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Shoreline change assessment due to coastal structure development: a case study of Plumbon Estuary, Central Java, Indonesia

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Abstract
Plumbon Estuary shoreline erosion have been a serious problems since early 2000's. Several mitigation have been implemented to sustain wave abrasion and tidal erosion such as rubble mound. However the shoreline changes still occur as the implemented coastal structures could not match the wave force and tidal erosion to protect the shoreline. In this study, the analysis of coastal protection effectiveness was conducted based on field observation data and an analysis of abrasion forces caused by dominant waves and tidal currents. The objective of the present study were to identify the shoreline change due to the development of coastal structure in the area. The results indicate that the coastal protection structures implemented at the study site are under designed and their layout is not suitable for the wave configuration at the location.

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Keywords
Shoreline change assessment, Coastal structure development, Dominant waves, Tidal currents

Introduction
Coastal areas are vital to our global ecosystem, providing essential services such as shoreline protection, habitat support for diverse marine life, and economic benefits through fishing, tourism, and industry. However, these regions are increasingly threatened by both natural processes and human activities [1]. In North Java, Indonesia, coastal zones are particularly vulnerable due to rapid urbanization, land subsidence, and

climate change impacts like rising sea levels. The Plumbon Estuary, for instance, has experienced significant shoreline erosion since the early 2000s. This shoreline erosion has proven to adversely impacted local communities, infrastructure, and ecosystems [2]. Several implementations of structural measures have been implemented to addressing wave abrasion and tidal erosion, however the shoreline changes still occur as the implemented measures could not effectively protect the shoreline. Studies addressing compound flooding events in coastal areas of Indonesia have gained attention which has been the focus of recent research on inundation hazards resulting from combined coastal and fluvial influences [3–5]. However, there isn't a lot studies addressing the evolution of shoreline changes attributed to the construction of coastal structures. Understanding how coastal structures influence shoreline evolution is critical for effective coastal management and resilience planning.

In summary, while there is a growing body of work on compound flooding in Indonesia, more comprehensive research is necessary to elucidate the effects of coastal infrastructure on shoreline changes in North Java. Such studies could provide valuable insights for policymakers and stakeholders involved in coastal management and disaster risk reduction strategies.

Van Rijn. L, 2011 in his paper shows there are several approaches to prevent further erosion in the shoreline, however without proper understanding of the coastal dynamics it could led to worsen the shoreline status [6]. The failure of coastal structures has been reported in previous studies. Such as, the failure of many coastal structures in Eastern Coast of Japan caused by wave overflow and scouring of the ground under the structures [7,8] and the failure of revetment on Hujeong Beach in South Korea [9]. The failure of coastal structures in Plumbon Estuary could also indicates the inappropriate coastal structure design that led to the further shoreline erosion.

Coastal area are highly dynamics in nature, they morphology are constinuously modified through natural processes or through human induced processes. Satellite data utilization has been proven to be effective in studying the shoreline change phenomena by several studies [10–12]. Several studies also utilized the satellite imagery data of shoreline changes to validate the hydrodynamic model [13,14]. Therefore, in this present study satellite imagery will be very helpful for understanding the impact of coastal structures development in Plumbon Estuary to the shoreline morphology dynamics.

We conduct field observations and satellite imagery analysis to examine the morphodynamics of the Plumbon Estuary shoreline before and after the construction of coastal structures. These structures were intended to mitigate further erosion but collapsed due to natural processes. A hydrodynamic model using Delft3D is also employed to better understand the erosion forces from dominant waves and tidal currents [15–17]. This enhanced understanding of morphodynamic processes in the Plumbon Estuary will be useful for more effective coastal management studies to prevent further erosion in the area.

Method

There are three steps on this research, first is study area characterization with satellite imagery analysis and field observations work, second step is hydrodynamic modelling of coastal process using secondary data, final stages is the verification of hydrodynamic model using satellite imagery and field observations.

