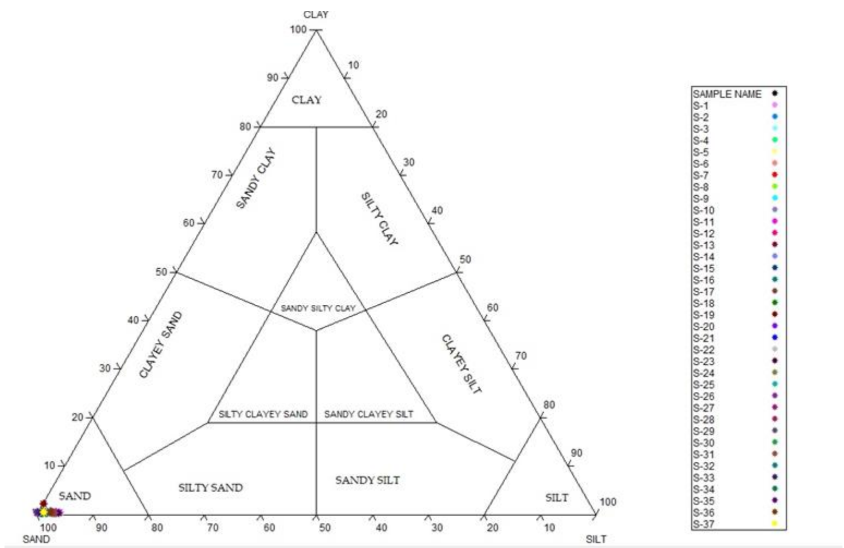


Fig. 3. Ternary diagram showing sand-silt-clay classes for core sample.

Results and Discussions

Table 1 presents the results of sand-silt-clay percentages and ecological parameters. The sand percentage varied from 95.6% to 99.7%, with a mean value of 98.09% (Table 1). The highest sand content was observed in the subsamples at a depth of 30-36 cm, while the lowest values were recorded at a depth of 0-3 cm. Silt content ranged from 0 to 4.2%, with an average value of 1.66%. The down-core plots (Fig. 2) indicate that the maximum silt content was registered at 0-3 cm, and the minimum values were recorded at a depth of 30-33 cm. Clay content ranged from 0.10% to 1.9%, with an average value of 0.25%. The highest clay content was observed at a depth of 54-57 cm, while the lowest values were found at depths of 24-30 cm, 33-39 cm, and 69-72 cm.

Generally, the core's high percentage of sand suggests a relatively medium to high energy environment during sediment deposition. The ternary diagram (Fig. 3) confirms that the sediments are predominantly sandy in nature.

Table 1. Sand-silt-clay, $CaCO_3$, and Organic matter (%) in samples.

Sample code	Depth (cm)	Sand%	Clay%	Silt%	$CaCO_3$	OM
S-1	0-3	95.6	0.2	4.2	23	3.14
S-2	3-6	98.78	0.24	0.98	24.5	2.46
S-3	6-9	97.64	0.17	2.19	17.5	3.36
S-4	9-12	98.77	0.15	1.08	25	1.92
S-5	12-15	99.56	0.18	0.26	22.5	1.52
S-6	15-18	98.91	0.23	0.86	22.5	2.78
S-7	18-21	97.85	0.23	1.92	30	2.51
S-8	21-24	97.27	0.2	2.53	32.5	1.88
S-9	24-27	99.4	0.1	0.5	22	1.39
S-10	27-30	99.5	0.1	0.4	28	1.52
S-11	30-33	99.7	0.3	0	27.5	2.37
S-12	33-36	99.7	0.1	0.2	30	2.06
S-13	36-39	96.38	0.1	3.52	30	1.79
S-14	39-42	98.2	0.3	1.5	30	1.7
S-15	42-45	99.5	0.32	0.18	31.5	1.92
S-16	45-48	97.25	0.4	2.35	30	1.83
S-17	48-51	98.2	0.22	1.58	32.5	2.51
S-18	51-54	98.9	0.3	0.8	32.5	2.33
S-19	54-57	97.8	1.9	0.3	32.5	1.92
S-20	57-60	96.4	0.23	3.37	35	3.27
S-21	60-63	97.2	0.19	2.61	32.5	3.72
S-22	63-66	98	0.3	1.7	34	2.46
S-23	66-69	96	0.17	3.83	37.5	2.01
S-24	69-72	97.2	0.1	2.7	32.5	1.88
S-25	72-75	98.27	0.18	1.55	33.5	1.57
S-26	75-78	96.7	0.18	3.12	37	1.61
S-27	78-81	97	0.2	2.8	35	2.01
S-28	81-84	99	0.19	0.81	32	2.06
S-29	84-87	98	0.17	1.83	38.5	1.74
S-30	87-90	98.8	0.15	1.05	34	1.21
S-31	90-93	96.8	0.15	3.05	33.5	0.44
S-32	93-96	99	0.16	0.84	32.5	1.57
S-33	96-99	98.7	0.2	1.1	32.5	2.24
S-34	99-102	98.8	0.23	0.97	32.5	1.43
S-35	102-105	99	0.18	0.82	34	2.28
S-36	105-108	97.2	0.19	2.61	37.5	1.92
S-37	108-111	98.6	0.2	1.2	36	1.92
MAX		**99.7**	**1.9**	**4.2**	**38.5**	**3.72**
MIN		**95.6**	**0.1**	**0**	**17.5**	**0.44**
AVG		**98.09**	**0.24**	**1.65**	**30.91**	**2.06**

Calcium Carbonate

The calcium carbonate concentration in the sediment ranges from 17.5% to 38.5%, with the highest values recorded at depth intervals of 84-87 cm and the lowest values noticed at 6-9 cm. On average, the concentration of $CaCO_3$ is 30.91% (Table 1). Figure 4 illustrates the down-core variations of calcium carbonate. The principal sources of carbonate materials for the sediments in the backwaters primarily consist of skeletal fragments of organisms, calcareous tests of microorganisms like foraminifera, and remnants of oyster beds. These contribute significantly to the presence of calcium carbonate in the sediment composition.

