Hydro-Morphological Conditions of the Coastline Post-Construction of Sea Dikes in Pekalongan, Central Java

Ilham Safikri[1], Muhammad Zainuri[2], Aris Ismanto[2]*

[1]Master of Marine Science, Faculty of Fisheries and Marine Science, Universitas Diponegoro
[2]Department of Oceanography, Faculty of Fisheries and Marine Science, Universitas Diponegoro
Jl. Prof. Jacub Rais. Tembalang Semarang Jawa Tengah 50265, Indonesia
Email: aris109@lecturer.undip.ac.id

Abstrak

Pekalongan is one of the cities in Central Java affected by tidal flooding. Tidal floods occur due to sea level rise and land subsidence in Pekalongan, so far the tidal floods have had an impact on the community. Infrastructure damage and disruption of community activities are examples of the impact of tidal floods in Pekalongan. One of the government policies in overcoming tidal floods is to build sea walls along the coast of Pekalongan. This policy will certainly have an impact on the morphological pattern of the coastal area. This study was conducted to determine the pattern of currents, waves, and sediment characteristics on the coast of Pekalongan after the sea wall. The analysis was conducted using current and wave modeling of delft-3d application. Sediment analysis was conducted by analyzing sediment grain size (Granulometry). The results show that currents and waves are influenced by seasonal winds that occur in Pekalongan. The dominant season in coastal Pekalongan occurs between December - January (West Season). Current conditions in the west season move with a speed of 0.2 -0.3 m/set moving eastward. West season wave conditions move with a height of 7.2 meters with a peak period of 7.2 seconds. While the sediment characteristics in Pekalongan are dominated by mud - sandy. From these sediment characteristics, it can be concluded that the influence of currents and waves of the west season can cause the distribution of sediments towards the east.

Keywords: Tidal Flood, Current, Wave, Sediment

INTRODUCTION

Pekalongan City, located in Central Java, is one of the areas affected by tidal flooding. Sea level rise due to climate change is the main factor causing tidal flooding in Pekalongan (Ryco *et al.*, 2023). In addition, flooding in Pekalongan is also affected by significant land subsidence (Gradiyanto *et al.*, 2025). Tidal flooding in Pekalongan has direct and indirect impacts on the surrounding communities (Riyatmoko *et al.*, 2022). Direct impacts include damage to homes, schools and public health in flood-affected areas. Indirectly, tidal floods disrupt the social and economic life of local communities.

Tidal flooding along the coast of Pekalongan has destroyed the natural protection function of the coastline. The shoreline is an important component in the natural defense against ocean waves (Zainuddin *et al.*, 2024). Based on Google Earth imagery (Figure 1), in 2013, Pekalongan's coastline still showed a stretch of sandy beach extending from the river mouth. However, in 2018, Google Earth images show that the area that in 2013 consisted of ponds, rice fields, and residential areas, has been affected by tidal flooding. This shows that tidal flooding has significantly changed the land use and coastal morphology around the affected areas.

The results showed that between 1988 and 2021, Pekalongan's coastline regressed by 232 meters (Chulafak *et al.*, 2022). Areas affected by coastal erosion include Bacanan, Depok, Semut, Pecakaran, Jeruksari, Bandengan, and Kandang Panjang. Meanwhile, areas affected by tidal flooding include areas around Bandengan, Jeruksari and Kandang Panjang. In 2020, the area affected by flooding in Pekalongan City reached 38.23% of the total city area.

The Pekalongan City Government, together with the Central Government and the Central Java Provincial Government, has made various efforts to tackle flooding and tidal flooding. One of the latest initiatives is the construction of a giant levee along the coastline and periodic increases in the height of the levee. This measure is targeted to

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reduce the area affected by flooding to 12.49% by 2026 (Bappeda Pekalongan, 2021). The handling of tidal flooding in Pekalongan City is also part of the National Strategic Program as stipulated in Presidential Regulation No. 79/2019 on the Acceleration of Economic Development.

The construction of these embankments, which aim to address tidal flooding, has the potential to significantly affect coastal morphology. The impact of such embankments can be either accretion or erosion, depending on their design and location (Sujivakand *et al.*, 2024). This is similar to what happened in Faxe Ladeplads, Denmark (Adell *et al*., 2024). Within the water column, such marine infrastructure can also alter flow patterns and currents around the construction area (Chu *et al.*, 2024). In addition, constructed coastal structures can affect the surrounding environment, including coastal morphology, hydrodynamics, ecology, and the tourism and recreation sector (Saengsupavanich *et al.*, 2022).

