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Spatial Analysis of Coastal Vulnerability Index (CVI) as a Basis for Coastal Design for Safety (DfS) Strategy in Balikpapan Timur District

Muhammad Daffa Rujid[1], Bimo Aji Widyantoro[1]*, Arief Hidayat[1], Mazlina Zaira Mohammad[2], Maryo Inri Pratama[1], Umar Mustofa[1]

[1]Department of Urban and Regional Planning, Institut Teknologi Kalimantan, Balikpapan, Indonesia
[2]Faculty of Civil Engineering, Universiti Teknologi MARA, Selangor, Malaysia

KEYWORDS
Coastal Vulnerability Index (CVI); Coastal Mitigation Strategy; Spatial Analysis; Geographic Information System (GIS); Balikpapan Timur;

ABSTRACT – The coastal area of Balikpapan Timur District, Balikpapan City, East Kalimantan, faces increasing coastal hazards from erosion and tidal flooding, threatening coastal ecosystems, settlements, tourist areas, and aquaculture ponds. Previous vulnerability studies here generally focused on physical parameters alone, without integrating vulnerability outcomes with land-use characteristics to determine spatially explicit mitigation priorities. This study assesses coastal vulnerability using the Coastal Vulnerability Index (CVI) and formulates mitigation priorities based on the integration of vulnerability and land-use characteristics. A descriptive quantitative approach integrated with a Geographic Information System (GIS) was applied, using five physical parameters: geomorphology, shoreline change (2015–2025), coastal slope, significant wave height, and tidal range. The resulting CVI was overlaid with 2025 land-use data to identify exposed coastal assets. The analysis identified 29 coastal segments after dissolution: 10 segments (34.48%) are high, 16 segments (55.17%) are medium, and 3 segments (10.35%) are low vulnerability. High-vulnerability segments are mostly in Teritip and parts of Manggar Baru, where shoreline erosion, unconsolidated landscapes, and steep slopes coincide. The overlay analysis shows that tourism areas, mangrove ecosystems, aquaculture ponds, settlements, and industrial areas require different mitigation priorities. Cross-referenced with the spatial pattern plan of the East Kalimantan Provincial Regional Spatial Plan (RTRW) 2023–2042, recommendations range from mangrove rehabilitation and coastal protection structures in high-vulnerability areas to space-use control and vegetation strengthening elsewhere. These findings support prioritizing mitigation investment and offer an effective framework for adaptive, sustainable coastal management. From a Design for Safety (DfS) perspective, these spatially differentiated recommendations support early elimination or reduction of foreseeable coastal risks through safer siting, land-use control, natural buffers, and protective design.

*Corresponding Author | Bimo Aji Widyantoro | ✉ (bimo.widyantoro@lecturer.itk.ac.id)

INTRODUCTION

Coastal zones are dynamic transitional environments that sustain critical ecological, economic, and social functions, hosting approximately 60% of the world's population and more than 75% of major global cities [1]. In Indonesia, coastal areas span roughly 327,000 km² with a coastline of 108,000 km, positioning them as centers of fisheries, port operations, tourism, and extractive industries [2]. The intensity of these activities, combined with oceanographic dynamics such as waves, currents, and tides, continues to place mounting pressure on coastal stability [3]. Climate change further exacerbates this pressure through accelerating sea-level rise, which has reached 3.3 mm/year globally and is projected to increase by up to 1.1 m by the end of the twenty-first century [4]. Consequently, more than 40% of Indonesia's coastline has experienced abrasion, with land loss reaching 5–10 m per year in several locations. These conditions have positioned coastal vulnerability assessment as a national planning priority, supporting policy instruments such as the National Action Plan for Climate Change Adaptation (RAN-API) and the Coastal and Small Islan7ds Zoning Plan (RZWP3K) [5].

Balikpapan City, East Kalimantan, is a coastal city whose economy depends substantially on fisheries, industry, tourism, and port activities [6]. The city's Coastal Disaster Risk Study 2022–2027 identifies extreme waves and abrasion as priority hazards [7]. Along the coastline of East Balikpapan District, an extreme wave event on 15 September 2022 damaged three houses and affected sixteen residents in Manggar Village, while local monitoring efforts have documented ongoing abrasion pressure on protective structures in Manggar Baru [8]. These recurring events, together with projected tidal extremes for the region [9], indicate that East Balikpapan

District requires a systematic, spatially explicit vulnerability assessment to support evidence-based mitigation planning, particularly as the local government has begun considering phased relocation of shoreline settlements.

