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SEDIMENTATION DYNAMICS AND SHORELINE CHANGES HARNESSING GRANULOMETRIC AND SATELLITE IMAGERY ANALYSIS IN COASTAL AREA OF SEMARANG, CENTRAL JAVA

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Abstract:
A big problem in coastal development is changes in the coastline. This is a global issue because it affects planning in the area. This study looked at how sediment movement affects the shoreline in northern Semarang. The aim was to study sediment at different points using core samples and satellite images from Landsat 5, 7, and 8 (1996–2024) with the Google Earth Engine and Digital Shoreline Analysis System. The results show that this area has a barrier island system with strong sediment movements. The study also found a local change since 2021 due to the closure of an inlet channel. Shoreline changes every four years from 1996 to 2024 showed that erosion is the main process, causing the shoreline to move back. Landsat images from 1996 were used because they had a good resolution. However, at points TRG-01 to TRG-04, local growth was observed, marked by channel closure and sediment buildup. The differences between satellite images and sediment data show variations in time and space, where erosion is a long-term trend and growth is a short-term local change. These findings show that Tugurejo coast is very dynamic, mainly due to erosion, but it also shows growth in certain areas.

Key words: Shoreline change, sediment dynamics, granulometry, DSAS, Semarang.

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INTRODUCTION

Changes in the world's coastlines have become a concern because they are related to territorial boundaries and space issues. Coastal vulnerability is a global concern, as shoreline changes are driven by both natural events and human activities, including the impacts of climate change (Nerves *et al*., 2024). The susceptibility of certain areas to erosion and sediment buildup underscores the importance of implementing effective management strategies to safeguard ecosystems and local communities (Palanisamy *et al*., 2024).

The growing threat of disasters in Asia is associated with the deterioration of coastal ecosystems, which can result in more intense effects from phenomena such as tsunamis and storm surges (Takagi and Heidarzadeh, 2023). Asian countries are highly susceptible to coastal erosion, as the interplay between rapid urbanization, land subsidence, and sea-level rise significantly accelerates shoreline retreat. (Pang *et al*., 2023). The impact of climate change in Southeast Asia is more intense and occurs faster than in other parts of the world (Hens *et al*., 2018). Southeast Asia's coastal regions are suffering from severe coastal erosion. It is the most sensitive and vulnerable to climate change, has broad and densely populated coastlines, and is under ecological pressure (Dong *et al*., 2024).

Semarang is the only one of the cities in Indonesia that is part of the 100 Resilient Cities, a global initiative aimed at enhancing urban resilience. This provides Semarang with the opportunity to build networks with other cities around the world to collaborate in addressing disaster-related issues, such as flooding, tidal inundation, and water scarcity, as well as social challenges, such as unemployment and poverty (Hofmann, 2021). Semarang is a city in Indonesia that is predicted to sink, and one of the areas affected is Tugurejo.

Geologically, the coastal region of Semarang, including Tugurejo, is composed of young Quaternary deposits that predominantly consist of sediments derived from fluvial and shallow marine processes. The geomorphology of this area is dominated by coastal alluvial plains, river mouths, and deltaic deposits that are actively evolving. Sedimentation processes in this region are influenced by tidal dynamics, ocean currents, and surface runoff from the Silandak River, which discharges into the Tugurejo area of the bay. These processes contribute to significant changes in bathymetry and shoreline positions annually (Halim *et al.*, 2023). The unique morphological and geological conditions of Semarang, with mountains in the southern part known as the highland area and lowlands in the northern part known as the lowland area,make Semarang different from several major cities in the world that experience the same problems.

Previous research in the Wulan Delta, Demak, revealed that longshore bar deposits migrated seaward because of the dominance of wave and longshore current activities (Atmojo *et al.*, 2016). At Tirang Beach, Semarang, a study using the Digital Shoreline Analysis System (DSAS) showed that the entire coastal area experienced erosion, with an average erosion rate of 7.92 m per year. The impacts of shoreline changes are considerable for coastal land use, particularly regarding the reduction in water bodies and mangrove areas (Gaol *et al.*, 2025). Specifically, this study aimed to examine the characteristics of sediments distributed at several shoreline points, map shoreline changes from 1996 to 2024 using remote sensing data, and evaluate the spatial relationship between sediment distribution and shoreline morphological change patterns. This approach is expected to provide scientific contributions in understanding the interaction between sedimentary processes and shoreline dynamics, as well as to offer a strong scientific basis for sustainable coastal zone management in the northern coastal area of Semarang City. With a better understanding of these dynamics, coastal management in Tugurejo can be carried out more effectively to mitigate the negative impacts of shoreline change and ensure the sustainability of coastal ecosystems and the well-being of local communities.

DATA AND METHODS

The methodology used in this study consisted of three stages: preparation, data collection, and data processing. The preparation stage included a literature review and determination of sampling points. Field data collection involved the extraction of sediment core samples (Table 1) and the analysis of Landsat satellite imagery (1996–2024). The sediment cores were then subjected to sedimentological and stratigraphic analyses, followed by granulometric analysis. Sediment grain size analysis (granulometry) is useful for identifying energy conditions in the depositional environment because sediment grain size reflects the strength of the currents or waves that deposited the material (Folk, 1989). The stages of the granulometry analysis included sample collection and preparation.

Sediment samples collected using a hand coring device were cut into 1 cm intervals. The collected sediment samples were then dried to remove water content. Drying was performed using a MEMMERT UN30 oven. Initial weighing: Samples were weighed to determine the total weight before sieving or further analysis. Sieving involves placing samples on a series of sieves with different hole sizes, sorted from largest to smallest based on the Wentworth scale (1922). The sieving process was performed mechanically using a sieve shaker.

Statistical data processing: the weight data from each grain size fraction obtained through sieving or other analytical tools were processed to calculate the main statistical parameters that describe the characteristics of the sediment. The data results can be visualized in the form of cumulative distribution graphs or histograms, which facilitate the interpretation of the sedimentation process and sediment transport dynamics. Graphs from statistical calculations can be created manually or using software such as Gradistat (Blott and Pye, 2001).

Table 1. Sample collection sediment coring (Geographic coordinate systems).

No	STA	latitude	Longitude
1	TRG-01	6°57’16.04”S	110°21’9.67”E
2	TRG-02	6°57’15.97”S	110°21’9.73”E
3	TRG-03	6°57’16.92”S	110°21’9.76”E
4	TRG-04	6°57’17.08”S	110°21’9.73”E

Landsat imagery was analyzed using the Google Earth Engine and Digital Shoreline Analysis System (DSAS). Landsat image data processing involves several stages, as follows. The first step was to select Landsat imagery for the observation period and then process it in Google Earth Engine (GEE). The imagery was filtered by time and quality (cloud cover <30%), followed by cloud masking and the creation of a median composite to reduce noise. Relevant spectral bands (SR_B1–SR_B7) were then extracted and calibrated into Surface Reflectance before being clipped to the study area. Water bodies were detected using the MNDWI Index (MNDWI) (Green & SWIR1, threshold >0.3), and inland water, such as lakes and rivers, was removed using connected component analysis based on object size. The detected features were smoothed using a circular kernel and processed using morphological operations (erosion-dilation-erosion) to generate a clearer land-water boundary. The raster data were then converted to vector polygons (reduced To Vectors), simplified (5 m tolerance), and smoothed into line strings representing the shoreline. The shoreline length was calculated, and the data were exported as Shapefiles (shoreline) and GeoTIFF (composite imagery) in the geographic coordinate systems. This meth-

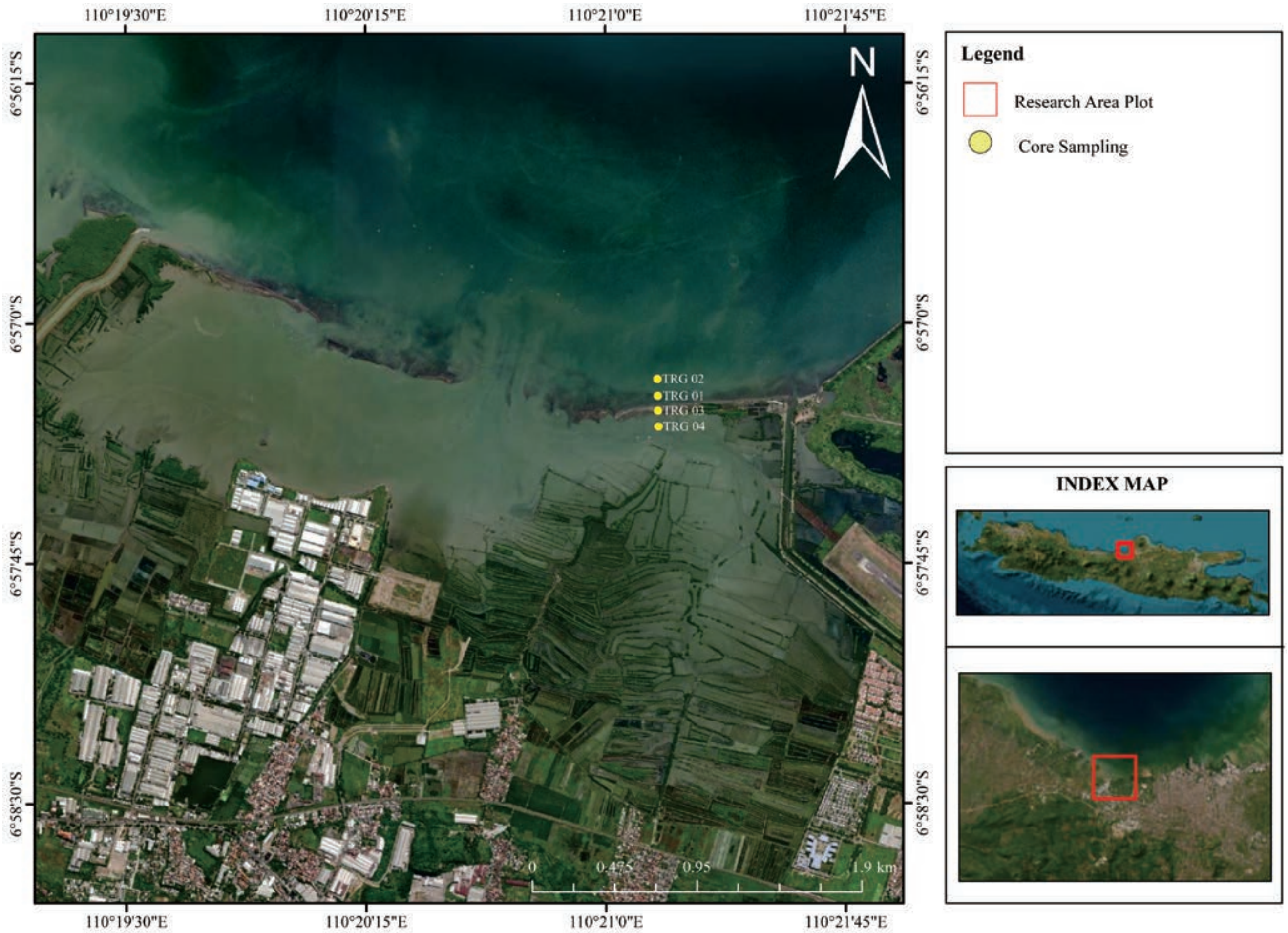


Fig. 1. The research location is indicated by the red box; it is part of the northern coast of Semarang and is included in the Tugu Area District of Semarang City. Core sampling location at the yellow point.

odology enables multi-temporal shoreline change analysis to identify erosion or accretion trends, while integration with field data provides validation and enhances the accuracy. The research area is located in the Tugurejo Subdistrict, Tugu District, Semarang, Central Java Province, which physiographically lies within the Northern Java Coastal Alluvial Plain Zone. Geographically, the study area is situated between Latitude and Longitude coordinates of 6°56'00"S – 6°58'45"S and 110°19'15"E – 110°22'00"E. The study block covered an area of 5 × 5 km with a total extent of approximately 25 km² (Fig. 1).

