DEPIK
Jurnal Ilmu-Ilmu Perairan, Pesisir dan Perikanan
Journal homepage: www.jurnal.usk.ac.id/depik

Grain size properties of estuary sediment from Aceh Jaya, Aceh

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ARTICLE INFO

Keywords:
Sediment grain distribution
Textural of sediment
Aceh Jaya Estuary
Sorting
Skewness

DOI: 10.13170/depik.13.1.36454

ABSTRACT

This study aimed to determine the sediment grain size distribution in four estuary locations in Aceh Jaya (Kuta Tuha, Lhok Geulumpang, Krueng No, Keude Unga). These findings will contribute to our understanding of sediment dynamics in estuarine environments and inform management strategies for these critical coastal habitats. The methods used in this study, such as mean, sorting, skewness, and kurtosis, and determination of sediment textural with ternary plot, were used to determine the sediment grain size distribution. In Addition, it will examine the relationship between sediment grain size composition and spatial distance to mouth bar using the Spearman correlation. Composition sediment at all locations dominated by fine sand. Grain size variations (26.735 – 198.709 µm) show that at all locations mainly consists of very fine sand whereas at Kuta Tuha combination of fine sand and medium sand. The variations of sorting (1.193 – 2.59), skewness (-0.625 – 0.876) and kurtosis (0.46 – 6.883) indicate moderately sorted, very coarse skewed, and very platykurtic sediments. Textural sediment classified as sand, silty sand, and very slightly silty sand. We also found positive correlation between spatial distance from mouth bar and sediment composition. These findings will contribute to our understanding of sediment dynamics in estuarine environments and inform management strategies.

Introduction

Aceh Jaya, with its coastline stretching 221.95 km and a sea area of approximately 2,718.50 km^2, is a home to 45 islands spread across 6 sub-districts (BPS Aceh Jaya, 2016). The coastal areas, classified as The Lowland Coastal Mountain Chain, are ecologically diverse, featuring sandy beaches, muddy river estuaries, and mangrove forests.

Estuaries are dynamic coastal water bodies where freshwater and saltwater interplay (Jordan *et al.*, 2021), creating a complex environment that significantly influences sediment movement and settling (Souza *et al.*, 2013; Zhao *et al.*, 2019; Syarifudin *et al.*, 2020). The sediment grain size distribution in these estuaries provides crucial insights into the source, transport, and deposition of sediments.

Sediments originate from diverse sources such as rivers, oceans, or surrounding land, each contributing distinct characteristics (Li *et al.*, 2021). For instance, river sediments are usually finer due to weathering and erosion during transport (Chang *et al.*, 2020), whereas ocean sediments are typically coarser (Flor-Blanco *et al.*, 2022), derived from marine organisms or wave action (Sampath *et al.*, 2011). Land sediments exhibit a mix of characteristics (Li *et al.*, 2021)., depending on the area's geology and topography. Hydrodynamic conditions, including tides, currents, waves, and wind, affect the movement and deposition of sediments (Magar, 2016; Flor-Blanco *et al.*, 2022). These conditions can vary within an estuary, creating different zones of sediment transport and deposition.

In Aceh Jaya, the sediment characteristics are influenced by several factors, such as the soil texture, the organic matter content, the heavy metal concentration, and the grain size distribution. The soil texture in Aceh Jaya is sand to clay, the C-organic content ranges from 0.10% to 2.83% (Hermi, 2020). The heavy metal concentration, especially mercury

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p-ISSN 2089-7790; e-ISSN 2502-6194
Received 27 December 2023; Received in revised form 18 January 2024; Accepted 02 February 2024
Available online 23 April 2024

(Hg), is relatively high in some areas due to the gold mining activities in the upstream region of the Krueng Sabee River (Suhud *et al.*, 2020). The grain size distribution varies from fine to coarse, depending on the location and the distance from the river mouth (Rahman *et al.*, 2017). These factors affect the sediment quality and the ecological health of the estuaries in Aceh Jaya.

This study aimed to determine the sediment grain size distribution in four estuary locations in Aceh Jaya (Kuta Tuha, Lhok Geulumpang, Krueng No, Keude Unga). These findings will contribute to our understanding of sediment dynamics in estuarine environments and inform management strategies for these critical coastal habitats. Previous research on sediment in the estuary area in Aceh Jaya has been conducted by Hermi (2020), focusing on sediment texture, and Rafanta (2019), studying drifting sediments in one of the estuary areas. To determine the sediment grain size distribution and its relationship with the spatial distance to the mouth bar, we used various statistical methods, such as

Table 1. Stations spatial coordinates and distances of sampling stations in four locations (KT: Kuta Tuha, LG: Lhok Geulumpang, KN: Krueng No and KU: Keude Unga).

