Prepublished copy

Nature Environment & Pollution Technology

This is a peer-reviewed prepublished version of the paper

The Study of Coastal Vulnerability in South Central Timor Regency, East Nusa Tenggara Province

Ludgardis Ledheng [1*], Emanuel Maria Yosef Hano'e [2], Marce Sherly Kase [3]

[1,2] Biology Education Study Program, The Faculty of Teacher Training and Educational Sciences, University of Timor

[3] Development Economics Study Program, The Faculty of Economics and Business, University of Timor, Kefamenanu. 85613,

***Email**: ludgardisledheng12@gmail.com

ABSTRACT

The presence of anthropogenic activities on the coastal areas of of the South Central Timor (SCT) Regency has weakened coastal resilience, which may exarcebate the impact of rising sea levels. One important factor that needs to be analyzed is the vulnerability assessment. This study, conducted from July to September 2024, aimed to determine the spatial distribution and variables that can influence the vulnerability in the coastal areas. The methods used were the Coastal Vulnerability Index (CVI) and the Social Vulnerability Index (SoVI) which then used Multi Criteria Analysis (MCA) to perform the standardization value. The integrated index values were then integrated into the Geographic Information System (GIS) for comprehensive spatial information. The results showed that, in general, the coastal areas of the SCT Regency was in the low (35%), medium (48%), and high (66%) risk categories. Areas of high physical vulnerability were alluvial lowland areas and those near hills. The karst hills that are characteristic of the coastal areas of the SCT regency have become a threat to the lives of coastal communities. Communities living in coastal hill areas, including the Kolbano and Oetuke coasts, and in the alluvial lowlands like the Tuafanu, Kualin, and Oni coasts, need to be the focus and priority areas for recovery efforts. This is due to the high level of vulnerability, both physically and socio-economically. Geomorphology is the primary contributor to physical vulnerability because these coastal hills and lowlands are prone to erosion and land degradation caused by waves, tides, and human activities. On the socio-economic side, land use, particularly mining activities, increases vulnerability by degrading the environment and threatening the livelihood of coastal communities. Key recovery efforts should focus on revegetation, which can help stabilize the soil, reduce erosion, and restore ecological balance while offering sustainable economic benefits to the local population.

Key Words	Vulnerability, Coastal Areas, MCA, CVI, Sea Level Rise, SoVI.
DOI	https://doi.org/10.46488/NEPT.2025.v24i02.D1719 (DOI will be active only after the final publication of the paper)
Citation of the Paper	Ludgardis Ledheng, Emanuel Maria Yosef Hano'e, Marce Sherly Kase, 2025. The Study of Coastal Vulnerability in South Central Timor Regency, East Nusa Tenggara Province. *Nature Environment and Pollution Technology*, 24(2), D1719. https://doi.org/10.46488/NEPT.2025.v24i02.D1719

INTRODUCTION

Coastal areas are dynamic and therefore have the potential to be easily damaged (Ward *et al*., 2011). The stone mining activities along the coastal areas of the SCT Regency, East Nusa Tenggara Province (ENT), have brought negative effects on environmental damages, especially in karst and marine landscapes (Maulana *et al*., 2017), both of which dominate the region. Karst land is spread across land areas with gentle to hilly topography, with bushes and rocks generally dominating the land cover. Meanwhile, residences are typically found around hill valleys or in areas with gentler topography. Marine landforms strecth along the coastline with flat to gentle topography, predominantly covered by sand and rocks (Maulana *et al*., 2017). In general, the land cover in the coastal areas of the SCT Regency is characterized by stretches of sand, gravel, and rocks found along the coast towards the land. Such conditions have influenced the coastal communities to work as sand and stone miners. However, this dependence has resulted excavation pits that leads to erosion. According to Fadilah, (2021), coastal erosion can affect by altering hydro-oceanographic conditions, especially the direction of the current, resulting in tidal flooding.

In addition, climate change that affects high waves and strong winds during the rainy season have also caused the coastal areas of the SCT Regency to be frequently hit by disasters. Meteorology, Climatology and Geophysics Agency (MCGA) reported the formation of tropical cyclone Frances in the Gulf of Papua, which has continued to develop (Gaol *et al*., 2018). The cyclonic activity occurring across the Timor Sea and the coast of the SCT Regency is one of the regions influenced by cyclone Frances (Gaol *et al.*, 2018).

The Timor Sea is located in the collision zone between the northwestern edge of the Australian continent, which is moving north, and the Indo-Australian ocean plate (Bachri, 2011). This movement has caused the southern coast of Timor Island to be frequently hit by very strong tectonic earthquakes (Gaol *et al*., 2018). The most recent disaster occurred in 2021, namely the Seroja cyclone, which damaged many residential areas. The ENT Provincial Disaster Management Agency reported that the southern coast of Timor Island was affected by the two cyclones, impacting 25 coastal villages in the SCT Regency. The risk of sea level rise can be influenced directly by the local topography, which is dominated by gentle to flat alluvial plains (Maulana *et al*., 2017). Given the existence of anthropogenic activities that can also threaten the coastal supporting capacity, it is necessary to manage and preserve the activities in utilizing the coastal area, as regulated by Law Number 27, Article 28, of 2007 (Government of the Republic of Indonesia, 2007). Therefore, one form of coastal management plan is through research, including the assessment of the physical and economic vulnerability in the community residing in this type of region (Maulana *et al*., 2017).

This study was aimed at examining the spatial distribution and factors influencing the vulnerability of the coastal areas of the SCT Regency, especially regarding sea level rise. Ramieri *et al*. (2011) presented a method to determine the level of physical vulnerability to the threat of elevated sea levels, namely the Coastal Vulnerability Index (CVI). This technique has been used in assessing sea level rise in various countries, including Spain (Koroglu *et al*., 2019), and for vulnerability assessment in Indonesia (Diposaptono *et al*., 2013). Meanwhile, the assessment of socio economic vulnerability has been done using the Social Vulnerability Index (SoVI) (Kurniawan, 2018). According to Sulma (2012), the magnitude of the contribution of physical and socio-economic variables to vulnerability can be known based on the standardized variables. Therefore, the assessment of coastal vulnerability focused heavily on Multi Criteria Analysis (MCA), which used the ranking system obtained from each standardized variable. The resulting combined vulnerability index value was then entered to the Geographic Information System (GIS), to obtain comprehensive spatial information.

RESEARCH METHODOLOGY

Research Site

This study took place in the southern coastal areas of the SCT Regency, including 25 villages: Baus, Fatumanufui, Meusin, Boking, Nunkolo, Hoineno, Nenoat, Sahan, Saenam, Op, Nualunat, Kot'olin, Hoibeti, Oetuke, Nununamat, Spaha, Kolbano, Noesiu, Tuapakas, Oni, Kualin, Tuafanu, Toineke, Oebelo, and Bena. The selection of the research area was based on the consideration that these 25 coastal villages have potential vulnerability to sea level rise. These specific locations were determined by creating a buffer parallel to the coastline with a distance of 1 km towards the sea and towards the land, while the perpendicular boundary of the coast used the village administrative boundaries. The consideration of using this size was based the assumption that each unit could represent the varied variables within the study location of ± 87.5 km, as well as ease of identification within the administrative area. The study area started from the easternmost village, namely Baus, to the westernmost village, Bena, according to the numbering (Figure 1).

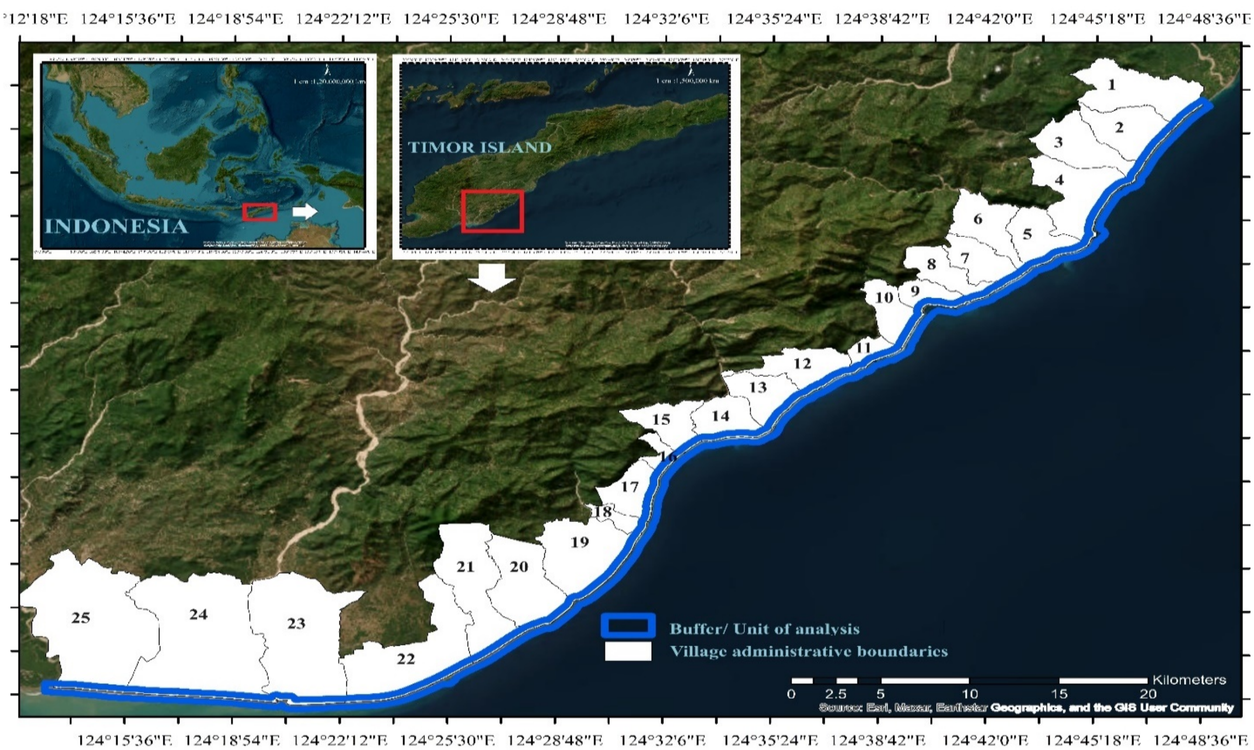


Figure 1. Research Site

Data Collection

This study used 9 variables derived from 6 physical variables: geomorphology, elevation, tidal range, coastline change rate, wave height, and sea level rise; and 3 socio-economic variables: land use, population density, and poverty rate. A higher poverty rate in an area corresponds to greater vulnerability to disasters. The research database consisted of various feature sets (point, line, polygon) and was registered with Datum WGS 1984 with Universal Transverse Mercator (UTM) projection system Zone 51 S. The technique of data collection both spatially tabulation data is further explained Table 1 below.

