Environment and Ecology Research 12(6): 601-619, 2024
DOI: 10.13189/eer.2024.120604 http://www.hrpub.org

Mapping Physical and Environmental Vulnerabilities for Port Development in Tanjung Carat, South Sumatra

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Received October 8, 2024; Revised November 30, 2024; Accepted December 23, 2024

Cite This Paper in the Following Citation Styles

(a): *[1] Herda Sabriyah Dara Kospa, Al Shida Natul, Hala Haidir, Shinta Puspasari, Mailendra , "Mapping Physical and Environmental Vulnerabilities for Port Development in Tanjung Carat, South Sumatra," Environment and Ecology Research, Vol. 12, No. 6, pp. 601 - 619, 2024. DOI: 10.13189/eer.2024.120604.*

(b): *Herda Sabriyah Dara Kospa, Al Shida Natul, Hala Haidir, Shinta Puspasari, Mailendra (2024). Mapping Physical and Environmental Vulnerabilities for Port Development in Tanjung Carat, South Sumatra. Environment and Ecology Research, 12(6), 601 - 619. DOI: 10.13189/eer.2024.120604.*

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Abstract Tanjung Carat in Banyuasin, South Sumatra is a vital area characterized by its extensive mangrove-dominated wetlands and diverse wildlife. Concerns have been raised regarding the potential environmental impact of the proposed Tanjung Carat International Port construction on this ecologically rich area. Aiming to minimize potential harm, there is a need to assess the vulnerability of the port development areas and develop policies to protect the environment. This study seeks to analyze the physical and environmental vulnerability of the port development areas using a geographic information system (GIS). To assess physical vulnerability, the study analyzed seven key parameters including geomorphology, geology, average wave height, elevation, average tide, coastline changes, and climatology. In addition, environmental vulnerability was evaluated using four parameters: protected forest areas, mangroves, shrubs, and nature reserve forests. Data from relevant agencies and direct field observations were used to conduct the assessment, employing the scoring method and the Coastal Vulnerability Index (CVI) formula. The findings reveal that the Tanjung Carat area exhibits high physical vulnerability due to its low elevation, flat geomorphology, and geology characterized by lake sediment formations, making it highly susceptible to ecosystem perturbations resulting from developmental activities. The analysis of environmental vulnerability further highlights the prevalence of high vulnerability, particularly due to the presence of protected forests, sanctuary forests, and mangroves, especially in Sungsang II and IV Villages. The insights gained from this study are intended to provide valuable guidance to stakeholders involved in evaluating the potential impact of development, particularly the proposed international port, on the physical and environmental vulnerability of the area.

Keywords Vulnerability Mapping, Coastal Vulnerability Index (CVI), Geographic Information System (GIS), Port Development

1. Introduction

Tanjung Carat, is positioned along the East Coast of South Sumatra, Indonesia bordering the Bangka Strait, making it a potential hub for maritime trade and port development [1]. This area is strategically situated near the Malacca Strait, one of the world's most heavily traveled maritime trade routes, highlighting its economic significance. This advantageous location establishes it as a crucial hub for both national and international logistics, enabling efficient shipping operations and enhancing economic connectivity through access to global markets [1].

This area is envisioned to play a pivotal role in enhancing South Sumatera's national logistics network and

fostering regional economic growth. This development is in line with the National Strategic Project (PSN) program, as stipulated in Presidential Regulation No. 3 of 2016, to address the critical need for a new port that will bolster export-import activities in South Sumatra.

However, the region's environmental and physical characteristics present challenges. Tanjung Carat comprises low-lying coastal zones, vulnerable to flooding, land subsidence, and coastal erosion. Its estuarine ecosystem, rich in mangroves and biodiversity [2,3,4], faces threats from deforestation and habitat degradation. Additionally, climate change exacerbates the risks of rising sea levels and extreme weather events, potentially undermining sustainable port development.

Various activities related to exploitation may have adverse impacts on the community and the environment, both within the industrial sector [5] and households [6,7]. With regards to port development, numerous prior studies in the Tanjung Api-Api (TAA) area have indicated that the operation of the port has led to disruptions in the sustainability of the ecosystem [8] due to land clearance, resulting in a reduction of more than 10% in the area of mangrove forests in the Banyuasin Waters since 2000 [9,10,11]. Moreover, port activities have led to an increase in the presence of heavy metal pollutants originating from ship oil waste and similar sources, which are transported by river flows or directly discharged into the waters [12,13].

In accordance with Government Regulation of the Republic of Indonesia No. 22 of 2021 regarding the Implementation of Environmental Protection and Management, the port development activities conducted in Tanjung Carat have the potential to impact the ecosystem in the area. These activities may lead to changes in land use, particularly in the function of the mangrove forest and the aquatic environment. Land reclamation, in particular, has the potential to affect the quality and abundance of natural resources, especially estuary ecosystems, as well as the marine biota and the number of mangrove ecosystems [14,15,16]. This impact could ultimately affect the incomes of fishermen and potentially contribute to an increase in the impoverished population in coastal areas [17,18].

In light of environmental considerations, it is of utmost importance to conduct comprehensive scientific studies to fully understand the potential impacts of port development activities in the Sungsang area. Mapping the level of physical and environmental vulnerability is critical in mitigating any potential environmental damage [19] caused by port activities. It is imperative to formulate policy directions aimed at increasing environmental resilience to guide policymakers in the region.

The groundbreaking of the Tanjung Carat Port is scheduled to begin in 2024 [20]. The construction activities of Tanjung Carat Port, located within Sungsang Villages, will impact the natural balance of the environment as it involves reclaiming 2,219 hectares of sea and utilizing land in the Air Telang Coastal Protected Forest area through a lease [21]. The environmental impacts of reclamation may include rising sea levels [22], erosion [22], sedimentation [23], coastal groundwater aquifer pollution [24], reduction in the hydraulic gradient of water flow [25], and the potential for mudflow [26]. Furthermore, the biological impacts are significant, encompassing the disruption of ecosystems such as plankton, nekton, and aquatic plants [27,28], as well as the interference with the development of mangrove vegetation, which acts as a habitat for marine life [19]. To minimize environmental damage, it is essential to undertake mitigation efforts by carefully assessing the susceptibility of the area around the development to potential declines in physical and environmental quality, referred to as the level of physical and environmental vulnerability[27,28].

The primary objective of this study is to conduct a thorough assessment and mapping of the various physical and environmental vulnerabilities present in the Tanjung Carat International Port development area. This involves analyzing factors such as geomorphology, geology, elevation, coastline changes, wave height and tides. Vulnerability mapping is essential for the port development in Tanjung Carat area. It helps identify physical and environmental risks that could affect the project's success. Tanjung Carat faces challenges like coastal erosion, land subsidence, rising sea levels, and sensitive ecosystems, which may impact construction and long-term operations. By recognizing these risks, stakeholders can create effective planning strategies and prioritize mitigation efforts, ensuring the project aligns with sustainability and climate resilience goals while protecting infrastructure and local communities.

The notion of vulnerability encompasses a wide range of factors, including social, economic, physical, and environmental elements [29]. An assessment has been conducted to gauge the level of socio-economic vulnerability in Sungsang Village [30]. The findings provide valuable insights into the impact of port development on the socio-economic well-being of coastal communities and suggest specific policy directions for mitigation [31].

Recent studies on coastal vulnerability mapping have highlighted the importance of assessing physical and environmental vulnerabilities to coastal hazards. Researchers have employed various methodologies, including the Coastal Vulnerability Index (CVI) and Analytical Hierarchy Process (AHP), to identify vulnerable areas along coastlines. These assessments often incorporate factors such as shoreline changes, sea level rise, wave height, and geomorphology [32]. However, methodological gaps persist, including limited inclusion of social considerations, lack of temporal dynamic dimensions, and insufficient local-scale assessments [34,35]. Additionally, there is a need for more transparent rationale in variable selection and increased use of predictive assessment methods [35]. Despite these challenges, coastal vulnerability mapping remains a crucial tool for understanding and mitigating the impacts of

climate change on coastal areas, supporting long-term coastal zone planning and adaptation strategies [33].