REGIONAL SETTING

Semarang is a unique city in Indonesia, as it consists of coastal (lowland) areas in the north and mountainous (highland) regions in the south, creating a diverse landscape that strongly influences its geomorphology, land use and socio-economic development (Marfai and King, 2008).

The Tugurejo coastal landscape is shaped by alluvial plains, tidal flats, and active fluvial deposits, which continue to evolve under the influence of tides, coastal currents, and sediment supply from the Silandak River. These dynamic settings make the area highly susceptible to shoreline changes while offering an excellent natural laboratory for studying sediment dynamics and coastal processes. Sediment sampling was carried out at four locations perpendicular to the length of the longshore bar to represent sediment deposits laterally. Core sampling was conducted in the Tugurejo area, specifically at the Longshore Bar area (Fig. 2).

Four sediment cores were collected, with thicknesses ranging from 50 to 100 cm. The primary objective of this sampling was to analyze the dynamics of sedimentation in the area, particularly at Longshore Bar area, using granulometric techniques to study the sediment characteristics and depositional processes. These sediment cores provide deeper insights into the structural changes in coastal sediments and their impact on shoreline dynamics.

Regional Physiography

According to Van Bemmelen (1949), the physiography of Semarang City belongs to the Alluvial Plains of the Northern Java Zone. This zone extends along the northern coast of Java Island and is characterized by lowlands composed of young alluvial deposits, such as sand, clay,

Fig. 2. Gravitational coring sample collection and field conditions of the longshore bar.

and silt, resulting from intensive sedimentation processes by major rivers flowing into the northern coast of Java and marine processes. The plain has a very flat topography with a slope of less than 2% and a maximum elevation of approximately 10 m above sea level.

Regional Stratigraphy

The Semarang City area has a unique geological character, dominated by the Quaternary alluvial deposits, particularly in the northern region, with relatively low topography. These deposits were formed through coastal, fluvial, and lacustrine sedimentation processes and are composed of clay, silt, and sand with variable thicknesses exceeding 50 m. The deposits are generally of Holocene age and represent the main characteristics of the alluvial plains along the northern coast (Fig. 3).

In the study area, stratigraphic data revealed several formations. The Kalibeng Formation (Tmpk) comprises napal, tuffaceous sandstone, and limestone. The Kerek Formation (Tmk) features alternating layers of claystone, napal, tuffaceous sandstone, conglomerate, volcanic breccia, and limestone. The claystone is light to dark gray and calcareous. The Damar Formation (Qtd) includes tuffaceous sandstone, conglomerate, and volcanic breccia, with brownish-yellow sandstone ranging from fine to coarse grains. The Kaligetas Formation (Qpkg) consists of breccia and lava with fine to coarse lava and tuff, and at its base, clay with mollusks and tuffaceous sandstone are present. The Kaligesik Volcano Formation (Qpk) is characterized by grayish-black basalt lava with a fine texture, composed of feldspar, olivine, and augite, and is notably hard. The Jongkong Formation (Qpj) contains andesite breccia with hornblende augite and lava flows, previously identified as Ungaran Lama volcanic rocks. The Gajah Mungkur Volcano (Qhg) is composed of grayish-black andesite lava with a fine, holocrystalline texture.

RESULTS

Shoreline Changes Characteristics

The shoreline is a dynamic boundary between the land and sea. According to Bird (2008), it represents the interface where land and ocean meet, which is constantly shifting due to physical processes driven by waves, tides, ocean currents, and human intervention. Shoreline changes are dynamic phenomena influenced by both natural factors and human activities. These changes occur naturally through physical processes such as abrasion and accretion. Abrasion occurs when ocean waves erode sections of the coast, whereas accretion occurs when sediments transported by water extend the shoreline. In addition, tidal fluctuations and wave energy play important roles in shaping shorelines. Strong waves can erode and damage coastal structures, whereas weaker waves can promote sand accumulation. Tugurejo is characterized by distinctive coastal environments and is one of the regions experiencing significant shoreline changes due to wave dynamics, tidal currents, and human activities.

Lithofacies

The analysis of the four sampling points revealed deposits composed of sand, gravel, and clay. Each lithology exhibited distinctive characteristics in terms of colour and sedimentary structures, resulting in considerable variation. This diversity formed the basis for determining lithofacies, referring to the concept of Miall (1978), which was later refined by Nichols and Fisher (2007) through a facies analysis approach. In the lithofacies classification, grain size and rock colour served as the primary criteria. This approach was chosen because, although sediments in the study area predominantly consisted of sand, differences in grain size and tonal variation were pronounced and could not be overlooked. Consequently, lithofacies classification was directed toward these two features, allowing the diversity within sandy deposits to be described more clearly and distinctly than before. The following are the results of the lithofacies descriptions:

– grey clay (CG): dark gray clay, the grains were small and tightly packed, there are no fossils.

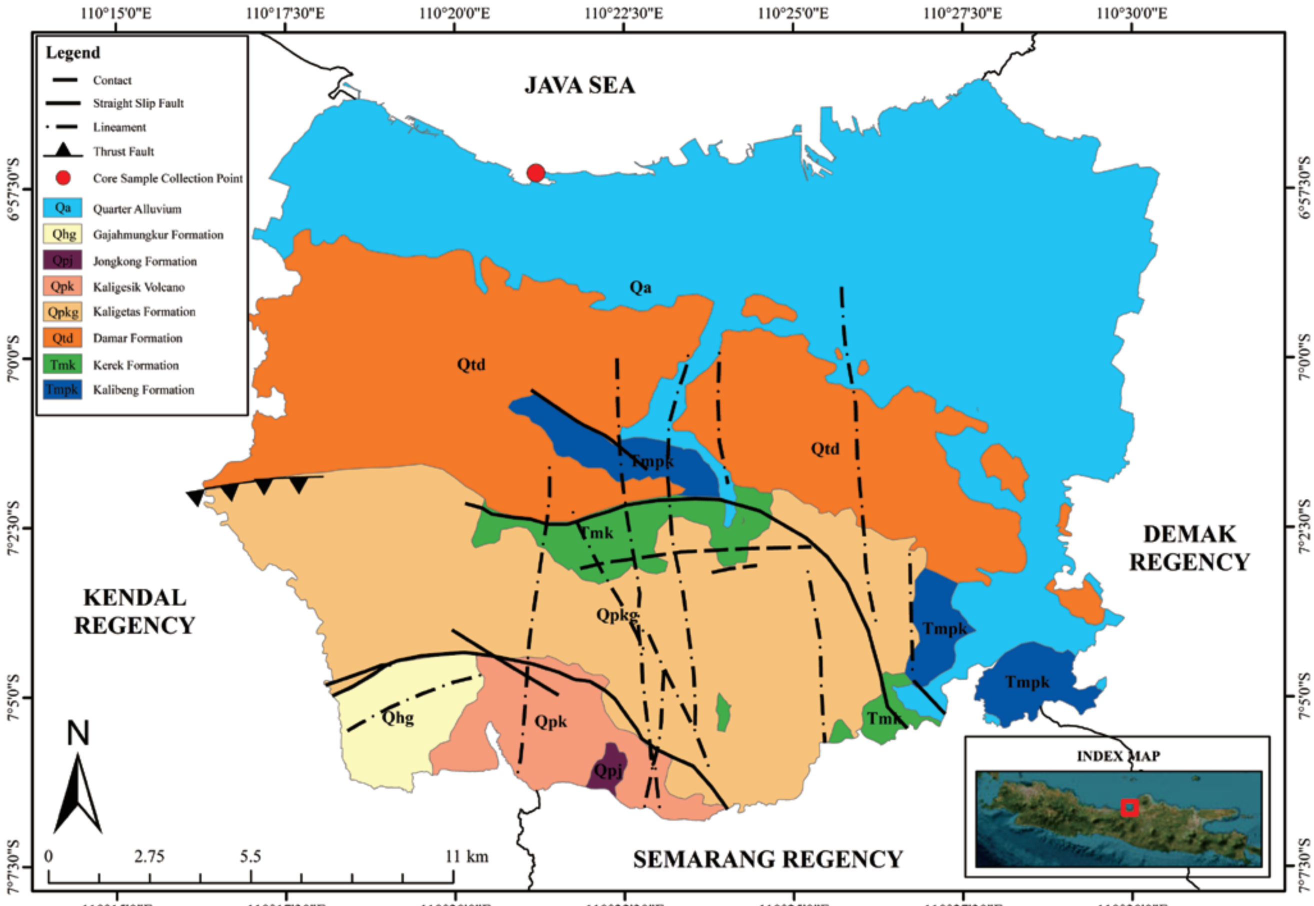


Fig. 3. The geological Map of Semarang City was modified from Thanden *et al.* (1996). The location consists of Quaternary Alluvial deposits, and the lineament is a line that indicates the presence of a structural pattern obtained from aerial photographs and radar imagery (SAR). Contact indicates the boundary between formations, with a dashed line if its location is estimated, and a dot if it is covered.

- blackish fine sand (FsB): gray to dark brown fine sand, the grains were tightly packed, there are no fossils, the dark color indicates the presence of organic material.
- blackish medium sand (MsB): gray to dark brown medium sand, the grains were tightly packed, it contains bivalve shells, the dark color indicates the presence of organic material.
- brown fine sand (FsBr): brown fine sand, the grains were tightly packed, it has layers and pieces of bivalve shells.
- brownish-gray medium sand (MsBr): brownish-gray medium sand, the grains were tightly packed, it has layers and pieces of bivalve shells.
- grey fine sand (FsG): gray fine sand, the grains were tightly packed, it has layers but no fossils are present.
- grey medium sand (MsG): grey medium sand, the grains were tightly packed, it has layers and bivalve shell fossils as well.
- brown coarse sand (CsBr): brownish-gray coarse sand, the grains were tightly packed, it contains bivalve shells.
- blackish coarse sand (CsB): dark gray coarse sand, the grains were tightly packed but not well sorted, it has many bivalve shells, the dark color indicates the presence of organic material.
- blackish very coarse sand (VCsB): gray to dark brown very coarse sand, the grains were tightly packed but not well sorted, it has many bivalve shells, the dark color indicates the presence of organic material.
- blackish gravel (GrB): dark brownish-black gravel, the grains were loosely packed and not well sorted, it contains bivalve shells, the dark color indicates the presence of organic material.

The lithofacies succession at TRG-01 (Fig. 4) shows a dominance of fine- to medium-grained sand with intercalations of coarse sand. The presence of blackish organic-rich material and bivalve fossils indicates a transitional coastal-shallow marine depositional environment. The occurrence of both structureless and laminated structures reflects fluctuating energy conditions, most likely resulting from the interaction between fluvial processes and wave/tidal dynamics (Fig. 4).