Spatial vulnerability assessment is widely regarded as an effective tool for supporting coastal adaptation planning, as vulnerability maps enable the identification of high-risk zones and inform prioritization in resource-limited management contexts [10], [11]. Among available methods, the Coastal Vulnerability Index (CVI), originally introduced by Gornitz [12] and later formalized by Hammar-Klose and Thieler [13] under the United States Geological Survey (USGS) framework, remains the most widely applied approach for assessing the physical susceptibility of coastlines to sea-level rise and erosion. The CVI integrates multiple geomorphological and oceanographic parameters into a single composite index, offering methodological simplicity and direct compatibility with Geographic Information System (GIS)-based spatial analysis [14], [15]. Complementary approaches exist for assessing non-physical dimensions of coastal risk, including the Social Vulnerability Index for socio-demographic exposure and the Economic Vulnerability Index for resource-dependency risk [16].

Several prior applications of the CVI in Indonesian coastal settings provide relevant methodological precedent. Handartoputra et al. [17] applied CVI in Sendang Biru, Malang, identifying geomorphology, shoreline change, coastal slope, wave height, and tidal range as the dominant vulnerability-determining parameters. Rachmadianti et al. [18] assessed Tanjung Pandan, Belitung, and found shoreline erosion to be the most influential parameter, while Prathanazal et al. [19] evaluated Jepara Regency and reported geomorphology as dominant, with CVI scores classified through a five-class scoring system. Yuliastini et al. [20] extended this approach to Kendal Regency using Landsat, DEMNAS, and reanalysis wave data, obtaining predominantly medium-to-low vulnerability classifications. Across these studies, a consistent limitation emerges: vulnerability mapping is generally treated as a terminal output, with limited integration between CVI results and existing land-use conditions to derive spatially differentiated, land-use-specific mitigation priorities [21]. In East Balikpapan Sub-district specifically, existing assessments have concentrated on shoreline-change detection or disaster documentation in isolation without a composite CVI analysis linked to land-use exposure.

This gap is consequential because vulnerability classification alone offers limited operational value unless it is cross-referenced with the specific assets exposed within each hazard zone such as settlements, aquaculture ponds, tourism infrastructure, and mangrove ecosystems since mitigation needs differ substantially across these land-use types even within the same vulnerability class [21]. Addressing this gap allows physical vulnerability assessment to be translated into actionable, location-specific mitigation strategies rather than generalized hazard maps. Accordingly, this study aims to assess coastal vulnerability in East Balikpapan District using the Coastal Vulnerability Index (CVI), analyze the spatial relationship between vulnerability levels and existing land-use characteristics through GIS-based overlay analysis and formulate land-use-differentiated coastal mitigation priorities consistent with the East Kalimantan Provincial Spatial Plan (RTRW) 2023–2042. The findings are expected to provide a scientific and spatially explicit basis for coastal management authorities in East Balikpapan District, while contributing a methodological reference for integrating physical vulnerability assessment with land-use planning in similar tropical coastal settings elsewhere in Indonesia.

Design for Safety (DfS), often discussed as Prevention through Design (PtD), is a proactive approach in which foreseeable safety risks are considered during planning and design so that hazards can be eliminated or reduced before construction and operation [22], [23]. Empirical evidence indicates that upstream design decisions can influence accident risk, while DfS research emphasizes early design-stage intervention and spatial consideration as important opportunities for risk reduction [22], [23]. In this study, DfS is extended as a risk-informed planning lens for coastal mitigation: the CVI-land-use overlay is used to avoid or limit exposure in vulnerable zones, reduce risk at source through safer spatial and protective-design choices, preserve natural buffers, and identify residual risks requiring ongoing controls. DfS is therefore not introduced as an additional CVI variable; rather, it provides the decision logic for translating vulnerability evidence into safer mitigation recommendations [24].