Studies have examined vulnerability of physical conditions [32,33] and the environment [34,35,36,37,38] in certain areas, but further research specifically focused on port development areas is needed due to the significant impacts of ecosystem changes. This study uses a geographic information system (GIS) to analyze disaster-prone area distribution [39,40]. The findings can help policymakers weigh decisions on development or construction in the area, serving as an initial step in mitigation [38,39].

2. Materials and Methods

A comprehensive vulnerability mapping survey was conducted in the Tanjung Carat Port Development Area, focusing on the Sungsang I, Sungsang II, Sungsang III, and Sungsang IV Villages within the Banyuasin II District, located in the Banyuasin Regency of South Sumatra. The details of the research location can be viewed in Figure 1.

This study analyzes multiple physical and environmental parameters to evaluate the vulnerability of the area. Physical vulnerability involves geology, hydrology, and coastal dynamics, which are important for planning risk reduction [43]. Weak geological conditions, like soft soil or weathered rock, increase the risk of landslides, erosion, and earthquake damage [44]. In addition, hydrological aspects such as rainfall and tides impact flooding and land erosion [45]. When drainage systems cannot manage runoff, vulnerability increases. Coastline changes and wave height also affect stability. Areas with rough coastlines face a higher risk of damage and land loss [46,47]. These factors—water management, coastal changes, and drainage—determine how vulnerable coastal areas, including ports, are to damage.

Meanwhile, Environmental vulnerability consists of Protected Forests, Nature Reserve Forests, Mangrove Forests, and Shrubs. When development disrupts large natural areas, the level of vulnerability increases due to the cumulative negative effects, which can lead to significant environmental damage. This not only diminishes essential services like clean water and disaster protection but can also exacerbate problems such as erosion and declining water quality [48,49]. These factors are crucial for assessing the impact of development on the ecosystem in the Tanjung Carat Port area.

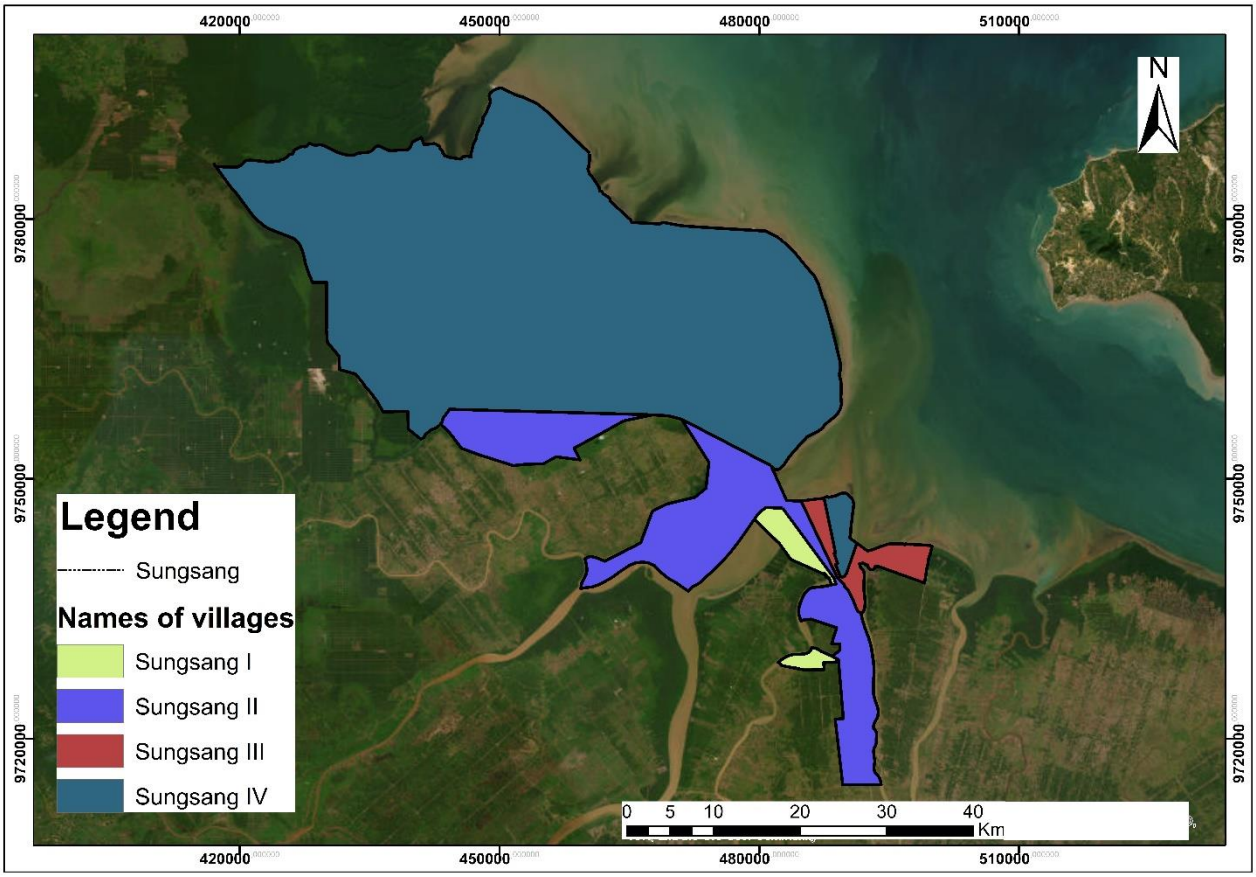


Figure 1. Research Location

Table 1. Data Source in CVI Calculation

Physical and Environmental Variables		
Variables	Data Source	Data Period
Geomorphology	Public Works and Spatial Planning Agency (PUPR) of Banyuasin Regency	2024
Geology	Public Works and Spatial Planning Agency (PUPR) of Banyuasin Regency	2024
Average Wave Height	Meteorology, Climatology and Geophysics Agency (BMKG) of South Sumatra Province	2021-2024
Elevation	Public Works and Spatial Planning Agency (PUPR) of Banyuasin Regency	2024
Average Tides	Pasanglaut.com	2021-2024
Coastline Changes	Geospatial Information Agency and analysis results	2021-2022
Climatology	Meteorology, Climatology and Geophysics Agency (BMKG) of South Sumatra Province	2024
Land Use	Development Planning Agency at Sub-National Level, Groundchecking	2024

Geographic Information Systems (GIS) are used to analyze spatial data by layering different types of information on maps. This approach allows for the calculation of the Physical Vulnerability Index, which assesses the vulnerability of an area to environmental issues [50]. GIS effectively displays the distribution of environmental features and creates maps that simplify data interpretation [51]. It integrates data from various sources, including field surveys, remote sensing, and numerical models, to provide a comprehensive view [51].

Remote sensing utilizes satellite and drone imagery to map and verify land use, including areas with shrubs, mangrove forests, nature reserves, and protected forests. This information supports the evaluation of environmental vulnerabilities and helps characterize the region [52].

Additionally, a field survey was conducted in the Tanjung Carat area, gathering direct data through interviews with local community members and sub-district officials, along with observations of existing conditions related to the development plan for the Tanjung Carat port. These research sources are summarized in Table 1.

The CVI equation = vulnerability index is as follows:

$$VI=\sqrt{\frac{a_1 \times a_2 \times a_3 \ldots \ldots a_n}{n}} \quad (1)$$

Where: a = variable and n = variable total.

