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Regular Research Article

Analysis Of Geomorphology Using the Coastal Vulnerability Index Method on the Coast of Prancak Village, Bangkalan Regency, Indonesia

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Abstract: Coastal areas are highly dynamic environments facing increasing threats from both natural processes and human activities, such as coastal erosion, sea level rise, and land use changes. Prancak Village is one such coastal area vulnerable to geomorphological changes. This study aims to assess coastal vulnerability through geomorphological analysis using the Coastal Vulnerability Index (CVI) method. Data were collected from primary and secondary sources, including satellite imagery, field surveys, digital elevation models (DEMs), and data from relevant agencies. The analyzed parameters comprised coastal morphology, beach slope, shoreline change, wave height, and tidal range. The CVI calculation yielded a value of 6.93, which falls within the 5.8–10.06 range classified as "low vulnerability" (20–40% vulnerability level), indicating that the study site has relatively low susceptibility to the physical factors assessed Although the overall index is low, local physical dynamics still pose risks in certain areas, confirming that geomorphology and coastal ecosystem conditions are more decisive in determining vulnerability than oceanographic parameters such as wave height.

Keywords: Coastal Vulnerability Index (CVI), Coastal Erosion, Vulnerability, Coastal Management

1. Introduction

Coastal areas are among the regions with the highest environmental dynamics, influenced by natural processes such as waves, currents, tides, and human activities such as reclamation, land conversion, and infrastructure development. [1]. Lack of government support, low education levels, and lack of public awareness increase coastal vulnerability. [2]. The main factors affecting coastal vulnerability include erosion, sea level rise, and changes in the coastline. [3]. High coastal vulnerability can result in ecosystem damage and threaten the social and economic activities of coastal communities. [4].

The level of coastal vulnerability affecting beach stability and resilience is directly related to geomorphological changes. [5]. Coastal geomorphological changes can occur due to natural processes, such as waves and tides. Human activities such as reclamation and land use conversion also accelerate geomorphological changes. [6]. Basically, the Coastal Vulnerability Index (CVI) utilizes geomorphological information to assess the extent to which coastal areas are vulnerable to environmental threats. [7]. In applying the CVI method to coastal areas, geomorphological analysis is one of the key components. [8]. The study by Prathanazal et al. (2021) analyzed coastal vulnerability in Jepara Regency using the Coastal Vulnerability Index (CVI) with a methodological approach relevant to the Indonesian coastal context. However, whereas coastal vulnerability in Jepara is associated with tourism pressures and coastal erosion, conditions in Prancak Village present a

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contrasting yet equally vulnerable dynamic: densely populated settlements and aquaculture ponds (tambak) are located directly along the shoreline. Furthermore, research by Insafitri et al. (2023) revealed that the Sepulu coastal area, including Prancak Village, exhibits high coral diversity, as confirmed by DNA barcoding analysis of seven coral species. This finding is pertinent to the present study, as the CVI results indicate physical coastal vulnerability due to erosion and geomorphological changes that could potentially threaten the conservation of coral ecosystems in the area. Applying a similar methodology as used by Prathanazal et al. (2021), but adapted to Prancak's unique local context, is expected to identify the most vulnerable zones within the study area, thereby providing a scientific basis for coastal spatial planning and more targeted adaptation strategies. This study aims to evaluate the CVI in the coastal area of Prancak Village, Bangkalan Regency, Indonesia, and to identify the parameters that contribute the highest and lowest weights in determining overall coastal vulnerability.

2. Materials and Methods

The research entitled "Geomorphological Analysis Using the Coastal Vulnerability Index Method on the Coast of Prancak Village, Bangkalan Regency, Indonesia" was conducted at coordinates -6.885782°S 112.966643 °E to the east to -6.885276°S 112.977203°E, Prancak Village, Sepulu District, Bangkalan Regency, Madura, East Java. The research location is shown in Figure 1.

