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Assessment of coastal vulnerability to support mangrove restoration in the northern coast of Java, Indonesia

Phidju Marrin Sagala [a,*], Rupesh K. Bhomia [a], Daniel Murdiyarso [a,b]

[a] *Center for International Forestry Research – World Agroforestry, Jl. CIFOR, Situgede, Bogor 16115, Indonesia*
[b] *Department of Geophysics and Meteorology, IPB University, Bogor 16680, Indonesia*

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ABSTRACT

The northern coast of Java has been more severely affected by sea level rise (SLR) than other islands in the Indonesian archipelago. This warrants a coastal area risk assessment to ascertain the multiple hazards that could impact on this densely populated island. Using environmental and physical variables – including geomorphology, rate of shoreline change, sea level rise, wave height, coastal slope, bathymetry, tidal range, and mangrove density – the main objective of this study is to determine a coastal vulnerability index (CVI) and mangrove vulnerability index (MVI) in the northern Javanese coastline. Assessment was carried out for three regencies – Banten, Demak, and Banyuwangi regency – with the goal of helping to identify areas where mangrove restoration efforts can be prioritized. Using line and 1×1 km^2 grid representation of the entire coastline, the research found that in terms of CVI, Demak coast is most vulnerable (with 82% of grids and 89% of coastline falling into the highly vulnerable categories), Banten coast ranked as moderately vulnerable (43% of grids and 35% of coastline fall into the moderately vulnerable categories), while 91% of grids and 93% of coastline in Banyuwangi fall into the least vulnerable category. Assessment of mangrove vulnerability revealed that Banten and Banyuwangi regency were low vulnerability as respectively, 100% and 94% of grids fell into this category, while Demak coast was highly vulnerable (with 46% of grids falling into highly vulnerable categories). This vulnerability mapping provides useful information to assist planners and managers to deploy resources for mangrove restoration and the long-term sustainable management of these coastal ecosystems.

1. Introduction

Global climate change and its unprecedented impacts can be attributed directly or indirectly to human activity (Intergovernmental Panel on Climate Change (IPCC), 2007) leading to changes in weather patterns, alteration in habitat conditions, loss of biodiversity (Ahmed et al., 2022a, 2022b) and significant disruptions for human society. As a result of interactions between terrestrial and marine systems, climate change impacts are expected to be especially severe in low-lying coastal areas where sea level rise (SLR) and increasing severity of extreme weather events such as heavy precipitation, cyclones/hurricanes, storm surges, and floods (EEA, 2017) are causing severe losses. These coastal areas and their communities are vulnerable to natural hazards due to their proximity to the sea, high population density, and dependence on coastal resources for livelihoods (Ashraful Islam et al., 2016; Sahoo and Bhaskaran, 2018). The growing risks of coastal hazards necessitates deployment of expensive coastal protection measures, planned relocation or climate-related migration (IPCC, 2023). The Indonesian Island of Java – home to more than 140 million (BPS, 2021), 56% of Indonesia's total population (Jones, 2013) – has been experiencing climate change impacts particularly on its northern coast (Ministry of Environment and Forestry Indonesia (MoEF), 2020).

The north coast of Java is highly vulnerable to sea level rise because of land subsidence at the worrying level (Susilo et al., 2023), caused by groundwater and natural gas extraction (Van Wesenbeeck et al., 2015; Lo et al., 2022). Dewi (2019), Sugianto et al. (2022), and Triana et al. (2023), reveal an area of high erosion-sedimentation in Cirebon, Demak, Semarang City in Central Java, with land subsiding at a rate of 1–20 cm annually (Yuwono et al., 2019; Widada et al., 2020). The alluvial deposits which make up Java's north coast stretching from Serang Banten to Situbondo East Java (Ongkosongo, 1979), consist of sediment that naturally compacted over time that can be measured by coastal change such as erosion and accretion. The presence of infrastructure accelerated the process of land compaction beyond natural conditions, resulting in

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* Corresponding author.
E-mail address: p.sagala@cifor-icraf.org (P.M. Sagala).

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land subsidence in the affected area. The compaction process was a natural occurrence in areas made up of clay and silt alluvial deposits. This also indicated that the alluvial deposition process was a significant contributor to land subsidence (Widada et al., 2020). Furthermore, excessive groundwater pumping in this industrial area has contributed to higher rate of land subsidence compared to other regions, for instance, Sarah et al. (2022) revealed a significant increasing groundwater extraction at the rate of 3.37 mln $m^3 \bullet y^{-1}$ from 1990–2006.

This increasing coastal vulnerability has coincided with a loss of mangrove cover along the northern Javanese coastal region (Maryantika and Lin, 2017; Nugraha et al., 2019; Irsadi et al., 2019). Mangroves are an important component of coastal sustainability, offering extensive services (provisioning, regulating, supportive, and cultural), and additional benefits for climate mitigation and biodiversity. Yet mangroves remain under threat in Indonesia due to deforestation, with mangrove losses accounting for approximately 6% of total forest loss in Indonesia (Murdiyarso et al., 2015). Aquaculture remains the biggest driver of mangrove loss in Southeast Asia (Richards and Friess, 2016), leading to an average 83% reduction in biomass and a 52% reduction in soil carbon (Sasmito et al., 2019).

Various vulnerability assessment tools are employed to support climate risk management and adaptation. These include videotape-assisted vulnerability analysis (AVVA), a quick and low-cost approach to meet data gaps in coastal areas (Coelho, 2005); the coastal zone simulation model (COSMO) (CZMC and Resource Analysis, 1994); and index-based methodologies, developed as a rapid and consistent way to characterize the relative vulnerability of the coast. Index-based approaches are preferred as they support the integration and combination of multiple variables, capturing various levels and dimensions of vulnerability. The coastal vulnerability index (CVI) approach (Gornitz, 1991) combines factors representing geological and physical processes into a single index, depending on the analytical goals and the unique characteristics of coastal areas (Ashraful Islam et al., 2016; Sahoo and Bhaskaran, 2018; Hoque et al., 2019; Jana, 2020). This approach has also been expanded to include variables like mangrove density, to determine a mangrove vulnerability index (MVI) (Mondal et al., 2022) alongside CVI, by utilizing semi-quantitative techniques (Ashraful Islam et al., 2016; Mahmood et al., 2020).

Despite the fact that the northern Javanese coast is more vulnerable to coastal hazards, coastal vulnerability assessment for this area has been limited (Ondara and Rahmawan, 2020) and no study has done a mangrove vulnerability assessment. To fill this gap, this study was aimed to develop vulnerability indices based on coastal and mangrove attributes. This subnational scale assessment aims to support decision makers and coastal managers by providing them with a broader vulnerability picture of the northern coast of Java as a whole, as well as the vulnerability of each of its coastal regencies. The main objectives of this study were to i) predefine the extent to which each variable contributes to the vulnerability index in the study area, and ii) provide an overall coastal and mangrove vulnerability outcome. Together, the CVI and MVI provide a uniform approach by which vulnerability maps can be generated; these can help to prioritize risk management measures and adaptation strategies, targeting the most vulnerable areas.

2. Methods

2.1. Delineating study sites

Assessment of coastal vulnerability was carried out in three regencies in the northern coast of Java – Banten, Demak, and Banyuwangi (Fig. 1).

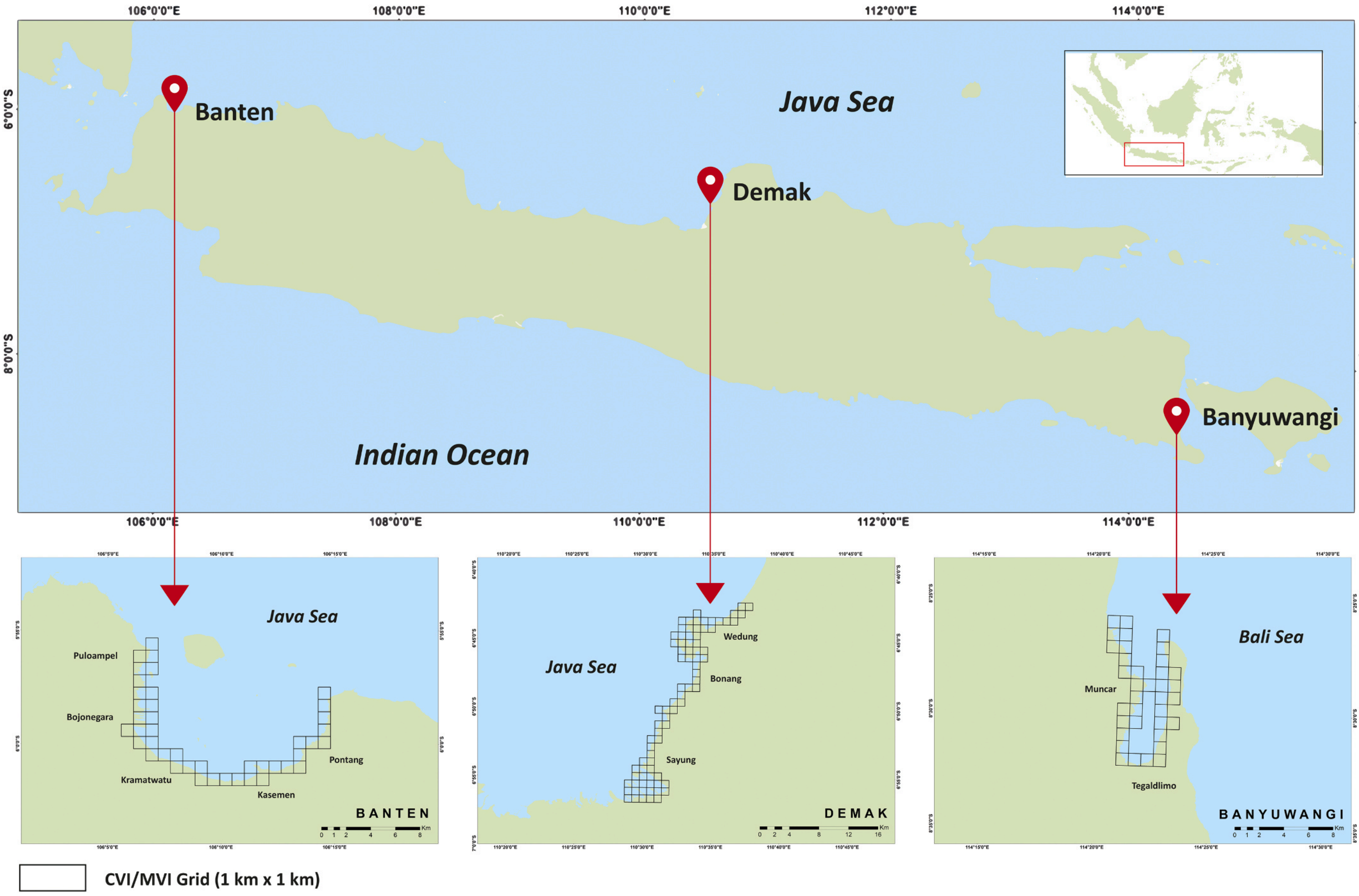

Fig. 1. Map of the study area showing the coasts of Banten, Demak, and Banyuwangi regencies. The 1 × 1 km^2 grid size was created using ArcMap 10.6.

Banten's shoreline spans 19.95 km; while Demak's shoreline is 102.94 km, and Banyuwangi is 37.03 km; population density in each location is 2456 (BPS Serang, 2020a), 1291 (BPS Demak, 2020b), and 302 people/km^2 respectively (BPS Banyuwangi, 2020c). Most of the study area is characterized by its low elevation, 0–30 m above mean sea level. All of these sites have a tidal plain with muddy relief; Demak regency is also crisscrossed by numerous streams, especially in Wedung district.

