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Coastal Vulnerability Assessment Based on Coastal Vulnerability Index (CVI) on the Coastal Area of Kolaka Regency, Southeast Sulawesi, Indonesia

Gaby Nanda Kharisma[a], Triani[b], Azura Ulfa[c], Rizki Adriadi Ghiffari[d], Hermis Anjas Sari[a]

[a] Department of Geography Education, Universitas Sembilanbelas November Kolaka, Kolaka, 93517, Indonesia

[b] Department of Physics Education, Universitas Sembilanbelas November Kolaka, Kolaka, 93517, Indonesia

[c] Research Center for Geoinformatics, BRIN, Jakarta, 40135, Indonesia

[d] Spatial Planning Laboratory, Department of Development Geography, Faculty of Geography, Universitas Gadjah Mada, Yogyakarta, 55581, Indonesia

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ABSTRACT

The main purpose of this study was to investigate vulnerability assessments along the coastal area and the small island of the Kolaka Regency, Southeast Sulawesi, Indonesia. This study used spatial analysis to estimate the Coastal Vulnerability Index (CVI). CVI was assessed using eight variables (geomorphology, coastal defense structures, beach slope, average significant wave height, average tidal range, relative Sea Level Rise (SLR), shoreline change, and land use). The variables generated five categories of coastal vulnerability, ranging from very low to very high category vulnerability. The coastal vulnerability in the Kolaka coastal area varies from very low to very high. Therefore, this study suggests that policymakers need to make a long-term plan for local coastal zones and prioritize a comprehensive hazard-based analysis through a long-term strategy for local coastal zones to mitigate future hazard losses.

Introduction

A significant number of coastal regions worldwide are susceptible to erosion and face the potential threat of tidal floods, hurricanes, storm surges, wave activity, sea-level rise, ecosystem debasement, and vulnerability to climate change [1–4]. Indonesia is widely known as the second longest coastline in the world and has ample natural resources and biodiversity [5,6]. However, high concentrations of economic activity have led to a higher potential for degradation in coastal areas [7].

The coastline of Indonesia is the most dynamic in terms of economic activities, such as marine transportation, offshore industry, maritime industry, and tourism [6]. However, a significant part of Indonesia's coastal area is sensitive to Sea Level Rise/SLR and is exposed to substantial impacts from climate change, catastrophic events, and anthropogenic variables [8,9]. Kolaka Regency is located in Southeast Sulawesi Province, which is categorized as a coastal regency [10]. There are 12 subdistricts in Kolaka Regency, 83% (10 subdistricts) of which are directly adjacent to the sea. Administratively, this regency has an area of 3,283.59 km^2 or equivalent to 8.63% of Southeast Sulawesi Province. The coastal zones of the Kolaka Regency are hydrologically dominated by the Bone Gulf in the west. The impact of climate change on the Kolaka Regency has affected an increase in average ± 0.804–0.866 °C, with the threat of flooding hitting the low-lying coast in the moderate categories [11]. However, there are no previous studies on the coastal vulnerability of the Kolaka Regency.

Because of its location, which is also related to the current population of ± 246,137 people, the annual population growth rate during 2020–2022 is 1.98%. This study is considered necessary as a first step in assessing disaster risk reduction strategies for coastal areas and small islands. This study investigates

Corresponding Author: Gaby Nanda Kharisma gabykharisma.usnkolaka@gmail.com Department of Geography Education, Universitas Sembilanbelas November Kolaka, Kolaka, Indonesia.

vulnerability assessments along the coastal area and the small island of Kolaka Regency, Southeast Sulawesi, Indonesia. Coastal vulnerability assessments have already been performed using a plethora of methods in several studies at different periods in Indonesia in the recent past to raise awareness about coastal disasters. Preliminary studies relating to the characteristics and typologies of some coastal areas and small islands in Kolaka Regency studied by Kharisma et al. [10] with the result that there are three types of coastal area typologies, including Marine deposition coast, Sub-aerial deposition coast, and Coast built by organisms

Material and Methods

Study Area

This research was conducted in the coastal area and small islands of Kolaka Regency, Southeast Sulawesi Province, Indonesia (Figure 1). The dominant number of subdistricts located in coastal areas and the dense population living in these areas add to the complexity of problems related to coastal vulnerability in Kolaka Regency. Kolaka is one regency in Southeast Sulawesi between latitudes 3°36'–4°35' S and longitudes 120°45'–121°52' E [12]. It encompasses 10 subdistricts: Iwoimendaa, Wolo, Samaturu, Latambaga, Kolaka, Wundulako, Pomalaa, Tanggetada, Watubangga, and Toari. The research period started from April to October 2023.

