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Spatial Analysis of Coastal Vulnerability Index to Sea Level Rise in Biak Numfor Regency (Indonesia)

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ABSTRACT

Assessing the vulnerability of coastal areas is important in evaluating impact of sea level rise due to global climate change. This study aimed to spatially analyze and map the vulnerability level of the Biak Numfor Regency's coastal area on Biak Island to the threat of sea level rise. The study area is limited to 500 m from the coastline and is divided into 383 grid cells. The Coastal Vulnerability Index (CVI) method was used to map the level of vulnerability of coastal areas based on four coastal geological variables (coastal elevation, coastal slope, geomorphology, and shoreline change) and three ocean physical process variables (tidal range, average significant wave height, and relative sea level rise). The results showed that the coastal areas of Biak Numfor Regency, belonging to the low, medium and high-risk vulnerability categories, were 77,685.63 km (32.18%), 159,084.38 km (65.74%), and 5,024.96 km (2.08%), respectively. The variables that contribute significantly to the level of vulnerability are coastal elevation, coastal slope, coastal geomorphology, and shoreline changes due to abrasion compared to tidal range, significant wave heights, and sea level rise rates. Vulnerability studies of other variables that can contribute to the vulnerability of coastal areas are needed, such as socio-economic variables and the impact of human activities on changes in the coastal environment, to obtain a comprehensive CVI value in supporting coastal mitigation planning efforts against sea level rise disasters so that they are more focused.

Keywords: spatial mapping, coastal vulnerability, coastal geologic variables, physical process variables, sea level rise, Biak Island.

INTRODUCTION

Coastal areas are relatively easy to reach and are targets for the development of human activities. The coastal area is also dynamic because processes influence it from land, sea and climate. The diversity and complexity of coastal areas in physical, chemical, biological and human dimensions make this area vulnerable to various changes. Many coastal areas face various pressures, development developments, and climate change. One characteristic of coastal areas is that they are most vulnerable to climate change, such as extreme waves and sea level rise [Mimura, 1999; Marfai and King, 2008; Triana and Wahyudi, 2020]. This vulnerability encourages all parties to plan and manage coastal areas according to their natural conditions and must be oriented towards saving the coastal environment and ecosystem. Sea level rise will have broad negative impacts, not only on the coastal environment, but also very detrimental from a social and economic standpoint, especially in coastal areas and small islands [Marfai and King, 2008].

Currently, several studies have concluded that there has been a rise in sea level in Indonesia with varying increases ranging from 0.72–14.10 mm/year [Susanto et al., 2010; Zikra et al., 2015;

Handoko et al., 2019]. Prabowo and Astjario [2012] stated that the rate of sea level rise of 2–8 mm/year is capable of inundating the coastal areas of Java Island, which have a sloping coastal morphology and will cause disasters in vulnerable coastal areas in the next 100 years. Therefore, early anticipation is needed to overcome the impact of sea level rise by conducting spatial studies of the vulnerability of coastal areas. One method to determine the vulnerability of coastal areas to sea level rise is the coastal vulnerability index (CVI). CVI is a relative ranking method based on an index scale of various variables such as geomorphology, coastal elevation, coastal slope, shoreline changes due to accretion and abrasion, relative sea level rise, wave height, and tides [Gornitz et al., 1997; Pendleton et al., 2010].

The CVI method has been used as a tool that can assist in managing coastal risk, conducting sensitivity analysis and choosing a ranking system that reflects local conditions appropriately, so that it can provide benefits for stakeholders to determine appropriate management programs in coastal areas that are vulnerable to the effects of sea level rise [Koroglu et al., 2019]. Determination of the vulnerability of coastal areas using the CVI method only uses two main variables, namely coastal geological variables (coastal elevation, geomorphology, and shoreline changes) and ocean physical process variables (tidal range, significant wave height, and sea level rise) [Gornitz, 1991]. Even so, the CVI method is relatively more popular than other methods in assessing the vulnerability of coastal areas in several countries. Various studies have used CVI to determine the vulnerability level of coastal areas. Imran et al. [2020] used CVI to assess the level of vulnerability of coastal areas after the tsunami in Palu Bay, Indonesia. Koroglu et al. [2019] applied CVI to the vulnerability of coastal areas in Barcelona, Spain. Pantus et al. [2018] used CVI for vulnerabilities along the Apulian coast of Italy. The CVI method is also used to map vulnerable areas in the coastal areas of Karnataka and Puducherry, India [Murali et al., 2013; Jana et al., 2016], coastal vulnerability in Krk Island, northern Adriatic Sea [Ružic et al., 2019] and coastal zone vulnerability of the Nile Delta, Egypt [El-Hatab, 2015].

The higher development activities and utilization of coastal areas in Biak Numfor Regency indirectly, the coastal areas are very vulnerable to coastal disasters, including sea level rise. Until now, CVI spatial information in the coastal area of Biak Numfor Regency has not been available. Therefore, this study aimed to spatially determine and map the vulnerability of the Biak Numfor Regency coastal area based on the CVI value. The results of this study are expected to provide an initial description of the coastal area of Biak Numfor Regency, which is vulnerable to sea level rise due to climate change, so that it can be used as input in planning for sustainable development and management of coastal areas.

MATERIALS AND METHODS

Study site

The administrative area of Biak Numfor Regency is mostly on Biak Island (the northern part of Papua Island, Papua Province, Indonesia) and in the waters of the Pacific Ocean. On Biak Island, there are two regencies, namely Biak Numfor Regency and Supiori Regency. This study covered ten districts in the coastal area of Biak Numfor Regency on Biak Island, namely Swandiwe, Biak Barat, Yendidori, Biak Kota, Biak Timur, Oridek District, Biak Utara, Yawosi, Warsa, and Bondifuar Districts (Figure 1). The coastal vulnerability study area is limited to 500 m from the coastline. It is divided into 383 grid cells to facilitate the process of spatial analysis of the vulnerability level of coastal areas.

Data acquisition and processing

Seven variables are used to determine the level of vulnerability of coastal areas in study locations, including coastal elevation, coastal slope, geomorphology, shoreline changes, tidal range, average significant wave height, and relative sea level rise. The data of the seven variables are mostly obtained from secondary data. In addition, field observations were carried out for the secondary data validation process, especially for coastal geomorphological, coastal slope, and shoreline change variables.

