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RESEARCH ARTICLE

The Coastline Change Pattern of Gresik Beach around the Madura Strait, Indonesia

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Abstract The coastal region is characterized by dynamic changes in its coastline, which can be attributed to various factors. However, the main causes of change along the Gresik coast have yet to be thoroughly studied. Therefore, this research aims to examine the patterns of coastline change along the Gresik coast around the Madura Strait and the influence of wind-generated waves on them. Specifically, the study focuses on four coastal zones: Ujung Pangkah, Sidayu, Bungah, and Manyar districts. The research utilizes satellite imagery and geographic information systems (GIS) as well as methods for calculating ocean waves to analyze the coastline change patterns. The study also examines the impact of ocean wave energy on coastal abrasion and accretion. The findings revealed that the accretion rate in the study area was higher than the erosion rate. The accretion in the coastal area of Gresik is attributed to the flow of the Bengawan Solo River, which carries sediment from upstream. The accretion and abrasion areas for the entire period from 2002 to 2019 were 1063.16 ha and 425.23 ha, respectively. The study also found that the mangrove areas exhibit a higher rate of accretion than abrasion, indicating their potential as a reliable indicator of the effects of sea level rise resulting from global warming. This study revealed that the northern part of Ujung Pangkah District and Bungah District experienced the highest abrasion patterns, whereas no abrasion was observed in Sidayu District. Between 2002 and 2019, the abrasion areas in Ujung Pangkah and Bungah districts totaled 243.96 ha and 178.29 ha, respectively. Wind-generated waves were likely the primary cause of the abrasion in these areas, though other factors may also have contributed to coastline changes. It is essential to consider these factors for effective coastal management in the region.

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1. Introduction

The coastal region is highly dynamic, influenced by both natural and human activities (Ahmeda et al., 2017; Balica et al., 2012; Jeong et al., 2022). Morpho-dynamic processes occur naturally in coastal areas due to geomorphological and oceanographic factors, while human activities exert additional pressures that can sometimes dominate natural processes. Activities such as logging of mangroves for aquaculture and settlements can also affect the dynamics of coastal areas. The dynamics of coastal change play a crucial role in disaster management, coastal planning, and environmental conservation.. (Khan and Hussain, 2018).

To monitor the land dynamics in the coastal area, GIS techniques and remote sensing can be used cost-effectively (Ghost et al., 2015; Kaddour et al., 2022). From a geomorphological perspective, the coastal area of Gresik Regency is highly dynamic, with land abrasion and accretion occurring at varying rates (Anggraini et al., 2017). The Bengawan Solo River in the area carries sediment, which is bound by the numerous mangroves present, leading to accretion. Mangroves are known to be established along sedimentary coastlines and intertidal areas of tropical and sub-tropical zones, as stated by Godoy (2018). However, the region also experienced erosion in the north of Ujung Pangkah and the east of Bungah, caused by wind-generated waves.

This coastal area serves multiple purposes, including aquaculture, settlement, industry, and conservation. Numerous ponds and residential areas are located in Ujung Pangkah, Sidayu, and Bungah, while several industrial areas are located in Manyar. Some of the industries present in the area include PT. Maspion Industrial Estate (MIE), PT. Petrochemical, PT. Smelting, PT. Karya Indah Alam Sejahtera, the wings group, and the Java Integrated Industrial and Ports Estate (JIIPE) project.

On the western side of the Madura Strait, various industries require coastal land for their activities. These companies, except for JIIPE, require a wider business location in line with their progress each year. As a result, these companies carry out reclamation activities in their boundaries with the sea. Since each company has a terminal-type dock for its use, the reclamation direction is approaching each of its docks.

The coastal area of Gresik has flat beaches, particularly in the Ujung Pangkah District of Gresik Regency. Although the tides and low tides are not significant, the tidal plains are wide. To reach a depth of nine meters, the distance from the shoreline is 1 to 1.5 km. Such coastal phenomena encourage each company to conduct reclamation up to 1 km with an area adjusted to the width of the coastline of the land owned by the company.

This reclamation activity in Gresik Regency can result in a reduction in the width of the Madura Strait, potentially disrupting shipping lanes around the Mireng River and Madura Strait. Therefore, research on abrasion and accretion, as well as an examination from an oceanographic perspective, especially wave height, is necessary. The results of this study can be beneficial in determining reclamation policies around the Madura Strait. This study aims to analyze the patterns of coastline change around the Gresik coast in the Madura Strait and the impact of wind-generated waves on them. The results of the study can help identify areas experiencing erosion, enabling sustainable coastal management in the region.

2. Methods

This study was conducted over an eight-month period, from December 2019 to August 2020. The research was carried out on the coast of Gresik in the Madura Strait of East Java, specifically at coordinates 7°03' South Latitude and 112°37' East Longitude, and 7°10' South Latitude and 112°43' East Longitude (as shown in Fig. 1). The data utilized in this research consisted of topographical maps at a scale of 1:25,000, satellite imagery data of Surabaya from multiple years, including TM data from 2002, Google Earth images from 2002, 2014, and 2019. This study utilized a restricted time frame for data analysis, encompassing five years for short-term changes and 17 years for long-term changes. The research employed three distinct software applications for processing satellite imagery and determining the extent of accretion and erosion: ArcMap 10.3/ArcView 3.3, and Image Analysis 1.1. The methodological approach adopted in this research entailed the combination of survey and GIS analysis techniques (Prasita, 2015).

The processing of spatial data was conducted using ArcView 3.3 software. In this research, several important spatial data processing operations were employed, including the digitization of maps, the overlaying process, the calculation of long shorelines and land areas, and the production of layout maps (Prasita, 2022). In the analysis of the shoreline data, a digitization process was conducted on the shorelines in 2002, 2014, and 2019. Prior to this, it was ensured that the images had undergone geometric correction in the previous stage. Subsequently, the digitized coastlines from 2002, 2014, and 2019 were overlaid in a single layer. Both shorelines were then utilized to cut the polygon, enabling the determination of the total area. Hence, the area resulting from changes in coastline areas could be determined using the count tool (Prasita, 2015). In assessing changes in the coastlines, a line perpendicular to the shoreline serves as the basis for determination. This study employed a line perpendicular to the coastlines of satellite imagery in 2002 as the baseline (Prasita, 2015).

This research primarily examined the alterations in coastline patterns resulting from the influence of wind-generated waves. Wave data was collected from a specific location, 113°E 6.5°S. The research process was depicted in the research flowchart (Fig.2). The study was limited to the effects of wind-generated waves and utilized data from the period between 2010 and 2019 to analyze the waves responsible for beach abrasion. The wave data was used to display significant wave heights and incoming wave directions, as well as to determine wave energy. The data source was the ERA 5 Climate Data Store, a collaboration between the European Center for Medium-Range Weather Forecast (ECMWF) and Copernicus Europe. The data had a monthly temporal resolution and a spatial resolution of 0.50° × 0.50°.

