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Research Article

The Pattern of Coastline Changes and Wave Modelling around the Expansion of PPI Popoh Tulung Agung, East Java

Nafla Aulia Miranda, Rudi Siap Bintoro and Viv Djanat Prasita*

Department of Oceanography, Hang Tuah University, Jl. Arif Rahman Hakim 150, Surabaya, Indonesia

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Popoh Beach,
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Abstract

The expansion of the Popoh PPI in Popoh Village, Tulungagung, East Java affects the movement of currents and waves in the vicinity. The purpose of this study was to analysis sediments and the pattern of coastline changes and to elaborate these using wave modelling based around the expansion of the Fish Landing Port Popoh. The methods used in this research were sieve analysis, remote sensing and GIS for processing Sentinel-2 imagery, and hydrodynamic modeling using DHI MIKE 21. Sediment sampling was carried out based on a purposive sampling method, with 10 points spread over land and water using a sediment grab. The findings of the study showed that there was a fairly large accretion from 2015 to 2021, with sand and clay sediment types. The accretion process dominated the abrasion process at Popoh Beach. In the period 2015 to 2018, the area of accretion was 17.78 hectares and, in the period 2018 to 2021, the area of accretion was 9.32 hectares, so that for 6 years there was an accretion of 18.79 hectares. The average wave energy was 1.5 kW/m per year on eroded beaches with sandy sediments.

1. Introduction

Coastal areas are very dynamic due to the influence of natural and human activities (Ahmeda et al., 2017; Balica et al., 2012). Examples of natural activities include waves, currents, sea tides, and river estuaries. Currently, human influence often occurs in coastal areas. Many studies show the workings of coastal man-made interventions (harbors, coastal defense structures) on watershed characteristics (e.g., dams, artificial channels), including changing sediment balance, directly affecting the evolution of the shoreline (Laksono et al., 2022). On the other hand, the role of coastal areas is quite significant in terms of economic, cultural, and social benefits. Coastal land use is often planned without sufficient thought to deal with the effects of natural disasters and human activities, so that coastal structures are increasingly vulnerable to inundation and wave damage. Therefore, studying the pattern of changes in the coastline is very important to evaluate coastal development activities, such as ports and breakwaters, to reduce the impact of losses on buildings, infrastructure, and beaches.

Forecasting the position of a coastline is a long-debated issue; shoreline evolution modeling that takes hydrodynamic conditions into account appears to be the most reliable tool for predicting shoreline evolution (Di Stefano et al., 2013). Shoreline evolution can be monitored using GIS and

*Corresponding author: Department of Oceanography, Hang Tuah University, Jl. Arif Rahman Hakim, Surabaya, Indonesia
E-mail address: viv.djanat@hangtuah.ac.id

remote sensing techniques; these techniques can be used to monitor in a cost-effective manner (Ghost et al., 2015).

For this paper, the GIS and remote sensing techniques, as well as hydrodynamic modelling, were applied to study the effect of widening the port at Popoh Beach. This hydrodynamic modelling was also used to review the hydrodynamics features and coastal vulnerability of Sayung SubDistrict, Demak, Central Java, Indonesia (Ondara et al., 2020).

Popoh Beach is a tourist beach located in East Java Province. This beach is in the form of a bay that opens to the southeast and faces the Indian Ocean directly. There is economic activity on the west coast in the form of the Pelabuhan Pendaratan Ikan (PPI) Popoh, the name of the fish landing port. Expansion of development that occurred near PPI aims to assist the development of office and port areas, as well as functioning as a breakwater. In addition, reclamation was carried out to strengthen the expansion area to protect the anchor pond from incoming waves. The Niyama River, which flows into Popoh Beach from the north, carries wastewater, as well as sediment that has accumulated along the coast. This deposition causes siltation, which disrupts ship activities in the anchor pool. In addition, abrasion and sedimentation are also affected by the expansion of PPI construction and wave conditions.

The causes of abrasion and sedimentation at Popoh Beach have never been studied before. Therefore, this study analyzes the sediments and the pattern of coastline changes, as well as elaborates these using wave modelling, based around the expansion of the PPI Popoh Tulung Agung, East Java.

2. Materials and methods

2.1 Research materials and tools

The research was carried out from June 2021 to December 2021 at Popoh Beach, Jalan Raya Prigi Beach, Watulimo, Popoh, Besole, Besuki, Tulungagung Regency, East Java, with an astronomical location of 8˚ 15' 43" South Latitude and 111˚ 48' 12" East Longitude, as can be seen in **Figure 1**.

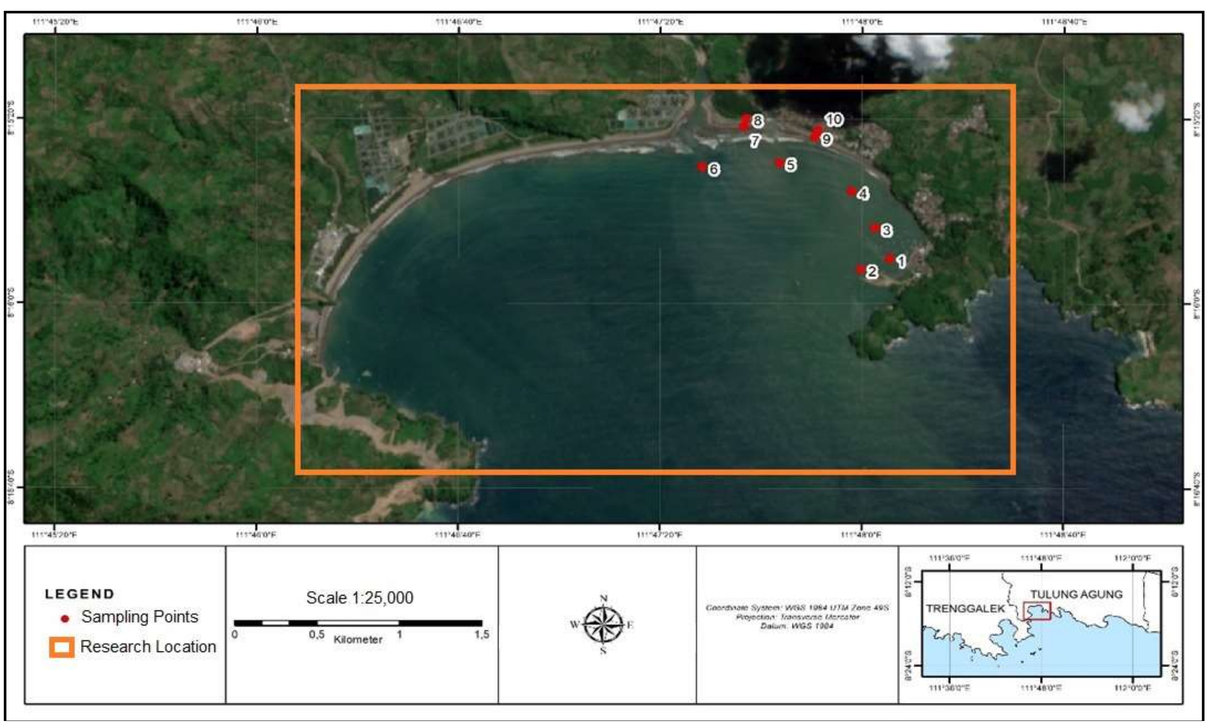


Figure 1 Research and Sampling Point location at Popoh Beach, Tulung Agung, East Java.