The position of the constructed embankment is shown in Figure 3. The area north of the embankment has almost entirely turned into sea, while the sandbar that used to exist is now gone. In addition, the condition of the mangrove ecosystem has been severely degraded when compared to the conditions in 2013 and 2018. This mangrove damage was caused by constant seawater flooding and lack of water circulation in the area (Ario *et al.*, 2016).

In addition to the presence of sea walls, sediment characteristics also affect beach morphology in the surrounding area. Pekalongan Beach has various types of sediments, including sand, silty sand, silt, silt-sand-clay, clayey silt, and clayey silt (Ikhwan, 2015). Sediment characteristics are a determining factor in coastal erosion processes. Sediment grain size stability is critical to changes in beach morphology, as instability can affect the overall dynamics of the beach shape. Instability of sediment. grain size can cause an imbalance in the sediment transport process, which in turn can increase the intensity of coastal erosion (Tarigan *et al.*, 2020).

Pekalongan City serves as the center of industry, trade, and settlement along the north coast of Central Java. The sustainability of the coastal ecosystem is expected to be maintained in the coastal area of Pekalongan. The construction of a sea dike will certainly affect the current and wave conditions around the dike site, which in turn will have an impact on sediment transport in the vicinity. Therefore, this study aims to understand the impact of levee construction on hydro-morphology in the surrounding area. To anticipate and manage these changes, a thorough understanding of the dynamics of coastal morphology is required.

This research involves analysis of sediment distribution along Pekalongan coast and hydro-morphological modeling. Coastal morphological modeling uses various instruments and analysis methods to project changes in coastal topography, which then guide effective coastal planning and management.

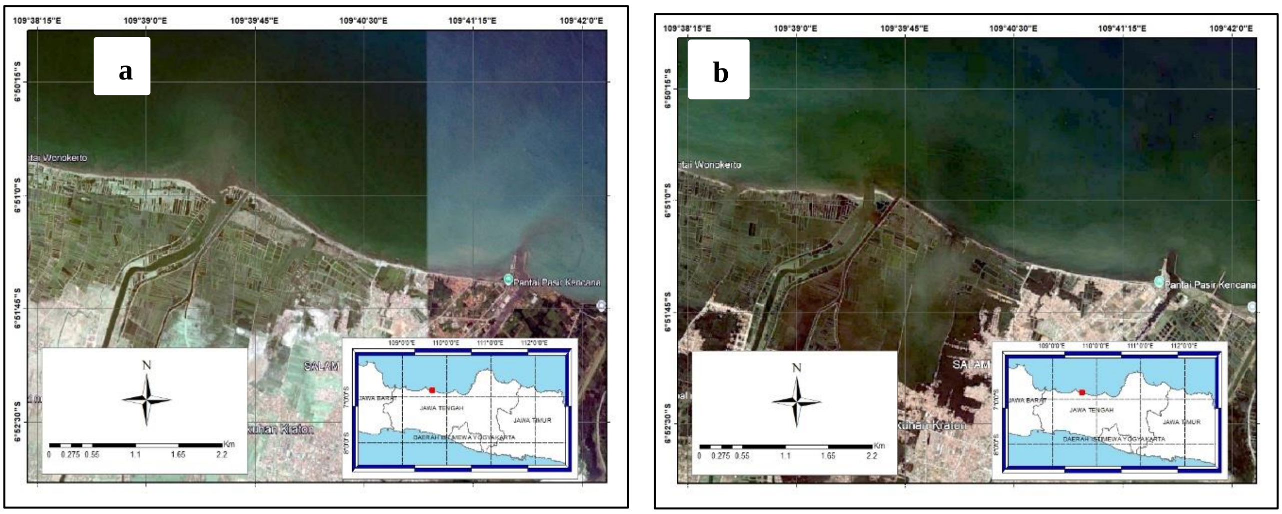


Figure 1. Pekalongan's condition: 2013 (a) and 2018 (b)

MATERIALS AND METHODS

The data used in this study consisted of primary and secondary data. The data used in the study are presented in Table 1 below. The tools and materials required for the study are shown in Table 2.

Bathimetry survey

Field bathymetry data collection is conducted through topographic surveys, also known as bathimetric survey. Bathimetric survey is an activity to obtain visual data on the topography of the seabed surface (Hidayat et al., 2014). The processes involved in this activity, namely measurement, processing and mapping. This survey was conducted using a single- beam echosounder. The sounding used a single- beam echosounder in accordance with Indonesian National Standard (SNI) number SNI 7646:2010.