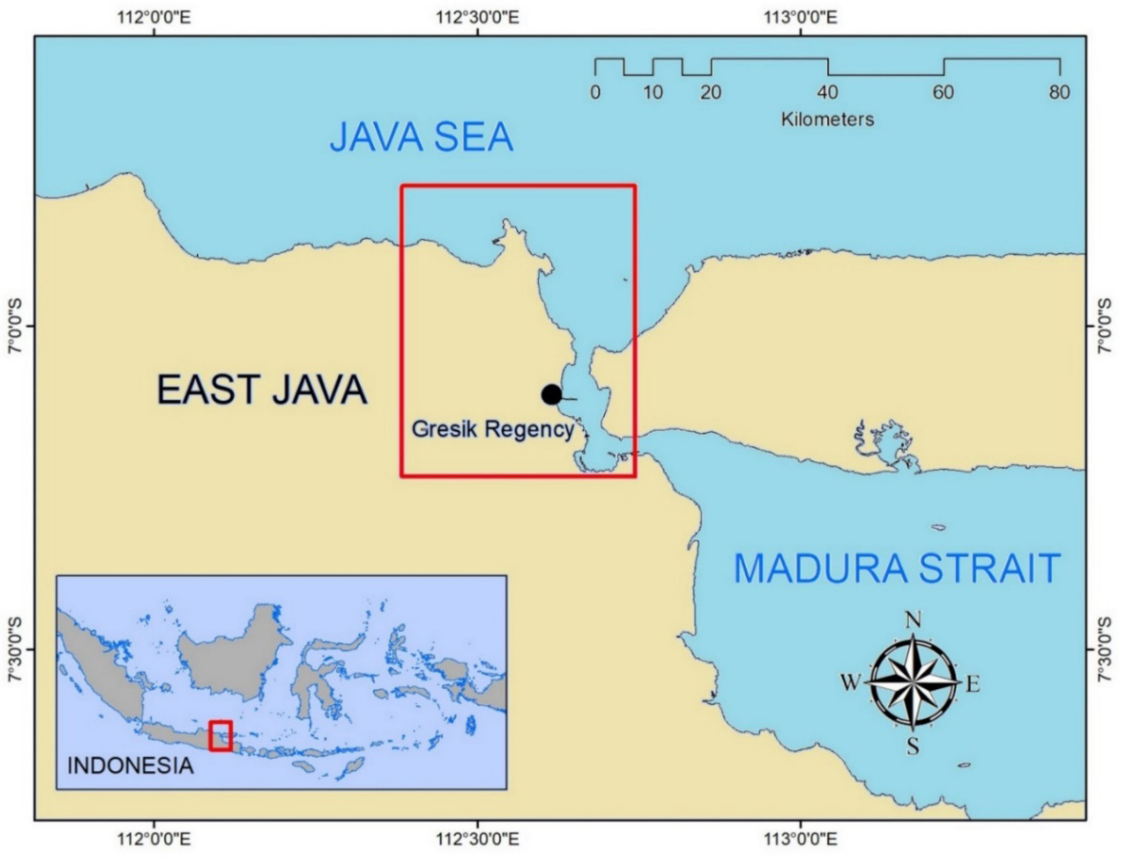

Figure.1 Research location of the Gresik Coast in Madura Strait East Java

Wave energy was calculated by the following formula

$$E = T^{\frac{1}{5}}.H_0^{\frac{12}{5}} \quad [1]$$

Where is wave energy, $T^{\frac{1}{5}}$ is wave period from the deep water, $H_0^{\frac{12}{5}}$ is significant wave height from deep water.

Conceptually similar to the more common "wave energy" (proportional to H^2), E, the "deepwater wave height contribution to Qs", more exactly represents how deepwater wave height and period contribute to Qs based upon the CERC formula (Ashton & Murray, 2006).

