GIS-based Geospatial Risk Modeling of Extreme Waves and Abrasion on the West Coast of Sumatra

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Abstract

Indonesia, with its second-longest coastline in the world, is vulnerable to coastal disasters such as extreme waves and coastal abrasion. Pesisir Barat Regency in Sumatra is one of the regions that is vulnerable to these threats. Extreme waves, although rarely occur because of tropical cyclones, can be triggered by the influence of cyclones in the Indian Ocean. In addition, coastal abrasion caused by the interaction of waves, currents, and winds is increasingly threatening coastal areas. This research aims to identify the risk of extreme waves and abrasion disasters in Pesisir Barat Regency using a research-based approach to Geographic Information Systems (GIS) and multi-criteria analysis. Data on marine hydrodynamics, coastal topography, and land cover conditions are integrated to produce disaster risk maps. The risk analysis results show that the Ngaras sub-district and several other sub-districts, such as Bangkunat, Lemong, and Ngambur, have a high level of risk, with a total risk area reaching 0.398 square kilometers (km^2). Meanwhile, most other sub-districts are in the low-risk class. Key factors influencing the risk level include coastal topography, vegetation cover, and the intensity of human activities in coastal areas. This study highlights the importance of coastal zone management based on risk mitigation and the need to protect coastal ecosystems to reduce disaster impacts. The findings are expected to serve as a reference for disaster mitigation policy planning in Pesisir Barat and other coastal areas. Additionally, these results could be utilized to develop holistic and practical disaster reduction effort by related stakeholders and coastal communities.

Keywords: *Abrasion, Capacity, Extreme Waves, Geographic Information System, Risk*

Introduction

Indonesia is an archipelago with the second longest coastline in the world, after Canada and Norway (Alfahmi *et al.*, 2019; Arifin *et al.*, 2019; Sui *et al.*, 2020). With more than 95,000 km of coastline, Indonesia naturally has a high vulnerability to natural disasters associated with coastal areas, such as extreme waves and abrasion (Sui *et al.*, 2020). Pesisir Barat Regency, which is located on the west coast of Sumatra Island, is one of the areas facing significant risks from such disasters (Fauzi *et al.*, 2024).

Coastal areas are vulnerable and threatened areas caused by two factors, namely natural and non-natural factors. Natural factors are hydro-oceanographic processes in the ocean which trigger natural disasters, generally caused by the effects of global warming (Muskananfola *et al.*, 2020; Wannewitz *et al.*, 2024).

Extreme waves can occur because of tropical cyclones, even though Indonesia is not in the path of such cyclones. The impact of tropical cyclones that occur around Indonesia, such as in the Indian Ocean, can cause an increase in wave height that has the potential to trigger disasters in coastal areas (Jullien *et al.*, 2024). On the other hand, abrasion is a process of coastal erosion that occurs due to the interaction between ocean waves, currents and wind. The phenomenon of abrasion poses a serious threat to the sustainability of coastal ecosystems and

DOI: 10.14710/ik.ijms.30.3.411-424 Accepted : 16-07-2025

infrastructure along the coastline (Bennett *et al.*, 2023).

Geographic Information System (GIS)-based disaster risk assessment has proven effective in mapping and analyzing potential hazards in coastal areas (Nadzir *et al.*, 2024). GIS technology allows the integration of data from various sources, such as remote sensing data, weather conditions, and coastal topography and geomorphology data (Hakim and Lee, 2020). With accurate risk mapping, local governments and communities can plan more purpose-fit mitigation measures facing extreme wave and abrasion hazards.

Previous research conducted by Hamsah and Nirmawala (2022) used tidal variables, speed and direction of ocean currents, wave height and wave period, type of coastal geological structure and sediment grain size, beach slope and shoreline direction, wind speed and direction. to map abrasion zoning in Polewali Mandar Regency. The results of this research show that GIS technology can accurately identify areas with a high level of risk where abrasion zones and sedimentation zones are more dominant compared to stable beaches. Apart from that, research (Lessy and Abdullah, 2021) shows that the significant wave height (SWH) influenced by the wind (U_{10}) in the waters west of Ternate Island ranges from 0.61–2.75 m and the wave period ranges from 3.29–6.82 sec, with variations based on season, cycle, wind speed as well as swell condition. (Bagdanavičiūtė *et al.*, 2019) developed a coastal risk index (CRI) to assess erosion and inundation hazards due to sea level rise and extreme storms in coastal Lithuania, identifying about 11% of areas with very high risk, especially in densely populated areas and near coastal engineering structures. In addition, Rumahorbo *et al.* (2023). Conducted a vulnerability assessment in Siak District and Sragi Coast using the Coastal Vulnerability Index (CVI) method with physical parameters (Tarigan, 2024). In addition, Sriwardani *et al.* (2023) also studied the hazard of abrasion using the parameters of wave height, current speed, vegetation density, beach profile and beach typology (Purbani *et al.*, 2019). Additionally, Noor and Maulud (2022) found that throughout Southeast Asia there are still many coastal countries at risk with gaps in the mitigation process.

However, existing research has often not considered the integration of different types of data needed for more accurate risk modeling in Indonesia's coastal areas, particularly in Pesisir Barat Regency. Some research (Tohir and Pramatana, 2020; Simarmata *et al.*, 2023, 2025) has used locations in Lampung Province, but not specifically in Pesisir Barat Regency. This research aims to fill the gap by conducting a GIS-based extreme wave and abrasion disaster risk assessment analysis in Pesisir Barat Regency. This study utilizes hazard, vulnerability and capacity assessments to map disaster risks in the coastal area. With this comprehensive approach, it is hoped that the research can make a real contribution to disaster mitigation efforts in the coastal areas of Pesisir Barat Regency, as well as becoming a reference for disaster risk studies in other coastal areas in Indonesia.