The lithofacies succession at TRG-02 (Fig. 2) was characterized by alternating medium sand, very coarse sand, and gravel with a dominant blackish coloration, reflecting a high organic material content. The presence of abundant bivalve shell fragments suggests a high-energy depositional setting, likely within a nearshore to tidal

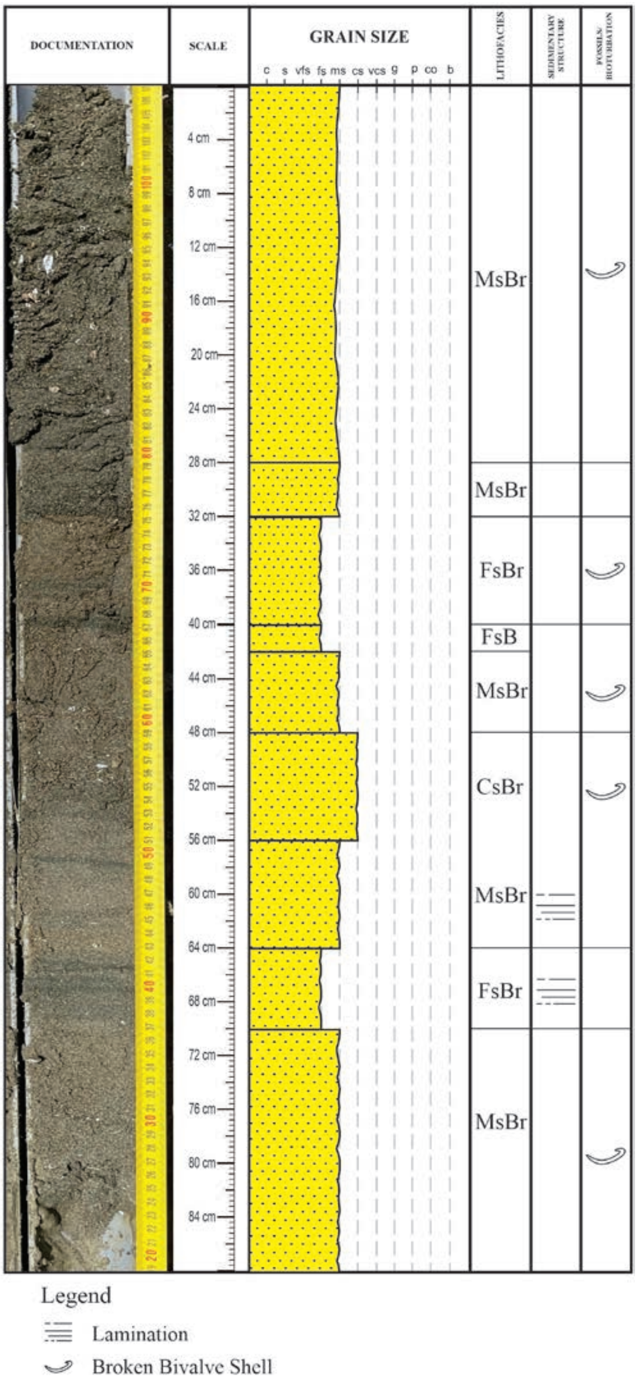


Fig. 4. Vertical stratigraphic column of TRG-01.

channel environment, where strong currents transported and deposited coarser sediments. Poor sorting in the coarse-grained facies further supports deposition under relatively rapid sedimentation and fluctuating hydrodynamic energies.

The stratigraphy at TRG-03 (Fig. 6) reveals a complex depositional environment characterized by dynamic energy conditions and a marine influence. The predominance of medium-to-very coarse sand facies indicates a high-energy setting, likely in the nearshore zone or within tidal channels. The frequent presence of abundant shell fragments, particularly bivalves, further supports the existence of a marine depositional environment. The alternating pattern of medium, very coarse, and coarse sand facies suggests fluctuating energy levels, possibly due to variations in wave action, tidal currents or storm events.

The poor sorting observed in the very coarse sand layer (VCsB) indicates rapid deposition during high-energy events, such as storm surges or strong tidal currents. These episodes likely resulted in the transport and deposition of a wide range of grain sizes, leading to the poorly sorted nature of sediments. In contrast, the laminated structures found in some medium sand layers indicate periods of more stable, yet still fluctuating, energy conditions. These laminations may represent alternating periods of stronger and weaker currents, possibly influenced by tidal cycles or seasonal variations in the wave energy. The overall stratigraphy suggests a dynamic coastal environment subject to frequent changes in depositional conditions, reflecting the complex interplay between marine and terrestrial processes in the nearshore zone of the coast.

The succession in TRG-04 (Fig. 7) exhibits a clear fining-upward trend, transitioning from medium-coarse sand facies at the base to fine sand and clay facies at the top. This sequence provides valuable insights into the evolving depositional environments. The basal medium-coarse sand facies, characterized by shell accumulations, indicate a

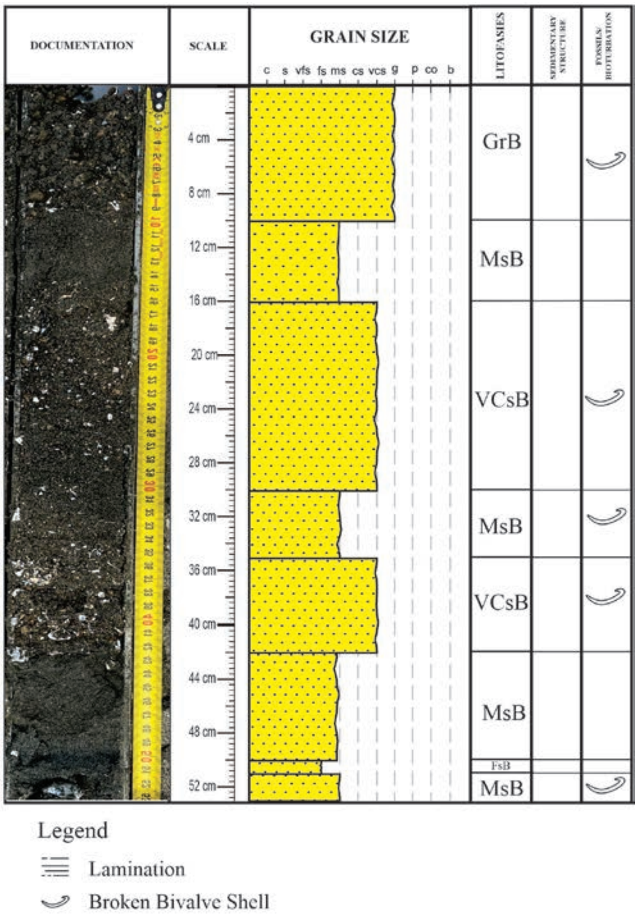


Fig. 5. Vertical stratigraphic column of TRG-02.

high-energy nearshore or tidal channel setting. In such environments, strong currents and wave action can transport and deposit coarser sediments while concentrating shell fragments. As the sequence progressed upward, the gradual shift to finer sand and ultimately clay facies suggested a reduction in hydrodynamic energy and a transition to a lower-energy depositional setting.

These vertical facies changes likely represent a shift from an active nearshore or tidal channel environment to a more protected tidal flat or lagoonal setting. The persistent presence of shell fragments throughout the sequence underscores the shallow-marine nature of the depositional environment, indicating sustained benthic life activity. The clay unit at the top of the succession is particularly significant as it reflects deposition under quiet water conditions. This could be attributed to factors such as increased water depth, reduced wave or tidal influence, or the development of protective barriers that shelter the area from high-energy processes. The overall fining-upward trend may be indicative of various processes, including transgression, channel abandonment, or gradual infilling of a tidal basin or lagoon.

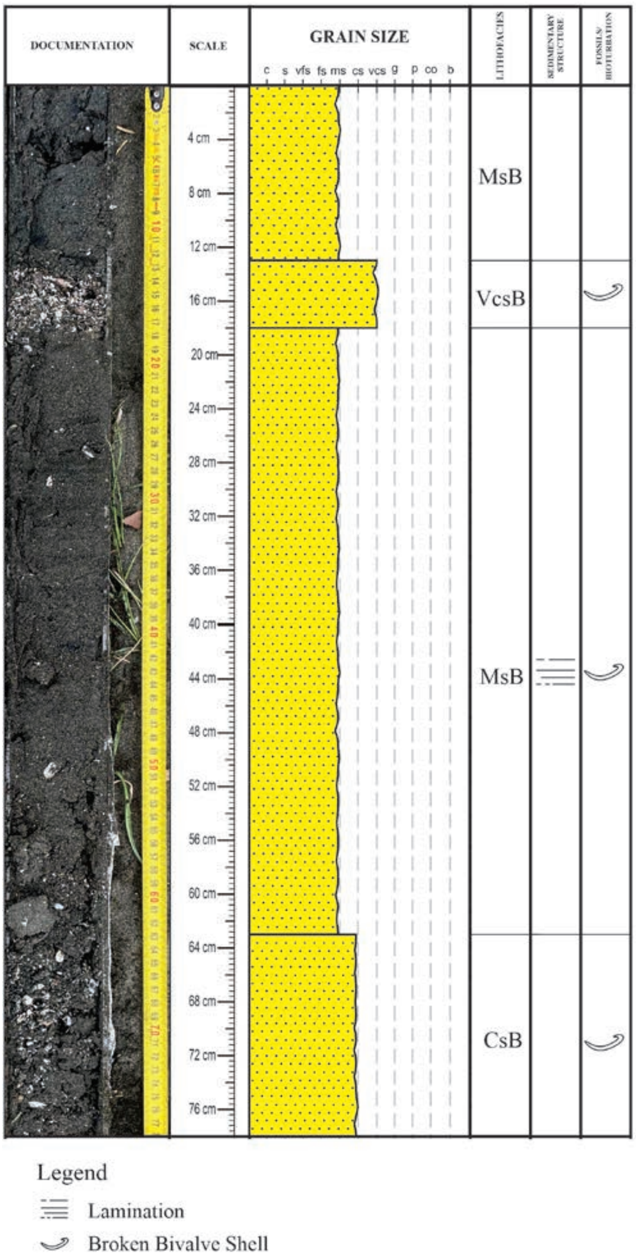


Fig. 6. Vertical stratigraphic column of TRG-03.

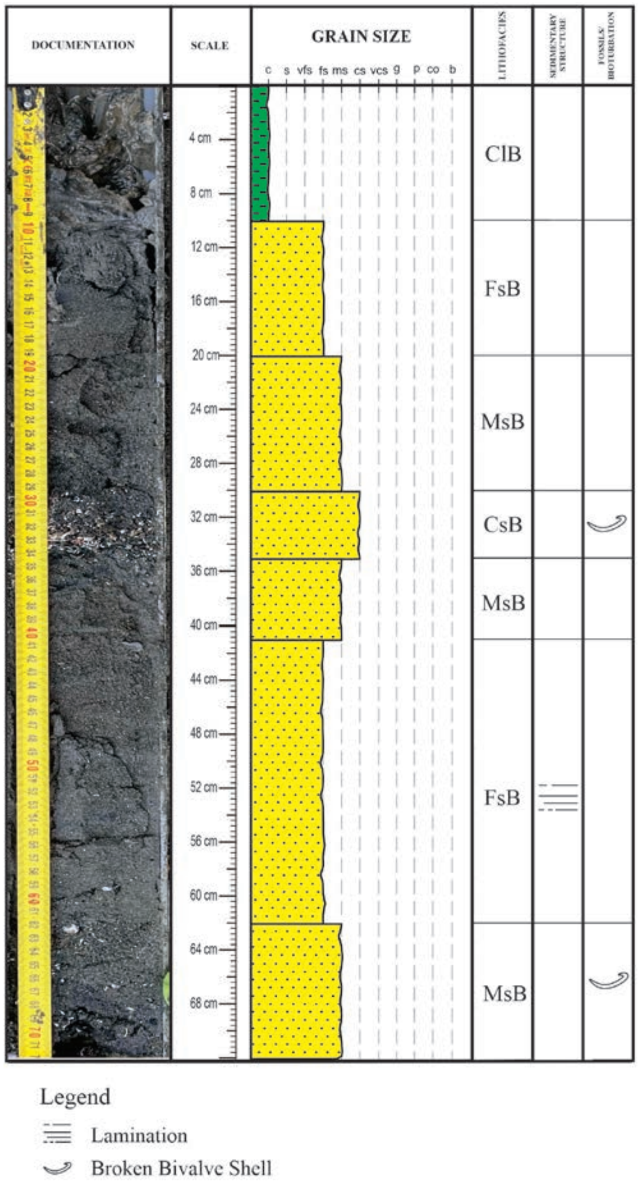


Fig. 7. Vertical stratigraphic column of TRG-04.

Facies Associations

Facies associations were determined using the model proposed by Reinson (1984). This model helps clarify facies development in the study area, which is driven by a rather complex coastal morphology. Based on the identified lithofacies, the study area can be grouped into three facies associations (Fig. 8), of which the first is described as follows.