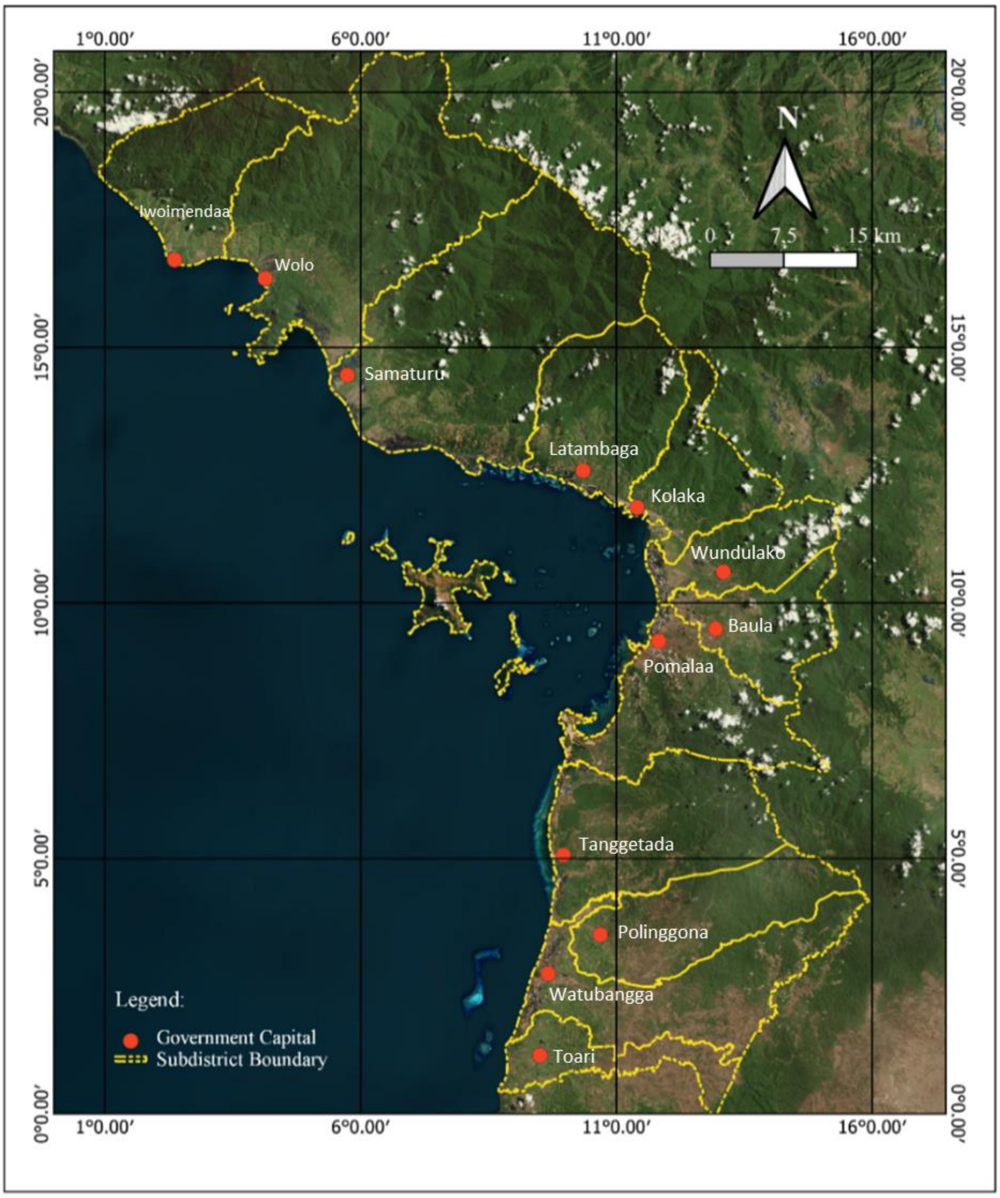

Figure 1. Map of the study area.

Data Collection

An overview of coastal vulnerabilities using the CVI method considers eight variables: 1) geomorphology; 2) coastal defense structures; 3) beach slope; 4) average significant wave height; 5) average tidal range; 6) relative Sea-Level rise; 7) shoreline change; and 8) land use. All variables were classified and scored as described in a previous research [13]. Geomorphology is determined by interpreting morphological aspects, constituent materials, and geomorphological processes. The morphology of the study area was obtained by interpretation of the Indonesian Topographic Map (*Rupa Bumi Indonesia/* RBI). The constituent materials were obtained from the Kolaka Sheet Geological Map (2111–2211). The geomorphological process was obtained by identifying aerial photos and Landsat 8 OLI imagery for 2023. These three aspects were used to identify the geomorphology of each coastal type. Coastal defense structures were interpreted using the latest aerial photos and satellite images, and field checks were performed. The slope was generated using the Indonesia Digital Elevation Model (DEM) known as DEMNAS (7 m of spatial resolution) which was provided by the Indonesian Geospatial Information Agency known as *Badan Informasi Geospasial* (BIG). DEM data encompassed 34 scenes.

Significant wave heights are derived from and derived from altimetry satellites provided by the European Center for Medium-Range Weather Forecasts (ECMWF). Tidal ranges are calculated by processing the datum data and harmonic constants. Shoreline changes are obtained from the shoreline extraction stage, which combines the single-band and band ratio methods [13]. Landsat 7 ETM+ (2000–2012) & Landsat 8 OLI imagery (2014–2022) and use Digital Shoreline Analysis System (DSAS). The DSAS enables users to compute statistical measures of the rate of change based on a sequential collection of vector coastline positions over time [14]. Meanwhile, the land use used in this analysis was obtained from the Indonesia Topographic Map (RBI) 2022, with boundary for interpretation set at 100 m, in accordance with Regulation Ministry of Marine Affairs and Fisheries Republic of Indonesia No. 21/PERMEN-KP/2018 on the Coastal Boundary Calculation Scheme.

Analysis Method

To examine the coastal vulnerability along the coast of Kolaka Regency, a method was implemented, as presented in Figure 2, based on previous research [15] with modifications. The subdistricts were used as analytical unit to ensure accuracy. All variables were classified and scored as described in a previous research [13]. The CVI variables are presented in Table 1, while the CVI equation is shown in Equation 1. Additionally, Table 2 provides the CVI percentile classification based on previous studies [13,16].

