Geospatial modelling of coastal exposure index along the Madura Strait

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Abstract. The Madura Strait region is an area with high community activity and population density within East Java Province. This region is also known as the estuary of several major rivers, resulting in a relatively well-preserved mangrove ecosystem.This study aims to evaluate the impact of the mangrove ecosystem in the Madura Strait using the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) software. The analysis focused on the Coastal Exposure Index (CEI) under the scenarios with the prcenses od mangrove as habitats. The CEI results categorized the coastline into four vulnerability classes: Low, Moderate, High, and Critical. The results of this study indicate that the CEI categories in the Madura Strait primarily fall under the Low category, covering 324.51 km (48.98% of the total coastline length). The Critical and High categories span 117.97 km and 30.71 km, respectively, accounting for 17.81% and 4.64%. The regions with the highest vulnerability are Sidoarjo, Surabaya, Pamekasan, and Sampang. The primary factors influencing vulnerability in these areas are wave exposure and the elevation of the region. It is also noted that mangrove ecosystems play a significant role, with coastlines that have dense mangrove cover exhibiting relatively lower vulnerability levels.

1 Introduction

The Madura Strait is a region in East Java Province characterized by significant economic activity, largely due to its location in a densely populated area. It is situated at the confluence of two major rivers on the island of Java, the Bengawan Solo and Brantas rivers. These rivers deposit large amounts of sediment in the estuarine area, creating ideal conditions for the growth of mangrove ecosystems. The abundant sedimentation supports the establishment and development of mangrove forests. As a result, the local coastal communities in the Madura Strait are heavily dependent on the mangrove ecosystems for a range of ecological and economic services [1].

Mangrove are an important ecosystem in coastal areas that provide vital ecosystem services for the coastal environment, such as being breeding grounds for fish, carbon sink, filtering waste and sediment from the land, as well as protecting the coastline [2–4]. As one of the tropical forest ecosystems, mangroves have a complex structure that serves as a protector of coastlines from various phenomena such as abrasion and rising sea levels. Results from several previous studies indicate that areas located behind the mangrove

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ecosystem experience very little damage when coastal abrasion or storm phenomena occur at sea [5,6].

Climate change has emerged as a critical global issue in recent decades. Based on previous research using Global Mangrove Watch (GMW) data, mangrove in East Java Provinces tend to show an expansion in area coverages. The Madura Strait Region, particularly in Sampang Regency is frequently affected by flooding causing by the seawater or tidal flooding [7]. For island nations such as Indonesia, rising sea levels represent a substantial and immediate threat to both the environment and human settlements. [8,9]. The North Coast of Java (commonly referred to as Pantura) is a region highly susceptible to the impacts of sea-level rise and related threats. Presently, the Java Sea is experiencing an average sea-level rise of approximately 3.4 mm per year, indicating significant vulnerability to coastal flooding and erosion. [10]. Several studies have highlighted the high coastal vulnerability of major cities along the North Coast of Java, including Semarang, Pekalongan, and Jakarta. However, there is a relative lack of research on coastal vulnerability in the eastern region of East Java Province, particularly regarding the role of mangrove ecosystems. This study aims to address this gap by employing a geospatial modelling approach to assess the Coastal Exposure Index (CEI), incorporating the influence of mangrove ecosystems in the Madura Strait area.

2 Data and Methods

2.1 Study Location

This study was carried out in the Madura Strait, East Java, Indonesia (Figure 1). The region, which separates the Java mainland from Madura Island, is characterized by extensive mangrove ecosystems. According to the 2021 National Mangrove Map, the total mangrove area in this region covers 7,688.554 hectares. Analysis of historical data indicates a positive trend in mangrove expansion over the past two decades, with an average increase of 164 hectares per year [1,11]. The Madura Strait is a semi-enclosed body of water, with its eastern portion being notably wider than the western part. The western side of the strait is dominated by the large river estuaries of Java Island, including the Brantas and Bengawan Solo rivers.