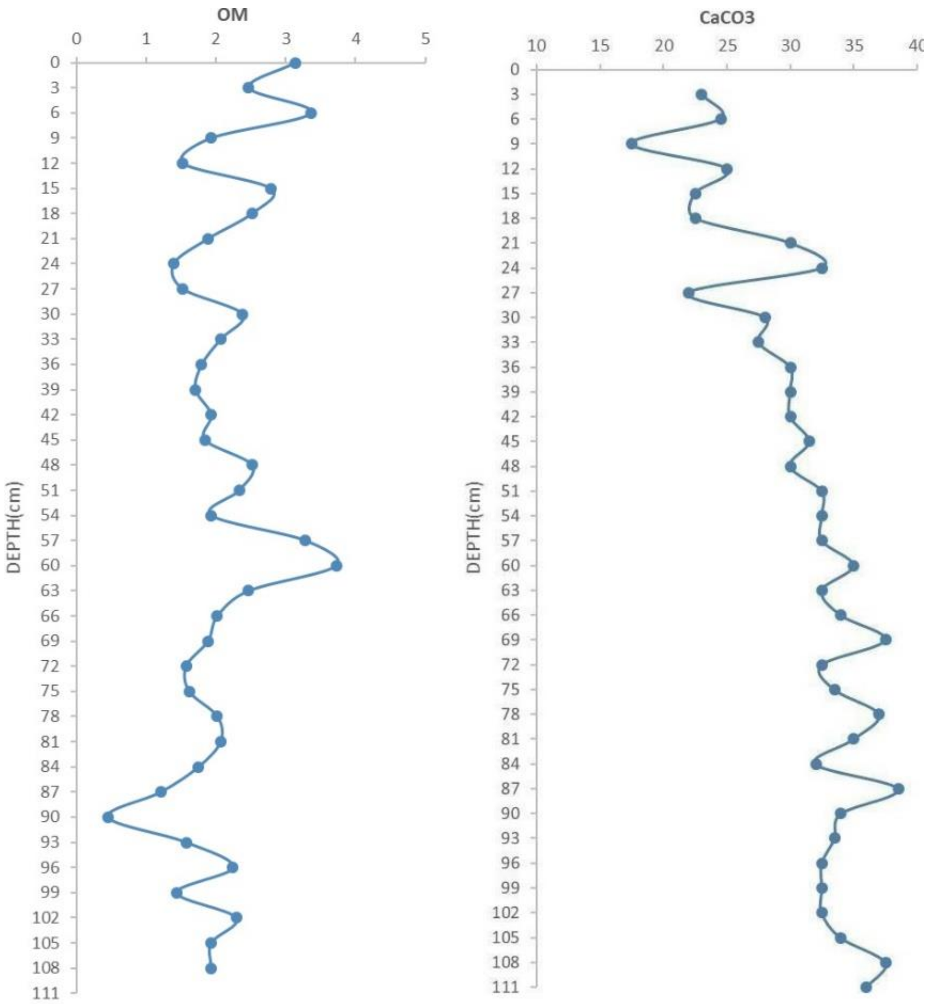


Fig. 4. Down Core Variation of organic matter and $CaCO_3$%

Organic Matter

The organic matter percentage in the subsamples of the core varies from 0.44% to 3.72%, with an average value of 2.06% (Table 1). The lowest value of organic matter is found at the bottom portion of the core (90-93 cm), while the highest value is registered at the depth interval of 60-63 cm (Fig. 4). An abnormally high peak of clay at a depth of 57 cm could be associated with the higher value of organic matter at the same depth. Throughout the core, a lower concentration of organic matter is observed, which may be attributed to sparse vegetation, a predominance of the sand fraction, or the washing out of organic matter due to tidal fluctuations.

Cluster analysis

Cluster analysis was employed to discern local microenvironmental fluctuations in the core. The dendrogram was plotted using the PAST V.3 program (Paleontological Statistics Version 3), considering parameters such as Sand-Silt-Clay, $CaCO_3$, and Organic matter percentage. Four distinct biotopes were identified, and their interpretation was carried out based on their interrelationships. Notably, the core displayed only slight fluctuations in the mentioned sedimentological variables, which were represented on the graph. All 37 subsamples were included in the dendrogram (Fig. 5).

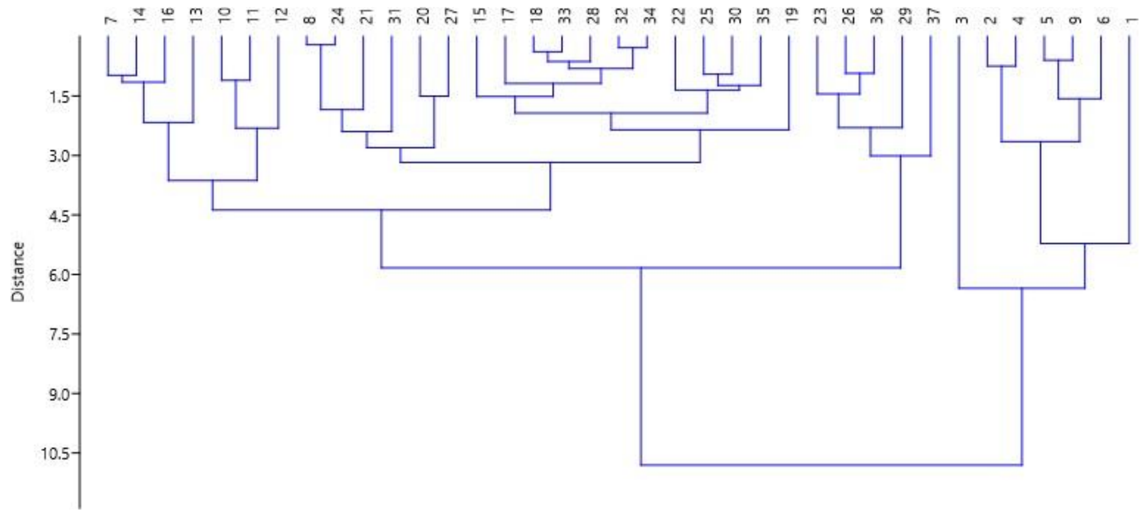


Fig. 5. Dendrogram of Cluster Analysis.