Location	Stations	Latitude	Longitude	Distance to mouth bar (m)	Distance to mangrove (m)
KT	KT1	4.535619	95.71071	455.15	40.62
KT	KT2	4.534881	95.71104	330.3	114.43
KT	KT3	4.533999	95.71145	230.71	233.77
LG	LG1	4.711227	95.51483	179.7	6.7
LG	LG2	4.710607	95.5145	93.2	55.88
LG	LG3	4.710531	95.51413	35.79	95.71
KN	KN1	4.938056	95.37583	51.52	5.09
KN	KN2	4.937778	95.37583	45.89	8.35
KN	KN3	4.937778	95.37611	43.95	6.72
KU	KU1	5.010556	95.37194	174.4	124.37
KU	KU2	5.010833	95.37194	131.31	157.96
KU	KU3	5.01	95.37306	334.64	4.3

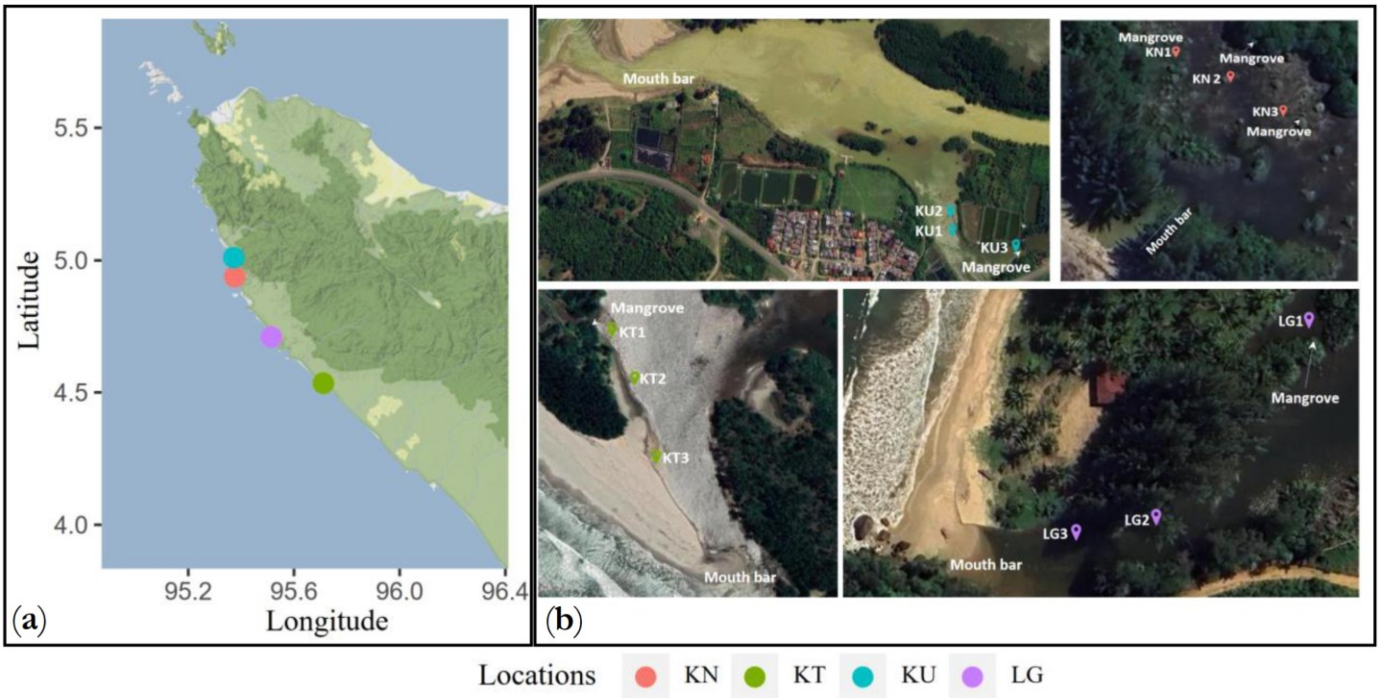

Figure 1. (a) Location of the study area, (b) Stations at each location with mark of mouth bar and nearest mangrove vegetation (KT: Kuta Tuha, LG: Lhok Geulumpang, KN: Krueng No, and KU: Keude Unga).

mean, sorting, skewness, and kurtosis, as well as graphical methods, such as the ternary plot by Blott and Pye (2012). The details of these methods are explained in the methods section.

Materials and Methods
Sediment Sampling

Sediment samples from the Aceh Jaya estuary were collected in November 2023, at four locations (Kuta Tuha, Lhok Geulumpang, Krueng No, Keude Unga), each with three stations (Table 1 and Figure 1).The samples were collected using a 2.5-inch PVC pipe with a height of 20 cm.

Table 2. Statistical equation used in the calculation geometrically and logarithmically of grain size parameters by Folk and Ward (1957) (*P* is percentile size of grain, measured in µm, φ is percentile size of grain, measured in " φ ").