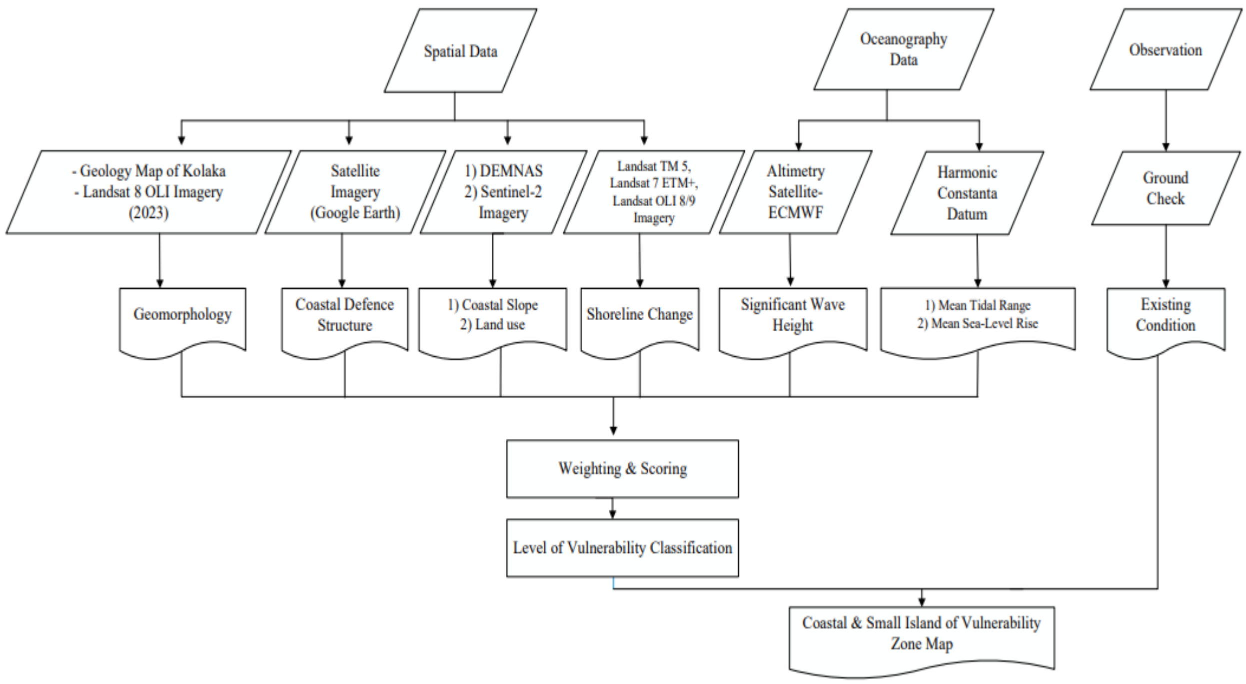

Figure 2. Research flowchart.

Table 1. Rank of coastal vulnerability variables.

Code	Variables	Vulnerability ranks				
		Very low (1)	Low (2)	Moderate (3)	High (4)	Very high (5)
a	Geomorphology	*Rocky Cliff, Coastal fjord*	*Medium Cliff, Incented Coast*	*Low Cliff, Glacial Drift, Alluvial Plains*	*Cobble Beaches, Estuary, Lagoon*	*Barrier Beaches, Sand Beaches, Salt Marsh, Mud flats, Delta, Mangroves, Coral Reefs*
b	Coastal structure	*Emerged Seawall*	-	*Submerged breakwaters and groins*	*Jetty*	*No structure*
c	Slope (%)	> 12	12–9	9–6	6–3	< 3
d	Wave Height (m)	< 0.8	0.9–1.3	1.4–1.8	1.9–2.3	> 2.4
e	Tidal range (m)	< 0.5	0.5–1	1–1.5	1.5–2	> 2
f	Sea-Level Rise (SLR) (m)	< 0.24	0.25–0.3	0.31–0.4	0.41–0.5	> 0.51
g	Shoreline change (m/y)	> 2	1.9–1	0.9–0.9	–1–1.9	< –2
h	Landuse	*No Development*	*Forest*	*Agriculture and pasture*	*Industry*	*Urban*

$$\mathrm{CVI} = \sqrt{\frac{a \times b \times c \times d \times e \times f \times g \times h}{8}} \quad (1)$$

Table 2. Percentile classiffication of CVI.

Percentile	Classiffication
≤ 20	Very low
20–40	Low
40–60	Moderate
60–80	High
≥ 80	Very high

Results and Discussion

The location of the coast of the Kolaka Regency has a significant impact on the existence of Bone Gulf. The Gulf is situated on the western part of Kolaka Regency and is located between the South and the southeast arms of Sulawesi Island, occupying an area of approximately ± 50,000 km^2 with the deepest part reaching 2.5 km [17].

Geomorphology

According to the results of the interpretation of Kolaka Sheet Geological Map 2111–2211, the coastal territory of Kolaka Regency is part of the Alangga Formation, the Pompangeo Complex, the Mekongga Complex, and part of the Ultramafic Complex. As a result of the analysis of geomorphological aspects in the area of study, there are ten units of landforms. Geomorphology is the study of landforms, which encompasses three major elements: landform, geomorphic processes, and land-surface history [18]. However, in its natural state, the physical characteristics of a coastline are shaped by a balanced and dynamic relationship between the coastal landform and forces exerted by waves and tidal currents [19].