Following the CVI calculation, the level of physical and environmental vulnerability in the area can be determined and categorized into three levels: less vulnerable (index one), moderate (index two), and high (index three). This analysis also facilitates the identification of specific areas with varying vulnerability levels.

The calculation results are showcased on a map, delineating the levels of physical and environmental vulnerability. Subsequently, the vulnerability map undergoes thorough analysis to identify factors influencing the vulnerability in the research area. The study culminates in a mitigation policy for the new Tanjung Carat port development, considering its impact on the local community's physical and environmental conditions.

The processing of spatial data for physical and environmental vulnerability incorporates the utilization of a geographic information system (GIS) along with a scoring method for all parameters (Table 2). The Coastal Vulnerability Index (CVI) equation, which has been adapted from [38], employs a straightforward approach to calculate all physical and environmental vulnerability parameters. This equation offers a numerical basis for categorizing different segments of the coastline based on their susceptibility to physical and environmental changes, thus facilitating the identification of areas with heightened vulnerability. The environmental data processing refers to the Indonesian Disaster Risk (RBI) book, published by the National Disaster Management Agency (BNPB) in 2016 [40].

This study has certain data limitations. The tidal data, sourced from secondary providers, covers only the past five years, which means it does not fully capture long-term trends or rare events like extreme tidal floods caused by climate change. Nevertheless, it provides valuable insights into the average tidal patterns in the Tanjung Carat Port area. In addition, collecting primary data through field surveys, including ground checks and drones, is limited by accessibility to certain key locations. However, representative sampling at strategic points has been conducted to verify spatial data and provide an accurate representation of field conditions.

Data limitations primarily impact detailed analyses, such as identifying weaknesses in port structures or evaluating short-term environmental quality. Nevertheless, the findings of this study are valuable for strategic decision-making. However, more current and comprehensive data are necessary for effective operational policies.

Table 2. Classification for Physical and Environmental Vulnerability Analysis

Level	Low	Moderate	High
Parameter	**1**	**2**	**3**
Physical			
Geo-morphology	High Cliff, Medium Cliff	Low Cliff, Salt, Marsh, Coral, Reef, Mangrove	Coastal Structures, Estuary, Lagoon, Alluvial Plain, Sandy Beach, Pebble Beach, Delta
Geology	Plantonic, Volcanic, Rock Conglomerate	Sedimentary Rocks	Consolidated Sediment, Clay, Silt, Unconsolidated Sediment, Gravel, Sand
The average wave height (m)	0 –4,9	5,0-5,9	6,0 - >6,9
Elevation (m)	20,1 – >30	10,1 -20,0	10 –
The average tidal range (m)	1,0– 2,0	2,1 – 4,0	4,1 - >6,0
The coastline change (m/year)	>2 Accretion 1 - 2 Accretion	1 – -1 Stable	-1 - <-2 Erosion
Land use	Industrial, Urban Area	Bare Land	Agricultural, Green Area
Climatology (mm/year)	<15 – 25,0	25,1 – 35,0	35,1 >45,0
Environmental			
Protected Forest	< 20 Ha	20 – 50 Ha	> 50 Ha
Mangrove	<10 Ha	10 - 30 Ha	> 30 Ha
Shrubs	<10 Ha	10 - 30 Ha	> 30 Ha
Nature Reserve Forest	<5 Ha	5 - 20 Ha	> 20 Ha

3. Results

3.1. Results of Physical Parameter Vulnerability Analysis

The physical vulnerability analysis of the Tanjung Carat port development area uses 7 (seven) parameters, namely: 1) geophormology; 2) geology, 3) average wave height, 4) elevation, 5) average tide, 6) changes in the coastline; and 7) climatology.

3.1.1. Geomorphology

The geomorphological data used in this study were obtained from Public Works and Spatial Planning Agency (PUPR) of Banyuasin Regency in 2024. Geomorphological processes are natural processes that occur on the Earth's surface, leading to changes in landforms. These changes result in different forms on the Earth's surface, each with unique physical and visual compositions [53]. These differences can be identified through the characteristics of relief /morphology, structure /lithology, and geomorphological processes [54]. Geomorphological parameters can indicate the erodibility of different types of landforms [55].

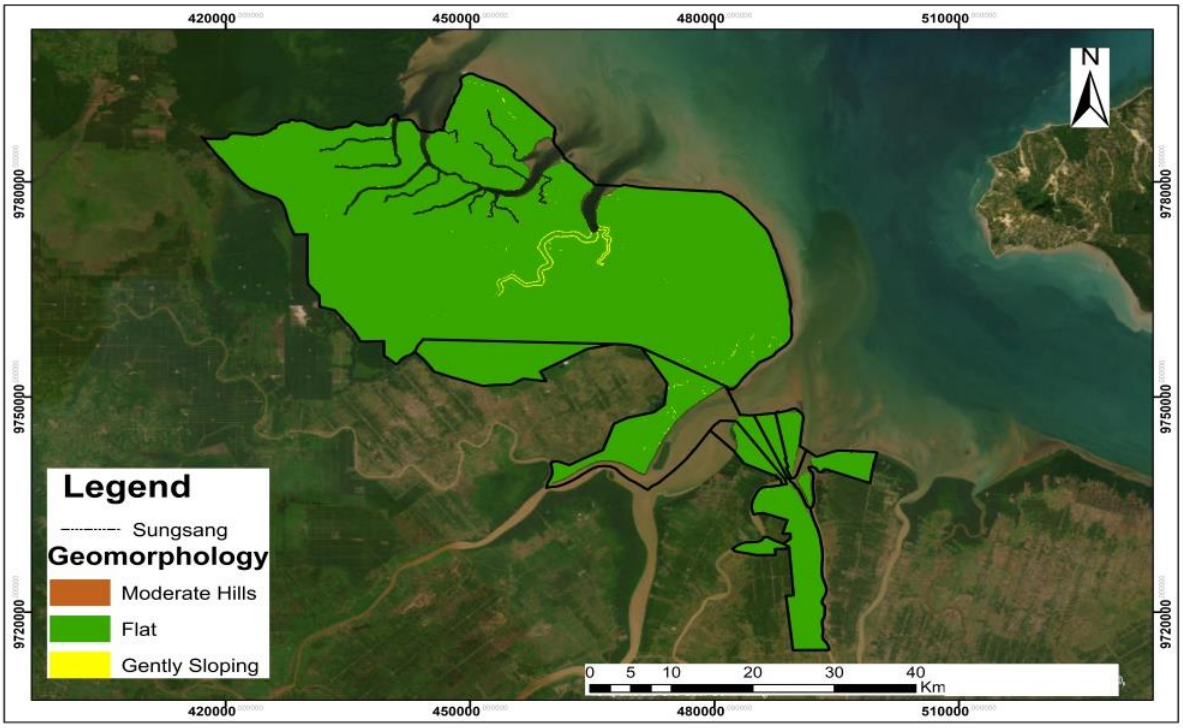
The analysis of the geomorphological vulnerability in the study area, along with ground checking, reveals that the majority of the Tanjung Carat area is a flat coastal area (Table 3), covering approximately 199,767 hectares, which is classified as high vulnerability. In contrast, the sloping area covers 1,225 hectares, and only 6 hectares (0.0033%) of the area are considered moderately hilly.

Table 3. Area Based on Geomorphological Score

No.	Geomorphology	Score	Total Area (ha)
1	Hill/Moderate Hills	1	6,83
2	Flat	3	199.767,49
3	Sloping	2	1.225,49
Total			200.999,81

Source: Analysis, 2024

Landforms with sloping and steep slopes are more resistant to waves and abrasion, allowing them to maintain stable environmental conditions [56]. Areas with sloping land are less vulnerable because they can withstand strong energy exposure, while flat areas are more vulnerable because they typically receive low energy exposure. Sandy beaches, mangrove forests, and wetlands are typically found in areas with high or very high vulnerability. Coastal vegetated wetlands and mangrove forest communities are particularly sensitive to climate change and long-term sea level changes due to their close proximity to sea level [56] [57]. The geomorphological classification map of the Tanjung Carat Area is illustrated in Figure 2.