Parameters	Geometric
$\bar{x}$	$\bar{x} = exp\frac{\ln P_{16} + \ln P_{50} + \ln P_{84}}{3}$
s	$\sigma = \exp\left(\frac{\ln P_{16} - \ln P_{84}}{4} + \frac{\ln P_5 - \ln P_{95}}{6.6}\right)$
Sk	$Sk = \frac{\ln P_{16} + \ln P_{84} - 2(\ln P_{50})}{2(\ln P_{84} - \ln P_{16})} + \frac{\ln P_5 + \ln P_{95} - 2(\ln P_{50})}{2(\ln P_{25} - \ln P_5)}$
K	$K = \frac{\ln P_5 - \ln P_{95}}{2.44(\ln P_{25} - \ln P_{75})}$
Parameters	**Logarithmic**
$\bar{x}$	$\bar{x} = \frac{\varphi_{16} + \varphi_{50} + \varphi_{84}}{3}$
s	$\sigma = \frac{\varphi_{84} - \varphi_{16}}{4} + \frac{\varphi_{95} - \varphi_5}{6.6}$
Sk	$Sk = \frac{\varphi_{16} + \varphi_{84} - 2\varphi_{50}}{2(\varphi_{84} - \varphi_{16})} + \frac{\varphi_5 + \varphi_{95} - 2\varphi_{50}}{2(\varphi_{95} - \varphi_5)}$
K	$K = \frac{\varphi_{95} - \varphi_5}{2.44(\varphi_{75} - \varphi_{25})}$

Sediment Grain Size Measurements

Each sample was placed in a labeled plastic tray. All samples were dried at room temperature for up to 10 days. After dryieng, the clumped sediment was crushed manually by hand, and further segregation of sediment grain size was performed using sieve with mesh sizes from the largest to the smallest: 1 mm, 0.5 mm, 0.125 mm, 0.063 mm, and 0.0385 mm. Later on, the sieves were shaken manually for 1 hours. After proper shaking, the sediment deposited on each sieve was measured using a balance with an accuracy of 0.1 g.

The weighing results are then tabulated into the mm and phi (φ) size scales, with weight data transformed into percentages. the percentage of particles falling into each predetermined size fraction, identified from Udden (1914), Wentworth (1922), and Blott and Pye (2001).

Data analysis

The parameters of mean grain size, sorting, skewness, and kurtosis were calculated using Folk and Ward (1957) methods either geometrically based on the log-normal distribution with metric size values or logarithmically based on the log-normal distribution with the value of phi size. The equations used in these calculations are shown in Table 2.

Using the R application and the G2Sd package (Fournier, 2014), we calculated the values of mean grain size, sorting, skewness, and kurtosis. This package is a newer version of the Gradistat v.4.0 macro for MS Excel, which Blott and Pye (2001) designed for phi sieves and laser granulometer. It can handle data from sieves that use either metric (µm) or phi (φ) units.

We classified the particle size distribution suggested by Blott and Pye (2012) on the basis of the

Depik Jurnal Ilmu-Ilmu Perairan, Pesisir dan Perikanan
Volume 13, Number 1, Page 54-63

percentages of sand-silt-clay (SSC ternary plot) because Blott and Pye (2012) classification systems are more logical and provide a higher level of discriminatory power and descriptive precision, and have the potential for wide adoption. We also calculated the Spearman correlation (R) between sediment particle size distribution and distance from each stations the to mouth bar (as proxy changes in tidal current velocity along the estuary) that were grouped by locations using the stat_cor function in the ggpubr package (Kassambara, 2023) , data that had previously been transformed into the form of log (x + 1). The results were plotted using the ggplot2 package (Wickham, 2016) and combined using the patchwork (Pederson, 2023) package in R.

Results

Sediment grain size composition

The most dominant type of sediment at all stasions is fine sand, which makes up more than half of each bar in most stations (Figure 3). The average percentage of fine sand across all stations is 62%. The highest percentage of fine sand is at Krueng No (KN3) with 84.91%, and the lowest percentage is at station Keude Unga (KU1) with 34.87%.

The second most dominant type of sediment is very fine sand, which varies across stations but generally occupies a smaller portion than the fine sand of each bar. The average percentage of very fine sand across all stations is 20.81%. The highest percentage of very fine sand is at Keude Unga (KU3) (47.07%), and the lowest percentage of very fine sand is at station LG3 (1.84%).

The least dominant materials are very coarse silt and coarse sand, which are present in minimal amounts at each station. The average percentage of very coarse silt across all stations is 3.79 %, and the average percentage of coarse sand across all stations is 0.61%. The highest percentage of very coarse silt is at station KU3 (9.40 %), and the highest percentage of coarse sand is at station KT2 (1.51%).

Sediment grain size variations

Sediment grain-size characteristics reveal a great deal about the sedimentary environment and can be used to identify sediment sources. Descriptive statistical measures, such as mean size (μm), sorting (σ), skewness (Sk), and kurtosis (K) of the grain size analysis in the 12 stations are shown in Table 3.

The mean grain size values of all stations, calculated both geometrically and logarithmically, vary significantly . These variations range from 26.735 to 198.709 μm and 1.856 to 3.459 φ respectively, with average grain sizes of 93.392 μm and 2.766 φ. The grain sizes are divided into three classifications: very fine sand (LG2, KN1, KN2, KU1, KU2, and KU3), fine sand (KT1, LG1, and KN3), and medium sand (KT2, KT3, and LG3).