Sediment Survey

Sediment sampling is the primary data collected using sediment collection tools. Sediment obtained by sediment capture represents the surface sediment characteristics of the water body. The placement of sediment capture stations corresponds to the number of designated stations, and the location of these stations is chosen to represent the sediment characteristics at each study site.

Table 1. Data

No.	Data	Source	Fungsi
1	Sediment Type and Size	Granulometric Analysis	Granulometry
2	Current	Survey	Model Validation
3	Waves	*Ecmwf-era5*	Model Input
4	River Discharge	BBWS	Model Input
5	Bathymetry	BATNAS 2023	Model Input
6	Tidal	BIG 2023	Model Input
7	Wind	BMKG Pekalongan	Model Input
8	Geospatial map of Indonesia	Ina Geoportal	Spatial Analyst

Table 2. Tools and Materials

No	Tools and Materials	Function
1	Laptop	Data Processor
2	Delft3d	Hydro-oseanographic Modeling
3	Garmin 75 GPS	Sampling
4	Boats/motorboats	Survey
5	Sediment Trap	TSS retrieval
6	Plastic	Water sample container
7	*Alluminum foil*	Sample container
8	Seafer	Filtering sediment according to grain size
9	Iron spatula	Stirrer
10	*Drying Oven*	Sediment dryer

Tidal Analysis

Tidal data analysis can be done with the admiralty method. The admiralty method is a harmonic method used to calculate two harmonic constants, namely amplitude and phase difference in a short time span (29 days) (Ichsari et al., 2021). From the processing of tidal data with the admiralty method, the tidal components are M2, S2, N2, K1, O1, P1, M4, MS4, and K2. Furthermore, in determining the type of tide, calculations are carried out through the Formzahl equation as follows:

$$F= ((AK1)+(AO1))/((AM2)+(AS2))$$

Note: F= Formzahl value; AO1= Amplitude of the main single tidal component due to lunar drag; AK1 = Amplitude of the main single tidal component due to solar drag; AM2 = Amplitude of the main double tidal component due to lunar drag; AS2 = Amplitude of the main double tidal component due to solar drag.

Bathymetry

The depth data from the bathymetry was corrected with the tranducer and the position of the sea surface at the time of measurement to obtain the actual depth value. Bathymetry correction is done using the following equation:

$$rt = TWLt - (MSL + Z0)$$

Note: rt = The amount of reduction (correction) given to the depth measurement result at time t; TWLt = True water level at time t; MSL = Mean Sea Level; Z0 = Dep th of tidal front below MSL.

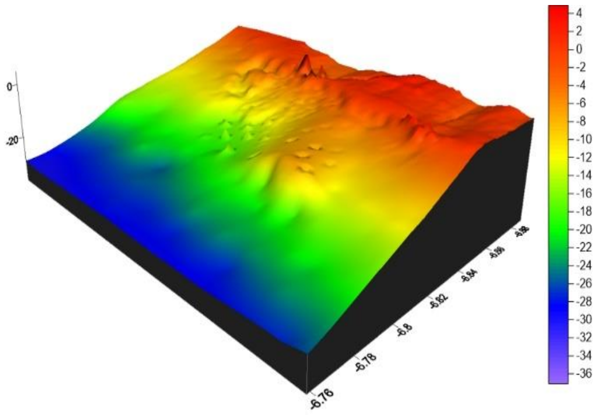


Figure 2. 3D Bathymetry Pekalongan

The figure 2 displays a 3D bathymetric map of the seafloor near Pekalongan. The depth values are color-coded, ranging from shallow areas in red and orange hues to deeper regions in green, blue, and purple. The elevation scale on the right side of the image shows depths from 0 meters (in red) to approximately -36 meters (in purple). The terrain appears to slope downward from the coastline (right side) toward the deeper offshore areas (left side). The map provides a detailed visualization of the underwater topography, showing various seabed features such as ridges and depressions, which are crucial for understanding marine environments and coastal dynamics.