Table 1. Data source

A. Physical Variables		
Type of Data	Data Source	Vulnerability Indicators
Geomorphology (landforms)	Obtained from the Digital Elevation Model (DEM) sourced from the Geospatial Information Agency in the form of a digital map of the Indonesian Landforms on a scale of 1:25,000 https://tanahair.indonesia.go.id/unduh-rbi/#/	Geomorphology can indicate the resilience of a coastal section to erosion and accretion processes caused by rising sea levels.
Beach Elevation	Obtained from the Digital Elevation Model (DEM) sourced from the Geospatial Information Agency in the form of a digital map of the Indonesian Landforms on a scale of 1:25,000 https://tanahair.indonesia.go.id/unduh-rbi/#/	The existence of low-lying areas is associated with the vulnerability of a coast to the risks of inundation, as well as the rate of retreat or advance of the coastline The existence of low-lying areas is associated with the vulnerability of a coast to the risks of inundation, as well as the rate of retreat or advance of the shoreline
Ebb and Flow	Obtained from MIKE 21 Prediction in July 2000 and field measurements in July 2024 at 2 locations, namely Toineke village and Nunkolo.	Differences in tidal range contribute to the risk of coastal inundation, with macrotidal areas (characterized by large tidal ranges) being more vulnerable than microtidal areas.
Coastline Change Rate	Obtained from Landsat 7 ETM imagery recorded on September 26, 2000 (USGS Glovis, Path 110 and Row	Coastal erosion or accretion indicates the rate

	67) and July 2024 coastline coordinate point data taken using GPS RTK. Line analysis using Digital Shoreline Analysis System (DSAS).	at which a section of the coastline is being eroded or accreted.
Sea Level Rise	Obtained from AVISO in the form of sshd data from multi-mission altimetry satellite observations, namely the TOPEX/Poseidon, Jason-1, Jason-2, and Jason-3 satellites during the period 1992 to 2019. This data has a NetCDF (.nc) format in grid form with a spatial resolution of 0.25° x 0.25°.	The higher the rate of sea level rise, the greater the risk of erosion and inundation.
Wave Height	Retrieved from the Copernicus Marine Service data base (https://data.marine.copernicus.eu/produc ts)	The higher the wave height, the greater the impact on changes in the coastline and the geomorphological conditions of the area
B. Socio-economic Variables		
Land Use	Obtained from the 2024 Digital Elevation Model (DEM) sourced from the Geospatial Information Agency in the form of a digital map of the Indonesian Landforms on a scale of 1:25,000. https://tanahair.indonesia.go.id/unduh-rbi/#/	Land use that has high social and economic value will increase the vulnerability of an area in the event of a disaster.
Population Density	Population statistics calculation from field survey in July 2024	The population density in a given area indicates that as the population becomes denser, the vulnerability of that area to disasters increases.
Poverty Rate	Statistical calculation of the number of under-privileged population from the field survey in July 2024.	A higher poverty rate in an area will further increase its vulnerability to disasters.

Multi-Criteria Analysis (MCA) was used to analyse vulnerability in the physical and socio-economic aspects. This approach aimed to standardize the ranks of variables by using the CVI and SoVI methods. Next, the Kasim equation (2011) was used to determine the standard value for each variable in the analysis unit as follows:

$$\text{Xin} = \frac{(\text{xin} - \min \text{xi})}{(\max \text{xi} - \min \text{xi})} \quad (1)$$

where:

X_{in} = the standard value of the *i*-th variable on the *n*-th grid,

x_{in} = the original value of the *i*-th variable on the *n*-th grid

max xi = the highest value of variable

min xi = the lowest value of variable

The value of the standardized variable results was used for the calculation of CVI-MCA and SoVI-MCA, which were then categorized into five groups based on percentile distances: very low (<0.2), low (0.2-0.4), medium (0.4-0.6), high (0.6-0.8), and very high (>0.8). Using this categorization, the calculation of the physical vulnerability index value referred to the CVI equation of Pendleton *et al*., (2010):

$$\text{CVI} = \frac{\sqrt{a*b*c*d*e*f}}{\text{n}} \quad (2)$$

where:

a = coastal geomorphology

b = elevation

c = tidal range

d = coastline change rate

e = sea level rise

f = wave height

n = total

Table 2. CVI Variable Categories

No	Variable	Not Vulnerable (1)	Less Vulnerable (2)	Medium (3)	Vulnerable (4)	Very Vulnerable (5)

1	Geomorphology	High Cliff	Moderate cliffs, indented coast	Low cliff	Estuary, lagoon	Alluvial plains sandy, gravelly, muddy, deltaic coasts
2	Elevation (m)	>30	20.1-30.0	10.1-20.0	5.1-10.1	0.0-5.0
3	Tidal Range (m)	< 1.0	1.0 - 2.0	2.0 - 4.0	4.0 - 6.0	> 6.0
4	Coastline Change Eate (m/ year)	> 2.0 Accretion	1.0 - 2.0 Accretion	+1 - (-1) Stable	≤ (-1) – (-2) Abrasion	< (-2.0) Abrasion
5	Sea Level Rise (cm/year)	< 1.8	1.8 - 2.5	2.5 - 3.0	3.0 - 3.4	> 3.4
6	Wave Height (m)	< 0.55	0.55 – 0.85	0.85 – 1.05	1.05 – 1.25	> 1.25

Source: Pendleton *et al*., 2010

Meanwhile, the SoVI equation with weighting given to each variable followed the Kurniawan equation (2018):

$$\text{SoVI} = \frac{\Sigma\,(\text{weighted variable} * \text{rank})}{3} \qquad (3)$$

Table 3. Weights for SoVI variables

Variable	Weight
Land Use	0.5
Population Density	0.25
Poverty Rate	0.125

Sorce: Sulma, (2012)

Population density was calculated by dividing the number of residents within each analysis unit by the area of that unit, expressed in persons per square kilometer (person/km^2). The land use values were then transformed into scores according to the classifications provided in Table 4:

Tabel 4. Vulnerability levels based on land use

Class	Score
Body of water	1
Empty land, bushes	2
Mixed garden, Mangrove forest	3
Moorlands, Plantations, Rice Fields, Ponds	4
Residential, Road, Industry, Office	5

Source: Sulma, S. (2012)

Based on the relationship between the index values in equation (2), the standardization of these values with the CVI-MCA approach then used the normalization approach introduced by Kasim (2011). The formula is as follows:

$$\text{NS} = \frac{(\text{nub} - \text{nlb})}{(\text{oub} - \text{olb})} * ((OS - olb) + nlb) \quad (4)$$

Where:

NS = new index value

OS = original index value

nub = the highest limit of new index value

nlb = the lowest limit of new index value

oub = the highest limit of the original index value

olb = the lowest limit of original index value

The physical vulnerability index categories based on percentile distance are defined by the following relationship:

$$0 \leq \text{min} \leq \text{indeks CVI MCA} \leq \text{max} \leq 1 \quad (5)$$

Similarly, the socio-economic vulnerability index follows the following relationship:

$$0 \leq \text{min} \leq \text{indeks SoVI MCA} \leq \text{max} \leq 1 \quad (6)$$

The coastal vulnerability index, which incorporates both physical and socio-economic conditions as defined by Szlafsztein (2005), is expressed as the Total Vulnerability Index (TVI). This was calculated using the same method, namely the average of the physical vulnerability index and socio-economic vulnerability index, weighted equally, as per the Sulma equation (2012):

$$\text{TVI} = \frac{(\text{CVI MCA} + \text{SoVI MCA})}{2} \quad (7)$$

RESULTS AND DISCUSSION

Physical Variables

a. Elevation

The observation results showed that elevations in the range of 0.71-4.43 m were found on the coasts of Bena, Oebelo, Toineke, Tuafanu, Kualin, Kolbano, Meusin, Fatumanufui and Baus. In contrast, elevations in the range of ≥ 8 to 33.24 m were found in the coasts of Hoineno, Boking, Nunkolo, Nenoat, Op, Oetuke, Sahan, Hoibeti, Spaha, Nualunat, Nununamat, Kot'olin, and Saenam. Based on these elevation values, it is known that 9 coastal villages (Bena, Oebelo, Toineke, Tuafanu, Kualin, Kolbano, Meusin, Fatumanufui, and Baus) are highly vulnerable to tidal flooding because they are situated in the range below 5 m (Table 2). According to Sulma (2012), when a tidal wave occurs, a beach with a low elevation will allow water to enter further inland, increasing the overflow. Conversely, higher elevations prevent water from moving inland. The elevation values act as indicators of potential threats from coastline advancement and retreat (Hamuna *et al.*, 2018). The distribution of elevation values on the coastal areas of the SCT Regency is presented in Figure 2.

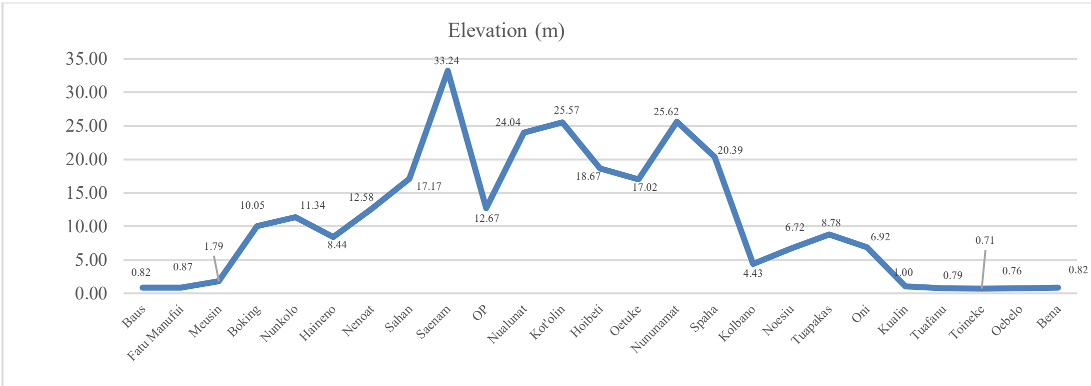


Figure 2. The distribution of coastal elevation values in the SCT Regency

According to Kalay, Lopulissa & Noya (2018), the dynamics of sediment transport in the formation of coastal alluvial areas impact changes in coastal slope. A decrease in the slope percentage indicates a corresponding decrease in elevation over a distance of 100 m, disrupting the coastal balance process. The range of elevation values on the coastal areas of the SCT Regency is presented in Figure 3.