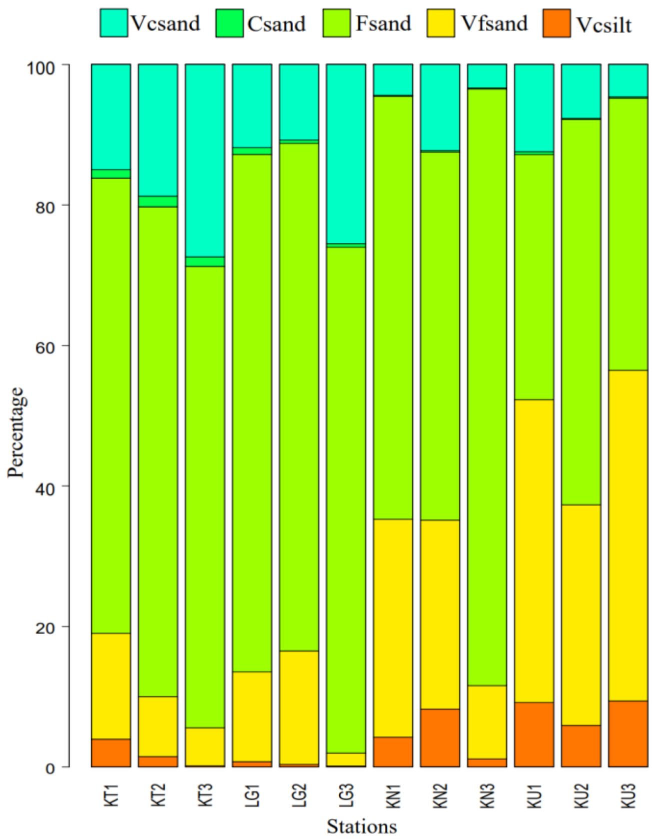

Figure 2. Sediment grain size composition in all stations, Very Coarse Sand (Vcsand) , Coarse Sand (Csand) , Fine Sand (Fsand), Very Fine Sand (Vfsand), and Very Coarse Silt (Vcsilt).

The sorting values, calculated both geometrically and logarithmically, also show several variation. These variations range from 1.193 to 2.59 μm and 0.225 to 1.373 φ respectively, with averages of 1.947 μm and 0.919 φ. The sorting values are divided into five classifications: poorly sorted (KT1, KT2, KT3, and LG3), moderately sorted (LG2, KN2, KU1, and KU2), moderately well sorted (LG1, and KU3), well sorted (KN1), and very well sorted (KN3).

The skewness values of the sediments, calculated both geometrically and logarithmically, range from -0.625 to 0.876 μm and -0.876 to 0.625 φ respectively, with averages of 0.233 μm and -0.233 φ . The skewness values are divided into five classifications: symmetrical (LG2 and KU2), coarse skewed (LG1), very coarse skewed (KT1, KT2, KT3, LG3 KU1, and KU3), fine skewed (KN2), and very fine skewed (KN1 and KN3).

The kurtosis values, calculated both geometrically and logarithmically, vary from 0.46 to 6.883 μm and

Depik Jurnal Ilmu-Ilmu Perairan, Pesisir dan Perikanan
Volume 13, Number 1, Page 54-63

0.46 to 6.883 φ respectively, with an average of 2.99 µm and 2.99 φ.

The kurtosis values are divided into three classifications: very platykurtic (KT3, LG3, KN, and KU), very leptokurtic (KN2, KN3, KU1 and KU2) extremely leptokurtic (KT1, KT2, LG1, and LG2).

Table 3. Analysis result of the textural characteristics of the sediment at 12 stations calculated geometrically (µm) and logarithmically (φ) (Folk and Ward method) (Index: $\bar{x}$-mean size, σ -sorting, *Sk* - skewness, *K* – kurtosis.

Locations	Stations	Geometric (µm)				Logarithmic (φ)			
		$\bar{x}$	σ	*Sk*	*K*	$\bar{x}$	σ	*Sk*	*K*
KT	KT1	86.143	2.504	0.409	6.231	2.497	1.324	-0.409	6.231
KT	KT2	185.87	2.59	0.685	6.551	1.906	1.373	-0.685	6.551
KT	KT3	198.047	2.579	0.706	0.553	1.856	1.367	-0.706	0.553
LG	LG1	96.304	1.622	0.241	6.883	2.824	0.697	-0.241	6.883
LG	LG2	60.077	1.818	-0.09	6.755	3.052	0.862	0.09	6.755
LG	LG3	198.709	2.385	0.876	0.46	1.858	1.254	-0.876	0.46
KN	KN1	48.941	1.403	-0.625	0.55	3.161	0.489	0.625	0.55
KN	KN2	48.848	1.952	-0.101	1.708	3.152	0.965	0.101	1.708
KN	KN3	94.912	1.193	-0.344	2.368	2.839	0.255	0.344	2.368
KU	KU1	27.848	1.97	0.664	1.641	3.424	0.978	-0.664	1.641
KU	KU2	48.269	1.901	-0.086	1.669	3.164	0.927	0.086	1.669
KU	KU3	26.735	1.447	0.466	0.608	3.459	0.533	-0.466	0.608