The area includes a variety of landform units such as alluvial plain, delta, sand beach, laguna, mangrove, estuary, embankment, salt marsh, low cliff, and moor (Figure 3a). The most prevalent landform units are alluvial plains and mangroves along The Kolaka Coast. These represent the Holocene Epoch from the Quaternary period. Mangrove ecosystems have spread throughout the coastal regions of this district. Mangroves are vegetation along the coastline that can adapt to seawater and provide benefits in several areas of life [20]. Based on the previous research, the mangrove ecosystem in this location appears to be in good condition, with a high density and percentage of mangrove coverage, particularly in the coastal area of Latambaga District, which has the potential to act as a carbon sink and store. It has been reported that the total carbon stocks stored in mangrove vegetation range from 35.75 to 106.57 tons per hectare [21]. Despite their high density and coverage, previous studies [22] have explained that geomorphic units such as mangrove ecosystems, mudflats, beach terraces, spits, salt pans, beaches with sand-dominant material, sand dunes, and estuaries are identified as very highly vulnerable to SLR and coastal erosion. In the context of coastal vulnerability, these units have a high potential to be inundated by SLR and damaged by coastal erosion in low-lying areas. Based on the vulnerability classification of geomorphological aspects (Table 1), this region is moderate to very high, which is spatially shown in Figure 3b.

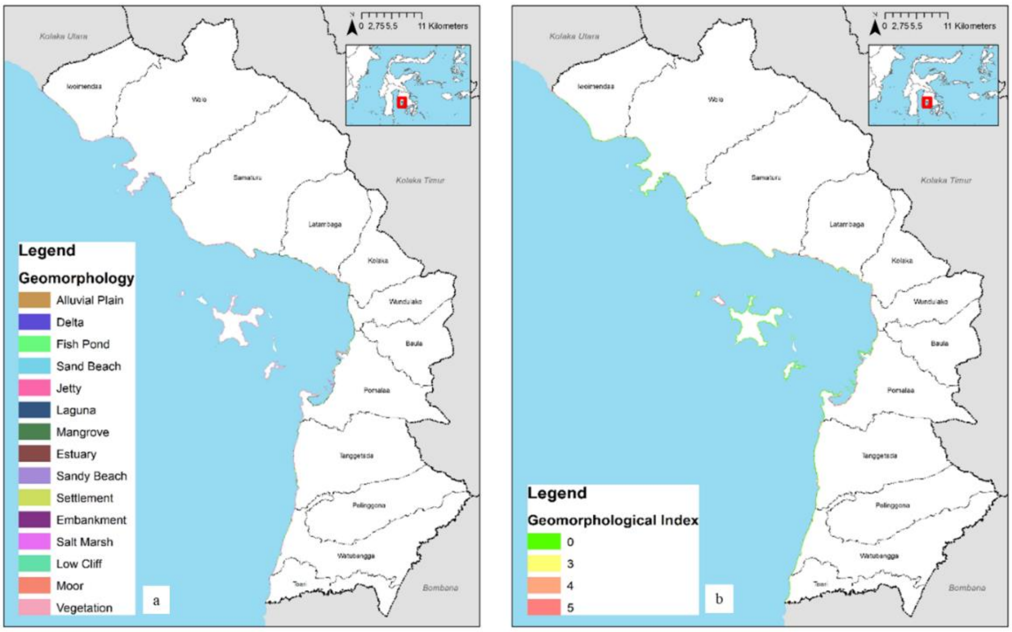

Figure 3. Geomorphology classification (a); Geomorphological Index (b).

Coastal Defense Structures

Coastal protection conserves and stabilizes the territory from the land side and protects it from coastal flooding [23]. The coastal defense structure in this study is an artificial structure. The structure was interpreted using the latest satellite imagery and Google Earth Pro (version 7.3.6), as well as field survey to verify the existing conditions. Coastal defenses at the study site were divided into three categories: jetty, embankment, and no coastal structure defense (Figure 4a). However, defensive structures were found in six subdistricts, including Kolaka, Wundulako, Baula, Pomalaa, Tanggetada, and Toari, as shown in Figure 4a. Moreover, the vulnerability ranks varied from high to very high (Figure 4b).

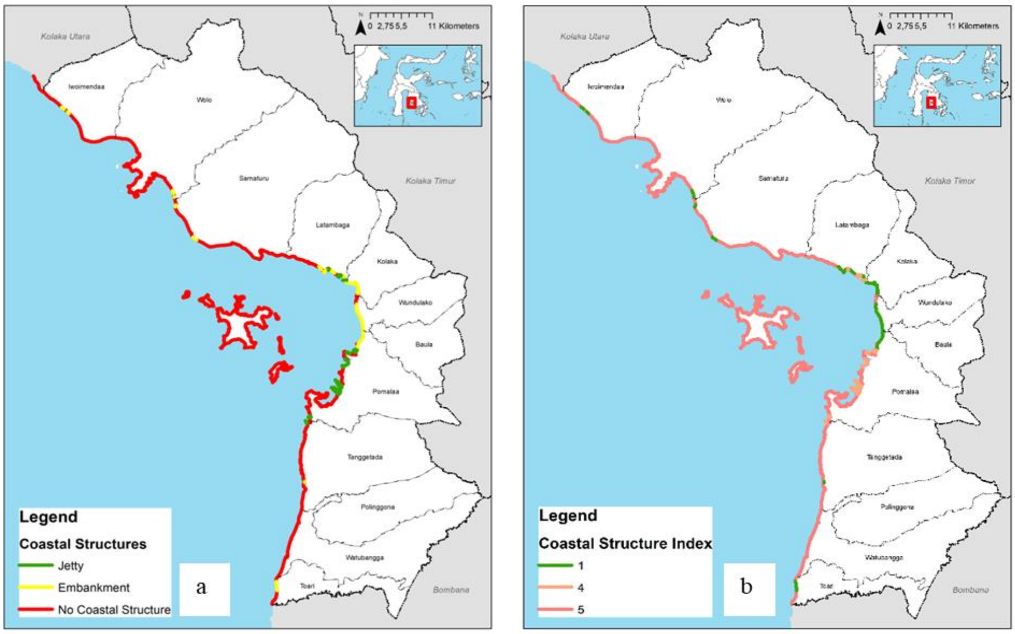

Figure 4. Coastal structure (a); Coastal Structure Index (b).