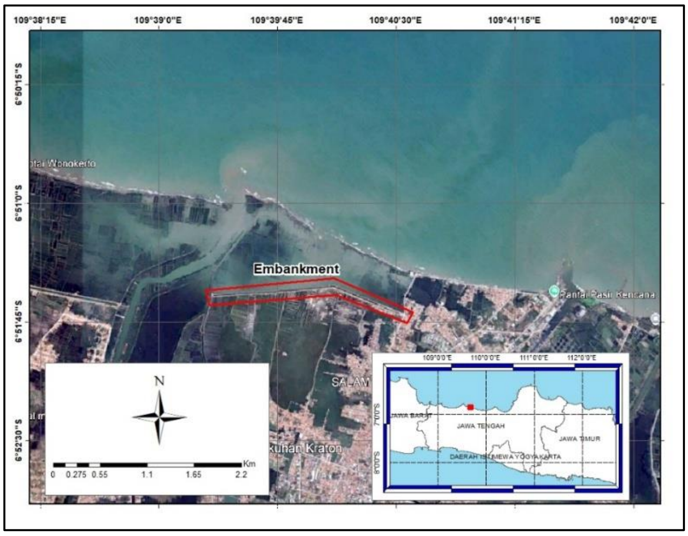


Figure 3. Condition of Pekalongan after the embankment was built in 2020

$$D = dT - rt$$

Note: D= Actual depth; dT = Corrected Depth Tranduser; rt = Reduction (correction) of sea tides
Grain Size Analysis

Basic sediment from field data collection, then laboratory testing will be carried out to determine grain size. Sediment grain size analysis testing is carried out to determine the size of sediment grains, from the size of sediment grains can be known sediment type. In analyzing the size of sediment grains, it is carried out using the sieve method (Gelhardt et al., 2021) and hydrometer analysis (Zhang, 2024). The grain size analysis test method is based on the Indonesian National Standard (SNI: 3423: 2008).

RESULT AND DISCUSSION

Wind

Figure 4 illustrates the wind speed distribution patterns in the Pekalongan waters, represented using wind rose diagrams. The diagrams categorize wind speed ranges (in knots) and display the directional frequency of wind occurrences, offering a comparative analysis across different conditions in the region.

Wind data processing was carried out using wind data from 2013-2023. This data processing is divided by season, namely the west season, transitional season 1, east season, and transitional season 2. In the west season, the wind is dominated from the west with maximum speeds exceeding 22 knots. In transitional season 1, winds are dominated from the south, north, and west with speeds ranging from 0 to 22 knots. In the east season, winds are dominated from the south and east with speeds ranging from 4 to 21 knots. Meanwhile, in transitional season 2, winds are dominated from the south and east with speeds ranging from 1 to 11 knots.

Tidal Analysis

The tidal component was obtained using the admiralty method. The calculation results are shown in Table 3 and resulted in a Formzhal value of 0.277, which indicates that the water type in Pekalongan waters is a Mixed Type that tends to be Single. Based on the calculation of tidal components for June 2023, the Average Sea Level (MSL) in Pekalongan is 1.711 meters (Figure 5).

Current

Current simulation was conducted by integrating wave results. This current condition represents longshore currents. Longshore currents, or currents parallel to the shore, move differently depending on the wave quadrants, which are typically influenced by seasonal or daily variations (Fernandes, 2024). These shore-parallel currents can transport and distribute suspended materials such as sediments, plastics, and debris (Hanes, 2022).

The simulation results (Figure 6) indicate that during the west monsoon, longshore currents flow from west to east. At high tide, the currents move with a velocity of 0.7 to 0.32 m/s. At the lowest ebb, the currents move with a velocity of 0.064 to 0.34 m/s. Conversely, during the east monsoon, the currents flow from east to west. At high tide, the current velocity ranges from 0.021 to 0.1 m/s, while at the lowest ebb, the currents move with a velocity of 0.019 to 0.15 m/s.

Wave

Wave analysis was conducted using the hindcasting method based on SPM 1984. The results are presented in Table 4, showing that the most dominant significant wave height (Hs) and wave crest period (Tp) occur in the west season, with Hs reaching 1.5 meters and Tp of 7.24 seconds. This analysis is based on wind data from 2013 to 2024 along Pekalongan Beach.