Materials and Methods

The method to be used in this research includes a multi-criteria approach to assess vulnerability to extreme waves and abrasion. First, data on maximum wave height, currents, coastal typology, vegetation cover and shoreline shape will be collected from remote sensing data sources and weather conditions. Next, the data will be integrated using GIS technology to create disaster risk mapping. Risk classification is done by determining the hazard category based on low, medium and high parameters, and identifying areas with significant damage potential.

Vulnerability analysis will be carried out by considering social, physical, economic and environmental components (Barzehkar *et al.*, 2024). This assessment will use spatial methods Multi Criteria Decision Analysis (MCDA) which combines various criteria based on the value and weight of each component. Regional capacity will also be analyzed to determine the extent to which the region can manage risks and deal with potential disasters effectively. Therefore, this research aims to conduct a GIS-based analysis of the risk of extreme wave and abrasion disasters in Pesisir Barat Regency.

Extreme waves are high waves caused by the effects of tropical cyclones around Indonesia and have a strong potential to cause natural disasters. Indonesia is not a tropical cyclone track area, but the presence of tropical cyclones has a strong influence on the occurrence of strong winds, high waves, and heavy rain. Meanwhile, abrasion is the process of eroding the coast by the destructive power of ocean waves and ocean currents. Abrasion is also known as coastal erosion. Damage to the coastline due to abrasion is triggered by the disruption of the natural balance of the coastal area (http://www.bnpb.go.id/).

Hazard assessment

The assessment of extreme wave and abrasion hazards in Pesisir Barat Regency was conducted based on several parameters: the hazard parameters of land cover, wave height, current and coastline. Details of the parameters and data used in the calculation of these parameters can be seen in Table 1. The mapping of extreme waves and abrasion hazards is only carried out in land areas because the potential vulnerability to be calculated is only found on land. Referring to this, the parameters used aim to see the level of exposure of coastal areas to hazards. The values of wave height and current speed were used as initial data to calculate potential hazards on land. Each parameter is classified into three categories: low, medium and high. Wave height classification is considered low when the wave height at the shoreline is less than 1 m, medium when the height is between 1 - 2.5 m, and high when it is more than 2.5 m (WinklerPrins *et al*., 2023). For current speed, it is considered low when the speed is less than 0.2 $m.s^{-1}$, medium when the speed is between 0.2 - 0.4 $m.s^{-1}$, and high when the speed is more than 0.4 $m.s^{-1}$.

After the potential hazards are known, the level of exposure of the coastal area to these hazards is assessed systematically and parametrically. Therefore, further parameters such as coastal typology (formation process), shoreline shape and land cover are used to assess the potential exposure (Igigabel *et al*., 2024). For example, high waves of more than 2.5 m will not be very dangerous in coastal areas that are cliff-shaped with >2.5 m height difference between the coastline and the closest land area or in areas where there is a lot of mangrove forest. These three parameters were also classified into three categories: low, medium and high. The coastal typology classification is categorized as low when the coastal typology is rocky, medium when the coastal typology is sandy, and high when the coastal typology is muddy (Hulskamp *et al*., 2023; Hibatullah and Mutaqin, 2024). The shape of the coastline has a low potential for exposure, a straight coastline has a medium potential for exposure, and a straight coastline has a high potential for exposure. The last parameter, land cover, has a low potential for exposure when the land cover is high such as mangrove forests, medium when the land cover is shrubs, and high when there is no vegetation.

Overlay of all parameters is carried out to determine the hazard index for extreme waves and abrasion. Before overlaying, each parameter is given a score and weight according to its influence on the intensity of the hazard. To cover the area affected by the hazard, it is assumed to reach 200 meters from the coastline towards the mainland. The score and weight itself were computed independently to each other, based on available technical documents, existing policies from stakeholders as well as up-to-date technological framework.

Vulnerability assessment

Vulnerability is a condition of a community or society that leads to or causes inability to deal with disasters. The more “vulnerable” a community group is to disasters, the greater the losses experienced in the event of a disaster in that community group (Isia *et al*., 2023). Vulnerability analysis is conducted spatially by combining all the constituent components of vulnerability, where each vulnerability component is also obtained from the results of the merging process of several constituent parameters. The constituent components and vulnerability parameters consist of social vulnerability, physical vulnerability, economic vulnerability and environmental vulnerability.

The method used in combining all vulnerability components, as well as each parameter that makes up the vulnerability component is the spatial MCDA method. MCDA is a spatial combination of several criteria based on the value of each criterion (Barzehkar *et al*., 2024; Zhang, 2024). Combining several criteria is carried out using a mathematical operations overlay process based on the score and weight values of each component and the parameters that make up the components, referring to BNPB regulation number 2/2012 (BNPB, 2012). The general equation that can be utilized is as follows, with FM_{linear} (Linear Fuzzy Membership Function), v (Vulnerability indices), w (Weight of each component) and n (Number of parameters) included.

$$= FM_{linear}((w.\ v1) + (w.\ v2) + \cdots (w.\ vn)).$$

Social vulnerability

Social vulnerability consists of population density parameters and vulnerable groups. Vulnerable groups consist of the sex ratio, vulnerable age group ratio, poor population ratio, and disabled population ratio. Each parameter is analyzed using the MCDA method in accordance with BNPB Regulation Number 2/2012 (BNPB, 2012) to obtain a social vulnerability index value. The data sources used in the calculation of each parameter can be seen in Table 2.