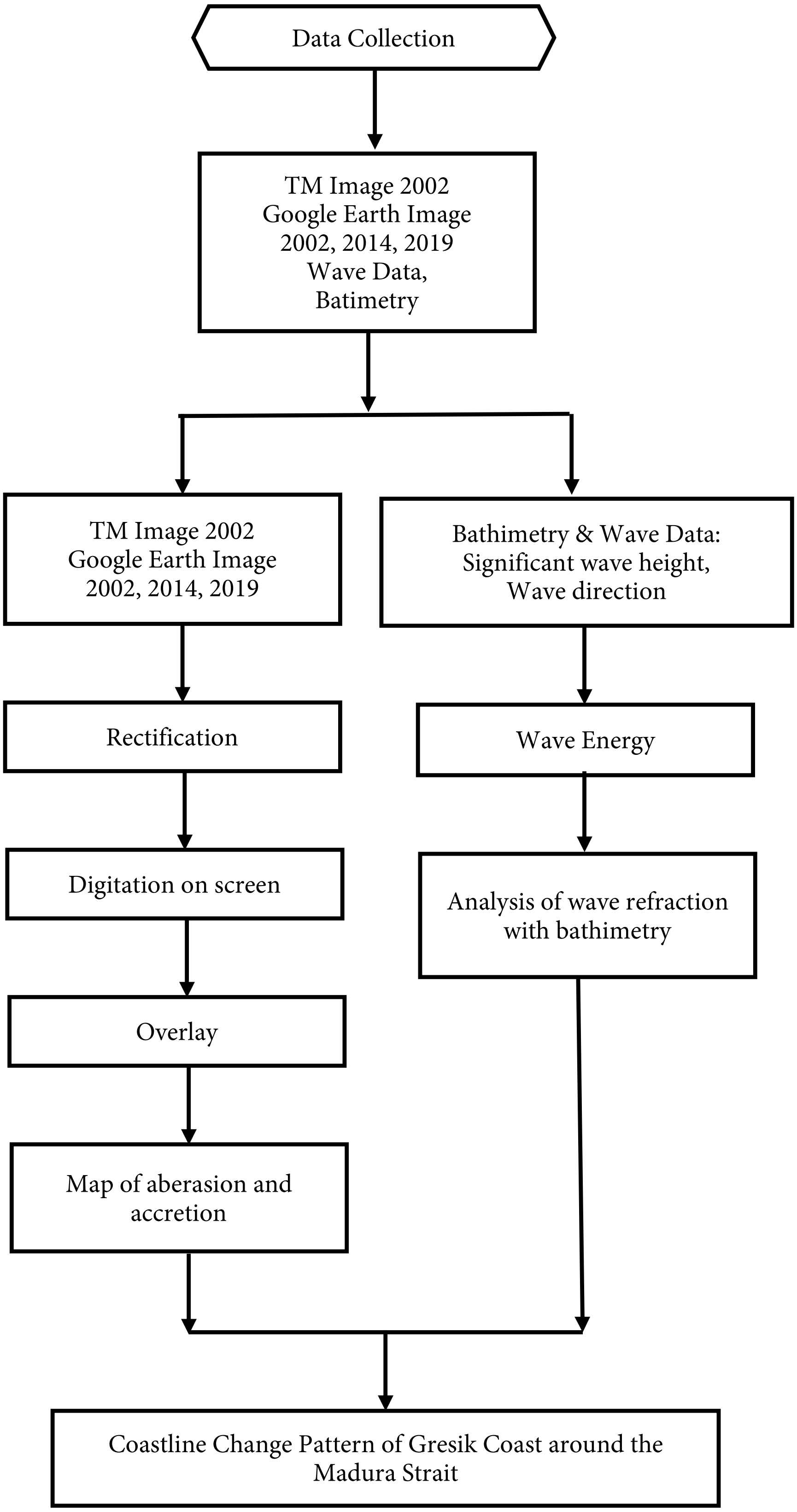

Figure 2. Research flowchart of the Gresik Coast in Madura Strait East Java

3. Result and Discussion

Coastline Changes from Satellite Image Analysis

Based on satellite images from 2002, 2014, and 2019, the coast of Gresik Regency underwent both accretion and abrasion. The sub-district of Ujung Pangkah experienced a greater degree of these events due to the prevalence of aquaculture areas in the region, which resulted in sediment-rich soil conditions. Accretion predominantly occurred in the eastern part of the sub-district, while abrasion was primarily confined to the northern area. Although accretion and abrasion events were observed in other sub-districts, they were not as widespread as in Ujung Pangkah. Reclamation activities were responsible for the prominent accretion observed in Manyar District (see Fig. 3 and Fig. 7).

The research area for determining the extent of abrasion and accretion in Gresik Regency includes Ujung Pangkah District, Sidayu District, Bungah District, and Manyar District. The total area of abrasion that occurred in these four sub-districts over a five-year period, from 2014 to 2019, was 895872.08 square meters (89.59 hectares). In contrast, the total area of accretion was 6818695.17 square meters (681.87 hectares). Over a 12-year period, from 2002 to 2019, the total area of abrasion was 4252302.51 square meters (425.23 hectares), while the total area of accretion was 10631574.50 square meters (1063.16 hectares). See Table 1.

The changes in coastal abrasion in Gresik Regency over a five-year period from 2014 to 2019 were substantial, amounting to 89.59 ha with a rate of change of 17.92 ha/year. When examined over a 17-year period from 2002 to 2019, the area of abrasion was more significant, totaling 425.23 ha with an abrasion rate of 25.01 ha/year. These findings indicate that the condition of coastal abrasion in Gresik Regency has slowed.

In contrast, the condition of coastal accretion for the five-year period from 2014 to 2019 was greater than abrasion, amounting to 681.87 ha with a rate of change of 136.374 ha/year. Over a 17-year period from 2002 to 2019, the area of accretion was 1063.16 ha with an accretion rate of 62.53 ha/year. These results show that the condition of coastal accretion in Gresik Regency is accelerating. The overall coastal change in Gresik Regency is increasing because the accretion rate is greater than the abrasion rate. To better understand the pattern of abrasion and accretion in Gresik Regency, the following describes the changes in the coast in each sub-district. These findings are illustrated in Figure 4. Therefore, the findings of the research reveal that mangrove areas exhibit a higher rate of sediment accumulation as opposed to erosion, which suggests that they can function as a trustworthy indicator of the consequences of sea level rise caused by global warming.

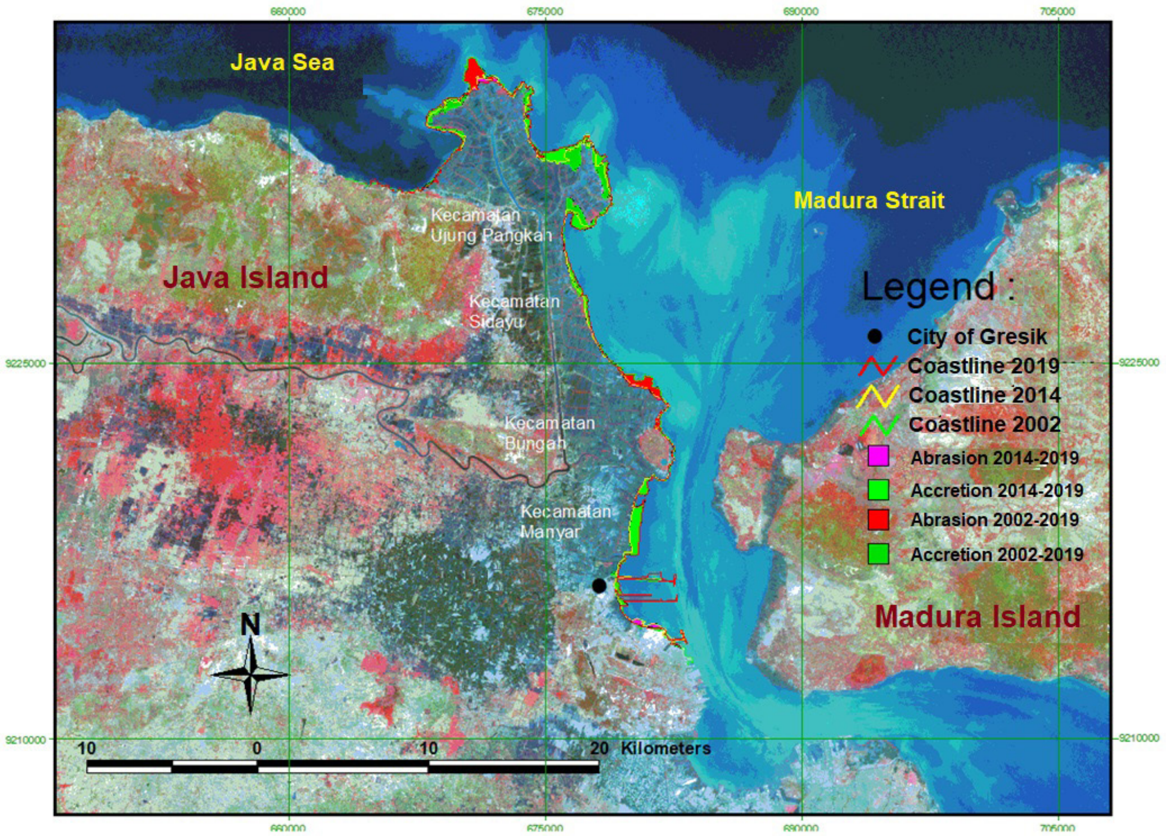

Figure.3 The condition of the shoreline of Gresik, Madura Strait, East Java in 2014 and 2019 with the background of the 2002 TM satellite image.

Table 1. Area of Coastal Abrasion and Accretion in the Madura Strait, Gresik Regency

Coastline changes	Areas (m^2)	Areas (Ha)
Abrasion 2014-2019 (5 years)	895872.08	89.59
Accretion 2014-2019 (5 years)	6818695.17	681.87
Abrasion 2002-2019 (17 years)	4252302.51	425.23
Accretion 2002-2019 (17 years)	10631574.50	1063.16

Figure.4 The coastal conditions with mangrove plants that trap small sediments in Ujung Pangkah so that accretion occurs.

Changes in Abrasion and Accretion in Ujung Pangkah District

The changes in abrasion and accretion in the Ujung Pangkah District hold the most significant position when compared to other districts, as evident from both Table 2 and Fig.5.

The most significant coastal erosion event occurred in the northern region of Ujung Pangkah sub-district, while coastal sedimentation took place in the eastern area (as shown in Table 2). Notably, the rate of change in the accumulating coastline in Ujung Pangkah Subdistrict was more rapid than the rate of erosion, both for a period of five years and 17 years.

