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The Impact of Seawall on Sediment Characteristics and Morphodynamics Along The Northeastern Coastal of Bengkalis Island, Sumatra, Indonesia

Annisa Ulfa Khaira, Rifardi Rifardi*
Department of Marine Sciences, Faculty of Fisheries and Marine Sciences, Universitas Riau, Indonesia
***Corresponding Author: rifardi@lecturer.unri.ac.id**

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ABSTRACT

Understanding the spatial variability of coastal sediment characteristics is important for managing dynamic shorelines, particularly in regions affected by both natural process and human activity. This study was conducted in October 2024 on the northeastern coastal of Bengkalis Island, Riau Province, Indonesia, and aimed to study the impact of seawall construction on coastal sediments and assess the morphodynamics of its coastal area. A survey-based approach was employed in this research, with observation stations selected based on an analysis of two decades of shoreline change data (2004–2024) derived from satellite imagery in the coastal zone of Pambang Pesisir Village. Sediment was collected from three stations, each comprising five sampling points. The sediment analysis revealed a dominance of mud and muddy sand, with grain size fractions ranging from medium sand to fine mud (2.33 Ø – 7.2 Ø). These variations indicate diverse energy conditions along the coastline. The measured current velocity, ranging from 0.29 to 0.36 m/s, along with wave energy levels varying between 0.008 and 0.614 J, were identified as primary factors influencing the sediment dynamics. Sorting analysis classified the sediments as poorly to very poorly sorted, suggesting active transport processes. Additionally, positive skewness values indicate a prevalence of finer particles, while kurtosis values range from very platykurtic to extremely leptokurtic, demonstrating heterogeneity in sediment deposition. Notably, the presence of seawall, specifically sheet piles, significantly altered local hydrodynamic regimes, leading to spatial differences in sediment accumulation. The research provides valuable insights into sediment behavior in coastal areas affected by human activities and offers notable information for sustainable shoreline management and coastal protection strategies in Indonesia.

INTRODUCTION

Coastal zones are among the most dynamic and ecologically significant environments on Earth. They serve as critical buffers between land and sea, supporting a wide range of biodiversity while sustaining millions of people's livelihoods. However, these areas are increasingly threatened by complex environmental processes, including sedimentation, abrasion and accretion. These processes, driven by both natural forces and human interventions, often lead to drastic changes in shoreline position, which have profound implications for spatial planning, infrastructure development, and the socio-economic well-being of coastal communities **(Rifardi *et al*., 2022)**.

One such vulnerable area is Pambang Pesisir Village, located in the Bengkalis Regency of Riau Province, Indonesia. The village lies directly along the Malacca Strait, a high-energy marine corridor where tidal currents and wave action significantly influence sediment dynamics. This exposure renders the coastline highly susceptible to abrasion, with consequences that include the loss of residential land, the degradation of productive agricultural areas, and the destabilization of critical ecosystems such as mangrove forests. Bengkalis itself is an island-based regency on the eastern coast of Sumatra, geographically situated between 00°17'–20°30' North Latitude and 100°52'–102°00' East Longitude, and encompassing a total area of approximately 11,481.77 km² **(Regional Environmental Resources, 2016)**. Pambang Pesisir, positioned on the eastern flank of Bengkalis Island, represents a microcosm of these broader coastal challenges. The mangrove belts in this area provide essential ecosystem services, including shoreline stabilization, biodiversity conservation, and carbon sequestration. Nevertheless, rapid and unmanaged coastal changes, documented in some areas as shoreline retreat of up to 14 meters per year **(Sarah *et al*., 2022)**, pose severe risks to both natural systems and human settlements.

However, the local government has constructed sea walls as a preventive measure against coastal abrasion which is expected to worsen and potentially damage the area. Sea walls are coastal defense structures usually made of concrete, stone, or other durable materials, built parallel to the coastline with the main function of absorbing and deflecting wave energy. The construction of seawalls as coastal protective structures can have a significant impact on sediment characteristics, particularly in terms of sediment transport, deposition, and grain size distribution. Seawalls can alter current and wave patterns, which in turn affect the type of sediment that is deposited in a given location.