The northern coast of Java experiences a tropical monsoon climate, with annual rainfall ranging between 2000–2500 mm (Nugroho, 2016). For low-lying coastal zones crisscrossed by rivers, creeks and canals, coastal flooding is common due to extreme storm conditions, rising sea levels (Sofian, 2010; Suroso and Firman, 2018) and land subsidence (Erkens et al., 2015; Sarah and Soebowo, 2018). Between 1990 and 2020, relative humidity in the zone ranged between 72.69–86.06%, wind speed was 1.12–2.51 m/s, and surface pressure was 99.29–100.62 kPa (Table S1). Annual rainfall (Table S1) at each site is classified as high, with an average of > 2000 mm (Nugroho, 2016).

Geologically, the northern coast of Java has formed through deposits of sediment or alluvial plain, which consists of unconsolidated clay, silt, sand, and gravel of quaternary age (Bemmelen, 1949). Coastal erosion of this compounded sediment results in increased environmental risk and vulnerability for cities along this coastline. These threats are worsening due to mangrove conversion for aquaculture and/or settlements; Hartanto and Rachmawati (2017) reveal that between 2000 and 2014, in Wedung district (Demak regency) mangrove forest decreased by 79% while human settlements doubled.

2.2. Data processing and analysis

This study followed a similar methodological framework as suggested by Mondal et al. (2022) in which seven variables are used to create a coastal vulnerability index (CVI). These variables include geomorphology, rate of shoreline change, rate of sea level rise, significant wave height, coastal slope, bathymetry, and mean tidal range, while an additional variable – mangrove density – has been used to produce a mangrove vulnerability index (MVI) (Table 1) using semi-quantitative technique that had been developed to calculate the index (Ashraful Islam et al., 2016; Sahoo and Bhaskaran, 2018; Hoque et al., 2019; Jana, 2020; Mondal et al., 2022). This involved categorization of all parameters into five classes using natural breaks, and then resampling categorized data into grids (with a grid size of 1 km by 1 km), which were then assigned vulnerability ranks.

ArcGIS software was used for shoreline extraction, grid generation, and developing CVI and MVI. A total of 155 grids and 209 km of coastal length in Banten, Demak, and Banyuwangi regencies were taken for 2020, to serve as a baseline from which to assess the risk for each grid, based on each variable. The ranking (or score) for each variable for every grid was then combined to determine risk value for that grip and used to derive an overall CVI and MVI for each of the three studied sites. This research following the methodological framework (Fig. S1) proposed by Mondal et al. (2022) but do not use the regional elevation parameter, instead we use coastal slope.

Geomorphology data was obtained from the Center for Geological Survey of the Ministry of Energy and Mineral Resources of Indonesia (https://geologi.esdm.go.id/). An on-screen digitization method (Islam et al., 2016; Hoque et al., 2019) was used to delineate geomorphic zones in the coastal region of each study area and resampled into grid of 1 km along the coast. The predominant geomorphological features of these dynamic deltaic zones were sand beaches, salt marshes, mud flats, and deltas.

Shoreline change was determined from Landsat 5 TM/MSS, Landsat 7 ETM, and Landsat 8 OLI/TIRS data that was downloaded from the United States Geological Survey website (https://earthexplorer.usgs.gov/). Change was calculated based on shoreline records from 2000 and 2020 (Luijendijk et al., 2018). The Digital Shoreline Analysis System (DSAS) tool of ArcGIS was used to calculate the digitized shoreline records. The DSAS calculated rate-of-change statistics for the time series using the measurement baseline method (Leatherman and Clow, 1983). Transects of the shoreline were cast by the DSAS application, using the baseline as their starting point. Transects were positioned at 5 m intervals along the shoreline stretch. The End-Point Rate (EPR) technique was then used to determine shoreline change (m/yr) and calculate the rate of shoreline change over time. The EPR results were displayed, indicating accretion or erosion rates by representing positive or negative values resulting from natural processes.

Rate of sea level rise data was obtained from the satellite image of Altimeter TOPEX/POSEIDON and Jason 1–3 (www.star.nesdis.noaa.gov). Changes in sea level could result in morphological changes to the coast and lead to coastal degradation. Areas experiencing high rates of sea level change were considered highly vulnerable.

Significant wave height was extracted for 2000–2020 from the European Centre for Medium Range Weather Forecast (ECMWF) Interim data (ERA5). Significant wave height is a proxy for wave energy and a significant variable in assessing coastal vulnerability because it influences coastal erosion by driving the transport of sediments (Gaki-Papanastassiou et al., 2010).

Coastal slope was derived from the National Digital Elevation Model for Coastal Application (DEMNAS) with a spatial resolution of 0.27″ (https://tanahair.indonesia.go.id/). This included IFSAR data (resolution 5 m), TERRASAR-X (resolution 5 m), and ALOS PALSAR (11.25 m) and was calculated using spatial analyst tools in ArcGIS software. Five rankings were assigned based on the natural breaks' method. The coastal slope was calculated using Eq. 1, referred to in the United States Army Core of Engineers (United States Army Corps of Engineers (USACE), 2003).

Table 1
Vulnerability rank of all variables.

No.	Variables (units)	Vulnerability ranking				
		Very low 1	Low 2	Moderate 3	High 4	Very high 5
1.	Geomorphology (qualitative feature)	Rocky, cliffed coast	Medium cliffs, indented coasts	Low cliffs, lateritic plain	River deposits, alluvial plain	Coastal plain, beach, mud flats, mangroves
2.	Shoreline erosion/accretion (m/year)	> 2.00	1.00 – 2.00	(−1.0) – 1.0	(−2.0) – (−1.0)	< (−2.00)
3.	Coastal slope (degrees)	Cliffed coast (> 45)	Steep slopes (>20.1-45)	Moderate slopes (10.1-20.0)	Gentle slopes (6.1-10.0)	Low plains (0.0-6.0)
4.	Rate of sea level rise (mm/yr)	< 3.0	-	-	> 3.0	-
5.	Significant wave height (m)	< 0.55	0.55 – 0.85	0.85 – 1.05	1.05 – 1.25	> 1.25
6.	Mean tidal range (m)	> 4.0	2.0 – 4.0	1.0 - 2.0	0.5 – 1.0	< 0.5
7.	Bathymetry (m)	(-) < 15.70	(-) 9.53 to (-) 15.69	(-) 5.89 to (-) 9.53	(-) 2.95 to (-) 5.88	> (-) 2.94
8.	Mangrove density (area in %)	0.00-9.17	9.18-28.27	28.28-48.14	48.15-71.45	71.46-97.44
	Vulnerability ranking		**Low**	**Moderate**	**High**	**Very high**
	CVI	-	0.00 - 11.95	11.96-23.90	23.91-35.85	35.86-47.80
	MVI	-	0.00 - 20.00	20.01-40.00	40.01-60.00	60.01-80.00

$$\tan\beta = \frac{d}{m} \quad (1)$$

where:

d= water depth (m).

m= distance from shoreline to depth d (m).

β = beach slope (°).

Bathymetry data was obtained from Batimetri Nasional (BATNAS), at a 6″ resolution (Fig. S7); this was resampled to 1 km (http://batnas.big.go.id/). This study assumed that nearshore areas with gentle slopes were highly vulnerable, and the further away from the coast with steeper slopes, the less vulnerable the area will become. In terms of vulnerability ranking, coastlines with shallow depths were ranked 5, while those with deeper depths were ranked 1.

Mean tidal range data for 2000–2020 was acquired from the Geospatial Information Agency (https://tides.big.go.id/). Based on previous research (Dwarakish, 2008; Mujabar and Chandrasekar, 2013; Gorokhovich et al., 2013), this study adopted the notion that a higher mean tide range results in lower coastal vulnerability.

Mangrove density used Landsat-8 OLI data (https://earthexplorer.usgs.gov/) for all study areas and was determined through a two-step process. First, the mangrove and non-mangrove vegetation identification was based on data extracted from the 564-composite Landsat 8 OLI images and produced raster data containing mangrove and non-mangrove pixel/grid values and revealed that mangroves were located in the land-sea transitional zones along Banten, Demak, and Banyuwangi coast. Supervised classification was applied to interpret and group the mangrove pixel values, then compare these with the true-color RGB image to produce more accurate results.

Then zonal statistics and a raster calculator in ArcGIS software was used to calculate the percentage of mangrove area in each grid (1 km x 1 km). Grids with higher mangrove density were ranked as more vulnerable (rank 5), because of the greater potential for mangrove loss compared to areas with no mangrove.

2.3. CVI and MVI calculations

A semi-quantitative technique using seven variables (Table 1) was used to calculate the CVI (Ashraful Islam et al., 2016; Mahmood et al., 2020) and then by including the mangrove density variable, the MVI (Mondal et al., 2022). This was achieved by ranking each variable separately and then calculating the CVI and MVI using the square root of all variables. The resulting numerical data could not be directly correlated with specific physical effects, but it effectively identified areas where coastal vulnerability was likely to be the greatest. The final CVI and MVI for each grid along the Banten, Demak, and Banyuwangi coast were then divided into four ranks of vulnerability, ranging from low to very high, based on quartile classification techniques. This gave specific index values for each grid, as well as a vulnerability classification for each length of the coast, according to the magnitude of the specific grid index values combined. This study tackling geophysical vulnerabilities are mostly adapted from Gornitz (1991) and all the required data have been stored and manipulated within a geographic information system.

$$\text{CVI} = \sqrt{((a*b*c*d*e*f*g)/7)} \quad (2)$$

$$\text{MVI} = \sqrt{((a*b*c*d*e*f*g*h)/8)} \quad (3)$$

where, a = geomorphology, b = rate of shoreline change, c = rate of sea level rise, d = significant wave height, e = coastal slope, f = bathymetry, g = mean tidal range, h = mangrove density.

After ranks were assigned to each variable of each grid and coastal length separately, the composite CVI and MVI value was calculated and compared for all coastal stretches under study. Subsequently, the vulnerability categories were represented with percentile ranges as 0–25%, 25–50%, 50–75%, and 75–100% (Thieler and Hammar-Klose, 2000). In other words, a value of 1 represents the lowest vulnerability and a value of 4 represents the highest vulnerability. Once the MVI was complete, it was then possible to analyze the proposed afforestation and restoration zone goal estimates, following the methodology by Mondal et al. (2022). Based on the result, this research concluded that restoration policies should be prioritized in areas the MVI values rank as being moderately to very highly vulnerable, while areas ranked as being low to very low in vulnerability should be proposed as afforestation areas.

3. Results

3.1. Coastal vulnerability index (CVI)

Based on the calculated CVI for the northern coast of Java (Table 2), Demak Regency had the largest percentage of area classed as high and very high vulnerability; 64 (82%) out of 78 grids (64 km^2) were classed as highly vulnerable. A positive correlation with these grid values was found when examining vulnerability across total coastal length; about 98.33 km (approximately 89%) of this regency's coast was classed as highly vulnerable. Two districts – Wedung and Kedung – were particularly vulnerable; 10.77 km of coastline length and 13 grids in these areas were classed as very highly vulnerable. In contrast, the majority of the grids in Banten Regency were classified as moderate or low vulnerability; there was no significant difference seen between both of these categories, while in terms of coastline length, just over half of the coastline length (57%) – 31.92 km – was classed as low vulnerability; 19.88% was classed as moderately vulnerable and only 4% was highly vulnerable. A possible explanation for this might be the presence of Pulau Dua Nature Reserve, as well as reclamation areas in the district of Bojonegara and Puloampel (Fig. 1) in Banten Regency. No areas were classified as high or very high vulnerability in Banyuwangi Regency. Here, 32 out of a total 35 grids (32 km^2) – 91% of the study area – were classed as low vulnerability; while roughly 40.19 km of coastline length (93%) in this regency was also classed as low vulnerability. This result could be due to the steep slopes of its topography and low erosion rates, resulting in low vulnerability zones.