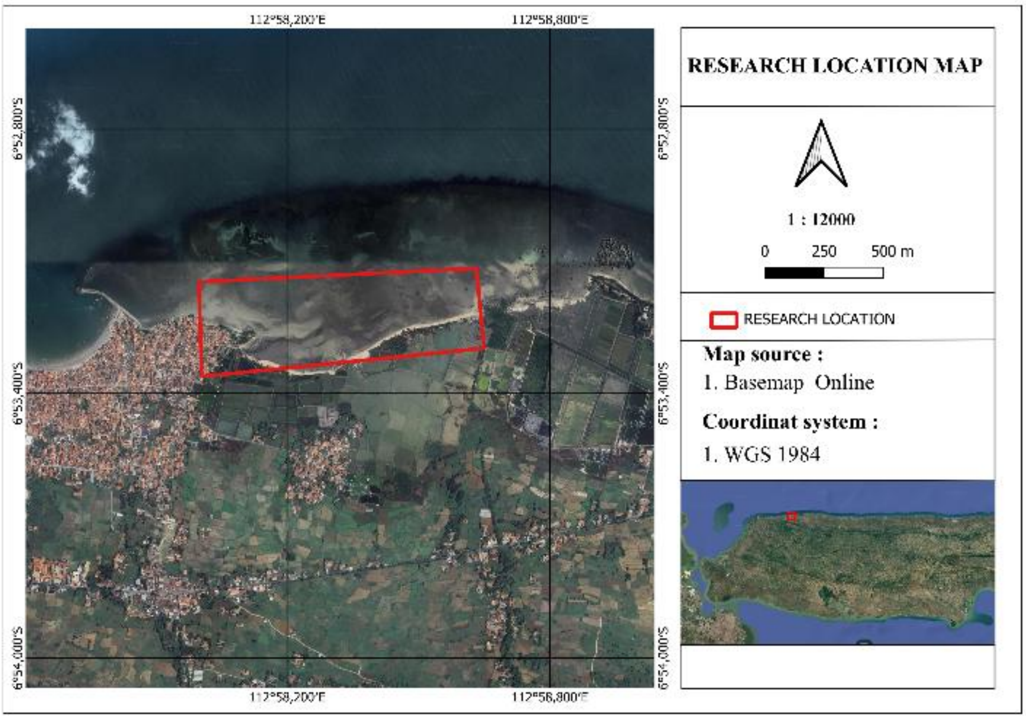

Figure 1. Map of the study area

The Coastal Vulnerability Index (CVI) method is used to assess the vulnerability of coastal areas to various natural factors such as erosion, tidal fluctuations, and sea-level rise. This approach integrates physical parameters, including geomorphology, elevation, and shoreline change, to produce an index value that indicates the level of coastal risk. [7]. In this study, the CVI method evaluates coastal vulnerability by considering geomorphology, land elevation, and wave-related threats as primary factors. The resulting index values support sustainable coastal management planning and enhance the resilience of coastal ecosystems to natural hazards. [8]. According to Theocharidis *et al*. (2024) [10], their research applied the CVI assessment to evaluate coastal risks driven by human activities along the Limassol coastline in Cyprus. Their findings demonstrate that the CVI method effectively identifies high-vulnerability zones, enabling targeted mitigation measures and more effective coastal management policies.