Source: Analysis, 2024

Figure 2. Geomorphological Map in Tanjung Carat Area

3.1.2. Geology

The geological data for the Tanjung Carat Area were obtained from the Public Works and Spatial Planning Department of Banyuasin Regency in the form of shapefiles. The geology of the Tanjung Carat Area is classified into two types: Lacutrine Deposit and Muara Enim Formation. However, the area is mainly composed of Alluvium stratigraphy, which is formed by the Lacustrine Deposit with a Quaternary geological age covering two periods, namely Holocene and Pleistocene. Based on the predominant geological rock type in the Tanjung Carat Area, it is evident that the area has a high geological score as indicated in Table 6. Each type of rock has a soil sensitivity to abrasion or erosion, with alluvium having a low soil-bearing capacity [58].

3.1.3. Average Wave Height

The size of waves plays a crucial role in the process of erosion and sedimentation. The strength of the waves depends on the energy they carry as they reach the shore. This energy is determined by the height of the waves before they break. The height of the waves also impacts the vulnerability of the coastline and the overall geomorphological conditions of the area. Furthermore, wave height is linked to the risk of seawater flooding and the movement of sediment on the beach [59]. Changes in wave patterns correspond to shifts in water levels, demonstrating that breaking waves are influenced by the depth of the water [60]. Vegetation, such as mangroves, can increase friction, reduce wave formation, and help attenuate the impact of waves [61].

The significant wave height (SWH) is calculated by sorting the wave heights from highest to lowest and then taking the average of the highest third of the waves. These data are collected through in situ wave observation and requires information from altimetry satellites processed by BMKG (Sub Section Marine Integrated Data and Analysis System /http://202.90.199.148/ekstraksi_d ata/significant_ wave_height.php) for the period from 2021 to 2024.

The analysis of the average wave height map in the Tanjung Carat area shows that the wave heights range from 0 to 4.9 meters, which corresponds to a score of 1. The low wave height in the area is attributed to the stable daily pattern and minimal changes in wave height. Based on this parameter, the Tanjung Carat area is classified as having low vulnerability, with coastal wave heights of less than 1 meter, making it relatively safe from potential disasters [62][63]due to development.

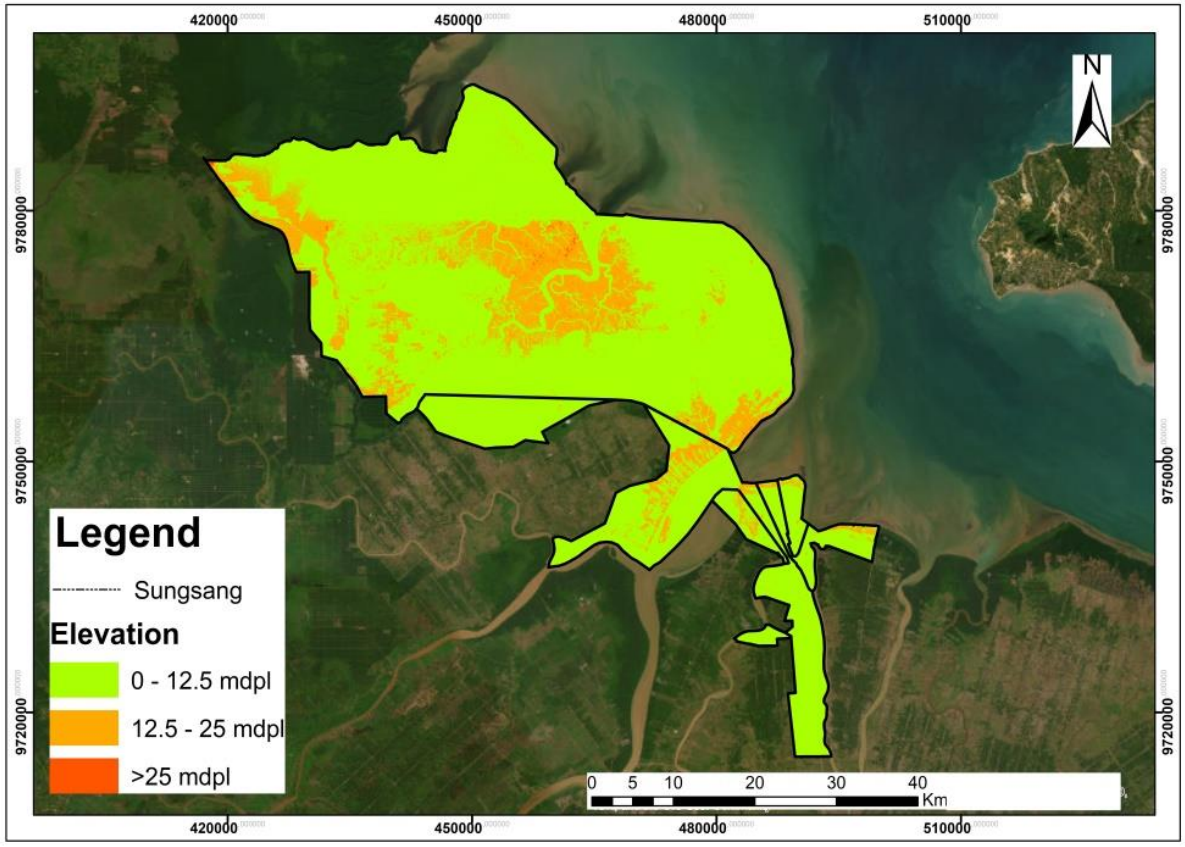
3.1.4. Elevation

The elevation data in this study were obtained from data processed by the Public Works and Spatial Planning Agency (PUPR) of Banyuasin Regency. The area is divided into three categories of elevation scores, as shown in Table 4. The elevation of the Tanjung Carat area is depicted on the map shown in Figure 3.

Table 4. Area Based on Elevation Score

No.	Elevation	Score	Total Area (ha)
1	>25 masl	1	1.225,49
2	12.5 - 25 masl	2	199.767,49
3	0 - 12.5 masl	3	6,83
Total			200.999,81

Source: Analysis, 2024



Source: Analysis, 2024

Figure 3. Elevation Map in the Tanjung Carat Area

The coastal slope refers to the steepness of the intertidal area between the highest high tide and lowest low tide lines. The elevation of the coastal area is a crucial factor that can determine the potential for inundation and the speed at which the coastline advances or retreats. The coastal area's elevation can also impact the extent of seawater inundation due to rising sea levels. In the event of a tidal wave, a beach or coast with a gentle slope (low elevation) can result in water penetrating the land over a considerable distance, leading to widespread water overflow [64]. Gornitz [42] noted that the danger decreases progressively as the average elevation increases.

The elevation level analysis results based on a predetermined score level in the study area indicate that the majority of the area (82%, equivalent to 165,061 hectares) has a coastal slope value of 0-12.5 meters above sea level (masl), falling into the high score category (score 3). Additionally, 17% of the area (35,608 hectares) located in the nature reserve forest area and production forest in Sungsang IV has a coastal slope ranging from 12.5 to 25 masl, placing it in the moderate score category. The analysis also reveals that part of the Tanjung Carat Area is susceptible to inundation due to rising sea levels, with lower elevations facing a higher risk of seawater inundation caused by sea waves or rising sea levels.