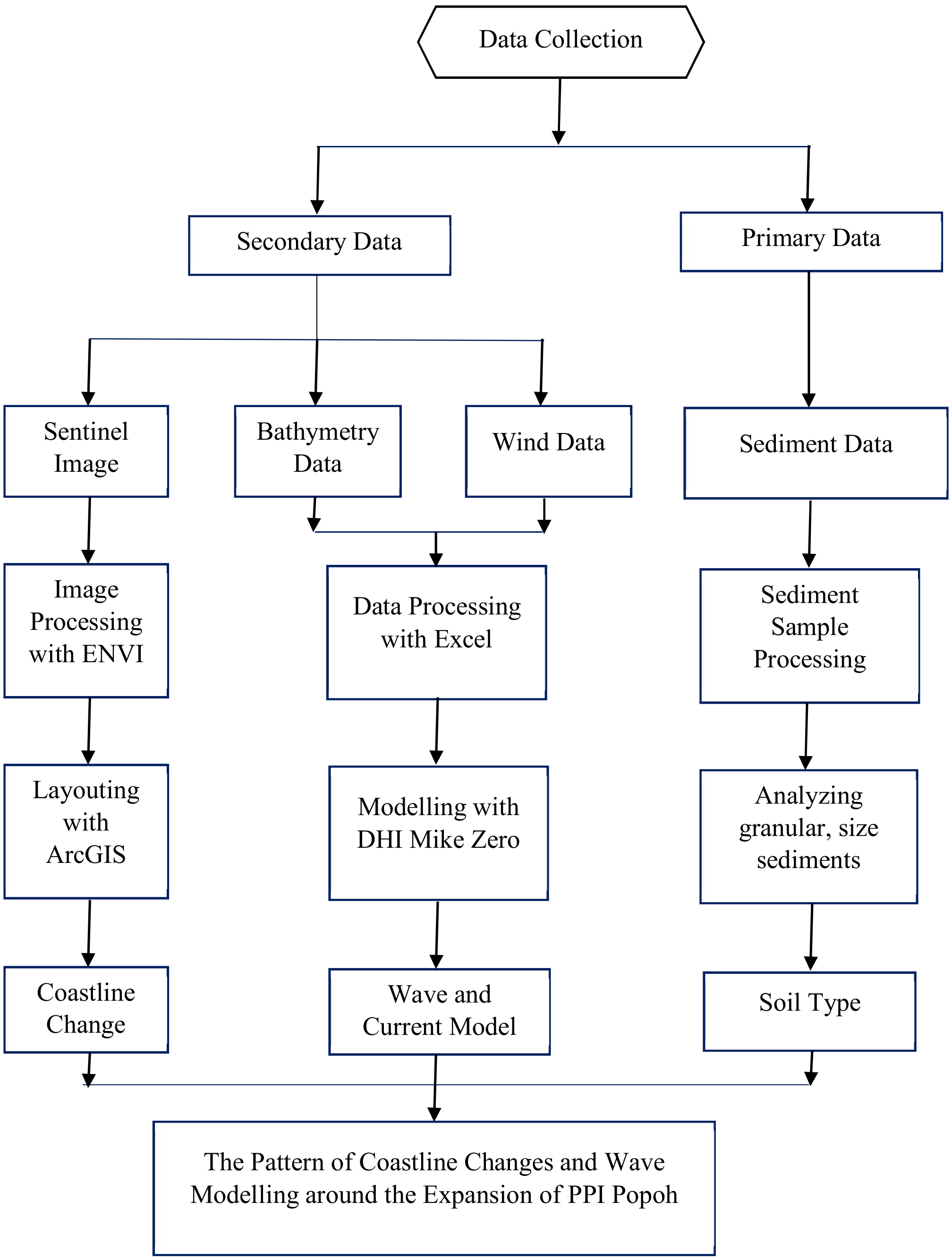


Figure 2 Flowchart of research.

The material used in this research consisted of primary data and secondary data. The primary data used is the sediment, while the secondary data were bathymetry, Sentinel-2 satellite imagery from 2015, 2018, and 2021, and wind and wave data. The determination of the sample point was divided into land and water parts, which can be seen in **Figure 1**, based on the purposive sampling method, which is a method that can represent the overall state of a research area (Yudowaty et al., 2012). This study was limited to the study of changes in accretion and abrasion and their effects on wind-generated waves.

The methods and materials used in this study consisted of several survey tools and software. Software Google Earth was used to define research position. ENVI software was used for correcting satellite image data. ArcGIS was used for processing coastline data and layouting, making wave fetch, and bathymetry of the research location. Microsoft Excel was used for data processing and making descriptive statistical charts. WRPlot was used to make wind and wave roses (Prasita et al., 2022). Software and usability are stated in **Table 1**. The overall data processing flowchart is shown in **Figure 2**.

Table 1 Software and usability as a research tool.

No	Tools/Software	Function
1	GPS	Determine the sampling position of latitude and longitude
2	Sediment Grab	Take samples of seafloor sediments
3	Sieve analysis	Determine percentage by weight of grains that pass through a sieve
4	Software ENVI	Software for correcting satellite image data
5	Software ArcGIS	Software for processing coastline data and layouting, making wave fetch, and bathymetry of research location
6	DHI MIKE ZERO Software	Software for modelling waves and currents
7	Ocean Data View Software	Software to change wind data format
8	WRPLOT Software	Software for creating wind rose and wind distribution charts
9	Microsoft Excel	Software for processing raw data

2.2 Coastline data processing

Coastline data processing was carried out after downloading wind, wave, and bathymetry data on available websites, and river water discharge and satellite imagine data obtained from agencies. The secondary data processed were Sentinel-2 satellite imagery from 2015, 2018, and 2021, with the selected location being Popoh Beach, Tulungagung, East Java (ERA Sentinel, 2021). Then, the coastline data were extracted using ENVI by applying the algorithm for coastline extraction obtained from the Band Ratio approach. The ratio of mid-infrared waves to green waves in bands 11 and 3 produced a land-sea boundary of the area covered by sand and soil (Nugraha et al., 2016). Values of less than one were for the sea, and of more than one were for land (Winarso et al., 2001).

$$binner = \frac{(band\ SWIR \times band\ Green)}{(band\ NIR \times band\ Green)} \tag{1}$$

2.3 Wind data processing

Fetch is an area of ocean wave generation which is limited by the surrounding land (Wakkary et al., 2017). Fetch is also defined as a wave generating area in the direction of the wind (Wakkary et al., 2017). The formula for calculating the fetch size is shown:

$$F_{eff} = \frac{\sum xi \cos \propto i}{\sum \cos \propto i} \tag{2}$$

where F_{eff} = effective fetch length (km), Xi = fetch length from point to boundary area (km), and αi = angle between Fetch lines.

2.4 Wind Height, duration, and stability correction

Wind height correction was carried out to obtain a wind height of 10 meters above sea level.

$$U_{(10)} = U_{(t)} \left(\frac{10}{z}\right)^{1/7} \tag{3}$$

where $U(10)$ is wind speed at an elevation of 10 m (m/s), $U(z)$ is wind speed at measurement altitude (m/s), and z is measurement height(m).

Duration correction was carried out to produce the corrected wind speed and the desired duration of time. *Ut* and *t* were calculated to get the specified duration.

$$\frac{U_t}{u_{3600}} = c \tag{4}$$

where u_f is maximum wind speed resulting from elevation correction (m/s), u_t is average wind speed at desired duration (m/s), and t is desired time duration(s).

This stability correction was carried out if there was a temperature difference between air and seawater, with the calculation formula shown in Eq. (5) (Wakkary et al., 2017).

$$U = R_T U(10) \tag{5}$$

where U is wind speed after correction (m/s), $U(10)$ is wind speed before correction (m/s), and R_T is stability coefficient.

To obtain the wind stress factor, the parameter used is U, which is the corrected wind speed.

$$U_a = 0.71U^{1.23} \tag{6}$$

where U_a is wind stress factor (m/s), and U is wind velocity (m/s).