Coastal elevation and slope data were obtained from Digital Elevation Model (DEM) data. DEM can provide information on the elevation and slope of an area, facilitating interpretation. In this study, elevation and slope data for Biak Island were obtained from DEM-National (DEMNAS) produced by the Geospatial Information Agency of Indonesia (Badan Informasi

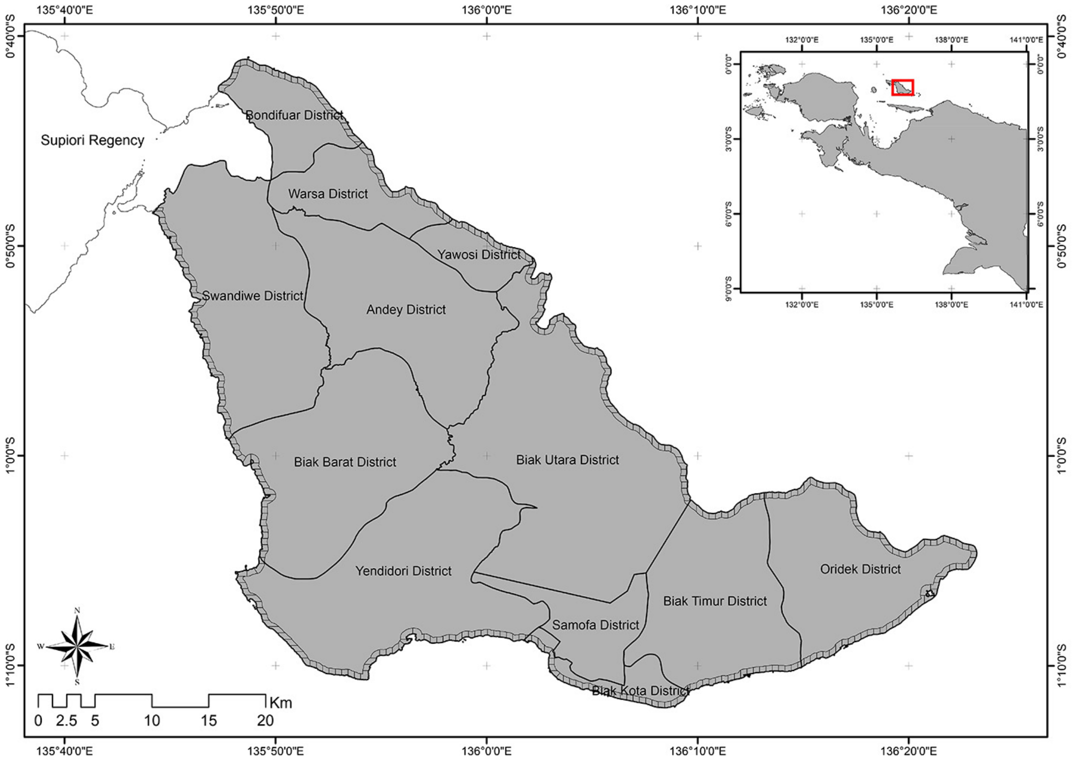

Figure 1. Map of the study area in the coastal area of Biak Island (Biak Numfor Regency, Indonesia) and the grid cell area is 500 m from the coastline

Geospasial; BIG), which can be downloaded from the website https://tanahair.indonesia.go.id/demnas. DEMNAS is generated from several data sources, including IFSAR data (5 m resolution), TERRASAR-X (5 m resolution), and ALOS PALSAR (11.25 m resolution), by adding Masspoint data resulting from stereo-plotting. DEMNAS uses the EGM2008 vertical datum with a spatial resolution of 0.27-arcsecond in the Geotiff 32-bit float data format. After the DEM data is obtained, an image mosaic is performed from 6 DEM data files, so that it becomes 1 file stored using the Universal Transverse Mercator projection system (UTM53S) and the World Geodetic System datum (WGS84). Furthermore, DEM data is cut according to the study area using the boundaries of the Biak Numfor Regency (Shp. format). Finally, the DEM data is converted into a polygon feature (Shp. format) to produce elevation and slope data. The entire DEM data processing process to produce a spatial map of elevation and slope vulnerability uses ArcMap 10.8.1 software.

Coastal geomorphology data were obtained from land cover maps produced by the Geospatial Information Agency of Indonesia (Badan Informasi Geospasial; BIG), while the mangrove spatial distribution maps from Bunting et al. [2022] and Hamuna et al. [2019]. The coastal areas with low, medium, and high cliffs were identified using the approach of the slope of the land near the coast and based on direct identification in the field. These geomorphological data are grouped into vulnerability classes, according to Gornitz [1991]. The geomorphological data obtained is a non-numeric variable, so it needs to be converted into a numerical variable using a transformation matrix to obtain numerical data for the geomorphological variable in the form of a ranking that represents the resistance of each group of geomorphological data [Hamuna et al., 2018].

Changes in the coastline at the study location refer to the results of the authors' previous research [Rumahorbo et al., 2022], where the determination of the coastline used several satellite image datasets because the study area was large and Landsat images which were free of cloud cover were not available. The coastline in 2013 used Landsat imagery on 01/12/2013, 14/10/2013, and 21/04/2013, while the coastline in 2022 used Landsat imagery on 06/04/2022. The authors used the Digital Shoreline Analysis System (DSAS) in ArcMap 10.8.1 software to determine changes in the shoreline. Shoreline changes were analyzed to obtain the shoreline change rate using the End

Point Rate (EPR) technique based on the following equation [Thieler et al., 2009]:

$$\text{EPR [m/year]} = \frac{\text{Distance between 2013 and 2022 shorelines}}{\text{Time between 2013 and 2022 shorelines}} \quad (1)$$

The tidal data used were obtained from the Geospatial Information Agency of Indonesia (Badan Informasi Geospasial; BIG), which can be downloaded from the website http://ina-sealevelmonitoring.big.go.id/ipasut/. The tidal data period used is May 2021 to April 2022. In this study, the tidal range is used as a determinant of coastal vulnerability from tidal variables. The tidal range is the difference in sea level at the Higher High-Water Level (HHWL) with the water level at the Lower Low-Water Level (LLWL).