Overall, these results provide important insights into coastal vulnerability of northern coast of Java. The estimated minimum value of CVI calculated for the case study was 5.2, while the maximum value was 47.8 – the higher the value of CVI, the more vulnerable the area is. Sorted from the most to the least vulnerable, Demak Regency had the highest coastal vulnerability as it was dominated by high vulnerability

Table 2
Coastal Vulnerability Index for the studied sites along the northern coast of Java.

Study area	Parameters (units)	CVI ranking			
		Low	Moderate	High	Very high
Banten Regency	*No. of grids*	18	18	6	0
	Area (km^2)	18	18	6	0
	Area percentage (%)	42.86	42.86	14.29	0
	Coastline length (km)	31.92	19.88	4.46	0
	Coastline length percentage (%)	56.73	35.34	7.93	0
Demak Regency	*No. of grids*	0	1	64	13
	Area (km^2)	0	1	64	13
	Area Percentage (%)	0	1.28	82.05	16.67
	Coastline length (km)	0	1.2	98.33	10.77
	Coastline length percentage (%)	0	1.08	89.15	9.77
Banyuwangi Regency	*No. of grids*	32	3	0	0
	Area (km^2)	32	3	0	0
	Area Percentage (%)	91.43	8.57	0	0
	Coastline length (km)	40.19	2.74	0	0
	Coastline length percentage (%)	93.62	6.38	0	0

areas; this was followed by Banten Regency, which was moderately vulnerable overall, and Banyuwangi Regency, which was the least vulnerable, based on the CVI calculations (Table S2).

3.2. Variables influencing the CVI

Results from this preliminary CVI analysis were compared across each of the seven variables which were analyzed to determine the contribution of each variable to coastal vulnerability at the examined sites. This information is important in understanding the specific conditions that might be contributing to the sites' vulnerability levels and could help in planning management actions to reduce these risks.

CVI and MVI were calculated by assigning equal weight to each of these variables into three different areas. For instance, the shoreline change value: if the value is negative, then the area experiences erosion (with a vulnerability ranking of moderate, high, and very high), while a positive value indicates accretion (with a vulnerability ranking of very low and low). All variables presented in Table 1 were applied to different sites. Remarkably, the different sites showed different CVI values range (Table S2); for example, in Demak regency, the CVI value reached 48 because the majority of the variable values were in the high and very high categories (4 and 5), while in Banyuwangi the CVI value was composed of variables in very low and low categories (1 and 2). The variables can change over time, which was why some locations may rank higher on one metric but low on others.

3.2.1. Geomorphology

Analysis of geomorphology showed that 60.87% (34.25 km) of the total length of the Banten coast (approximately 56.27 km) was ranked as moderate vulnerability, with vulnerable areas located mainly in the western part of the study site (the district of Bojonegara and Puloampel) which was subject to anthropogenic pressures due to industrial development. The remaining 37% (20.74 km) of the Banten coast was in the high to very high vulnerability category, and about 2% (1.27 km) was classed as low vulnerability. In comparison, results for the Demak coastline, with a total length of 110.30 km, depicted that 82% (89.98 km) was geomorphologically very high vulnerability and about 18% (20.31 km) was highly vulnerable. Meanwhile, the results for Banyuwangi coast with a total length of 42.94 km showed that 86% (36.75 km) was high to very high vulnerability and about 14% (6.18 km) was moderately vulnerable.

Out of the 42 grids in Banten regency, 18 grids or 18 km^2 (43%) were moderately vulnerable, while 60 out of 78 grids in Demak regency, 60 km^2 (76.9%) were very high vulnerability. In Banyuwangi, very high vulnerability ranking was dominant; results showed that 22 of 35 grids or 22 km^2 (63%) were categorized at this level. Overall, the Banten and Demak coasts have been eroded due to land use change and sea water intrusion and the geomorphological form consists of sandy coastal plains and alluvial plains (Fig. S2), while the Banyuwangi coast experienced accretion due to large sediment loads from upstream drained by tidal creeks and channels (Fig. S2).

3.2.2. Rate of shoreline change

Between years 2000 and 2020, the whole study area was dominated by erosion (Fig. S3). Coastal Banten, Demak, and Banyuwangi regencies experienced an average rate of shoreline change of − 2.21 m/yr, − 8.96 m/yr, and + 0.36 m/yr respectively. Furthermore, the maximum rate of erosion for Banten, Demak, and Banyuwangi regencies was − 52.78 m/yr, − 153.9 m/yr, and − 28.23 m/yr, and the accretion rate was + 40.38 m/yr, + 116.78 m/yr, and + 50.34 m/yr respectively. Most of the Demak coast (86%) experienced negative shoreline change (<0 m/yr), putting it into the high vulnerability ranking (95.19 km; 66 grids), while about 69% (39.10 km; 24 grids) along the Banten coast was categorized as very low vulnerability due to accretion, as well as reclamation or rebuilt coastal land area for infrastructure and industry between 2000 and 2020.

However, Banyuwangi coast mostly had positive shoreline change (>0 m/yr) and fell into the low and very low vulnerability categories, with about 42% (18.15 km; 16 grids) and 58% (24.79 km; 19 grids), respectively. Erosion was dominant near the eastern and southern part of the Banten coast (Pontang and Kramatwatu), all of Demak coast (Sayung, Bonang, Wedung districts), while in the Banyuwangi coast, accretion was dominant near the district of Tegaldlimo and Muncar in Banten regency (Fig. S3).

3.2.3. Rate of sea level rise

Results highlighted that the coastlines of Banten, Demak, and Banyuwangi regencies were highly vulnerable to island degradation as a result of changes in sea level. From 1993 to 2016, historical sea level change rates of over 3.0 mm/yr were recorded along the coastline. The yearly mean sea level trend was determined to be in the range of 5.8 − 6.0 mm/yr (42 grids or 42 km^2) for Banten regency, 5.8 − 6.2 mm/yr (78 grids or 78 km^2) for Demak regency, and 5.6 − 5.8 mm/yr (35 grids or 35 km^2) for Banyuwangi regency (Fig. S4). The entire study area was deemed to be highly vulnerable to sea level rise, as indicated by Fig. 2.

3.2.4. Significant wave height

Mean significant wave height ranged between 0.2 − 0.7 m in Banten regency, 0.2 − 1.0 m in Demak regency, and 0.3 − 0.8 m in Banyuwangi regency, with average values of 0.42 m, 0.41 m, and 0.52 m, respectively (Fig. S5). All grids in Banten and Banyuwangi regencies were found to rank as very low vulnerability for significant wave height between 2010 and 2020, while in Demak regency, 21 grids or 21 km^2 (27%) were categorized as low vulnerability (Fig. 2).

3.2.5. Coastal slope

Banten and Demak regencies were characterized by gentle slopes and low plains, making them vulnerable to coastal hazards such as coastal flooding (Fig. S6). Results also determined that 40% (17 km^2 or 17 grids) in the Banten area were ranked as high vulnerability, while 45% (19 km^2 or 19 grids) were categorized as having very high vulnerability. The Demak coast was identified as the most vulnerable, with 71.79% (56 km^2 or 56 grids) in the high vulnerability category and 28% (22 km^2 or 22 grids) ranked as very high vulnerability, as they were mapped with a slope of 0 − 6.0 degrees. Banyuwangi regency, on the other hand, mostly had steep slopes with low vulnerability (43%, 15 km^2) or moderate vulnerability (49%, 17 km^2).

In terms of coastline length, 46% of Banten's 25.85 km was in high vulnerability, while 41.10% of 23.13 km was in very high vulnerability. Demak regency had 87.99 km (80%) in high vulnerability and 22.30 km (20%) in very high vulnerability. Banyuwangi regency had 48% of its 20.81 km in low vulnerability and 44% of its 19.03 km in moderate vulnerability.

3.2.6. Bathymetry

Bathymetry analysis indicated that the Banten coast was very highly vulnerable, with 59.5% (25 grids or 25 km^2) having bathymetry in the 0 − 2.94 m range (Fig. S7). Interestingly, grids representing parts of the Pulau Dua Nature Reserve and Bojonegara in Banten regency were categorized as low (5%, 2 km^2) and very low vulnerability (26%, 11 km^2). However, on the Demak coast, about 99% (77 km^2) and 1% (1 km^2) were found to be in very high and moderate vulnerability categories. Most of the Banyuwangi coast had a shallow bathymetric configuration near the shoreline, with about 7 km^2 (20%) and 22 km^2 (63%) found to be in the high and very highly vulnerable categories (ranked as 4 and 5 respectively).

3.2.7. Mean tidal range

Tidal range was inversely related to vulnerability, with high tidal range indicating lower vulnerability and vice versa. The mean tidal ranges for Banten and Demak coastlines were 0.5 m and 1 m, resulting in

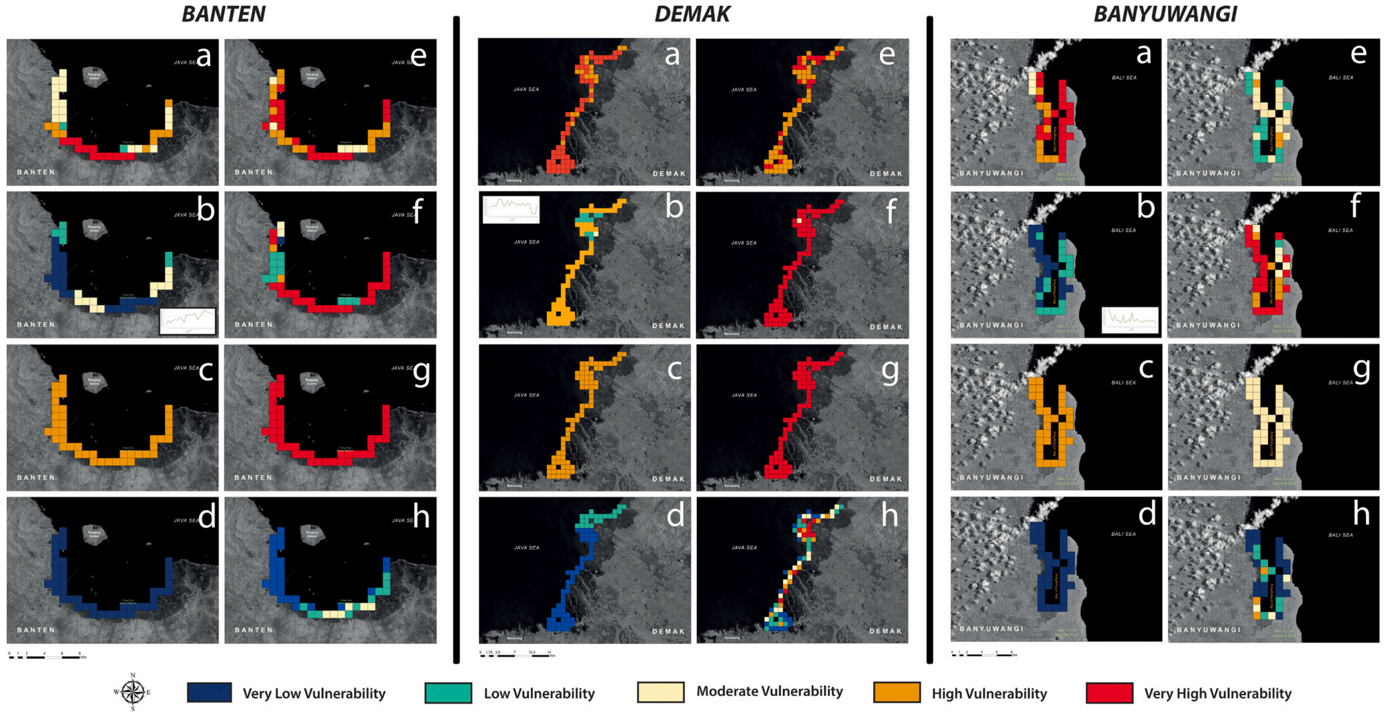

Fig. 2. Vulnerability ranking in Banten, Demak, and Banyuwangi of all variables respectively: *a*) geomorphology; *b*) shoreline change rate; *c*) rate of sea level rise; *d*) significant wave height; *e*) coastal slope; *f*) bathymetry; *g*) mean tidal range; *h*) mangrove density.

very high vulnerability (Fig. S8). Meanwhile, the Banyuwangi coastline had moderate vulnerability with a mean tidal range between 2 m and 1 m, which ranked it 3 on the vulnerability scale.