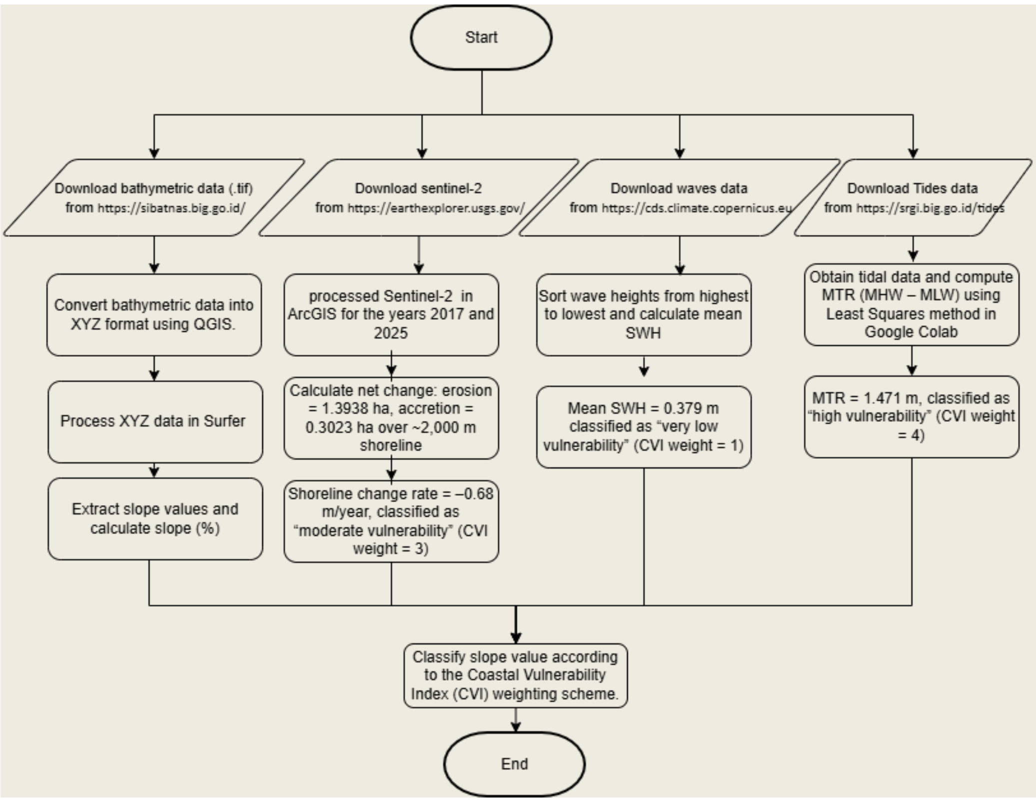

Figure 2. Flow chart of analysis

The research began with problem identification to understand coastal vulnerability driven by geomorphological and ocean dynamic factors. Based on this, clear and measurable research objectives were formulated. A literature review was then conducted to gather relevant theories and prior studies on the Coastal Vulnerability Index (CVI) method. Data collection followed, combining primary data from field surveys and secondary data such as maps, satellite imagery, and oceanographic records. As shown in Table 1, the collected data were processed through geomorphological and coastal physical analyses required for CVI calculation. The CVI was then computed by integrating all parameters and visualized as a coastal vulnerability map, classifying areas into low, medium, and high vulnerability zones, displaying zones with low, medium, and high levels of vulnerability.

Table 1. data used in the research

No.	Data	Date Acquired	Access
1.	Geomorphology	2025	observation
2.	Tides	Agust 2024 -Agust 2025	https://srgi.big.go.id/tides
3.	Sentinel-2	2017 and 2025	https://earthexplorer.usgs.gov/
4.	Bathymetry	2025	https://sibatnas.big.go.id/
5.	Waves	2020-2024	https://cds.climate.copernicus.eu

Data analysis was continued by processing the parameters used in the Coastal

Vulnerability Index (CVI) method. Geomorphological parameters were obtained through primary data from field surveys by taking photographs of coastal conditions. This survey aimed to directly observe the geomorphological characteristics of the coast to reinforce the analysis results. Wave parameters were obtained from the ECMWF website for the period 2020–2024. The data was then processed using Excel by sorting the wave heights from highest to lowest and then averaging them to determine the significant wave height (SWH). Tidal parameters were taken from the SRGI website for the period August 2024 to August 2025, then processed using the Least Squares method on Google Colab to obtain the average tidal value. Coastal change parameters were obtained from Copernicus for the 2017 and 2025 periods, then analyzed using ArcGIS and Google Earth Pro software. Slope data were obtained from the 2025 Ina Geoportal website and processed using ArcGIS and Surfer software. These parameters were then classified according to Table 2 below:

Table 2. Parameters Coastal Vulnerability Index [10].