Social vulnerability parameters apply equally to all potential disasters, except for forest and land fires. Forest and land fires do not consider social vulnerability because the disaster is outside the settlement area, so the population is not included in the analysis. To calculate population density, the method often used is to divide the total population into an administrative area (village/district/district) by the size of the administrative area. The resulting population density value is then mapped to the administrative unit. This method is called the choropleth method. When one wants to estimate the number of people exposed to a disaster, this method becomes less relevant because it is not detailed. One such method is the dasymetric method.

The dasymetric method uses a general theorem, as follows:

$$Vs = FM(0.6v_{kp}) + FM(0.1v_{rs}) + FM(0.1v_{ru}) + FM(0.1v_{rd}) + FM(0.1v_{rm})$$

The equation consists of FM (Fuzzy Membership Function), Vs (Social vulnerability index), v_{kp} (Population density index), v_{rs} (Sex ratio index), v_{ru} (Vulnerable age ratio index), v_{rd} (Disabled population ratio index), and v_{rm} (Poor population ratio index).

Physical vulnerability

Physical vulnerability consists of house parameters, public facilities and critical facilities. Each parameter was analyzed using the MCDA method according to BNPB regulation number 2 of 2012 (BNPB, 2012) to obtain a physical vulnerability index value. Physical vulnerability covers the physical facilities/buildings used by humans to live and/or carry out activities. The three main parameters used in calculating physical vulnerability are the number of houses, public facilities and critical facilities. The vulnerability value is obtained by calculating the value of loss/damage to physical facilities affected by the hazard. The nominal value of losses is calculated from the assumed unit price of compensation for each parameter.

The house parameter is the number of houses affected by hazards that have the potential to suffer material damage/loss in a village. House layer data is generally difficult to obtain, especially at the village level. Data on the number of houses that can be accessed by the public is available only until 2008 through the Village Potential data (PODES). The 2008 PODES data stated that the average number of people in one house was 5 people. Therefore, the assumption of the number of houses following the 2008 PODES was used with the following equation with rij (Number of houses on smallest unit) and Pij (Total population on i-th and j-th grid) as parameters.

$$r_{ij} = \frac{Pij}{5} \text{ and if } P_{ij} < 5 \text{ so } r_{ij} = 1$$

The loss value of the number of houses obtained is then calculated by referring to the loss compensation value applied in each district for each level of damage and adjusted to the hazard class, divided into three classes. The first one is low hazard where it was assumed there was no damage. Second one is called medium hazard with 50% of the number of houses affected by minor damage is multiplied by the regional unit price. The third is high hazard where 50% of the number of houses affected by moderate damage multiplied by the regional unit price and 50% of the number of houses affected by severe damage multiplied by the regional unit price. The use of a value of 50% is an assumption that not all houses affected by the hazard are damaged.

The public facilities parameter is the number of buildings that function as public services affected by hazards that have the potential to experience material damage/loss in a village. Spatial data on public facilities are widely available in the form of points or polygons. The minimum data required are education facilities and health facilities. Data on public facilities affected by hazards were calculated for the value of losses within one village by referring to the cost of replacing/repairing damage to facilities in the respective districts adjusted to the three-hazard class. These are low, medium and high hazards. The first class is assumed to have no damage. Whereas the second class assumes 50% of the number of houses affected by minor damage multiplied by the regional unit price. Then, the third one utilizes 50% of the number of houses affected by moderate damage multiplied by the regional unit price and 50% of the number of houses affected by severe damage multiplied by the regional unit price.

The critical facilities parameter is the number of buildings that function during a critical emergency affected by a hazard that has the potential to cause material damage/loss within a village. Some examples of critical facilities include airports, ports, and power plants. Critical facility data in the form of points and areas are also available. The minimum data required is the location of the airport building, the location of the harbor building, and the location of the power plant building. Data on critical facilities affected by hazards were calculated for the value of losses within one village by referring to the cost of

Table 1 Hazard parameters of extreme waves and abrasion

No	Parameter	Data Used	Data source
1	Wave Height	Maximum Wave Height Data	BMKG
2	Current	Flow Data	BMKG
3	Beach Typology	Beach Typology Map	BIG
4	Vegetation Cover	Land Cover Map	KLHK
5	Coastline Shape	Coastline	BIG

Source: Adapted from BNPB Regulation Number 2 of 2012 (BNPB, 2012).

Table 2. Data source for social vulnerability parameters

No	Parameter	Data Used	Data source
1	Total population	Districts in Figures	BPS
2	Age Group	Districts in Figures	BPS
3	Disabled Population	Village Potential	BPS
4	Poor Citizens	Individuals with welfare conditions up to the lowest 10% in Indonesia, above 10% - 20%, above 20% - 30%, above 30% - 40% lowest in Indonesia	National Team for the Acceleration of Poverty Reduction (TNP2K)

Source: Adapted from BNPB Peka No.2 of 2012 and BNPB Disaster Risk Technical Module, 2019.

replacement/repair of damaged facilities in the respective District or Central Government adjusted to different hazard class. The first is low hazard that is assumed to have no damage. Then, the medium hazard class estimates that 50% of the number of houses affected by minor damage multiplied by the regional unit price. Finally, the high hazard class uses 50% of the number of houses affected by moderate damage multiplied by the regional unit price and 50% of the number of houses affected by severe damage multiplied by the regional unit price.