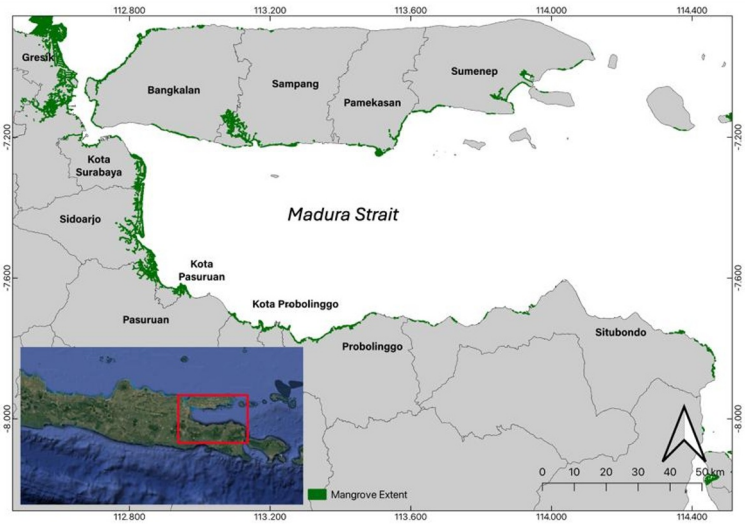

Fig. 1. Research Location of Madura Strait.

2.2 Data

This study utilizes several datasets as input for the model. Details of these datasets are presented in Table 1. The datasets will be processed using the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) software.

Table 1. Dataset that used for calculate CEI using InVEST Software

Variable	Source
Digital Elevation Model	Reference Body (Initials followed by last name)
Continental shelf	Natural Capital Project, 2016
Landmass	Topographic Maps of Indonesia (RBI)
Sea Level Rise	Marine Copernicus Data
Natural Habitats	National Mangrove Maps [12]
Bathymetry	Geospatial Information Agency (BIG)
Coastal Geomorphology	Visual Interpretation from Sentinel-2 Imagery
Wind Dataset	Natural Capital Project, 2016

In this study, the Digital Elevation Model (DEM) and bathymetry data were obtained from the National DEM provided by Indonesia's Geospatial Information Agency (BIG), accessible through https://tanahair.indonesia.go.id/portal-web/. The DEM dataset integrates multiple data sources, including IFSAR, TERRASAR-X, and ALOS PALSAR, offering a fine spatial resolution of 0.27 arcseconds. Meanwhile, the National Bathymetry Data (BATNAS) is derived from gravity anomaly inversion based on altimetry data, supplemented with bathymetric survey measurements from BIG. The BATNAS dataset provides a spatial resolution of 6 arcseconds, referenced to the Mean Sea Level (MSL) datum.

In this study, physical data related to sea level rise and coastal geomorphology were derived from satellite imagery analysis. Sea level rise (SLR) was estimated using Sea Level Anomaly (SLA) data sourced from the Copernicus Marine Service (CMEMS), utilizing the GLORYS12V1 dataset. This dataset offers a monthly temporal resolution and a spatial resolution of 0.25 degrees, and can be accessed through the https://data.marine.copernicus.eu/product/GLOBAL_MULTIYEAR_PHY_001_030/description. The estimation of SLR was based on a linear trend analysis of the time series data spanning from 1993 to 2023. The equation for calculated the linear trend was using by calculating the slope for the linear regression. Next for the Coastal geomorphology was assessed through visual interpretation of Sentinel-2 satellite imagery, supported by high-resolution datasets such as Google Earth. The interpretation was conducted along the entire coastline of the study area, providing detailed insights into the geomorphological characteristics of the coastal zone.

Regarding coastal habitats, the data used in this research is the mangrove ecosystem coverage in the Madura Strait area, sourced from the National Mangrove Map by the Ministry of Environment and Forestry (MoEF) [12]. The dataset was generated through the integration of multi-satellite imagery, including Landsat, Sentinel, and SPOT, to develop a standardized dataset for mapping mangrove ecosystems across Indonesia.