Sediment dynamics, a key driver of such transformations, are influenced primarily by wave and current activity. The process begins with erosion, where soil and rock particles are mobilized and transported via water flows. As flow velocity diminishes, these sediments are deposited along the transport path—a process known as sedimentation or sediment transport **(Rifardi, 2012)**. Coarser sediments generally settle near the source, while finer particles may be carried farther offshore, leading to spatial variability in sediment characteristics. Such variations are critical to understand, since they influence benthic habitat structures, coastal resilience, and the effectiveness of mitigation efforts. Therefore, this study aimed to understand the impact of seawall construction to characterize coastal sediments and assess the morphodynamics of its coastal area.

MATERIALS AND METHODS

1. Time and place

This research was conducted in October 2024 on Bengkalis Island, Riau Province, Indonesia.

2. Sample collection method

The method used in this study was a survey method, by direct observation in the field to determine the condition and potential of the coastal area, and the data were analyzed qualitatively and quantitatively. Sediment sampling was carried out at three stations, each with five sampling points. Station 1 is located within a mangrove forest area in Pambang Pesisir Village. Station 2 is situated at a shipyard area in Pambang Pesisir Village. Station 3 is positioned near a beach tourism site characterized by high levels of anthropogenic activity, also within Pambang Pesisir Village.

3. Landsat image analyst

The station points to be analyzed are determined from the results of image data processing of coastline changes in the years 2004 to 2024 on the island of Bengkalis. Landsat image analysis was carried out using DSAS software, by applying the End Point Rate (EPR) approach to calculate the rate of coastline change. The EPR method divides the distance between the oldest coastline and the current coastline by the elapsed time period. A positive distance (+) indicates an advancing coastline, while a negative distance (-) indicates a retreating coastline **(Setiani, 2017)**.

4. Characterized the sediment

Sediment grain sample analysis was conducted on sand and gravel fractions in the laboratory using a sieving/filtering method. Six levels of sieves were used. The sieve mesh size was classified according to the Wenworth scale, while the silt fraction was analyzed using a pipette method. Sediment characteristics are physical parameters used to describe the nature and dynamics of sediment in aquatic environments. These characteristics describe the depositional process, transport dynamics, and sediment source materials. Analyzing sediment characteristics is essential for understanding coastal dynamics, the impacts of human activities, and local oceanographic processes **(Rifardi, 2012)**. In this research, grain size separation is conducted on a loose sand sample. This analysis aimed to determine key sediment parameters, including mean grain size (Mz), sorting coefficient (δ1), skewness (Sk), and kurtosis (K). These values can be obtained through both graphical and mathematical approaches. In this study, the graphical method based was employed to determine the mean grain size (Mz) **(Rifardi, 2012)**.