After obtaining the index data for each parameter that makes up physical vulnerability, the next process is to combine all parameter indices into a physical vulnerability index using the following equation with $\boldsymbol{Vf}$ (Social vulnerability index), $\boldsymbol{FM}$ (Fuzzy Membership Function), $\boldsymbol{v_{rm}}$ (House loss index), $\boldsymbol{v_{fu}}$ (Public facilities loss index) and $\boldsymbol{v_{fk}}$ (Critical facilities loss index).

$$Vf = FM(0.4v_{rm}) + FM(0.3v_{fu}) + FM(0.3v_{fk})$$

Economic vulnerability

Economic vulnerability consists of GRDP (Gross Regional Domestic Product - PDRB) parameters and productive land area. Each parameter was analyzed using the MCDA method based on BNPB Regulation Number 2 of 2012 (BNPB, 2012) to obtain an economic vulnerability index value.

After obtaining index data for each parameter that makes up economic vulnerability, the next process is to combine all parameter indices into an economic vulnerability index using the following equation, adapted from available policy document with $\boldsymbol{Ve}$ (Economic Vulnerability), $\boldsymbol{FM}$ (Fuzzy Membership Function), $\boldsymbol{vpd}$ (GRDP Contribution index), and $\boldsymbol{vlp}$ (Productive Land Area loss index).

$$Ve = FM(0.6vpd) + FM(0.4vlp)$$

Environmental vulnerability

Environmental vulnerability consists of the parameters of protected forests, natural forests, mangrove forests, bushes and swamps. Each parameter is used based on the type of disaster that has been determined and analyzed using the MCDA method based on BNPB Regulation Number 2 of 2012 (BNPB, 2012) to obtain an environmental vulnerability index value.

Environmental vulnerability parameters are assessed for all potential disasters, except extreme weather. Extreme weather does not use this parameter, because it does not damage land functions or the environment. Additionally, in this research, extreme weather is not one of the disaster types to be analyzed.

The analysis of environmental vulnerability parameters does not involve weighing between parameters because it is spatial data, with each area corresponds to the land use and class, shown in Table 3. The nature of the data made it unable to be intersected with each other and can be available directly in the land use/cover data. Each parameter in the environmental vulnerability assessment is analyzed as the amount of land area in km^2 of ecological function of the environment that has the potential to not only being affected but also to suffer damage due to being in a disaster area. In other words, area with non-zero hazard index. The adjustment of parameter conditions to each hazard class can be assumed into three classes. They are Low Hazard where no damage has happened, medium hazard with 50% damaged area and high hazard, where 100% area has been damaged.

Capacity assessment

Regional capacity index is the ability of regions and communities to take actions to reduce threats and potential losses due to disasters in a structured, planned and integrated manner. At the district/city level for disaster risk assessment, regional capacity consists of 2 main components, namely regional resilience and community preparedness (Shi *et al.*, 2020). Regional resilience is assessed based on the achievements of policy makers (agencies/ institutions) at the district/city government level. Meanwhile, community preparedness is assessed based on the achievements of the community at the village level.

Table 3. Weight of environmental vulnerability parameters

Parameter	Class			
	Low (0–0.333)	Medium (0.334–0.666)	High (0.667–1)	Midpoint (min+(max-min/2))
Protected Forest [a,b,c,d,e,f,g,h]	<0.2 km^2	0.2 – 0.5 km^2	>0.5 km^2	0.35 km^2
Natural Forest [a,b,c,d,e,f,g,h]	<0.25 km^2	0.25 – 0.75 km^2	>0.75 km^2	0.5 km^2
Mangrove Field [a,b,c,d,e,f,g,h]	<0.1 km^2	0.1 – 0.3 km^2	>0.3 km^2	0.2 km^2
Shrubs [a,b,c,d,e,f,g]	<0.1 km^2	0.1 – 0.3 km^2	>0.3 km^2	0.2 km^2
Swamps [e,f,g]	<0.05 km^2	0.05 – 0.2 km^2	>0.2 km^2	0.125 km^2

The symbol inside Table 3 represents a) Landslides, b) Volcanic Eruptions, c) Drought, d) Forest and Land Fires, e) Floods, f) Flash Floods, g) Extreme Waves and Abrasion, and h) Tsunamis.

Assessment of hazard, loss, capacity and risk levels

The hazard level indicates the level of exposure of the population to hazards, but not all hazards threaten the population, of which dependent on the vulnerability index. The higher the hazard level combined with the vulnerability index, the more exposed the population is in Pesisir Barat Regency District. The loss level shows the level of damage to buildings, houses, productive land and the environment against the hazard level. The capacity level shows the comparison between the hazard level and the capacity index. Then, the risk level indicates the combination of all three indices: hazard, vulnerability, and capacity, adapted from policy documents and existing technical documents, BNPB Regulation Number 2 of 2012 (BNPB, 2012). It is further adapted from the Sendai Framework of 2025 (Nadzir *et al*., 2024).

Results and Discussion

Hazard analysis

Extreme waves are high waves caused by the effects of tropical cyclones around Indonesia and have a strong potential to cause natural disasters. Although Indonesia is not included in the tropical cyclone track area, tropical storms can strongly influence the occurrence of strong winds and high waves accompanied by heavy rain. Meanwhile, abrasion is the process of coastal erosion by the destructive power of ocean waves and currents. Based on Figure 1, extreme wave and abrasion hazards in Pesisir Barat Regency only affect the Lemong, Ngambur, Ngaras, and Pesisir Selatan sub-districts. The disruption of the coastal area's natural balance triggers the coastline's damage due to abrasion. Although natural phenomena can cause abrasion, humans are often cited as the leading cause (Hamid *et al*., 2021).