2.5 Wave energy

The amount of wave energy is calculated to find out how influential this energy is on changes in coastal morphology (CERC, 1984; Prasita et al., 2022).

$$E = \frac{\rho g H^2}{8}$$

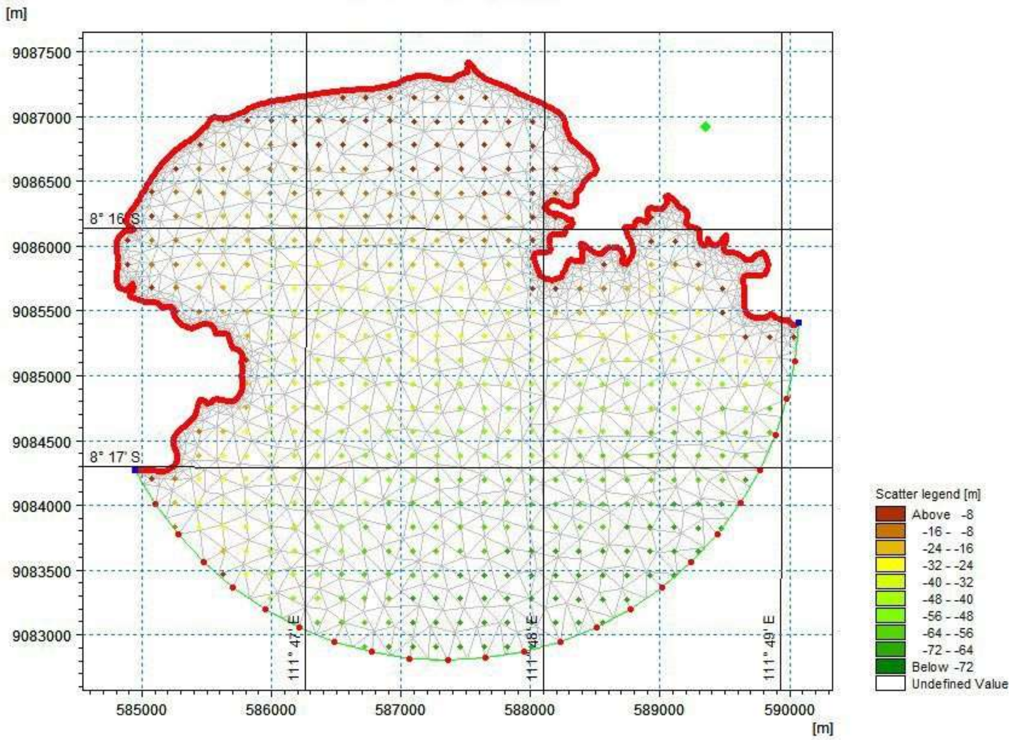
where ρ is seawater density (1.030 kg/m^3), g is earth's gravity (9.81), and H^2 is highest wave.

2.6 Modelling hydrodynamics

Shoreline and bathymetry data was entered to determine the water limit and water depth at Popoh Beach. Spectral Waves FM determines the direction of motion and the significant height of the waves, while the Flow Model FM is for modelling currents which can determine the direction of current motion.

Hydrodynamic module (HD) is the basic module in MIKE 21 FM. This module provided the basis for calculations performed on hydraulic modules and environmental phenomena. The hydrodynamic module can also simulate sea level variations and flow responses to lakes, estuaries, and coastal areas (DHI, 2017). According to DHI (2017), there were effects and facilities for this module, namely: deep water pressure, deep wind pressure, barometric pressure gradient, Coriolis energy, momentum dispersion, source and depth, evaporation, flooding and drought, and pressure wave radiation.

Hydrodynamic modelling steps were (1) Entering shoreline and bathymetry data. The shoreline was needed to determine the water boundaries and bathymetry to determine the depth of the waters of Popoh Beach according to the research area, (2) Meshing model area was needed to see the bathymetry distribution of Popoh Beach waters, **Figure 3**, and (3) Wave modelling was made to determine the direction of motion, as well as the significant height of the waves in the waters of Popoh Beach.



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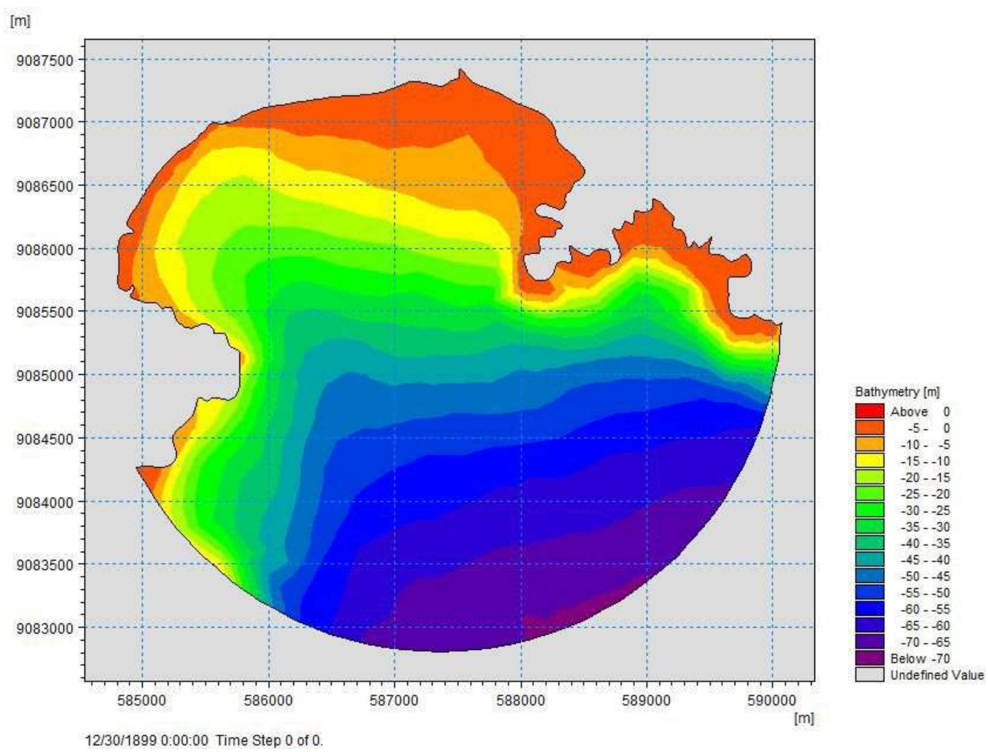


(b)