The study on coastline alteration was additionally conducted by Prasetyo et al. (2017). The research determined the area of abrasion in Ujung Pangkah District for a ten-year period (2006-2016) to be 177.64 hectares, while the accretion area was 411.38 hectares. Therefore, the abrasion rate in the sub-district was 17.76 hectares per year, and the accretion rate was 41.1 hectares per year. Although we were unable to make a direct comparison due to the different time periods, these findings were highly beneficial and could be utilized as part of the body of evidence for shoreline changes at the Ujung Pangkah location.

The pattern of coastal change in the Ujung Pangkah District has consistently exhibited an upward trend as a result of sedimentation. Sedimentation is a process that takes place due to the flow of the Bengawan Solo River, which carries material from upstream and results in the accretion of the coastline. The impact of river sedimentation has been more prominent than that of coastal abrasion.

Abrasion, on the other hand, occurs in the north and is influenced by waves caused by wind in the Madura Strait. However, it is important to note that these waves are not the sole cause of coastline changes, and further research, such as the examination of currents in the Madura Strait, is necessary to gain a comprehensive understanding of the factors that contribute to coastal change.

Accretion in Sidayu District

The coastal area in Sidayu District was found to be the least compared to other beaches in Gresik Regency, resulting in only coastal accretion as the observed change. This process was attributed to the Bengawan Solo River and can be seen in Fig. 6. The accretion area for a period of five years amounted to 13.89 hectares, while the accretion area for a period of 12 years amounted to 23.47 hectares (as per Table 3).

Table 2. Area of Accretion Abrasion in Ujung Pangkah District, Gresik Regency 2002-2019

Coastline changes	Areas (m^2)	Areas (Ha)	Speed of changes (Ha/year)
Abrasion 2014-2019 (5 years)	384912.29	38.49	7.69
Accresion 2014-2019 (5 years)	3717632.52	371.76	21.86
Abrasion 2002-2019 (17 years)	2439696.21	243.96	14.35
Accresion 2002-2019 (17 years)	7508911.98	750.89	44.17

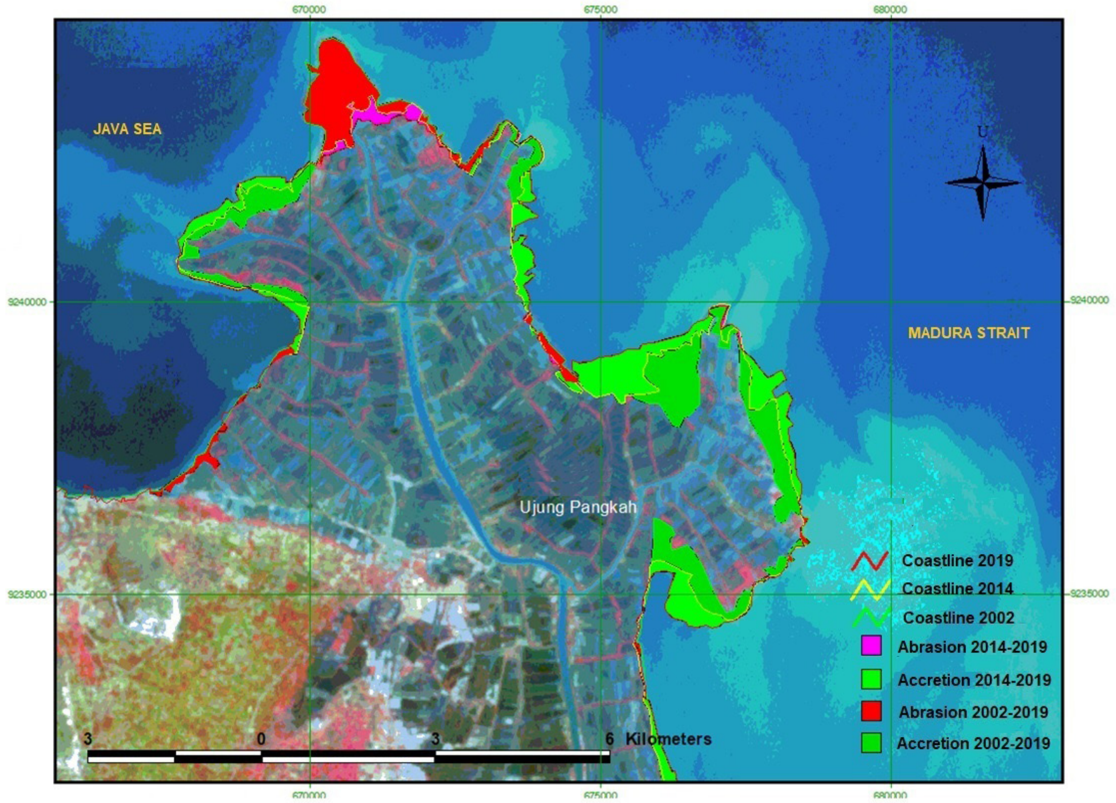

Figure.5 The coastal conditions with mangrove plants that trap small sediments in Ujung Pangkah so that accretion occurs.