3.1.5. Average tides

Tides refer to the regular rise and fall of sea levels caused by the gravitational forces of celestial bodies, particularly the sun and moon, on the Earth's water mass. Tide data is a crucial factor in evaluating the physical vulnerability of coastal regions. Information on tides in

Sungsang was sourced from https://pasanglaut.com/id/sumatera-selatan/soengsang-palembang-river. According to this data, the average tide in the Tanjung Carat area ranges from 1 to 2 meters, categorizing it as a low score.

3.1.6. Coastline Change

The data for shoreline changes from 2021 to 2022 were obtained from the Geospatial Information Agency. The data were processed to calculate shoreline change values, which were then analyzed using DSAS (Digital Shoreline Analysis System). Shoreline change refers to the condition of the coast advancing or retreating due to the addition or reduction of sediment, leading to accretion or erosion. The changes in the shoreline of the Tanjung Carat area during 2021-2022 can be found in Table 6, and a map of shoreline changes in the study area is available in Figure 4.

Based on secondary data obtained from the Geospatial Information Agency, it is observed that there was no significant change in the coastline on the Sungsang coast during the given period. Therefore, the value of the change in the coastline is 1- (-1), indicating stability and a moderate score. The primary factors influencing changes in the coastline are hydro-oceanographic and anthropogenic factors. These changes are largely influenced by processes in the surrounding coastal areas (nearshore processes), as the coast constantly adapts to various conditions. This complex process is affected by the combination of waves and currents, sediment transport, and coastal configuration, all of which influence each other. These factors change spatially and temporally, persisting for extended periods. Field surveys indicate that the study area experiences small and short waves.

Source: Analysis, 2024

Figure 4. Map of Coastline Changes in the Tanjung Carat Area

3.1.7. Climatology

Based on the latest data from BMKG, it's clear that the Tanjung Carat area experiences an average annual rainfall ranging from 1500 mm to 2500 mm, categorizing it as having low rainfall.

3.2. Final Results of the Physical Vulnerability

After analyzing the CVI formula, Table 5 shows the final weighting for the physical and environmental vulnerability parameters based on the CVI value. Based on the results of data processing through overlay and calculation using CVI, the vulnerability results for each physical parameter are shown in Table 6.

The calculation of the CVI visualized in Figure 5 is based on seven physical vulnerability parameters, resulting in the identification of three levels of vulnerability: low, medium, and high vulnerability. The mapping of physical vulnerability in the Tanjung Carat Area reveals that nearly the entire area (99%), covering approximately 218,984 hectares, is classified as highly vulnerable. The remaining 758.17 hectares are moderately vulnerable, and only 5.59 hectares are categorized as low vulnerability.

Table 5. Final Weighting of Physical and Environmental Vulnerability

No.	Class Category	CVI Value	
		Environmental Vulnerability Parameters	Environmental Vulnerability Parameters
1	Low	0,93 – 1,55	0,93 – 1,55
2	Moderate	1,55 – 2,16	1,55 – 2,16
3	High	2,17 – 2,78	2,17 – 2,78

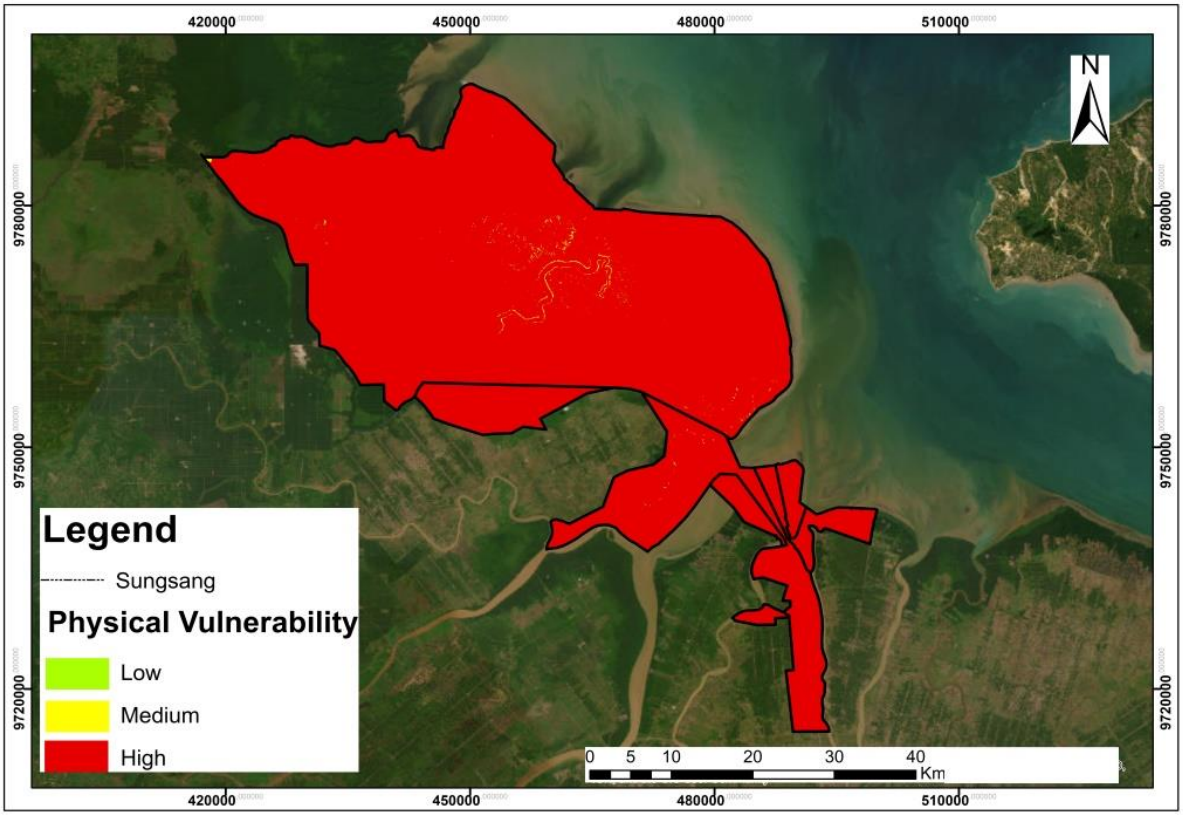
Source: Analysis, 2024

Table 6. Physical Vulnerability Parameter Score

Cell	Physical Vulnerability Parameters							
	Coastline Change	**Wave Height (m)**	**Climatology**	**Tides (m)**	**Geology**	**Elevation (masl)**	**Geo-morphology**	**Total Area (Ha)**
1	1 - (-1) Stabile	0 -4,9	15 - 25	1,0 - 2,0	Lake Sediment	0 - 12,5	Flat	183.011,40
2	1 - (-1) Stabile	0 -4,9	15 - 25	1,0 - 2,0	Lake Sediment	12.5 - 25	Flat	35.176,32
3	1 - (-1) Stabile	0 -4,9	15 - 25	1,0 - 2,0	Lake Sediment	>25	Flat	328,22
4	1 - (-1) Stabile	0 -4,9	15 - 25	1,0 - 2,0	Lake Sediment	0 - 12,5	Hill/Moderate Hills	2,12
5	1 - (-1) Stabile	0 -4,9	15 - 25	1,0 - 2,0	Lake Sediment	0 - 12,5	Sloping	796,77
6	1 - (-1) Stabile	0 -4,9	15 - 25	1,0 - 2,0	Lake Sediment	12.5 - 25	Hill/Moderate Hills	4,52
7	1 - (-1) Stabile	0 -4,9	15 - 25	1,0 - 2,0	Lake Sediment	12.5 - 25	Sloping	427,83
8	1 - (-1) Stabile	0 -4,9	15 - 25	1,0 - 2,0	Lake Sediment	>25	Hill/Moderate Hills	0,18
9	1 - (-1) Stabile	0 -4,9	15 - 25	1,0 - 2,0	Lake Sediment	>25	Sloping	0,88
Total								**219.748,25**