The data on significant wave height and sea level rise were obtained from The Copernicus Program, which can be downloaded from the website https://marine.copernicus.eu/. Significant wave height data is 3 hourly instantaneous data for December 2020 to November 2021 with a spatial resolution of 0.2° × 0.2°. Meanwhile, the sea level rise data is extracted from daily sea surface height data for January 2020 to December 2021 with a spatial resolution of 0.083° × 0.083°. The data on significant wave height and sea level rise were processed using Microsoft Excel software. The Inverse Distance Weighting (IDW) interpolation technique in ArcMap 10.8.1 software was used to determine the spatial distribution of significant wave heights and sea level rise.

Data analysis

The CVI calculation in the coastal area of Biak Numfor Regency is determined by combining the values of the seven variables used to obtain vulnerability indicators. There are many criteria for the vulnerability of coastal areas that have been proposed by researchers. In this study, determining the level of elevation vulnerability refers to Gornitz [1991], coastal slope, geomorphology, shoreline changes, tidal range, and relative sea level rise refer to Pendleton et al. [2010], and the average significant wave height refers to Jadidi et al. [2013]. This reference is ideal for this study because the study area is in the Pacific Ocean and is an oceanic island. The vulnerability levels of the seven variables are grouped into 5 categories that refer to CVI calculations: very low risk, low risk, moderate, high risk, and very high risk (Table 1). The CVI method applies a simple approach to determining the vulnerability of coastal areas, which refers to the following equation (Gornitz, 1990; Pendleton et al., 2010):

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

where: a, b, c, d, e, f, and g are the variables of coastal elevation, coastal slope, geomorphology, shoreline change, tidal range, mean significant wave height, and relative sea level rise, respectively.

Finally, CVI class division refers to the vulnerability index division method of Gornitz and White [1992]. However, the number of vulnerability classes determined in this study are three categories of vulnerability, namely low, moderate, and high risk, which refer to the provisions of the National Disaster Management Agency of Indonesia [Badan Nasional Penanggulangan Bencana, 2012]. The percentage of each vulnerability category is 33.3%.

Table 1. Vulnerability level category of each variable for determining CVI

Variable	Very Low	Low	Moderate	High	Very High
Elevation (m)	>30	20.1–30	10.1–20	5.1–10	<5
Coastal slope (%)	>14.7	10.9–14.69	7.75–10.89	4.6–7.74	<4.59
Geomorphology	High cliffs	Medium cliffs	Low cliffs, alluvial plains	Cobble beaches, estuary, lagoon	Barrier beaches, sand beaches, salt marsh, mud flats, deltas, mangrove, coral reefs
Shoreline change (m/year)	>2.0	1.0–2.0	-1.0–1.0	-2.0–-1.0	<-2.0
Mean tidal range (m)	>6.0	4.0–6.0	2.0–4.0	1.0–2.0	<1.0
Mean wave height (m)	<0.5	0.5–1.0	1.0–1.5	1,5–2.0	>2.0
Relative sea level rise (mm/year)	1.8	1.81–2.5	2.51–3.0	3.01–3.4	>3.4

RESULTS AND DISCUSSION

Coastal elevation and slope

Figure 2 presents the elevation and slope levels of Biak Island (specifically in Biak Numfor Regency). In general, the elevation in the study area is highly variable. There are 5 districts in the northern part (Districts of Bondifuar, Warsa, Yawosi, Andey, and Swandiwe), which are relatively dominated by moderate elevations (>300 m), where the highest elevation is in Bondifuar District at around 727 m (Figure 2a). Meanwhile, low elevations are found along the coastal area (the lowest is in the coastal area of the Oridek District, which is -6 m below the average sea level, a swamp and mangrove area). Likewise, the slope level of the Biak Numfor Regency area also varies greatly, whereas the coastal areas with low elevations have a gentle slope. In contrast, inland areas are dominated by steep slopes (Figure 2b). On the basis of the data in the Biak Numfor KPHL Long Term Forest Management Plan [Kesatuan Pengelolaan Hutan Lindung Model Biak Numfor, 2014], the slope level of the Biak Numfor Regency area is dominated by slopes of >45% compared to slopes of 8–15%, 15–45%, and 0–8% with an area of 89,422.93 ha, 49,404.25 ha, 41,136.47 ha, and 2,902.56 ha, respectively. Slopes of >45% are dominant at elevations of 100–300 m, while slopes of 0–8%, 8–15%, and 15–45% are dominant at elevations <100 m.

On the basis of the vulnerability category of the coastal elevation variable to sea level rise used in this study, some of the study areas (500 m from the coastline) fall into the very low-risk category because high elevations (>30 m) predominate (Figure 3a). The very low-risk category is