Biotope A: Biotope A comprises sample numbers S7 (18-21cm), S14 (39-42cm), S16 (45-48cm), S13 (36-39cm), S10 (27-30cm), S11 (30-33cm), and S12 (33-36cm), despite the highest values being observed in samples S11 and S12. The absence of silt and minor variations in other sedimentological parameters distinguish them in a separate subbranch.

Biotope B: Biotope B includes sample numbers S8 (21-24cm), S24 (69-72cm), S21 (60-63cm), S31 (90-93cm), S20 (57-60cm), S27 (78-81cm), S15 (42-45cm), S17 (48-51cm), S18 (51-54cm), S33 (96-99cm), S28 (81-84cm), S34 (99-102cm), S22 (63-66cm), S25 (72-75cm), S30 (87-90cm), S35 (102-105cm), and S19 (54-57cm). In this group, relatively lower values of $CaCO_3$ are observed.

Biotope C: Biotope C consists of sample numbers S23 (66-69cm), S26 (75-78cm), S36 (105-108cm), S29 (84-87cm), and S37 (108-111cm). A high amount of calcium carbonate (38.5%) is observed in this group.

Biotope D: Biotope D includes samples S3 (6-9cm), S2 (3-6cm), S4 (9-12cm), S5 (12-15cm), S9 (24-27cm), S6 (15-18cm), and S1 (0-3cm). The sand percentage in sample S1 shows the minimum value, leading to its separation within Biotope D. This group exhibits relatively low calcium carbonate content (22.5%) but a higher amount of organic matter (3.3%), which sets it apart from the others.

Table 2. Statistical parameters (Folk and Ward, 1957).

Sample No.	**FOLK AND WARD VALUES (PHI)**				**FOLK AND WARD DESCRIPTION**			
	Mean	Sorting	Skewness	Kurtosis	Mean	Sorting	Skewness	Kurtosis
S-1	2.261	0.683	0.031	1.234	Fine Sand	Moderately Well Sorted	Symmetrical	Leptokurtic
S-2	2.306	0.666	0.031	1.263	Fine Sand	Moderately Well Sorted	Symmetrical	Leptokurtic
S-3	2.285	0.673	0.017	1.261	Fine Sand	Moderately Well Sorted	Symmetrical	Leptokurtic
S-4	2.199	0.675	0.027	1.188	Fine Sand	Moderately Well Sorted	Symmetrical	Leptokurtic
S-5	2.188	0.576	-0.083	1.01	Fine Sand	Moderately Well Sorted	Symmetrical	Mesokurtic
S-6	2.134	0.62	0.009	1.06	Fine Sand	Moderately Well Sorted	Symmetrical	Mesokurtic
S-7	2.173	0.707	0.036	1.069	Fine Sand	Moderately Sorted	Symmetrical	Mesokurtic
S-8	2.453	0.93	-0.109	1.02	Fine Sand	Moderately Sorted	Coarse Skewed	Mesokurtic
S-9	2.064	1.022	0.217	0.955	Fine Sand	Poorly Sorted	Fine Skewed	Mesokurtic
S-10	1.564	0.901	0.229	1.517	Medium Sand	Moderately Sorted	Fine Skewed	Very Leptokurtic
S-11	1.31	0.707	0.02	1.086	Medium Sand	Moderately Sorted	Symmetrical	Mesokurtic

S-12	1.249	0.645	-0.016	1.099	Medium Sand	Moderately Well Sorted	Symmetrical	Mesokurtic
S-13	1.074	0.737	0	0.87	Medium Sand	Moderately Sorted	Symmetrical	Platykurtic
S-14	1.135	0.874	-0.176	0.834	Medium Sand	Moderately Sorted	Coarse Skewed	Platykurtic
S-15	1.062	0.818	0.009	0.805	Medium Sand	Moderately Sorted	Symmetrical	Platykurtic
S-16	0.77	0.903	0.474	0.867	Coarse Sand	Moderately Sorted	Very Fine Skewed	Platykurtic
S-17	0.672	1.39	0.31	0.846	Coarse Sand	Poorly Sorted	Very Fine Skewed	Platykurtic
S-18	1.785	1.024	-0.194	1.526	Medium Sand	Poorly Sorted	Coarse Skewed	Very Leptokurtic
S-19	2.117	0.804	0.008	1.477	Fine Sand	Moderately Sorted	Symmetrical	Leptokurtic
S-20	2.419	0.634	0.056	1.079	Fine Sand	Moderately Well Sorted	Symmetrical	Mesokurtic
S-21	2.759	0.769	-0.139	1.268	Fine Sand	Moderately Sorted	Coarse Skewed	Leptokurtic
S-22	2.623	1.132	-0.442	1.082	Fine Sand	Poorly Sorted	Very Coarse Skewed	Mesokurtic
S-23	1.589	1.379	0.266	0.642	Medium Sand	Poorly Sorted	Fine Skewed	Very Platykurtic
S-24	1.16	1.036	0.093	0.989	Medium Sand	Poorly Sorted	Symmetrical	Mesokurtic
S-25	0.989	0.829	0.087	1.154	Coarse Sand	Moderately Sorted	Symmetrical	Leptokurtic
S-26	0.82	0.827	0.16	1.036	Coarse Sand	Moderately Sorted	Fine Skewed	Mesokurtic
S-27	0.663	0.696	0.122	0.874	Coarse Sand	Moderately Well Sorted	Fine Skewed	Platykurtic
S-28	0.666	0.699	0.087	0.837	Coarse Sand	Moderately Well Sorted	Symmetrical	Platykurtic
S-29	0.857	0.657	-0.182	0.874	Coarse Sand	Moderately Well Sorted	Coarse Skewed	Platykurtic
S-30	0.821	0.621	-0.088	0.822	Coarse Sand	Moderately Well Sorted	Symmetrical	Platykurtic
S-31	0.88	0.644	-0.127	0.848	Coarse Sand	Moderately Well Sorted	Coarse Skewed	Platykurtic
S-32	1.181	0.597	-0.178	1.22	Medium Sand	Moderately Well Sorted	Coarse Skewed	Leptokurtic
S-33	1.235	0.544	-0.114	1.434	Medium Sand	Moderately Well Sorted	Coarse Skewed	Leptokurtic
S-34	1.252	0.592	-0.082	1.383	Medium Sand	Moderately Well Sorted	Symmetrical	Leptokurtic
S-35	1.146	0.642	-0.132	1.22	Medium Sand	Moderately Well Sorted	Coarse Skewed	Leptokurtic
S-36	1.203	0.627	-0.083	1.316	Medium Sand	Moderately Well Sorted	Symmetrical	Leptokurtic
S-37	1.19	0.704	-0.07	1.112	Medium Sand	Moderately Sorted	Symmetrical	Leptokurtic