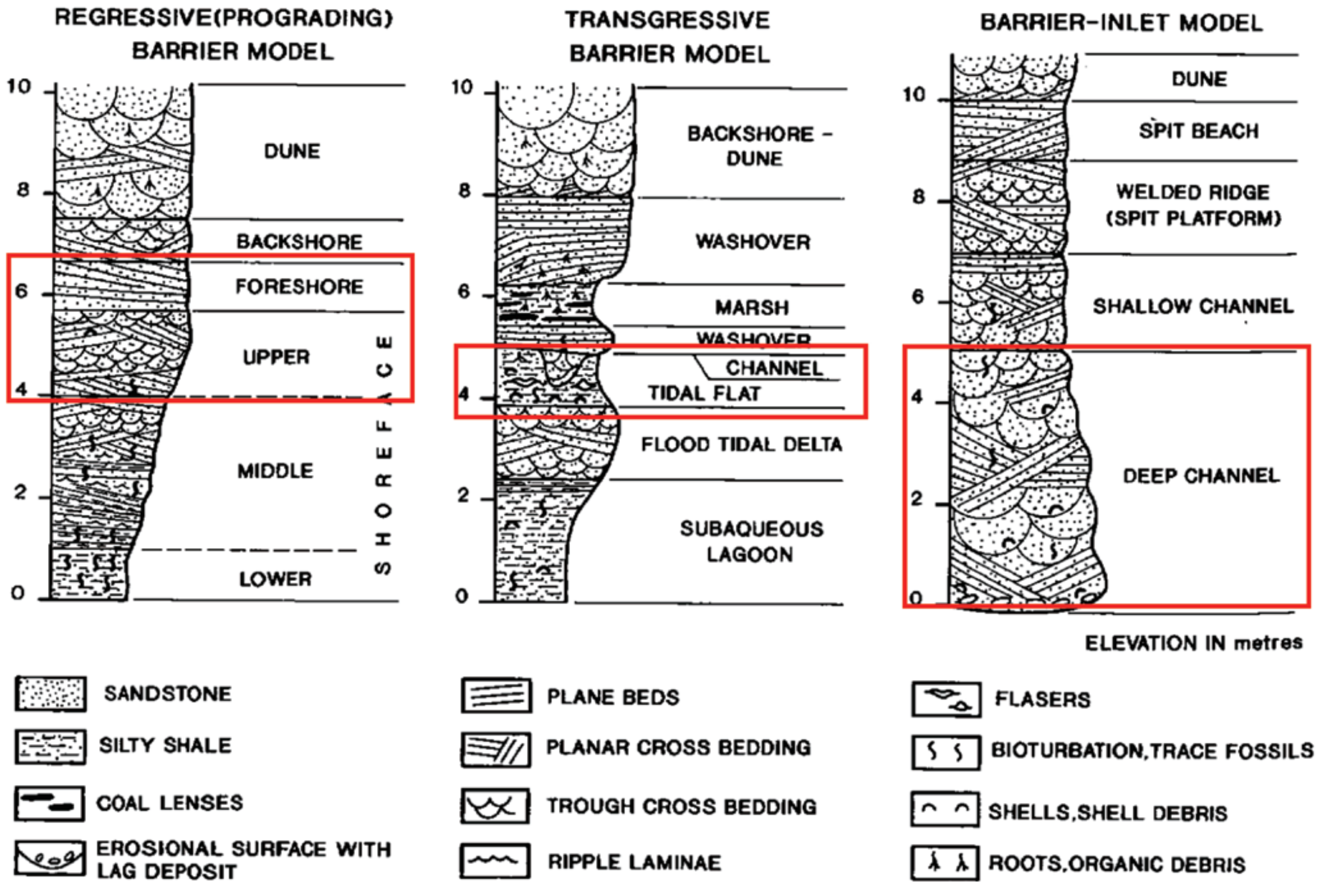


Fig. 8. Vertical succession of deep channel facies; red box indicates facies in the study area. (Walker and James, 1992).

Deep Channel

This facies association occurred in the back-barrier area, specifically at TRG-03 and TRG-04. It comprises FsB, MsB, CsB and VCsB. Sediments in this environment show a wide range of grain sizes, from fine to very coarse sand, indicating highly variable depositional energy. Although this association bears similarities to an upper shoreface facies association, it tends to display a fining-upward trend. Such upward fining likely results from a reduction in hydrodynamic energy, causing finer sediments to accumulate at the top of the sequence. This energy decrease can ultimately lead to the closure of the inlet channels on the barrier beach.

Foreshore

This facies association generally dominates the study area, with a thickness of up to 100 cm. It consists of FsBr, MsBr, FsG, MsG and CsBr. The facies are characterized by relatively uniform grain sizes and the presence of laminated structures, indicating deposition under relatively stable but fluctuating energy conditions. The foreshore is a coastal zone situated between the high tide and low tide lines and is directly influenced by wave activity and tidal fluctuations. This area functions as a highly dynamic transitional zone between land and sea, where significant changes in slope occur owing to wave action and variations in sea level. Under these conditions, the foreshore is strongly affected by physical processes driven by waves that continuously modify the sedimentary structures within this zone.

Upper Shoreface

This facies association was found at locations TRG-02, TRG-03, TRG-04, TRG-10, and TRG-1. At these points, the sediments consisted of FsB, MsB, CsB, VCsB and GrB. The sediments in this area display a wide range of grain sizes, from fine to coarse sand, indicating high and variable fluctuations in depositional energy. This suggests significant changes in the energy conditions during sedimentation.

The observed coarsening-upward pattern within the sedimentary layers indicates an increase in energy within this zone, likely caused by stronger currents or wave action. The predominance of blackish sediments reflects a high organic content within the material. This elevated organic content suggests that the sediments deposited in this zone most likely originated from riverine inputs that transported organic matter along with other sediments. The upper shoreface facies are associated with shallow marine zones located near the shoreline (Fig. 9), where the environmental conditions are strongly influenced by high wave energy

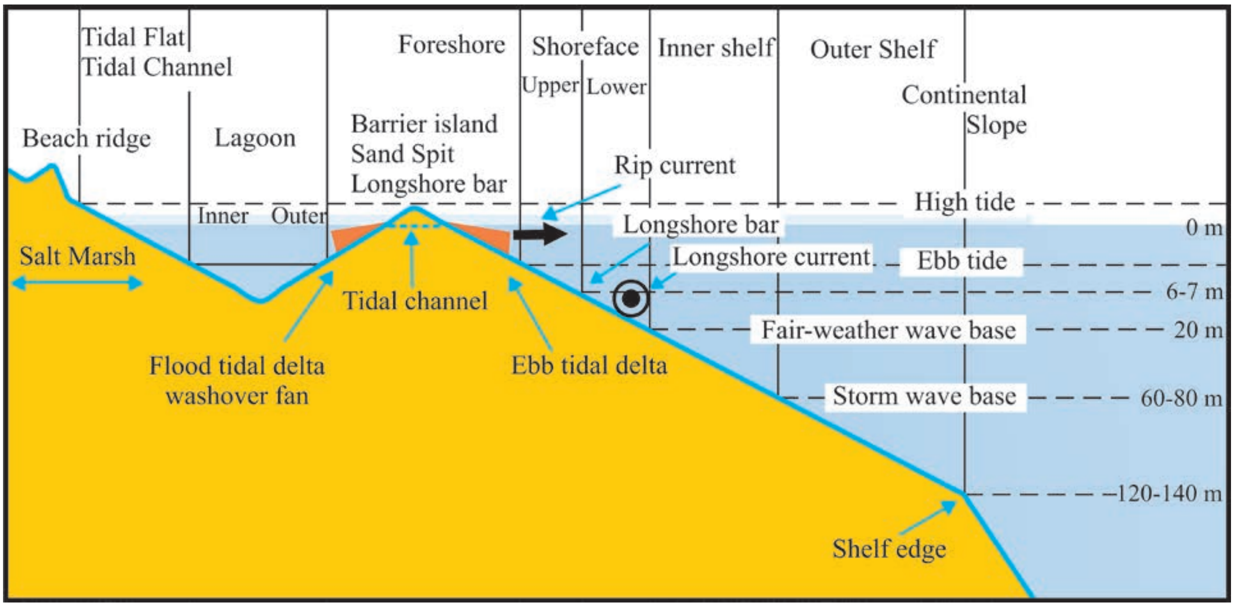


Fig. 9. Coastal–shallow marine depositional environments (modified from Reinson, 1984), research location indicated deposition in longshore bar, with influenced by tidal process the depth approximately 0–6 m below water base.

and significant tidal fluctuations. This zone forms part of a highly dynamic coastal environment, where continuous seawater movement alters both the physical and chemical conditions of the area. Strong tidal and wave processes lead to continuous modifications of the sedimentary structures that are deposited in this area.

Tidal flat

This facies association was identified at point TRG-04, where the sediment types consisted of CG and FsB, with grain sizes ranging from fine sand to clay. The sedimentary pattern observed at this point exhibited a fining-upward trend, indicating that the grain size of the sediments became progressively finer with increasing depth or distance from the energy source. This pattern indicates a decrease in depositional energy, suggesting that finer sediments were deposited after the previous higher-energy conditions subsided, either because of changes in current velocity or weaker wave action.

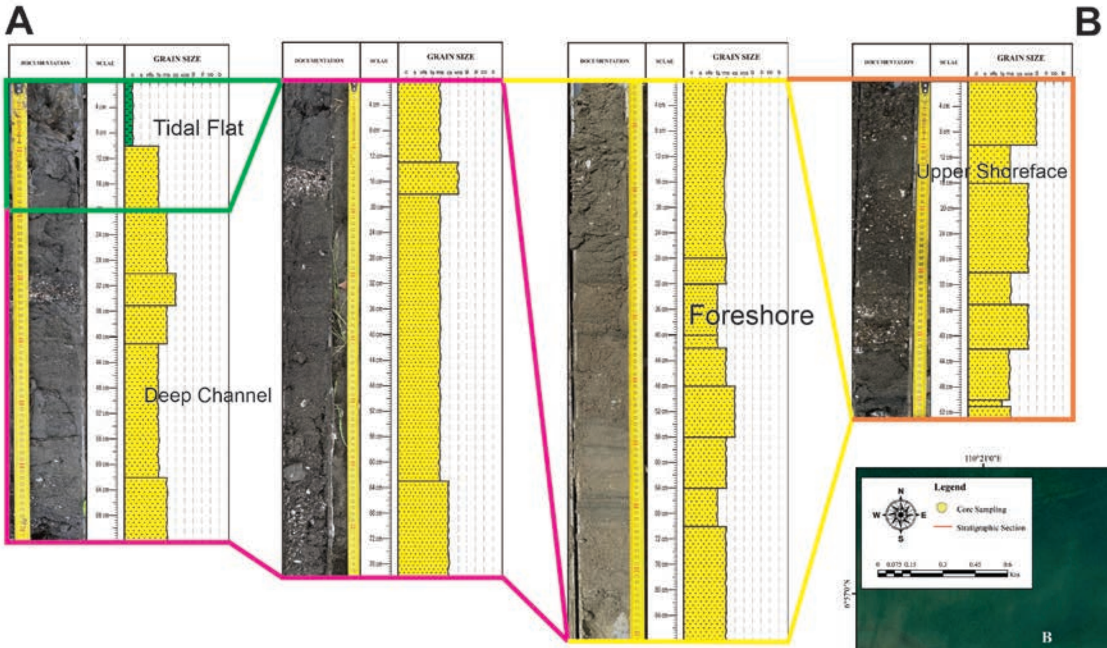
Stratigraphic correlation (Fig. 10) in this study was conducted by linking facies associations with similar characteristics for each core sample taken along the same transect line. The identification process utilized recognizable sedimentary patterns through the layering sequence from the base to the top of each core sample. These patterns are key to understanding variations in depositional environments and facies changes, both vertically and laterally.

The lithostratigraphic interpretation of the study area offers a comprehensive understanding of the depositional environment dynamics, shedding light on fluctuations in energy conditions and diverse sources of sediment input. By analyzing the vertical and lateral variations in lithology, sedimentary structures, and facies associations, researchers can infer the dominant depositional processes and their changes over time. This interpretation may reveal transitions between marine, coastal, and terrestrial environments, as well as variations in sediment supply, sea level changes, and tectonic influences on the basin.