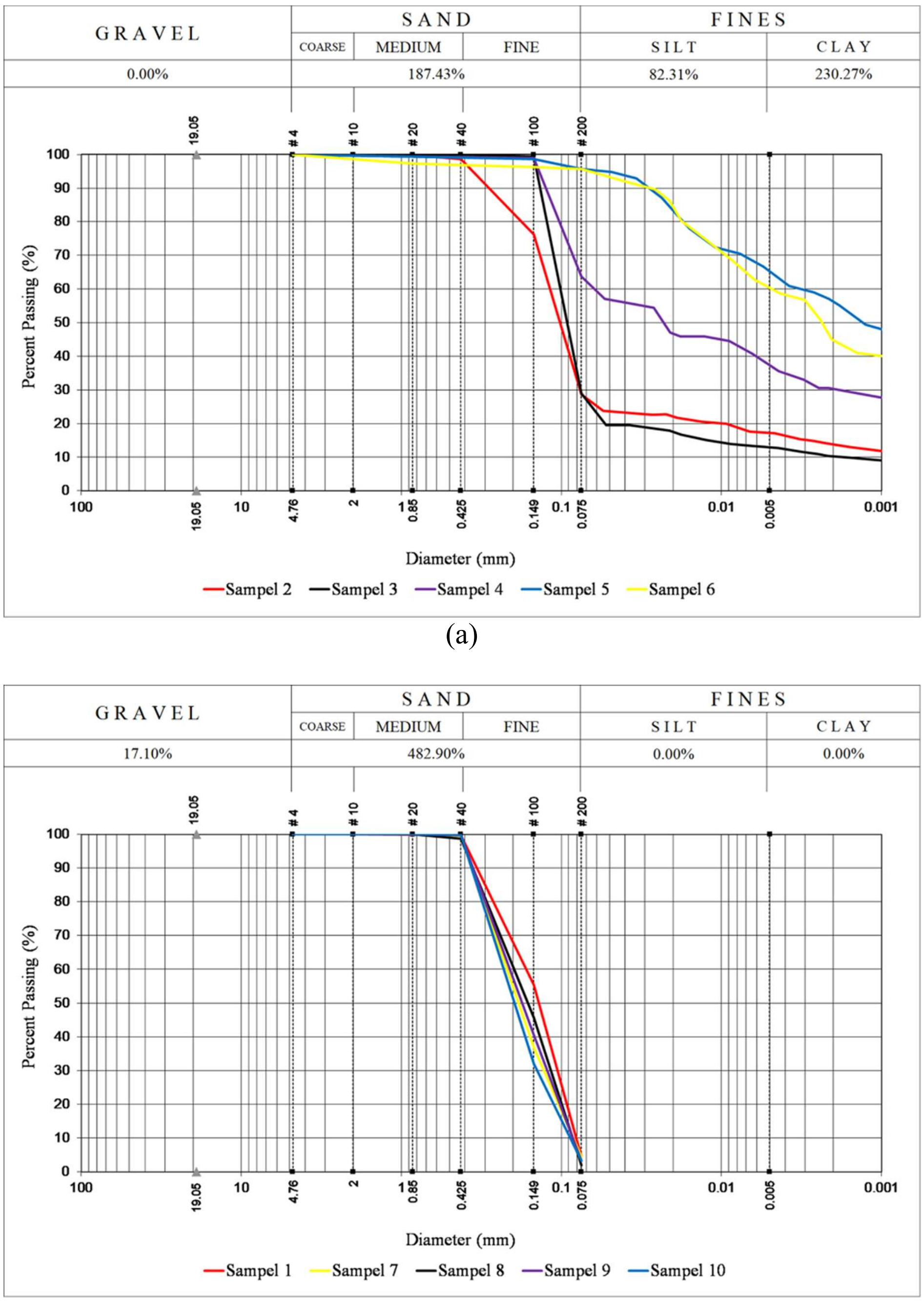
Figure 3 (a) Mesh of hydrodynamic model and (b) bathymetry of hydrodynamic model.

3. Results and discussion

3.1 Sediment size analysis

The purpose of this test was to determine grain size distribution and to define the kind of soil examined by analyzing grain size using sieving and hydrometer analysis. Samples that passed filter No. 200 and weighed ≥ 50 grams and were represented on semilogarithmic paper or grain size distribution curves were subjected to hydrometer examination.

Based on the results of the processing of 10 sediment samples, 5 samples (no. 2, 3, 4, 5, 6) passed the hydrometer analysis, represented in **Figure 4a**, while the other 5 samples (no. 1, 7, 8, 9, 10) did not pass due to their larger particle size, as shown in **Figure 4b**.



(a)

(b)

Figure 4 Grain distribution curve diagram.

Gravel, sand, silt, and clay are the varieties of sediment present on Popoh Beach. Fine-grained particles, ranging from sand to silt, dominated the composition of sediment in the study area. Sediments classified as fine sand were located at points 1, 2, 3, 7, 8, 9, and 10, as shown in **Table 2**, according to the results of the analysis of 10 samples. Sediments classified as clay sand were located at point 4, while those classified as clay silt were located at points 5 and 6. A variety of sand detritus dominates Popoh Beach's mainland up to 0.5 meters into the water. As sediment moves toward open water, its grain size decreases and becomes dominated by clay sediment, as shown in **Figure 5**.

Table 2 Type of sediment distribution.

Sampling Point	Time (GMT +7)	Depth (M)	Type			
			Gravel	Sand	Silt	Clay
1.	08:54	3	4.37 %	95.63 %		
2.	08:32	3		71.40 %	6.27 %	22.33 %
3.	08:24	4		71.11 %	12.58 %	16.31 %
4.	08:14	5		36.30 %	24.76 %	38.95 %
5.	07:49	7		4.26 %	23.87 %	71.87 %
6.	08:01	6		4.38 %	14.82 %	80.80 %
7.	09:44	0.5	4.33 %	95.65 %		
8.	09:47	Niyama Beach Sand	1.92 %	98.08 %		
9.	09:58	0.5	3.25 %	96.75 %		
10.	10:02	Sidem Beach Sand	3.20 %	96.80 %		

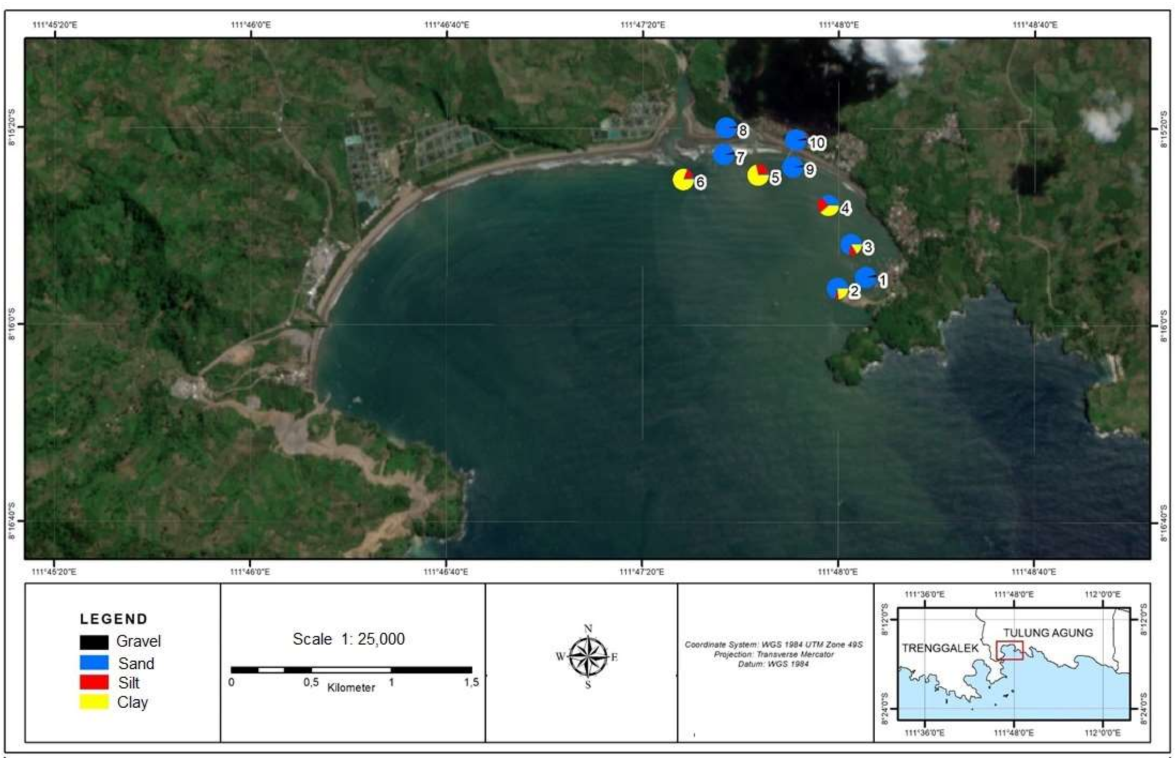


Figure 5 Sediment distribution map.

The presence of marine animal shells in land sediment samples indicates that sediment deposition originates from the ocean and is transported to each location before being distributed. Sand dominates the distribution of sediments near the mainland. As sediments move into open waters, silts and clays become the predominant particulates. This is due to the low current velocity conditions and the beach's geometry, which prevents strong currents from entering. According to the research of Wardheni et al. (2014), when the current speed is high, sediments with large granules are carried away and deposited, whereas when the current speed is low, only fine sediments can be transported based on the energy of the current.