Table 3. Tidal Component

	S_0	M_2	S_2	N_2	K_1	O_1	M_4	MS_4	K_2	P_1
P1A Cm	171.15	6.78	23.65	5.49	4.99	3.45	0.51	0.21	14.52	27.910
g^o		76.2	325.5	46.4	325.5	270.0	150.4	270.0	266.0	7.5

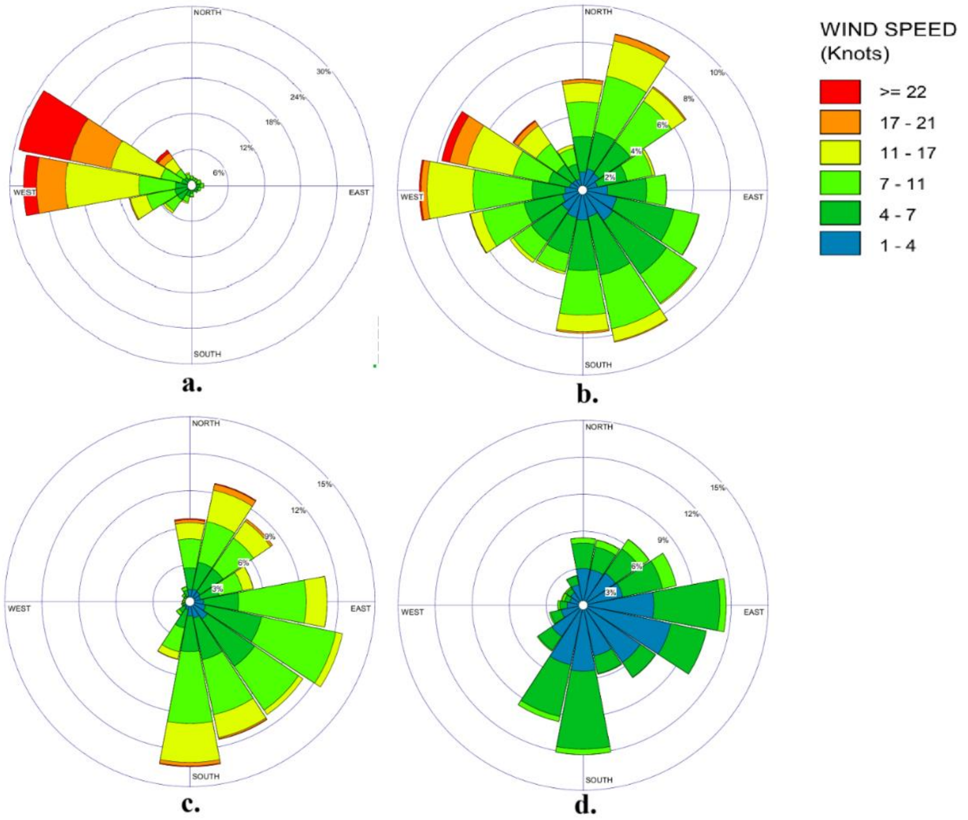


Figure 4. Wind rose: December - February (a); March - May (b); June - August (c); September - November (d)

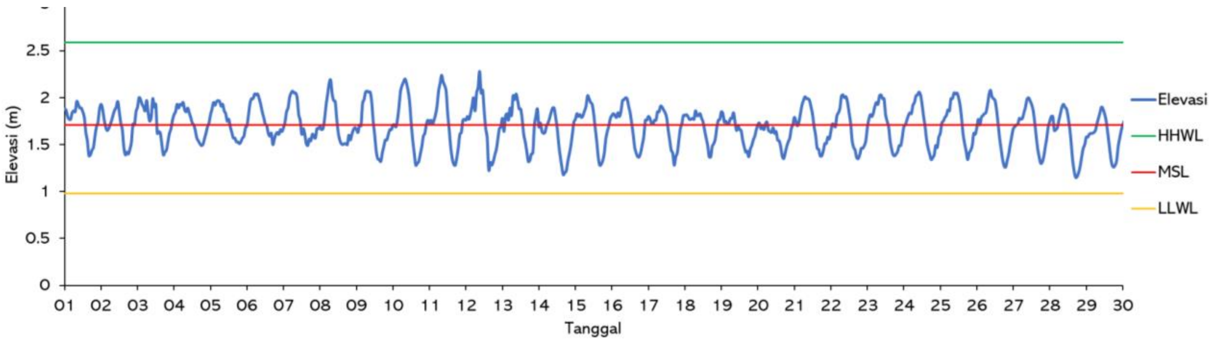


Figure 5. Pekalongan tides June 2023

Meanwhile, the model simulation was conducted according to the fetch analysis of the most dominant wave directions, namely from the northwest and north-northeast directions. The simulation results are shown in Figure 7, which shows that waves from the northwest move toward the shore, with the wave height gradually decreasing due to the influence of water depth. Upon reaching the shore, the waves bounce back and align with the shoreline. A similar pattern occurs for waves coming from the north-northeast direction.