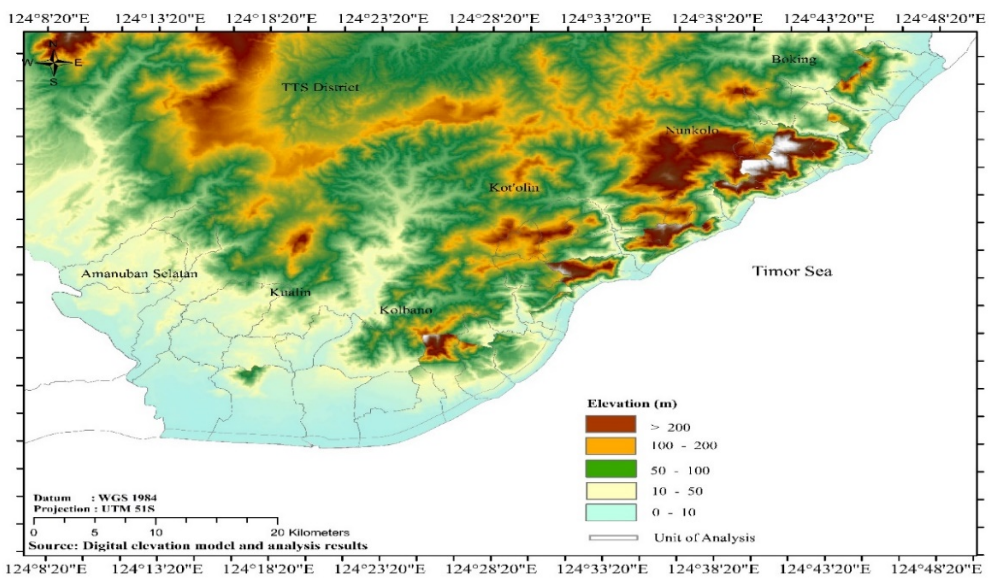


Figure 3. Range of coastal elevation values in the SCT Regency

b. Geomorphology

Landform classification refers to the resistance of landform types to erosion according to the CVI model (Table 2), including hilly coasts, estuaries, lagoons, alluvial plains, sandy beaches, muddy beaches, and deltas. In general, the coastal areas of the SCT Regency have two landforms, namely hills and marine. The hill categories are classified as low, medium, and high, dominating the coasts of Kot'olin and Nunkolo and parts of the coast of Kolbano District (Figure 4), with elevation values ranging from 11.3-33.2 m (Figure 2). According to Maulana *et al.* (2017), the hills found on the coastal areas of the SCT Regency are karst hills, and their distribution reaches the boundary of the marine area on a flat slope.

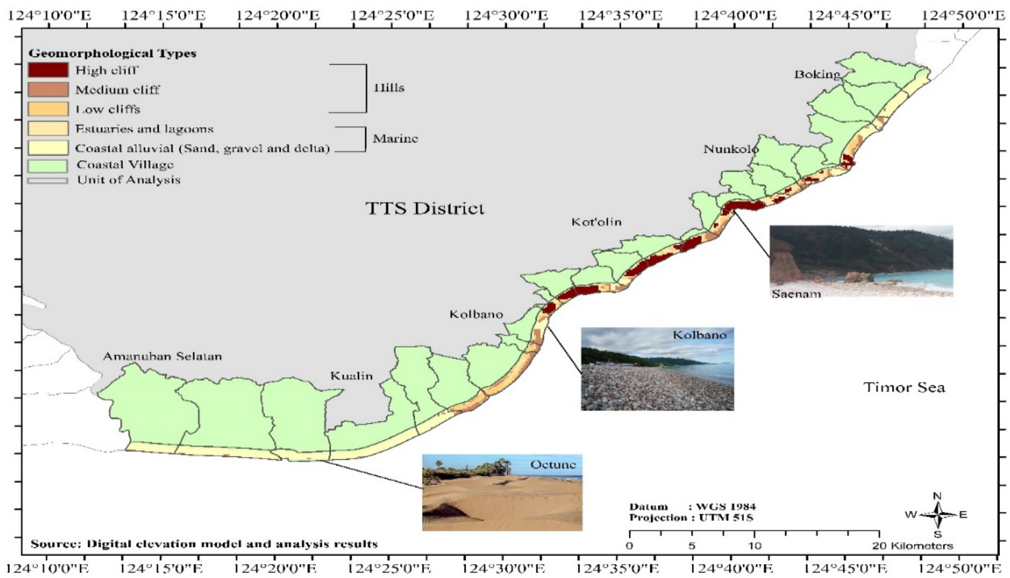


Figure 4. The distribution of land forms in the coastal analysis unit of the SCT Regency

Marine landforms dominate the western coast, namely Amanuban Selatan District, Kualin, some coastal villages in Kolbano District, and some coastal areas of Boking District (Figure 4). The coastal landscape consists of alluvial coastal plains with elevation values ranging from 0.8-1 m (Figure 2). According to Maulana *et al*. (2017), sand and stone mining activities were found in the hilly and marine areas on the Kolbano coast to the east of Saenam. Our observations revealed that the sand and stone mining activities in the southern coast significantly contribute to the landslides in the karst hills that border the beach. Meanwhile, the western coast, namely South Amanuban district and Kualin, is dominated by sand. The impact of sand shipments through rivers and wave currents has caused sand deposits in several areas such as Oetune Beach (Figure 4).

It is known that the materials on the coastal alluvial plains of the SCT Regency consist of marine sedimentary rocks, such as limestone, obtained from the sea through waves, and fluvial sedimentary rocks, such as sandstone and claystone, acquired from the sedimentation process (Bachri, 2011). Based on the vulnerability category (Table 2), alluvial plains are classified as very vulnerable areas. According to Sulma (2012), coastal alluvial plains are landforms resulting from coastal development towards the land, covered by weathering and sedimentation materials that have great erosion potential. The increasing mining activities in coastal areas indicate that the coastal resilience to hydro-oceanographic factor threats is very weak. Based on the results of the CVI analysis, the coasts of Bena, Oebelo, Toineke, Tuafanu, Kualin, Oni, Tuapakas, Noesiu, Kolbano, Spaha, Oetuke, Op, Nenoat, Hoineno, Nunkolo, Boking, Meusin, Fatumanufui, and Baus Villages are in the vulnerable to very vulnerable categories concerning sea level rise. Meanwhile, the coasts of Saenam and Kot'olin Villages are classified as moderate (Figure 5).

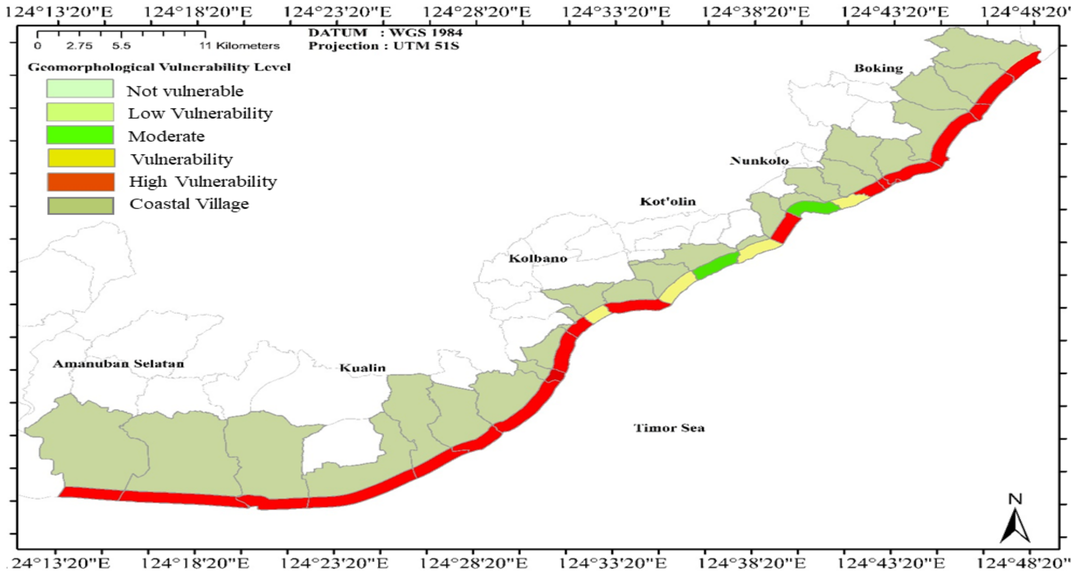
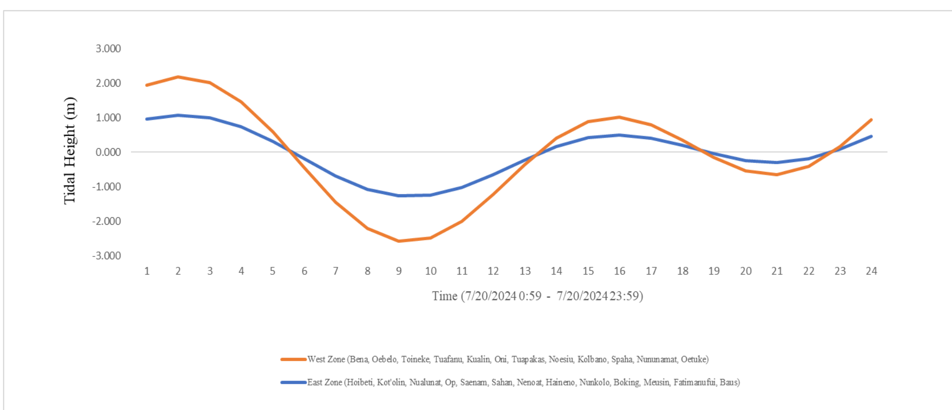


Figure 5. Level of vulnerability based on geomorphological variables

c. Tidal Range

The tidal data used in this study were the results of MIKE 21 modeling. Based on the Formzahl value, it can be found that the tidal pattern in this study area exhibited a mixed double daily trend, where the ebb and flow occurred twice twice each day, though it sometimes happened once a day. A one-day observation was conducted to determine the tidal type, with July 20, 2024, selected as the time sample. The Formzahl value in Toineke waters was 0.40 and Nunkolo waters was 0.43. The daily tidal pattern on July 20, 2024 on the coastal areas of the SCT Regency is presented in Figure 6.



Source: MIKE 21 modeling data and analysis results

Figure 6. Daily tidal pattern on July 20, 2024 on the coastal areas of the SCT Regency

Based on the difference in Formzahl values, the tidal observation area was divided into two parts: the western zone and the eastern zone (Figure 7). Data obtained from the tidal analysis included the highest average high tide, the lowest average low tide, and the tidal rise. To examine the coastal vulnerability index, the required value was the average of tidal rise in the study site for the period from July 2000 to July 2024 in both zones. the western and the eastern zones. The calculation results showed that the average rise in the western zone was 1.55 m, while that in the eastern zone was 1.48 m. The contribution of the tidal position was greater in affecting the western coast than the eastern part. The dynamics of the tides have caused the western coast, especially on the Tuafanu coast, to develop puddles that form parallel to the coastline (Figure 7). According to Pamungkas (2018), high tidal rises can cause permanent puddles. The average sea water tidal positions are presented in Table 5.