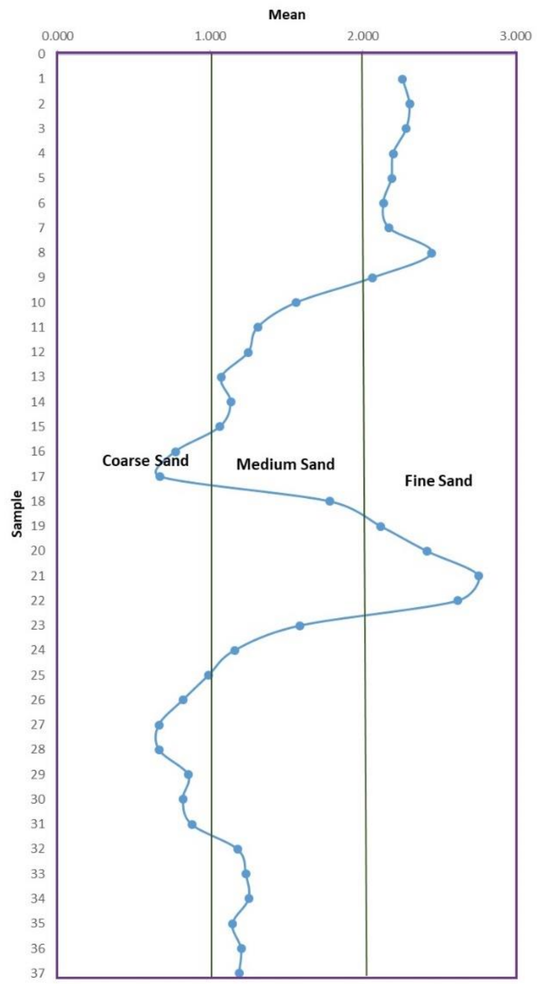


Fig. 6. Graph shows the down core variation of Mean.

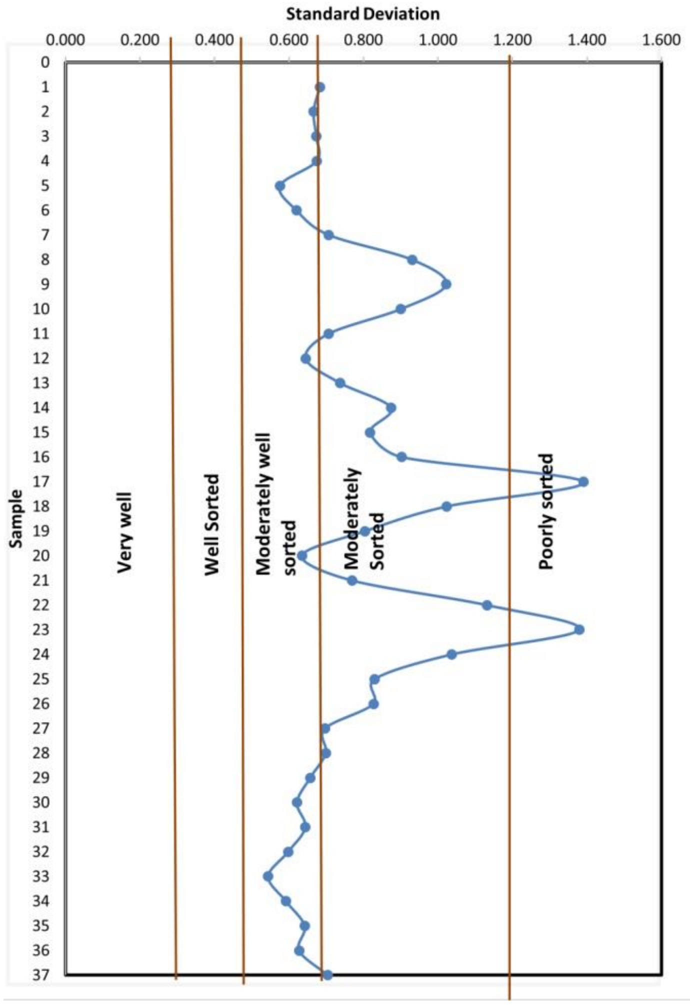


Fig. 7. Graph shows down core variation of sorting.