Cell	Physical Vulnerability Parameters Score							CVI Value	Vulnerability Level
	Coastline Change	**Wave Height (m)**	**Climatology**	**Tides (m)**	**Geology**	**Elevation (masl)**	**Geo-morphology**		
1	2	1	1	1	3	3	3	2,78	High
2	2	1	1	1	3	2	3	2,27	High
3	2	1	1	1	3	1	3	1,60	Moderate
4	2	1	1	1	3	3	1	1,60	Moderate
5	2	1	1	1	3	3	2	2,27	High
6	2	1	1	1	3	2	1	1,31	Low
7	2	1	1	1	3	2	2	1,85	Moderate
8	2	1	1	1	3	1	1	0,93	Low
9	2	1	1	1	3	1	2	1,31	Low

Source: Analysis, 2024



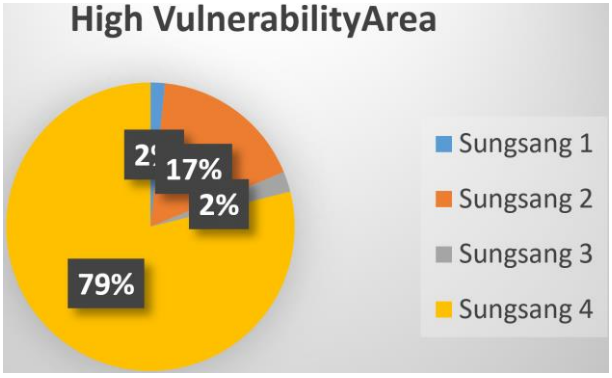
Source: Analysis, 2024

Figure 5. Physical Vulnerability Map of Tanjung Carat Area

Table 7. High Vulnerability Area

No.	Village	Total Area
1	Sungsang 1	3.529,55
2	Sungsang 2	37.675,22
3	Sungsang 3	4.974,70
4	Sungsang 4	172.805,53

Source: Analysis, 2024



Source: Analysis, 2024

Figure 6. Percentage of the High Vulnerable Area

Table 7 details the total area of Tanjung Carat identified as highly vulnerable, highlighting regions at risk from physical factors. The accompanying chart (Figure 6) visually represents these vulnerable areas, aiding in the identification of zones that may need immediate attention or action.

3.3. Results of Environmental Parameter Vulnerability Analysis

The environmental vulnerability analysis of the Tanjung Carat port development area involves evaluating four parameters: 1) protected forest, 2) mangroves, 3) shrubs, and 4) nature reserve forest. Each parameter is assessed using a scoring method and the Coastal Vulnerability Index (CVI) formula as per BNPB Regulation No. 2 of 2012 [19] to determine environmental vulnerability score values. The land use data at the research location in 2024 is sourced from the Banyuasin Regency Bappeda, satellite imagery, and ground checking, and is then mapped using ArcGIS.

3.3.1. Protected Forest

Sungsang Village is home to a protected forest spread across four villages, covering an extensive area of 8,804.65 hectares. The visual depiction of the distribution of protected forests in the study area refer to Figure 7.

3.3.2. Mangrove

The Sungsang area represents a significant mangrove

ecosystem situated on the eastern coast of South Sumatra. Following an overlay analysis, it has been determined that the mangrove forest within the Tanjung Carat Area spans 4,649.92 hectares, with the most expansive region located in Sungsang IV.

3.3.3. Shrubs

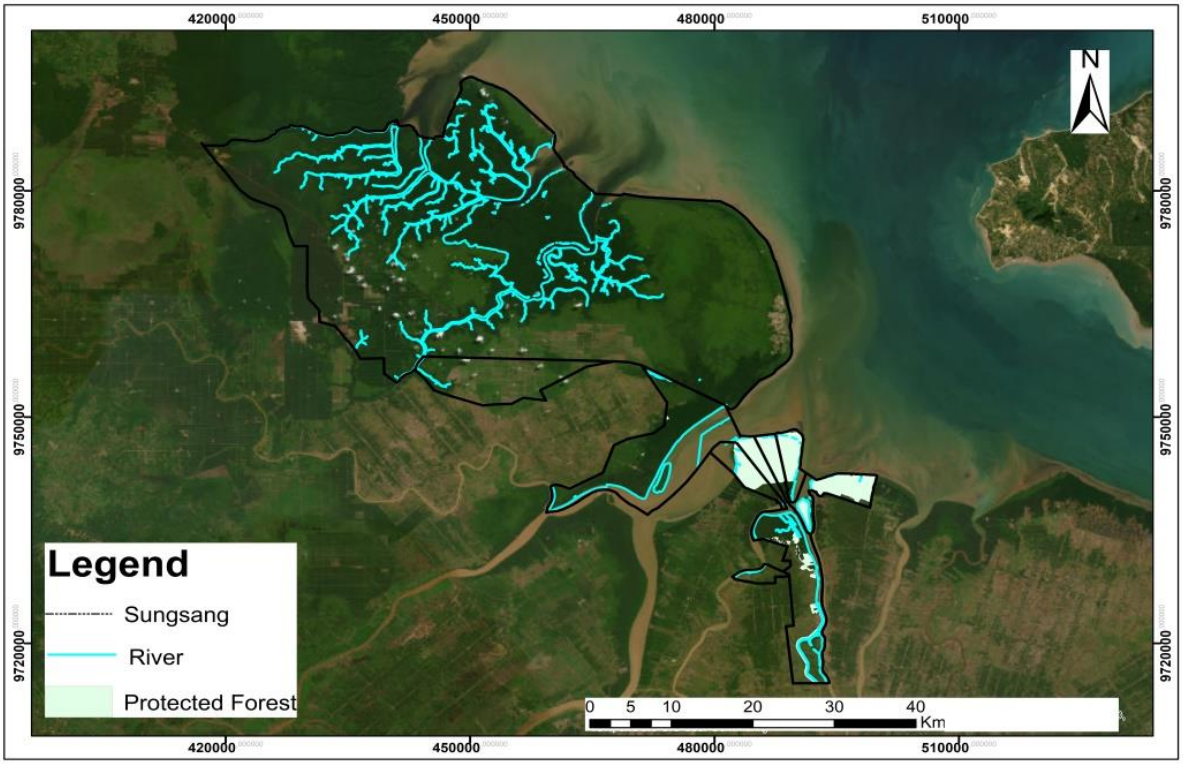
In the Tanjung Carat area, there is a total of 3,246.22 hectares of shrubland distributed across four villages, with the largest land areas located in Sungsang II and IV, covering 1,418.61 and 1,487.69 hectares, respectively.

3.3.4. Nature Reserve Forest

In accordance with Government Regulation No. 26 of 2008, which pertains to RTRWN, and Law No. 26 of 2007, which pertains to spatial planning, the spatial pattern classification policy of Banyuasin Regency involves categorizing nature reserve areas into national park areas and wildlife reserve areas. The nature reserve forest in the Tanjung Carat area is specifically situated in Sungsang II and IV Villages and falls within the Sembilang National Park area, covering an extensive area of 116,159.33 hectares. Figure 8 shows the distribution of nature reserve forest in Tanjung Carat Area.