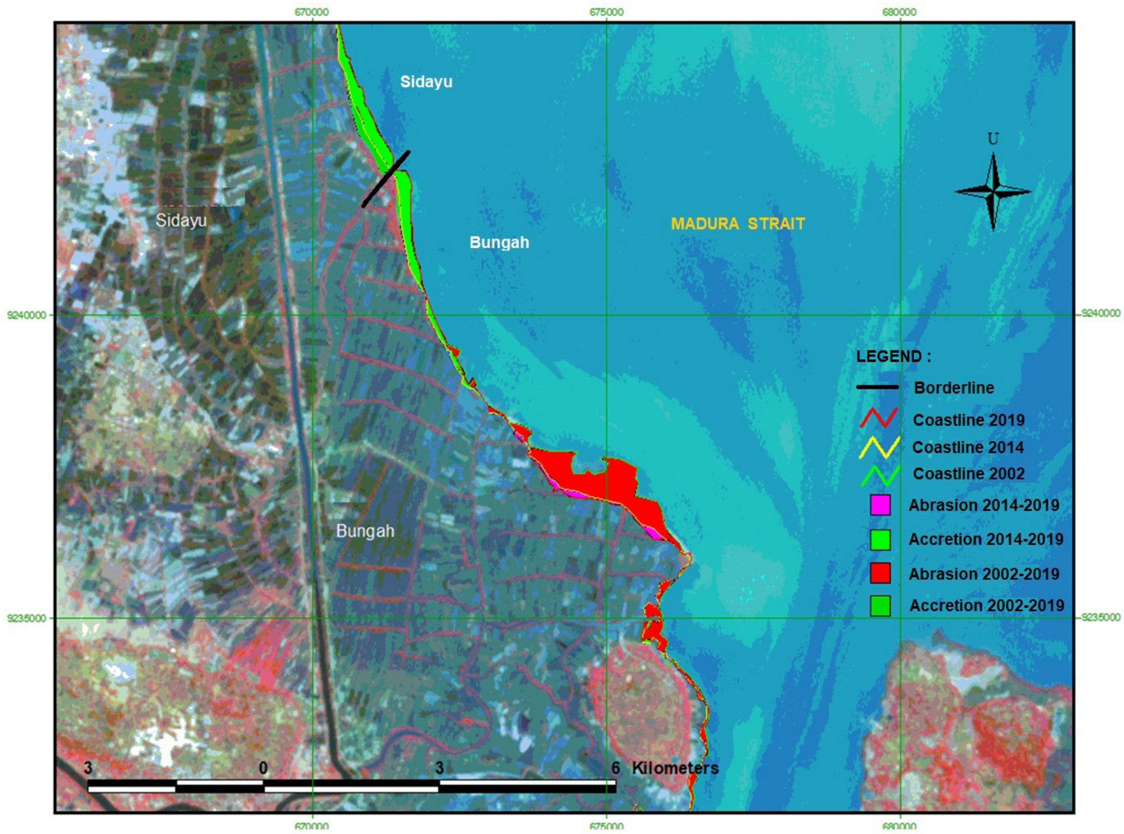

Figure.6 Map of coastal abrasion and accretion conditions in the Sidayu District and Bungah District, Gresik Regency.

Table 3 . Area of Accretion Abrasion in Sidayu District, Gresik Regency, 2002-2019

Coastline Changes	Areas (m^2)	Areas (Ha)
Abrasion 2014-2019	0	0
Accretion 2014-2019	138968.75	13.89
Abrasion 2002-2019	0	0
Accretion 2002-2019	234758.75	23.47

Abrasion and Accretion in Bungah District

Modifications in coastal accretion were observed in the northern region of Bungah District, whereas changes in coastal abrasion were noted in the southern area (as depicted in Fig.6). The extent of alteration in coastal abrasion within Bungah District surpassed that of accretion, resulting in a reduction in the overall number of beaches (as indicated in Table 4).

The pattern of coastal change in the Bungah District consistently exhibited a reduction due to the process of abrasion. This phenomenon was characterized by the occurrence of abrasion in the southern region, while accretion occurred in the northern region. The abrasion in the south was influenced by wind waves in the Madura Strait. However, it should be noted that these waves were not the sole cause of the changes in the coastline. Accretion was also a result of the sediment flow of the Bengawan Solo River. While the influence of coastal abrasion was more pronounced than the influence of river sedimentation, both mechanisms played a significant role in shaping the coastline of the Bungah District.

Abrasion and Accretion in Manyar District

The changes in coastal accretion in the Manyar District were not natural, but rather caused by human activities, specifically for the purpose of regional development, such as the construction of ports (as seen in Fig.7). The area of coastal accretion in the Manyar District was significantly greater than the area of abrasion, resulting in the beach becoming wider and wider. The coastal accretion area for the past five years was 252.02 Ha (as shown in Table 5). The majority of the accretion was attributed to beach reclamation at the BMS JIIPE Manyar Port location in the Manyar District.

Tabel 4. Area of Accretion Abrasion in Bungah District, Gresik Regency Year 2002-2019

Coastline Changes	Areas (m^2)	Areas (Ha)
Abrasion 2014-2019 (5 years)	155045.52	15.50
Accretion 2014-2019 (5 years)	441854.72	44.18
Abrasion 2002-2019 (17 years)	1782967.30	178.29
Accretion 2002-2019 (17 years)	393225.56	39.32

Table 5. Area of Accretion Abrasion in Manyar District, Gresik Regency Year 2002-2019

Coastline Changes	Areas (m^2)	Areas (Ha)
Abrasion 2014-2019 (5 years)	355914.27	35.59
Accretion 2014-2019 (5 years)	2520239.18	252.02
Abrasion 2002-2019 (17 years)	29639.01	2.96
Accretion 2002-2019 (17 years)	2494678.21	249.46

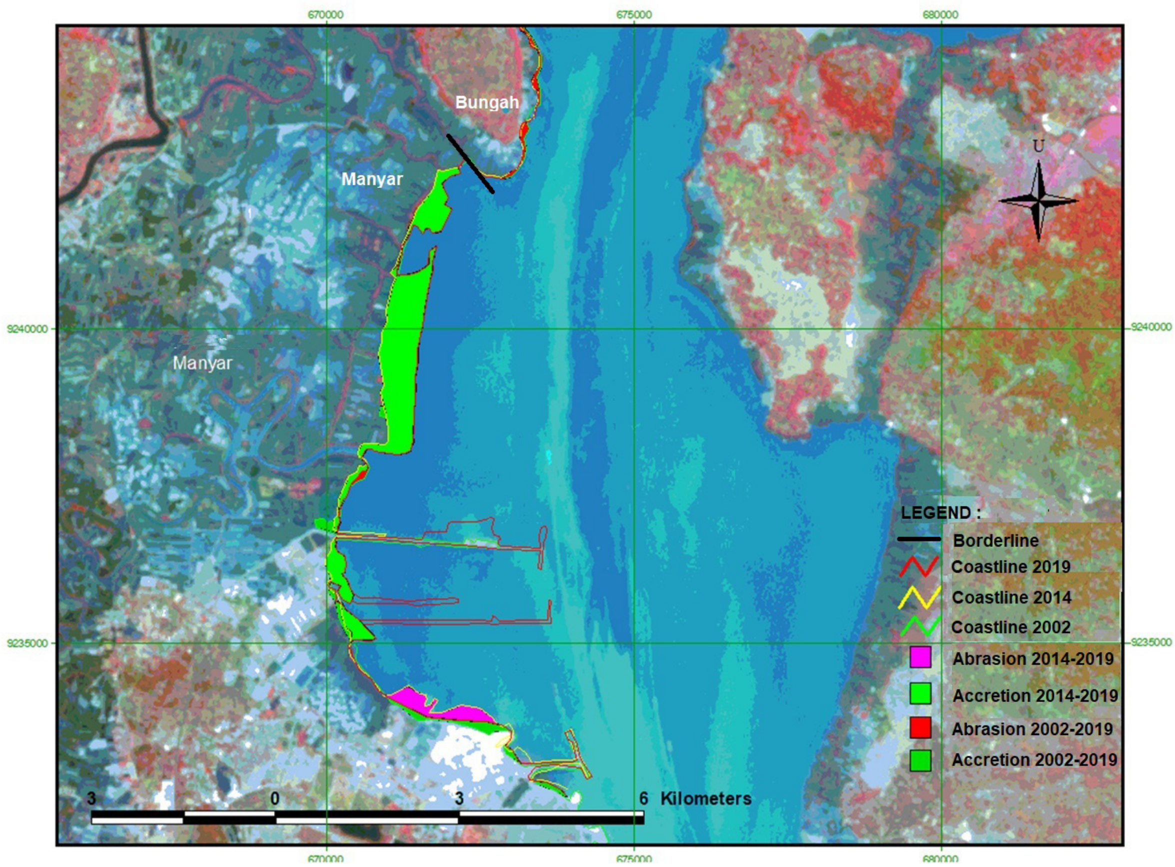

Figure.7 Map of coastal abrasion and accretion conditions in the Manyar District

Seasonal Analysis of Wave for the 2010-2019 Decade

The analysis of wind wave direction for the decade 2010-2019 demonstrated stability during the main seasons, particularly the west and east monsoons. During the west monsoon, as shown in Fig.8(a), wind waves generally moved from a range of 300° (west: southeast-west) with a deviation range of 290° -320°. This indicates a steady west monsoon in the study area. In contrast, during the east monsoon, wind waves typically moved from 90° with a deviation range of 85° -95° (Fig.10(a)). The short deviation range suggests that the waves were very stable, even more so than during the west monsoon. However, it is important to note that this east wave did not represent its existence as a wind that moves from east (southeast) to west (northwest) when high pressure was over Australia compared to Asia (Krishnamurti et al., 2012). This implies a strong local influence in the study area in responding to east wind waves. During the transition period (I and II), the wind wave direction had a more diffuse pattern as shown in Fig.9(a) and Fig.11(a).