3.2.8. *Mangrove density*

There has been significant loss of mangrove vegetation in Banten, Demak, and Banyuwangi regencies over the last few decades. Grid analysis of mangrove density in Banten regency revealed that more than 85% of grids fell into the very low and low vulnerability categories. This was because there were no mangroves left in those areas, so they were no longer able to be classified as vulnerable to mangrove loss. The absence of mangroves could have created other vulnerabilities or ecological imbalances, such as increased coastal erosion, reduced habitat for marine organisms, or reduced protection from storms and waves. These may have included greater erosion along the coast, a decrease in living space for marine organisms, and less defense against storms and waves. The area of Pulau Dua Nature Reserve in Banten regency was in the moderate vulnerability classification with 14% of grids falling into this zone.

On the Demak coast, about 51% (40 km^2) of all grids were found to be in the moderate, high, and very high vulnerability categories (Fig. S9). These areas were located in Wedung District in Demak regency (Fig. 2) and were more vulnerable to natural factors and anthropogenic pressures such as land-use change. The very low to low vulnerability areas were primarily those where mangroves were imperceptible, grew in certain estuarine conditions, or were planted in small patches. Of the Banyuwangi coast, 83% (29 grids, 29 km^2) was classed as very low to low vulnerability, with just 9% (3 grids, 3 km^2) and 8.6% (3 grids, 3 km^2) in the high and moderate vulnerability categories.

3.3. *Mangrove vulnerability index (MVI)*

The MVI was computed using eight variables, as seen in Eq. 3. Mondal et al. (2022) calculated grid-wise mangrove vulnerability zones based on physical and anthropogenic factors. In this study, mangrove vulnerability indicates the combined effect of eight natural variables and proposes mangrove management zones based on Mangrove Vulnerability Index values and rankings.

These results aimed to assess the ability of mangrove ecosystems to endure various hazards, as well as to understand the conditions of mangroves in terms of their vulnerability. Overall, Demak Regency still has the largest percentage of area and coastline length dominated by high vulnerability, affecting 46% of the area and 43% of coastline length (Table 3). Concentration of these rankings was distributed in the Sayung, Bonang, and Wedung districts, and there were no low-vulnerability grids in the study area. However, based on grid and coastline length, Banten and Banyuwangi regencies predominantly showed more than 90% of the results were low vulnerability. The estimated minimum value of MVI calculated for the case study was 2.45, while the maximum value was 80 – the higher the value of MVI, the

Table 3
Mangrove Vulnerability Index of three study areas.

Study area	Measurement	Mangrove Vulnerability Index ranking			
		Low	Moderate	High	Very high
Banten Regency	*No. of grids*	42	0	6	0
	Area (km^2)	42	0	0	0
	Area percentage (%)	100	0	0	0
	Coastline length (km)	56.27	0	0	0
	Coastline length percentage (%)	100	0	0	0
Demak Regency	*No. of grids*	0	30	36	12
	Area (km^2)	0	30	36	12
	Area percentage (%)	0	38.46	46.15	15.38
	Coastline length (km)	0	49.33	47.45	13.51
	Coastline length percentage (%)	0	44.72	43.02	12.25
Banyuwangi Regency	*No. of grids*	33	2	0	0
	Area (km^2)	33	2	0	0
	Area percentage (%)	94.29	5.71	0	0
	Coastline length (km)	40.8	2.14	0	0
	Coastline length percentage (%)	95.02	4.98	0	0

more vulnerable the mangrove is. Demak Regency had the highest MVI ranking, as it was dominated by high vulnerability areas, followed by Banyuwangi and Banten regencies which had lower vulnerability MVI values.

4. Discussion

4.1. *Coastal vulnerability index*

To the best of our knowledge, this is the first study that has undertaken a grid-wise coastal vulnerability assessment for Banten, Demak, and Banyuwangi regencies; while CVI has been utilized to assess other coastal areas in Indonesia (Loinenak et al., 2015; Husnayaen et al., 2018; Imran et al., 2020; Irham et al., 2021; Hastuti et al., 2022; Rumahorbo et al., 2023). The analysis (Fig. 3) shows that out of 78 grids (78 km^2) in Demak Regency, 64 ranked as moderately to highly vulnerable, which corresponds to 82% of total area. These findings are consistent with other studies, which determined the areas of Sayung and Bonang in Demak Regency to be vulnerable (Primasti et al., 2021). This study further supports the idea that high vulnerability zones in Demak Regency can be attributed to changes in land use from mangroves to aquaculture ponds (Ramadhani and Susanti, 2020) as well as the impact of sea level rise and erosion in recent years (Ervita and Marfai, 2017).

CVI analysis in Banten revealed that out of a total 42 grids, 18 ranked as low to moderately vulnerable, representing 43% of the study area; this suggests the Banten coastline is moderately vulnerable overall. These findings were similar to those of Rahmat and Handiani (2020), whose findings determined the coastline of the district of Bojonegara and Puloampel (Fig. 1) in Banten Regency to be moderately vulnerable. Areas with moderate to low CVI values were found to be in the mangrove conservation area of Pulau Dua Nature Reserve, where mangroves assist in trapping sediments transported by rivers (Susantoro et al., 2020). Pangpang Bay in Banyuwangi Regency was considered the least vulnerable area because the area was an essential ecosystem area with efforts to conserve mangroves, which had an impact on sedimentation contributed by the mangroves and minimal erosivity rates. In terms of CVI, this could have decreased the coastal vulnerability value through positive shoreline change (accretion). Based on CVI values (91% of this area was categorised as low vulnerability), compared to the regencies of Demak and Banten.

Several studies utilizing indexes to estimate CVI based on physical parameters have been conducted across various different scales; national (Bagdanavičiūtė et al., 2015; Royo et al., 2016; Rocha et al., 2020), regional (Ashraful Islam et al., 2016; Ghoussein et al., 2018; Ng et al., 2019; Hoque et al., 2019; Baig et al., 2021; Hastuti et al., 2022; Kovaleva et al., 2022; Handiani et al., 2022) or local (Sekovski et al., 2020) with reliable results. However, these does not examine socio-economic parameters such as: population density, infrastructure, routes, land use, ecological areas, cultural heritage, etc as input for assessing vulnerability (Behera et al., 2019; Ballesteros and Esteves, 2021; Bera and Maiti, 2021). Hence, it is imperative that forthcoming studies in the northern coast of Java incorporate socio-economic dimensions or other local factors as supplementary inputs to enhance the precision and accuracy of coastal vulnerability assessment. Moreover, it is also worth underscoring the critical role of maintaining dependable and current databases, particularly in the context of index-based methodologies like CVI (Pantusa et al., 2018).

De Serio et al. (2018) computed the CVI, both with and without the inclusion of weighted factors, arriving at the inference that the unweighted CVI tended to underestimate vulnerability, while the weighted approach demonstrated greater realism, aligning with the conclusions drawn in this study. Similarly, Bagdanavičiūtė et al. (2015) conducted CVI calculations involving weighted factors, which notably elevated the very high vulnerability classification, resulting in heightened accuracy and greater result consistency when compared to the unweighted CVI. However, increased coastal development and human activities have implications for heightened vulnerability to coastal disasters in these regions (Zonkouan et al., 2021). It is also important to note that irrespective of the land cover type in coastal areas, those with lower elevations are susceptible to seawater inundation (Hamuna et al., 2019). In addition, the phenomena of storm surges increased the vulnerability of the coastline and their destructive impact during a swash (Benkhattab et al., 2020).

The real importance of using CVI tools lies not only in determining the vulnerability of a particular coastal area, but also in attracting attention for action. By using a uniform process to obtain a score in a standard index, it becomes possible to compare the vulnerability of different areas and prioritize management actions. This information can help allocate funds and design interventions that may prevent serious losses in highly vulnerable zones. However, it is essential to note that the coastal environment is dynamic and constantly changing. The combination of natural and human actions ultimately determines the sustainability of a coastal zone. Thus, understanding CVI scores as a whole, and specific scores for each variable, can provide insights into what factors are causing the most negative impact and how they can be prevented.

4.2. *Contribution of each variable to the vulnerability index*

While CVI and MVI represents a combined score based on several (7 out of 8 variables), the contributions of each of these variables may not be uniform for each site, nor do these variables change in a relative manner. In other words, these 7 out of 8 variables behave rather independently, and a high or low score in any one variable does not necessarily correlate with scores on other variables, despite each affecting the final index value of CVI and MVI generated. For example, shoreline retreat was quite significant in the regencies of Banten and Demak with an average rate of 2.21 m/yr and 8.96 m/yr respectively, however Banyuwangi Regency experienced growth/build-up of shoreline of approximately 0.36 m/yr. Despite an area having a low vulnerability index value overall, specific index values highlighted those certain areas had higher vulnerability to specific risks. For instance, shoreline retreat indicated greater vulnerability to the erosion of the coast, while the accretion or growth of shoreline in Banyuwangi affected the total CVI value since it fell within the value range of 1 and 2 (very low and low vulnerability). The study determined that erosion was widespread in most areas of Demak Regency mainly due to high waves (Ervita and Marfai, 2017) and human activities such as conversion of mangrove forests into aquaculture ponds (Rudi and Harini, 2021). This finding confirmed that anthropogenic impacts include damage to the mangrove ecosystem. Settlements and aquaculture ponds that were economic sources for the local residents actually could result in reduction of coastal resources, and lead to social, economic, and environmental changes in the region (Bouchahma and Yan, 2014).