Granulometric studies

Over the past five decades, granulometric studies of unconsolidated sediments have been extensively researched due to their fundamental relevance to sediment transport and deposition mechanisms. Proper selection and combination of statistical parameters have proven effective in distinguishing various ancient and recent sediment deposition environments (Folk, 1966; Friedman, 1967; Hails and Hoyt, 1969). Additionally, particle size distribution significantly influences the mineralogical (Mishra, 1969; Patro et al., 1989) and chemical (Williams et al., 1978; Forstner and Wittmann, 1983) constituents of sediments. Sedimentologists widely use grain size analysis to classify sedimentary environments and understand transport dynamics. The grain sizes of sediments provide valuable insights into the shear stress required to initiate and maintain particle movement. Several factors, including wave and wind parameters, distance from the source, source material, agent velocity, topography, and transport mechanisms, influence grain size distribution. Grain size studies offer essential clues about sediment provenance, transport history, and depositional conditions (Folk and Ward, 1957; Friedman, 1979; Bui et al., 1990; Ganesh et al., 2012). Therefore, understanding textural parameters is crucial in differentiating various recent and ancient sedimentary environments (Mason and Folk, 1958; Friedman, 1961; Nordstorn,1977; Kumar et al., 2010). Different agents, such as wind and water, commonly segregate particles based on their size (Friedman and Sanders, 1978). Sediment texture is closely related to topography, wave, and current patterns, as well as depositional conditions (Singh et al., 1998). Worldwide, rivers transport approximately 15-16 × 109 tons of sediments to the oceans annually (Milliman and Meade, 1983; Walling and Webb, 1983). In the case of Indian rivers, Subramanian et al. (1987) reported an estimated annual sediment transport of about 1.2×109 tons. This study aims to understand the transportation mechanisms and establish relationships between statistical parameters by examining particle size distribution.

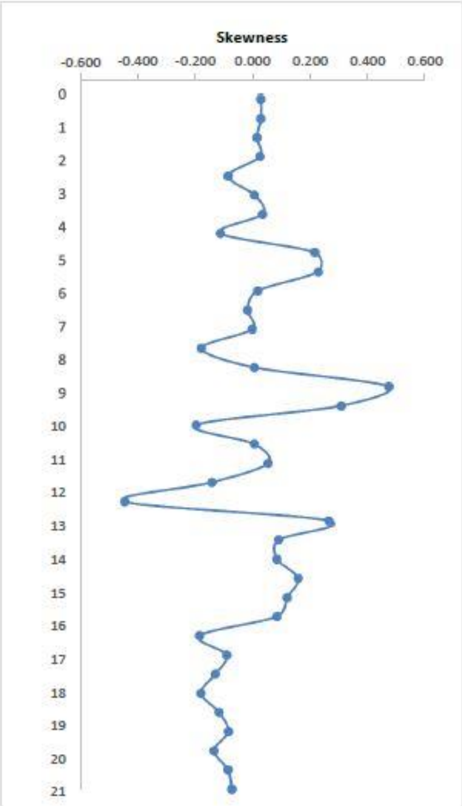


Fig. 8. Graph shows the down core variation of skewness.

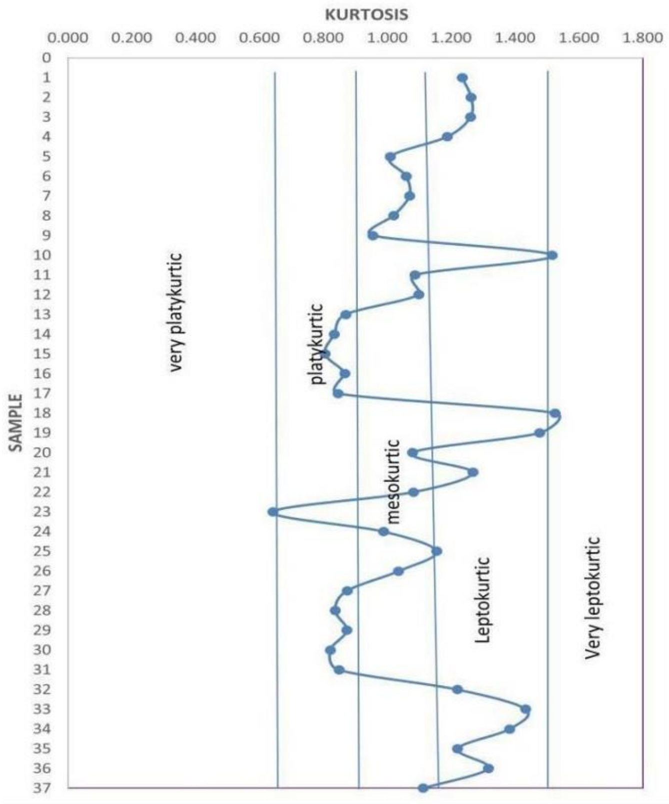


Fig. 9. Graph shows down core variation of kurtosis.

Statistical parameters

The statistical measures of frequency distribution are determined graphically, such as standard deviation, graphic mean, kurtosis, and skewness. In a cumulative percentage curve, the grain sizes corresponding to one percentage is termed the one percentile. The particle sizes corresponding to cumulative percentages 5, 16, 25, 50, 75, 84, and 95 were determined for each sample. The textural analysis of sediments and the weight percentages of sediment distribution are displayed in Table 2. Frequency distribution curves for mean size, standard deviation, skewness, and kurtosis were constructed to decipher statistically the significant variation in the sediments from different sub-environments. These plots enable the comparison of the range of sorting, skewness, etc. in each environment and also depict the degree of overlap (Mason and Folk, 1958).