Table 5. Average Sea Tide Position

Year	West Zone	East Zone
2019	1.55	1.48
2021	1.55	1.48
2024	1.55	1.48
Average	1.55	1.48

Source: Results of MIKE 21 Modeling Analysis from 2000 to 2024

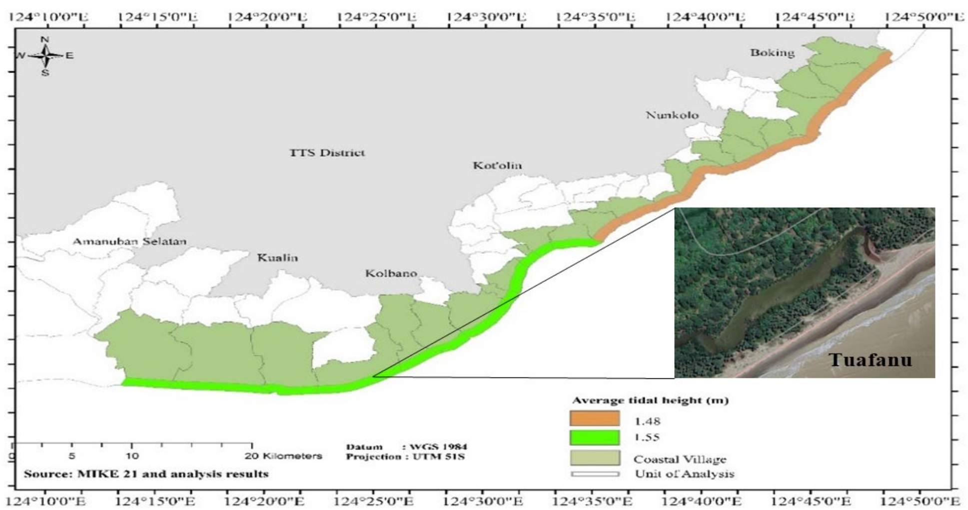


Figure 7. Tidal ranges in the western and eastern zones on the coastal areas of the SCT Regency

d. Coastline Change Rate

Based on the DSAS analysis on 8633 transects with a distance of 10 m, it was found that the shift of the coastline toward the land was almost evenly distributed along the alluvial plain coast and the karst hill area (Figure 9). The coastline that experienced the furthest shift inland was found in the Saenam coastal karst hill area, measuring 288.7 m (Figure 8).

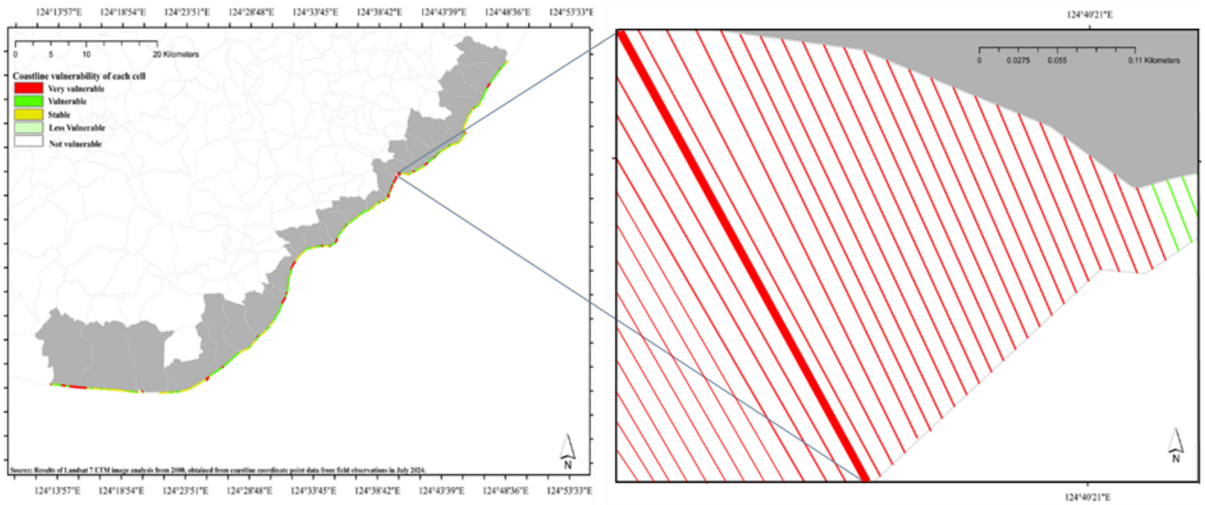


Figure 8. Maximum shoreline displacement on the Saenam coast

The results of the interviews with residents living around the hilly area revealed that rock and sand mining activities have made the hills fragile and prone to landslides. In general, landslides in karst hills are caused by mining activities or extreme weather, especially on moderate or steep slopes where rock movement is common (Rahmania *et al*., (2019). Coastal erosion can also occur on areas with low elevation values such as Bena, Oebelo, Tuafanu, Kualin, Fatumanufui, and Baus (Figure 9), particularly those on sandy alluvial plains (Figure 4). The sandy nature of these beaches makes them highly vulnerable to erosion (Suhana *et al*., 2020) from waves, tides, and wind, with wind-driven erosion forming sand dunes along the Oetune coastline..

Based on the average change in the coastline in each analysis unit for 24 years (2000-2024), land accretion occurred on the Toineke coast at a rate of 1.18 m/year. Meanwhile, other areas experienced land loss at a rate ranging from 0.73 to 2.47 m/year (Figure 9). The rate of land reduction in this study area on the south coast was lower compared to the north coast of North Central Timor regency (NCT), which had a rate of 26.60 m/year (Ledheng *et al*., 2023). This difference is due to variations in coastal slope gradients, with nearly 90% of the northern coast classified as flat, whereas only certain sections of the southern coast are flat. The flatter northern coast facilitates greater inland movement of seawater, contributing to the accelerated rate of land loss in that area.

Based on the CVI category (Table 2), areas experiencing line retreat, such as the Nunkolo, Nununamat, Oni, and Oebelo coasts were still in a stable condition, namely in the range of 0.73 to 0.86. Meanwhile, the coasts of Bena, Tuafanu, Kualin, Kolbano, Meusin, Fatumanufui, Baus, Hoineno, Boking, Nunkolo, Nenoat, Op, Oetuke, Sahan, Hoibeti, Spaha, Nualunat, Nununamat, Kot'olin and Saenam faced higher rates of abrasion (1.05 to 2.47 m/year), as shown in Figure 9. Abrasion in these areas is a result of the dynamic interaction of multiple physical factors such as geomorphology, elevation, tides, waves, and sea level rise. These factors collectively shape the coastal vulnerability and contribute to the erosion observed.

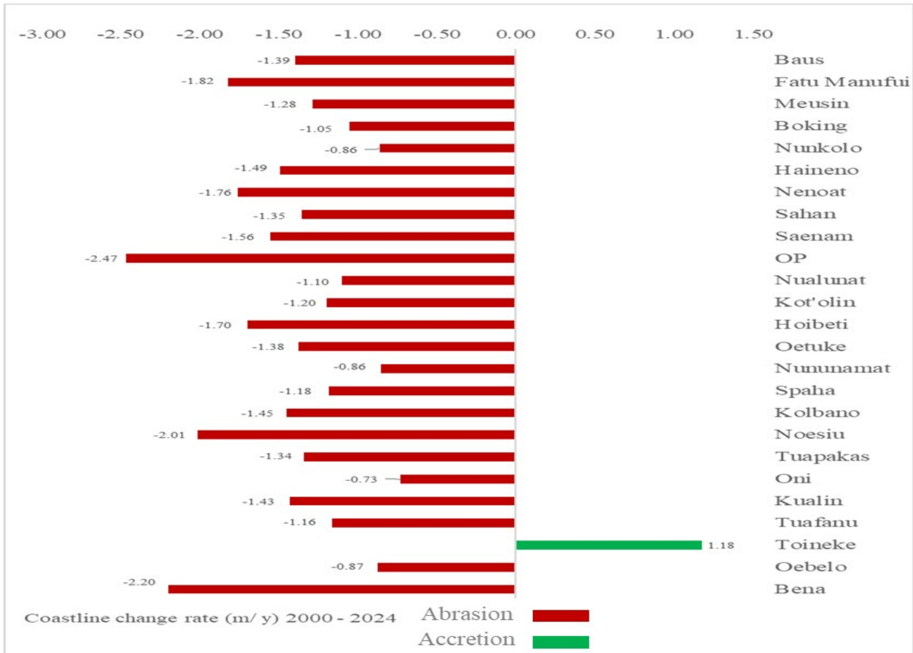


Figure 9. Coastline changes rate in each analysis unit over a 24-year period.

e. Sea Level Rise

The data of sea level rise was obtained based on data analysis sourced from multi-mission altimetry satellites, namely TOPEX/Poseidon, Jason-1, Jason-2, and Jason-3 during the period of 1992 to 2019. Figure 10 shows the trend of yearly sea level rise in the waters of the SCT Rregency, which generally ranged from 14 to 15 cm/year.

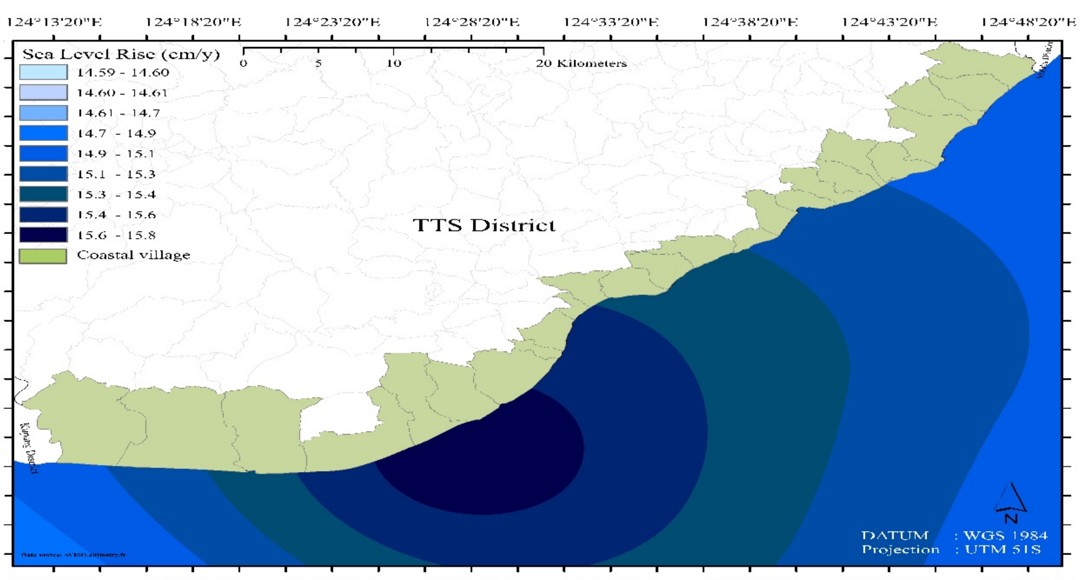


Figure 10. Sea level rise in the SCT Regency and its surrounding waters

The highest sea level rise occurred in the waters stretching from Toineke to the east of Oni, while the lowest was recorded in the waters of Nunkolo District to the easternmost, namely the Baus coast. The average sea level rise for each analysis unit based on the zonal statistical tool is presented in Table 6.