Coastal Slope

Coastal slope plays a significant role in delineating hydrodynamic and morphological processes while also assessing coastal vulnerability [24]. Coastal regions situated at low elevations, such as deltas, coastal wetlands, and coral atolls, are at risk of flooding due to SLR. The loss of land due to flooding is directly determined by the slope of the terrain; the flatter the slope, the more significant is the land loss [25]. This low-lying coastal areas are highly vulnerable to coastal disasters. From the results of the image analysis, the coastline varied from flat to sloping. The dominance of existing coastal slopes is categorized as flat (Figure 5a and 5b), for instance in the Iwoimendaa, Samaturu, Latambaga, and Kolaka Subdistricts. This condition was classified as highly vulnerable. The variation in coastal slope shows diversity, especially in the islands that are administered to the Wundulako District, with the results of the analysis of the slope categorized as very steep.

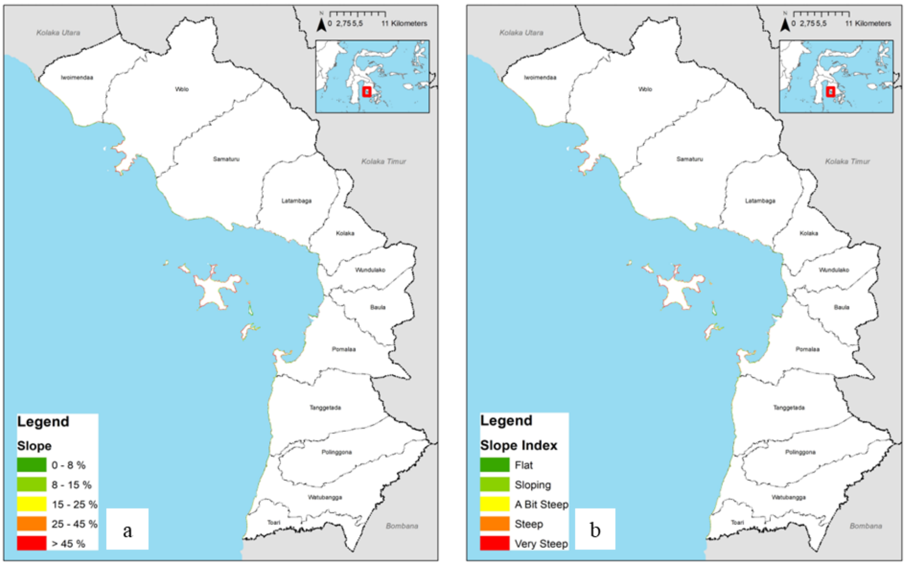

Figure 5. Coastal slope (a); Coastal Slope Index (b).

Significant Wave Heights

According to data obtained from ECMWF by altimetry satellite during 2014–2023 (full time and full day data), waves are identified as the primary hydrodynamic forces acting on coastal beaches, and are capable of triggering morphodynamics (6). The wave height in the coastal region of Kolaka regency is at an altitude of 0.60 to 0.63 m (Figure 6a). Overall, the significant wave height index was in the moderate category, with variations in wave altitude reaching less than 3 m, as shown in Figure 6b.

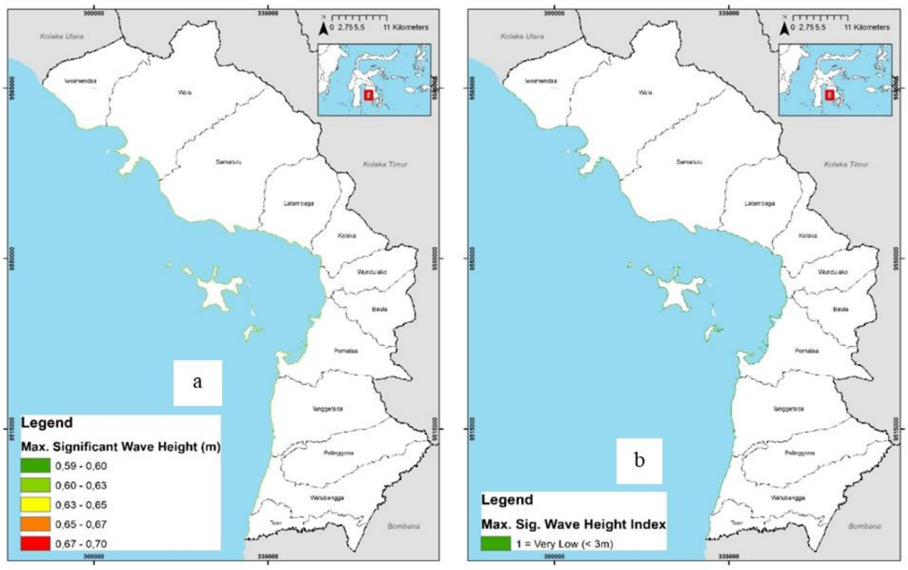

Figure 6. Significant wave height (a); Significant Wave Height Index (b).