Sediment textural classification

Based on Blott and Pye's (2012) classification of sediment texture sand-silt-clay ternary plot, the samples from four locations (Keude Unga, Krueng No, Lhok Geulumpang, and Kuta Tuha) can be categorized into three groups: sand, very slightly silty sand, and silty sand (Figure 3). All stations in Keude Unga are classified as silty sand, Based on the analysis results of the textural characteristics, the mean grain size particles in Keude Unga are indeed the smallest compared to other locations (Table 3). The sediment categories in the Krueng No location are the most varied as silty sand (KU2), very slightly silty sand (KU1), and sand (KU3).

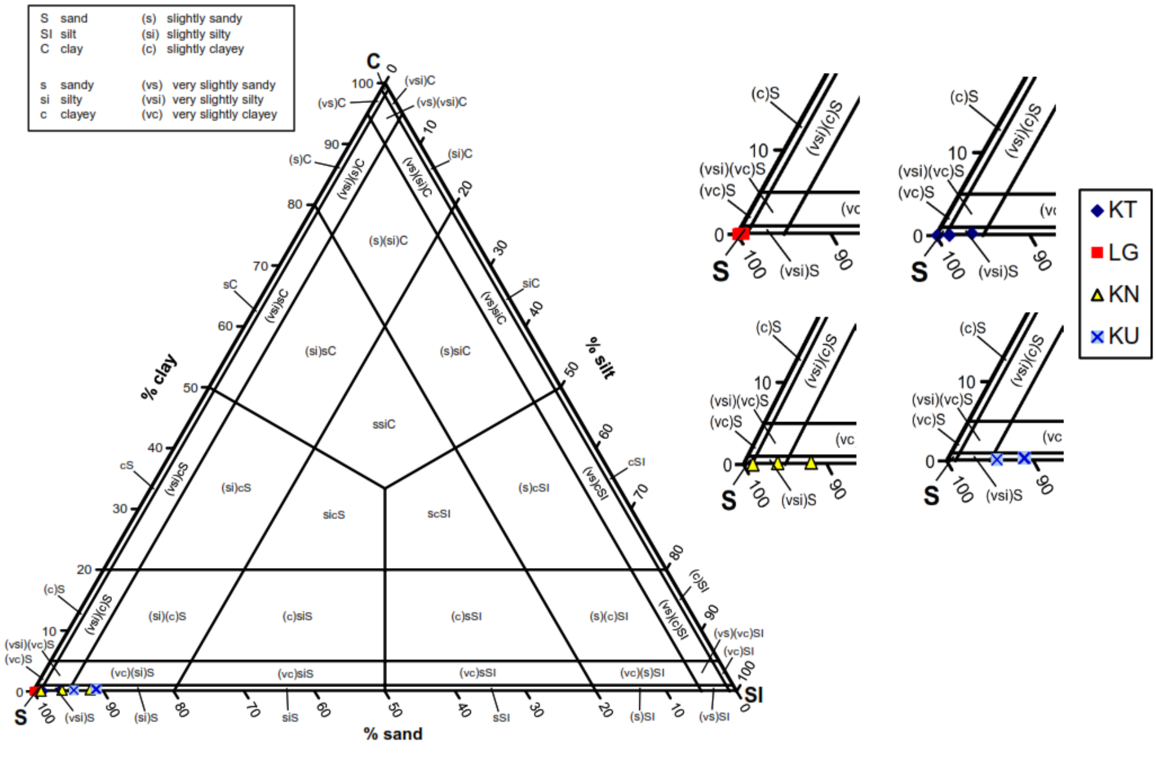

Figure 3. Trenary plot Blott and Pye base on sand-silt-clay classification in all stations

Sediment at Lhok Geulumpang classified as sand at all stations, The sediment in Lhok Geulumpang is classified as sand at all stations, because the percentage of silt at this location is the smallest (Figure 2). Sediment at Kuta Tuha location as very slightly silty sand (KT1) and sand (KT2 and KT3).

Discussion

Relationship between composition of sediment grain size and position from mouth bar

The high percentage of fine sand and very fine sediment at all stations, especially on medium-range stations with a mouth bar (KT3, LG2, KN3 and KU2) (Table 1) a strong impact on sediment transport and deposition in all locations. Fine sand and very fine are typically associated with high-energy environments, such as waves, currents, and tidal, which can erode and transport finer sediments away from the shore (Smith *et al.*, 2015). Fine sand and very fine sand particles may undergo many cycles of deposition (Poppeschi *et al.*, 2021) and re-entrainment (Grasso *et al.*, 2021) during their time in the estuary . Therefore, fine sand and very fine sand sediment particles are dominant in estuaries because they are connected with tides in multiple ways (Leuven *et al.*, 2016). The greater the tidal range, the greater the receding tide, the greater the degree of sediment diffusion, the higher the degree of sand bar cutting by the tidal channel, and the larger the number of sand bars (Zhang *et al.*, 2023).