Stratigraphic correlation, based on lithostratigraphic interpretation, extends this understanding across a broader spatial scale. By connecting stratigraphic units between different locations, it is possible to reconstruct the three-dimensional architecture of the depositional system. This correlation not only establishes a robust stratigraphic framework but also provides crucial insights into the geological history and environmental evolution of the area. This allows for the identification of regional trends, such as transgressive-regressive cycles, major depositional events, and significant unconformities. Consequently, stratigraphic correlation serves as a fundamental tool for unravelling the complex interplay of factors that have shaped the geological landscape of the study area over time.

Granulometry

Granulometry is the study of sediment grain size distribution, which is important for understanding the energy of depositional environments and sediment transport processes (Blott, 2001). According to Friedman (1979), granulometry provides insights into the physical conditions of the depositional environment, such as water depth, wave strength and current characteristics. Granulometric analysis measures sediment grain size and classifies it into various categories, ranging from fine mud to coarse sand and gravel. The results of this analysis provide an overview of the energy involved in sediment deposition and transport and can be used to interpret changes occurring in coastal areas.



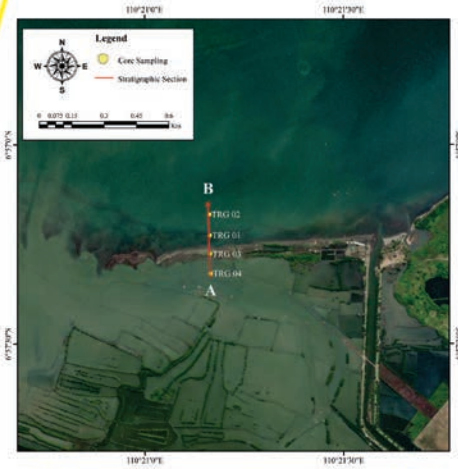


Fig. 10. The litostratigraphic correlation of TRG-01, TRG-02, TRG-03, and TRG-04 in the north-south direction is part of the northern coast of Semarang and is included in the Tugu Area district of Semarang city. The A–B line shows the direction of the cross-section trace used as a reference for constructing the stratigraphic correlation section, derived from the index map to the correlation figure.

Grain size analysis can be conducted using two approaches: graphical and mathematical (Boggs, 2006). The graphical approach produces three types of curves: histograms, frequency distributions, and cumulative curves. The histogram shows the percentage of mass within a given grain-size range. The frequency curve is a modified version of the histogram, converted into a line graph. The cumulative curve displays the relationship between the grain size and frequency expressed as the mass percentage. The mathematical approach uses several parameters, including mean (average grain size), sorting (uniformity of grain size within a sample), skewness (asymmetry of grain size distribution), and kurtosis (peakedness of the distribution) (Folk and Ward, 1957). These parameters were determined using the moment formula developed by Folk and Ward (1957). They are crucial for understanding sedimentary dynamics and provide information on the processes and energies involved in sediment transport and deposition.

Mean

The mean or average grain size is the most representative grain size in a sediment sample. This value reflects the average conditions of depositional energy exerted by water or wind that transports sediment particles (Richard, 1992, in Nugroho and Putra, 2017).

Sorting

Sorting indicates the degree of uniformity in grain size within sediment samples. Well-sorted sediments have grains of relatively similar sizes, whereas poorly sorted sediments consist of highly variable grain sizes. Sorting is strongly influenced by transportation and depositional processes, where stable currents or wave energy typically result in better sorting (Folk and Ward, 1957).

Skewness (Sk1)

Skewness is a statistical parameter that describes the degree of asymmetry in the sediment grain size distribution. This indicates whether a sample is dominated by finer or coarser grains. A positively skewed distribution has a long tail toward the finer fraction, whereas a negatively skewed distribution has a long tail toward the coarser fraction.

Kurtosis

Kurtosis measures the sharpness or flatness of the peak in the grain size distribution compared to a normal distribution. This parameter is useful for identifying the characteristics of depositional environments and sediment-transport processes.

Grain size analysis

It provides a more detailed and in-depth approach, revealing information about sediment grain size, distribution, and depositional characteristics that cannot be obtained through macroscopic observations alone. Based on the granulometric analysis and the classification of Folk and Ward (1957), the following are the characteristics of the deposits at each sampling point.

TRG-01

The sediments at depth of 0–88 cm were dominated by medium sand to fine sand, with mean values ranging from 1.93 to 2.36. Sorting is generally classified as very well sorted to well sorted (0.22–0.56), although some intervals exhibit moderately well sorted characteristics. Skewness ranged from -0.31 (very coarse skewed) to 0.56 (very fine skewed), with a dominant tendency toward finer grains.

Kurtosis shows a wide range from 0.88 (platykurtic) to 3.59 (extremely leptokurtic), reflecting grain size distributions from relatively flat to highly peaked. In general, these characteristics indicate a depositional environment with relatively stable energy, although certain intervals suggest fluctuations in energy and sediment mixing.

TRG-02

Grain size analysis at depths of 0–53 cm showed sediment textures ranging from very coarse sand to fine sand, with mean values between -0.07 and 2.53 Ø. Sorting varied from 0.24 (very well sorted) to 1.60 (poorly sorted), indicating conditions from very good to poor sorting. The skewness ranges widely from -0.79 (very coarse skewed) to 0.92 (very fine skewed), reflecting grain size distributions inclined toward either coarser or finer grains in certain intervals. Kurtosis also exhibited a broad range, from 0.49 (very platykurtic) to 6.24 (extremely leptokurtic), representing grain size distributions from relatively flat to highly peaked and concentrated. Overall, these characteristics indicate a depositional environment with highly variable energy dynamics, dominated by medium-fine sand, with intervals showing poor sorting and a tendency toward coarser grains.

TRG-03

Grain size analysis at depths of 0–78 cm showed textures ranging from coarse sand to fine sand, with mean values between 0.46 and 2.24 Ø. Sorting varied from 0.24 (very well sorted) to 1.47 (poorly sorted), indicating grain sorting from very good to poor. Skewness ranged from -0.79 (very coarse skewed) to 0.39 (very fine skewed), with most sediments tending to be symmetrical or slightly fine skewed. Kurtosis exhibited a wide range, from 0.51 (very platykurtic) to 5.15 (extremely leptokurtic), reflecting grain size distributions from flat to highly peaked and concentrated. Overall, these characteristics indicate depositional dynamics with fluctuating energy, dominated by medium to fine sand, but with intervals of coarse sand and poor sorting, reflecting variations in energy conditions during sedimentation.

TRG-04

Grain size analysis at depths of 0–72 cm showed a dominance of medium sand to fine sand, with mean values ranging from 0.34 to 2.92Ø. Sorting ranges from 0.23 (very well sorted) to 1.41 (poorly sorted), reflecting sediment sorting from very good to poor. Skewness varied between -0.70 (very coarse skewed) and 0.56 (very fine skewed), with most sediments showing symmetrical distributions or a tendency toward finer grains. Kurtosis exhibited a wide range from 0.49 (very platykurtic) to 7.96 (extremely leptokurtic), indicating grain size distributions from flat to highly peaked and concentrated. Overall, these characteristics reflect depositional conditions with relatively fluctuating energy, where the dominance of fine to medium sand indicates a generally stable environment, whereas intervals containing coarse sand and poorly sorted sediments suggest disturbances or changes in depositional energy.

Transportation Mechanism

The interpretation of the transportation mechanism based on grain size relationships provides valuable insights into sediment transport processes. Visher's (1969) method of analyzing cumulative grain size curves plotted on log-probability graphs reveals distinct subpopulations of grains transported by different modes. These curves typically exhibit two or three straight line segments, each representing a specific transport mode: suspension, saltation, and traction. This approach allows for a more nuanced understanding of sediment movement in the studied environment.

By applying Visher's (1969) method to the sampling points, researchers can identify the dominant transportation mechanisms at each location. This analysis helps reconstruct the depositional environment and understand the hydrodynamic conditions that prevailed during sediment deposition. The relative proportions of grains transported by suspension, saltation, and traction can provide information on factors such as flow velocity, turbulence, and bed roughness. Additionally, variations in these proportions across different sampling points can reveal spatial patterns in sediment transport and deposition, providing insights into the overall sedimentary system dynamics. The transportation mechanisms at each sampling point were summarized based on the Visher (1969) curves as follows.

TRG-01

Visher plot analysis of the TRG-01 sediments revealed a complex depositional history characterized by shifting transport mechanisms and flow energy. In the lower section (70–80 cm), the dominance of traction indicates a high-energy environment capable of moving coarse particles along the bed. This suggests a period of strong currents or wave action, potentially in nearshore or fluvial settings. As the sediment profile transitioned to the middle intervals (60–70 cm to 20–30 cm), the increasing prominence of saltation points indicated a gradual shift in hydrodynamic conditions. This change likely reflects an increase in flow turbulence or water depth, allowing the suspension and transport of finer particles over short distances.

The upper part of the sediment profile (0–20 cm) showcased further evolution of the depositional environment, with saltation becoming the primary transport mechanism. This indicates a significant increase in flow energy and turbulence, which can sustain finer particles in suspension for extended periods. The observed transition from traction-dominated to saltation-dominated transport throughout the profile suggests a dynamic depositional setting, possibly influenced by factors such as sea level changes, tectonic activity, or climatic variations. The resulting mixed-grain sediment layers provide valuable insights into the paleoenvironmental conditions and hydrodynamic variability of the area during deposition, offering potential clues about past geological and climatic events.

TRG-02

The Visher plot for TRG-02 indicates variations in the transport mechanisms, reflecting changes in the flow energy. At 50–60 cm, traction and saltation contributed equally (50% each), suggesting moderate flow conditions capable of transporting both fine and coarse particles. At 40–50 cm, saltation dominated (80%), indicating sufficient energy to lift fine particles, whereas coarse particles moved slightly by traction. At 30–40 cm, traction was dominant (90%), indicating a strong flow capable of moving coarse particles, whereas fine particles were minimally transported. In the 20–30 cm interval, transport was fully controlled by saltation (100%), indicating highly turbulent conditions dominated by fine particles. At 10–20 cm, transport was a mix of saltation (60%) and traction (40%), producing mixed sediments. The top layer (0–10 cm) was fully dominated by saltation (100%). Overall, this pattern shows flow energy fluctuations from moderate to high, resulting in deposits with textures ranging from mixed-to fine-grained dominance.

TRG-03

The Visher plot for TRG-03 shows transport variations reflecting changes in flow energy from bottom to top. At 70–78 cm, saltation and traction were balanced (50% each), indicating a moderate flow capable of moving both fine and coarse particles, producing mixed-grain layers. From 60–70 cm to 50–60 cm, transport was fully dominated by traction (100%), showing sufficient energy for coarse particles but insufficient to lift fine grains. In the 40–50 cm to 30–40 cm intervals, saltation dominated (60–70%), indicating increased flow energy, although traction still contributed to coarse particle movement. At 20–30 cm, the transport was fully controlled by saltation (100%). The upper layers (10–20 cm and 0–10 cm) were dominated by saltation (70–80%) with minor traction (20–30%), reflecting high energy capable of moving fine particles while partially transporting coarse particles along the bed. Overall, this pattern shows a transition from lower-traction dominance to upper-saltation dominance, indicating fluctuating flow energy from moderate to turbulent and producing deposits ranging from mixed to fine grained.

TRG-04

The Visher plot for TRG-04 shows near-complete dominance of saltation throughout the depth, with a minor traction contribution in some intervals. At the lower part (70–72 cm and 50–60 cm), transport was fully dominated by saltation (100%), indicating sufficient flow energy to lift fine particles, whereas coarse particles remained immobile. At 60–70 cm and 20–30 cm, saltation and traction were balanced (50% each), reflecting moderate flow conditions that produced mixed sediments. In the 40–50 cm, 30–40 cm, and 10–20 cm intervals, saltation dominated (70–90%) with minor traction, indicating sufficient energy to lift fine particles, whereas coarse particles moved slightly along the bed. The topmost layer (0–10 cm) was fully dominated by saltation (100%), indicating the most turbulent flow conditions transporting only fine particles. Overall, the TRG-04 sediments record a high-to-turbulent flow environment where particle transport predominantly occurs through saltation, with traction playing a limited role at certain intervals.