Label	Factor	Very Low (1)	Low (2)	Moderate (3)	High (4)	Very High (5)
(a)	Coastal slope (%)	>12	8–12	4–8	2–4	<2
(b)	Shoreline change(m/year)	>2	+1.0 s/d +2.0	–1.1 s/d +1.0	–1.1 s/d –2	< –2.0
(c)	Tidal range (m)	>6.0	4.0–6.0	2.0–4.0	1.0–2.0	<1.0
(d)	*Significant Wave Heights* (SWH) (m)	0 – <0.55	0.55–0.85	0.85–1.05	1.05–1.25	>1.25
(e)	Coastal geomorphology	Rocky coasts, fiords, peaks (Peak, ridge)	Medium cliffs, indented coasts (Shoulder, spur	Lowcliffs, glacial drift, alluvial plains (Flat, slope, footslope)	Cobble beaches, estuary, lagoon (Valley)	Barrier beaches, sandy beaches, salt marshes, deltas, mangroves, coral reefs (Basins, holes)

The Coastal Vulnerability Index (CVI) method is used to identify the vulnerability of coastal areas to various natural factors such as erosion, tides, and sea level rise. This approach combines physical parameters such as geomorphology, elevation, and coastline changes to produce an index value that indicates the level of coastal vulnerability risk [7]. The CVI method in this study assesses coastal vulnerability levels by considering geomorphology, land elevation, and wave threats as the main factors. The index calculation results are used to support sustainable coastal management planning and improve the resilience of coastal ecosystems to natural threats [8]. According to Theocharidis et al. [10], CVI assessment was applied to evaluate coastal risks caused by human activities along the Limassol coastline, Cyprus. This method helps identify areas with high vulnerability levels so that more effective mitigation measures and coastal management policies can be implemented.

The classification or weighting results are then calculated using the following formula:

$$CVI = \sqrt{\frac{a \times b \times c \times d \times e}{n}} \quad (1)$$

Explanation:

a = Coastal slope variable (%)
b = Coastline variable (m/year)
c = Tidal range variable (m)
d = Significant Wave Heights (SWH) variable (m)

e = Geomorphology variable
n = Number of variables

CVI = Coastal Vulnerability Index value

3. Results

3.1 Coastal Slope

Coastal slope data were sourced from the Ina Geoportal, which provides bathymetric datasets in GeoTIFF (.tif) format. To extract slope values, the bathymetric raster was first converted to XYZ point data using the Raster Conversion (Convert Format) tool in QGIS v3.28, followed by calculation of slope in percentage (%) using the Raster Analysis DEM (Terrain Models) module. The resulting XYZ file was imported into Golden Software Surfer 18, where a 3D surface map was generated using kriging interpolation (Figure 3).

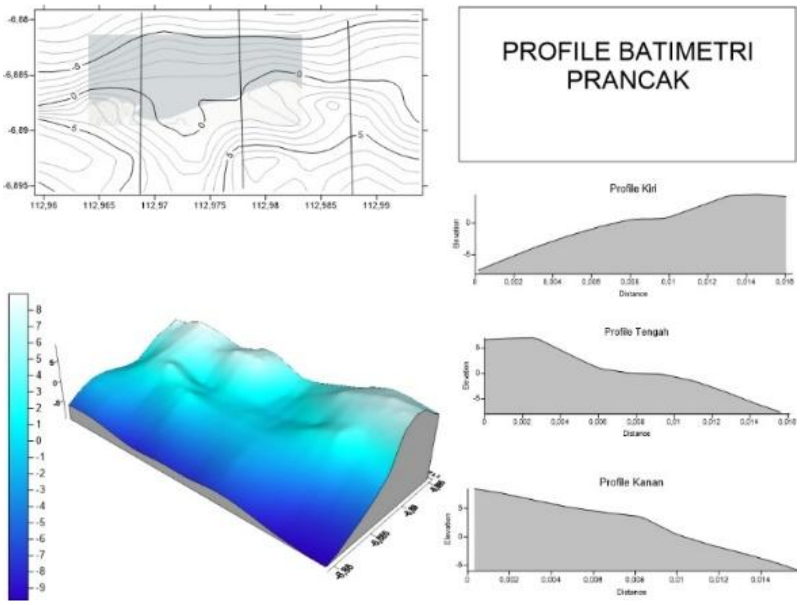

Figure 3. Slope analysis

For consistency in CVI calculation, a 1-km-wide buffer seaward from the coastline was delineated, and the mean slope value within this zone was computed. The average coastal slope was 3%, which, based on the CVI (Coastal Vulnerability Index) classification, falls into the "high" vulnerability category, corresponding to a weight of 4.