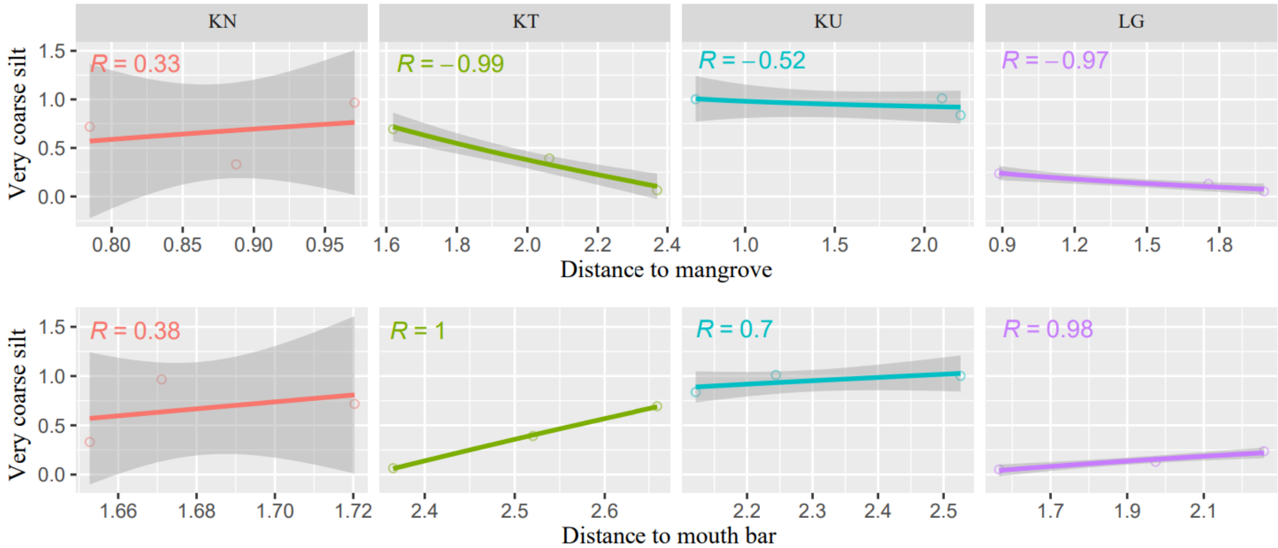

Figure 4. Spearman correlation between distance stations observation point to mouth bar and mangrove with percentage of very coarse silt at all location.

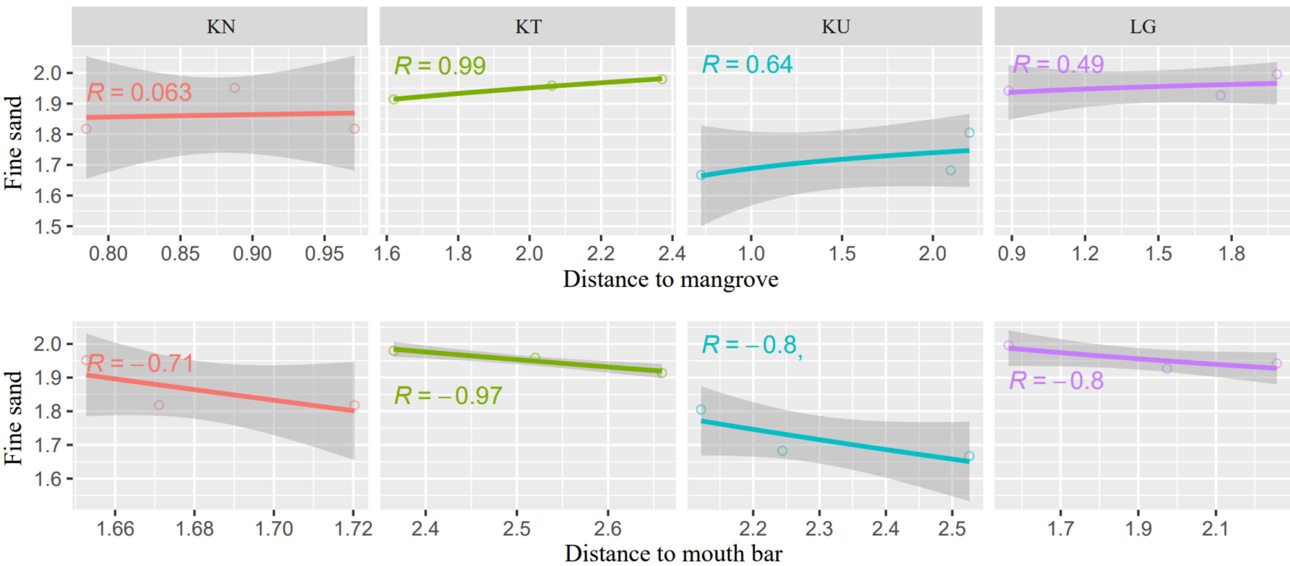

Figure 5. Spearman correlation between distance stations observation point to mouth bar and mangrove with percentage of fine sand at all location.