2.3 Method

In this study, the Coastal Variability index is derived from the Coastal Exposure Index (CEI), calculated using the InVEST software. This software facilitates the valuation and analysis of ecosystem services, integrating spatial data. One of its key modules focuses on Coastal Vulnerability assessment. Several datasets, listed as input parameters (Table 1), are used to compute the CEI based on the following equation:

$$CEI = \left(\prod_{i=1}^{n} R_i \right)^{\frac{1}{n}}$$

Where R represents the ranking of each parameter calculated based on Table 2. The CEI formula is a modified approach previously used for calculating physical parameters in determining the Coastal Vulnerability Index (CVI).

The CEI formula was calculated by the value of Rank (R) of each parameters. This equation was modified approach based on previously used for calculating physical paraemeters in determining the Coastal Vulnerability Index (CVI) [13]. The notation n in the equation refers to the number of parameters used, which explained in Table 2. Where in this research we used 6 parameters (Table 2). The notation in the equation indicates that the values of R for each parameter are multiplied together and then raised to the power of 1/n, representing the number parameter used. The result is the CEI value with a maximum calculation of 5.

Table 2. Dataset that used for calculating CEI using InVEST Software

Variable	Very Low (1)	Low (2)	Medium (3)	High (4)	Very High (5)
Digital Elevation Model	81 – 100 percentile	61 to 80 percentile	41 – 60 percentile	21 – 40 percentile	0 – 20 percentile
Wave exposure	0 – 20 percentile	21 – 40 percentile	41 – 60 percentile	61 to 80 percentile	81 – 100 percentile
Sea Level Rise	0 – 20 percentile	21 – 40 percentile	41 – 60 percentile	61 to 80 percentile	81 – 100 percentile
Natural Habitats	Coral reef, mangrove, coastal forest	High dune, marsh	Low dune	Seagrass, kelp	No habitat
Coastal Geomorphology	Rocky, high cliff, fjord, fiard, seawalls	Medium cliff, intended coast, bulkheads, small seawalls	Low cliff, glacial driff, alluvial plain, revertments, rip-rap walls	Cobble beach, estuary, lagoon, bluff	Barrier beach, sand beach, mud flat, delta
Surge potensial	0 – 20 percentile	21 – 40 percentile	41 – 60 percentile	61 to 80 percentile	81 – 100 percentile

The final CEI score was calculated using the weighted rankings of each parameter. This aggregated score was then classified into four categories based on quartile or Natural Break Point Method (25% percentile) distribution, resulting in the following classes: Critical, High, Moderate, and Low [14]. The subsequent analysis involved calculating the coastline length of each CEI class for each regency within the Madura Strait region. This process was performed using Quantum Geographic Information System (QGIS) and Python programming tools. To understand a complete description of each category can refer to Table 3 below.

Table 3. Description of each categories of CEI values

CEI Categories	Explanation
Critical	75 %> percentil of CEI value along Madura Strait. This categories means this location have the most exposure than other location based on CEI calculation. This location may have high exposure due and very vulnerable from the rising sea level, erotion, flooding, or any other phenomena.
High	50% – 75% percentile of CEI distribution. This categories means this location have the higher exposure than other averages CEI along the Madura Strait.
Moderate	25% - 50% percentile of CEI distribution. This categories means this location have the exposure slightly lower than averages along the location.
Low	<25% percentile of the CEI distribution. This categories means this location have the exposure is lower than other location. This could mean that the location is very safe due to its very low exposure values.

3 Result and Disscussion

The Coastal Exposure Index (CEI) for the Madura Strait coastline was assessed using a multi-parameter overlay analysis, incorporating data on Sea Level Rise (SLR), topographic relief, storm surge potential, wave action, and wind patterns. This overlay analysis produced CEI values, which were subsequently classified into four categories: Critical, High, Moderate, and Low. Overall, the CEI results provide an indicative measure of coastal vulnerability across the Madura Strait region. Figure 2 presents the weighted contribution of each input parameter used in the CEI calculation. Variations in the coastal color gradient illustrate the ranking of each parameter's influence in the assessment process. The findings reveal distinct value distributions across the parameters, highlighting their varying impacts in the vulnerability evaluation.