However, Banten and Banyuwangi regencies had commonly low vulnerability ranks, across 39.10 km (or 24 grids) and 24.79 km (or 19 grids) respectively. These results may suggest that the accretion process taking place in mangrove forests in several areas, especially since Pangpang Bay (Fig. 1) in Banyuwangi regency is the only wetland ecosystem in East Java that has been designated essential, due to its coastal area being surrounded by mangroves. Most of this area is managed by Alas Purwo National Park, the Indonesian State Forestry Enterprise (Perum Perhutani), and the local community. Accretion also occurred in mangrove conservation areas, such as Pulau Dua Nature Reserve. The low vulnerability ranking observed in the district of Bojonegara and Puloampel in Banten regency correlates with Suwandana (2019) findings, which show that both of these districts reclaimed approximately 86.03 ha and 22.5 ha of land respectively, between 2015 and 2019. Land reclamation is not necessarily positive, however; though an increase in shoreline results in a lower vulnerability score, this could conceal risks. The most extensive reclamation activities took place in the district of Bojonegara in Banten regency as this area was designated a

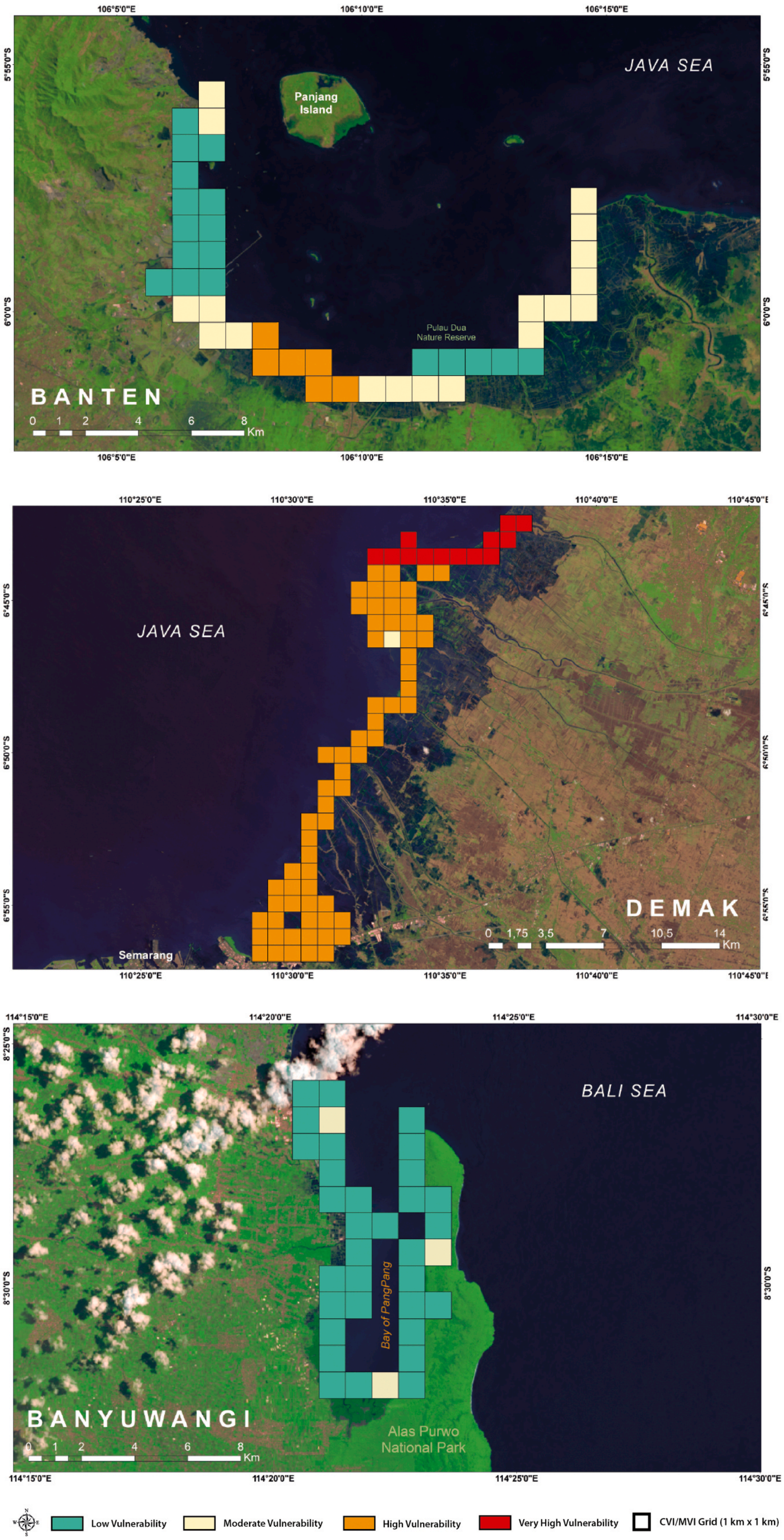

Fig. 3. Coastal vulnerability zones in the study area.

large and medium-sized industrial area for metal, basic chemical, and maritime industries, as per Serang Regency Regional Regulation No. 10 of 2011, on the Serang Regency Regional Spatial Plan for 2011–2031. Reclamation actually took place in the mangrove zone; findings by Liyubayina (2018) reveal that mangrove area here decreased by about 13 ha between 2009 and 2015. Likewise, reclamation of land for economic activities and infrastructure development in coastal areas is often detrimental to existing mangrove cover for reasons other than land use change. Such economic and development activities lead to degradation of mangroves, causing reduction of coastal resilience; the subsequent reduction in sediment trapping leads to destabilization of coast, and ensuing erosion makes an area vulnerable. Based on analysis, Reclamation increased the value of the shoreline change rate through the obtained EPR value, thus this variable was forced by the reclaimed area to obtain a range of very low to low vulnerability, it could decrease the value of the vulnerability index in total, which means it could make an area appear less vulnerable than it was in reality.

There could be an increase in vulnerable coastline areas due to sea level rise caused by global climate change. National Oceanic and Atmospheric Administration (NOAA) data on sea level rise suggests that this study area saw a rate of sea level rise of more than 3 mm/yr, higher than the mean sea level rise in Indonesia – 3.9 ± 0.4 mm/yr between 1992 and 2020 (NOAA, 2020). As a result, all of the study areas were ranked as high vulnerability in this aspect. Higher sea level contributes to coastal vulnerability due to shoreline erosion (Enriquez et al., 2019), which has similar effects to coastal subsidence; both result in coastline erosion, as observed in Demak Regency with its subsidence rates of ~ 17.91 cm/yr (Yuwono et al., 2019).

Coastal geomorphology was the reason that 60% of the Banten Regency coastline was classified as moderately vulnerable, due to low cliffs in the reclamation area (Bojonegara and Puloampel). Approximately 82% of the Demak coastline was ranked very highly vulnerable as this area is made up of coastal plain, beach, and mud flats. In Banyuwangi Regency, about 85.59% of coastline was in the high to very highly vulnerable categories. There was a small variation range of significant wave height, which averaged 0.42 m, 0.41 m and 0.52 m in Banten, Demak, and Banyuwangi regencies respectively. Overall, there was no significant difference or influence generated from this variable to the overall CVI score for each study site. However, mean tidal range did affect total CVI value, as all grids in Banten and Demak regencies were found to be in very high vulnerability category (>4 m), while all grids in Banyuwangi Regency ranked in the moderately vulnerable range (1–2 m).

While our study confirmed that tidal range vulnerability affected just 43% of Banten Regency currently, the trend of rate of sea level rise could increase this vulnerable area; it is because coastal slope and bathymetry along this coast ranked high to very high on the vulnerability scale. More than 95% (36 grids) of this area had a slope under < 10.0-degrees; this would allow water to enter coastal zones during floods or other natural hazards. This same vulnerability to sea level rise could impact the Demak coastline; the study revealed approximately 72% (56 grids) and 28% (22 grids) ranked as highly and very highly vulnerable due to their low sloping coastlines. However, most of the Banyuwangi coastline was considered moderately vulnerable in terms of coastal slope; about 49% (17 grids) ranked in this category. The level of vulnerability could also be enhanced due to the bathymetry value meant that 60%, 99%, and 63% of the grids in Banten, Demak, and Banyuwangi regencies respectively were found to be very highly vulnerable to the coastal hazard and the impact would get worse.

Physiochemical conditions such as salinity and coastal slope were some of the environmental factors affecting the existence of mangrove ecosystems in a place (Matatula et al., 2019). In terms of selecting rehabilitation sites, specific environmental conditions such as elevation and slope need be met for rehabilitation activities to be effective. A gradual slope helps to reduce erosion and filter run-off entering wetlands, as well as allows for surface drainage at low tide (Gilman and Ellison, 2007). Understanding and considering the specific geophysical conditions of mangrove ecosystems, such as coastline slope, is therefore key when planning rehabilitation or restoration activities.

This study offers a useful perspective to help determine vulnerability of the coast and existing mangrove systems yet there exists specific research limitations and challenges which necessitate future refinements to enhance its contributions to the field. Primary concerns include quality and consistency of data related to shoreline change rate, coastal slope, and geomorphology, leading to uncertainties in the study's results. Similarly, this study outcomes depend on sea level trends and tidal range data which is obtained from relatively sparse measuring stations in the study area. Additionally, the assessment and determination of vulnerability indices does not fully incorporate sediment deposition and subsidence dynamics in specific regions and disregards multifaceted impact of human activities on mangroves. Despite these limitations, the study's results can serve as a valuable guide for urban planners and decision-makers, providing a rapid and cost-effective CVI to empower informed mangrove conservation measures and policy decisions in coastal regions.

4.3. *Using the mangrove vulnerability index to prioritize restoration*

Analysis of MVI was completed in coastal areas of West Bengal (India) by Mondal et al. (2022) using the same variables as this study, with the exception of significant wave height. Mondal et al. (2022) found a direct relationship between land area loss and mangrove area loss along the Sundarbans shoreline. Correlating to this previous research, the present study revealed that all of the Banten coastline and most (95%) of the Banyuwangi Regency coastline ranked in the low vulnerability category on the mangrove vulnerability index (MVI). This result might be explained by the fact that these two regencies housed mangroves that were still able to withstand coastal hazards. Sediment entrapments have been introduced to the Pulau Dua Nature Reserve coastline in Banten regency, with the aim of reducing the impacts of high waves by maintaining the mangrove ecosystem between the boundary of Pulau Dua Nature Reserve in Banten regency and the seafront (Lestari et al., 2018). In Banyuwangi Regency, a mangrove wetland essential ecosystem area has been established in Pangpang Bay with support from local government. This support includes facilitating the establishment of a multistakeholder forum to collaborate around creating a mangrove management plan, advocacy and community services (Setyaningrum, 2016).

The results of this study indicate that Demak mangroves will no longer able to withstand various environmental pressures and threats. Crucial factors for this observation include the negative impacts on mangroves of anthropogenic pressures like mangrove conversion to aquaculture ponds (Rudi and Harini, 2021), land subsidence causing higher erosion along the coastline (Yuwono et al., 2019), and high waves (Ervita and Marfai, 2017). Approximately 51% of Demak ranked in the moderate, high, and very high vulnerability categories in the overall MVI score, particularly in the district of Wedung in Demak regency where combined impacts of natural factors and anthropogenic pressures is very high. While in Banten and Banyuwangi regencies, more than 80% mangroves ranked as low and very low vulnerability. This rather contradictory result is probably because mangroves in those areas were imperceptible, were growing in certain estuarine conditions, or were planted in small patches. It could also be said that the denser the mangroves, the more vulnerable they become, from an MVI perspective. This is the reason the index could be useful as a tool for restoration; because it helps to identify such an important, useful and easily understood techniques for proper and effective coastal zone and mangroves management.