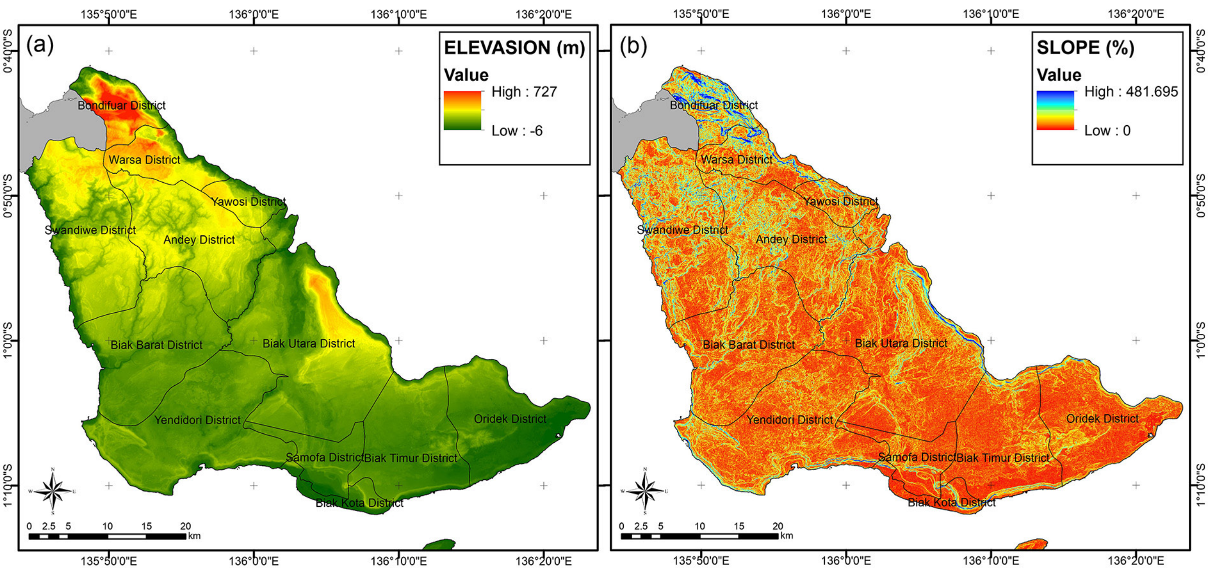

Figure 2. Map of elevation and slope of Biak Numfor Regency

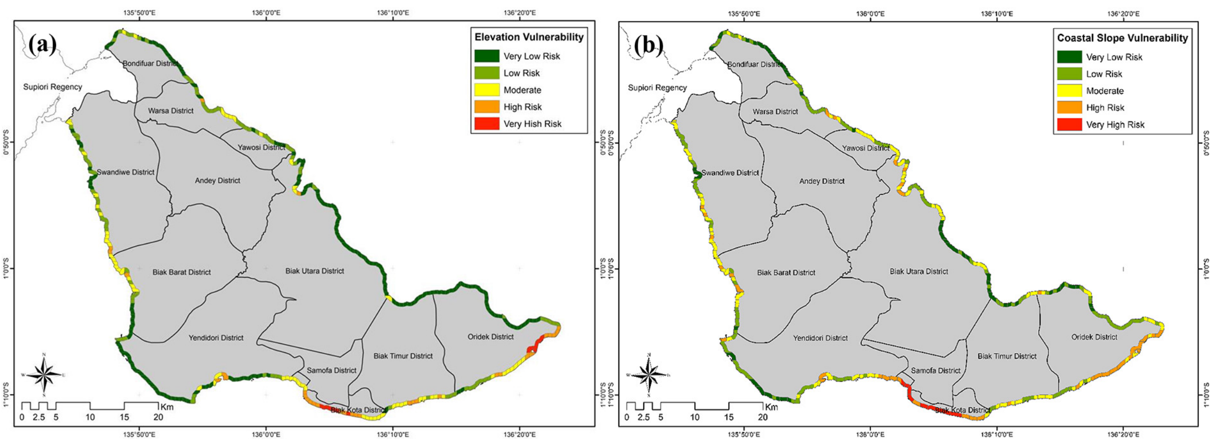

Figure 3. Map of the vulnerability of the coastal elevation and slope variables in Biak Numfor Regency

found along the coastal areas in the northern part of Biak Island, especially the Biak Utara, Bondifuar, Oridek Districts, and the northern part of the Biak Timur District. Meanwhile, in the southern part of Biak Island, the very low-risk category is found along the coastal area of the Yendidori District. The coastal area of the Biak Kota District is dominated by the moderate to the very high-risk category, because it has a lower elevation and is gentle (elevation <20 m). Similar to coastal elevation vulnerability, the level of vulnerability to the coastal slope is dominated by the very low-risk to low-risk categories, wherein that range is dominated by steep slopes (slope: >10%) (Figure 3b). However, the coastal areas along the Biak Kota District and the southern part of the Oridek District are dominated by the high risk and very high-risk categories, making them very vulnerable to sea level rise and other coastal disasters.

Coastal geomorphology

Coastal geomorphology (coastal land cover) in Biak Numfor Regency includes forests, shrubs or savanna, settlements and plantations, and alluvial plains used as rice fields and dry moor (Figure 4a). In addition to this land cover, sandy beaches and coral reefs are also found along the southern coast of Biak Island. The mangrove ecosystem is only found at certain points, namely in Swandiwe, Yendidori and Oridek Districts. In general, land cover in the coastal areas of Papua Province is dominated by forest areas (78.71%) [Badan Pusat Statistik Kabupaten Biak Numfor, 2021].

On the basis of coastal geomorphological variables, there are four categories of vulnerability: low risk, moderate, high risk, and very high risk (Figure 4b). The absence of high cliffs in the coastal area of Biak Numfor Regency results in no coastal areas with a very low-risk category. The low-risk category is only found in a few grid cells, namely in Bondifuar and Biak Utara Districts, with 2 and 6 grid cells, respectively. The moderate vulnerability category is found in almost all districts except Warsa District (high-risk category) and Biak Kota District (very high-risk category). Overall, the southern coastal area of Biak Numfor Regency is more vulnerable than the northern coastal area of Biak Numfor Regency. On the basis of the land cover, coastal areas included in the high-risk and very high-risk categories are coastal areas with land cover in the form of mangrove vegetation and settlements, where thin mangroves will make the area vulnerable and prone to inundation.

Shoreline change

On the basis of the EPR value, shoreline changes due to abrasion and accretion for 2013 to 2022 in Biak Numfor Regency vary greatly (Table 2). The average rate of shoreline changes due to abrasion ranges from -0.76 to -1.50 m/year, while due to accretion ranges from 0.53 m/year to 0.96 m/year. Abrasion is more dominant and quite significant than accretion in Biak Barat, Biak Kota, Biak Timur, Biak Utara, Oridek, Swandiwe, and Warsa Districts. In contrast, accretion is higher than abrasion only in Yawosi and Bondifuar Districts. Spatially, the levels of abrasion and accretion vary greatly along the coastal areas of Biak Numfor Regency, where most of the coastal areas experience abrasion. However, some coastal areas experience accretion (see Rumahorbo et