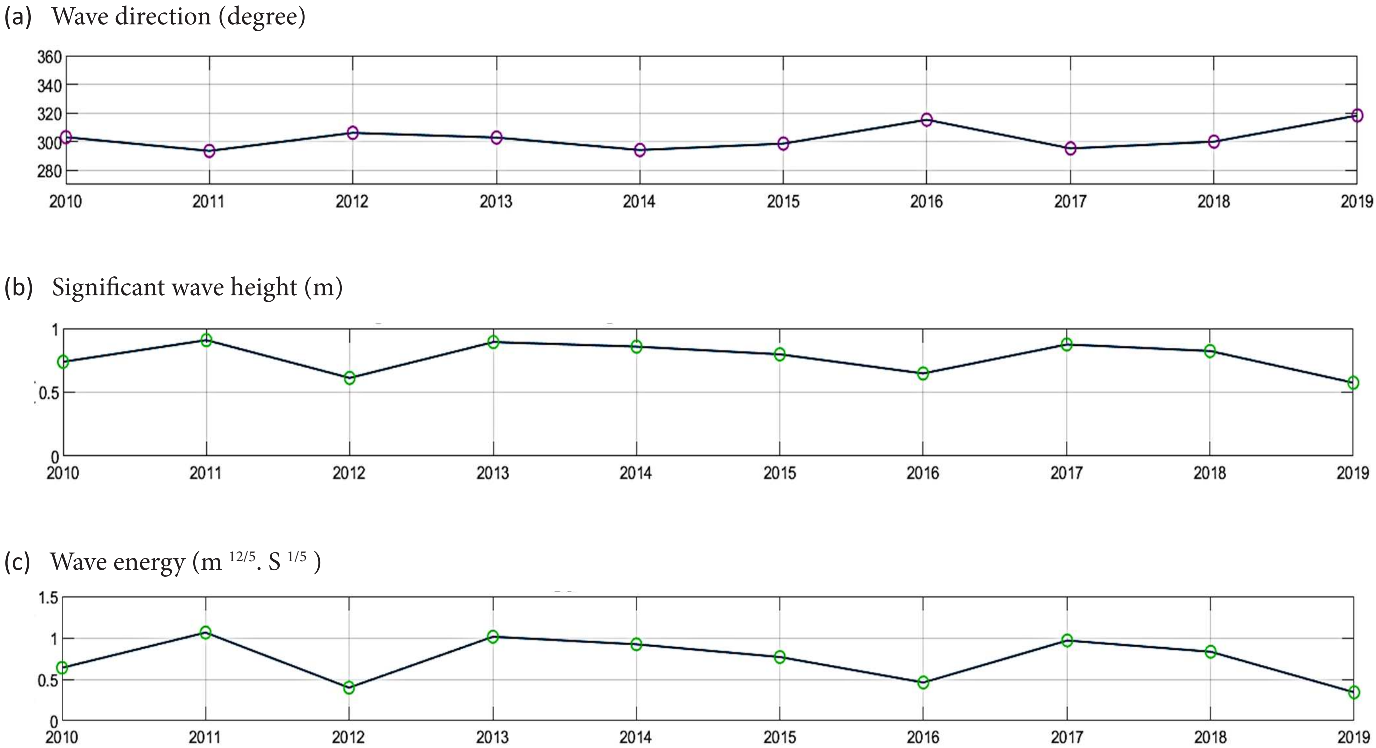

Figure.8 (a) Wave direction, (b) significant wave height, and (c) wave energy in the west monsoon 2010-2019.

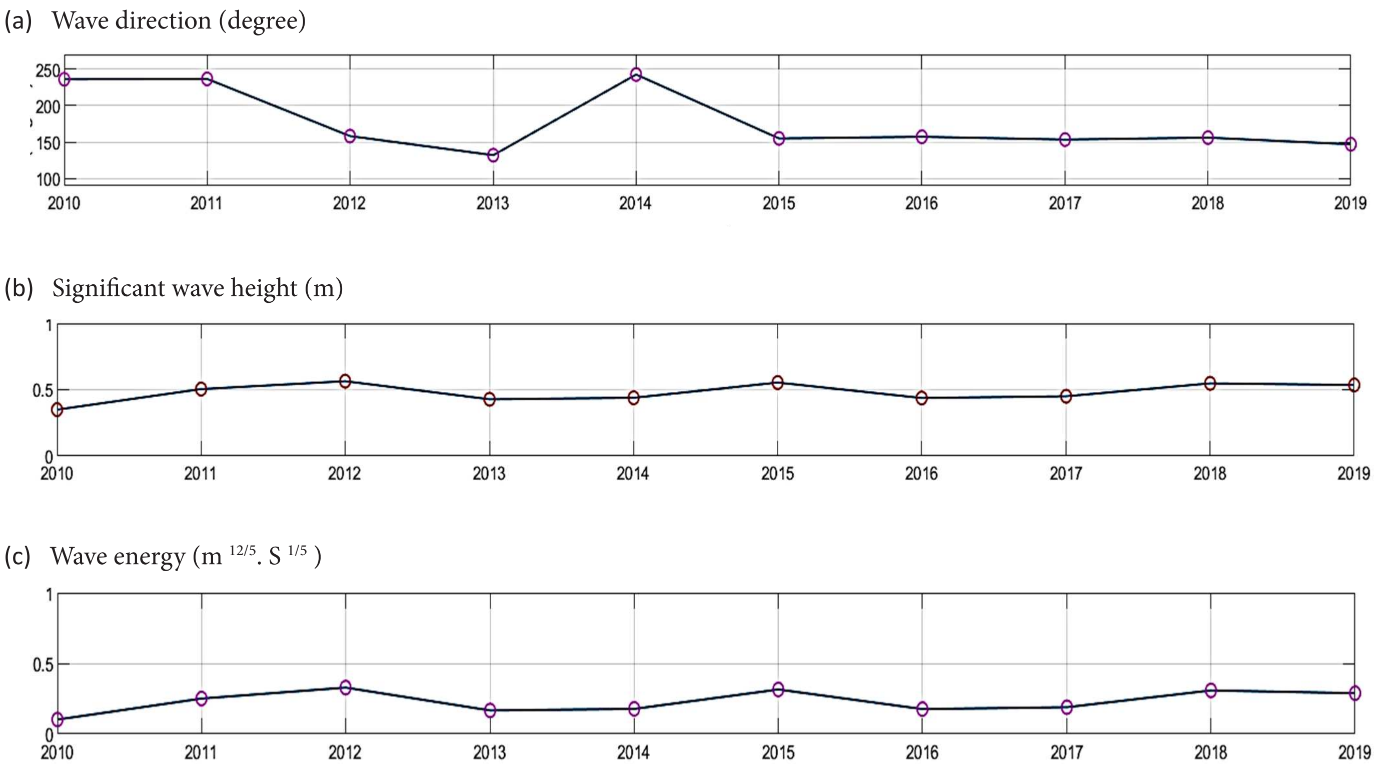

Figure.9 (a) Wave direction, (b) significant wave height, and (c) wave energy in the transition season I 2010-2019.