METHOD

The object of this research is the coastal area of East Balikpapan District, Balikpapan City, East Kalimantan Province, which consists of four coastal sub-districts, namely Manggar, Manggar Baru, Lamaru, and Teritip in Figure 1. This coastline was selected because it exhibits recurring abrasion and tidal-flooding events and contains heterogeneous land uses that are directly exposed to coastal hazards. The landward extent of the analysis was constrained to the coastal protected zone, defined as the area extending 200 m inland from the highest tide line, within which coastal land use is most directly exposed to abrasion and tidal-flooding hazards [25].

Data was acquired through two channels. Primary data were obtained via direct field observation to identify shoreline conditions, abrasion points, existing coastal protection structures, and existing land use; geographic coordinates and photographic documentation were recorded for validation.

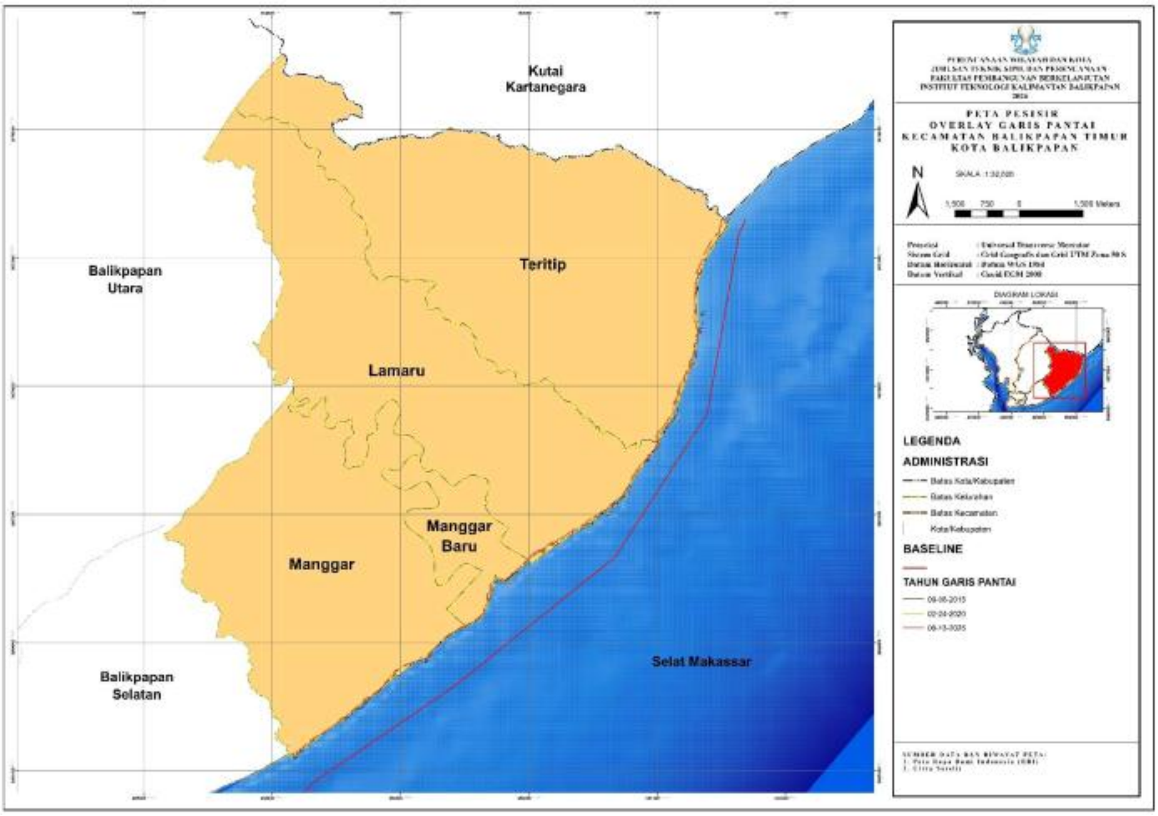

Figure 1. Map of East Balikpapan District

Secondary data were obtained from relevant government and remote-sensing institutions, as summarized in Table 1

Table 1. Data Collect

No	Data	Source	Format	Information
1	Administrative boundary	Geospatial Information Agency	Vector (.gdb)	Administrative division
2	Satellite imagery (Landsat)	U.S. Geological Survey (USGS)	Raster (.tiff)	Shoreline extraction and land-use interpretation
3	DEM Nasional (Demnas)	Geospatial Information Agency	Raster (.tiff)	Slope, elevation,
4	Wave height	Indonesian Agency for Meteorology, Climatology, and Geophysics	Tabulation (.xlsx)	Wave parameter
5	Tidal range	Geospatial Information Agency	Tabulation (.xlsx)	Tidal parameter
6	Geomorphological	Geospatial Information Agency	Vector (.shp)	Geomorphology classification
7	Field observation	Field survey	Tabulation (.xlsx)	Hazard identification