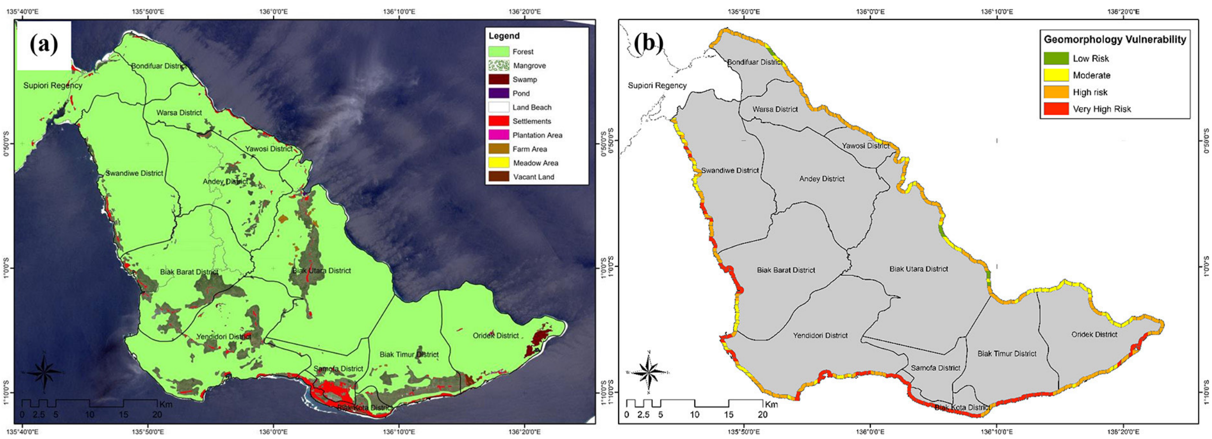

Figure 4. (a) Geomorphological (land cover) map in Biak Numfor Regency; (b) Map of the vulnerability of coastal geomorphological variables

Table 2. EPR along the shoreline of Biak Numfor Regency (from 2013 to 2022) [Rumahorbo et al., 2022]

Districts	Abrasion (m/year)	Accretion (m/year)	Average rate (m/year)
Biak Barat	-1.50	0.93	-0.41
Biak Kota	-0.76	0.62	-0.30
Biak Timur	-0.92	0.85	-0.32
Biak Utara	-1.18	0.77	-0.59
Bondifuar	-0.86	0.92	0.04
Oridek	-1.19	0.78	-0.64
Swandiwe	-1.19	0.90	-0.62
Warsa	-1.13	0.53	-0.80
Yawosi	-0.83	0.96	0.28
Yendidori	-0.81	0.75	-0.08

al., 2022). The breakwater that stretches almost along the coast of several villages in Biak Kota and Biak Timur Districts impacts low levels of abrasion, so that spatially it is dominated by the stable category [Rumahorbo et al., 2022]. Coastline changes take place slowly, but they can take place quickly if supported by natural factors and human activities [Muttaqin, 2017].

Shoreline change is a phenomenon, as well as a problem that is often encountered in coastal areas. Shoreline changes are important for assessing coastal vulnerability [Pendleton et al., 2010]. In the context of the vulnerability of coastal areas, shoreline changes are an indicator of the potential impacts of climate change and, at the same time, the resilience capacity of the coast [Koroglu et al., 2019]. The spatial distribution of shoreline change vulnerability based on the average EPR value for each grid cell is presented in Figure 5. The coastline in the Biak Timur District (southern and northern parts) is dominant in the moderate category. Likewise, the southern part of Oridek District's coastline is dominated by the moderate category. In several grid cells, there are high-risk and very high-risk categories, while the moderate to high-risk categories are dominant and spread more widely in the northern part of Oridek District. The high-risk category is almost spread along the coastline of North Biak Regency (except near the border with Yawosi District; the moderate category was dominant). Stable shoreline conditions (moderate category) are dominant in Yawosi

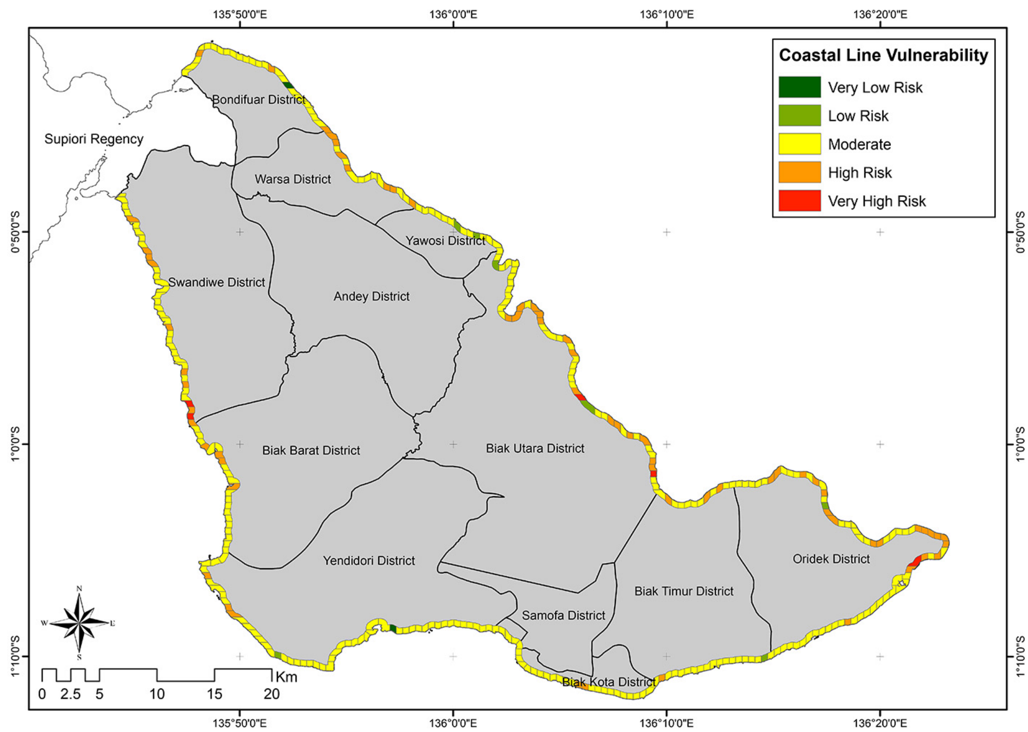

Figure 5. Map of the vulnerability of shoreline changes along the coastal area of Biak Numfor Regency

and Bondifuar Districts; even the accretion rate was more dominant than abrasion. However, the high-risk category is mostly found in Warsa District, located between the two districts. Abrasion events are also common in the Swandiwe District, where the northern part is in the moderate to high-risk category, while the southern part (border with Biak Barat District) is very high-risk. The moderate category is dominant along the coastline of Yendidori District to Biak Kota District. The very low-risk category is only in Bondifuar and Yendidori Districts (1 grid cell).