The sediment grain size composition in an estuary, which includes sand, silt, and clay, is influenced by a variety of factors, including the distance from the mouth bar or bar-built estuary. There is a strong and positive correlation between the distance to the mouth bar and the percentage of very coarse silt at the KT KU and LG locations with R values 1, 0.7 and 0.98, respectively, while at the KN location there is a quite strong positive correlation (R = 0.33) (Figure 4), meaning that the further the distance between an estuary location and the mouth bar, the higher the percentage of very coarse silt. As one moves away from the mouth bar, the energy of the water decreases, leading to the deposition of finer sediments such as silt and clay (Rumuri *et al.*, 2022).

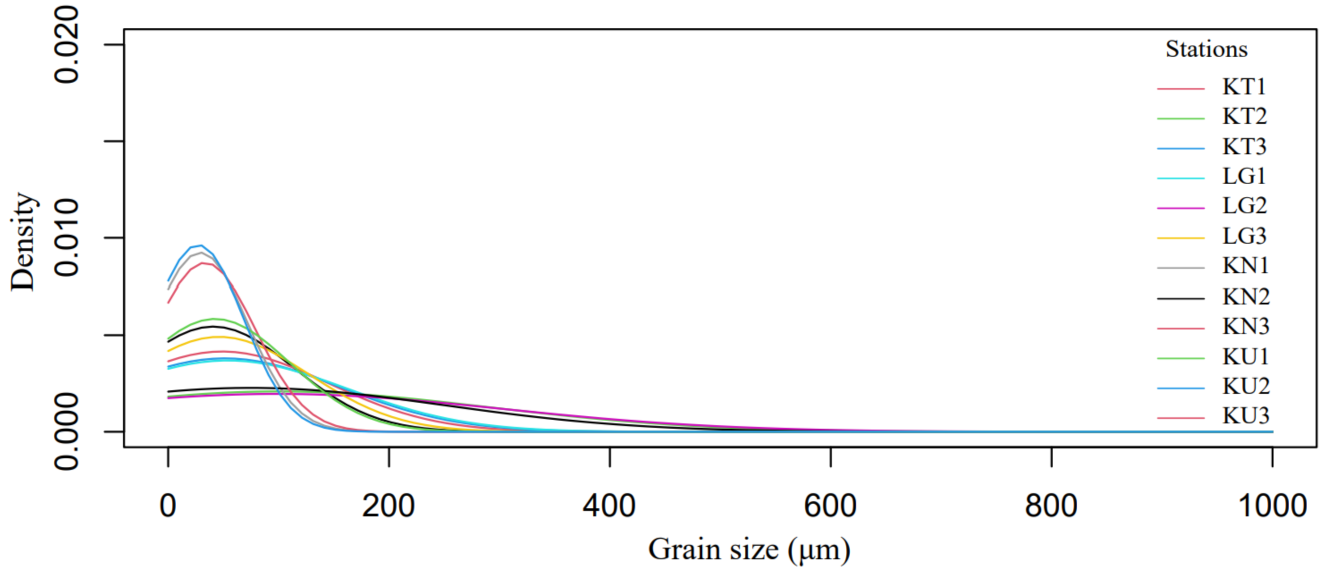

Figure 6. Kurtosis of grain size distribution across all stations

Conversely, coarser sediments such as fine sand are typically found closer to the mouth bar where the water energy is higher, as illustrated in the results of Spearman correlation analysis, which shows a strong negative correlation at all observation locations (KN: -0.71 , KT: -0.97, KU: -0.80 and LG: -0.80) (Figure 5). This distribution is largely due to the dynamics of sediment transport, which is influenced by factors such as mangrove vegetation (Le Minor *et al.*, 2019), tidal range (Du *et al.*, 2018), estuary length (Burchard *et al.*, 2022), and land use (Palinkas *et al.*, 2022) in the coastal catchment area.

Furthermore, environmental pressures, such as changes in land use, can lead to significant changes in estuary sediments. For instance, intensified agricultural land use can increase nutrient and sediment loads in estuaries, resulting in habitats dominated by muddy, organic-rich sediments (Reddy *et al.*, 2021).

The standard deviation or sorting reflects the dispersion of grain size values around the average and provides information about the distribution or arrangement of the sample. Lower standard deviation values, for instance, suggest well-sorted samples in environments with low depositional energy (López, 2017; Yun *et al.*, 2023).

Grain Size Characteristics

Variability of grain size, sorting, skewness, and kurtosis of sediments in the Aceh Jaya estuary. The results showed that the sediments exhibited significant variations in these parameters, reflecting different depositional environments and hydrodynamic conditions. The sediment's particle size distribution suggests that the Aceh Jaya estuary is primarily characterized by very fine to medium sand, aligning with the results of Azis *et al.* (2019) and Hermi *et al.* (2021) in Leupung Beach and Aceh Jaya. The grain size also reflects the influence of wave and current energy, as well as sediment supply and transport (Wang *et al.*, 2023). The stations with finer sand (LG1, LG2, KN1, KN2, KN3 KU1, KU2, KU3, and KT1) are located in sheltered areas with low energy, while the stations with medium sand sand (KT2, KT3, and LG3) are exposed to higher energy.