Mondal et al. (2022) simplified MVI to provide results that support the implementation of afforestation and restoration policies in the study area. Afforestation refers to the process of establishing a new mangrove forest in an area where no forest previously existed, while restoration

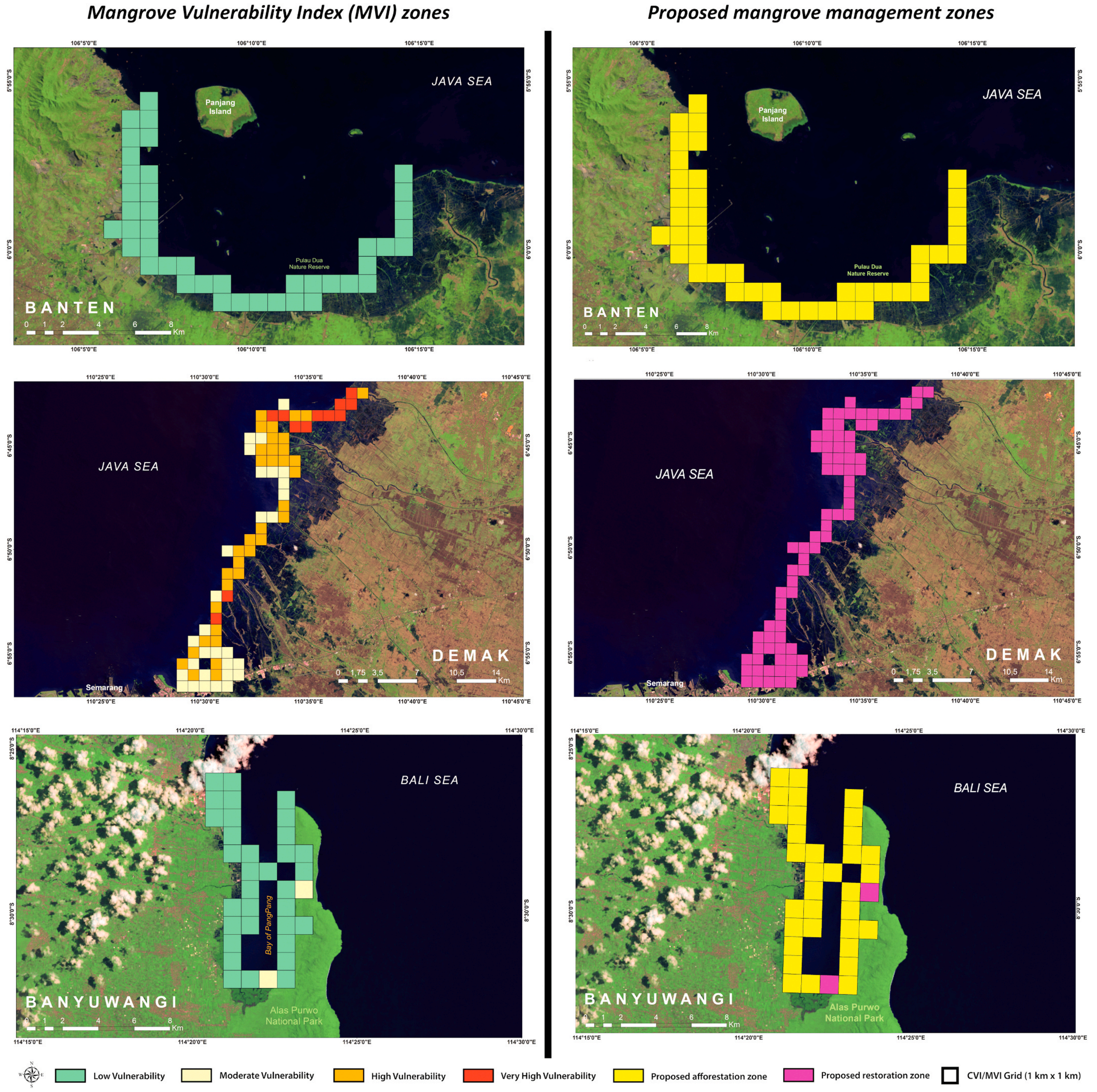

Fig. 4. Mangroves vulnerability zones of the study area and proposed mangrove management zone based on the MVI.

refers to the process of repairing and restoring the ecological biodiversity of degraded, damaged, or destroyed mangrove forests. The present study demonstrates that 78 grids in Demak Regency ranked between moderate to very high vulnerability; these areas should be prioritized for restoration policies. As climate change and anthropogenic impacts have already greatly deteriorated this area, a crucial step in restoration is to reduces vulnerability to erosion and other coastal hazards, by repairing degraded areas and restoring the natural processes that prevent erosion. Given high intensity of vulnerability observed in this area, restoration initiatives can be promoted on an urgent basis to protect the region). In contrast, as Banten regency (42 grids) and Banyuwangi regency (33 grids) ranked low or very low vulnerability in terms of MVI, these regencies should be proposed as afforestation areas. This is because these areas are more stable and suitable for afforestation-related activities; such an approach could be effective in stabilizing sediment in the coastal zone, as well as increasing the biodiversity of the coastal ecosystem; both tree density and species diversity in mangrove ecosystems have been proven to increase following restoration and conservation efforts (Hanggara et al., 2021). Such insights based on vulnerability assessment can help in regional and local coastal zone management policies to allow relevant agencies to allocate funding for most needed actions. It also offers national governments an opportunity to identify important coastal zones which might be important for national climate action (adaptation and mitigation goals). An understanding of existing risks and vulnerabilities also help in better preparedness in the context of natural disaster risks and assist in designing effective programs to meet sustainable development goals.

5. Conclusion

The northern coast of Java is mostly low lying, with sandy, muddy, and gravelly beaches. Because of global warming-induced sea level rise, coastal areas experience erosion, especially if underwater coastal areas near shore have a gentle slope. This study notes that (i) vulnerability results are influenced by sea level rise, sandy coastal and alluvial plains, coastal slope, low bathymetry depth, and low tidal mean range; (ii) based on their overall CVI scores, Demak regency is considered the most vulnerable coastal area in north Java, followed by Banten regency, with Banyuwangi regency the least vulnerable; (iii) the mangrove vulnerability assessment indicates that Banten and Banyuwangi regencies are low vulnerability, while Demak regency is highly vulnerable in this aspect.

Even though this research does not develop CVI by considering, for instance, the worst-case scenario of SLR projection in 2100 (Royo et al., 2016; Reimann et al., 2018), the results have warned us that the northern coast of Java is vulnerable. Coastal vulnerability indices have been developed for several coastal areas around the world (Hoque et al., 2019; Komi et al., 2022; Ahmed et al., 2022a, 2022b; Ariffin et al., 2023; Charuka et al., 2023), still, the coastal region of the northern coast of Java are not well represented in those studies. The development of MVI by incorporating mangrove density into CVI, as done by Mondal et al. (2022), not only helps in managing coastal land but also contributes to the sustainable conservation of mangroves.

This research recommend restoration and/or afforestation activities are concentrated in more vulnerable areas, rather than less vulnerable ones. Mangroves should be restored while taking into consideration requirements like growing locations, mangrove species, planting techniques, and water systems. Mangroves can play an important role in reducing the risks and enhancing the resilience of coastal areas. Identifying coastal zones that are more vulnerable therefore allows targeting of interventions and formulating policies that can help in restoration, thus strengthening the integrity of coastal ecosystems in the face of climate change. A secure and functionally intact coastline can offer sustainable delivery of ecosystem services that coastal biota and human communities depend on.

CRediT authorship contribution statement

Bhomia Rupesh Kumar: Writing – review & editing, Supervision, Data curation, Conceptualization. **Sagala Phidju Marrin:** Writing – original draft, Visualization, Validation, Formal analysis, Data curation, Conceptualization. **Murdiyarso Daniel:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.rsma.2024.103383.

References

Ahmed, F., Ali, I., Kousar, S., Ahmed, S., 2022a. The environmental impact of industrialization and foreign direct investment: empirical evidence from Asia-Pacific region. Environ. Sci. Pollut. Res. 29, 29778–29792. https://doi.org/10.1007/s11356-021-17560-w.

Ahmed, M.A., Sridharan, B., Saha, N., Sannasiraj, S.A., Kuiry, S.N., 2022b. Assessment of coastal vulnerability for extreme events. Int. J. Disaster Risk Reduct. 82, 103341 https://doi.org/10.1016/j.ijdrr.2022.103341.

Ariffin, E.H., Mathew, M.J., Roslee, A., Ismailluddin, A., Yun, L.S., Putra, A.B., Yusof, K. M.K.K., Menhat, M., Ismail, I., Shamsul, H.A., Menier, D., Ghazali, N.H.M., Lee, L.H., 2023. A multi-hazards coastal vulnerability index of the east coast of Peninsular Malaysia. Int. J. Disaster Risk Reduct. 84, 103484 https://doi.org/10.1016/j.ijdrr.2022.103484.

Ashraful Islam, Md, Mitra, D., Dewan, A., Akhter, S.H., 2016. Coastal multi-hazard vulnerability assessment along the Ganges deltaic coast of Bangladesh–A geospatial approach. Ocean Coast. Manag. 127, 1–15. https://doi.org/10.1016/j.ocecoaman.2016.03.012.

B.D. Yuwono S. Subiyanto A.S. Pratomo Najib Time series of land subsidence rate on coastal demak using GNSS CORS UDIP and DINSAR E3S Web Conf. 94 2019 04004 doi: 10.1051/e3sconf/20199404004.

Bagdanavičiūtė, I., Kelpšaitė, L., Soomere, T., 2015. Multi-criteria evaluation approach to coastal vulnerability index development in micro-tidal low-lying areas. Ocean Coast. Manag. 104, 124–135. https://doi.org/10.1016/j.ocecoaman.2014.12.011.

Baig, M.R.I., Shahfahad, Ahmad, I.A., Tayyab, M., Asgher, M.S., Rahman, A., 2021. Coastal vulnerability mapping by integrating geospatial techniques and Analytical Hierarchy Process (AHP) along the Vishakhapatnam Coastal Tract, Andhra Pradesh, India. J. Indian Soc. Remote Sens 49, 215–231. https://doi.org/10.1007/s12524-020-01204-6.

Ballesteros, C., Esteves, L.S., 2021. Integrated assessment of coastal exposure and social vulnerability to coastal hazards in East Africa. Estuaries Coasts 44, 2056–2072. https://doi.org/10.1007/s12237-021-00930-5.

Behera, R., Kar, A., Das, M.R., Panda, P.P., 2019. GIS-based vulnerability mapping of the coastal stretch from Puri to Konark in Odisha using analytical hierarchy process. Nat. Hazards 96, 731–751. https://doi.org/10.1007/s11069-018-03566-0.

Bemmelen, R.W. van, 1949. The Geology of Indonesia. V. I-A. Martinus Nijhoff, The Hague, p. 732.

Benkhattab, F.Z., Hakkou, M., Bagdanavičiūtė, I., Mrini, A.E., Zagaoui, H., Rhinane, H., Maanan, M., 2020. Spatial–temporal analysis of the shoreline change rate using automatic computation and geospatial tools along the Tetouan coast in Morocco. Nat. Hazards 104, 519–536. https://doi.org/10.1007/s11069-020-04179-2.

Bera, R., Maiti, R., 2021. An assessment of coastal vulnerability using geospatial techniques. Environ. Earth Sci. 80, 306. https://doi.org/10.1007/s12665-021-09616-4.

Bouchahma, M., Yan, W., 2014. Monitoring shoreline change on Djerba Island using GIS and multi-temporal satellite data. Arab J. Geosci. 7, 3705–3713. https://doi.org/10.1007/s12517-013-1052-9.