Sediment Distribution

Figure 8 shows the distribution of sediment types along the Pekalongan coast, based on samples collected in 2024. The results show that sediments in Pekalongan consist of three types: sand, silt and clay. Near Mrican River, the sediments are dominated by sand and mud, while around Loji River, the sediments mainly consist of clay and mud. In contrast, the area near the Sengkarang River is dominated by sand and silt.

According to the percentages presented in Table 5, mud shows the highest percentage at almost every sampling station. The presence of sand is most dominant near the Sengkarang River, while analysis at the Loji River shows the absence of sand in its sediment composition

Analysis of each parameter can provide predictions of morphological changes around the Pekalongan coastline. For example, seasonal modeling of the coastal parallel currents, as shown in Figure 6, reveals that the dominant current speed. during the westerly season is 0.32 m/s. Beach parallel currents are a significant factor that can cause erosion or accretion along the coast. The analysis of the currents indicates that sediment transport will be mostly directed from west to east.

Table 3. Wave Hs and Ts in Pekalongan Waters in 2013-2023

Season	Hs	Ts
West Season	1.57	7.24
Transitional Season I	0.62	5.93
East Season	0.28	5.31
Transitional Season II	0.25	5.01

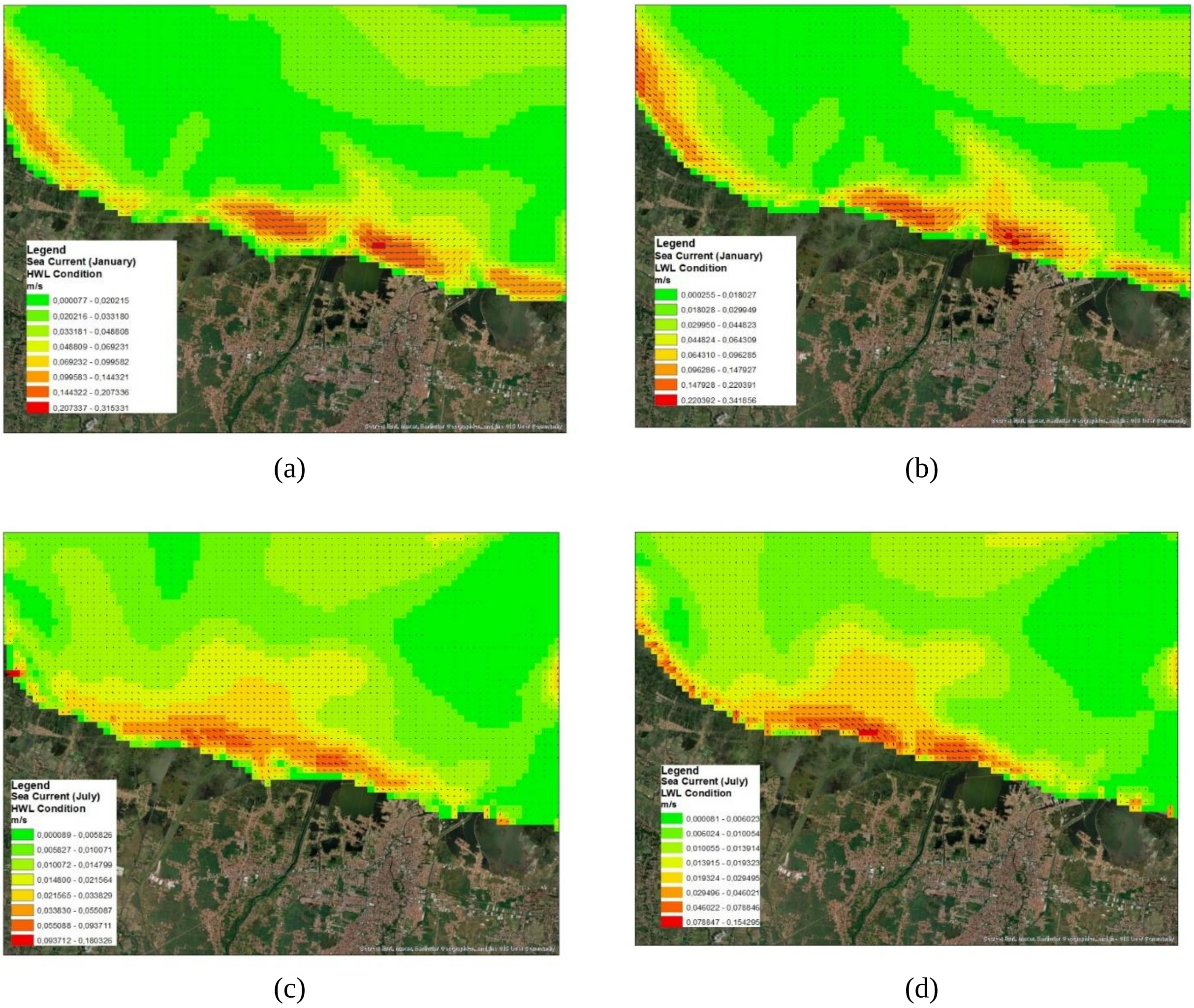
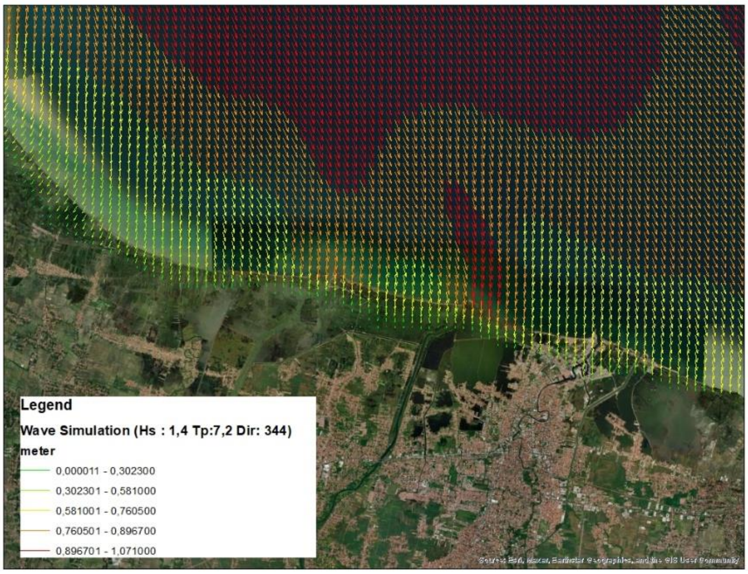