Graphic Mean (Mz)

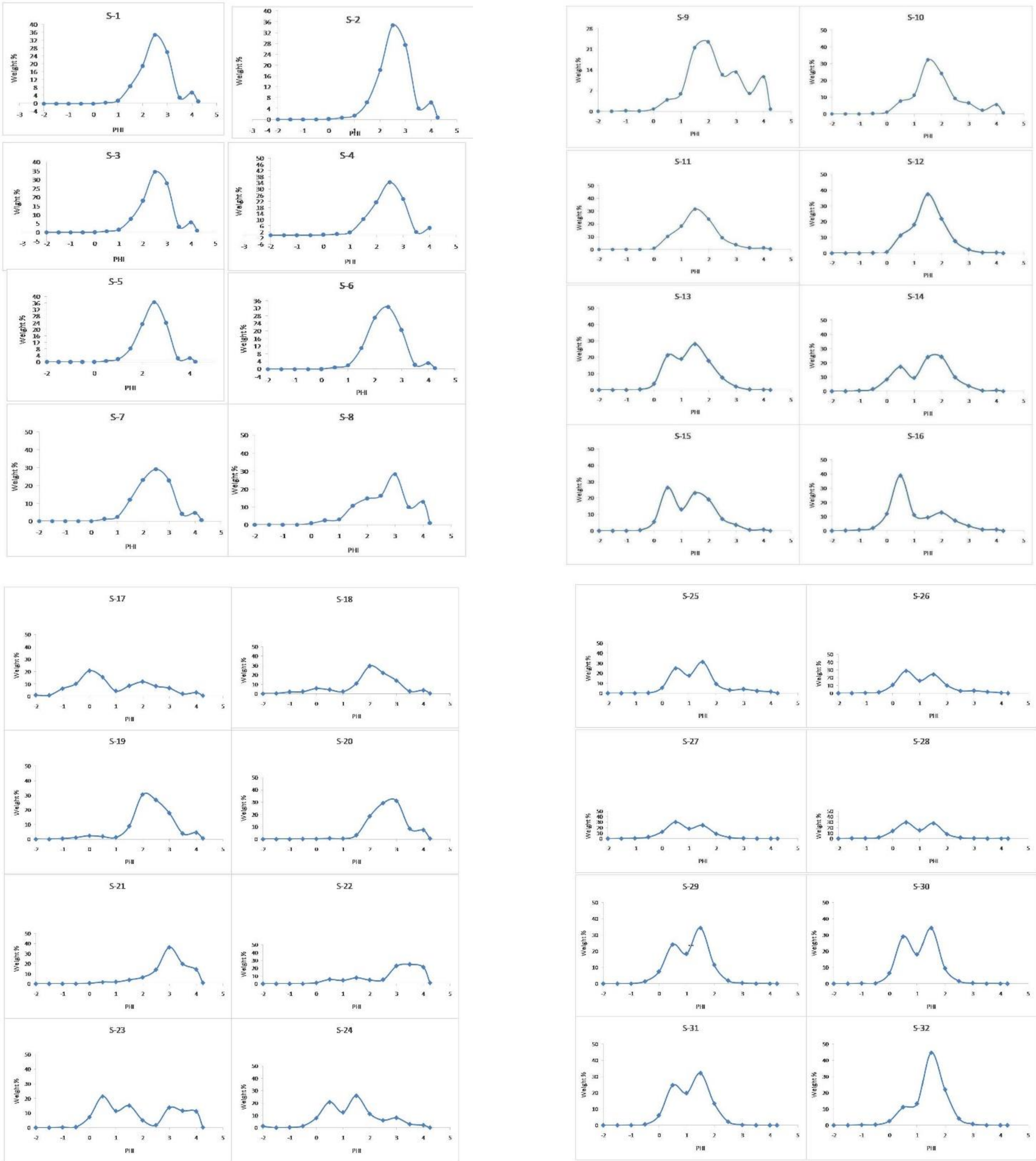
The sediments' mean size ranges between 0.663Φ and 2.759Φ, with an average of 1.520Φ, suggesting medium-sized environments. Medium sand contributes approximately 40.3%, and fine sand makes up 24% of the total samples (Table 2, Fig. 6). The presence of medium to fine-sized sand indicates a high-energy condition prevailing in the area during deposition. This observation is further supported by grain-size photographs. The variations in Ø mean size reflect the differential energy conditions of the depositing medium, providing insight into the average kinetic energy of the depositing agent (Sahu, 1964).

Standard deviation

The graphic standard deviation (σI) serves as a measure of sediment sorting, indicating fluctuations in the energy conditions of the depositional environment. However, it does not necessarily quantify the extent to which the sediments have been mixed (Spencer, 1963). In the present samples, the standard deviation ranges between 0.544 Ø and 1.390 Ø (Table 2, Fig. 7), with an average of 0.783 Ø. Approximately 39.64% of the samples exhibit moderately well-sorted characteristics, while 36.26% show moderately sorted characteristics. The moderately well-sorted nature can be attributed to partial winnowing action and the addition of sediments in beach environments due to aeolian processes (Ramamohan Rao et al., 1982; Narayana Rao et al., 1991; Angusamy et al., 2006; Rajesh et al., 2007).

Skewness

The graphic skewness values of the Muttukadu estuary samples range from -0.442 to 0.474, indicating a range from very coarsely skewed to very finely skewed sediments. The distribution is as follows: symmetrically skewed (54%), coarsely skewed (24%), finely skewed (14%), very finely skewed (5%), and very coarsely skewed (3%) (Table 2; Fig. 8). The wide variation in skewness values suggests that erosion, transportation, and sedimentation conditions were not uniform throughout the deposition of the sediments. Positive skewness of sediments indicates deposition in sheltered, low-energy environments, while negative skewness indicates deposition in high-energy environments (Reddy et al., 2011). The majority of samples in the study area exhibit negative skewness, indicating a high-energy nature of beach erosion in general (Friedman, 1961) and multidirectional sediment transport (Martins, 1965). The pie diagram in (Fig. 8) illustrates that symmetrically skewed sediments (54%) followed by coarsely skewed sediments (24%) dominate the distribution.