The independent variables examined are the five physicals namely geomorphology, shoreline change rate, coastal slope, significant wave height, and tidal range. The dependent variable is the composite CVI score and its resulting vulnerability class (low, moderate, high, very high) for each coastal segment. The main variation applied in this study is temporal and spatial: shoreline position is compared across three time points (2015, 2020, 2025) to derive a rate of change rather than a single-period value, and the resulting vulnerability classes are cross-tabulated (overlaid) against existing 2025 land-use categories to generate a second layer of variation. This study applies the Coastal Vulnerability Index (CVI) in East Balikpapan District. The CVI was chosen because it is specifically designed to quantify physical exposure using measurable, remotely sensed parameters.

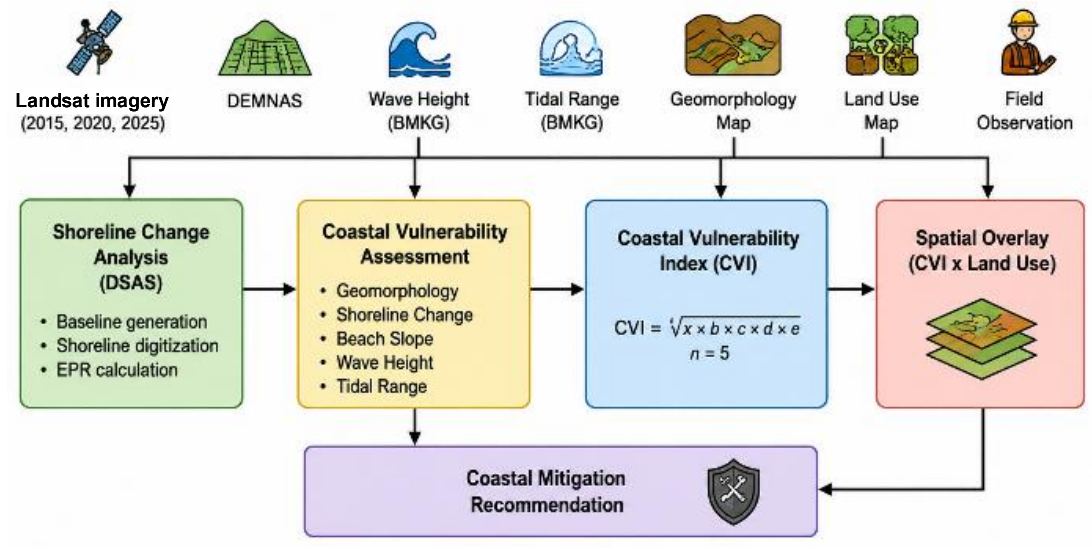

Figure 2. The research framework

The research framework adopted in this study consists of four sequential stages in Figure 2. The first stage involves the collection of primary and secondary data. Primary data were obtained through field observation to identify shoreline conditions, erosion sites, and existing coastal land use. Secondary data consisted of landsat satellite imagery from 2015, 2020, and 2025, Demnas , geomorphological maps, observations of significant wave heights obtained from the BMKG and tides obtained from the BIG, as well as land use maps and administrative boundary data. Shoreline change analysis is using the historical shorelines (2015, 2020, 2025) digitized from multi-temporal imagery and processed in the Digital Shoreline Analysis System (DSAS) using the End Point Rate (EPR) method:

$$\mathrm{EPR} = \mathrm{D}/\mathrm{T} \tag{1}$$

Where D is the distance (m) between the oldest and most recent shoreline positions along each transect, and T is the elapsed time (years) between the two shoreline dates. Negative EPR indicates erosion (higher vulnerability); positive EPR indicates accretion (lower vulnerability).