Table 6. Average Sea Level Rise for each analysis unit

Coastal Village	Sea Level (cm)
Baus	14.99
Fatu Manufui	15.01
Meusin	15.03
Boking	15.06
Nunkolo	15.11
Haineno	15.14
Nenoat	15.16
Sahan	15.18
Saenam	15.21
Op	15.25
Nualunat	15.30
Kot'olin	15.35
Hoibeti	15.41
Oetuke	15.45
Nununamat	15.49
Spaha	15.51
Kolbano	15.56
Noesiu	15.60
Tuapakas	15.66
Oni	15.74

Kualin	15.77
Tuafanu	15.65
Toineke	15.45
Oebelo	15.28
Bena	15.12

The values of sea level rise observed in the waters of the SCT Regency were still within the range of global observations by the National Oceanic and Atmospheric Administration (NOAA), which reported sea level increases within a 0-20 cm range (Lindsey, 2019). According to Karsidi (2011), the results of altimetry satellite monitoring published by AVISO France showed the consistency with the data of sea level rise acquired from observations of the National Tidal Station Network operated by Bakosurtanal. The differences that can occur may be due to differences in calculation methods and observation periods (Sulma, 2012). Additionally, in this study, sea level rise observations did not include data on the impact on coastal groundwater quality, a factor that can influence community drinking water consumption levels. This absence of spatial data on groundwater consumption at the time of the study prevents a full analysis of this aspect.

f. Wave Height

According to the data of average monthly significant wave height from the Copernicus Marine Service during the period of 2000-2024 in April (Figure 11), it was observed that the wave heights in the western waters of Timor were generally higher than in the eastern waters. Figure 9 shows the dynamics of the maximum wave heights during the west season in April for the years 2000, 2017, 2021, and 2024. The average wave height in 2000 ranged from 0.2 to 1.4 m (Figure 11). Furthermore, during the period from 2017 to 2021, the southern coastal areas of Timor experienced significant natural events, such as Hurricane Frances in 2017 and Hurricane Seroja in 2021, which caused maximum wave heights to reach up to 3 m (Figure 11).

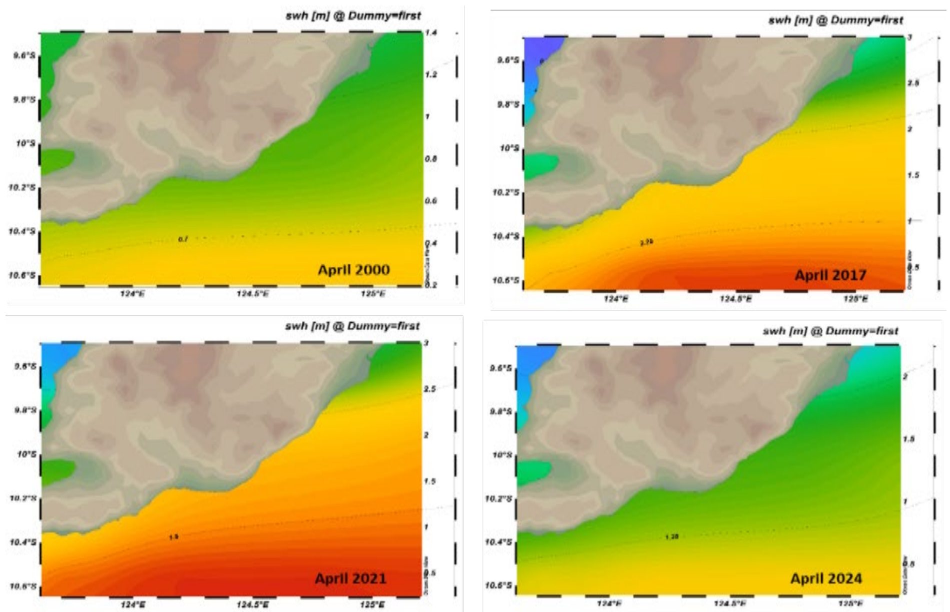


Figure 11. Average maximum wave height in Timor waters in April 2000, 2017, 2021, and 2024

Gaol *et al.* (2018) confirmed that the maximum wave direction during Frances Hurricane in the Timor Sea waters in April 2017 reached speeds of 24-28 knots, forming a cyclonic vortex moving westward (Figure 12).

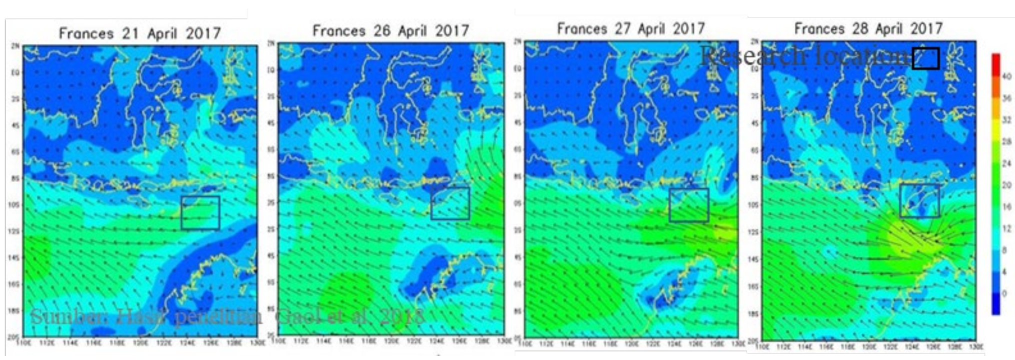


Figure 12. Cyclonic currents began to appear on April 21-28, 2017

The wave heights in April 2024 ranged from 0.5 to 2 m (Figure 11). Figure 13 shows the results of the analysis of the average annual wave height for the period from 2000 to 2024 in the research area, which ranged from 1.07 to 1.95 m. The highest waves occured in the southern waters of the western part of Timor Island, namely in the Bena waters, ranging from 1.5 to 1.6 m. In contrast, the lowest wave heights were found in the waters around Kualin District and part of Boking District. Based on the CVI category (Table 2), the southern waters of the SCT Regency fall into the vulnerable to very vulnerable category (Figure 13). The most destructive sea waves were those generated by Hurricane Frances, resulting in damage to residences in four coastal districts: Kualin, Kolbano, Kotolin, and Boking (Besie, 2017).

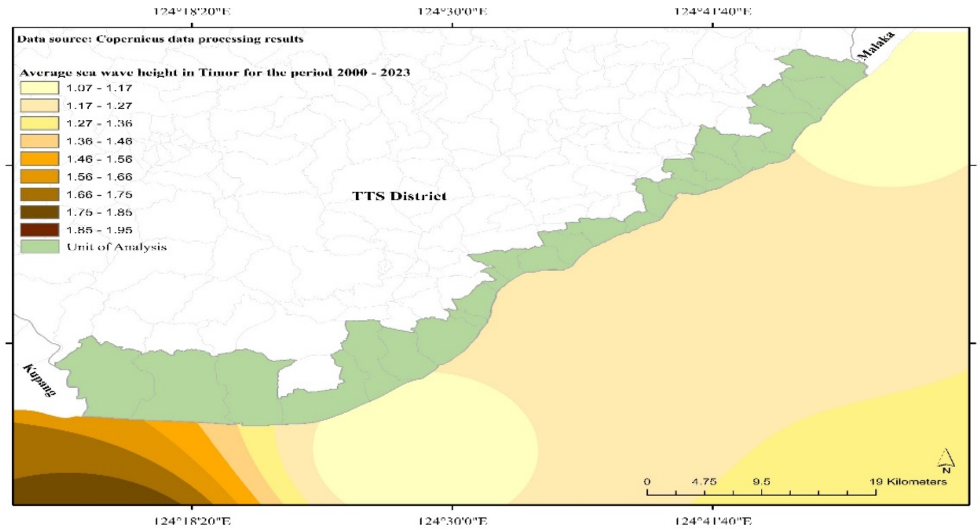


Figure 13. Average wave height from 2000 to 2024 in the waters of the SCT Regency and its surroundings

Socio-Economic Variables

a. Land Use

Land use classification is based on the socio-economic value of each land, referencing to the research results of Sulma (2012) and adjusting to the conditions in this study area (Table 4). The indicator used was the type of land use that has high social and economic value, which can increase the vulnerability of an area if a disaster occurs. Based on the classification along the coastal areas of the SCT Regency, there were 7 types of land use: water bodies, bushes, fields, gardens, rice fields, residences, and roads (Table 7). The distribution of land use along the coastal areas of the SCT Regency is presented in Figure 14.

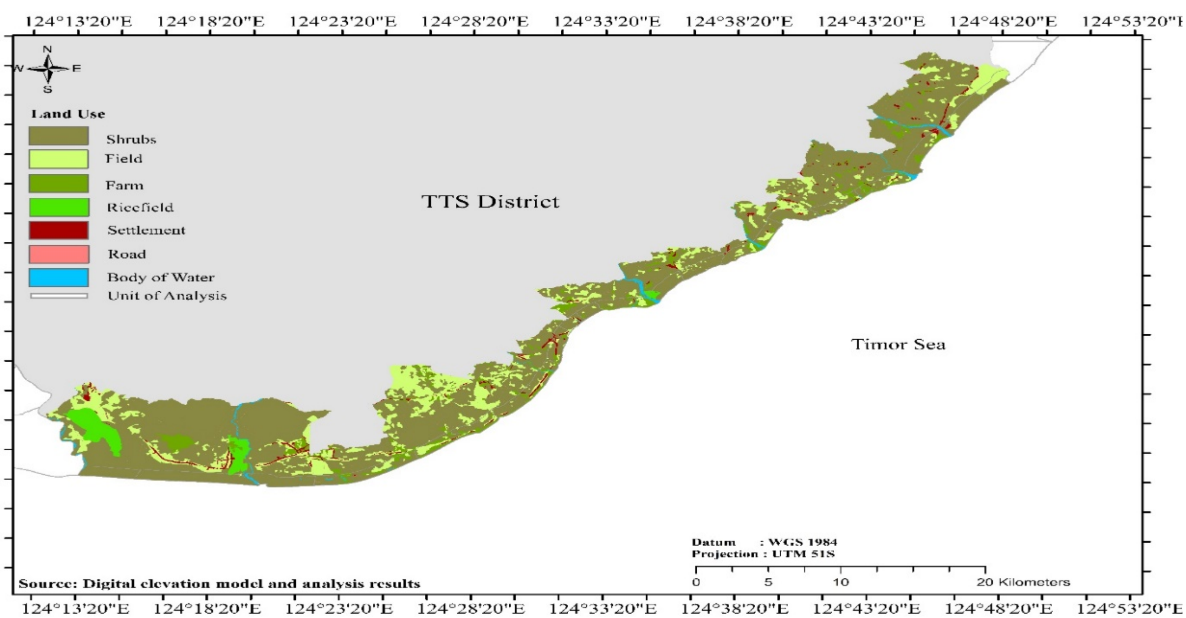


Figure 14. Distribution of land use on the coastal areas of the SCT Regency

Based on the analysis of Digital Elevation Model (DEM) data, in general, the category of non-agricultural land (shrubs) dominated almost all coastal villages. In each analysis unit, it occupied 59.2% while highways covered 1.4% of the area (Table 7). In non-agricultural areas, sand and stone mining activities were found in the community, especially in Kolbano District and its surroundings. Although this non-agricultural area was not classified as vulnerable due to the absence of immediate dangerous impacts on the population, it creates a serious risk for residents, as the presence of stone mining activities has gradually increased the area's vulnerability to abrasion. According to Hantoro (2020), anthropogenic activities can cause ecosystem damage that is increasingly difficult to control. Even though sandy and rocky areas are in large quantities, the impact of exploitation often exceeds the recovery capacity of the area.