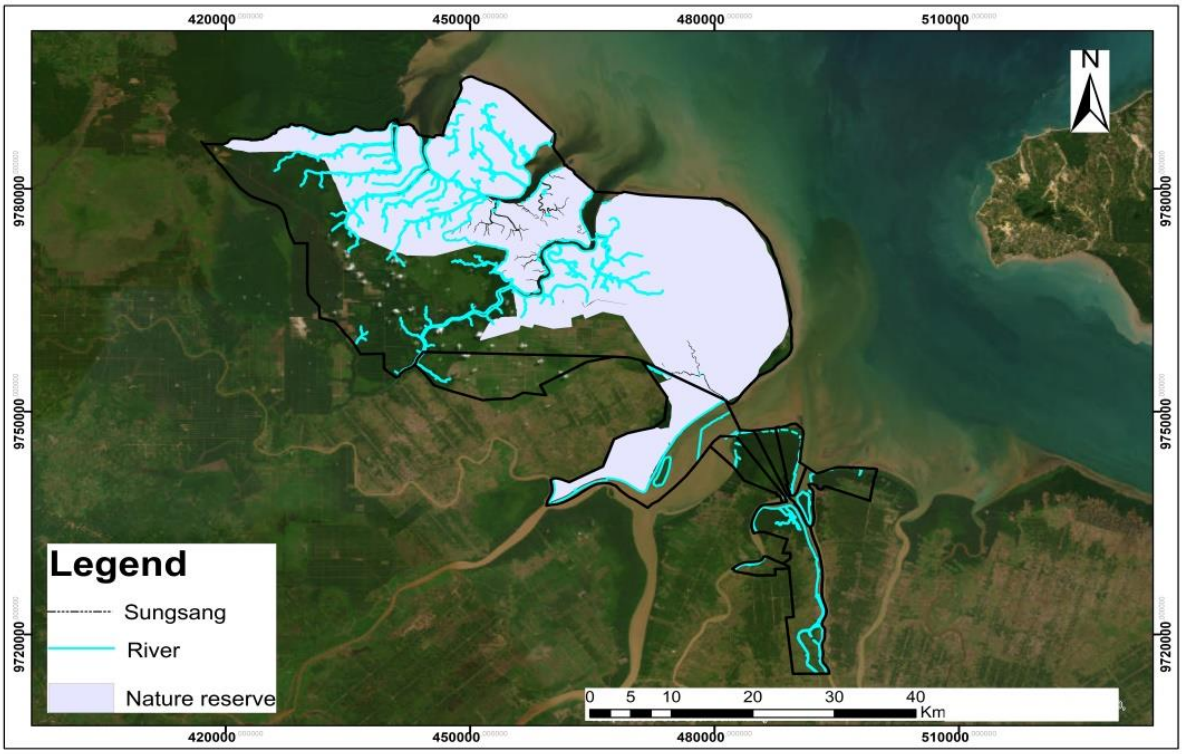
3.4. Final Results of Environmental Vulnerability in Tanjung Carat Area

The environmental vulnerability results for each village have been derived from data processing using overlay and calculations with CVI, and are presented in Table 8. Furthermore, Figure 9 provides a visual representation of environmental vulnerability in the Tanjung Carat Area.



Source: Analysis, 2024

Figure 7. Protected Forest Map in the Tanjung Carat Area



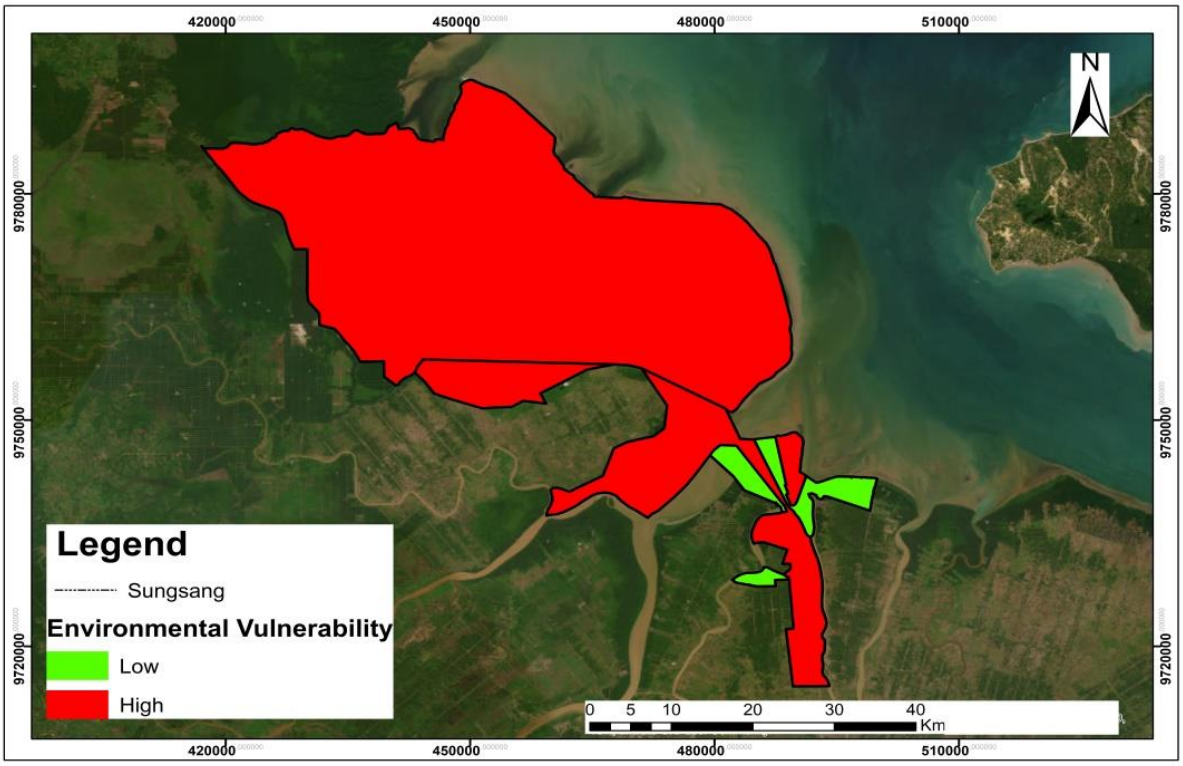
Source: Analysis, 2024

Figure 8. Map of Nature Reserve Forest in Tanjung Carat Area

Table 8. Environmental Vulnerability Score

Land Use	Total Area (Ha)	Score	CVI Value	Category
Sungsang I	**1.488,55**			
Protected Forest	1.268,91	3	2,60	Low
Mangrove Forest	90,07	3		
Nature Reserve Forest	-	1		
Shrubs	129,57	3		
Sungsang II	**13.915,07**			
Protected Forest	2.289,95	3	4,50	High
Mangrove Forest	1.232,89	3		
Nature Reserve Forest	8.773,62	3		
Shrubs	1.618,61	3		
Sungsang III	**3.749,89**			
Protected Forest	3.716,71	3	1,73	Low
Mangrove Forest	22,83	2		
Nature Reserve Forest	-	1		
Shrubs	10,35	2		
Sungsang IV	**113.705,97**			
Protected Forest	1.529,08	3	4,50	High
Mangrove Forest	3.303,50	3		
Nature Reserve Forest	107.385,71	3		
Shrubs	1.487,69	3		
Grand Total	**132.859,48**			

Source: Analysis, 2024



Source: Analysis, 2024

Figure 9. Environmental Vulnerability Map of Tanjung Carat Area

4. Discussion

Physical Vulnerability Findings

The comprehensive analysis of the physical and environmental characteristics of the Tanjung Carat area clearly demonstrates that the area is highly susceptible to vulnerability. The analysis of physical vulnerability reveals that various parameters, including elevation, geomorphology, and geology, are influential factors contributing to the region's susceptibility. While the level of environmental vulnerability is influenced by the presence of protected forests, mangroves, shrubs, and nature reserve forests in the four villages.

According to analysis of each physical parameters, high level of vulnerability in the study area is primarily due to factors such as low elevation, flat landforms, and geology characterized by sediment or alluvium with low soil-bearing capacity. This research revealed that the elevation, geological type, and geomorphology in the Tanjung Carat area are believed to have a significant impact on the area's vulnerability.