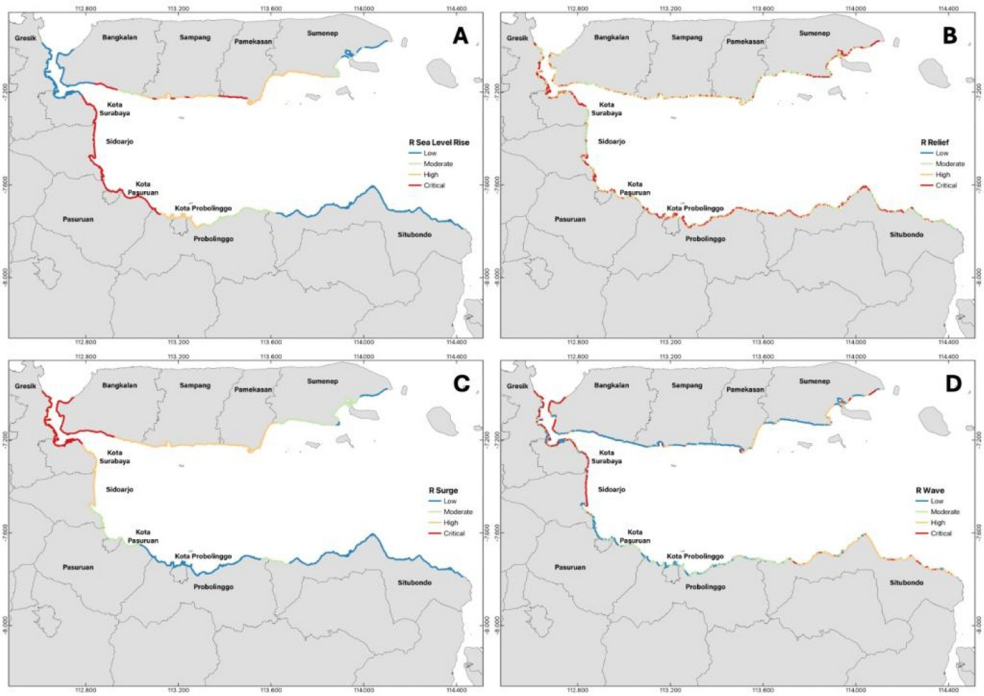

Fig. 2. Coastal Exposure Index (CEI) in Madura Strait. A) Sea Level Rise; B) Relief; C) Surge Potential; and D) Wave

The Sea Level Rise (SLR) parameter reveals that the areas with the highest risk (Critical) are located in Sidoarjo, Surabaya, and parts of Pamekasan (Figure 2A). The total coastline length classified as Critical is 318.17 km, which constitutes 42.61% of the overall coastline. The remaining categories each account for less than 20% of the total coastline in Madura Strait (Table 3). The overall rate of sea level rise in the Madura Strait, based on data analysis, is approximately 3.0 mm/year. This result aligns with previous studies, particularly in the Java Sea region, where the average sea level rise exceeds 3.2 mm/year [10]. Both regions are characterized by relatively low elevations around 0 – 5 m above sea level, rendering them highly vulnerable to the impacts of sea level rise. In contrast, areas categorized as Low and Moderate in terms of SLR are generally associated with gentler slopes.

Table 3. Dataset that use d for calculating CEI using InVEST Software

Class	**Length of Rank per Parameters (km)**				
	Wind	**Wave**	**Surge**	**SLR**	**Relief**
Critical	235.786	251.171	339.834	318.173	232.909
High	158.641	156.299	143.045	99.113	190.505
Moderate	188.541	186.157	118.039	157.984	178.223
Low	163.743	153.084	145.793	171.441	145.074
Total	**746.711**				

The relief parameter is an indicator derived from the slope gradient of the coastline. It is calculated using DEM (Digital Elevation Model) data, which is processed to determine slope values. The study area mainly consists of low slope gradients, leading to a large portion of the Relief parameter being classified as critical (Figure 2B). Several areas, including the

coastal regions of Surabaya, Probolinggo, Situbondo, and parts of Sumenep, fall under the critical category. The coastline length identified as critical based on the Relief parameter is approximately 232.90 km (31.19%). The High category covers about 190.50 km (25.51%). These results suggest that the Madura Strait region, based on slope gradient, is highly vulnerable with significant exposure risks.