Table 7. Area of land use along the coast in each analysis unit

Land Use	Wide (km^2)	%
Bush	50.41	59.24
Water Body	2.24	2.63
Field	13.43	15.78
Garden	13.65	16.03
Rice Field	2.49	2.93
Residence	1.64	1.92
Road	1.25	1.46

Source: Results of the analysis of DEMNAS data on the appearance of Indonesia in 2024

b. Population density

Based on the density analysis on the southern coast of the SCT Regency, the area within one kilometer from the coastline toward the land has a density ranging from 13 to 227 people/km^2. According to Triyastuti (2019), a high population density is categorized as more than 1000 people/km^2, while an ecologically ideal density falls between 50 and 100 people/km^2. The results of observations in 25 coastal villages indicated that the blue areas (Figure 15) still had an ideal population density, below 100 people/km^2. The vulnerability index for these blue areas, namely the Tuafanu, Kualin, Tuapakas, Noesiu, Oetuke, Nenoat, and Boking coasts, showed that they were categorized as having low vulnerability. The green areas, namely the Kolbano, Nualunat and Meusin coasts, were categorized as having moderate vulnerability. The orange areas, namely the Spaha, Op, Saenam and Sahan coasts, were categorized as having high vulnerability, with the Oni coast classified as the highest vulnerability (red area). Conversely, the white areas, omprising the coasts of Bena, Oebelo, Toineke, Nununamat, Kot'olin, Hoibeti, Nunkolo, Hoineno, Fatumanufui, and Baus, did not have any residences, resulting in a population density value of 0 and categorizing them as non-vulnerable (Figure 15).

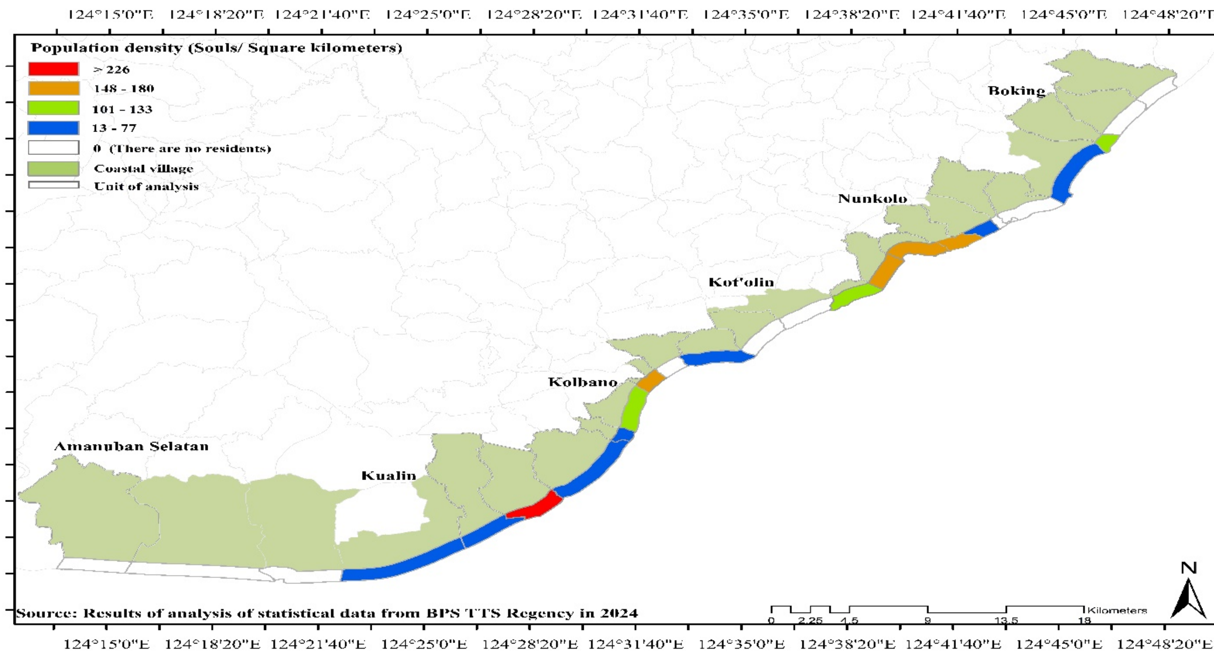


Figure 15. Population density in each analysis unit

c. Poverty Rate

The poverty rate was represented by the analysis unit at the pre-prosperous level. The observation results revealed that the poverty rate in the coastal areas of Bena, Oebelo, Toineke, Nununamat, Hoibeti, Kot'olin, Hoineno, Nunkolo, Fatumanufui, and Baus was zero as no residents inhabitated these areas (Figure 16). According to Sulma (2012), if the number or density of population is zero, the poverty rate will also be zero. These unhabitated areas were generally located far from highway access and were characterized by flat topography, increasing the risk of seawater inundation. This indicates a form of adaptation carried out by the community to avoid the threat of rising sea levels. The numbers of poor people in the 1 km area from the coastline in the very vulnerable category was found in Sahan, Oetuke, Spaha, Noesiu, and Tuafanu Villages, while in the moderate to low vulnerability categories, respectively, were Kualin, Tuapakas, Nualunat, Op, Oni, and Kolbano Villages. In general, the coastal communities of the SCT Regency who were poor worked as farmers and stone/sand miners (Figure 16). The porverty rate in all analysis units can be seen in Figure 16.

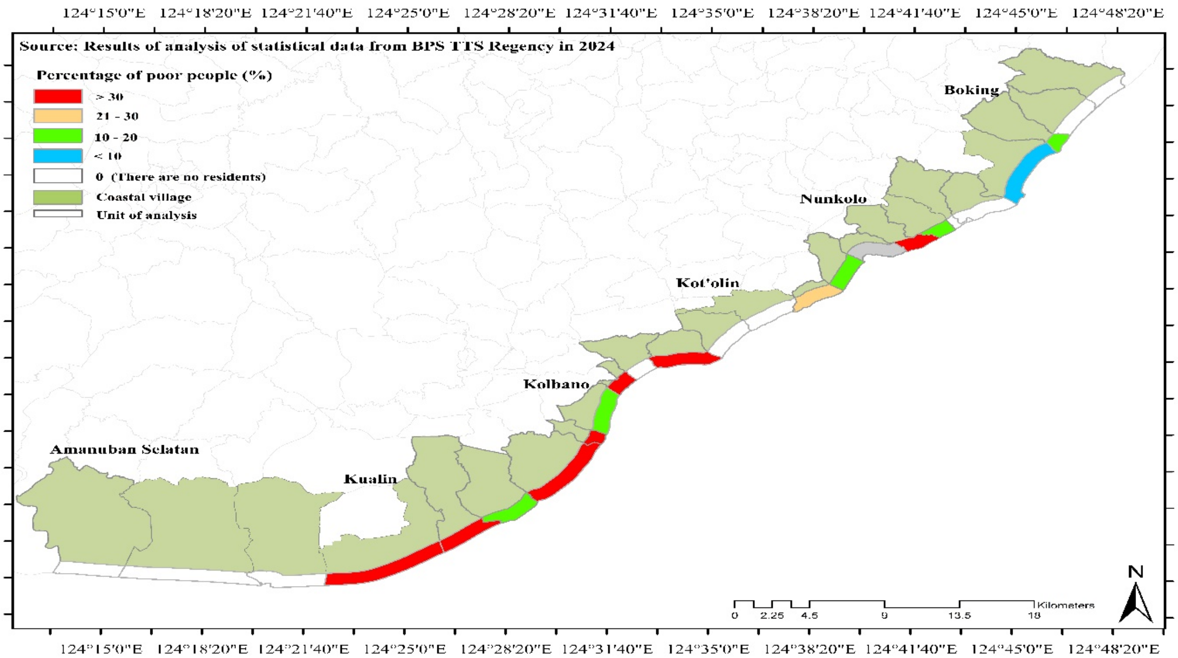


Figure 16. Povery rate in each analysis unit

The higher the poverty rate in an area, the greater the vulnerability of the area in facing a disaster. This is related to safety efforts and the community's ability to face disasters.

Vulnerability Analysis

The results analysis of six physical variables showed that the coasts of Bena, Oebelo, Toineke, Tuafanu, Kualin, Oni, Tuapakas, Noesiu, Kolbano, Spaha and Oetuke (Figure 17) were in the range of high to very high vulnerability. The high vulnerability in these coastal areas is due to the location of these coasts on a gentle to flat alluvial coastal plain, making the land more susceptible to shrinkage caused by hydrooceanographic factors, such as the inland shift of the coastline, with the exception of the Toineke coast, which is experiencing accretion (Figure 9). The accumulation of several hydrooceanographic variables with high vulnerability scores, specifically tides and waves (Figure 13), causes the Toineke coast to have vulnerable status. According to Sulma (2012), beaches with flat topography are generally dominated by sand, which is easily eroded by waves and tides. Meanwhile, those falling into low vulnerability category, namely the Kot'olin, Nualunat, Saenam, Nenoat, Nunkolo, and Boking coasts, are generally located in hilly areas. The type of hills on the coastal areas of the SCT Regency are karst hills that are classified as erosional zone. The shifting coastline in the Saenam karst hills shows that in terms of genesis, this type of karst belongs to the erosional karst group. The distribution of physical vulnerability levels is presented in Figure 17.