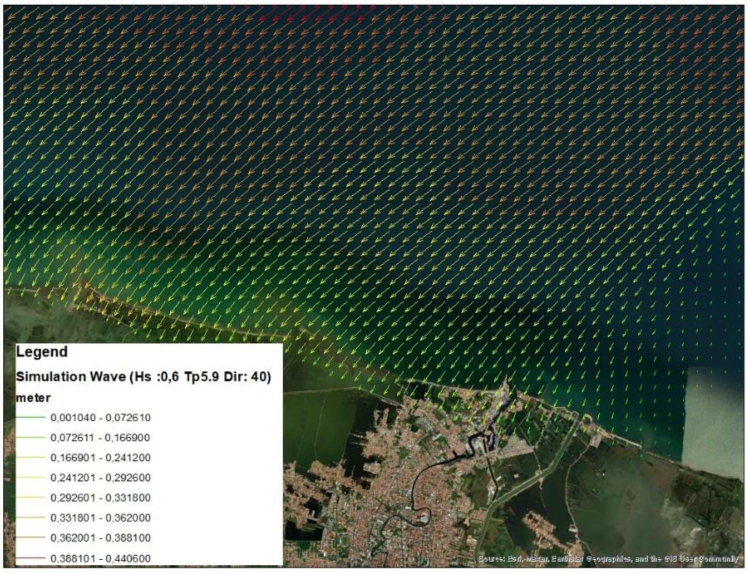
Figure 6. The sea current simulation during the condition of a) west season and highest tide, b) west monsoon and lowest tide, c) East season and highest tide, and d) East season and lowest tide

Table 4. Percentage of type sediment

Stasiun	X	Y	Sand	Mud	Clay
SM_1	109.6195	-6.8476	42.086 %	56.06 %	1.85 %
SM_5	109.6203	-6.83947	42.63 %	57.37 %	0 %
SM_9	109.6343	-6.84191	28.24 %	70.98 %	0.77 %
SS_2	109.6502	-6.8579	52.76 %	45.53 %	1.7 %
SS_15	109.6561	-6.84229	14.32 %	85.23 %	0.44 %
SS_17	109.6653	-6.84506	50.23 %	47.21 %	2.47 %
SL_3	109.6857	-6.85693	0 %	78.16 %	21.83 %
SL_2	109.6914	-6.86261	0 %	93.70 %	6.29 %