Satellite imagery data has been extensively used in shoreline changes detection. Several studies have shown its effectiveness to characterize shoreline dynamics. Satellite images were collected from Google Earth with time windows 2002-2022 to analyzed the shoreline changes in the period of time. Besides to better understand the characteristics of the shoreline dynamics in study area a short field observation study also performed, but due to the limited time and high cost for data measurement the field observation study result is very limited.

There are a limited information from satellite imagery analysis and field observation, therefore to analyze the erosion forces in study area. Hydrodynamic modelling based on numerical simulation of Delft3D software is also performed to analyze the dominant wave and tidal currents effect. Several study has proven that Delft3D could simulate accurately the flow pattern and wave propagation in coastal area [15–17]. In this paper the case study will be modelled based on secondary data since the limitation of time and budget.

A verification of the model is important to indicates weather simulation are heading on the right direction. Therefore, the simulation result will be compared with several satellite data such satellite imagery and tides prediction also the simulation result will be compared with field observations data.

Results and Discussion

Satellite Imagery Analysis

Plumbon Estuary shoreline change through the natural and human induced process can be analyzed in geographic information system (GIS) by comparing the differences of shoreline locations in the past and the present. The analysis based on Google Earth imagery data collected from 2002 to 2022. Several studies has proven satellite imagery analysis to be efficient in understanding the characteristic of shoreline change process [9–11].

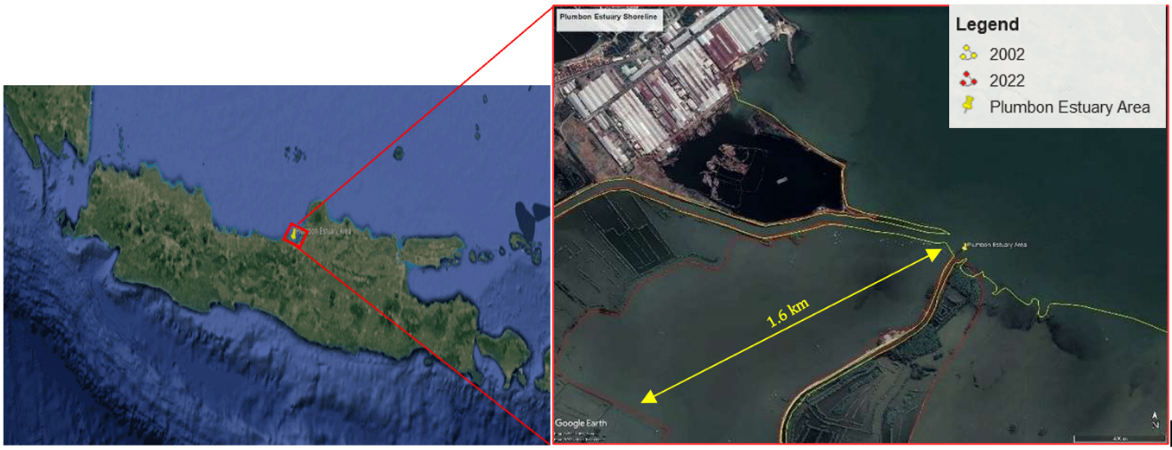


Figure 1. Plumbon Estuary Shoreline Change

Based on Google Earth imagery data from 2002 to 2022, the coastline has shifted approximately up to 1.6 km, as illustrated in Figure 1. This land degradation highlights significant changes in the Plumbon Estuary. Detailed time-series satellite imagery, as shown in Figure 2, illustrates the sedimentation and erosion processes affecting the estuary.

Based on satellite imagery, we observed that erosion intensified between 2008 until 2016. The intensified shoreline erosion is shown by the collapse of coastal structures by natural process, which led to sections of the river becoming part of the sea, exacerbating shoreline erosion. Between 2016 and 2018, the erosion became even more severe following the structural failures. In response, satellite imagery shown an efforts were made from 2018 to 2020 to restore and reinforce the coastal defences. The attempts to restore and reinforce the coastal structures tends to follow the layout of the structure as it was before its collapse in 2008. Unfortunately, this approach was not effective. The 2022 satellite imagery reveals that the structures failed once again, leading to further erosion in the area. Similar issues have been observed in Taiwan, specifically at Hsinchu Fishery Harbor, where studies have shown that morphological changes were primarily caused by the interaction of wave energy and coastal structures [18,19]. In the Plumbon Estuary, the repeated collapse of structures suggests a similar interaction between wave energy and coastal defences. To address this, wind data from the ECMWF ERA5 Reanalysis, spanning from 2004 to 2023, are being collected to determine the dominant wave conditions. The significant wave height and period are obtained through a hindcasting process, as referenced in [20] that also shows that satellite wind data performed quiet good for representing the condition in the field.