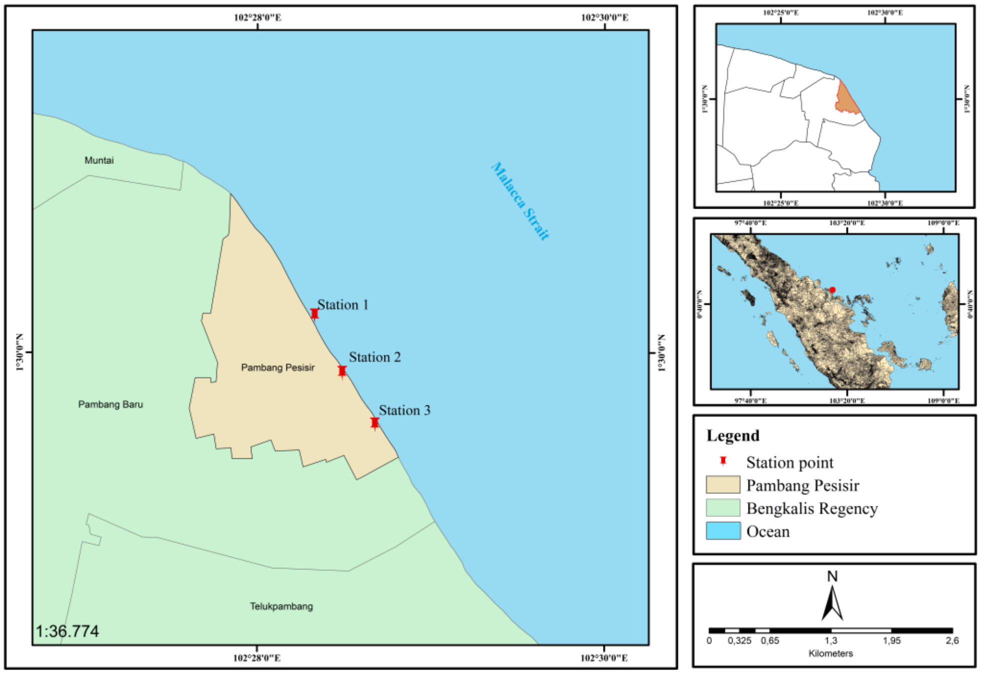


Fig. 1. Station point determination map

RESULTS

1. Coastline changes 2004-2024

Coastline changes at each research station from 2004-2024 can be seen in Table (1).

Table 1. Coastline Changes at each research station 2004-2024

Station	Value (meters/year)	Category
1	7.81	Accterion
2	6.1	Accterion
3	6.]90	Accterion

Based on the analysis of image data on the coastline change map, it is known that throughout the Pambang Pesisir Village area, Bengkalis Regency, there have been changes in the coastline, both abrasion and accretion. The results of the analysis of coastline changes from 2004 to 2024 in Pambang Pesisir Village, Bengkalis Regency using DSAS software show that there has been quite significant accretion. The accretion rate at Station 1 was 7.81 m/year, at Station 2 it was 6.1 m/year, and at Station 3 it was 6.90 m/year. These results indicate that there has been quite significant land growth, especially at Station 1, which indicates that there is sediment carried and accumulated in the area in large quantities. The causes for such accumulation can be from ocean currents, waves, or human activities that affect sediment movement. Pambang Pesisir Village is an area that is very prone to abrasion since it faces the Malacca Strait which has quite strong currents and waves. According to **Hariyoni *et al.* (2013)**, the open coastal conditions make this area vulnerable to waves from various directions. The soil structure in this village is classified as unstable, so that this coastal area is very susceptible to erosion due to sea waves, with frequent cracks in the soil. These cracks are at risk of accelerating the rate of abrasion if not addressed with artificial structures. However, currently this area is experiencing increased accretion. This phenomenon is likely influenced by various factors, such as local community activities and the installation of retaining walls that help add material to the area. The installation of coastal protection devices, such as concrete or stone, functions to break incoming waves and reduce coastal erosion. The construction of this retaining wall also caused accretion in Pambang Pesisir Village. According to **Rangel-Buitrago *et al.* (2018)**, coastal protection using artificial construction structures (hard structures), such as sea walls and breakwaters, is the main strategy to overcome the problem of coastal erosion, especially in tourist areas. The purpose of building a retaining wall is to reduce the rate of abrasion, as shown in Fig. (2).