The Madura Strait is a semi-enclosed region where wind and wave exposure tend to be relatively moderate. Analysis indicates that the western part of the strait experiences higher levels of exposure, likely due to its direct connection with the open waters of the Java Sea. In contrast, the southern coast of Madura Island generally faces lower wave exposure compared to the southern coast of Java. This is because the southern part of Madura is directly influenced by wind and currents from the open waters of the Bali Sea, located to the east of the island. Meanwhile, the northern coast of Madura Strait is more protected from wind and wave action originating from the south. For a detailed overview of coastline lengths categorized by wind exposure levels, refer to Table 3.

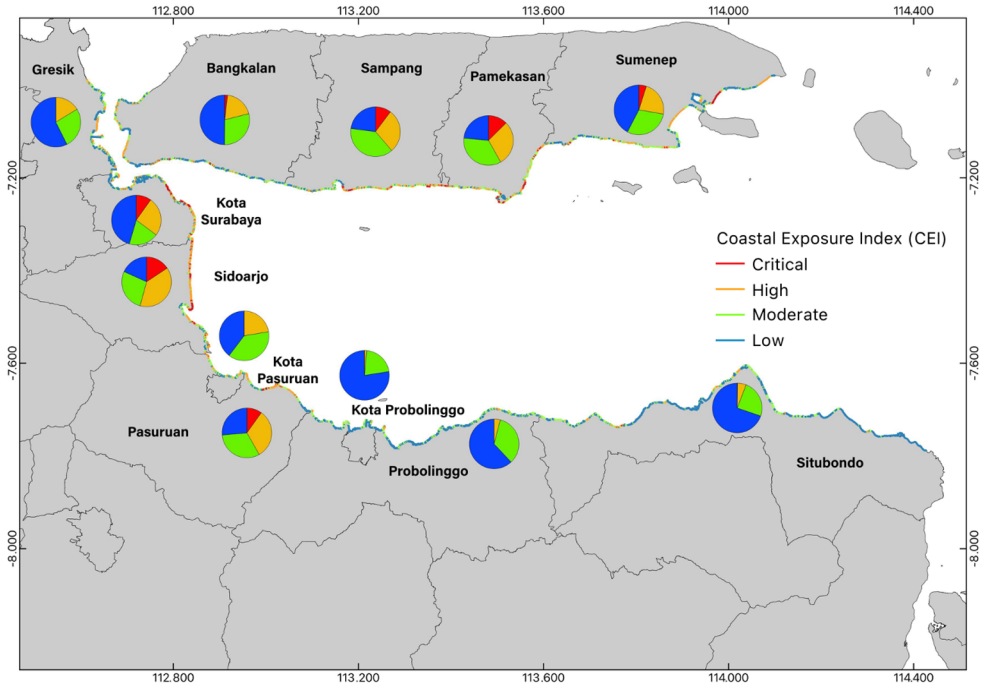

Fig. 3. Coastal Exposure Index (CEI) along the Madura Strait

Figure 3 presents the analysis of the Coastal Exposure Index (CEI) values along the Madura Strait coastline. The results indicate that the majority of the CEI categories in the Madura Strait fall within the Low category, covering 48.98% (324.51 km), followed by the Moderate category at 28.57% (189.27 km). The Critical category, however, only spans 30.71 km (4.64%). Generally, the Madura Strait is divided into two sections: the northern part (Southern of Madura Island) and the southern part (Northern of Java Island). The southern section, including the districts of Sidoarjo, Surabaya, and Pasuruan, predominantly exhibits Critical and High categories. Additionally, the northern districts of Sampang and Pamekasan also show relatively high proportions of Critical and High categories. In contrast, the eastern section, including the areas of Probolinggo and Situbondo, predominantly falls within the Low and Moderate categories.