3.2 Shoreline Change

Shoreline positions for 2017 and 2025 were extracted from Sentinel-2 Level-2A satellite imagery (10 m spatial resolution) using ArcMap 10.8. The shoreline was initially delineated using the Normalized Difference Water Index (NDWI) with a threshold optimized for local conditions, followed by manual refinement to account for spectral confusion in mangrove and turbid water zones. Temporal shoreline change was quantified using the Digital Shoreline Analysis System (DSAS v5.1), which computed net shoreline movement (NSM) and annualized end-point rates (EPR) along 50-m spaced transects perpendicular to the coast.

The analysis revealed a net landward shift over the eight-year interval, with an abrasion area of 1.3938 ha and a much smaller accretion area of 0.3023 ha along a ~2,000 m coastline. The average shoreline change rate was –0.68 m/year, indicating persistent erosion. This rate aligns with a moderate vulnerability weight of 3 in the CVI framework. The imbalance between erosion and accretion suggests a sediment budget deficit, likely influenced by reduced fluvial sediment input and/or altered nearshore hydrodynamics.

3.3 Tidal Range

Tidal data spanning 2020–2024 were obtained from the nearest operational tide gauge station. Hourly water level records were processed using harmonic analysis via the Least Squares method implemented in Python (Google Colab) with the *UTide* library. Mean High Water (MHW) and Mean Low Water (MLW) were calculated, yielding a Mean Tidal Range (MTR) of 1.471 m.

According to the CVI classification (Thieler & Hammar-Klose, 1999) in Isdianto et al (2022)[8]An MTR between 1.0–2.0 m corresponds to "high vulnerability", assigned a weight of 4. Although larger tidal ranges typically dissipate wave energy across broader intertidal zones, the study area features a narrow tidal flat, limiting this natural buffering effect. Consequently, even a moderate tidal range concentrates hydrodynamic energy near the shoreline, enhancing erosion potential, particularly during spring tides or storm events.

3.4 Significant Wave Height (SWH)

Significant Wave Height (SWH) data were sourced from the Copernicus Climate Data Store (CDS) via the ERA5 hourly global reanalysis dataset for 2020–2024. Data were extracted for the study coordinates using the CDS API within a Python workflow (Google Colab), filtered for hourly records, and averaged across the entire period. The mean SWH was calculated as 0.379 m.

This value falls below the 0.55 m threshold for "very low vulnerability" in standard CVI schemes, resulting in a weight of 1. Although low average wave energy implies minimal ongoing erosion, it is important to note that extreme wave events such as those associated with monsoonal lows or distant cyclones are smoothed out in the temporal average. Nevertheless, under typical conditions, the sheltered nature of the coastline (partially protected by offshore reefs and adjacent landforms) significantly dampens wave energy, rendering SWH the least influential parameter in the local CVI assessment.

3.5 Coastal geomorphology

The results of geomorphological identification through observation indicate that the coastal area studied is classified as having a very high CVI value. This condition is influenced by the dominance of natural landscapes in the form of sandy beaches, mangrove mudflats, and coral reefs located in areas that are highly vulnerable to abrasion and changes in the coastline. This location also has small rivers that will influence geomorphological or lithological changes. Direct observation data in the field reinforce that the area does not have strong natural protection, such as hard rock cliffs or dense coastal vegetation. Therefore, this area is highly vulnerable to the effects of waves, tides, and sedimentation.

Based on the weighting results obtained in Table 3, the geomorphological parameter showed the highest value of 5, making it the dominant factor in determining coastal vulnerability. The coastal slope and tidal range parameters each weighted 4, indicating that slope conditions and tidal range also contributed significantly to vulnerability. The coastline factor weighted 3, indicating a moderate level of influence on coastal change dynamics. Meanwhile, the significant wave heights (SWH) parameter has the lowest weight of 1, so it is considered to contribute little to the vulnerability of the study site. Overall, these results show that physical coastal conditions, especially geomorphology, slope, and tidal range, play a more important role than wave factors in influencing coastal vulnerability.