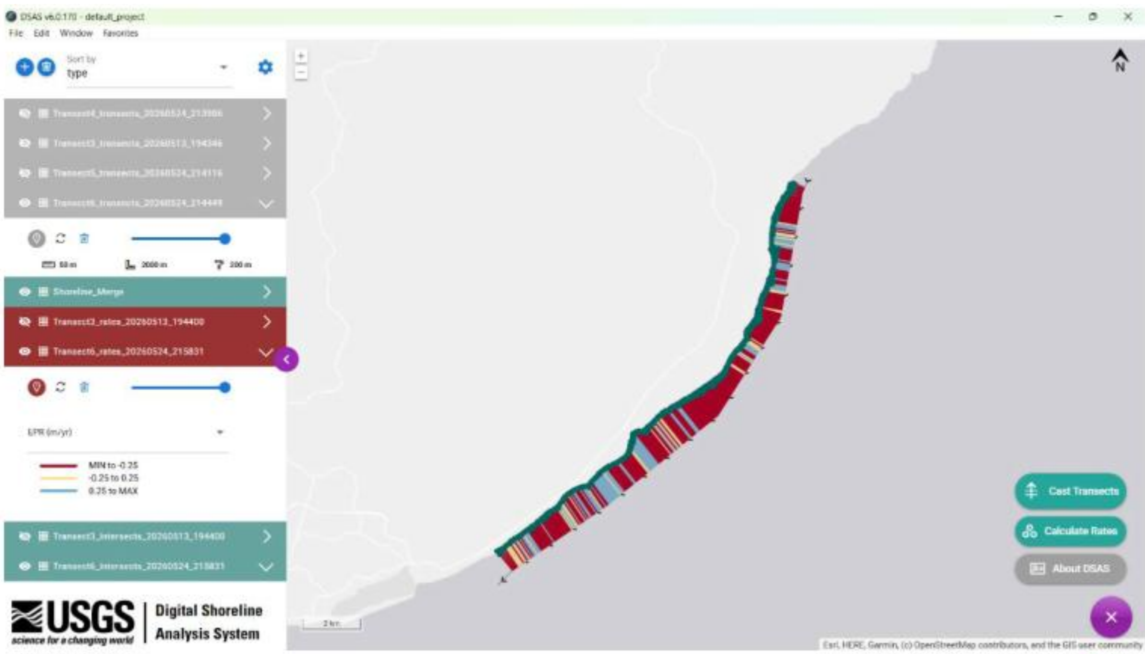

Figure 3. Offshore baseline and transect

Each of the five parameters was classified into five vulnerability classes (score 1 = very low to score 5 = very high), following criteria adapted from Gornitz [12] and modified by Hammar-Klose and Thieler [13] in Table 2 about :

Table 2. CVI Criteria

No	Variable	Very Low (1)	Low (2)	Moderate (3)	High (4)	Very High (5)
1	Geomorphology	High cliffs, rocky	Medium cliff, rocky	Low-cliff, rocky, alluvial plains	Rocky, gravel, estuary, lagoon	Sandy, brackish swamp, delta, muddy
2	Shoreline changes (m/year)	>2.0 (accretion)	1.0 – 2.0 (accretion)	-1.0 – 1.0 (stable)	-2.0 – -1.0 (erosion)	< -2.0 (erosion)
3	Slope of the coast (°)	> 10	6 – 9.9	4 – 5.9	2 – 3.9	< 2
4	Wave height (m)	< 0.55	0.55 – 0.85	0.85 – 1.05	1.05 – 1.25	> 1.25
5	Tidal range (m)	< 1.0	1.0–2.0	2.0–4.0	4.0–6.0	> 6.0

After setting the vulnerability score for each parameter, the CVI for each coastal segment is calculated using the following equation:

$$CVI = \sqrt{\frac{A \times B \times C \times D \times E}{5}} \quad (2)$$

Where A - E are the scores for geomorphology, shoreline change, coastal slope, wave height, and tidal range, respectively. This equation combines five parameter scores using a geometric mean to produce a single vulnerability value for each coastal segment. Higher CVI values indicate greater physical vulnerability to coastal hazards, whereas lower values indicate relatively stable coastal conditions. By integrating multiple coastal characteristics into a single representative indicator, this approach enables comparison of vulnerability levels among coastal segments. The resulting CVI values were then classified into four vulnerability categories namely low, medium, high, and very high, presented in Table 3.