A detailed analysis by district reveals that the longest stretch of the Critical category is found in Sidoarjo, covering 7.11 km, which constitutes 15.07% of its total coastline in Sidoarjo. This is followed by Surabaya and Pamekasan, with 6.36 km and 5.04 km, respectively, representing 9.9% and 12.6% of their total areas of each regency. In contrast, the longest stretches of the Low category are observed in Situbondo, covering 89.7 km (69.77%), and Sumenep, spanning 32.51 km (42.35%). A more detailed breakdown of the CEI category lengths for each district is provided in Table 4.

Table 4. Length of the CEI Class per Regency along the Madura Strait

Regency	CEI Class Length (km)			
	Critical	**High**	**Moderate**	**Low**
Bangkalan	1.172	12.076	18.267	31.394
Gresik		9.066	14.655	31.894
Kota Pasuruan		2.091	3.549	3.705
Kota Probolinggo		0.279	4.05	14.864
Kota Surabaya	6.361	16.242	12.424	29.19
Pamekasan	5.045	11.72	13.869	9.405
Pasuruan	2.837	9.17	9.136	7.57
Probolinggo		3.673	31.095	56.78
Sampang	4.145	11.436	15.469	9.22
Sidoarjo	7.113	17.458	12.453	8.26
Situbondo	0.287	7.261	31.324	89.719
Sumenep	3.758	17.503	22.987	32.517

The coastal area of the Madura Strait is a semi-enclosed region, offering significant protection from the open ocean. It serves as the estuary for several major rivers, leading to high sedimentation rates, especially in the western section [15]. This has led to healthy development of mangrove ecosystems in the region, with several areas demonstrating notable increases in mangrove coverage [1,16]. The results of this study also indicate that mangrove ecosystems play a significant role in reducing the Coastal Exposure Index (CEI) values in the Madura Strait region.

Sidoarjo and Surabaya districts exhibit the highest critical levels of the Coastal Exposure Index (CEI) among all assessed areas. Historically, these regions were part of the delta and estuarine system of the Brantas River Basin [17]. This leads to the region having lower and more gently sloping terrain. Furthermore, the impact of sea level rise in this area is likely to be more pronounced, resulting in higher vulnerability compared to the eastern side of the Madura Strait. Previous research also suggests that Surabaya City may face significant vulnerability if coastal urban planning is not effectively managed [18,19].

On the Madura Island side, the districts of Sampang and Pamekasan exhibit relatively high CEI levels. These regions are known to be prone to flooding during high tides or the rainy season [7,20]. Similar to Surabaya and Sidoarjo, both Sampang and Pamekasan have relatively low elevations, which contributes to their high vulnerability. Previous studies have shown that the elevation of a location is a critical parameter in determining the level of coastal vulnerability [21]. Areas with lower elevations tend to be more vulnerable compared to those with higher elevations.

The geospatial approach in this study aims to obtain a comprehensive assessment of coastal exposure conditions. The availability of Earth Observation data, whether from Remote Sensing Satellites, Modelling Approaches, or a combination or assimilation of several data sources, plays a critical role. Geospatial modelling in this study can provide an overview of the exposure conditions of an area based on the available data. However, this approach should ideally be supported by field verification, either for input data or for the outputs of the generated model. The results of this study show that geospatial modelling can provide a rapid assessment in calculating coastal vulnerability exposure values.

4 Conclusion

This study reveals that the majority of the Madura Strait region exhibits relatively low vulnerability levels. The areas with higher vulnerability include Sidoarjo, Surabaya, Sampang, and Pamekasan. The primary contributing factors to vulnerability in these regions are elevation and wave exposure. Furthermore, the presence of mangrove ecosystems plays a crucial role in mitigating coastal vulnerability. It is recommended that further research be conducted to better understand the extent to which mangrove ecosystems in the Madura Strait act as protective buffers for the coastal zone.

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