Figure 3 illustrates that in the study area, waves predominantly come from the east, accounting for over 37% of the annual wave activity. This dominant wave direction likely contributes to the ongoing erosion in the Plumbon Estuary River area, as the coastal structures were not designed to account for these eastward waves. In contrast, approximately 4 km to the west, Port Kendal, as shown in Figure 4, has coastal structures designed to account for wave patterns from the east. This highlights the importance of aligning structure design with prevailing wave conditions.

Figure 2. Detailed Time-Series Google Earth Image of Plumbon River Shoreline

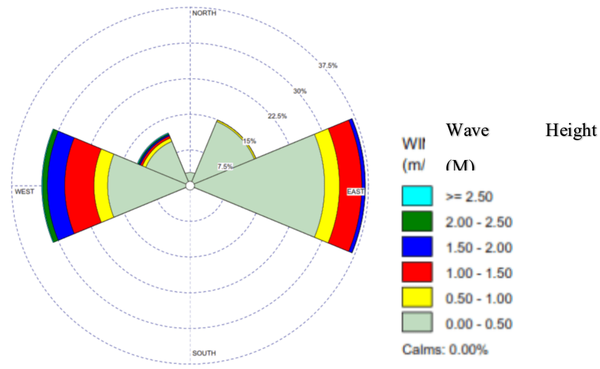
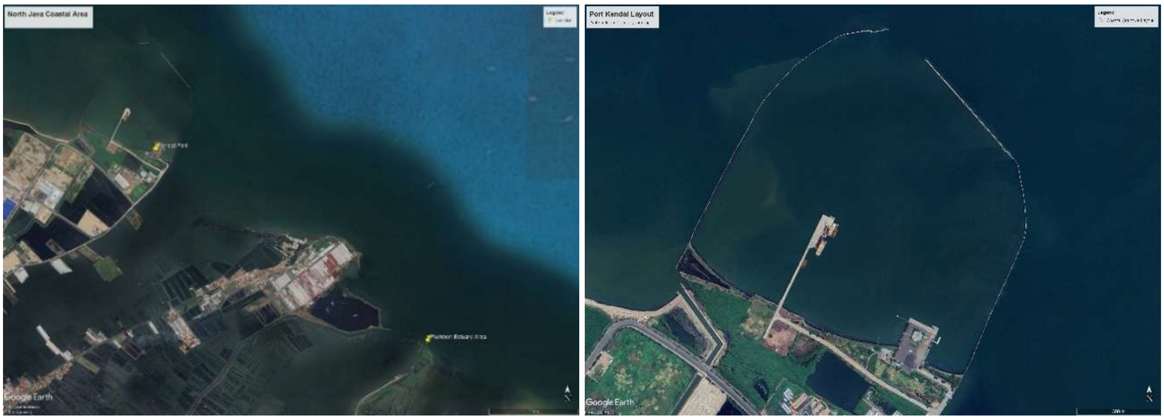


Figure 3. Waverose from Hindcasting Process Using ECMWF ERA5 Reanalysis Wind Data



(i) (ii)

Figure 4. Port Kendal Area position to Study Area (i) Coastal Structures Layout of Port Kendal (ii)

Hydrodynamic Modelling

To illustrate shoreline erosion caused by wave forces and tidal currents, this research also conduct numerical simulations using the Delft3D software. The simulation's geometry and boundary conditions are based on secondary data, with boundary conditions obtained from the Delft TPXO 7.2 Tide Database, and bathymetry generated from BATNAS data. The wave conditions in this numerical model are divided into two scenarios: one where waves are generated from the west and another where waves are generated from the east. These scenarios are based on the dominant wave directions in the study area, as shown in Figure 3.