Based on the extreme wave and abrasion hazard parameters, the potential hazard area and hazard class of extreme wave and abrasion in Pesisir Barat Regency were obtained. Table 4 shows the results of the hazard assessment of extreme wave and abrasion disasters for 11 sub-districts of Pesisir Barat Regency. Based on the hazard area and hazard class affecting all sub-districts, the resulting area of extreme wave and abrasion disaster in Pesisir Barat Regency District is 0.3981 ha in total. The sub-district with the largest hazard area is in Ngaras Village 0.1706 ha or 42% of the total area of extreme weather hazard. Previous research conducted by Jasmani *et al*. (2019) resulting in variable extreme wave and coastal abrasion threats where the influencing factors are geographical conditions and hydro-oceanographic activity.

Additionally, Sriwardani *et al*. (2023) assessing the hazard of abrasion using the parameters of wave height, current speed, vegetation density, beach profile, and beach typology shows the level of abrasion hazard on the Batupoaro coast is at a high level. In line with this research, it shows that marine hydrodynamics, coastal topography, and land cover conditions have an influence on the high and low hazard of this disaster, where the hazard of extreme waves and abrasion shows an average hazard in the high class.

Lastly, Purbani *et al*. (2019) showed that 80.67% of Karimunjawa's coastal areas face the threat of extreme wave height and abrasion, especially in plantation areas and limited mangrove forests. Compared to studies on the north coast of Java and Sumatra, areas with better vegetation cover, such as mangroves, have a lower risk of abrasion. Based on previous research, vegetation conditions and coastal typology play an important role in reducing the threat of coastal disasters, with more protected areas tending to experience lower risk. This was the case with Pesisir Barat Regency, especially on Krui Selatan and Pulau Pisang, although both sub-districts located in similar situation with Ngambur and Ngaras.

Vulnerability analysis

The assessment of vulnerability for extreme wave and abrasion disasters in Pesisir Barat Regency

Table 4. Potential Hazard of Extreme Waves and Abrasion Per District in Pesisir Barat Regency

No	Subdistrict	Hazard				
		Hazard Area (km^2)			Total Area (km^2)	Class
		Low	Medium	High		
1	Bangkunat	0	0	0.1077	0.1077	High
2	Karya Penggawa	0	0	0	0	Low
3	Krui Selatan	0	0	0	0	Low
4	Lemong	0	0	0.0116	0.0116	High
5	Ngambur	0	0	0.1073	0.1073	High
6	Ngaras	0	0	0.1706	0.1706	High
7	Pesisir Selatan	0	0	0.0009	0.0009	High
8	Pesisir Tengah	0	0	0	0	Low
9	Pesisir Utara	0	0	0	0	Low
10	Pulau Pisang	0	0	0	0	Low
11	Way Krui	0	0	0	0	Low
Pesisir Barat Regency		0	0	0.3981	39.81	High

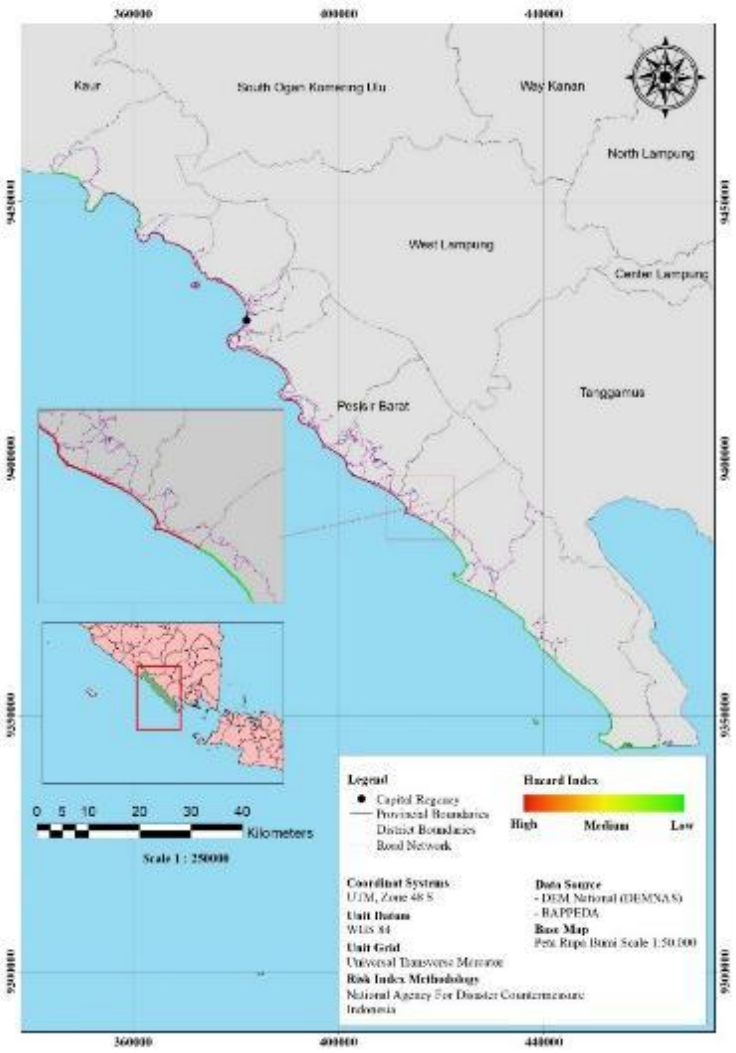

Figure 1. Map of Extreme Wave and Abrasion Hazards for Pesisir Barat Regency District

is derived from the potential exposed population and vulnerable groups as well as potential losses, both physical, economic, and environmental damage. The potential number of exposed populations and potential losses are analyzed and then displayed in the form of extreme wave and abrasion disaster vulnerability classes (Irmawan *et al*., 2024). The recapitulation of the potential exposed population and potential losses caused by extreme waves and abrasion disasters in Pesisir Barat Regency has a medium to high index.