3.1 Coastline change at Popoh Beach

Based on the results of the analysis of the Sentinel-2 satellite image, there was a change in the coastline Popoh Beach in the 2015-2021 period, shown in **Figure 6**. The causes of the coastline changes are thought to be due to natural and artificial factors (Ahmeda et al., 2017; Balica et al., 2012). Accretion is a change in the coastline to the waters due to the process of sedimentation from the Neyama River. Abrasion occurs because of the erosion of the coast by the impact of ocean waves, which causes a decrease in the land area. In this period, the coastline change was dominated by the accretion process. The extent of abrasion and accretion can be seen in **Table 3**. A map of coastline changes from 2015 to 2021 can be seen in **Figure 7**. This shows wider and more significant shoreline changes. This period also showed the expansion of PPI Popoh's development over the next six years.

Changes in the coastline at Popoh Beach in the 2015-2018 period were more dominant by accretion (**Figure 6a**). In this period, the addition of land was very large compared to the reduction of land; namely, the area of accretion was about 11 times the area of abrasion (**Table 3**). Meanwhile, in the period from 2018 to 2021, changes were still dominated by the accretion process, but were smaller than the previous periods and in different regions (**Figure 6b**). In addition to the expansion of development that was taking place, the presence of the river estuary which carries sediment material accelerated deposition and compaction so that it became new land (Suhardi et al., 2020). The area of abrasion is 5.52 hectares and the area of accretion is 9.32 hectares.

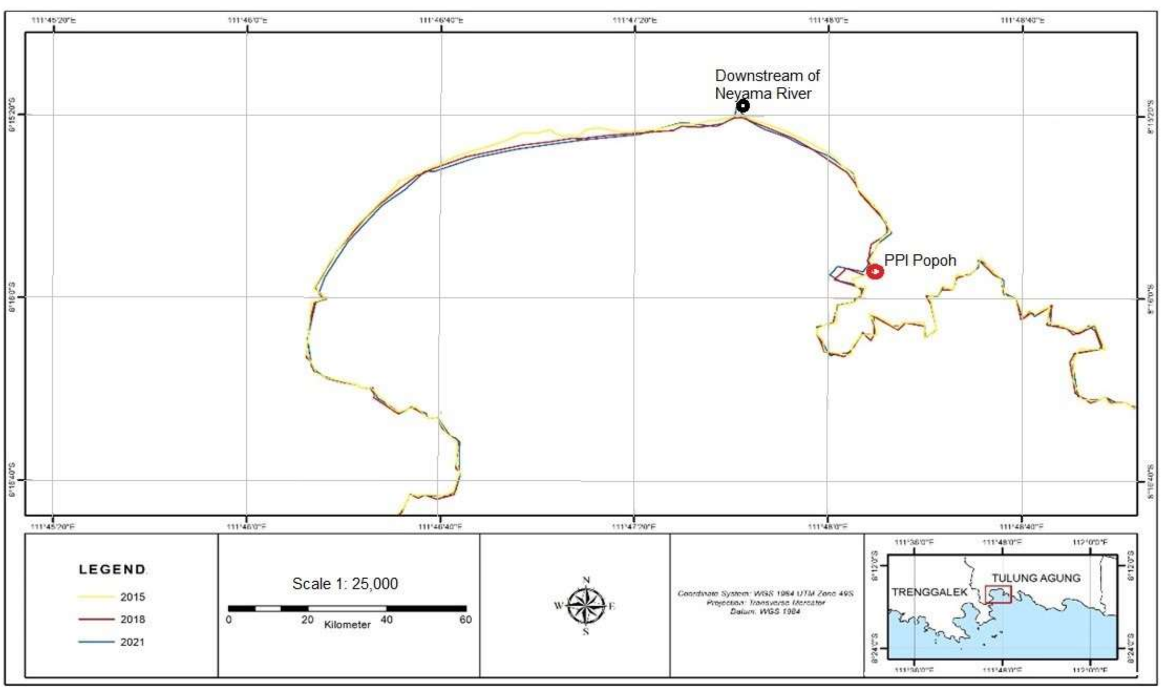
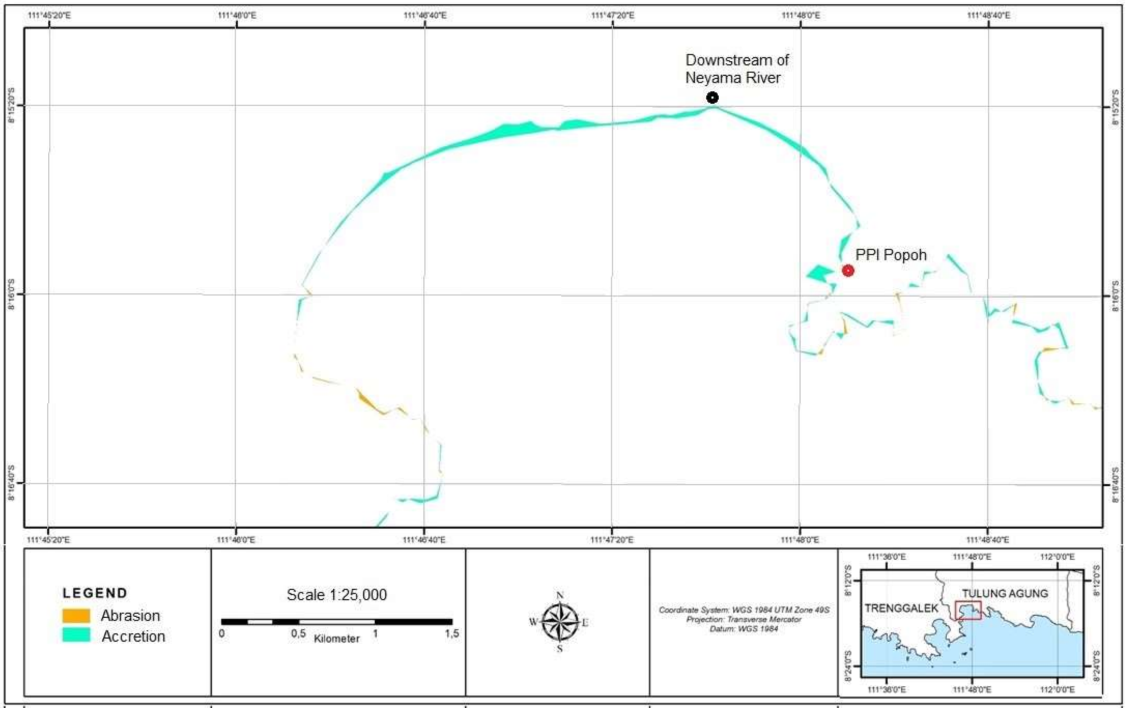


Figure 6 Coastline change map for 2015-2021.

One of the changes in the morphology of the beach was influenced by the direction of the sea waves towards the beach. The changing direction of the sea waves was caused by the construction of the PPI Popoh breakwater.