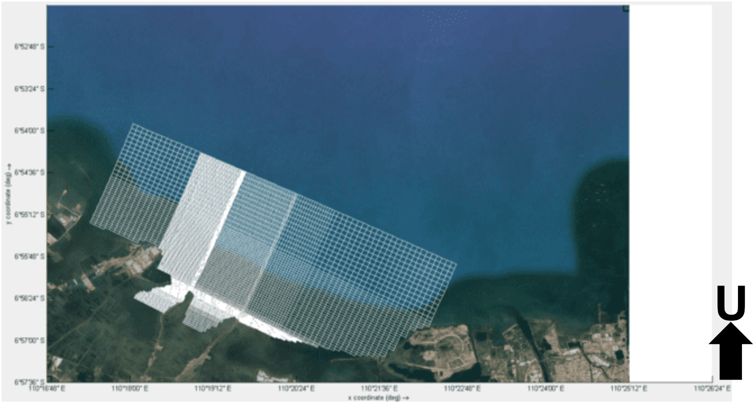
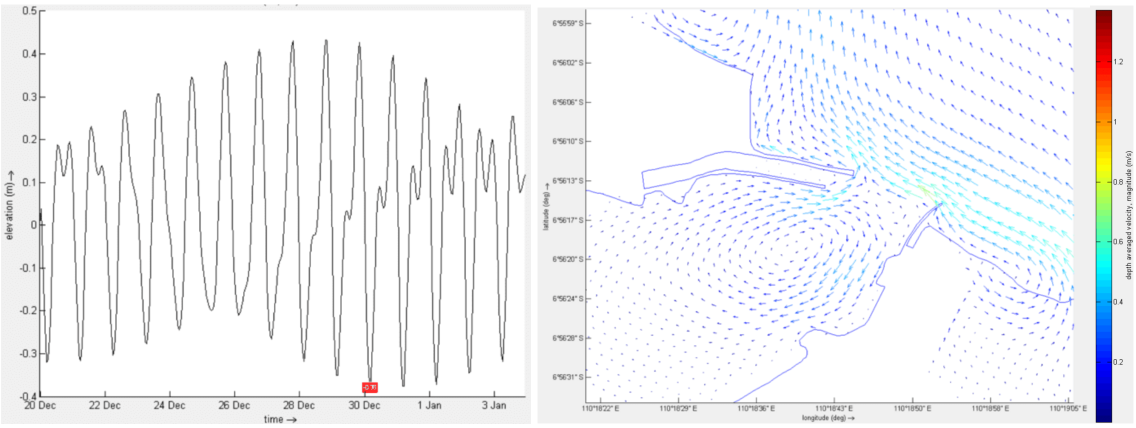


Figure 5. Hydrodyanamic model grid of Plumbon Estuary Area

Figure 5 shows the grid for numerical simulations to illustrate the tidal-wave current pattern in study area.



(i) (ii)

Figure 6. Flow pattern during low tides condition : Water Level Value (i) Flow Pattern on Plumbon Estuary Area (ii)