The sub-districts with the highest potential population exposure to extreme wave and abrasion hazards are Bangkunat, parts of Ngambur, South Krui and South Pesisir, which are located off the coast of the Indian Ocean. The number of potential vulnerable population categories can illustrate the population ratio of vulnerable groups and can be used as a reference in planning the fulfillment of basic logistical needs in tsunami contingency plans, which could act as the contingency in the event of extreme waves event. In line with research from (Rumahorbo *et al*., 2023; Barzehkar *et al*., 2024) which analyzed the vulnerability of coastal areas to sea level rise using the Coastal Vulnerability Index (CVI) method with the results of 65.74% of coastal areas classified as moderate risk, with variables such as coastal elevation, slope, geomorphology, and changes in coastline due to abrasion being dominant factors. Other variables such as tides and wave height play a smaller role (Hastuti *et al*., 2022; Rocha *et al*., 2023). However, the same research (Rumahorbo *et al*., 2023) has not emphasized socio-economic variables and the impact of human activities on changes in the coastal environment.

Disaster mitigation needs to be carried out to minimize the impact of natural disasters. Preventive actions that can be taken include (Prasetyo *et al*., 2024) physical development as a form of preparation to reduce long-term risks. (Haryani *et al*., 2019) showed varying vulnerability in some locations, with mitigation focused on coastal space conservation approaches and planting vegetation such as mangroves and Pinago trees. While in this study using physical, environmental, social and economic parameters. More details of the vulnerability map are shown in Figure 2. (Permatasari, 2021) indicates that the medium and high vulnerability value of a high area is influenced by several factors, namely the high population density and vulnerable groups, the high number of poor family heads and fishing groups, the high density of settlements and the lack of vegetation in coastal areas in facing disaster threats. Mariso sub-district has a high vulnerability value category due to population and settlement density and the presence of vulnerable groups.

Based on previous research, it could be shown that local knowledge and wisdom influence the level of vulnerability, although it is not the main factor and under-represented on the existing equation to compute the index, since almost no consideration into social structure was parametrized. However, on the specific location in Pesisir Barat Regency and Lampung in general, the indexing equation fulfills the requirement to be used and fully represents the actual condition.

Capacity analysis

Based on the assessment of the capacity of Pesisir Barat Regency in facing extreme waves and abrasion, the capacity class in facing extreme waves and abrasion is obtained. The disaster capacity of extreme waves and abrasion can be seen in the following figure, Figure 3. Meanwhile, the detailed list of all 11 sub-districts in Pesisir Barat Regency is shown in Table 5.

The data calculation is based on the combined results of regional resilience with community preparedness. Overall, sub-districts in Pesisir Barat Regency have a low-capacity class. The district capacity class is obtained from the average capacity value of all sub-districts exposed to extreme wave and abrasion hazards in Pesisir Barat Regency. According to the data, South Krui and Ngambur sub-districts already have good community preparedness and capacity. However, in other sub-districts there is a need to increase regional resilience, community preparedness, and regional capacity through both the community and the government itself to anticipate extreme wave and abrasion disasters.

Risk analysis

The long coastline of the West Coast has implications for the high level of exposure to extreme waves and abrasion. The height and magnitude of ocean waves on the West Coast are caused by the morphology of the coast in the form of bays and steep sea floors. The energy of the waves will be more concentrated in the bay, and the steep sea floor will allow the waves to hit the cliff area faster. In addition, rock resistance will also affect the ability of the cliffs to withstand the propagation of waves that hit the cliffs along the West Coast coastline. Based on the results of the wave and abrasion risk assessment in Pesisir Barat Regency District that is shown in Table 6, the entire area identified as high risk covers only 0.3981 km^2. Sub-districts affected by high risk include Bangkunat, Lemong, Ngambur, Ngaras and Pesisir Selatan, with the total risk area varying from 0.0009 to 0.1706 km^2. Other sub-districts such as Karya Penggawa, South Krui, Central Pesisir, North Pesisir, Pulau Pisang, and Way Krui are categorized in the low-risk class as they do not show any significant abrasion risk area.

This analysis indicates that most of the high risks are concentrated in sub-districts that are more vulnerable to extreme waves and abrasion, while most other areas are relatively safe. This provides guidance for determining mitigation priorities, especially in high-risk sub-districts such as Ngaras and Ngambur. Additionally, this finding could be further utilized as a basis to establish and train specific communities on the location to be ready for extreme waves and to mitigate while decreasing the impact and speed of abrasion on the area. This means having a more sustainable approach to lessening the impact and risk of both types of disaster.

The results of the analysis show that all sub-districts have a risk level in the low class. Determination of the medium risk class at Pesisir Barat Regency level based on the maximum risk class at the sub-district level. The wave height classification is considered low when the wave height on the shoreline is less than 1 m, medium between 1 – 2.5 m, and high when it is more than 2.5 m. Current speed is considered low when the speed is less than 0.2 $m.s^{-1}$, medium when the speed is between 0.2 – 0.4 $m.s^{-1}$, and high when the speed is more than 0.4 $m.s^{-1}$ (Pribadi *et al.*, 2023).