BPS, 2021. Statistical Yearbook of Indonesia. ⟨https://www.bps.go.id/publication/2021/02/26/938316574c78772f27e9b477/statistik-indonesia-2021.html⟩. (Accessed 23 February 2023).

BPS Banyuwangi, 2020c. Kabupaten Banyuwangi dalam angka 2020 [banyuwangi regency in figure 2020].⟨https://banyuwangikab.bps.go.id/publication/2020/02/28/00e63a1e4d39071af957721e/kabupaten-banyuwangi-dalam-angka-2020–penyediaan-data-untuk-perencanaan-pembangunan.html⟩. (Accessed 24 February 2023).

BPS Demak, 2020b. Kabupaten Demak dalam angka 2020 [demak regency in figure 2020]. ⟨https://demakkab.bps.go.id/publication/2020/04/27/8b6a9862046d7d23d2ee17cd/kabupaten-demak-dalam-angka-2020.html⟩. (Accessed 24 February 2023).

BPS Serang, 2020a. Kota Serang dalam angka 2020 [serang city in figure 2020]. ⟨https://serangkota.bps.go.id/publication/2020/04/27/354286a76093052203a44878/kota-serang-dalam-angka-2020.html⟩. (Accessed 24 February 2023).

Charuka, B., Angnuureng, D.B., Brempong, E.K., Agblorti, S.K.M., Antwi Agyakwa, K.T., 2023. Assessment of the integrated coastal vulnerability index of Ghana toward future coastal infrastructure investment plans. Ocean Coast. Manag. 244, 106804 https://doi.org/10.1016/j.ocecoaman.2023.106804.

Coelho, C.D.B., 2005. Riscos de exposição de frentes urbanas para diferentes intervenções de defesa costeira. Universidade de Aveiro.

CZMC, and Resource Analysis, 1994. COSMO Manual. ⟨https://puc.overheid.nl/PUC/Handlers/DownloadDocument.ashx?identifier=PUC_41723_31&versienummer=1⟩.

De Serio, F., Armenio, E., Mossa, M., Petrillo, A.F., 2018. How to define priorities in coastal vulnerability assessment. Geosciences 8, 415. https://doi.org/10.3390/geosciences8110415.

Dewi, R.S., 2019. Monitoring long-term shoreline changes along the coast of Semarang. IOP Conf. Ser.: Earth Environ. Sci. 284, 012035 https://doi.org/10.1088/1755-1315/284/1/012035.

Dwarakish, G.S., 2008. Integrated coastal zone management plan for Udupi coast using remote sensing, geographical information system and global position system. J. Appl. Remote Sens. 2, 023515 https://doi.org/10.1117/1.2919101.

EEA (European Environment Agency), 2017. Climate change adaptation and disaster risk reduction in Europe. Enhancing coherence of the knowledge base, policies and practices. ⟨https://www.eea.europa.eu/publications/climate-change-adaptation-and-disaster⟩. (Accessed 25 January 2023).

Erkens, G., Bucx, T., Dam, R., de Lange, G., Lambert, J., 2015. Sinking coastal cities. Proc. IAHS 372, 189–198. https://doi.org/10.5194/piahs-372-189-2015.

Ervita, K., Marfai, M.A., 2017. Shoreline change analysis in Demak, Indonesia. J. Environ. Prot. 08, 940. https://doi.org/10.4236/jep.2017.88059.

Gaki-Papanastassiou, K., Karymbalis, E., Poulos, S.E., Seni, A., Zouva, C., 2010. Coastal vulnerability assessment to sea-level rise bαsed on geomorphological and oceanographical parameters: the case of Argolikos Gulf, Peloponnese, Greece. Hell. J. Geosci. 45, 109–121.

Ghoussein, Y., Mhawej, M., Jaffal, A., Fadel, A., El Hourany, R., Faour, G., 2018. Vulnerability assessment of the South-Lebanese coast: a GIS-based approach. Ocean Coast. Manag. 158, 56–63. https://doi.org/10.1016/j.ocecoaman.2018.03.028.

Gilman, E., Ellison, J., 2007. Efficacy of alternative low-cost approaches to mangrove restoration, american samoa. Estuaries Coasts 30, 641–651. https://doi.org/10.1007/BF02841961.

Gornitz, V., 1991. Global coastal hazards from future sea level rise. Palaeogeogr. Paalaeoclimatol. Palaeoecol. 89 (4), 379–398. https://doi.org/10.1016/0031-0182(91)90173-O.

Gorokhovich, Y., Leiserowitz, A., Dugan, D., 2013. Integrating coastal vulnerability and community-based subsistence resource mapping in Northwest Alaska. J. Coast. Res. 30, 158–169. https://doi.org/10.2112/JCOASTRES-D-13-00001.1.

Hamuna, B., Kalor, J., Tablaseray, V., 2019. The impact of tsunami on mangrove spatial change in eastern coastal of Biak Island, Indonesia. J. Ecol. Eng. 20, 1–6. https://doi.org/10.12911/22998993/95094.

Handiani, D.N., Heriati, A., Gunawan, W.A., 2022. Comparison of coastal vulnerability assessment for Subang Regency in North Coast West Java-Indonesia. Geomat. Nat. Hazards Risk 13, 1178–1206. https://doi.org/10.1080/19475705.2022.2066573.

Hanggara, B.B., Murdiyarso, D., Ginting, Y.R.S., Widha, Y.L., Panjaitan, G.Y., Lubis, A.A., 2021. Effects of diverse mangrove management practices on forest structure, carbon dynamics and sedimentation in North Sumatra, Indonesia. Estuar. Coast. Shelf Sci. 259, 107467 https://doi.org/10.1016/j.ecss.2021.107467.

Hartanto, I.S., Rachmawati, R., 2017. Assessing the spatial-temporal land use change and encroachment activities due to flood hazard in North Coast of Central Java, Indonesia. Indones. J. Geogr. 49, 165–176. https://doi.org/10.22146/ijg.28402.

Hastuti, A.W., Nagai, M., Suniada, K.I., 2022. Coastal vulnerability assessment of Bali Province, indonesia using remote sensing and gis approaches. Remote Sens. 14, 4409. https://doi.org/10.3390/rs14174409.

Hoque, M.A.-A., Ahmed, N., Pradhan, B., Roy, S., 2019. Assessment of coastal vulnerability to multi-hazardous events using geospatial techniques along the eastern coast of Bangladesh. Ocean Coast. Manag. 181, 104898 https://doi.org/10.1016/j.ocecoaman.2019.104898.

Husnayaen, Rimba, A.B., Osawa, T., Parwata, I.N.S., As-syakur, AbdR., Kasim, F., Astarini, I.A., 2018. Physical assessment of coastal vulnerability under enhanced land subsidence in Semarang, Indonesia, using multi-sensor satellite data. Adv. Space Res. 61, 2159–2179. https://doi.org/10.1016/j.asr.2018.01.026.

Imran, Z., Sugiarto, S.W., Muhammad, A.N., 2020. Coastal vulnerability index aftermath tsunami in Palu Bay, Indonesia. IOP Conf. Ser.: Earth Environ. Sci. 420, 012014 https://doi.org/10.1088/1755-1315/420/1/012014.

Intergovernmental Panel on Climate Change (IPCC), 2007. In: Core Writing Team, Pachauri, R.K., Reisinger, A. (Eds.), Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 104. IPCC, Geneva, Switzerland. ⟨https://www.ipcc.ch/report/ar4/syr/⟩ (Accessed 24 January 2023).

Intergovernmental Panel on Climate Change (IPCC), 2023. Climate Change 2022 – Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, 1st ed.,. Cambridge University Press. https://doi.org/10.1017/9781009325844.

Irham, M., Rusydi, I., Haridhi, H.A., Setiawan, I., Ilhamsyah, Y., Deli, A., Rusdi, M., Siregar, A.M., 2021. Coastal vulnerability of the West Coast of Aceh Besar: a coastal morphology assessment. J. Mar. Sci. Eng. 9, 815. https://doi.org/10.3390/jmse9080815.

Irsadi, A., Anggoro, S., Soeprobowati, T., Helmi, M., Khair, A., 2019. Shoreline and mangrove analysis along Semarang-Demak, Indonesia for sustainable environmental management. J. Pendidik. IPA Indones. 8, 1–11. https://doi.org/10.15294/jpii.v8i1.17892.

Jana, S., 2020. Micro-level coastal vulnerability assessment in relation to post-Aila landscape alteration at the fragile coastal stretch of the Sagar Island, India. Reg. Stud. Mar. Sci. 33, 100908 https://doi.org/10.1016/j.rsma.2019.100908.

Jones, G.W., 2013. The 2010–2035 Indonesian Population Projection: Understanding the causes, consequences and policy option for population and development. UNFPA Indonesia, Jakarta, Indonesia.

Komi, A., Petropoulos, A., Evelpidou, N., Poulos, S., Kapsimalis, V., 2022. Coastal vulnerability assessment for future sea level rise and a comparative study of two pocket beaches in Seasonal Scale, Ios Island, Cyclades, Greece. J. Mar. Sci. Eng. 10, 1673. https://doi.org/10.3390/jmse10111673.

Kovaleva, O., Sergeev, A., Ryabchuk, D., 2022. Coastal vulnerability index as a tool for current state assessment and anthropogenic activity planning for the Eastern Gulf of Finland coastal zone (the Baltic Sea). Appl. Geogr. 143, 102710 https://doi.org/10.1016/j.apgeog.2022.102710.

Leatherman, S.P., Clow, J.B., 1983. UMD shoreline mapping project: IEEE Geoscience and Remote Sensing Society Newsletter 22:5–8.

Lestari, T.A., Priyanto, E.B., Fitriyanto, D., Kuswantoro, Rahadian, A., Vidyan, S., 2018. Kajian Risiko Bencana Pesisir, Studi Kasus Kelurahan Banten dan Kelurahan Sawah Luhur, Kecamatan Kasemen, Kota Serang, Banten; Desa Purworejo, Desa Morodemak, Desa Surodadi dan Desa Timbulsloko, Kabupaten Demak, Jawa Tengah. Wetlands International Indonesia: Bogor.

Liyubayina, V., 2018. Analisis dampak reklamasi teluk Banten terhadap kondisi lingkungan dan sosial ekonomi (studi kasus: Kecamatan Bojonegara). J. Planol. 9 (1).

Lo, W., Purnomo, S.N., Dewanto, B.G., Sarah, D., Sumiyanto, 2022. Integration of numerical models and insar techniques to assess land subsidence due to excessive groundwater abstraction in the coastal and lowland regions of semarang city. Water 14, 201. https://doi.org/10.3390/w14020201.

Loinenak, F.A., Hartoko, A., Muskananfola, M.R., 2015. Mapping of coastal vulnerability using the coastal vulnerability index and geographic information system. IJTech 6, 819. https://doi.org/10.14716/ijtech.v6i5.1361.

Luijendijk, A., Hagenaars, G., Ranasinghe, R., Baart, F., Donchyts, G., Aarninkhof, S., 2018. The state of the world's beaches. Sci. Rep. 8, 6641 https://doi.org/10.1038/s41598-018-24630-6.

Mahmood, R., Ahmed, N., Zhang, L., Li, G., 2020. Coastal vulnerability assessment of Meghna estuary of Bangladesh using integrated geospatial techniques. Int. J. Disaster Risk Reduct. 42, 101374 https://doi.org/10.1016/j.ijdrr.2019.101374.

Maryantika, N., Lin, C., 2017. Exploring changes of land use and mangrove distribution in the economic area of Sidoarjo District, East Java using multi-temporal Landsat images. Inf. Process. Agric. 4, 321–332. https://doi.org/10.1016/j.inpa.2017.06.003.