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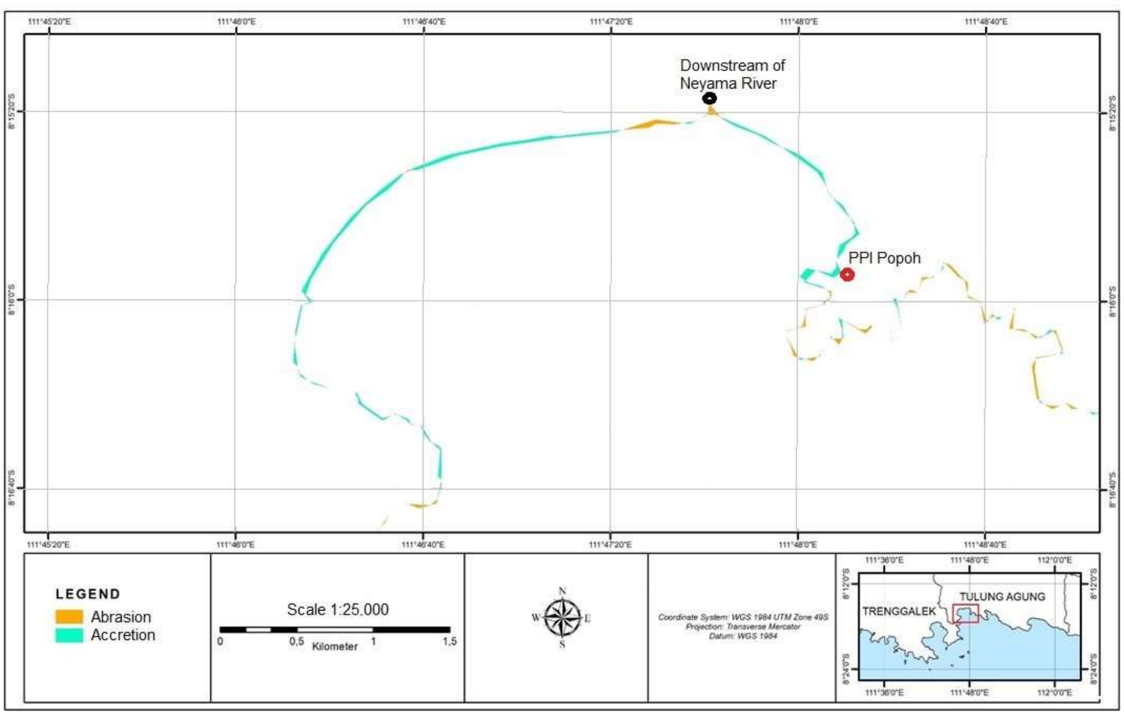


(b)

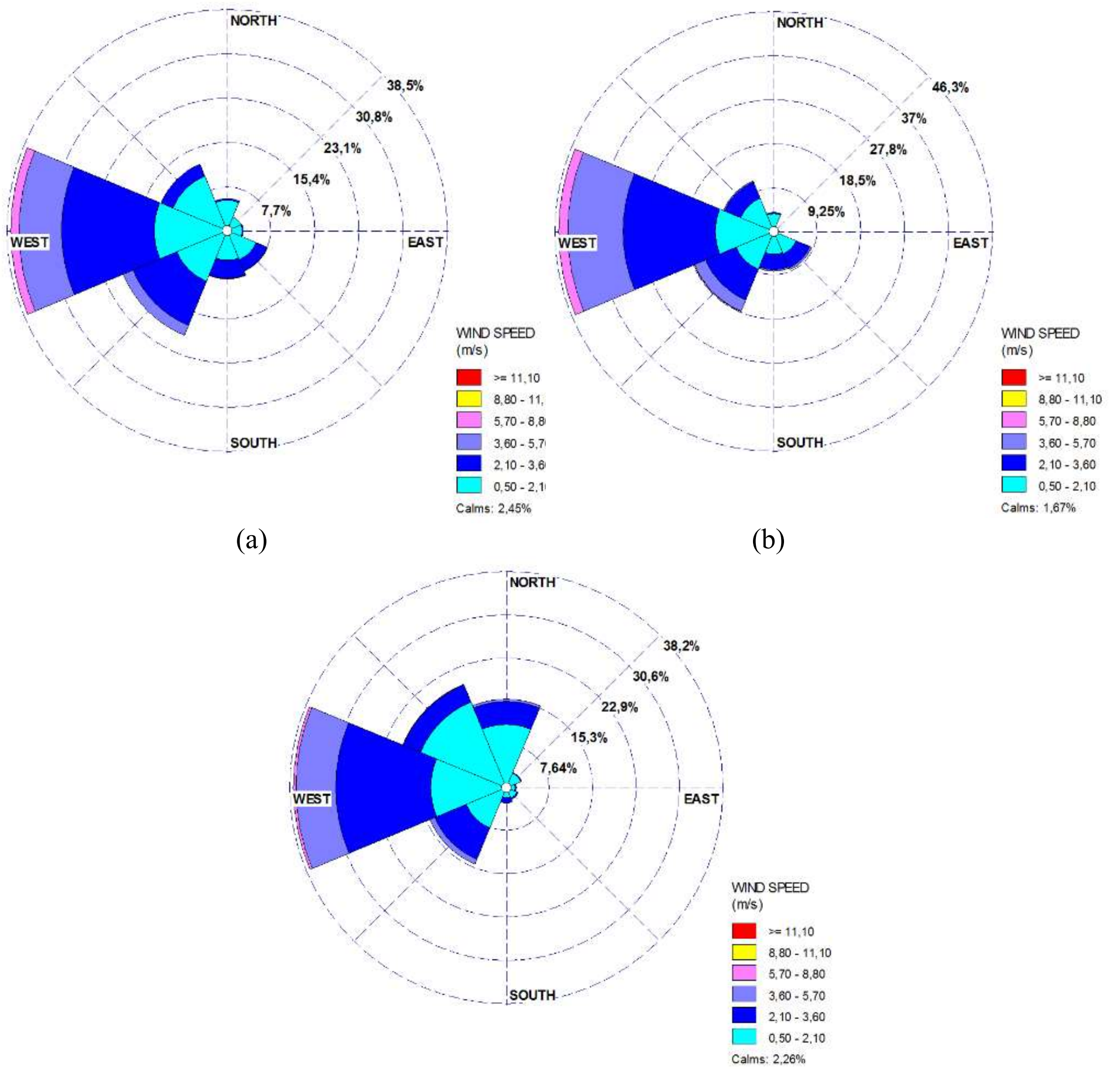
Figure 7 Abrasion and accretion map for (a) 2015-2018, (b) 2018-2021.

Table 3 Changes in abrasion and accretion areas for 2015-2018.

Coastline Change	2015-2018	2018-2021
	Areas (hectares)	Areas (hectares)
Abrasion	1.55	5.52
Accretion	17.78	9.32

3.2 Seasonal wind 2015, 2018, 2021 at Popoh Beach

During the west monsoon in the years 2015 to 2021, shown in **Figure 8**, the dominant wind blew from west to east, with fairly low average wind speeds of 2.64, 2.52, and 2.01 m/s. The wind tended to be low in this season because of the shape of the beach that opens to the southeast and because this season's condition of the sun being in the northern hemisphere, causing the Asian continent to be hotter than the Australian continent. This condition resulted in the wind blowing from Australia to Asia (Sudarto, 2011).

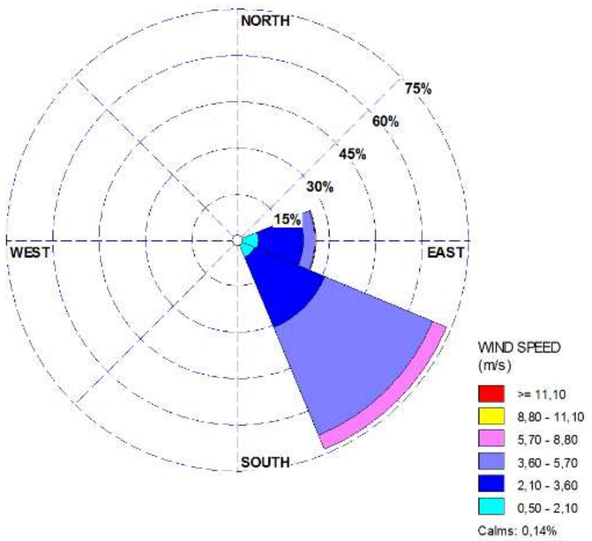


(a) (b)

(c)

Figure 8 Wind roses of west monsoon season (a) 2015, (b) 2018, (c) 2021.

Meanwhile, during the east monsoon between 2015-2021, the dominant winds blew from southeast to northwest. They tended to be high, with wind speeds of 3.51, 3.57, and 2.02 m/s, as shown in **Figure 9**.