The level of risk of extreme waves and abrasion is obtained from the results of the level of hazard, vulnerability, and capacity of extreme waves and abrasion in Pesisir Barat Regency which are shown in Figure 4.

Figure 4 shows that these areas with yellow and red color are at more risk of abrasion and extreme waves, which may be due to geographical and environmental factors such as more open coastal topography, a lack of natural barrier vegetation such as mangroves, or a high frequency of extreme waves. In contrast, other sub-districts such as Karya Penggawa, Krui Selatan, Pesisir Tengah, Pesisir Utara,

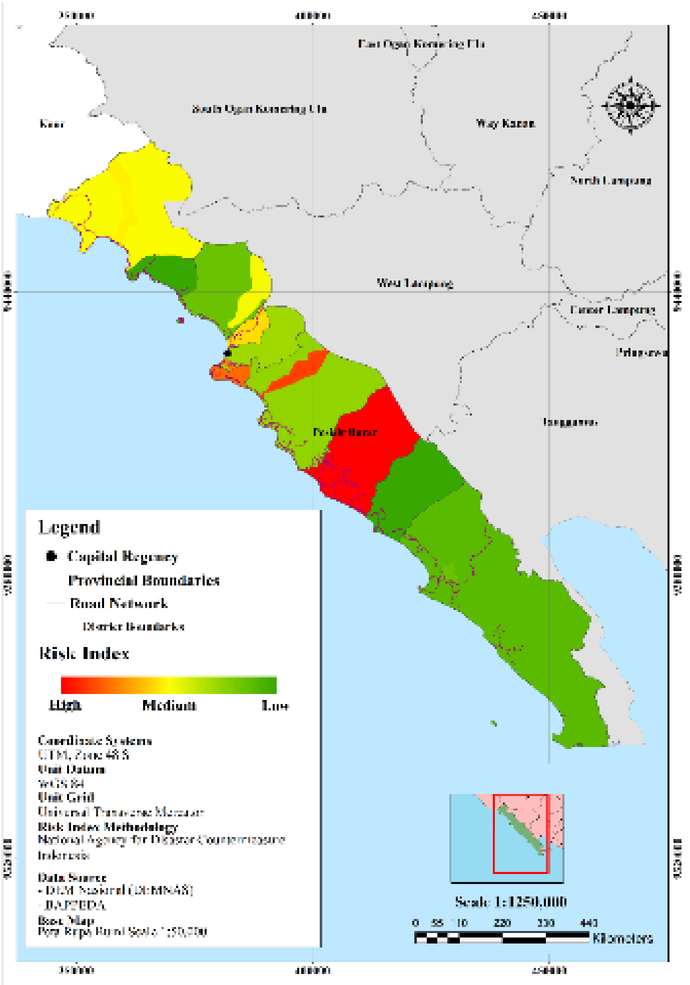

Figure 2. Capacity Map of Extreme Wave and Abrasion for Pesisir Barat Regency District

Table 5. Capacity Level on Pesisir Barat Regency District

No	Sub-District	Region Capacity Index	Preparedness Index	Capacity Index	Class
1	Bangkunat	0.24	0.29	0.26	Low
2	Karya Penggawa	0.24	0.04	0.07	Low
3	Krui Selatan	0.24	0.04	0.02	Low
4	Lemong	0.24	0.13	0.16	Low
5	Ngambur	0.24	0.35	0.19	Low
6	Ngaras	0.24	0.2	0.22	Low
7	Pesisir Selatan	0.24	0.47	0.34	Medium
8	Pesisir Tengah	0.24	0.16	0.18	Low
9	Pesisir Utara	0.24	0.59	0.41	Medium
10	Pulau Pisang	0.24	0.04	0.14	Low
11	Way Krui	0.24	0.1	0.14	Low
Pesisir Barat Regency		0.24	0.21	0.19	Low