Tidal Range

The tidal varies depending on geographical location and local conditions, ranging from a few centimeters to several meters [26]. The maximum tidal distance was used for purpose of this study. In coastal areas, the maximum tidal distance varied from 2.79 to 3.10 meters (Figure 7a). The maximum tidal range in Iwoimendaa, Wolo, and Samaturu Subdistricts ranging from 2.79 to 2.85 meters. Latambaga District, Kolaka District, Wundulako District, and Pomalaa District vary from 2.85 to 2.97 meters. Meanwhile, Tanggetada District, Watubangga District, and Toari District range from 2.97 to 3.10 meters. The maximum tidal range index was categorized as moderate, with a range of 2–4 m (Figure 7b). On behalf of coastal vulnerability, higher tidal ranges can induce rapid erosion and coastal collapse owing to increased wave attack and vertical range [22], and a high tidal range could lead to a high potential for coastal disasters.

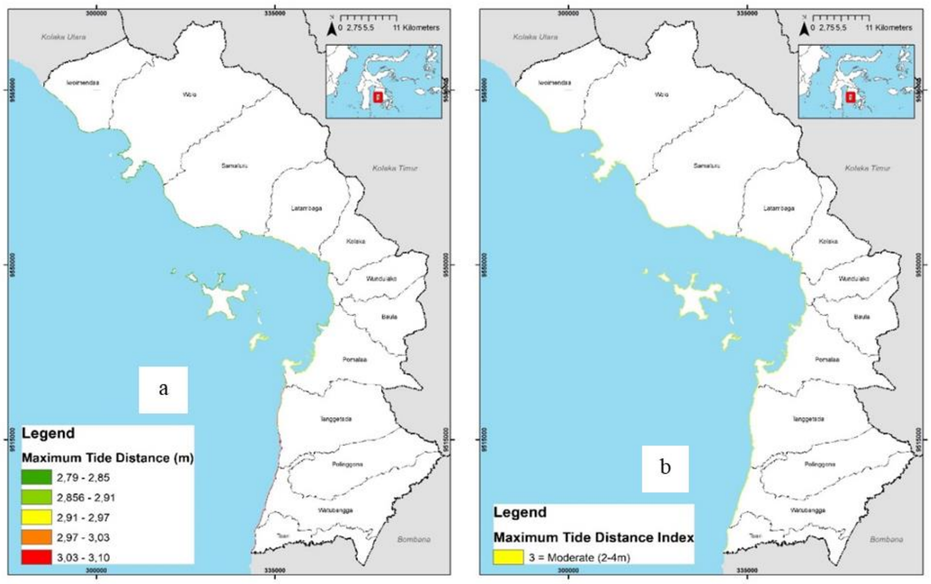

Figure 7. Maximum tide distance (a); Maximum Tide Distance Index (b).

Shoreline Changes

Coastal zones are generally influenced by fluctuations in oceanic conditions, atmospheric dynamics, and anthropogenic activity [27]. Based on the time series data from Landsat 7 ETM+ & Landsat 8 OLI, coastline changes in the coastal area of the Kolaka Regency have been observed over a period of 37 years. This district has experienced erosion and accretion (Figure 8).

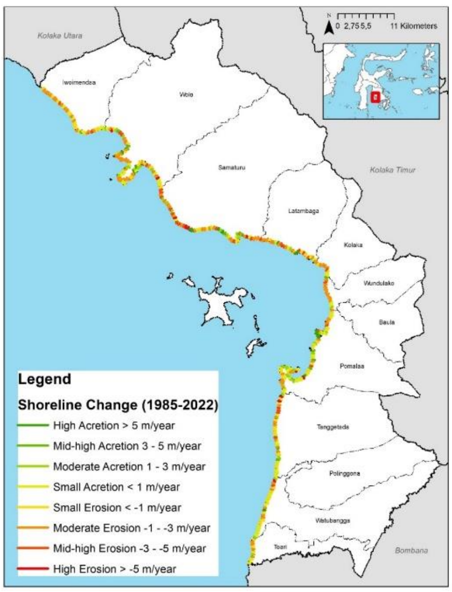

Figure 8. Shoreline change 1985–2022.

Shoreline change estimation is an essential step in identifying accretion, erosion, and morphodynamics using multi-temporal Landsat satellite images [28]. Variations in erosion occur, ranging from low to high vulnerability. Coastal areas experiencing accretion are considered less vulnerable as land is added when the coast moves towards the ocean. Conversely, areas experiencing coastal erosion are considered vulnerable owing to the loss of private and public property, as well as important natural habitats beaches, dunes, and marshes [29]. High erosion (abrasion) occurred in Samaturu, Pomalaa, Tanggetada, and Watubangga. The abrasion in the Samaturu District has lasted for three years (2021–2023), as shown in Figure 9a and Figure 9b for comparison.

Figure 9. (a) Abrasion in Konaweha Village, Samaturu District, in 2021 (10); (b) Abrasion in Konaweha Village, Samaturu District, in 2023-present study.