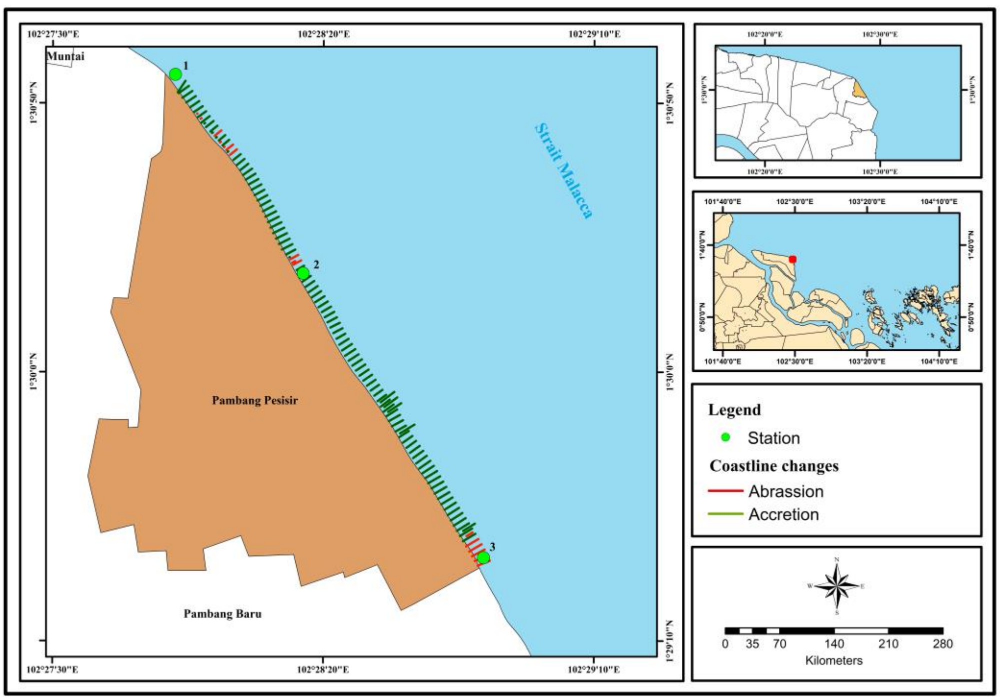


Fig. 2. Coastline changes 2004-2024

2. Installation of sheet piles in Pambang Pesisir Village

The condition of the Pambang Pesisir Village area, which has experienced both abrasion and accretion after the installation of sheet piles, can be seen in Fig. (3).

(**a**) (**b**)

Fig. 3. (a) Abrasion conditions in Pambang Village, (b) Accretion conditions in Pambang Pesisir Village after the construction of seawall

The construction of sea wall along the coastal area is one of the methods used to prevent coastal abrasion caused by high waves and current speed. Processing of shoreline change data shows that accretion occurs more than abrasion. The latest coastal protection project in Pambang Pesisir Village carried out in 2013-2015 was the construction of retaining seawalls and breakwaters by the Provincial Government and Bengkalis Regency Government, with initial construction starting in 2010. The retaining walls that were built initially functioned as sea walls (coastline barriers), which were then continued with the construction of breakwaters. The existence of the seawall has trapped sediment in two locations (north and south), thus forming land and creating a land area. Although development efforts have been made, the coastal area is not yet fully protected from abrasion and requires sustainable management **(Zainal, 2020)**. If not designed properly, current turbulence and wave reflection can exacerbate erosion in the surrounding area due to increased current turbulence and wave reflection. Therefore, an optimal coastal protection strategy should combine turbulence installation with nature-based approaches, such as mangrove restoration or construction of sea wall structures, to balance shoreline protection and ocean hydrodynamics. Turbulence, which was initially built as a sea wall, was then followed by the construction of a sea wall. The sea wall successfully trapped sediment in two locations (north and south), thus forming land and creating an accretion area of 80,359.4 m² **(Miswadi *et al.*, 2017)**.

3. Sediment characteristics

Sediment characteristics are physical parameters used to describe the nature and dynamics of sediment in aquatic environments. These characteristics describe the depositional process, transport dynamics, and sediment source materials. Analyzing sediment characteristics is essential for understanding coastal dynamics, the impacts of human activities, and local oceanographic processes **(Rifardi, 2012)**. In this research, grain size separation is conducted on a loose sand sample. This analysis aimed to determine key sediment parameters, including mean grain size (Mz), sorting coefficient (δ1), skewness (Sk), and kurtosis (K). These values can be obtained through both graphical and mathematical approaches. In this study, the graphical method was employed to determine the mean grain size (Mz) by **(Rifardi, 2012)**.