The wave records in the north of Gresik waters over several decades reveal that the significant wave heights during the west and east monsoons are relatively larger compared to the transitional seasons between these two periods. Specifically, the significant wave heights during the west monsoon fall within the range of approximately 0.57 to 0.91 meters, with the highest and lowest waves exhibiting significant fluctuations. Similarly, the east monsoon also experiences significant wave heights within the range of approximately 0.65 to 0.88 meters, with waves during this season being relatively lower than those observed during the west monsoon. While significant waves with a height of approximately 1 meter were recorded during the west monsoon in 2011, 2013, 2014, 2017, and 2018, the east monsoon experienced significant waves of a similar height only in 2015 and 2019. During the transitional seasons, the significant wave heights fluctuate significantly, with a mean height of approximately 0.5 meters within the range of 0.4 to 0.7 meters.

For the period of a decade (2010-2019) in the northern waters of Gresik, the wave energy experienced significant fluctuations due to its linear dependence on the significant wave height. The west season demonstrated the highest wave energy compared to the east season, while the wave energy generated during transition season 1 and transition 2 was not as significant as that generated during the two main seasons, as depicted in Figures 8-11(c). During the west monsoon, the minimum wave energy was 0.34 $m^{\frac{12}{5}}.s^{\frac{1}{5}}$ and the maximum wave energy was 1.06 $m^{\frac{12}{5}}.s^{\frac{1}{5}}$. The greatest wave energy gains were observed ~1 $m^{\frac{12}{5}}.s^{\frac{1}{5}}$ in 2011, 2013, and 2017, with the nadir touching ~0.5 $m^{\frac{12}{5}}.s^{\frac{1}{5}}$ in 2012. Conversely, the greatest wave energy gain in the east monsoon was observed ~1 $m^{\frac{12}{5}}.s^{\frac{1}{5}}$ in 2015 and 2019. In general, the wave energy during the transitional season remained below 0.5 $m^{\frac{12}{5}}.s^{\frac{1}{5}}$, with the highest gain of ~0.55 $m^{\frac{12}{5}}.s^{\frac{1}{5}}$ observed during the east season in 2015.

Wave analysis of shoreline changes over the ten years 2010-2019.

A noticeable erosion zone was identified in the northern region of the Ujung Pangkah District headland and the northeastern side of Bungah District (as illustrated in Fig.6). The northern area of the Ujung Pangkah District, which serves as the terminus of the Bengawan Solo River system, has the potential to form headland morphology due to the accumulation of massive sediment deposits. The majority of the suspended sediment concentrations present in the Bengawan Solo estuary's waters are derived from alluvial sources, which are influenced by tidal currents and river discharge movement. The Bengawan Solo River itself exhibits a fluvial sedimentation pattern dominated by clay, sand, and silt (as reported by Banjarnahor et al, 2016). Furthermore, according to Hidayah et al. (2023), the concentration of suspended solids was found to be high during low tide and low during high tide.

The location of the Cape of Ujung Pangkah, which lies at the intersection of the monsoon system, is characterized by a reversal of wind and wave directions (as depicted in Fig.3). Despite the change in wave refraction caused by the shifting monsoon, the cape remains vulnerable to significant wave energy due to the concentration of energy on its protrusion. The area around the cape is subject to periodic impact from west and east monsoon winds, depending on the direction of the wave generator and its associated wave energy ~0.5–1.

In their research on long-term and short-term coastal erosion in South Brazil two decades ago, Esteves et al. (2002) highlighted the significant role that coastal topography plays in determining wave energy. This finding was supported by Seenipandi et al. (2013), who demonstrated that high levels of wave energy, in conjunction with high littoral current velocity, can result in a continuous erosion process. This process can lead to significant erosion in a particular area when compared