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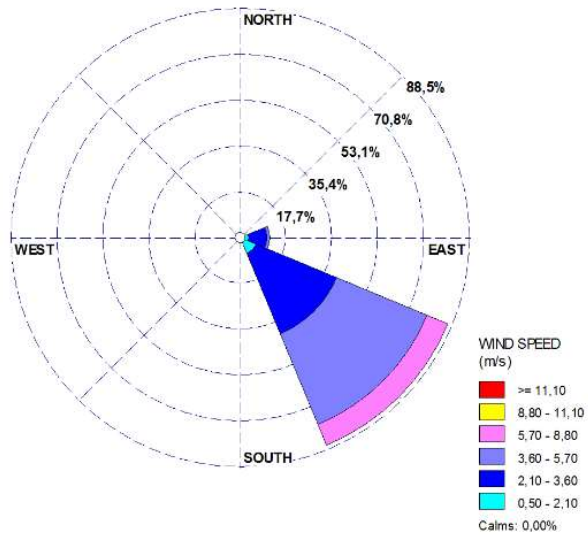

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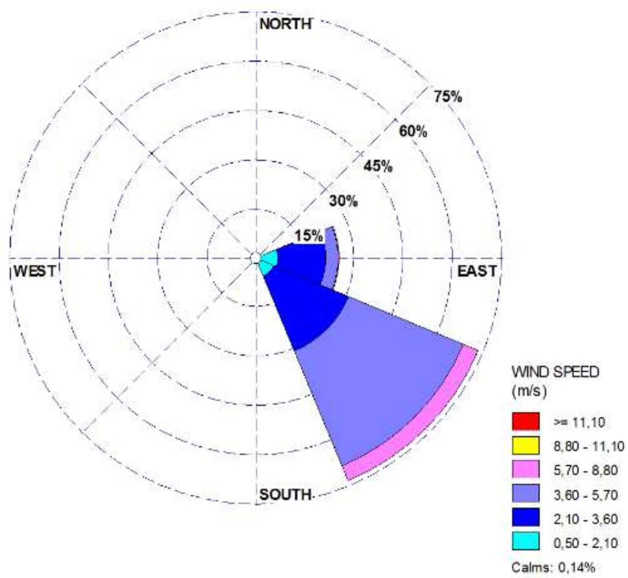


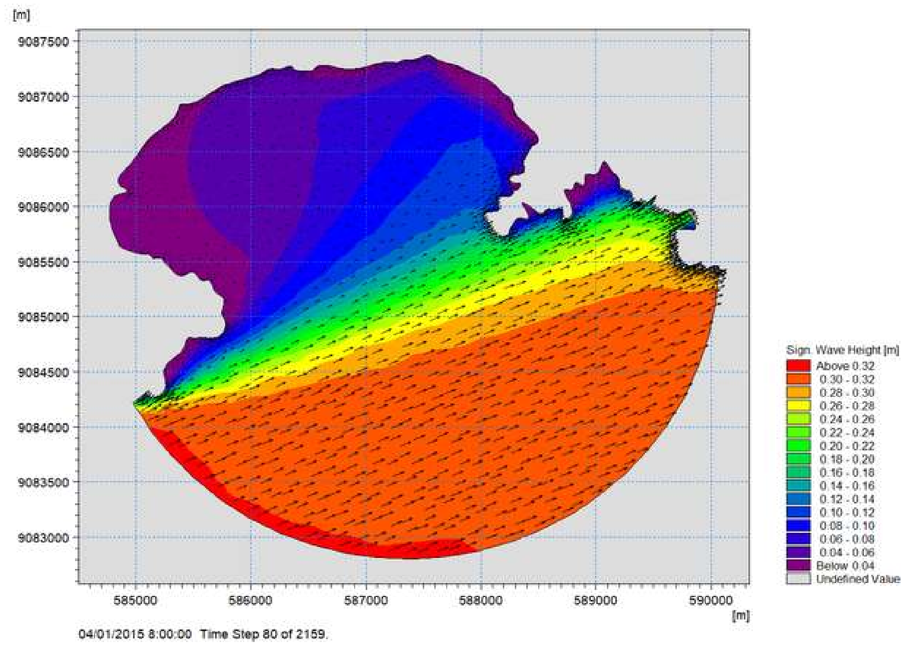
(c)

Figure 9 Wind roses of east monsoon season (a) 2015, (b) 2018, (c) 2021.

3.3 Seasonal wave modelling in 2015, 2018, 2021

Based on the research results, the ocean waves during the west monsoon season, shown in **Figure 10**, moved from southwest to northeast. They had an average wave energy of 7.58 kW/m, with the highest significant wave occurring in 2021, at 0.48 m. This wave energy had a direct effect on beach abrasion around PPI Popoh, but had less effect on erosion to the east of Popoh Beach.

During the east monsoon season, waves moved from southeast to northwest. Significant waves occurred in 2015 and 2018 as high as 1.65 m, shown in **Figure 11**. The shape of Popoh Beach faces southeast, causing the dominant oceanographic parameters such as waves and currents to enter from the southeast. This matter was similar to the research by Setyawan and Pamungkas (2017), where the condition of the beach was opened to the southwest and was surrounded by mountains, affecting the oceanographic parameters. The shape of the physical environment causes the water mass to only enter the beach from the southeast, and the beach was protected from winds that came from the north.