Bivariate Analysis

Depositional environment interpretation can be conducted using granulometric data, which provide essential information on the characteristics of deposited sediment grain sizes (Boggs, 2006). These data reflect how physical processes in the depositional environment, such as water flow, wind, or waves, affect sediment grain size distribution. One widely used method for analysing and interpreting granulometric data is the approach proposed by Friedman (1967).

Friedman (1967) suggested using a two-component grain size variation diagram, where two statistical parameters—skewness and standard deviation (sorting)—are plotted against each other. By plotting these parameters,

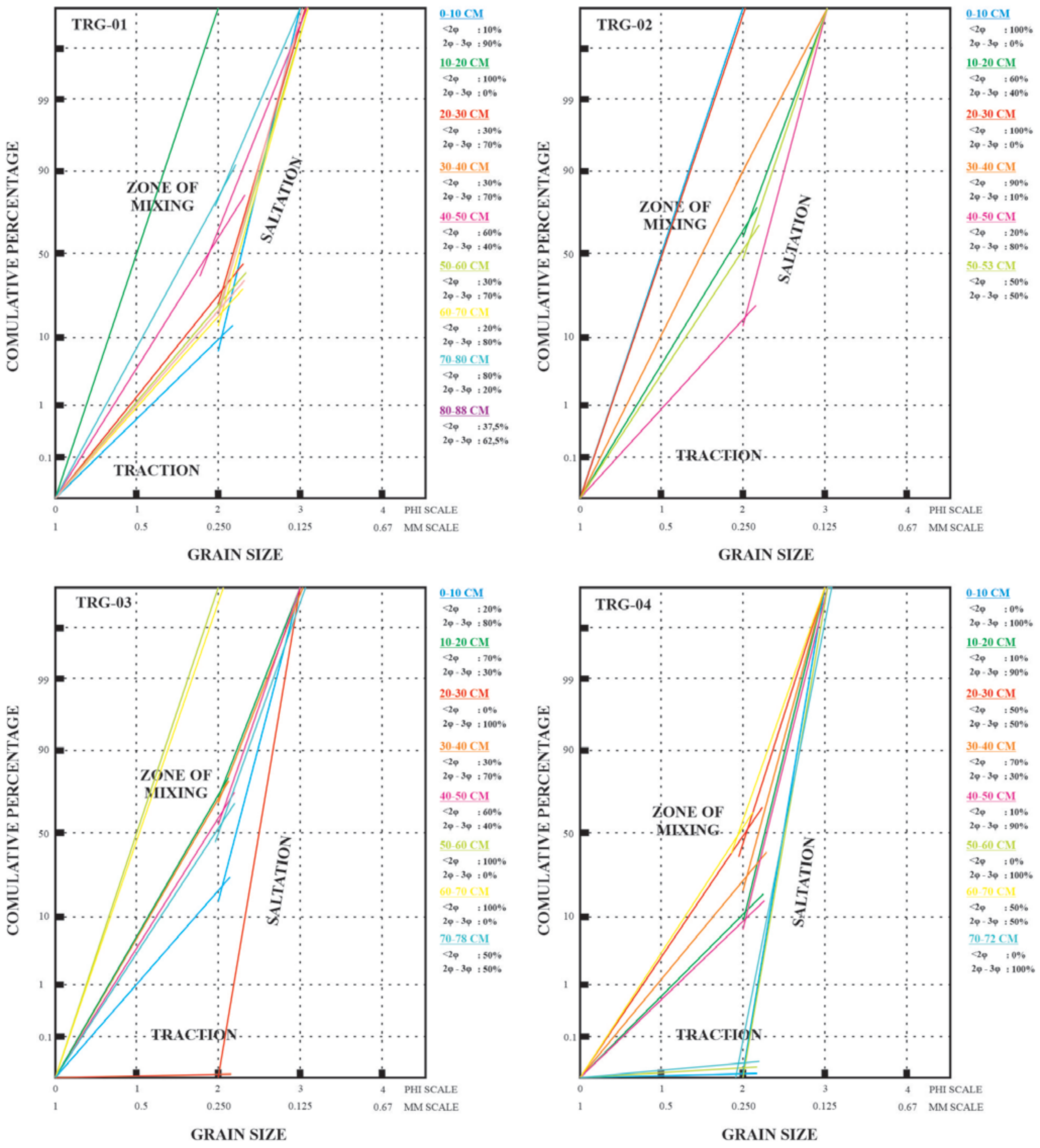


Fig. 11. The relationship between sediment transport dynamics and the population distribution as well as grain size of the longshore bar deposits at TRG-01, TRG-02, TRG-03, and TRG-04 (Visher, 1969, in Boggs, 2006).

the Friedman method allows separation into two main environments: beach and fluvial environments. Beach environments are typically characterized by positive skewness and good sorting, whereas fluvial sediments usually show negative skewness with poor sorting. Based on the bivariate analysis (Fig. 12), the sediments in the study area were predominantly marine in origin. This marine dominance was particularly evident in the TRG-01 sample. Sediments at these points exhibited positive skewness toward fine grains and good sorting, indicating deposition in a stable environment, such as a beach or coastal area influenced by waves.

At TRG-03 and TRG-04, the percentages of fluvial and beach sediments were nearly equal, indicating that the influences of river and marine energy were almost the same. This is reflected in the even distribution of sediments with both positive and negative skewness and

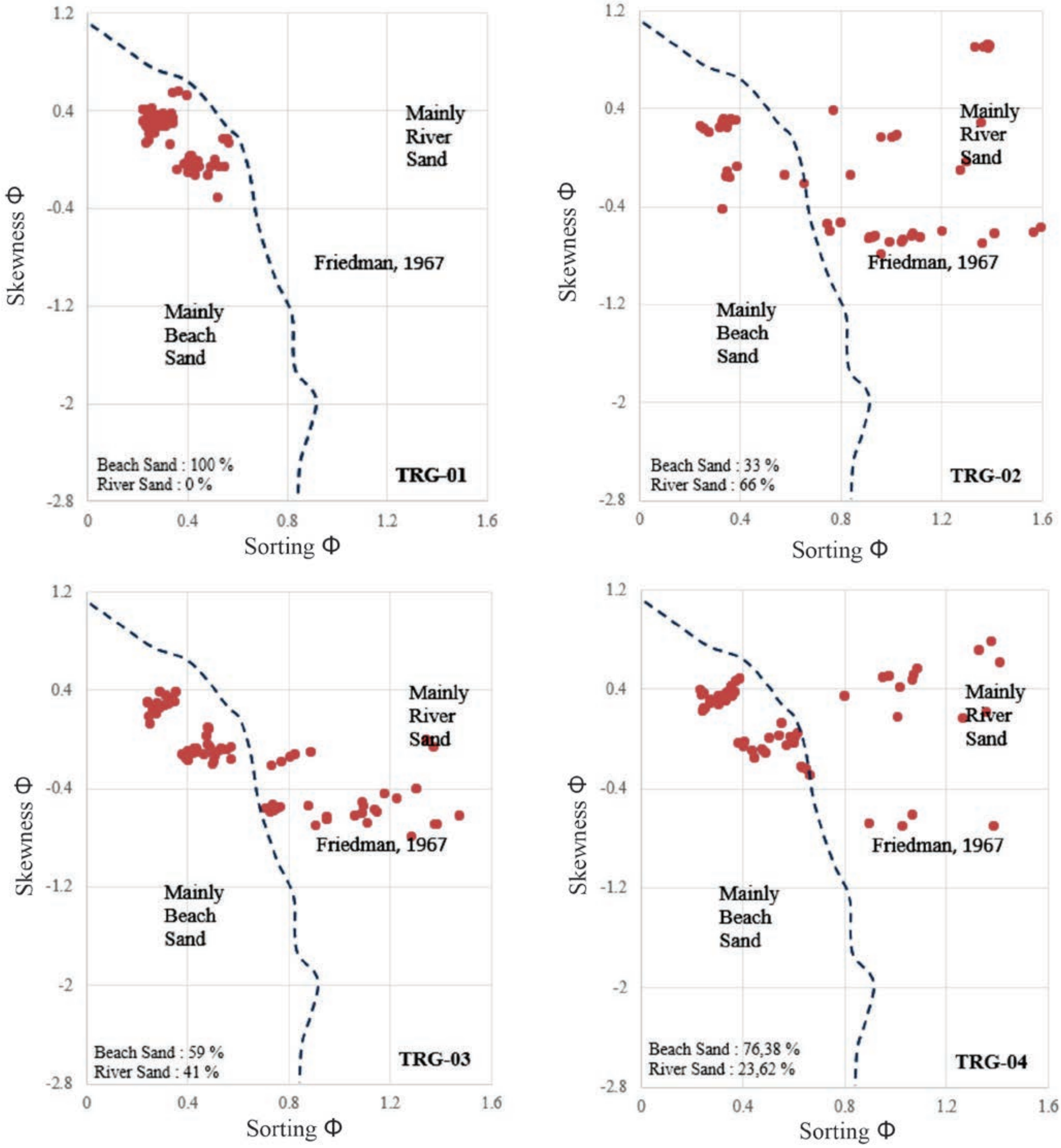


Fig. 12. The bivariate plot of grain size for skewness versus sorting shows the dominance of beach and fluvial sediments at TRG-01, TRG-02, TRG-03, and TRG-04 (Friedman, 1967, in Boggs 2006).

diverse sorting values. This observation correlates with facies associations based on lithofacies, indicating tidal flat and deep channel environments. In TRG-02, the proportion of fluvial sediments increased, and fluvial environments dominated. At TRG-02, 66% of the sediments were fluvial and 33% were marine. At TRG-12, fluvial sediments accounted for 88.23%, whereas marine sediments constituted only 11.76%. This is because sediments at these points are dominated by negative skewness toward coarse grains and relatively poor sorting, indicating deposition in a less stable environment influenced by strong river currents. This pattern aligns with the facies associations based on lithofacies, where the area corresponds to the upper shoreface. The high proportion of fluvial sediments in the upper shoreface association is due to the proximity of the study area to river mouths, which transport sediments via marine currents and deposit them along the coastal zone.

DISCUSSION

Depositional Environment

Boggs (2006) defined facies as a group of rock layers with specific geometric, lithologic, and sedimentologic characteristics that distinguish them from the surrounding environments. Selley (1985) further explains that sedimentary facies are identifiable units that can be differentiated based on geometry, lithology, sedimentary structures, fossils, and paleocurrent patterns, all of which result from deposition processes within a specific sedimentary environment. Thus, facies not only describe the physical properties of rocks but also reflect the environmental conditions and depositional processes at the time of their formation.

A depositional environment is a set of physical, chemical, and biological conditions present in an area where sedimentary materials accumulate (Selley, 1988). According to Boggs (2006), a depositional environment represents a geomorphic setting in which ongoing physical, chemical, and biological processes determine the type of sedimentary deposits formed. The characteristics of the resulting sediments are influenced by the intensity of the depositional processes and the duration over which they occur (Boggs, 2006). Depositional environments are generally categorized into three types: continental, transitional, and marine (Boggs, 2006).

Based on facies and granulometric analyses, the study area is generally dominated by sand deposits, which develop across a range of environments, including fluvial, transitional, and deep marine settings. Facies associations reveal the presence of lithofacies characteristics of the barrier island environment (Fig. 13). This environment is not uniform but consists of three distinct sub-environments: the barrier island itself, the back-barrier area, and the channels connecting the back-barrier to the open sea. Each sub-environment has unique characteristics that influence sediment deposition in the area.

Sediment transport processes in this barrier island system are similar to those on beaches. The main transportation mechanisms are saltation and traction, where larger and heavier sediment particles are moved by strong waves or river currents. Both mechanisms require significant energy, indicating that this area is influenced by high-energy conditions from both waves and river flow. Deposition in tidal channels, tidal flats, marshes, and back-barrier complexes also plays an important role in shaping sediment characteristics.

However, this environment differs from a typical beach because of the additional deposition processes in tidal channels and tidal flats. This reflects more complex energy dynamics and stronger tidal fluctuations in these areas, where transport energy varies and deposition processes are more intricate (Visher, 1969).