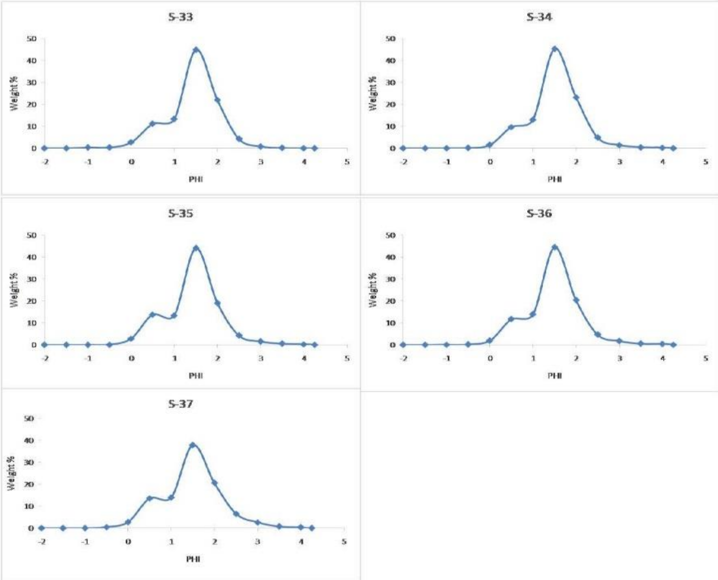


Fig. 10. Frequency distribution of Curves of the Muttukadu backwater samples (S-1 to S-37).

Kurtosis

Kurtosis measures the ratio between the sorting in the tails of the distribution and the sorting in the central portion of the distribution. It is a measure of the degree of peakness of a curve. Curves that are more peaked than the normal distribution curve are referred to as leptokurtic, while those that are flatter than the normal curve are known as platykurtic. In the study area, the graphic kurtosis varies and ranges from 0.642 to 1.526, with an average of 1.086. Based on Folk's classification, the samples from the study area are leptokurtic, followed by the mesokurtic nature of the sediments (Table 2, Fig. 9). Leptokurtic indicates a high angularity of the sediments.

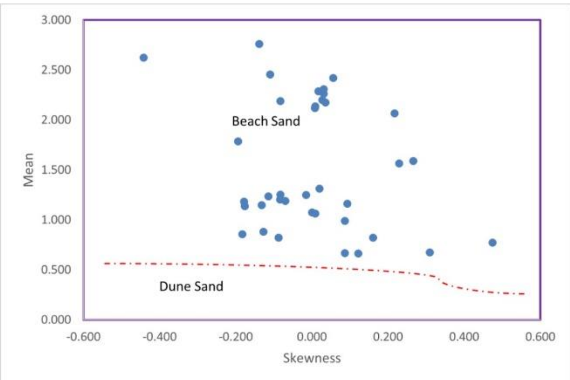


Fig. 11. Graph shows bivarient plots of skewness v/s mean.

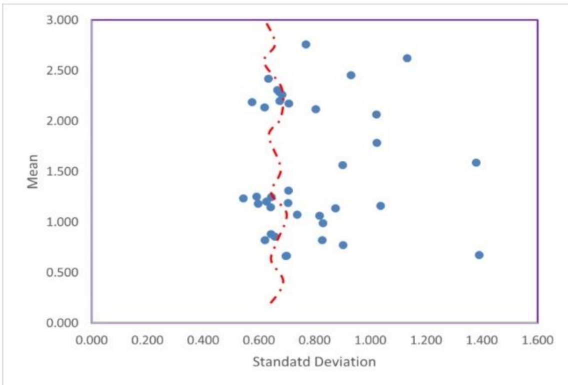


Fig. 12. Graph shows bivarient plots of standard deviations v/s mean.

Frequency Distribution Curves

The frequency curves in the study exhibit typical patterns of sediment distribution at different depths, including unimodal, bimodal, and polymodal patterns. Samples 11 and 12 (Fig. 10) display a clear unimodal distribution. A bimodal distribution is observed in the top and bottom samples, indicating sediments from two different sources. Polymodal distribution is represented by samples 8, 9, 10, 17, 18, 22, 23, and 24, suggesting multiple sources for these sediments. The majority of the sediments in the study area display a bimodal nature, with only a few showing polymodal or unimodal distribution. The unimodal distribution in the remaining stations indicates sediment deposition primarily influenced by waves and currents. Overall, the sediments appear to have originated from two main sources, likely river and beach environments. The transportation of sediments is influenced by longshore current action and erosional activities during monsoonal conditions.

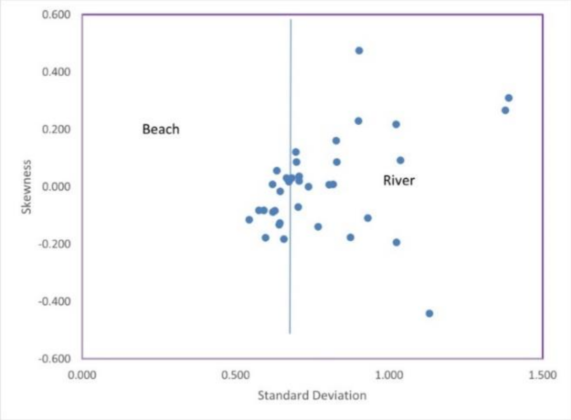


Fig. 13. Graph shows bivarient plots of standard deviations v/s skewness.

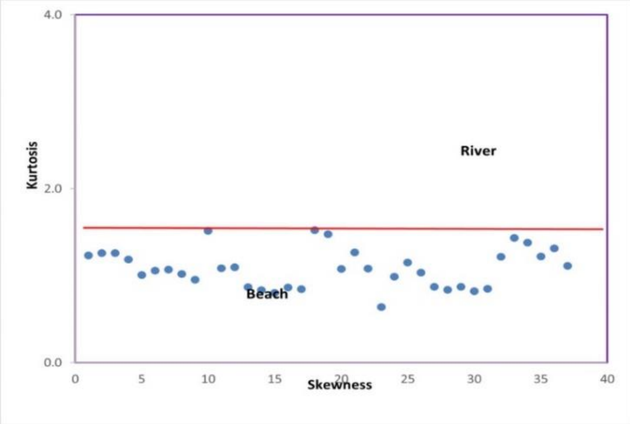


Fig. 14. Graph shows bivarient plots of skewness v/s kurtosis.