The Tanjung Carat area is characterized by alluvial land that includes sandy and gravel beaches, which are particularly vulnerable to erosion [65]. This coastal region is composed of various lake deposits, including layers of clay, silt, sand, and gravel. The specific combination of these materials increases the area's susceptibility to both erosion and landslides, posing significant challenges for land stability and coastal management [66][67].

Additionally, the Tanjung Carat area is notably vulnerable, particularly at elevations between 0 and 12.5 meters above sea level. This susceptibility exposes the region to tidal flooding during high tides and heightens the risk associated with rising sea levels, posing threats to both the local ecosystem and infrastructure [68][69][70].

The coastline of the Tanjung Carat area has demonstrated a notable level of stability, characterized by changes in the coastline measurements that fluctuate between 1 and -1. This stability places the area within a moderate vulnerability category concerning coastal erosion and environmental impacts. Meanwhile, the evaluation of tidal patterns, climatic conditions, and average wave heights falls within the low vulnerability range, suggesting that these factors have a minimal impact on the physical vulnerability of the area and indicate a resilient coastal ecosystem.

Environmental Vulnerability Findings

The Protected Forest is a designated area by the government located in the southern part of Tanjung Carat, along the estuary where the river meets the sea. The protected forest in the Tanjung Carat area is characterized as a wet tropical rainforest dominated by mangroves, with its formation significantly influenced by climatic, edaphic,

and stand composition factors. This vital forest helps maintain ecological balance and reduce disaster risks, such as flooding and coastal erosion. It serves as a sanctuary for a diverse range of flora and fauna, including various migratory bird species that use the area as a crucial stopover during their travels. Overall, the Protected Forest is essential for supporting biodiversity and providing refuge for wildlife.

The mangrove forests in the Tanjung Carat area are mainly found along the coastline, with significant areas in Sungsang 2 (1,232.89 hectares) and Sungsang 4 (3,303.50 hectares), directly adjacent to the sea. These mangroves play a crucial role in reducing coastal erosion by acting as natural barriers that absorb wave impacts and protect shorelines [71][72]. They also provide essential habitats for a variety of marine and terrestrial species, supporting local biodiversity. Furthermore, studies show that the presence of mangroves helps stabilize the coastline in Tanjung Carat. Their ecological and economic importance is significant for local communities that rely on coastal resources [71][73][74].

The Nature Reserve Forest in the Tanjung Carat Area is the largest among the four studied parameters. Designated by the government as a conservation zone, it includes Sungsang 2, covering approximately 8,773.62 hectares, and Sungsang 4, which spans around 107,385.71 hectares. Both areas are considered highly vulnerable to environmental threats, highlighting the need for targeted conservation efforts.

In the Tanjung Carat area, shrubs are abundant and categorized as high-density vegetation. Although their ecological value is lower than that of protected forests or mangroves, they play a crucial role as a natural buffer between urban development and sensitive ecosystems. Shrubs help prevent soil erosion, an issue that can arise when these areas are lost, leading to sedimentation in nearby water bodies and negatively impacting aquatic life. Additionally, the removal of shrubland can disrupt habitats for various species and alter local water dynamics. Thus, preserving shrubland is vital for maintaining ecological balance and protecting surrounding ecosystems [75].

Practical Implications and Future Directions

The findings of this study indicate that the majority of Tanjung Carat is highly vulnerable due to its low elevation, flat geomorphology, unstable geological formations, and dynamic changes along the coastline. These vulnerabilities necessitate careful consideration in port planning to minimize environmental degradation and infrastructure risks.

Firstly, site selection for the port and its associated infrastructure should prioritize areas with lower vulnerability to reduce the risks of flooding, erosion, and geological instability. In cases where high-vulnerability areas cannot be avoided, adaptive engineering solutions should be employed, including elevated platforms, reinforced foundations, and erosion control structures such as seawalls or breakwaters to enhance resilience [76][77].

Secondly, it is crucial to preserve mangrove ecosystems, which play a vital role in stabilizing the coastline and mitigating storm surges. This can be achieved through the establishment of buffer zones and the restoration of mangroves when necessary to strengthen these natural defenses [78][79].

Thirdly, construction activities must adhere to best practices by limiting dredging and land reclamation in ecologically sensitive areas to prevent exacerbating sediment displacement and coastline erosion [80]. Implementing comprehensive environmental management plans, which include routine environmental monitoring and community engagement programs, can help identify and mitigate potential impacts throughout the project lifecycle [81][82].

Lastly, policies that support biodiversity offset programs, such as creating protected zones for mangroves and wildlife habitats, can help compensate for any unavoidable ecological disruptions [83]. This ensures that the port's development aligns with the principles of sustainable and resilient infrastructure planning.

To ensure the sustainable development of the proposed port in Tanjung Carat, it is essential to conduct further research and implement robust monitoring programs to address the area's significant physical and environmental vulnerabilities. One crucial research area involves detailed modeling of coastal dynamics, including sediment transport, wave action, and tidal patterns [84]. This modeling will help predict how port construction might alter these processes, potentially leading to coastal erosion or habitat loss [85].

Additionally, vulnerability assessments should incorporate climate change projections, such as sea-level rise and increased storm intensity, to identify long-term risks to both the port infrastructure and surrounding ecosystem [86]. It is also critical to investigate the ecological impacts on mangrove forests and sanctuary forests, focusing on aspects such as species composition, carbon sequestration potential, and the role of these habitats in supporting biodiversity and local livelihoods [87].

For effective monitoring, the establishment of a long-term coastal observation program is vital. This program should employ remote sensing technologies, Geographic Information Systems (GIS), and in-situ measurements to track changes in shoreline position, elevation, and geomorphological features over time [88][89]. Regular assessments of biodiversity should be conducted to evaluate the health of mangroves, wildlife populations, and other sensitive habitats, using indicators such as vegetation density, species richness, and habitat connectivity [90].

Hydrological monitoring is also important to examine changes in water quality, salinity levels, and sedimentation rates resulting from development activities [91], [92]. Social monitoring programs, which include stakeholder consultations and community impact assessments, can help

evaluate how port development affects local communities, ensuring that mitigation measures address both environmental and socioeconomic concerns [93,94].

By combining these research efforts and monitoring systems, policymakers and planners can make informed and adaptive decisions that balance economic development with environmental protection and long-term sustainability in Tanjung Carat.

5. Conclusions

In conclusion, this study highlights the critical importance of understanding the physical and environmental vulnerabilities of Tanjung Carat to inform sustainable port development in South Sumatra. The vulnerability mapping indicates that the region's low elevation, flat geomorphology, unstable geological formations, and dynamic coastline significantly increase its susceptibility to environmental and physical risks, particularly flooding and erosion. The presence of ecologically sensitive habitats, such as mangrove forests and protected areas, further complicates the situation, as these ecosystems are crucial for biodiversity and act as natural buffers against environmental impacts. To address these challenges, it is essential for decision-makers to prioritize development in less vulnerable areas and to implement adaptive engineering solutions, like reinforced coastal barriers and improved drainage systems. Additionally, robust environmental protection measures should be established to safeguard sensitive habitats through regulations and reforestation efforts. By incorporating these strategies into planning processes, policymakers can reduce ecological disruptions, enhance the resilience of coastal infrastructure, and ensure future port developments are sustainable and aligned with environmental principles. This balanced approach not only protects Tanjung Carat's unique ecological assets but also sets a precedent for sustainable coastal development in the region.

Acknowledgements

We would like to express our sincere gratitude to the Ministry of Education, Culture, Research, and Technology of Indonesia for their generous support of this research through the "Hibah BIMA 2024" grant program, contract number 104/E5/PG.02.00.PL/2024.

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