Tidal range

The type of tide in the coastal area of Biak Island is mixed tide, prevailing semi-diurnal, where there are two highs and lows in one day, but sometimes there is one high and low tide in a day with different heights and times (Figure 6). On the basis of tidal data, the tidal range in the study area ranges from 0.99 m (lowest tide) to 3.36 m (highest tide). The average value of the tidal range is 2.37 m, so it is mesotidal. Gornitz (1991) emphasizes that the coastal areas with high tidal ranges are considered very vulnerable, while low tidal ranges are considered areas with low vulnerability. On the basis of the tidal range, the entire coastal area of Biak Island is included in the moderate vulnerability category.

Significant wave height

On the basis of the average seasonally significant wave height data (Table 3), the significant wave height in the West Season (December to February) tends to be higher than in other seasons. Spatially, significant wave heights in the waters of the northern part of Biak Island tend to be higher than those in the southern part of Biak Island (Figure 7a). This difference occurs because the waters of the northern part of Biak Island directly face the Pacific Ocean, with the dominant wave direction coming from the north. Therefore, the coastal area of the southern part of Biak Island tends to be in the very low-risk category (except for the coastal area of the Oridek District). In contrast, the northern part is dominated by the low-risk category (only in Yawosi District and Biak Utara District are moderate categories) (Figure 7b).

Waves are the main variable causing abrasion or sedimentation processes in coastal areas. The impact depends on how much energy the waves throw towards the coast. The higher the significant waves that occur, the more they will affect the coastline and the geomorphological conditions of the coastal area; thus, the level of vulnerability of the coastal area will be increased. In addition, wave height is related to the danger of seawater flooding and sediment transport in coastal areas [Pendleton et al., 2005].

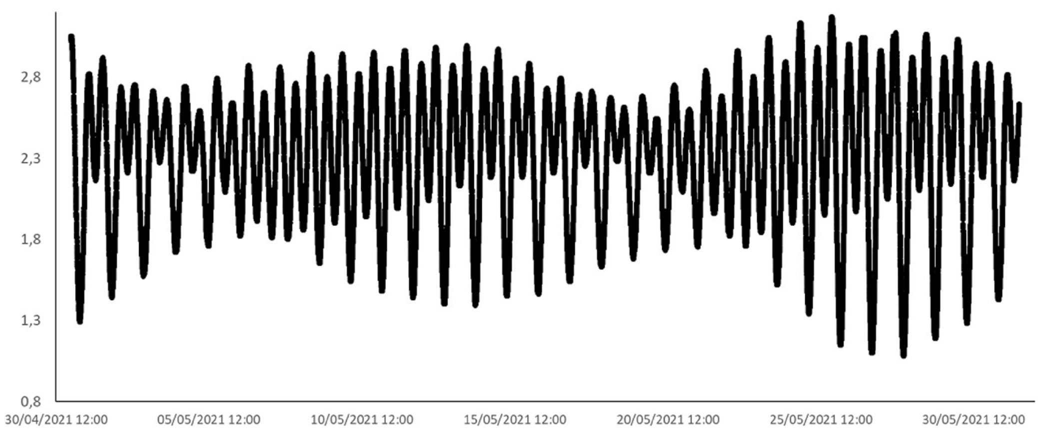

Figure 6. The tidal curve for the coastal area of Biak Numfor Regency (from 1 May to 31 May 2021)

Table 3. The average significant wave height for the period December 2020 to November 2021

Significant wave height	Period				Annual average
	December–February	March–May	June–August	September–November	
Maximum	1.481	1.257	0.713	0.964	1.101
Minimum	0.157	0.157	0.059	0.072	0.099
Average	0.934	0.793	0.434	0.592	0.683

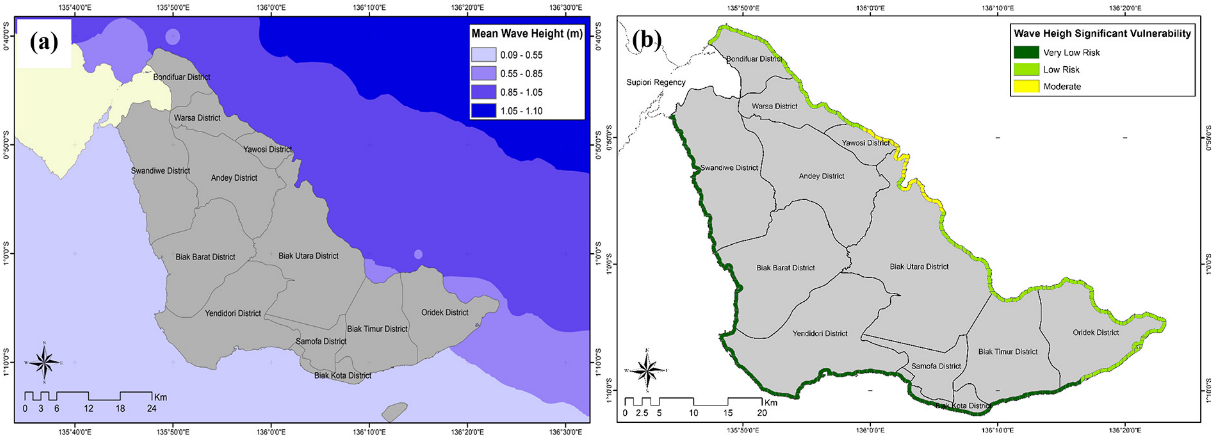

Figure 7. Map of significant wave heights in the waters of Biak Island; (a) Spatial distribution of average significant wave heights (data period: 01 January to 31 December 2021); (b) Vulnerability map of significant wave height variables