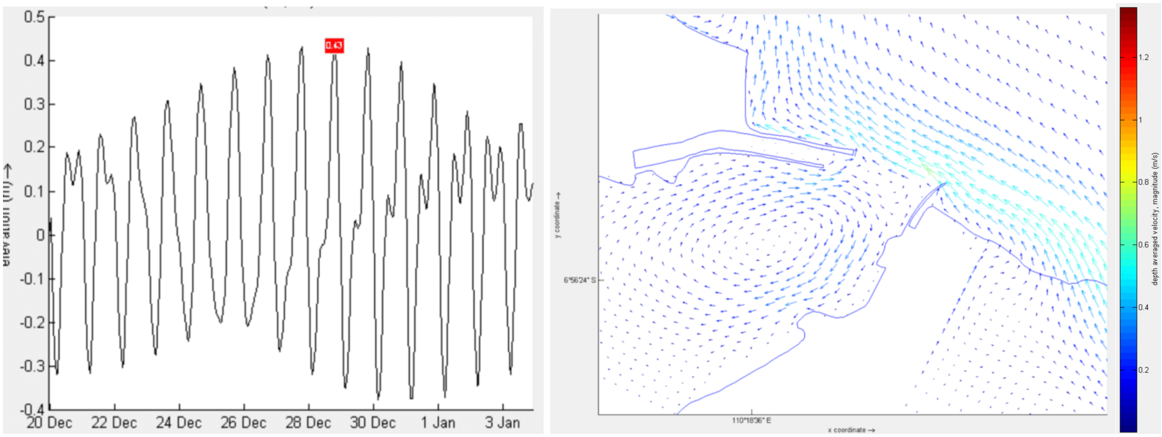


Figure 7. Flow Pattern during High Tides condition : Water Level value (i) Flow Pattern on Plumbon Estuary Area (ii)

Figure 6 and Figure 7 constantly shows that the flow pattern during the low tides and high tides are tends to create a vortices pattern around the coastal structure. These flow patterns could indicates that there is a possibility the failure of the coastal structure are caused by scouring at the landward toe of the coastal structures.

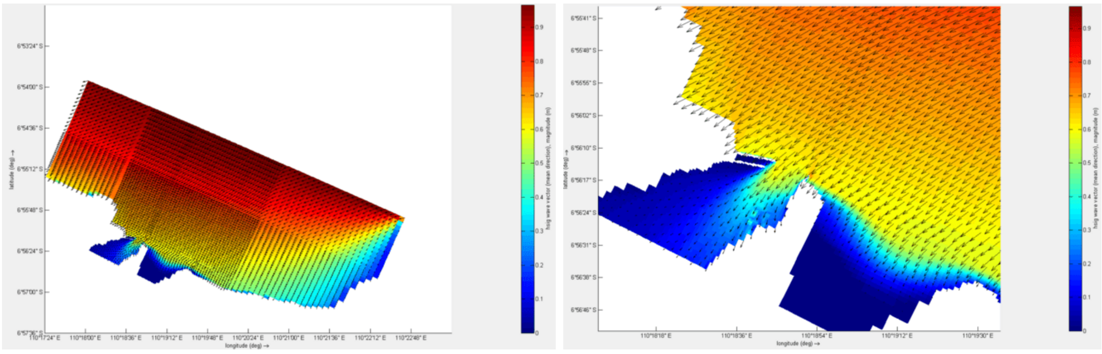


Figure 8. Easward wave propagation in the study area

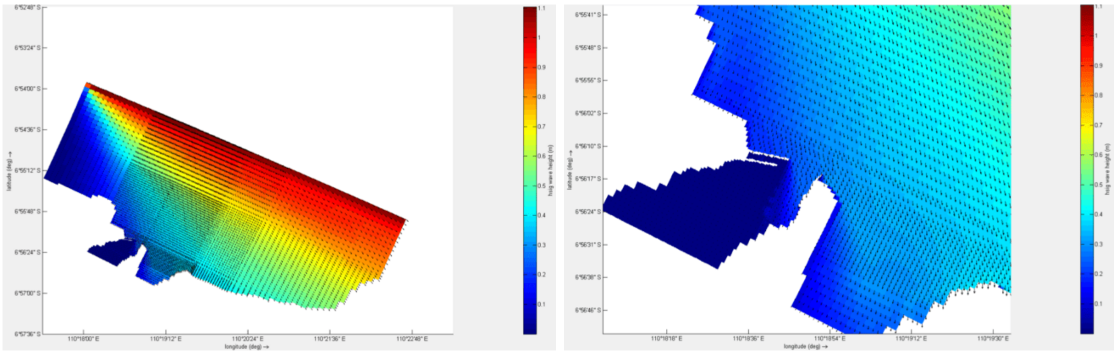


Figure 9. Westward wave propagataion in the study area

Figures 8 and 9 illustrate the propagation of eastward and westward waves. Numerical simulations show that the eastward wave does not dissipate over the bathymetry and propagates far inland. This indicates that the coastal structures are ineffective at reducing the impact of waves from the east, leading to shoreline erosion in the study area.