Land Use Changes

Land use data were generated from Sentinel-2 Level-2A in August 2022 and July 2023 from Copernicus. Land use change refers to the alteration of land utilization patterns, which vary from previous practices, and may occur due to many factors, such as social, economic, cultural, or industrial, which are related to increasing built-up areas and decreasing non-built-up areas [30,31]. The classification of coastal land use in this district varies from urban to forested, agricultural, and pasture. There are a number of subdistricts whose territory is dominated by urban classification, namely Kolaka District and Pomalaa District, spatially shown in Figure 10. Urban areas occupied the classification with the highest vulnerability values. Subsequently, a considerable population inhabits the region, potentially impacting land use ranking [6], such as the urban category in this study.

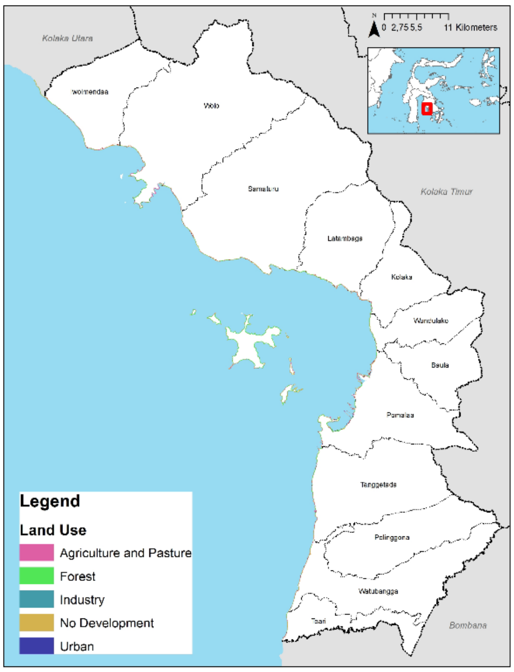

Figure 10. Land use classification.

Coastal Vulnerability Index Analysis

Figure 11 represents the coastal vulnerability index of the study area and shows the overall ranking distribution of several parameters, including geomorphology, coastal structure, slope, wave height, tidal range, sea-level rise (SLR), shoreline change, and land use. The subdistricts of Iwoimendaa, Wolo, Latambaga, Kolaka, Watubangga, and Tanggetada have the lowest of the three vulnerability classes: low, moderate, and high. The Kolaka District is the most populous district in the Kolaka regency, with a population density of 308.14 km^2, as well as the center of the Kolaka regency government (regency headquarters).

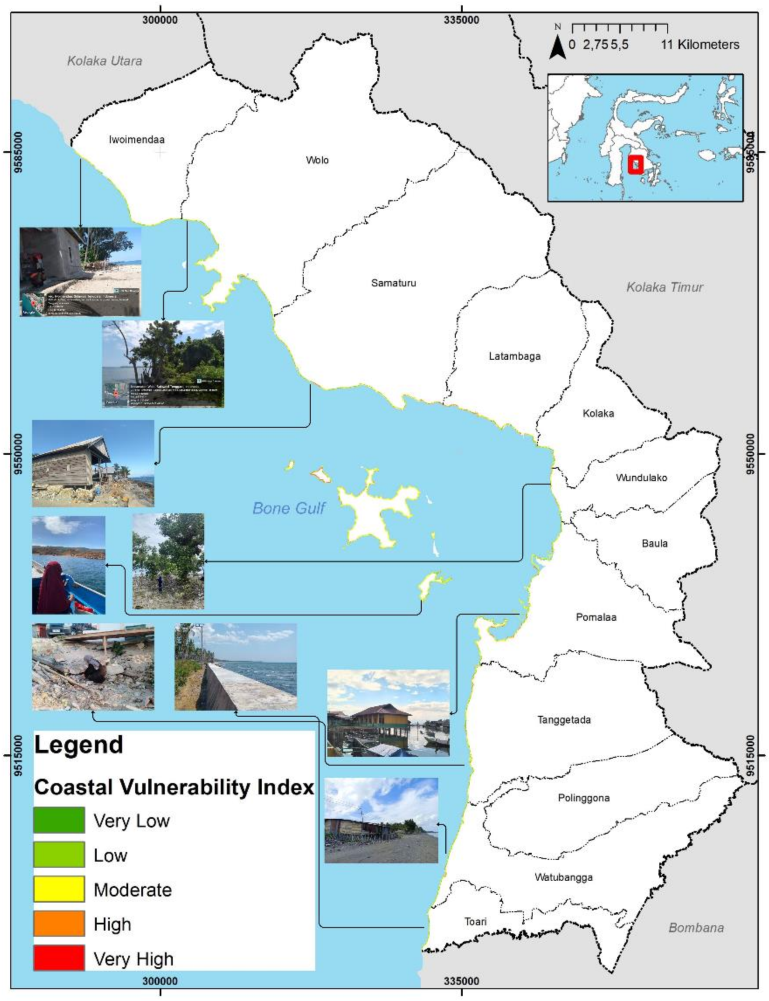

Figure 11. Coastal vulnerability rank of coastal area of Kolaka Regency.

Samaturu District has four vulnerability classes: low, moderate, high, and very high, with a percentile value of 20 to ≥80. Based on interviews with the people of Konaweha Village, Samaturu District, two houses have been damaged due to abrasions since 2021. The coastal defense structure construction project is a 400-meter-long groin type-T and a 600-meter-long breakwater that is currently being constructed in 2023 by the *Satuan Kerja Balai Wilayah Sungai Sulawesi IV Kendari*.