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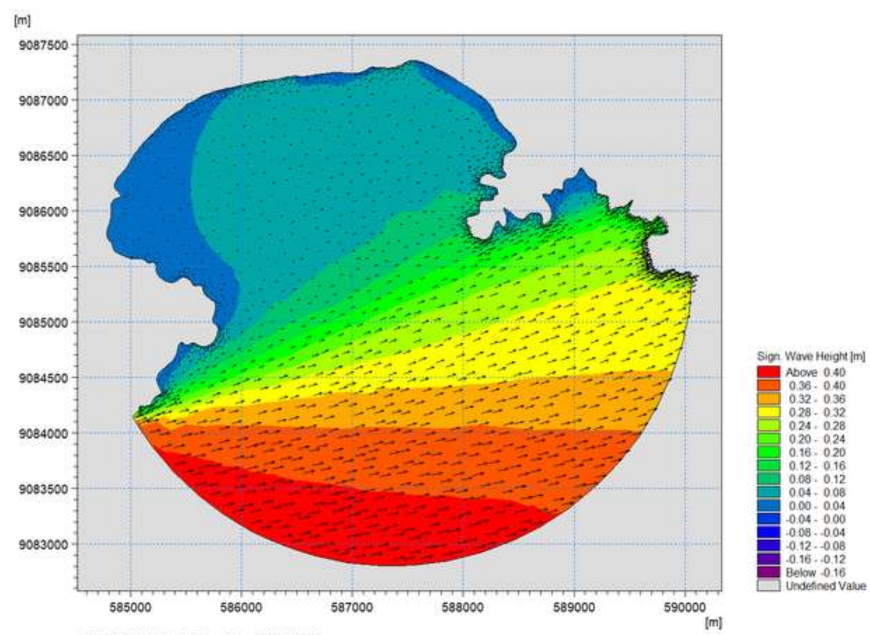
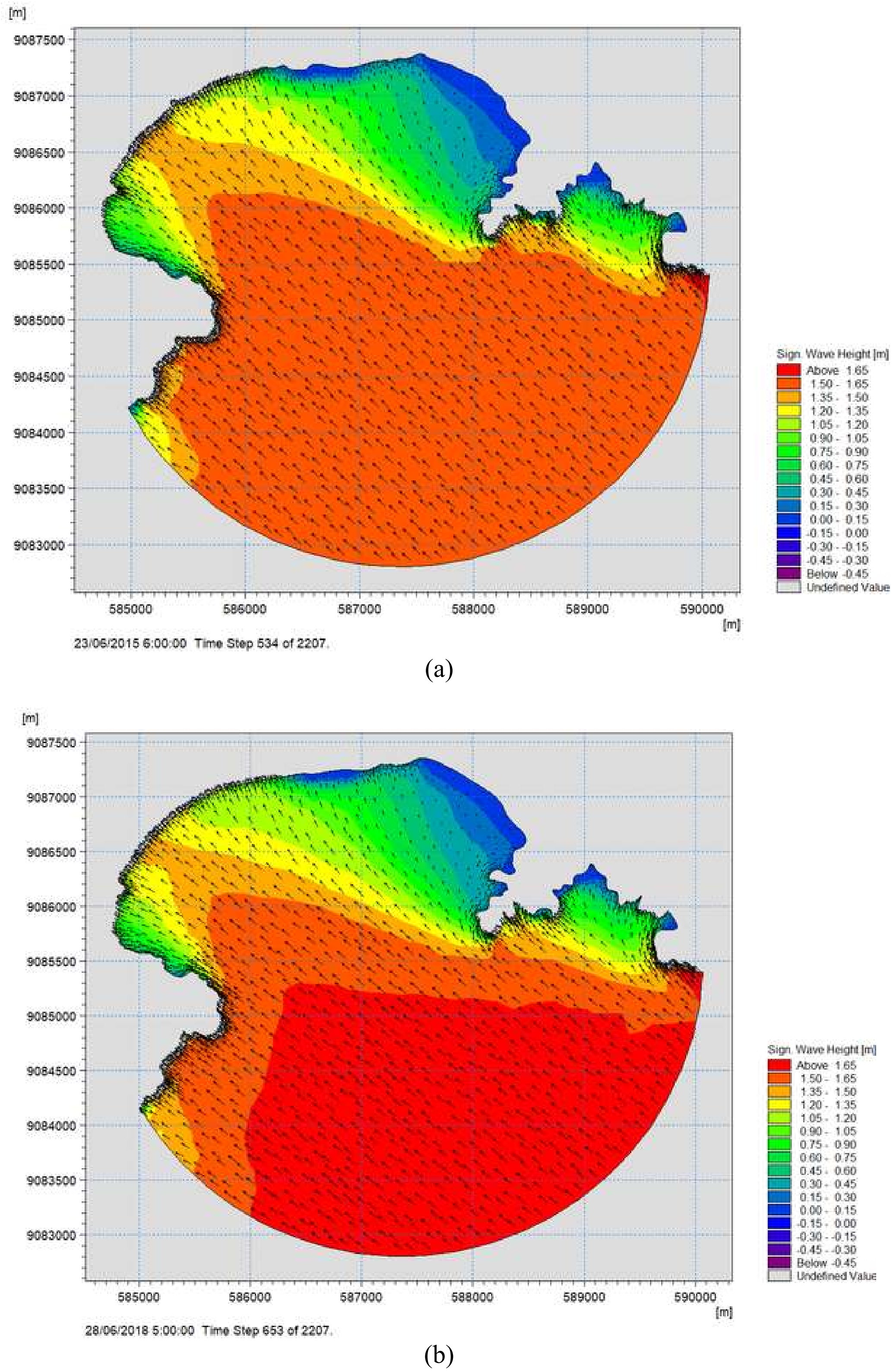


(b)

Figure 10 Wave modelling for west monsoon season (a) 2015, (b) 2018.

The expansion of the new PPI development that occurred in 2015 was not wide enough to prevent the entry of waves into the anchor pond; that year's waves experienced refraction with decreasing height when near land. In 2021, waves from the south, which hit the expansion of the PPI development, experienced a diffraction towards the back of the land, causing abrasion.



(a)

(b)

Figure 11 Wave modelling for east monsoon season (a) 2015, (b) 2018.

Even though the expansion of the PPI Popoh development resulted in additional land, several other parts of the coastline experienced abrasion, including areas that were suspected to have silted due to the impact of human intervention. Wave modelling of this area around the PPI Popoh is shown in **Figure 12**.

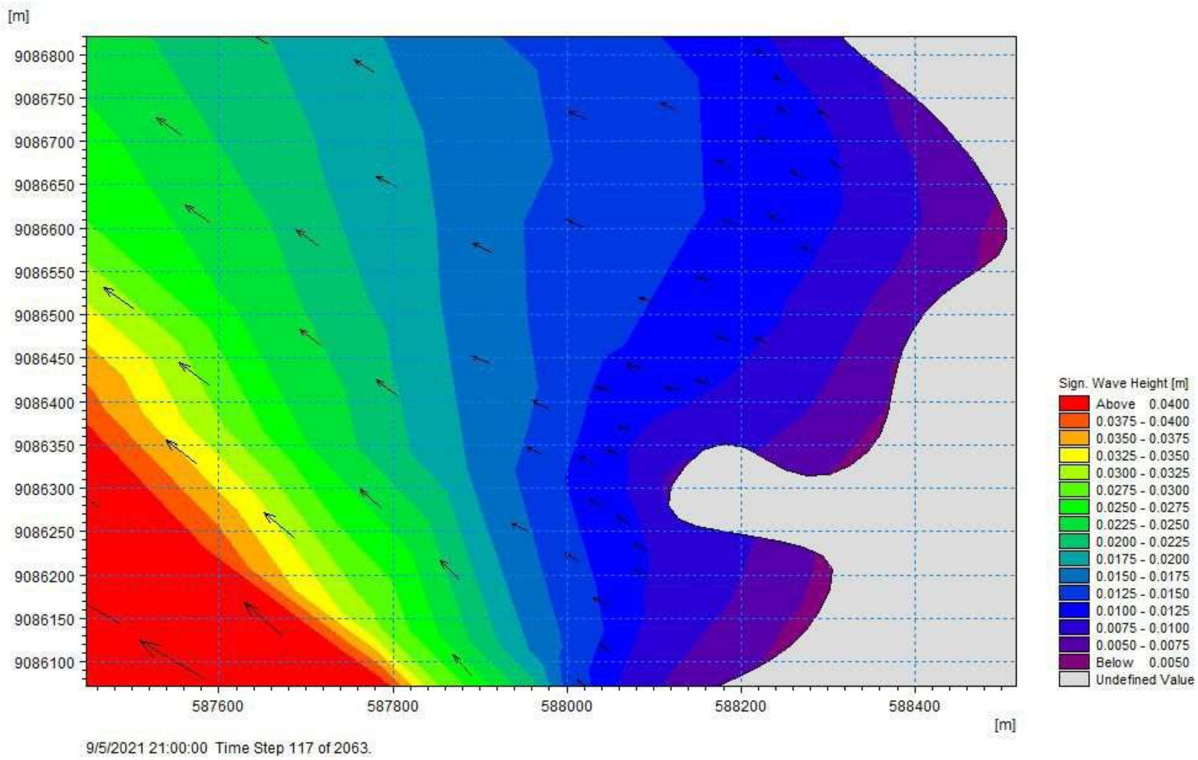


Figure 12 Wave model of area around the PPI Popoh.

4. Conclusions

The presence of marine animal shells in land sediment samples suggests that sediment from the ocean is transported to each location before being deposited. Sand dominates the distribution of sediments near the mainland. As sediment moves into open waters, silt and clay become the predominant particulates. This is due to the low current velocity conditions and the beach’s geometry, which prevents strong currents from entering.

Accretion is the dominant process in Popoh Beach’s coastal sediment deposition, influenced by material flowing from the Niyama River. However, this process tends to decrease over time, while abrasion, caused by wind-generated waves at Popoh Beach, tends to increase.

Based on the results of hydrodynamic modelling, it was found that the average wave energy per year at Popoh Beach exceeded 1.5 kW/m. This is important because high wave energy can lead to increased erosion and coastal instability. In 2021, waves from the south hit the expansion of the PPI development. These waves experienced diffraction towards the back of the land, causing abrasion. The expansion of the PPI Popoh had a direct impact on the Niyama River, which transported sediments into Popoh Beach.

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