Sediment fraction in Pambang Pesisir Village

Sediment fraction is the division of sediment grain size classified based on the diameter of the constituent particles, which reflects the origin, energy of the sedimentary environment, and the transportation process experienced by the sediment. In general, sediment fractions are grouped into several types, namely gravel, sand, silt, and clay. From the calculation results of the sediment fraction in Pambang Pesisir Village, it is known based on the results of the sediment sample analysis. Table (2) shows how to calculate the sediment fraction.

Table 2. Sediment fractions in Pambang Pesisir Village

Station	**Sampling Point**	**Sediment Fraction (%)**			**Type Sediment**
		Silt	Sand	Clay	
I	A	0	33.64	66.36	Clay Sand
	B	0	18.99	81.01	Clay
	C	0	15.36	84.64	Clay
	D	0	36.81	63.19	Clay Sand
	E	0	48.45	51.55	Clay Sand
II	A	0	10.55	89.45	Clay
	B	0	24.62	75.38	Clay
	C	0	18.61	81.39	Clay
	D	0	19.14	80.86	Clay
	E	0	8.48	91.52	
III	A	0	58.81	41.19	Sand Clay
	B	0	19.02	80.98	Clay
	C	0	13.55	86.45	Clay
	D	0	14.51	85.49	Clay
	E	0	18.04	81.96	Clay

The sediment analysis revealed two types of sediment: sandy mud, muddy sand and mud. At Station I, the dominant sediment type was sandy mud, with the highest percentage at point A, which was 66.36% mud and 33.64% sand. At Station II, mud was the dominant sediment type, with the highest percentage at point E, 91.52%. Meanwhile, at Station III, the highest rate of mud was found at point C, which was 86.45%. To view the sediment fraction analysis in Pambang Pesisir Village, the sediment fractions at each station varied. This is likely due to currents and waves, which are the primary forces determining the direction and distribution of sediment and the sedimentation process **(Rifardi *et al*., 2022)**.

This is in accordance with the statement by **Rifardi (2012)**, in addition to natural factors such as waves and currents, sediment formation is also significantly influenced by anthropogenic activities on land. In the case of Pambang Pesisir Village, the substrate is predominantly composed of muddy sediments.

Mean size (Mz) of Sediment in Pambang Pesisir Village

The Mean size of sediment grains indicates the sedimentation energy present in an area. The larger the grain size, the higher the energy required to deposit the sediment. The mean size of sediment grains reflects the energy level of the depositional environment; coarser sediments are typically deposited under high energy conditions, while finer sediments tend to accumulate under lower energy conditions **(Gao *et al.*, 2021)**. From the calculation results, the mean size of sediment grains (Mz) in Pambang Pesisir Village obtained can be seen in Table (3).

Table 3. Mean size (Mz) of sediment

Station	Sampling Point	Mean Size (Ø)	Type
I	A	5.26	Coarse silt
	B	5.23	Coarse silt
	C	5.56	Coarse silt
	D	5.33	Coarse silt
	E	5.26	Coarse silt
II	A	7.2	Fine Silt
	B	5.36	Coarse silt
	C	6.53	Medium Silt
	D	5.46	Coarse silt
	E	5.7	Coarse silt
III	A	2.33	Medium sand
	B	5.5	Coarse silt
	C	7.16	Fine Silt
	D	7.16	Fine Silt
	E	6.1	Medium Silt

Based on the calculation results of the mean size (Mz) value, the sediment at Station I is mostly dominated by coarse silt with sediment sizes ranging from 5.23 to 5.56 Ø, indicating stable environmental conditions with a relatively uniform sedimentation process. Meanwhile, Station II has a wider range of sediment sizes, from fine silt to coarse silt, with a range of 5.36 to 7.2 Ø. Station III shows the most varied characteristics, with sediment sizes ranging from medium sand at point A (2.33 Ø) to fine silt at points C and D (7.16 Ø). The presence of medium sand at point A of station III indicates a stronger current than at other points, which facilitates the deposition of larger particles. This is in line with the sedimentation theory which states that smaller sediment particles can remain suspended longer in higher energy environments **(Folk & Ward, 1957)**.