Wundulako District (including the uninhabited island clusters of Padamarang Island, Lambasina Besar Island, Lambasina Kecil Island, Buaya Island, and Maniang Island), and Pomalaa District are the most vulnerable regions, with the most variable levels ranging from very low, low, moderate, high, and very high. The percentile values ranged from ≤20 to ≥80. The Toari District, located on the border between Kolaka and Bombana, has four vulnerability classes: very low, low, moderate, and high. Percentile value range from ≤20 to 80. Research using the CVI method showed that the Mataram coastal area (± 9,000 m from this coast,) is classified as moderate-to-high risk, which is influenced by geomorphological factors and shoreline changes [32]. Meanwhile, in a study conducted by Rachmadianti et al. [33], the level of vulnerability in the coastal area of Tanjung Pandan, Belitung Regency, was categorized as low to medium vulnerability. A comparison of the study cases based on the coastal vulnerability scenarios is presented in Table 3.

Table 3. Previous studies based on coastal vulnerability.

No	Topic	Variables considered	Location	Techniques	References
1	Coastal vulnerability assessment on erosion and coastal change	Shoreline change, beach width, local elevation, slope, Bathymetry, geomorphology, level change rate, mean tidal range & significant wave height.	Gulf of Mannar, India	GIS & field Survey	[22]
2	Assessing coastal vulnerability using geospatial techniques	Geographical factors (geomorphology, coastal elevation, coastal slope) and social composition (population density, literacy, housing structure, & land use)	Chittagong District, Bangladesh	GIS	[34]
3	Coastal vulnerability assessment of tourism site	Shoreline change, coastal slope, geomorphology, mean tidal range, sea level rise (slr) rate, mean significant wave height	Mataram, Indonesia	Remote Sensing (RS), GIS, and field survey	[32]
4	Modelling of Coastal Vulnerability Index due to SLR impact	Slope, lithology, geomorphology, slr change, shoreline change, tidal range, wave height	The eastern coast of Peninsular Malaysia	Remote Sensing (RS) & GIS	[35]
5	Coastal Vulnerability of small islands	Geomorphology, coastal structure, slope, wave height, tidal range, slr, shoreline change, & landuse	Karimunjawa & Kemunjan Island, Central Java, Indonesia	GIS and field survey	[13]
6	Coastal Vulnerability Assessment Based on Coastal Vulnerability Index (CVI)	Geomorphology, coastal structure, slope, wave height, tidal range, slr, shoreline change, & landuse	Kolaka Regency, Indonesia	Remote Sensing (RS), GIS & field survey	*present study*

Coastal vulnerability assessments using CVI or modified CVI conducted in various regions worldwide also indicate different vulnerability rankings. The coastal vulnerability assessment conducted in the Gulf of Mannar, situated on the southeastern coast of India, faced challenges due to human activities, including industrialization and sand and coral mining. The CVI scores pertaining to coastal vulnerability were classified into four distinct categories, namely: low, moderate, high, and extremely high-risk [22]. The present study investigated the susceptibility of the Chittagong District, Bangladesh, to coastal hazards through the application of geospatial techniques. This study analyzed a combination of physical and social characteristics using the Physical Vulnerability Index (PVI), Social Vulnerability Index (SVI), and Coastal Vulnerability Index (CVI). The findings indicate that rural areas have a higher degree of susceptibility to disasters than urban areas, with vulnerability rates of 66 %, 48 %, and 43 %, respectively [34].

The present study delineates seven distinct variables that contribute to the PVI. These variables encompass: geology, shoreline change, coastal slope, wave height, tidal range, SLR & rock type. While the Socioeconomic Vulnerability Index (SeVI) is a metric that examines three key factors: quality of life, economic value, and infrastructure. CVI was used to assess the comprehensive vulnerability of a certain coastal region. Kuantan is identified as the most elevated index within the coastal region, whereas Tumpat is recognized as the least elevated [35]. Another study conducted in the eastern part of Karimunjawa Island showed that it exhibits low coastal vulnerability, characterized by medium cliff geomorphology. Similarly, coastal areas with a low cliff geomorphology demonstrated low coastal vulnerability. In contrast, moderate coastal vulnerability has been observed in regions with mangrove forests and land use. The northern part of Kemujan Island, on the other hand, displays high coastal vulnerability to agricultural land use, and very high coastal vulnerability is associated with settlements and other infrastructure [13]. A review of the results of the CVI assessment carried out on the coastal area of the Kolaka Regency and a small island is needed. The formulation of a long-term strategy for local coastal zones demands the involvement of policymakers who must prioritize a comprehensive disaster-based analysis to mitigate future harm caused by disasters.

Conclusion

CVI remains a useful tool for assessing coastal vulnerability to natural hazards. Eight parameters were used to assess the CVI of coastal zones and small islands in Kolaka Regency: 1) geomorphology; 2) coastal defense structures; 3) beach slope; 4) average significant wave height; 5) average tidal range; 6) relative SLR; 7) shoreline change; and 8) land use. The vulnerability classes in the coastal Kolaka and small islands are divided into five classes: very low to very high. Overall, several parts of the seven subdistricts (Iwoimendaa, Wolo, Samaturu, Latambaga, Kolaka, Wundulako, Pomalaa, Tanggetada, and Wundulako) were categorized as very highly vulnerable to disasters. Several parts of the Toari sub-district are categorized as highly vulnerable. An integrated coastal vulnerability index has been developed using geospatial techniques to comprehend the issue and provide essential coastal management recommendation. However, this should be combined with other methods and tools to provide a more comprehensive assessment of coastal vulnerability. The CVI does not consider the adaptive capacity of society. Future management should coalesce adaptive measures, encompass strategic local-scale coastal zone management in the Kolaka Regency, to support resilient coastal hazards.

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