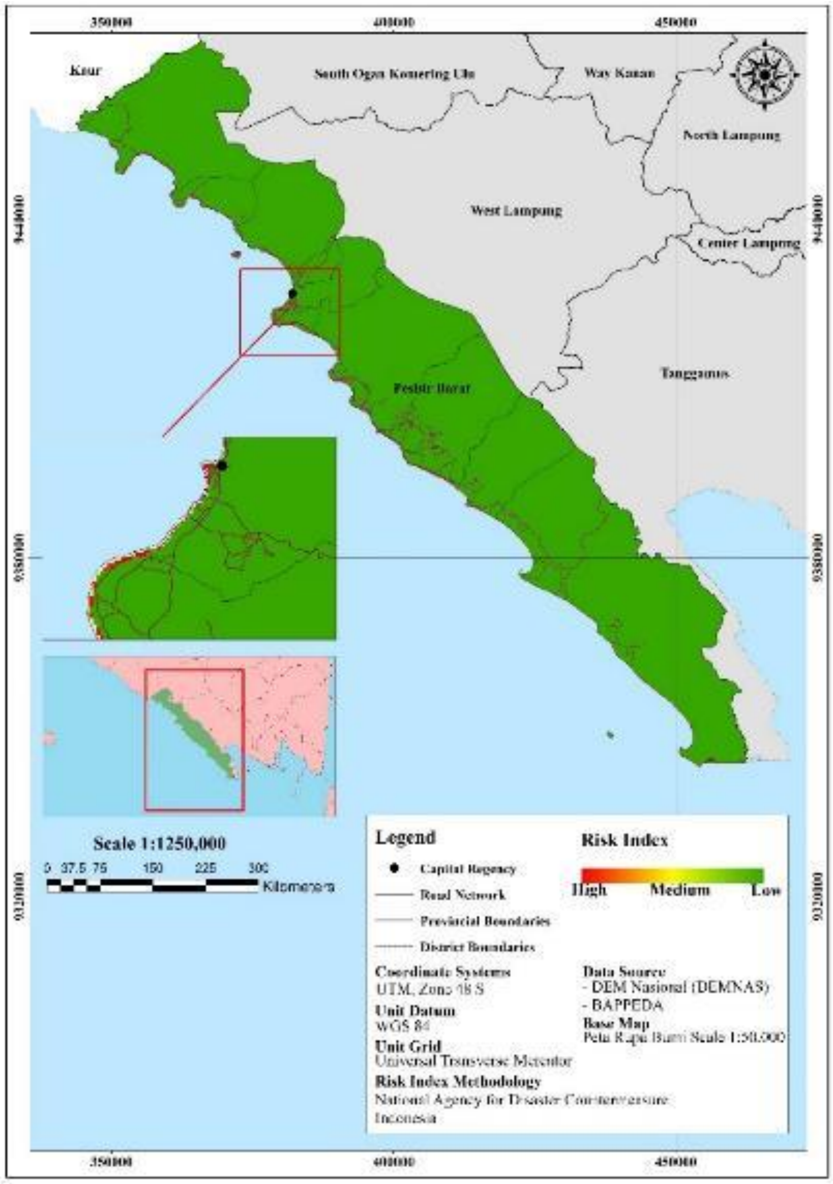

Figure 3. Risk Map of Extreme Waves and Abrasion for Pesisir Barat Regency District

Table 6. Risk Class for Extreme Waves and Abrasion in Pesisir Barat Regency

No	Sub-District	Risk				
		Risk Area (km²)			Total Area (km²)	Class
		Low	Medium	High		
1	Bangkunat	0	0	0.1077	0.1077	High
2	Karya Penggawa	0	0	0	0	Low
3	Krui Selatan	0	0	0	0	Low
4	Lemong	0	0	0.0116	0.0116	High
5	Ngambur	0	0	0.1073	0.1073	High
6	Ngaras	0	0	0.1706	0.1706	High
7	Pesisir Selatan	0	0	0.0009	0.0009	High
8	Pesisir Tengah	0	0	0	0	Low
9	Pesisir Utara	0	0	0	0	Low
10	Pulau Pisang	0	0	0	0	Low
11	Way Krui	0	0	0	0	Low
Pesisir Barat Regency		0	0	0.3981	0.3981	High

Pulau Pisang, and Way Krui do not show any significant threat of abrasion risk, which indicates the need for a different mitigation approach. The low-risk class in these sub-districts may be due to natural protection, such as coral reefs or coastal vegetation, as well as spatial planning that supports protection from waves and abrasion. These vast differences in risk underscore the importance of focused and sustainable mitigation strategies. In high-risk sub-districts, mitigation priorities include planting coastal vegetation such as mangroves, building abrasion-retaining structures, and increasing community capacity through outreach and disaster education. Meanwhile, in sub-districts with low risk, maintenance of existing natural conditions must be considered to keep the area safe from potential threats in the future.

To mitigate abrasion and flooding in coastal areas, it is recommended to build retaining structures such as walls and embankments to reduce waves, as well as planting mangrove vegetation as an effort to rehabilitate the ecosystem. Evacuation infrastructure such as safe places and evacuation routes are also important to protect the community when a disaster occurs. Increasing public awareness about the early signs of disaster and self-rescue training must be carried out regularly. In addition, the construction of flood-resistant houses and an effective early warning system must be implemented to minimize the impact of disasters. Meanwhile, (Budjang *et al*., 2021) emphasizes a combination of structural and ecosystem mitigation, such as planting mangroves and coastal forests, which is more environmentally friendly and sustainable. This ecosystem-based approach is also more commonly applied in coastal areas that have similar geographic and ecosystem conditions, such as mitigation research in the coastal areas of Kalimantan and Sumatra.

Conclusion

Pesisir Barat Regency has the potential for significant danger from extreme waves and abrasion, mainly caused by the influence of tropical cyclones and environmental changes in coastal areas. Of the 11 sub-districts analyzed, Ngaras Sub-district was the area with the highest level of hazard, with an exposed area of 0.1706 km², followed by Ngambur and Bangkunat Sub-districts. Overall, the total area potentially affected by disasters in all districts reached 0.3981 km², classified as high risk. In addition, capacity analysis shows that most sub-districts have low capacity to deal with extreme wave and abrasion disasters. Only Krui Selatan and Ngambur show relatively better (medium) preparedness. This indicates that most areas in Pesisir Barat Regency do not have adequate preparedness, both in terms of regional resilience and community preparedness, which could worsen the impact of the disaster. These findings call for prioritizing high-risk areas, strengthening protective infrastructure and risk-informed planning, and expanding community education and training. Future research should develop more accurate prediction models using remote sensing and GIS for near-real-time coastal change monitoring and examine socio-economic drivers of capacity so interventions can be better targeted and regional resilience improved.

Acknowledgement

This research was carried out thanks to the support of various parties. The author would like to thank the Regional Government of Pesisir Barat Regency for the support on providing data as well as for the financial assistance which greatly helped the smooth running of this research. Appreciation was also given to the Institut Teknologi Sumatera (ITERA) for its research funding and academic facilities that support the development of coastal disaster mitigation solutions in Pesisir Barat Regency.

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