Sediment sorting (δ1) in Pambang Pesisir Village

Sorting refers to the degree of uniformity in sediment grain size. Well-sorted sediments indicate stable depositional conditions, while poorly sorted sediments indicate fluctuations in depositional energy. Poor sorting often indicates stronger transport processes. Sorting is an important indicator of transport processes and depositional environments. Less sorted sediments exhibit higher energy variations and complex hydrodynamic conditions **(Hussain *et al.*, 2020)**. Table (4) shows the results of the calculation of sediment sorting in Pambang Pesisir Village.

Table 4. Sorting value (δ1)

Station	Sampling Point	Sorting Value ($d1$)	Classification
I	A	2.59	Very poorly sorted
	B	2.97	Very poorly sorted
	C	2.34	Very poorly sorted
	D	2.37	Very poorly sorted
	E	2.38	Very poorly sorted
II	A	1.01	Poorly sorted
	B	2.77	Very poorly sorted
	C	1.58	Poorly sorted
	D	2.36	Very poorly sorted
	E	1	Poorly sorted
III	A	3.64	Very poorly sorted
	B	2.4	Very poorly sorted
	C	1.16	Poorly sorted
	D	1.05	Poorly sorted
	E	2.09	Very poorly sorted

Based on the results of the calculation of the sorting value, the highest sorting was found at Station III Point A with a value of 3.64 indicating that the mud particles were very poorly sorted. The lowest sorting value was found at Station II Sampling Point E with a value of 1 indicating that the mud particles were poorly sorted. **Rifardi (2008)** added that sorting indicates the level of stability of oceanographic conditions in the sediment environment. The results of the analysis showed that the process of sediment particle distribution in Pambang Pesisir Village was dominated by the Poorly Sorted classification. In addition to the type of particles, currents and waves that affect the sediment distribution process at Pambang Pesisir Beach are influenced by the slope of the beach, the distance between the highest and lowest tides, and the presence of sea walls in coastal areas.

Skewness (Sk 1) sediment in Pambang Pesisir Village

Skewness measures the extent to which the grain size distribution of sediment is asymmetric. A positive skewness indicates a predominance of finer particles, while a negative skewness reflects a predominance of coarser particles. From the calculation results of the Skewness (Sk 1) sediment in Pambang Pesisir Village, it can be seen in Table (5).

Table 5. Skewness value (Sk 1)

Station	Sampling Point	Skewness Value (Sk 1)	Classification
I	A	0.16	Fine skewed
	B	0.003	Near symmetrical
	C	0.29	Fine skewed
	D	0.27	Fine skewed
	E	0.27	Fine skewed
II	A	11.8	Very fine skewed
	B	0.1	Fine skewed
	C	1.18	Very fine skewed
	D	0.26	Fine skewed
	E	0.09	Near symmetrical
III	A	0.4	Fine skewed
	B	0.28	Fine skewed
	C	5.82	Very fine skewed
	D	0.62	Fine skewed
	E	0.69	Fine skewed

Based on the calculation of Skewness (Sk 1) values, the highest skewness was found at Station II, Point A, with a value of 11.8, indicating very fine skewed sediment. The lowest skewness value was found at Station I, Sampling Point B, with a value of 0.003, indicating near symmetrical sediment. The high-energy environment allows coarser particles to be more easily suspended and transported to other locations, while smaller particles remain on the substrate and accumulate. As a result, this location shows a pattern dominated by fine particles with skewness towards smaller materials. The positive skewness value indicates that the curve is heavily skewed to the right, with the substrate being dominated by fine sand. Skewness is used to identify the distribution tendency of sediment grain sizes. A positive skewness value (+) indicates that the data distribution is skewed to the right, which suggests a dominance of finer particles. Conversely, a negative skewness value (–) indicates a leftward skew in the distribution, reflecting a dominance of coarser particles **(Rifardi, 2008)**.