Bivariate granulometric analysis showed that sediments with positive skewness and good sorting dominated most samples, indicating deposition in relatively stable environments, such as beaches or tidal flats, influenced by wave action. These sediments are generally finer, with a more regular grain-size distribution, reflecting relatively stable transport energy. Conversely, sediments exhibiting negative skewness at certain locations, such as tidal flats within back-barrier complexes, deep channels in connecting channels, and upper shoreface areas, suggest deposition under higher-energy, less stable conditions. Strong currents or tidal flows transport coarser particles, reflecting dynamic conditions. This aligns with observations in tidal flats, deep channels, and upper shoreface settings, where deposition is influenced by fluctuating energy during the tidal cycles. Transport via traction and saltation deposits larger particles, but coarser sediments with negative skewness

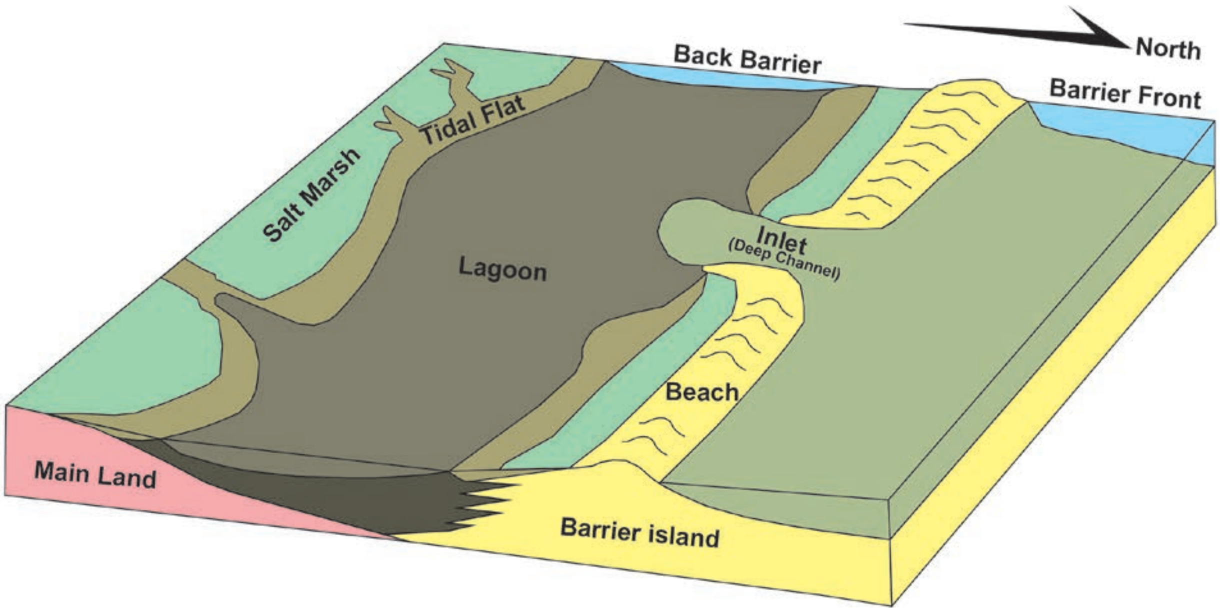


Fig. 13. Barrier-Island Depositional Environment Classification from research area, Modified from Reinson, (1984), The research location is a transitional sedimentation system from land to sea, and is a representation of the current research area.

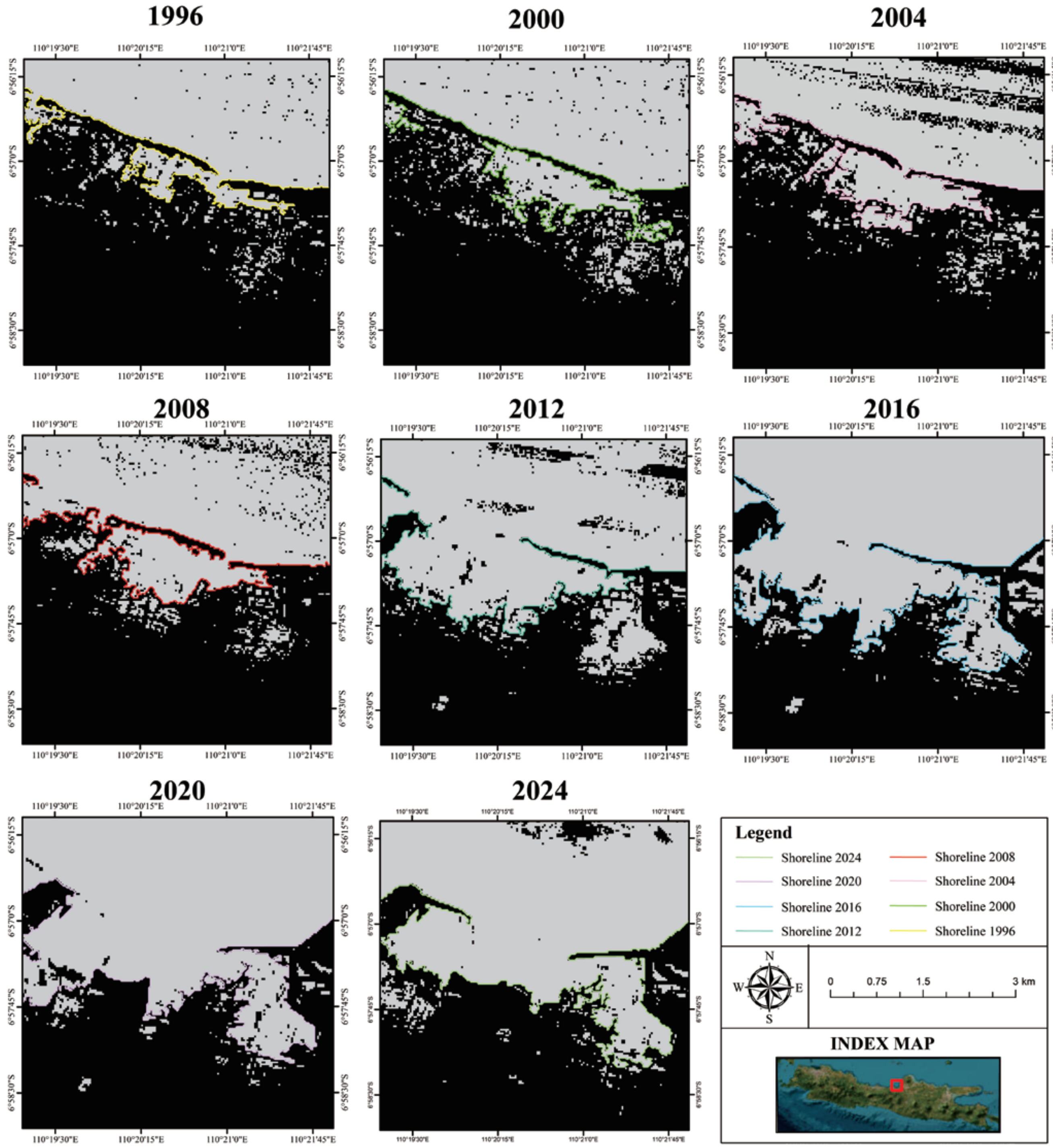


Fig. 14. MNDWI Extraction Results for the Tugurejo Coast from 1996 to 2024.

and poor sorting indicate fewer stable conditions than more stable beach environments.

One important finding from the analysis was the discovery of lithofacies associated with a sub-environment connecting channel between the backwater area and the open sea. This indicates that a connecting channel was formed during sediment deposition at the study site. The existence of this connecting channel usually occurs when the energy of ocean or river currents is sufficient to form a channel that connects the two areas. The presence of this channel may be due to the sufficiently high transport energy during the sedimentation period. in this study area.

Shoreline Changes

The process of satellite image data processing to analyze shoreline changes along the Tugurejo Coast began with Landsat 5, 7, and 8 imageries from 1996 to 2024. Landsat imagery was selected based on data availability

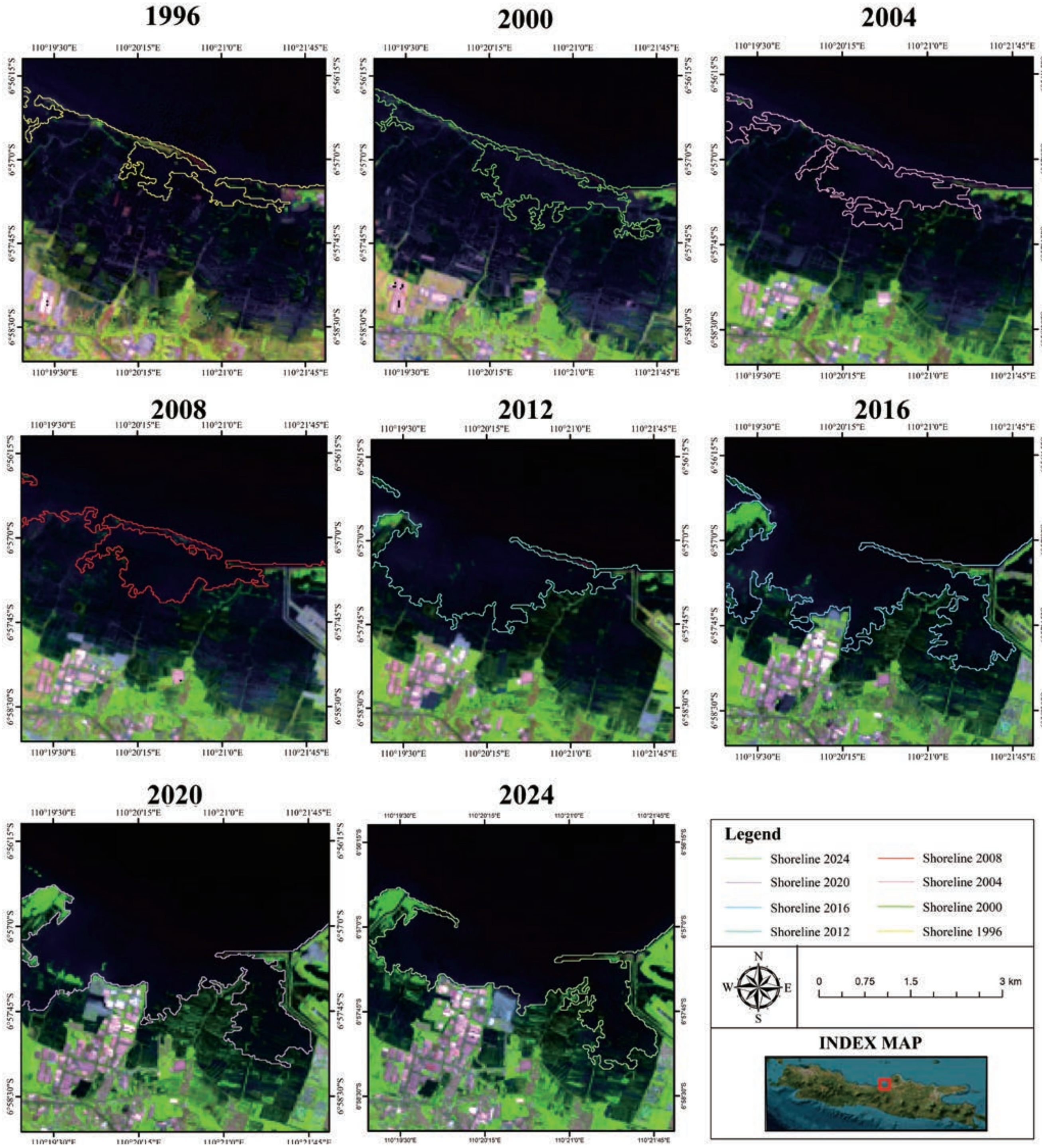


Fig. 15. Shoreline Change Map of Tugurejo from 1996 to 2024.

and its ability to provide sufficiently high spatial resolution, allowing for long-term monitoring of shoreline changes (Setiawan and Masitoh 2024). However, before these data could be used for further analysis, the satellite images had to undergo several processing steps to ensure accurate shoreline extraction.