Relative sea level rise

Spatially, the relative sea level rise in the northern part of Biak Island (except Bondofuar District) is higher than in the southern part of Biak Island (Figure 8a), where the rate range of sea level rise ranges from 1.57 to 1.97 mm/year. Thus, the vulnerability level of Biak Island's coastal area is relatively low based on the variable sea level rise. The range of sea level rise in the study area is low compared to some waters in Indonesia, which range from 0.72–14.10 mm/year [Susanto et al., 2010; Zikra et al., 2015; Handoko et al., 2019]. Aside from the effects of global climate change in Indonesian waters, extreme natural phenomena (such as El Niño and La Niña) are also related to sea level variability on an annual and decade scale [Fenoglio-Marc et al., 2012]. Globally, the predicted rising sea level by observing tide gauges has been 1.80 mm/year for the last 70 years [Douglas, 2001]. The predictions using altimeter satellite data show that there has been a sea level rise of up to 3.10 ± 0.70 mm/year during the period 1993–2003 [Intergovernmental Panel on Climate Change, 2007].

Spatial distribution of coastal vulnerability index

Spatially, the coastal vulnerability index (CVI) map in Biak Numfor Regency to the risk of sea level rise disasters is mostly in the moderate category in all districts in Biak Numfor Regency (Figure 9). The low-risk category is also found in almost all districts except Yawosi District. The high-risk category is only found in a few grid cells in Oridek and Biak Utara Districts, where the grid cells are dominated by mangrove forests, swamps and bay areas which are very susceptible to change and are found in coastal areas with very low elevations. Overall, the low, medium, and high-risk categories are 77,685.63

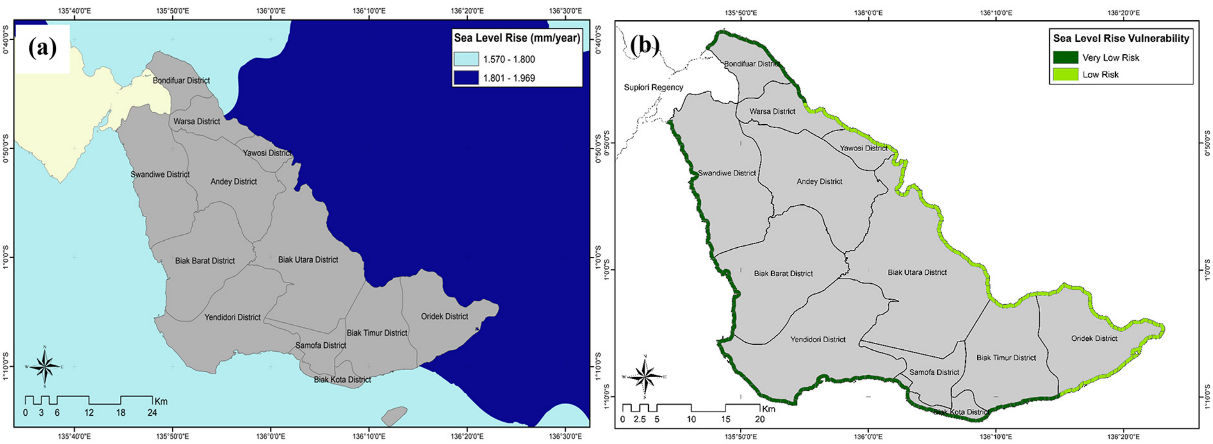

Figure 8. Map of sea level rise in the waters of Biak Island; (a) Spatial distribution of relative sea level rise (data period: January 2020 to December 2021); (b) Vulnerability map of relative sea level rise variables

km (32.18%), 159,084.38 km (65.74%), and 5,024.96 km (2.08%), respectively (Table 4). The proportion of each CVI category can indicate the spatial characteristics of each vulnerability category in a coastal area. According to Kasim and Siregar [2012], the proportion of ranking for each vulnerability category varies, indicating that the category's spatial characteristics are local (relative) on the assessment area scale. Conversely, if it is constant or almost constant along the coastline, it indicates that the vulnerability category is regional to global.

In this study, the variables that affect the vulnerability of coastal areas in Biak Numfor Regency are coastal geology variables, including coastal elevation, coastal slope, coastal geomorphology, and shoreline changes due to abrasion. Coastal elevation and slope are relevant coastal variables. They can affect the morphological and hydrodynamic processes in coastal areas, such as sedimentation rates, wave characteristics, sediment size distribution, and lowland inundation [Athanasiou et al., 2019; Oloyede et al., 2022]. The coastal elevation is closely related to the weakness of coastal areas to the dangers of seawater inundation [Gornitd, 1991; Shaw et al., 1998; Hamuna et al., 2018], while the slope of the coast is not only related to the relative risk of inundation but is also