Bivariant Plots

Bivariate plots between certain parameters offer valuable insights into energy conditions, transportation mediums, and deposition modes. Passega (1957), Visher (1969), Folk and Ward (1957), and others have described how these trends and interrelationships observed in bivariate plots can indicate the mode of deposition and help identify specific environments. Mason and Folk (1958) and Friedman (1961) have claimed that these scatter plots are effective in differentiating between aeolian, beach, and river sediments. In the case of the Muttukadu estuary core sediments, an attempt has been made to utilize these scatter plots. The study region reflects the influence of both fluvial and beach environments. The Skewness vs. mean bivariate plot (Fig. 11) allows for discriminating between beach sand (eolian) and dune sand, following the classification proposed by Friedman (1961). The bivariate plot of mean vs. standard deviation (Fig. 12) indicates that the sediments in the fluvial environment are moderately well sorted (Fig. 13). Additionally, this plot suggests that these sediments may be the result of flash floods or storm surges, where the river input outweighs the littoral current. The frequency distribution in the study area reveals that the majority of these sediments exhibit a bimodal nature, followed by a polymodal distribution. The Muttukadu core sediments are characterized by medium sand with moderate to good sorting. Skewness analysis indicates a symmetrical nature of sediment deposition, while kurtosis values suggest a combination of leptokurtic and mesokurtic characteristics in the sediments (Fig. 14). These observations collectively indicate that the sand in the study area was deposited in a relatively high-energy environment.

Discussion

The core study results reveal that sand is the dominant component of the sediments. All the samples in the sand-silt-clay triangular plot belong to the sand category, indicating variations in energy conditions and different source materials from the vicinity and coastal processes. Kalpana and Usha Natesan (2014) observed that the percentage of sand in Muttukadu sediments is higher during the monsoon, attributed to the winnowing activity of monsoonal floods and tidal actions. The core also exhibits a high content of calcium carbonate in the down-core direction. Decreased freshwater flows can influence the amount of organic matter entering a coastal waterway and its rate of flushing into the ocean (Becking and Moore, 1959). The surface sediments in the Muttukadu backwaters consist predominantly of silty clay and sand. Fine-grained sediments demonstrate a positive correlation with Fe and show a higher affinity for organic matter, likely due to increased dust and fine-grained terrestrial influx transported into the deeper Muttukadu backwaters. Seven species of benthic foraminifera were identified throughout the entire core, including *Ammoniabeccarii, Psuedorotalia schroeteriana*, *Quinqueloculina seminulum*, *Triloculina trigonula*, and *Rupertinella rupertiana*. The presence of these foraminifera species suggests a shallow marine environment, and their distribution throughout the core can be attributed to the prevailing tidal oscillations during that period (Fig. 15). Distribution of Foraminifera species in Muttukadu backwater core sample. The textural data and size analysis indicate that the sediments fall within Wentworth's size class of medium sand, suggesting high energetic conditions of transportation in coastal sediments. The variations in phi mean size reflect differences in the energy conditions of the depositing medium, providing insight into the average kinetic energy of the depositing agent. Most of the core samples exhibit a moderately well-sorted to moderately sorted nature, with sorting variations suggesting differences in water turbulence and the velocity of the depositional current. The moderately well-sorted nature can be attributed to partial winnowing action and the addition of sediments to the beach environment through aeolian processes.

The graphic skewness values range from coarse to symmetrical to finely skewed. Positive skewness of sediments indicates deposition in high-energy environments, while negative skewness, observed in the majority of the samples from the study area, indicates the high-energy nature of beach deposits in general and multidirectional sediment transport. The graphic kurtosis values range from leptokurtic to mesokurtic, suggesting that extremely high or low values of kurtosis imply that some sediments achieved their sorting in a high-energy environment elsewhere. The variation in kurtosis values reflects the flow characteristics of the depositional medium. The frequency curves show a dominant presence of medium sand, suggesting deposition under high fluvial discharge and high-energy currents as suspended load. The study area's frequency distribution indicates that most of the sediments are bimodal in nature, with the remaining stations showing unimodal distribution, likely reflecting deposition by waves and currents. The sediments appear to have originated from two sources, possibly river and beach environments. Bivariate plots reveal that most points concentrate in the river field, with a spread of plots in the beach field, indicating a beach environment. The study demonstrates that scatter plots are a powerful tool for isolating different environments.

Fig. 15. Distribution of Foraminifera species in Muttukadu backwater core sample.

Conclusions

Based on the grain size studies and their bivariate plots, it can be inferred that the sediments in the top portion of the core, specifically at 51-54 cm, indicate a depositional environment, while the sediments in the remaining portion, from 58-104 cm, indicate an erosional environment. The presence of a consistent foraminiferal assemblage throughout the entire core suggests a shallow marine environment, which was influenced by tidal oscillations during that period. The down-core plots reveal that the maximum silt content is registered at 0-3 cm depth, with minimum values recorded at a depth of 30-33 cm. The clay content ranges from 0.10% to 1.9%, with an average value of 0.25%. The maximum clay content is recorded at a depth of 54-57 cm, while the minimum values are observed at depths of 24-30 cm, 33-39 cm, and 69-72 cm. Generally, the high percentage of sand in the core suggests a relatively medium to high-energy environment during the deposition of sediments. The core displayed a low concentration of organic matter, likely due to limited vegetation, the flushing out of organic material by tidal fluctuations, or a higher percentage of sand. These sediments were likely transported by longshore currents and erosional activities during monsoonal conditions. Moreover, bivariate plots between statistical parameters proved valuable in interpreting energy conditions, transportation medium, mode of deposition, and other relevant factors.

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