After cloud masking, the Landsat images were processed using the Modified Normalized Difference Water Index (MNDWI) threshold to separate land and water (Fig 14). The threshold values differed for each image because of variations in image quality (Table 2). Once the water bodies were identified, irrelevant elements such as small islands and temporary ponds were removed to ensure that the analysis focused only on stable shorelines. Morphological operations, including erosion and dilation, have also been applied to smooth land-water boundaries (Sutanto *et al.*, 2017; Kumar *et al.*, 2018).

The final image that has been produced is then con-

Table 2. MNDWI Threshold Value for the Tugurejo Area.

Year of Image Acquisition	MNDWI Treshold
1996	0.70
2000	0.70
2004	0.70
2008	0.73
2012	0.60
2016	0.45
2020	0.40
2024	0.45

verted into vector form because the image is still in raster form. The raster image, which consists of a grid of pixels, was converted into a more structured vector format. In the vector format, the identified coastline is depicted as a clear boundary between land and sea. The resulting vector was extracted in a shapefile format, as shown in Fig. 15. The extracted coastline results were then analyzed using the DSAS to identify and interpret the patterns of change that occurred during the study period. The distance between transects in the DSAS analysis was set at 30 m, which was selected based on the spatial resolution of the image used. The Landsat images had a spatial resolution of 30 m. The actual transect distance was determined based on the resolution of the image used to obtain more accurate details.

The shoreline extraction results from 1996 to 2024 showed significant changes along the Tugurejo coast, with a general trend of shoreline retreat toward the land owing to erosion. In 1996, the shoreline was relatively stable, but between 2000 and 2004, it began to shift into aquaculture areas vulnerable to erosion, resulting in many ponds being permanently inundated by seawater (Gaol *et al.*, 2025). This shoreline retreat became more pronounced between 2008 and 2016 and worsened further during 2020–2024, whereas mangrove areas remained stable, effectively absorbing wave energy and trapping sediments (Rahajeng, 2018). Conversely, some central and eastern areas experienced accretion due to coastal reclamation, which increased the land area for development purposes. Land reclamation can provide benefits such as creating new, more stable land for human use and reducing the risk of erosion. However, if not properly managed, reclamation can damage natural habitats, such as mangroves, alter water flow and sedimentation patterns, and degrade coastal ecosystem quality. Therefore, although reclamation contributes to land accretion, sustainable management is necessary to minimize its negative impact (Lai *et al.*, 2015; Wu *et al.*, 2018; Rahmadi and Yuniastuti, 2023).

Erosion and Accretion Rates

The erosion and accretion rates along the Tugurejo coast were analyzed using the Digital Shoreline Analysis System (DSAS) through transects as reference points for shoreline changes (Fig 16). The analysis for the 1996–2024 period showed significant dynamics of alternating erosion and accretion. Maximum accretion was recorded at 17.05 m/year and minimum at 1.08 m/year, influenced by natural factors such as tides, currents, sedimentation, and reclamation. Conversely, maximum erosion reached 58.05 m/year with a minimum of 0.36 m/year, which is closely related to climate change, sea-level rise, and human activities disrupting coastal equilibrium.

The average shoreline changes along the Tugurejo coast from 1996 to 2024 showed an accretion rate of 7.37 m/year, but erosion was more dominant with an average of 23.71 m/year. Overall, the shoreline displacement reached 19.34 m/year, which, according to the Ministry of Public Works and Public Housing (PUPR) research and development (1993) classification, falls into the very severe erosion category (<-10 m/year). This condition indicates significant coastal erosion influenced by wave action, disrupted sediment transport, land subsidence, human activities, and sea level rise due to climate change (Winarto, 2012).

Relationship between sedimentation dynamics and shoreline changes

The analysis of the relationship between sedimentation dynamics and shoreline changes along the Tugurejo Coast showed a complex interaction between regionally dominant erosion and localized progradation at several points (TRG-01, TRG-02, TRG-03, TRG-04). This progradation begins with the formation of inlets that allow sediment transport to the land, which are later closed by deposition, promoting accretion and shoreline advancement toward the sea. Satellite imagery from 2021–2022 illustrates these changes, although erosion remains dominant and continues to cause shoreline retreat. This contrast indicates that satellite images capture long-term trends (erosion), whereas core sediment analyses reveal short-term local dynamics (progradation). Thus, the Tugurejo coast is highly dynamic, with regional erosion dominating, while local resilience persists through progradation processes.

CONCLUSIONS

This study effectively identified the direction and trends of shoreline alterations in the Tugurejo coastal region by employing Landsat imagery, which offers more extensive spatial and temporal coverage than that of several earlier studies. By combining satellite-based analysis with sedimentological data, this study enhances the reliability of interpreting coastal changes. The comparison of sedimentation characteristics through granulometric analysis was particularly crucial, as it allowed for the identification of variations in depositional energy and their connection to the shoreline dynamics. Sediment grain size is highly responsive to hydrodynamic energy and serves as a vital indicator for reconstructing the evolution of the sedimentary environment and evaluating the extent of coastal change processes, such as erosion, accretion, and longshore drift. However, several areas could be improved in future re-

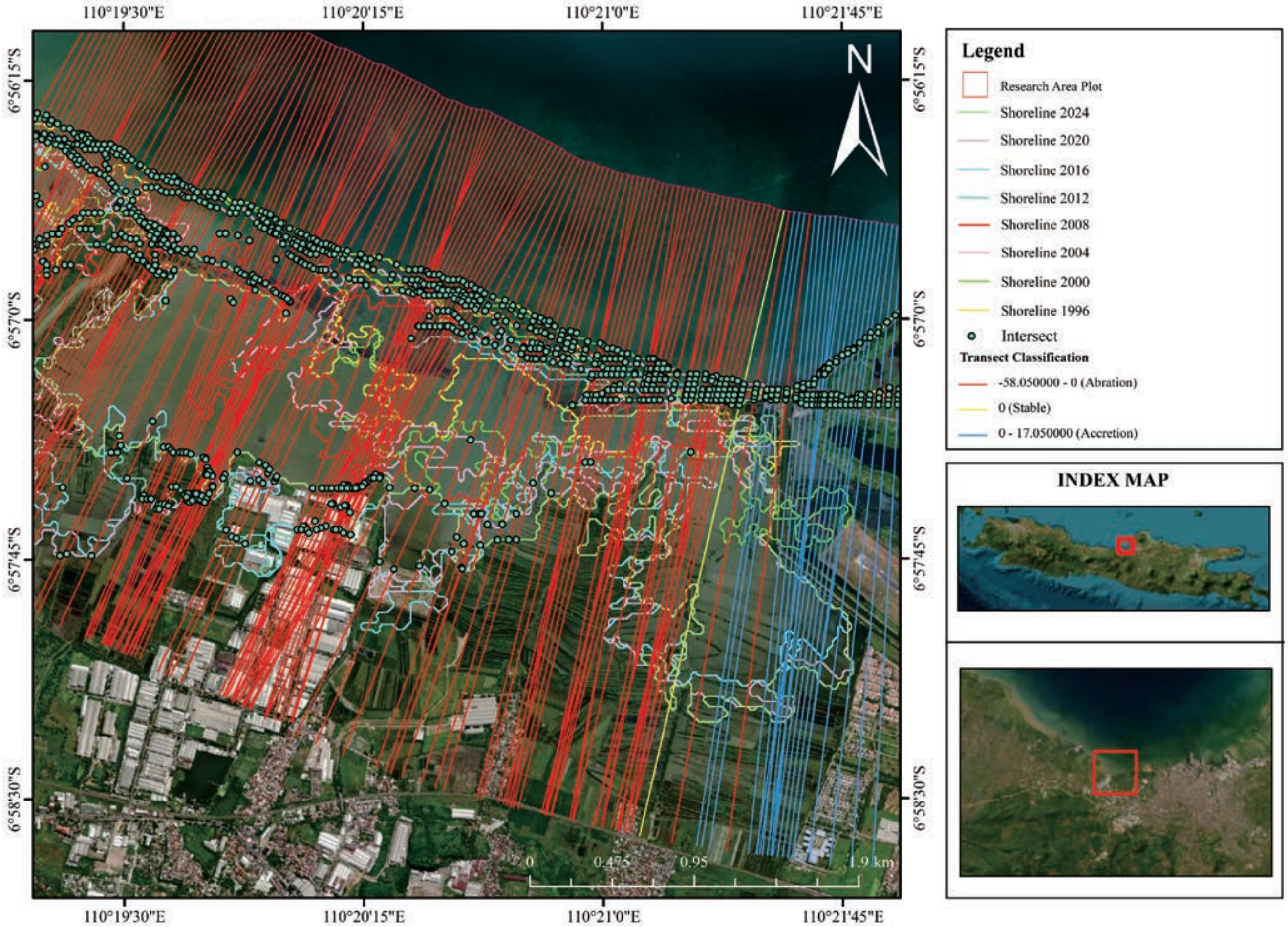


Fig. 16. Overlay map of Tugurejo shoreline 1996–2024 and shoreline transect results 1996–2024.

search. Sediment sampling locations should be planned both perpendicular and parallel to the longshore bar to provide a more comprehensive representation of sediment distribution patterns along the coastal profile. This approach enhances the spatial resolution of the dataset and offers a better understanding of the lateral continuity of sedimentary facies. Additionally, using higher-resolution satellite imagery, such as Sentinel 2 or UAV-based orthophotos, could significantly improve the accuracy of shoreline delineation and morphological change detection. Incorporating such high-precision data would enable more detailed temporal analyses and strengthen the robustness of coastal-monitoring efforts.

In addition to remote sensing and granulometric methods, integrating hydrodynamic modelling and in-situ current measurements would offer deeper insights into sediment transport mechanisms and their controlling factors. These complementary datasets can clarify the interactions between wave energy, tidal currents, and sediment supply, which collectively influence shoreline evolution in the Tugurejo area. Thus, a multidisciplinary approach involving geomorphology, oceanography, and sedimentology is crucial for developing a more comprehensive understanding of coastal dynamics. Future studies should also consider evaluating human influences, such as land reclamation, coastal infrastructure development, and mangrove degradation, which have been shown to accelerate shoreline retreat and alter sediment transport pathways.

Overall, the findings of this study contribute to the expanding body of knowledge on coastal morpho dynamics in northern Java. The methodological framework, which combines remote sensing analysis with granulometric characterization, demonstrates a reliable approach for assessing shoreline evolution in sediment-dominated environments. The results not only provide scientific insights into ongoing sedimentation processes but also have practical implications for coastal zone management, particularly in formulating strategies for shoreline stabilization and habitat conservation in the Tugurejo coastal region of Semarang.

The Visher plot for the TRG-01 sediments illustrates variations in transport mechanisms with depth, indicating fluctuating flow energy. In the lower section (70–80 cm), traction predominated, suggesting that coarse particles settled owing to sufficient flow energy to mobilize larger materials along the bed. In the middle intervals (60–70 cm to 20–30 cm), saltation became more prevalent, indicating increased flow energy capable of lifting finer particles. In the upper section (0–20 cm), transport was predominantly governed by saltation, reflecting increasingly turbulent conditions dominated by fine particles. This transition from traction dominance at lower depths to saltation dominance at greater depths signifies dynamic energy conditions, resulting in mixed-grain sediment layers and indicating depositional environments with variable hydrodynamic conditions. Based on the analysis of sedimentation dynamics in the Longshore Bar area, the depositional environment is complex and active, characterized by barrier island systems. Granulometric analysis revealed that sediment transport in this area is largely governed by high-energy mechanisms such as saltation and traction. The predominance of these mechanisms, as evidenced by the absence of suspended sediments in the Visher curves, suggests that the depositional environment is continuously influenced by strong wave and marine currents.

Another significant finding was the occurrence of progradation or land addition beginning in 2021, although this process was not uniform. Progradation was observed at several observation points, including TRG-01, TRG-02, TRG-03, and TRG-04. This is clearly observed in the vertical facies succession, where inlet closure is followed by the deposition of foreshore, upper shoreface, and tidal flat facies over older deep channel facies.

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