Kurtosis (K) of sediment in Pambang Pesisir Village

Kurtosis measures the extent to which the sediment grain size distribution is peaked. High kurtosis values (leptokurtic) indicate a sharper distribution, while low values (platykurtic) indicate a flatter distribution. The calculation results of Kurtosis (K) of sediment in Pambang Pesisir Village can be seen in Table (6).

Table 6. Kurtosis (K) value

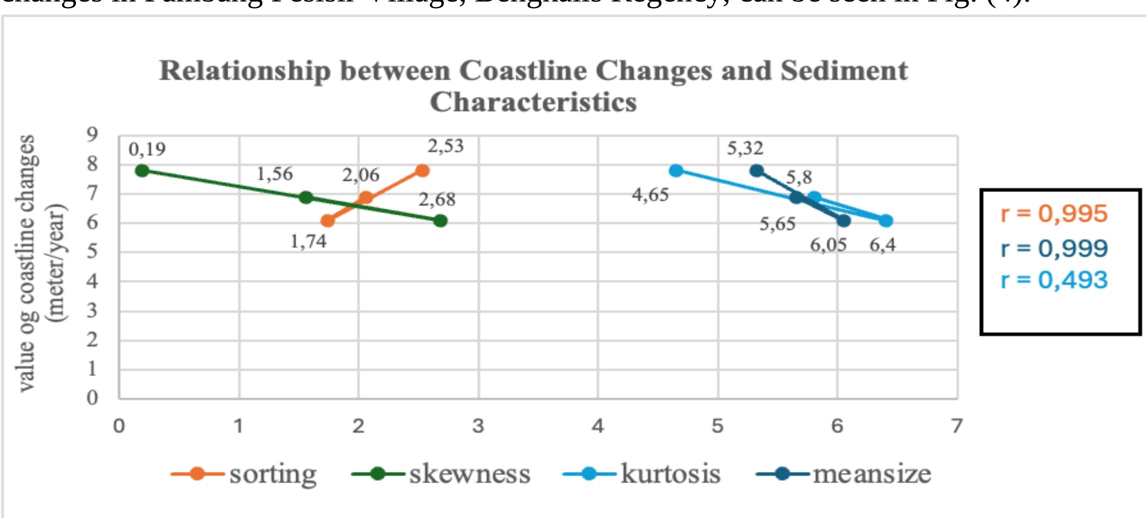
Station	Sampling Point	Kurtosis Value (K)	Classification
I	A	0.55	Very platykurtic
	B	12.7	Extremely leptokurtic
	C	9.1	Extremely leptokurtic

	D	0.48	Very platykurtic
	E	0.45	Very platykurtic
II	A	8.4	Extremely leptokurtic
	B	1.2	Leptokurtic
	C	6.6	Extremely leptokurtic
	D	6.8	Extremely leptokurtic
	E	9.01	Extremely leptokurtic
III	A	0.54	Very leptokurtic
	B	6.76	Extremely leptokurtic
	C	7.06	Extremely leptokurtic
	D	6.65	Extremely leptokurtic
	E	8.02	Extremely leptokurtic

The kurtosis values in Pambang Pesisir Village show that Station I had the highest kurtosis value of 12.7, classified as Extremely Leptokurtic at Point I B, and the lowest value of 0.45, classified as Very Platykurtic at Point I E. At Station II, the highest kurtosis value was 9.01, classified as Extremely Leptokurtic at Point II E, and the lowest value was 1.2, classified as Leptokurtic at Point II B. At Station III, the highest kurtosis value was 8.02, classified as Extremely Leptokurtic at Point III E, and the lowest value was 0.54, classified as Very Platykurtic at Point III A. Areas that are still submerged during low tide have a Very Platykurtic classification, characterized by a flat curve. A very flat curve represents poorly sorted sediments, or a Bimodal curve, which is referred to as Platykurtic. A curve with a very sharp peak indicates well-sorted sediments and is referred to as Leptokurtic **(Rifardi, 2008)**.