Table 3. Results obtained[7]

Grade	Factor
4	Coastal Slope
3	Shoreline change
4	Tidal Range
1	Significant Wave Heights (SWH)
5	Coastal Geomorphology

The values based on the weighting of each parameter are then calculated using the CVI formula. The results of the Coastal Vulnerability Index (CVI) calculation show a value of 6.93. Based on the classification in Table 4, this value is in the range of 5.8–10.06, which is in the low category with a percentage of 20–40%.

Table 4. Vulnerability categories[10]

Quartile Range	CVI
0 – 20%	2,73 - 5,8
20 – 40%	5,8 – 10,06
40–60%	10,06 – 19,36
60–80%	19,36 – 25,98
80–100%	25,98 – 37,5

This means that the coastal area at the study site has a relatively low level of . vulnerability to the physical factors analyzed.

The visualization of the coastal vulnerability map of Sepulu District in Figure 3 shows variations in vulnerability levels, which are classified as low, medium, and high. The high vulnerability category, marked in red, is generally concentrated in the central to eastern segments of the coastline. Geomorphological conditions, particularly the dominance of sandy beaches and alluvial plains, are key factors contributing to the high vulnerability of these areas to abrasion.

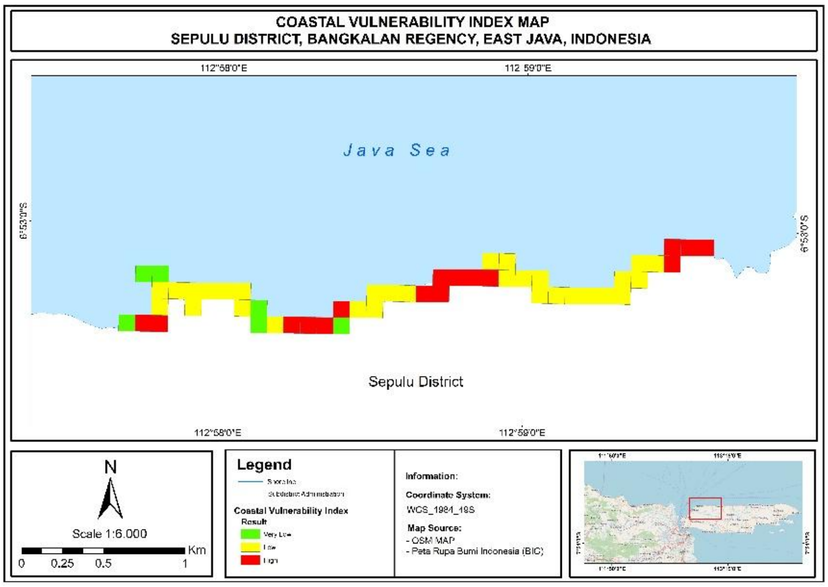

Figure 4. Coastal Vulnerability Index Map

4. Discussion

Gentle coastal slopes, ranging from less than 2–4%, are classified as vulnerable because they are unable to effectively dissipate wave energy. Analysis of shoreline changes based on Sentinel-2 imagery (2017–2025) reveals that the rate of abrasion (-0.68 m/year) is more dominant than accretion, confirming the high vulnerability of several locations. The tidal range, which is in the range of 1–2 meters, puts additional pressure on the stability of the coast in this region. The wave height (SWH) parameter has the least influence on the vulnerability calculation results, so it does not dominate the final map. However, the combination of waves and a gentle beach slope still has the potential to increase abrasion at certain points. Areas with low to moderate vulnerability, indicated by green and yellow colors, can still be found, especially in the western part, which has a steeper slope and stable geomorphology. The CVI (Coastal Vulnerability Index) value of 6.93 is classified as low, consistent with the map visualization dominated by green and yellow colors, although there are several critical points (red spots) that need to be watched.