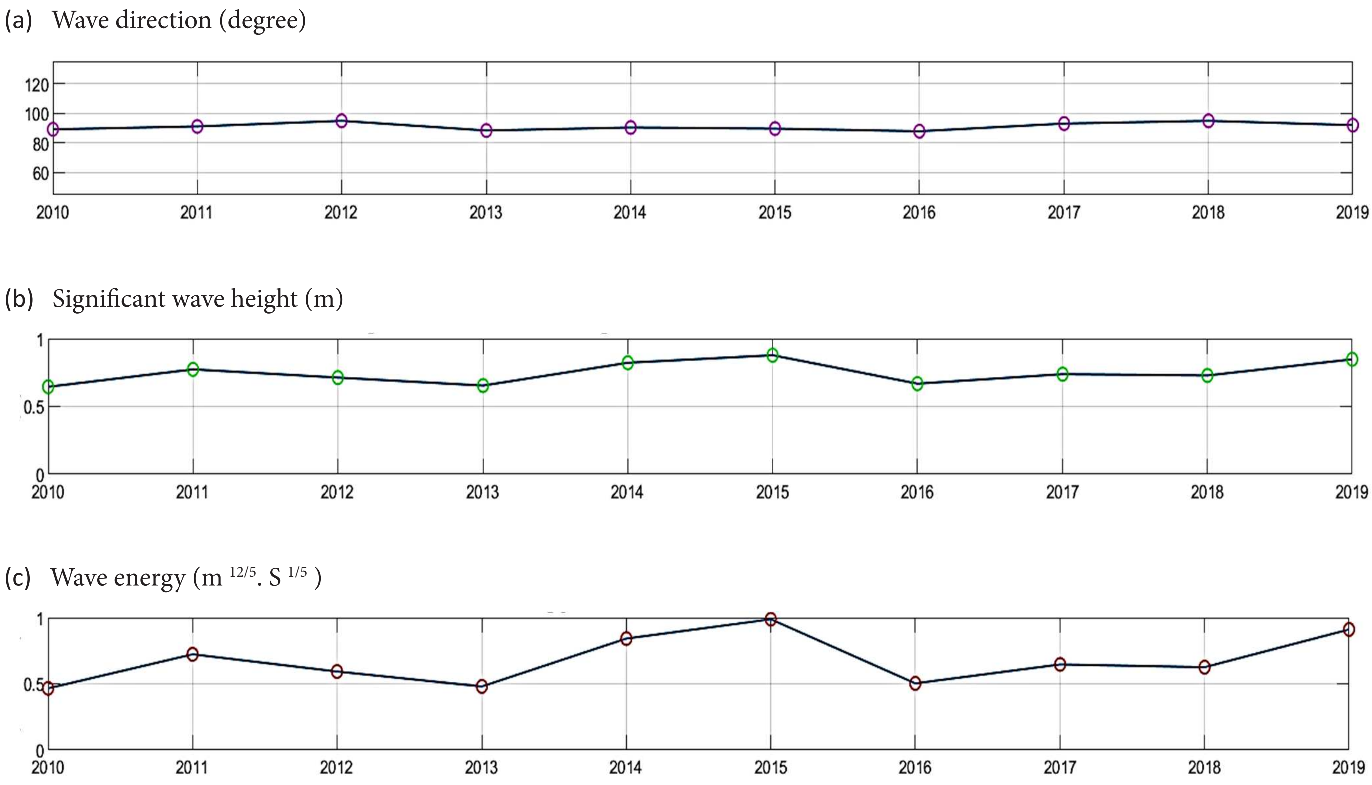

Figure.10 (a) Wave direction, (b) significant wave height, and (c) wave energy in the East Monsoon 2010-2019.

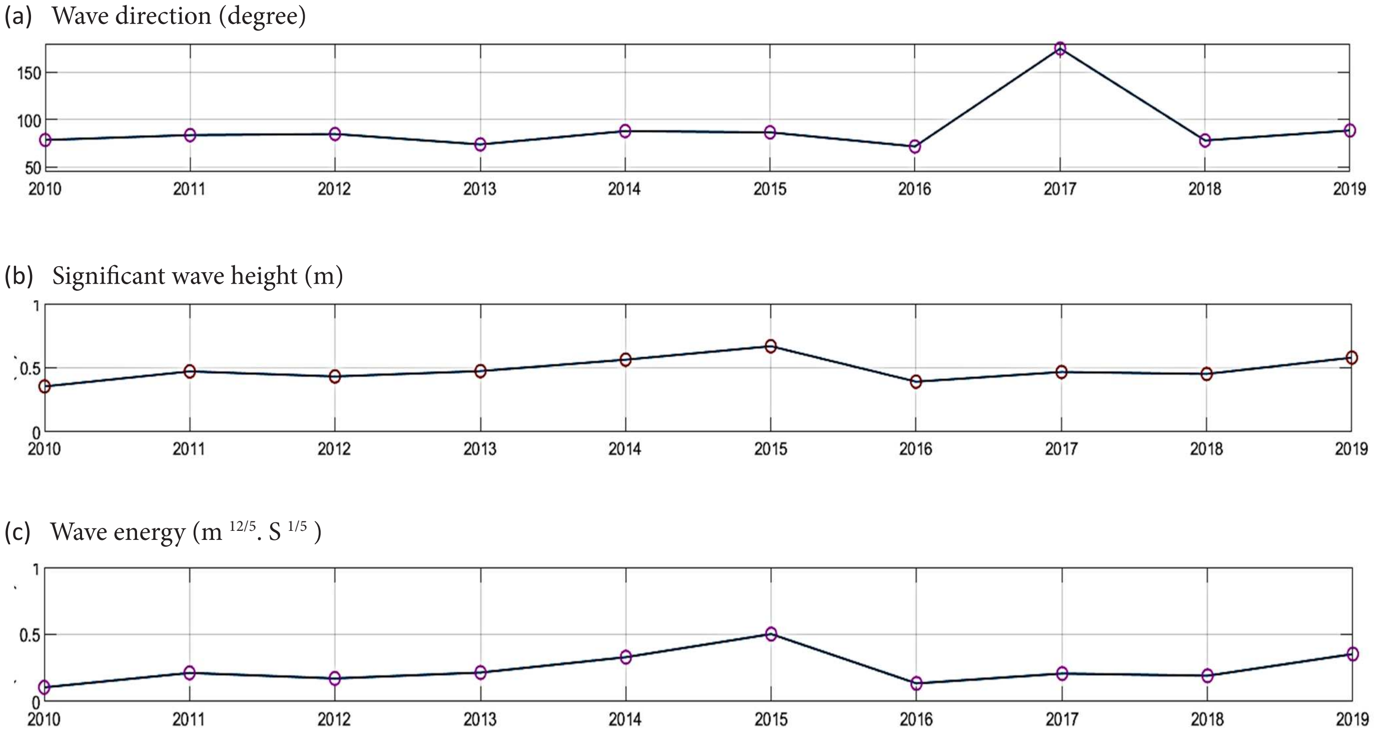

Figure.11 (a) Wave direction, (b) significant wave height, and (c) wave energy in the Transition II season 2010-2019.

to the surrounding region. The convergence of incoming waves, as noted by Joevivek et al. (2019), can result in high-energy wave conditions and subsequent erosion. This conclusion was further reinforced by Vann Jones et al. (2018), who stated that erosion in headland areas tends to be more significant than in bay areas due to variations in the transfer of wave energy that occur in these distinct shoreline features. Finally, Barcelona (2015) found, based on ocean wave modeling results, that waves in Ujung Pangkah waters experience convergence refraction with an average refraction coefficient value of 0.94.

The same condition was observed in the north-northeast area, which forms a smaller promontory with a relatively more confined location towards the inlet in the Madura Strait neck (Fig.3). The westerly and easterly winds will adjust the wind pattern and wave generation. As stated by Joevivek et al. (2019) and Seenipandi et al. (2013), the monsoon can cause differences in the direction of wave motion and trigger current movements that affect sediment shifts. The more confined location of the Bungah coast implies a reduction in wind and wave speed and direction deviation compared to the same wind and waves that occur in more open oceanic water areas such as the Ujung Pangkah coast. As a result, the erosion process occurring on the land mass protrusion occurred with relatively more muted intensity, so the eroded area was not as extensive as that which occurred in more open areas with wider land masses and located further protruding towards the sea, such as at the Cape of Ujung Pangkah.

Conclusion

The study's findings indicate that the shoreline changes were primarily characterized by accretion, with some areas experiencing abrasion, particularly in Ujung Pangkah and Bungah Districts. This accretion process took place continuously due to the flow of the Bengawan Solo River. Between 2014 and 2019, accretion in Ujung Pangkah and Bungah amounted to 371.76 hectares and 44.18 hectares, respectively, while the same process over a 17-year period (2002-2019) resulted in 750.89 hectares and 39.32 hectares of abrasion in these areas. The study found that mangrove ecosystems exhibit a greater rate of sediment accumulation rather than erosion, which indicates their potential to serve as a reliable indicator of the consequences of sea level rise caused by global warming.

However, the abrasion process also occurred as a result of wind-generated waves. From 2014 to 2019 and over a 17-year period (2002-2019), abrasion in Ujung Pangkah and Bungah amounted to 38.49 hectares and 15.50 hectares, and 243.96 hectares and 178.29 hectares, respectively. Nevertheless, these waves were not the sole cause of shoreline changes, and further research, such as studies on currents and tides in greater detail in the Madura Strait, is needed.

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