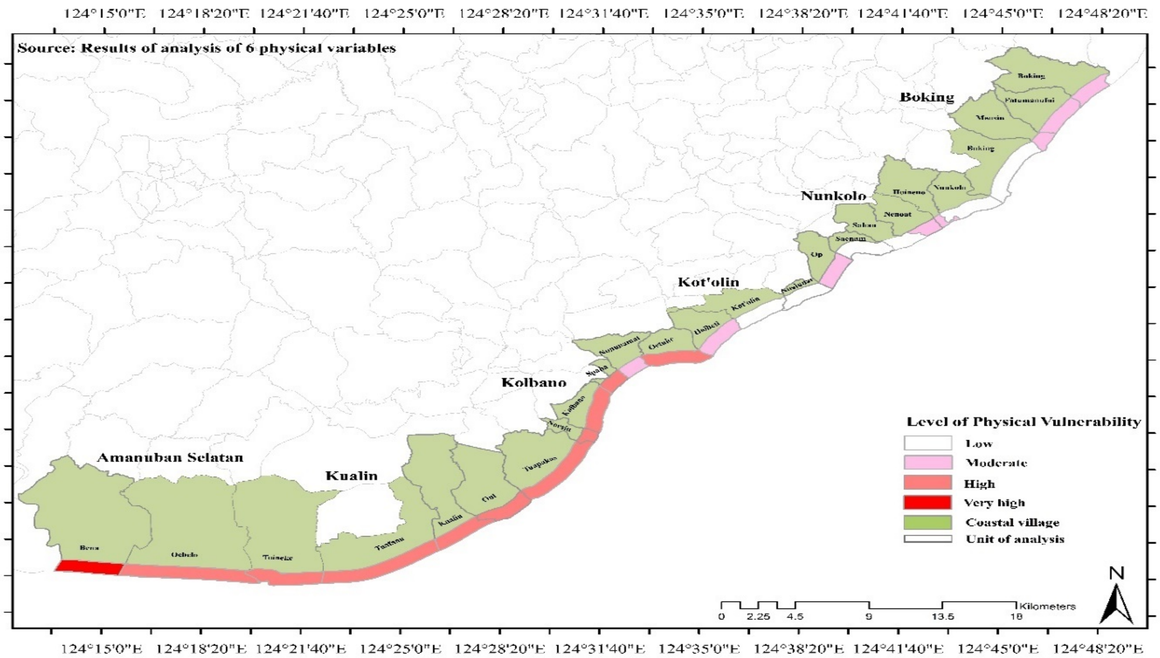


Figure 17. Physical vulnerability levels of the SCT Regency's coastal areas

The standardization calculation of the average values of physical variables reveals that geomorphology holds the highest influence on the physical vulnerability of the SCT Regency's coastline, with a score of 0.78. Following this, elevation ranks at 0.69, coastline change rate at 0.68, average tidal range at 0.48, sea level rise rate at 0.43, and wave height at 0.22 (Table 8). The results analysis has shown that geomorphological conditions have highest influence on the high level of physical vulnerability on the coastal areas of the SCT Regency, followed by elevation, coastline change rate, tidal range, sea level , and wave height.

Table 8. The results of standardization of physical variable values in each analysis unit

Analysis Unit	Elevation	Geomorphology	Tidal Range	Coastline Change Rate	Sea Level	Wave Height
1	0.996	1.000	0.000	0.706	0.011	0.000
2	0.995	1.000	0.000	0.823	0.011	0.021
3	0.967	1.000	0.000	0.675	0.036	0.039
4	0.713	0.844	0.000	0.613	0.080	0.076
5	0.673	0.823	0.000	0.559	0.144	0.122
6	0.762	0.793	0.000	0.731	0.175	0.142
7	0.635	0.684	0.000	0.805	0.196	0.155

8	0.494	0.561	0.000	0.694	0.225	0.170
9	0.000	0.000	0.000	0.750	0.264	0.187
10	0.632	0.826	0.000	1.000	0.317	0.204
11	0.283	0.415	0.000	0.625	0.376	0.218
12	0.236	0.237	0.000	0.651	0.437	0.230
13	0.448	0.639	0.000	0.789	0.506	0.239
14	0.499	0.697	1.000	0.701	0.567	0.243
15	0.234	0.413	1.000	0.558	0.607	0.244
16	0.395	0.690	1.000	0.647	0.640	0.242
17	0.886	0.990	1.000	0.720	0.698	0.227
18	0.815	1.000	1.000	0.875	0.749	0.206
19	0.752	1.000	1.000	0.690	0.831	0.157
20	0.809	1.000	1.000	0.524	0.930	0.088
21	0.991	1.000	1.000	0.716	0.957	0.050
22	0.998	1.000	1.000	0.643	0.810	0.101
23	1.000	1.000	1.000	0.000	0.566	0.406
24	0.998	1.000	1.000	0.562	0.345	0.773
25	0.996	1.000	1.000	0.927	0.156	1.000
Average	**0.69**	**0.78**	**0.48**	**0.68**	**0.43**	**0.22**

Based on the analysis results of three socio-economic variables Noesiu Village exhibited high socio-economic vulnerability, while other areas fell into medium, low, and very low levels of vulnerability (Figure 18). Table 9 indicates that land use and poverty rate in the coast of Noesiu significantly contributed to the high socio-economic vulnerability. All population of Noesiu Village lived in an area of 1 km from the coastline towards the land. Their livelihoods generally depended on stone and sand mining. These mining activities extend across several coastal areas, including Kolbano, Oetuke, Nenoat, Hoineno, and Nunkolo. The vulnerability observed along the coastal area was predominantly influenced by land use, as shown in Table 9. This is primarily due to the conversion of non-agricultural land into sand and stone mining zones, a practice that has accelerated erosion along the coastline. This land-use change has created a nearly uniform pattern of coastal erosion, further destabilizing the area and increasing its susceptibility to environmental degradation.

Table 9. Results of standardization values of socio-economic variable in each analysis unit

Analysis Unit	Land use	Population Density	Poverty rate
1	0.605	0.000	0.000
2	0.202	0.000	0.000
3	0.555	0.652	0.148
4	0.365	0.265	0.064
5	0.710	0.000	0.000
6	0.871	0.000	0.000
7	0.610	0.340	0.132
8	0.291	0.467	1.000
9	0.438	0.557	0.000
10	0.380	0.585	0.196
11	0.522	0.792	0.248
12	0.185	0.000	0.000
13	0.311	0.000	0.000
14	0.643	0.111	1.000
15	0.198	0.000	0.000
16	0.344	0.446	0.959
17	0.595	0.669	0.129
18	1.000	0.236	1.000
19	0.325	0.207	0.511
20	0.558	0.999	0.154

21	0.511	0.222	0.582
22	0.474	0.056	1.000
23	0.000	0.000	0.000
24	0.015	0.000	0.000
25	0.013	0.000	0.000
Average	**0.43**	**0.26**	**0.28**

The standardization of average variable value from largest to smallest revealed three main socio-economic factors contributing to vulnerability along the coastal areas of the SCT Regency: land use (0.43), poverty rate (0.28), and population density (0.26). The analysis results showed that, in general, land use has contributed hugely on the high level of socio-economic vulnerability, followed by poverty rage and population density, respetively (Table 9). The distribution of socio-economic vulnerability levels in the coastal areas of the SCT Regency is presented in Figure 18.

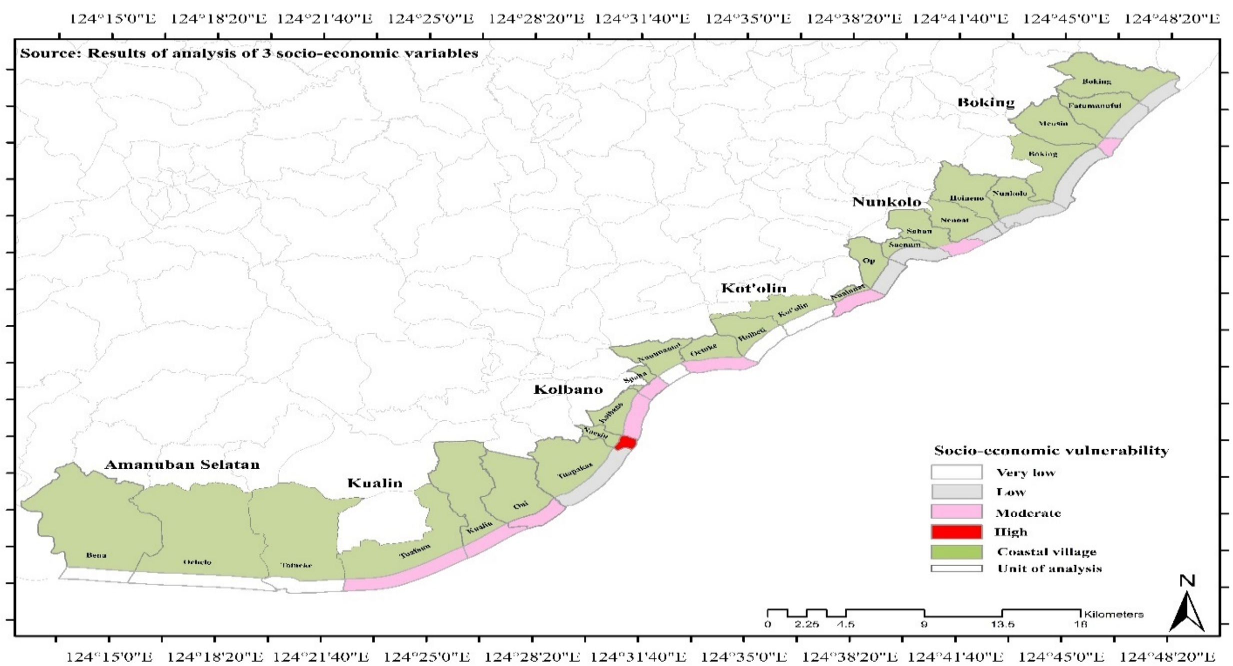


Figure 18. Levels of socio-economic vulnerability of the coastal areas of the SCT Regency

The results of the analysis of physical and socio-economic variables in the research site showed that the Kot'olin coast was the area with very low vulnerability. This was primarily due to its residences being located further inland, coupled with the fact that its residents were not categorized as poor, which reduced the impact of potential coastal hazards. Meanwhile the Tuafanu, Kualin, Oni, Noesiu, Kolbano, and Oetuke coasts were found to have high vunerability (Figure 19). These areas, situated within one kilometer from the coastline, experienced significant damage due to both anthropogenic activities and the dynamic influences of hydro-oceanographic factors. Figure 19 illustrates the spatial distribution of these vulnerabilities.