The sorting values of the sediments range from poorly sorted to very well sorted, indicating different

Depik Jurnal Ilmu-Ilmu Perairan, Pesisir dan Perikanan
Volume 13, Number 1, Page 54-63

degrees of sediment reworking and mixing (Porter *et al*., 2018). The stations with poor sorting (KT1, KT2, KT3, and LG3) are affected by the complex interactions of waves, currents, and tides, which create a heterogeneous sediment mixture (de Mahiques, 2016). The stations with moderate to well sorting (LG2, KN2, KU1, KU2, LG1, and KU3) are located in more stable environments, where the sediments are more homogenous. The station with the best sorting (KN1 and KN3) is influenced by the river discharge, which brings well-sorted sediments from the hinterland (de Mahiques, 2016).

The skewness values of the sediments range from very coarse skewed to very fine skewed, indicating different modes of sediment deposition and erosion (Xie *et al*., 2020). The stations with coarse skewness (KT1, KT2, KT3, LG3, LG1, KU1, and KU3) are characterized by positive skewness, meaning that they have more coarse grains than fine grains. This suggests that these stations are dominated by erosion and winnowing processes (Aigbadon *et al*., 2022), which remove the finer sediments and leave behind the coarser ones. The stations with fine skewness (KN2, KN1, and KN3) are characterized by negative skewness, meaning that they have more fine grains than coarse grains. This suggests that these stations are dominated by deposition and accumulation processes (Deepthi *et al*., 2018), which trap finer sediments and bury coarser ones.

The kurtosis values of the sediments range from very platykurtic to extremely leptokurtic, indicating different shapes of the grain size distribution curve (Hsu, 2013 and Barudzija *et al*., 2020). The stations with very platykurtic kurtosis (KT3, LG3, KN, and KU) have low kurtosis values, meaning that they have flat and broad curves. This implies that these stations have various of grain sizes, with no dominant mode or peak. The stations with very and extremely leptokurtic kurtosis (KN2, KN3, KU1, KU2, KT1, KT2, LG1 and LG2) have high kurtosis values, meaning that they have sharp and narrow curves (Figure 6). This implies that these stations have a narrow/similar range of grain sizes (Kermani *et al*., 2023), with a distinct mode or peak.

The results provide valuable information on the spatial variability of sediment characteristics, which can be used to plan appropriate estuary management. For example estuary management could focus on biodiversity conservation at the locations with dominant of Very Fine Sand sediment characteristics, or it could involve measures to reduce energy and erosion at the locations with poorly sorted sediment distribution.

This study possesses certain restrictions that should considered when interpreting the findings. Initially, the sample size was comparatively limited, with only 12 stations covering a large area of the Aceh Jaya estuary. This may limit the representativeness and generalizability of the results, as there may be spatial variations and heterogeneities that were not captured by the sampling design. Second, the sampling method was based on pipe sampling, which only collects surface sediments. This may not reflect the vertical variations and stratification of the sediments, which may be influenced by the sediment deposition and erosion history.

To overcome these limitations, future research should increase the sample size and spatial coverage of the study area, using a more systematic and comprehensive sampling design. Future research should also use coring or drilling techniques to collect subsurface sediments, which can provide more information on sediment depth profiles and layers. Future research should also apply different methods and techniques to analyze the grain size distribution, such as the moment and graphical methods, as well as the fractal and multifractal methods, which can reveal more details and features of the sediment complexity and diversity.

Conclussion

The sediment characteristics of four locations in theAceh Jaya estuaries, showed significant variations in grain size, sorting, skewness, and kurtosis. The most dominant type of sediment is fine sand, followed by very fine sand, whereas very coarse silt and coarse sand are the least dominant. The mean grain size ranges from very fine sand to medium sand, and the sorting ranges from poorly sorted to very well sorted. The skewness ranges from very coarse skewed to very fine skewed, and the kurtosis ranges from very platykurtic to extremely leptokurtic. The sediment textural classification reveals that the samples belong to three groups: sand, very slightly silty sand, and silty sand. These results indicate that the sediment dynamics and depositional environments of the study area are complex and influenced by various factors, such as wave action, river discharge, coastal erosion, and human activities. This study contributes to the understanding of the coastal geomorphology and sedimentology of the Aceh Jaya estuaries, which is important for coastal management and disaster mitigation.

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How to cite this paper:
Nasution, MA., R. Hermi, H. Heriansyah, F. Lubis, M.M. Rahmi. 2024. Grain Size Properties of Estuary Sediment from Aceh Jaya, Aceh. Depik Jurnal Ilmu-Ilmu Perairan, Pesisir dan Perikanan, 13(1): 54-63.