Field Observation

While satellite imagery provides a broad view of changes in the Plumbon Estuary, field observations are essential for understanding the specific factors behind the failure of coastal structures and characterizing shoreline dynamics in the study area.

On 3 august 2024, a field observation are conducted to get a more view of the condition in study area. Figure 10 shows the findings that confirm our hypothesis regarding shoreline changes in study area due to the development of the coastal structure back in 2020.

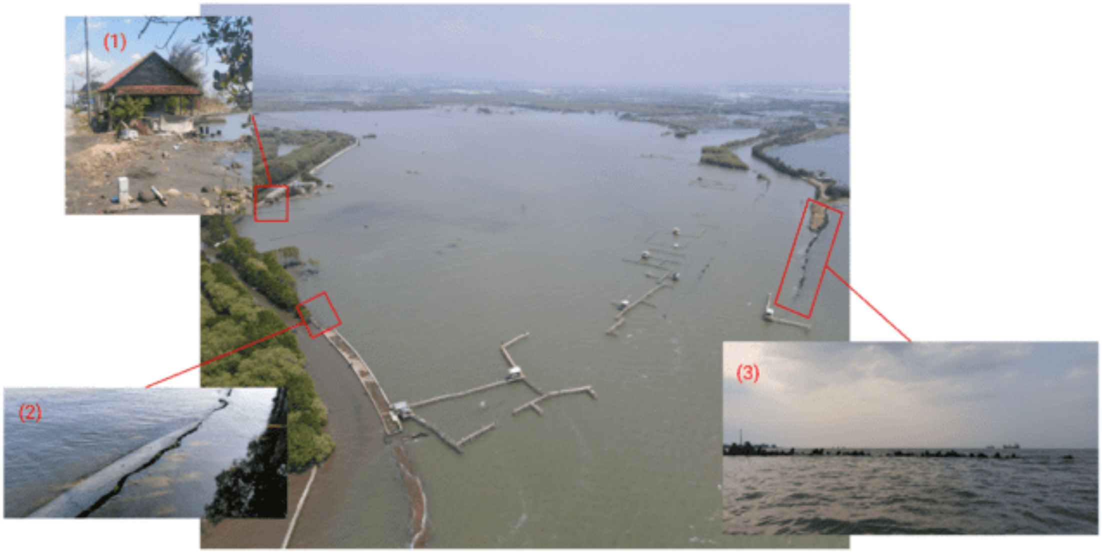


Figure 10. Field observation findings (1) Sand Sediment Accumulation Around the Area (2) Structural Failure of Coastal Structure (3)Ruins of coastal structures from 2022

Several findings in Figure 9 somewhat validate the hypothesis from the numerical simulation. Picture (1) in Figure 9 shows accumulated sand sedimentation, indicating that the wave propagated approximately 400 meters inland from the estuary mouth. Picture (2) shows structural failure, possibly caused by tidal wave currents that eroded and scoured the landward toe of the structure, as there is no visible toe protection. However, these observations are preliminary and require further in-depth study with primary data for confirmation.

Conclusion

In this study we presented the process of satellite imagery analysis and hydrodynamic modelling to do an assessment of Plumbon Estuary shoreline change due to the development of coastal structures. Satellite imagery shows that the coastal structure are collapsing by natural processes and then get restorated in 2020 and then the structure collapses again in 2022. Satellite Imagery and Hydrodynamic Modelling shows that the layout of the coastal structures does not take into account the eastward wave that led to the further erosion of the shoreline area in Plumbon Estuary. Several findings from field observations also confirms the hypothesis from hydrodynamic modelling of Plumbon Estuary Shoreline though it is a very robust.

Further erosion in Plumbon Estuary shoreline could negatively affect the coastal communities. The Findings from this study could help understanding better the shoreline change character in the Plumbon Estuary. Several studies have shown a positive result on utilizing building with nature in muddy coastal area to mitigate the shoreline erosion [21–23]. With the findings from this study it'll help in designing the implementation of building with nature to prevent further erosion in the study.

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