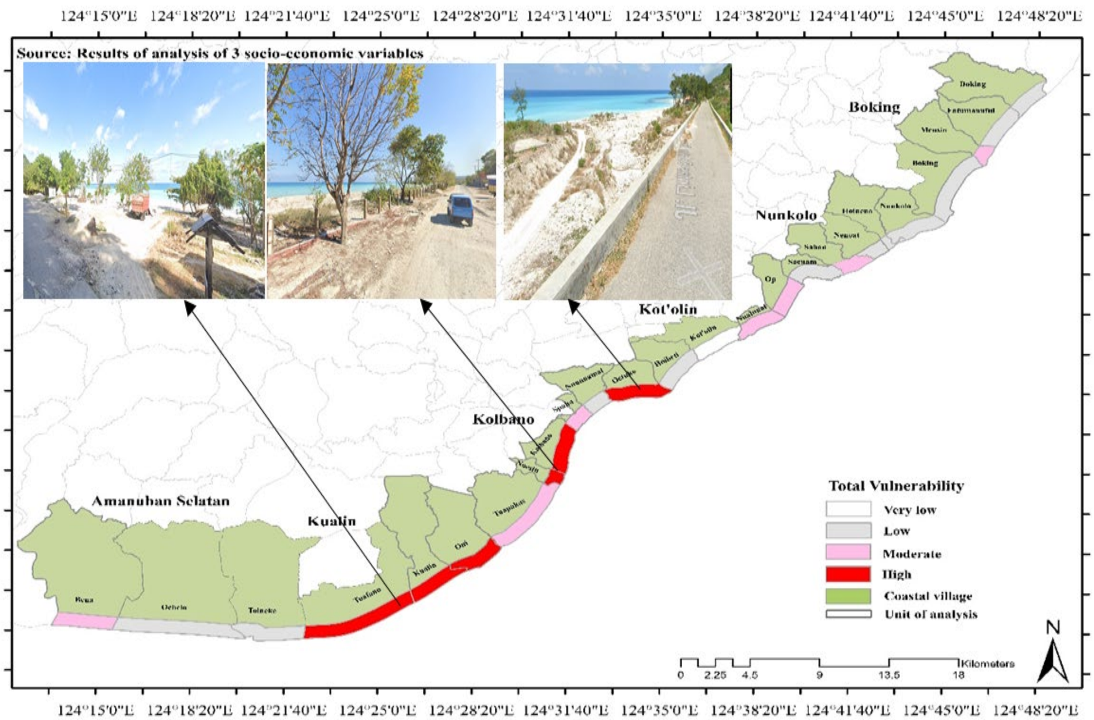


Figure 19. Total vulnerability levels of the SCT Regency's coastal areas

CONCLUSION

The coastal areas of the SCT Regency are classified as vulnerable to rising sea levels, with low (35%), medium (48%), and high (66%) vulnerability categories. Areas with a high level of vulnerability were physically lowland areas with fragile coastal landforms. Karst hills, which are characteristic of the SCT Regency's coastline, pose a threat to the lives of coastal communities, as these hill types are categorized as an erosion zone. Communities living in coastal hill areas, including those in the Kolbano, Spaha, and Oetuke coastal areas, as well as in flat alluvial regions like Tuafanu, Kualin, and Oni, should be prioritized in coastal development and restoration efforts due to their high vulnerability in both physical and socio-economic aspects. The physical condition that most contributes to the coastal vulnerability of the SCT Regency is geomorphology, while the most influential socio-economic factor is land use. One necessary recovery effort involves revegetation, supported by the synergy between human activities and nature, guiding communities to utilize natural resources for economic livelihoods while maintaining ecological balance.

ACKNOWLEDGMENT

This research was carried out through funding from the Ministry of Education, Culture, Research and Technology with number: 100/E5/PG.02.00.PL/2024. Therefore, we would like to thank the Ministry and the Research Institute of the University of Timor for carrying out this research.

REFERENCES

Bachri, S. 2011. Technostraffication of the Outer Banda Arc with Reference to the Western Part of Timor Leste and the Eastern Part of Seram Island. *Journal of Geology and Mineral Resources*, 21(2): 53-62. https://doi.org/10.33332/jgsm.geologi.v21i2.135

Diposaptono, S., Budiman and Agung, F. ~~2009~~ 2013. Dealing with Climate Change in Coastal Areas and Small Islands. Popular Scientific Books. Bogor. https://surajis.files.wordpress.com/2017/12/menyiasati-perubahan-iklim-di-wp3k.pdf

Fadilah 2021. Analisis Faktor Hidro-Oseanografi Terhadap Kerusakan Pantai Kecamatan Pondok Kelapa Kabupaten Bengkulu Tengah dan Penentuan Konsep Penanganannya. Jakad Media Publishing. Surabaya. https://books.google.co.id/books/about/Analisis_Faktor_Hidro_Oseanografi_Terhad.html?id=b1crEAAAQBAJ&redir_esc=y

Gaol, A. L., Siadari, E. L., Ryan, M. and Kristianto, A. 2018. The impact of tropical cyclone France on the upwelling of the Timor Sea and its surroundings. *Journal of Meteorology Climatology and Geophysics*, 5(3): 37-45. https://jurnal.stmkg.ac.id/index.php/jmkg/issue/view/10

Hantoro, W.S. 2020. Kerentanan-Ketahanan Kawasan Landai Pesisir dan Pulau Kecil: Mitigasi dan Adaptasinya. Pusat Penelitian Geoteknologi. LIPI Press. Jakarta. https://doi.org/10.14203/press.144

Hamuna, B., Sari, A. N. and Alianto, A. 2018. Kajian kerentanan wilayah pesisir ditinjau dari geomorfologi dan elevasi pesisir Kota dan Kabupaten Jayapura, Provinsi Papua. *Jurnal Wilayah dan Lingkungan*, 6(1): 1-14. http://dx.doi.org/10. 14710/jwl.6.1.1-14

Kalay, D. E., Lopulissa, V. F. and Noya, Y. A. 2018. Analisis Kemiringan Lereng Pantai dan Distribusi Sedimen Pantai Perairan Negeri WAAI Kecamatan Salahutu Provinsi Maluku. Triton: *Jurnal Manajemen Sumberdaya Perairan*, 14(1): 10-18.

Kasim, F. 2011. Penilaian Kerentanan Pantai Menggunakan Metode Integrasi CVI-MCA dan SIG, Studi Kasus Garis Pantai Pesisir Utara Indramayu. *Forum Geografi*, 26(1): 65 – 76. DOI: 10.23917/forgeo.v26i1.5051

Karsidi, A. 2011. Workshop Dampak Kenaikan Permukaan Laut pada Lingkungan Pantai Indonesia. http://www.bakosurtanal.go.id

Koroglu, A., Ranasinghe, R., Jiménez, J. A. and Dastgheib, A. 2019. Comparison of Coastal Vulnerability Index Applications for Barcelona Province. Ocean and Coastal Management. https://doi.org/10.1016/j. ocecoaman.2019.05.001

Kurniawan, R., Siagian, T. H., Yuniarto, B., Nasution, B. I. and Caraka, R. E. 2018. Construction of social vulnerability index in Indonesia using partial least squares structural equation modeling. *International Journal of Engineering & Technology*, 7(4): 6131-6136. doi: 10.14419/ijet.v7i4. 24648

Ledheng, L., and Hano'e, E. M. Y. 2023. Analysis of Shoreline Change of North Central Timor Regency, Indonesia. *Nature Environment & Pollution Technology*, 22(2): 777-787 https://doi.org/10.46488/NEPT.2023.v22i02.020

Lindsey, R. 2019. Climate Change: Global Sea Level. National Oceanic and Atmospheric Administration (NOAA), National Ocean Service, Silver Spring. https://www.climate.gov/news-features/understanding-climate/climate-change-global-sea-level

Maulana, E., Ambarwulan, W., Wulan, T. R., Saputro, G. B., Setiawan, N., Muharram, F. W. and Putri, G. A. 2017. Evaluasi ODTW Pantai Kolbano untuk Peningkatan Ekonomi Lokal Masyarakat di Desa Kolbano, Kecamatan Kolbano, Kabupaten Timor Tengah Selatan. http://hdl.handle.net/11617/9186

Government of the Republic of Indonesia 2007. Undang-Undang Republik Indonesia Nomor 27 Tahun 2007 tentang Pengelolaan Wilayah Pesisir dan Pulau-Pulau Kecil. Jakarta: Sekretaris Negara Republik Indonesia. https://peraturan.bpk.go.id/Details/39911/uu-no-27-tahun-2007

Pamungkas, A. 2018. Karakteristik parameter oseanografi (pasang-surut, arus, dan gelombang) di perairan utara dan selatan Pulau Bangka. *Buletin Oseanografi Marina*, *7*(1): 51-58.

Pendleton, E. A., Thieler, E. R. and Williams, S. J. 2010. Importance of Coastal Change Variables in Determining Vulnerability Sea and Lake Change. *Journal of Coastal Research*. 26(1): 176-183. https://doi.org/10.2112/08-1102.1

Ramieri, E., Hartley, A., Barbanti, A., Santos, F.D., Gomes, A., Hilden, M., Laihonen, P., Marinova, N., Santini, M. 2011. Methods for Assesing Coastal Vulnerability to Climate Change.ETC CCA Background Paper Copenhagen (DK) 8-9 June 2011. https://www.academia.edu/72046359/Methods_for_assessing_coastal_vulnerability_to_climate_change_ETC_CCA

Suhana M.P., Putra, R., Muliadi, M. and Shafitri, L. F. 2020. Tingkat Kerentanan Pesisir Di Utara Dan Timur Pulau Bintan Provinsi Kepulauan Riau Tahun 2020. *Jurnal Teknologi Perikanan dan Kelautan*, 11(1): 11–27. Doi: 10.24319/jtpk.11.11-27

Sulma, S. 2012. Kerentanan Pesisir Terhadap Kenaikan Muka Air Laut (Studi Kasus: Surabaya dan Daerah Sekitarnya). [Tesis] Sekolah Pasca sarjana Universitas Indonesia: Depok. https://lontar.ui.ac.id/detail?id=20315253\

Szlafsztein, C. F. 2005. Climate change, sea-level rise and coastal natural hazards: A GIS-based vulnerability assessment, State of Para, Brazil. *J. Coast. Conserv*, *11*: 53-66. https://www.researchgate.net/publication/253948902_Climate_change_Sea level_rise_and_Coastal_Natural_Hazards_A_GIS-Based_Vulnerability_Assessment_State_of_Para_Brazil

Rahmania, T., Apriyanto B. and Astutik S. 2019. Potensi Terjadinya Longsor pada Kawasan Karts Gunung Sadeng Puger karena Adanya Aktivitas Pertambangan. *Majalah Pembelajaran Geografi*, *2*(1): 161-171. https://jurnal.unej.ac.id/index.php/PGEO/article/view/11937

Ward, P. J., Marfai, M. A., Yulianto, F., Hizbaron, D. R., and Aerts, J. 2011. Coastal inundation and damage exposure estimation: a case study for Jakarta. Natural Hazards, 56: 899-91. DOI 10.1007/s11069-010-9599-1

Triyastuti, D. 2019. Pengaruh Kepadatan Penduduk Terhadap Kualitas Hidup Masyarakat di Kecamatan Ngemplak Kabupaten Boyolali Tahun 2013 dan 2017 (Doctoral dissertation), Universitas Muhammadiyah Surakarta, Indonesia. https://eprints.ums.ac.id/79812/12/NASKAH%20 PUBLIKASI.pdf