4. Relationship between sediment characteristics and coastline changes

The graph of the relationship between sediment characteristics and coastline changes in Pambang Pesisir Village, Bengkalis Regency, can be seen in Fig. (4).



Figs 4. Graph of the relationship between sediment characteristics and coastline changes

Based on the graph showing the relationship between coastline changes and sediment characteristics, it is evident that coastline changes have a very strong correlation with several sediment parameters, namely sorting (r = 0.995), skewness (r = 0.999), kurtosis (r = 0.493), and mean size (r = 0.990). The correlation values approaching 1 indicate a very close positive relationship between sediment characteristics and the degree of coastline changes. From the results, it is found that shoreline changes and sediment characteristics have a very strong relationship. In the context of seawall installation in coastal areas, this structure can modify sediment characteristics by reducing the wave and current energy reaching the shoreline. With the presence of the seawall, sediment transport may decrease since the seawall acts as a barrier that prevents direct abrasion by the waves. In the area of Pambang Pesisir Village, accretion has occurred due to the installation of the seawall, which had previously experienced erosion.

5. Impacts of seawall

The effect of the seawall installation can influence the coastline changes and sediment characteristics. However, in some cases, the seawall may also cause erosion on the opposite side of the structure due to changes in current patterns, leading to an imbalance in sediment distribution. Therefore, seawall installation must be carried out with proper coastal geomorphological studies to avoid negative impacts on coastline changes and coastal sediment stability. Coastal areas with muddy sediment characteristics are more vulnerable to erosion because the material is more easily transported by currents **(Setiawan & Rahmat, 2018)**.

The installation of seawalls has a noticeable impact on both coastline dynamics and sediment characteristics. In the study area, the presence of seawalls has contributed to shoreline accretion at several locations by reducing wave energy and current velocity, which promotes sediment deposition in the protected zone. This is consistent with previous studies reporting that hard coastal structures can stabilize the backshore area and encourage sediment accumulation immediately in front of the wall. However, these structures also modify the natural longshore sediment transport, which can result in erosion on the downdrift side of the seawall. This occurs because the interruption of littoral drift leads to sediment deficit in adjacent areas, thereby accelerating shoreline retreat. Such effects were observed in some segments of the Pambang Pesisir coast, where accretion occurred near the seawall, but erosion was detected further alongshore.

The construction of seawalls significantly modifies the natural sediment dynamics and morphodynamic processes along the shoreline. Numerous studies have shown that hard coastal protection structures, including vertical and sloped seawalls, often lead to beach narrowing and coastal squeeze, particularly in areas with limited space for natural shoreline retreat during sea-level rise or storm events **(Sanitwong-Na-Ayutthaya, 2023)**. This process reduces the intertidal zone and alters sediment exchange between nearshore and backshore environments.

CONCLUSION

This study successfully characterized the coastal sediments and assessed the morphodynamic changes along the shoreline of Pambang Pesisir Village, Bengkalis Island. The sediment analysis showed variations in mean size, sorting, skewness, and kurtosis that are strongly correlated with shoreline change patterns. Between 2004 and 2024, the coastline experienced significant accretion at several locations, particularly at Station 1, with an average rate of 7.81 m/year. These changes are closely linked to the presence of seawalls, which reduce wave and current energy, thereby promoting sediment deposition and decreasing erosion rates. Overall, the results indicate that seawall construction has a significant influence on both sediment characteristics and shoreline dynamics in this muddy coastal environment. These findings highlight the importance of integrating sediment characteristics and coastal morphodynamics into seawall planning for effective coastal management.

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