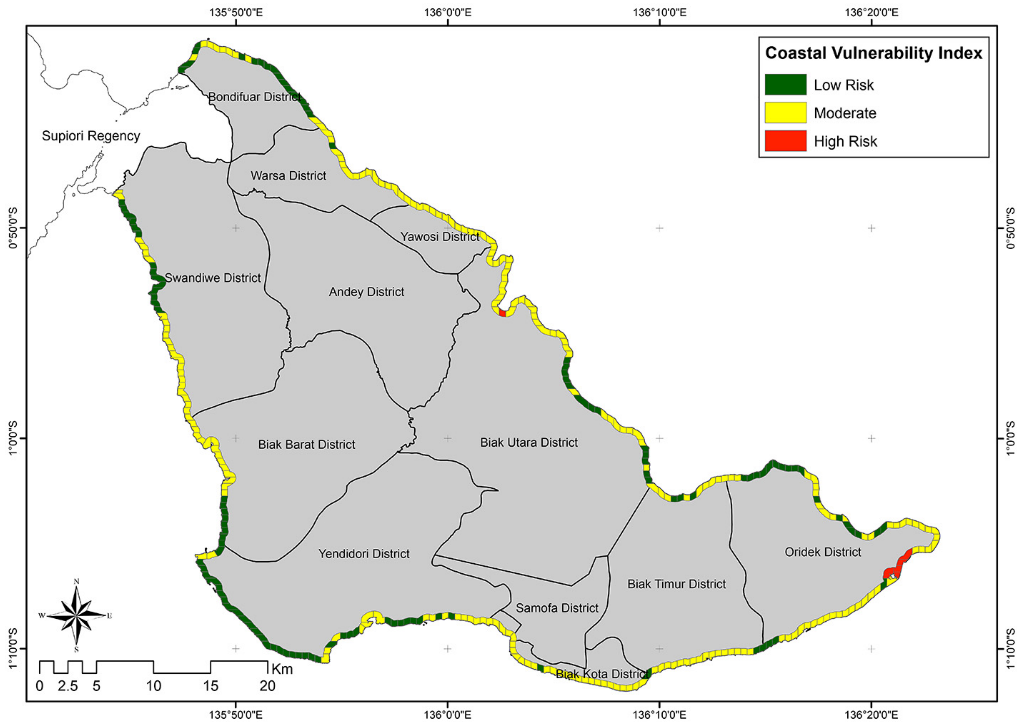

Figure 9. Spatial distribution of the coastal vulnerability index in the coastal area of Biak Island (Biak Numfor Regency)

Table 4. Coastal vulnerability index along the coastal area of Biak Numfor Regency

Districts	Coastal Vulnerability Index		
	Low risk (km)	Moderate (km)	High risk (km)
Biak Barat	4,331.75	10,577.22	-
Biak Kota	1,152.03	18,060.38	-
Biak Timur	3,095.98	17,105.52	-
Biak Utara	8,327.52	26,152.97	627.09
Bondifuar	11,850.72	5,711.60	-
Oridek	12,732.50	30,480.32	4,397.87
Swandiwe	10,556.89	16,081.97	-
Warsa	600.39	11,333.73	-
Yawosi	-	8,211.55	-
Yendidori	25,217.85	15,369.12	-

an indicator of the potential speed of shoreline retreat [Nageswara Rao et al., 2008; Lopez Royo et al., 2016; Koroglu et al., 2019]. The impact of sea level rise will not be significant in steep coastal areas when compared to sloping coasts, where sea level rise can submerge most of the coastal areas [Nageswara Rao et al., 2008] and allows for permanent seawater inundation in coastal areas with low elevations near the coastline [Koroglu et al., 2019]. The contribution to shoreline changes due to abrasion is highly dependent on other variables, such as natural factors and human activities [Marfai, 2014; Passeri et al., 2015; Rumahorbo et al., 2022]. Variable slope (coastal elevation and slope) and abrasion rate are important variables for coastal vulnerability because slopes and abrasion rates can vary along the coastline [Duriyapong and Nakhapakorn, 2011; Imran et al., 2020].

Most of the significant geomorphological variable contributions come from land cover types dominated by infrastructure (buildings and settlements) and coastal ecosystems (coral reefs and seagrasses) scattered along the coastal areas. The development of residential locations is closely related to the work of most fishermen, so the settlements are located along the coastal areas. In addition, Biak Numfor Regency is a coastal city, so city development is more concentrated in coastal areas. The implication of increased development and human activity in coastal areas will increase the vulnerability of coastal areas to coastal disasters (Zonkouan et al., 2022). It should be remembered that regardless of the form of land cover in coastal areas, with low elevation it will provide opportunities or impact seawater inundation [Hamuna et al., 2018].

Variables of ocean physical processes such as tides, significant wave heights, and sea level rise rates have no significant effect on the vulnerability of coastal areas in the study locations. However, it must be remembered that these variables (especially significant waves and sea level rise) are temporal so that they can have a significant effect in the future. The significant wave height data used in this study is the average annual significant wave height, so some coastal areas may become vulnerable to very vulnerable when using daily significant wave height data, especially during the western season (December to February). The rise in global sea levels is highly anticipated to increase in 2030, 2050, and 2100, as high as 9–18 cm, 15–38 cm, and 30–130 cm, respectively [Wuebbles et al., 2017]. Likewise, in the report of the Intergovernmental Panel on Climate Change [2013], coastal areas in Southeast Asia will experience a sea level rise 10–15% higher than the global average sea level rise. Of course, significant wave highs and sea level rise will impact other vulnerability variables, namely changes in the coastline (especially abrasion due to sea waves).

The CVI value generated in this study is predicted to be still able to change along with the high level of infrastructure and settlement development in coastal areas. This condition will result in considerable pressure on environmental conditions along the coastal area. In addition, the limited number of variables used as input in coastal vulnerability assessment affects the vulnerability status in coastal areas. Coastal vulnerability assessment using the CVI method is only based on an assessment of physical variables. Still, it does not consider the impact of human activities on changes in the coastal environment in the physical processes being assessed [Abuodha and Woodroffe, 2010]. Moreover, the increase in sea level can impact changes in the vulnerability status of coastal areas, even if for quite a long period. Increased CVI must be watched out for, because it will affect decision-making in determining the appropriate management program in coastal areas with a high level of vulnerability.

CONCLUSIONS

This study has produced a spatial description of the coastal area of Biak Numfor Regency with CVI values that are at low to high risk of sea level rise. The level of vulnerability of the coastal area of Biak Numfor Regency is grouped into three vulnerability categories, namely low, moderate, and high risk along 77,685.63 km (32.18%), 159,084.38 km (65.74%), and 5,024.96 km (2.08%), respectively. The high-risk category is only found in Oridek and Biak Utara Districts, dominated by mangrove forests, swamps and bay areas which are vulnerable and found in coastal areas with very low elevations. The variables that contribute significantly to the level of vulnerability of coastal areas are coastal elevation, coastal slope, coastal geomorphology, and shoreline changes due to abrasion. However, the limited number of variables used in this study is certainly a consideration for further studies. For example, adding socio-economic variables and the impact of human activities on changes in the coastal environment to obtain a comprehensive CVI value so that coastal mitigation plans for sea level rise are more focused and facilitate policy choices for coastal authorities in making decisions for setting mitigation priorities appropriate in the coastal areas that have high vulnerability.

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