Matatula, J., Poedjirahajoe, E., Pudyatmoko, S., Sadono, R., 2019. The spatial spread of mangrove forest environmental condition at Kupang seashore. J. Nat. Resour. Environ. Manag. 9, 467–482. https://doi.org/10.29244/jpsl.9.2.467-482.

Ministry of Environment and Forestry Indonesia (MoEF). 2020. Roadmap Nationally Determined Contribution (NDC) of Climate Change Adaptation. Ministry of Environment and Forestry Indonesia. ⟨https://ditjenppi.menlhk.go.id/reddplus/images/adminppi/adaptasi/dokumen/Roadmap_NDC_API_opt.pdf⟩. (Accessed 12 December 2022).

Mondal, B., Roy, A., Saha, A.K., 2022. Vulnerability assessment of mangrove areas in coastal West Bengal, India. Remote Sens. Appl.: Soc. Environ. 25, 100680 https://doi.org/10.1016/j.rsase.2021.100680.

Mujabar, P.S., Chandrasekar, N., 2013. Shoreline change analysis along the coast between Kanyakumari and Tuticorin of India using remote sensing and GIS. Arab J. Geosci. 6, 647–664. https://doi.org/10.1007/s12517-011-0394-4.

Murdiyarso, D., Purbopuspito, J., Kauffman, J.B., Warren, M.W., Sasmito, S.D., Donato, D.C., Manuri, S., Krisnawati, H., Taberima, S., Kurnianto, S., 2015. The potential of Indonesian mangrove forests for global climate change mitigation. Nat. Clim. Change 5, 1089–1092. https://doi.org/10.1038/nclimate2734.

Ng, K., Borges, P., Phillips, M.R., Medeiros, A., Calado, H., 2019. An integrated coastal vulnerability approach to small islands: the Azores case. Sci. Total Environ. 690, 1218–1227. https://doi.org/10.1016/j.scitotenv.2019.07.013.

Nugraha, R.B.A., Syaharani, L., Iska, R., Mulyana, D., Wahyudin, Y., Purbani, D., Jayawiguna, H., Triyono, Setiawan, A., Fajar, P., 2019. The impact of land used changes on mangrove forest and shoreline dynamic in Muara Gembong, Bekasi, West Java. IOP Conf. Ser.: Earth Environ. Sci. 241, 012018 https://doi.org/10.1088/1755-1315/241/1/012018.

Nugroho, B.D.A., 2016. Fenomena Iklim Global, Perubahan Iklim, dan Dampaknya di Indonesia. Gadjah Mada University Press.

Ondara, K., Rahmawan, G.A., 2020. Pemantauan sedimentasi menggunakan data batimetri high frecuency di perairan Sayung, Demak, Jawa Tengah. JIG 26, 1. https://doi.org/10.24895/JIG.2020.26-1.987.

Ongkosongo, O.S.R., 1979. The nature of coastline changes in Indonesia. Workshop on Coastal Geomorphology. UNESCO, Singapore-Malaysia. ⟨https://archive.unu.edu/unupress/unupbooks/80130e/80130E06.htm⟩ (Accessed 12 December 2022).

Pantusa, D., D'Alessandro, F., Riefolo, L., Principato, F., Tomasicchio, G., 2018. Application of a coastal vulnerability index. a case study along the Apulian Coastline, Italy. Water 10, 1218. https://doi.org/10.3390/w10091218.

Primasti, T.P.G., et al., 2021. Pemantauan kerentanan fisik di pesisir Kabupaten Demak (Studi Kasus Perubahan Garis Pantai. Indones. J. Oceanogr. 3 (1), 44–54. https://doi.org/10.14710/ijoce.v3i1.9997.

Rahmat, P., Handiani, D.N., 2020. Kerentanan pesisir di pantai utara Provinsi Banten. Prosiding FTSP Series. ⟨https://eproceeding.itenas.ac.id/index.php/ftsp/article/view/383⟩.

Ramadhani, Y.H., Susanti, R., 2020. Dynamics land cover changes of Wulan Delta in 2003-2017 approach by remote sensing technology. IOP Conf. Ser.: Earth Environ. Sci. 561, 012042 https://doi.org/10.1088/1755-1315/561/1/012042.

Reimann, L., Vafeidis, A.T., Brown, S., Hinkel, J., Tol, R.S.J., 2018. Mediterranean UNESCO World Heritage at risk from coastal flooding and erosion due to sea-level rise. Nat. Commun. 9, 4161. https://doi.org/10.1038/s41467-018-06645-9.

Richards, D.R., Friess, D.A., 2016. Rates and drivers of mangrove deforestation in Southeast Asia, 2000–2012. Proc. Natl. Acad. Sci. U. S. A. 113, 344–349. https://doi.org/10.1073/pnas.1510272113.

Rocha, C., Antunes, C., Catita, C., 2020. Coastal vulnerability assessment due to sea level rise: the case study of the Atlantic Coast of Mainland Portugal. Water 12, 360. https://doi.org/10.3390/w12020360.

Royo, M.L., Ranasinghe, R., Jiménez, J.A., 2016. A rapid, low-cost approach to coastal vulnerability assessment at a National Level. coas 32, 932–945. https://doi.org/10.2112/JCOASTRES-D-14-00217.1.

Rudi, F.S., Harini, R., 2021. The externalities value of mangrove forest conversion into fishponds in the coastal area of wulan delta in demak regency. IOP Conf. Ser.: Earth Environ. Sci. 683, 012021 https://doi.org/10.1088/1755-1315/683/1/012021.

Rumahorbo, B.T., Warpur, M., Tanjung, R.H.R., Hamuna, B., 2023. Spatial analysis of coastal vulnerability index to sea level rise in Biak Numfor Regency (Indonesia). J. Ecol. Eng. 24, 113–125. https://doi.org/10.12911/22998993/157539.

Sahoo, B., Bhaskaran, P.K., 2018. Multi-hazard risk assessment of coastal vulnerability from tropical cyclones – A GIS based approach for the Odisha coast. J. Environ. Manag. 206, 1166–1178. https://doi.org/10.1016/j.jenvman.2017.10.075.

Sarah, D., Soebowo, E., 2018. Land subsidence threats and its management in the North Coast of Java. IOP Conf. Ser.: Earth Environ. Sci. 118, 012042 https://doi.org/10.1088/1755-1315/118/1/012042.

Sarah, D., Soebowo, E., Wirabuana, T., Mulyono, A., Satriyo, N.A., 2022. Towards sustainable land subsidence mitigation in Semarang and Demak, Central Java: analysis using DPSIR Framework. J. Water Land Dev. 2022 (No 55), 150–165. https://doi.org/10.24425/jwld.2022.142317.

Sasmito, S.D., Taillardat, P., Clendenning, J.N., Cameron, C., Friess, D.A., Murdiyarso, D., Hutley, L.B., 2019. Effect of land-use and land-cover change on mangrove blue carbon: a systematic review. Glob. Change Biol. 25, 4291–4302. https://doi.org/10.1111/gcb.14774.

Sekovski, I., Del Río, L., Armaroli, C., 2020. Development of a coastal vulnerability index using analytical hierarchy process and application to Ravenna province (Italy). Ocean Coast. Manag. 183, 104982 https://doi.org/10.1016/j.ocecoaman.2019.104982.

Setyaningrum, E.W., 2016. Area Development Model Based on Mangrove Wetland Essential Ecosystem, in Pangpang Bay Banyuwangi Indonesia.

Sofian, I. 2010. Scientific Basis: Analysis and projection of sea level rise and extreme weather event. Indonesia climate change sectoral roadmap. U. H. Triastuti. Republic of Indonesia, Bappenas. ⟨https://perpustakaan.bappenas.go.id/e-library/file_upload/koleksi/migrasi-data-publikasi/file/Policy_Paper/analysis-and-projection-of-sea-level-rise-and-extreme-weathe_20110217130224_1.pdf⟩. (Accessed 14 December 2022).

Sugianto, D., Widiaratih, R., Widada, S., Suripin, S., Handayani, E., Cahyaningtyas, P., 2022. Analysis of structural and non-structural disaster mitigation due to erosion in the Timbulsloko Village, Demak – Central Java. J. Ecol. Eng. 23, 246–254. https://doi.org/10.12911/22998993/144559.

Suroso, D.S.A., Firman, T., 2018. The role of spatial planning in reducing exposure towards impacts of global sea level rise case study: Northern coast of Java, Indonesia. Ocean Coast. Manag. 153, 84–97. https://doi.org/10.1016/j.ocecoaman.2017.12.007.

Susantoro, T.M., Wikantika, K., Yayusman, L.F., Tan, A., Ghozali, M.F., 2020. Monitoring of mangrove growth and coastal changes on the north coast of brebes, Central Java, using landsat data. Int. J. Remote Sens. Earth Sci. 16, 197–214. https://doi.org/10.30536/j.ijreses.2019.v16.a3221.

Susilo, S., Salman, R., Hermawan, W., Widyaningrum, R., Wibowo, S.T., Lumban-Gaol, Y. A., Meilano, I., Yun, S.-H., 2023. GNSS land subsidence observations along the northern coastline of Java, Indonesia. Sci. Data 10, 421. https://doi.org/10.1038/s41597-023-02274-0.

Suwandana, E., 2019. Pemanfaatan data Google Earth resolusi spasial tinggi untuk pemetaan perubahan morfologi pantai. Depik 8, 193–206. https://doi.org/10.13170/depik.8.3.14309.

Thieler, E.R., Hammar-Klose E.S., 2000. National assessment of coastal vulnerability to sea-level rise: preliminary results for the U.S. Pacific Coast. U.S. Geological Survey Open-File Report. 00- 178. ⟨https://pubs.usgs.gov/of/2000/of00–178/⟩. (Accessed 23 January 2023).

Triana, K., Solihuddin, T., Husrin, S., Risandi, J., Mustikasari, E., Kepel, T.L., Salim, H.L., Sudirman, N., Prasetyo, A.T., Helmi, M., 2023. An integrated satellite characterization and hydrodynamic study in assessing coastal dynamics in Cirebon, West Java. Reg. Stud. Mar. Sci. 65, 103107 https://doi.org/10.1016/j.rsma.2023.103107.

United States Army Corps of Engineers (USACE). 2003. Coastal hydrodinamics part II, coastal sediment process's part III. Washington DC. Department of the Army, US Army Corps of Engineers.

Van Wesenbeeck, B.K., Balke, T., Van Eijk, P., Tonneijck, F., Siry, H.Y., Rudianto, M.E., Winterwerp, J.C., 2015. Aquaculture induced erosion of tropical coastlines throws coastal communities back into poverty. Ocean Coast. Manag. 116, 466–469. https://doi.org/10.1016/j.ocecoaman.2015.09.004.

Widada, S., Zainuri, M., Yulianto, G., Satriadi, A., Wijaya, Y.J., 2020. Estimation of land subsidence using sentinel image analysis and its relation to subsurface lithology based on resistivity data in the coastal area of Semarang City, Indonesia. J. Ecol. Eng. 21, 47–56. https://doi.org/10.12911/22998993/127394.

Zonkouan, B.R.V., Bachri, I., Beda, A.H.J., N'Guessan, K.A.M., 2021. Monitoring spatial and temporal scales of shoreline changes in Lahou-Kpanda (Southern Ivory Coast) using landsat data series (TM, ETM+ and OLI). GaEE 16, 145–158. https://doi.org/10.7494/geom.2022.16.1.145.