These results are in line with the journal by Wahyudi *et al*. [11], which states that the bathymetric characteristics of Madura waters are generally shallow and vulnerable to sedimentation and abrasion dynamics. Thus, although the overall vulnerability index is relatively low, physical factors such as geomorphology, slope, and coastal line changes remain important indicators that must be considered in the coastal management of Prancak Village.

According to Cahya *et al*. [12], who emphasize the importance of bathymetric analysis to understand sedimentation levels, especially during the west monsoon season in the Koarmatim Surabaya dock basin. The journal explains that sediment dynamics caused by currents and waves can result in changes to the morphology of the water base, which ultimately also affects coastal stability. The relevance of this research is that geomorphological parameters and coastlines have a significant weight in CVI assessment, because changes in sediment and coastal morphology are key indicators of coastal vulnerability. Thus, both the sedimentation study at the dock and the coastal vulnerability analysis in Prancak Village confirm that physical processes in the water play a dominant role in shaping the level of coastal vulnerability.

These findings are consistent with the study by Akbar et al. [13], which emphasized the critical role of mangrove ecosystems as natural buffers against coastal erosion in tropical regions. They demonstrated that coastal areas affected by mangrove degradation or conversion experience erosion rates 2 to 5 times higher than those with intact mangrove cover. In the present study area, mangroves are still present but exist in a fragmented and discontinuous condition, significantly limiting their effectiveness as coastal protection. Akbar et al. [13] Further highlighted that in tropical countries, ecological factors, particularly mangrove conditions, often play a more decisive role in determining coastal vulnerability than oceanographic parameters such as significant wave height (SWH). This reinforces our conclusion that coastal geomorphology and the integrity of nearshore ecosystems are the primary drivers of vulnerability, even when physical parameters like SWH fall into the "very low" category.

On the other hand, the study by Theocharidis et al. (2024) along the Limassol coastline in Cyprus offers a complementary perspective from a non-tropical, anthropogenically modified coastal environment. They found that coastal infrastructure, including ports, seawalls, and land reclamation projects, significantly disrupts sediment dynamics and exacerbates erosion in adjacent natural shoreline segments, even where natural vulnerability indicators (wave energy and slope) suggest low risk. Their results demonstrate that CVI assessments based solely on physical parameters tend to underestimate actual vulnerability in areas heavily influenced by human interventions.

This assessment is limited to five physical parameters and does not account for several other critical factors. Human interventions such as coastal infrastructure (e.g., breakwaters, seawalls), sand mining, and upstream dam construction were not incorporated, despite their well-documented impacts on sediment budget and coastal dynamics. Additionally, future sea-level rise, land subsidence due to groundwater extraction, and non-linear hydrodynamic interactions (wave-current coupling during extreme events) were not modeled. The static nature of the Coastal Vulnerability Index (CVI) also hinders the identification of temporal trends in erosion hotspots. Future studies are therefore recommended to integrate dynamic modeling, climate projection scenarios, and socio-ecological indicators to support more comprehensive and adaptive coastal resilience planning.

5. Conclusions

Analysis using the Coastal Vulnerability Index (CVI) method on the coast of Prancak Village, Bangkalan Regency, an index score of 6.93 was obtained, which falls into the low category. However, spatial variation reveals several high-vulnerability hotspots driven by gentle slopes (<2–4%), dominant erosion (−0.68 m/year), and susceptible geomorphological conditions. The geomorphology parameter carries the highest weight in the CVI assessment, confirming its dominant influence on coastal vulnerability. In contrast, the Significant Wave Height (SWH) parameter has the lowest weight, contributing minimally to the final index. The presence of fragmented and discontinuous mangroves further reduces natural coastal protection against erosion. Despite the low overall index, localized physical dynamics pose significant risks in specific areas. These findings underscore that geomorphology and nearshore ecosystem integrity are more decisive in determining vulnerability than oceanographic factors like wave height. Therefore, effective coastal management in Prancak Village should prioritize preserving landform features and restoring coastal ecosystems as primary mitigation strategies

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