(a)



(b)

Figure 7. Wave simulation during the most dominant wave directions a) Northwest, b) North-Northeast

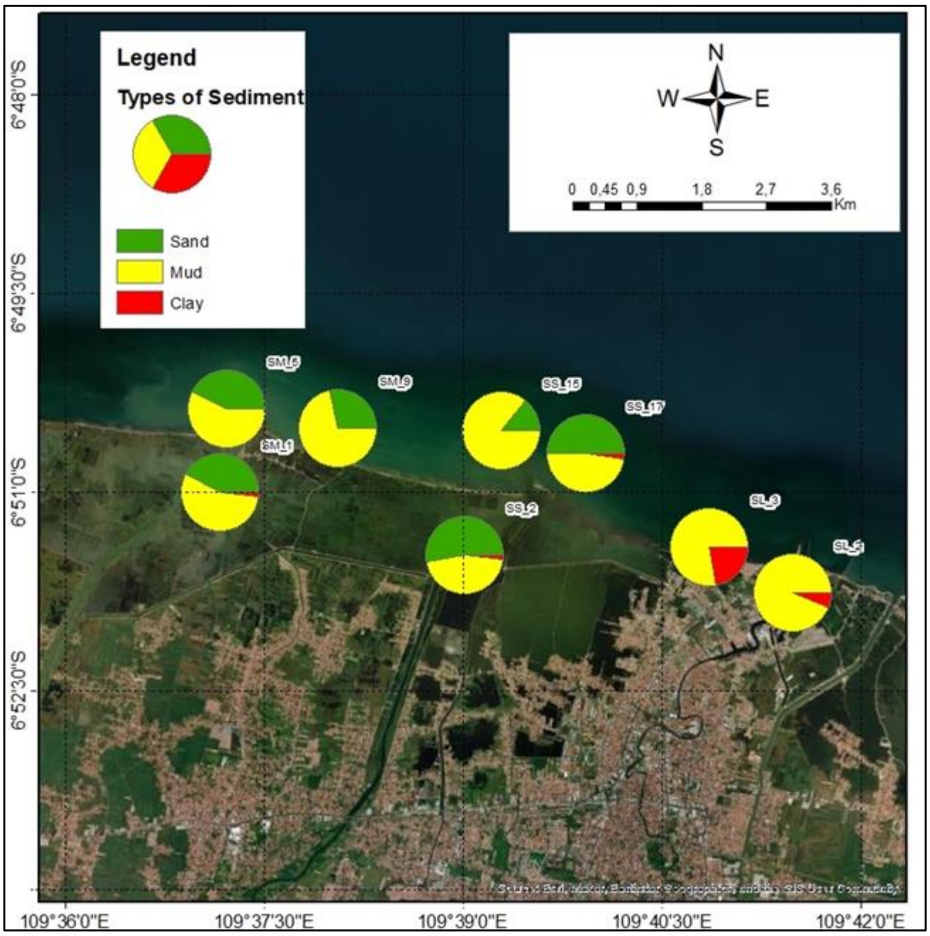


Figure 8. Sediment Size distribution

CONCLUSIONS

Seasonal agin movement shows that Pekalongan waters are dominated by the west season. This causes wave movement from the west with a height of 1.5 meters and a Peak Period (Tp) of 7.24 seconds. In wave propagation, the wave height of 1.5 meters will be reduced to 0.30 - 0.58 meters due to siltation. The occurrence of these waves certainly affects the movement of currents around the coast. This current is also known as longshore current. Where this current moves parallel to the coastline, so that the current can cause coastal abrasion. Simulation of longshore currents in the west season in the coastal region of Pekalongan moves at a speed of 0.2 - 0.3 meters per second towards the east. From the simulation can show the movement of sediment will move towards the east as well.Grain size analysis shows that Pekalongan waters are characterized by sandy to mud sediments. At the location of the Mrican and Sengkarang rivers, the results show that mud is still so much compared to sand. while at the Loji River location there is no sand type sediment. In addition, the characteristics of river estuaries in the Pekalongan region taken at the location of the Sengkarang and Mrican rivers show the dominance of sand, 42.086% and 52.76% respectively. The characteristics of sediments in the Pekalongan region in terms of type and grain size are relatively more transportable by current movements.

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