Table 3. CVI Classification

No	CVI Value	Classes
1	< 4.75	Low
2	4.75 – 10.64	Intermediate
3	10.65 – 19.66	Height
4	> 19.66	Very High

The CVI map was overlaid with the 2025 land-use map using the Intersect geoprocessing tool, producing polygons carrying both the CVI class and land-use category simultaneously. Area per land-use type per vulnerability class was computed using Calculate Geometry and Summary Statistics and cross-checked with field observation and the RTRW Kota Balikpapan 2023–2042 to derive mitigation priorities.

Following the overlay stage, the identified vulnerability-land-use combinations were interpreted using DfS principles. Consistent with the principle of eliminating or reducing foreseeable risk during design [23]-[25], the recommendations prioritized: (i) avoiding or controlling new exposure in higher-vulnerability coastal areas where practicable; (ii) reducing risk at source through coastal setbacks, mangrove rehabilitation, vegetation buffers, and appropriately designed coastal protection; and (iii) communicating and managing residual risks for construction, operation, and maintenance. This DfS step did not alter the CVI calculation or vulnerability classes, it was applied only when translating the CVI-LULC results into the final mitigation strategy.

RESULTS AND DISCUSSION

Identification of Abrasion And Flood Events

Field observation across Teritip, Lamaru, Manggar Baru, and Manggar identified recurring abrasion indicators retreating shorelines, narrowing beach width, exposed vegetation roots, and damaged coastal vegetation concentrated most heavily in Teritip and Manggar Baru, both of which face the Makassar Strait directly and therefore receive greater wave energy. In contrast, segments in Manggar and Lamaru retain denser mangrove cover, which visibly reduces wave energy and slows the abrasion rate.

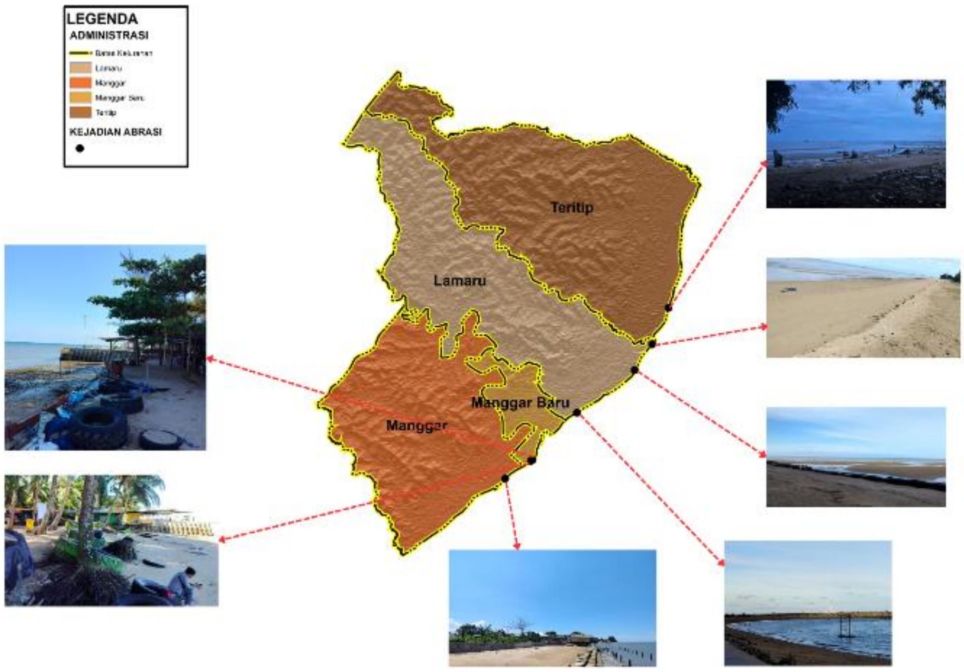

Figure 4. Map of abbration di East Balikpapan District

Based on Figure 3, abrasion indications were identified at several locations along the coastline of East Balikpapan District. These indications are evidenced by shoreline retreat, narrowing of beach width, loss of sedimentary material, exposed vegetation roots, and damage to portions of coastal vegetation. These conditions indicate that the coastal erosion process is ongoing and continues to influence changes in coastline morphology. The findings further show that the severity of abrasion varies across observation sites. Coastal areas in Teritip Village and Manggar Baru Village exhibit more pronounced abrasion indicators than other locations, as they directly face the Makassar Strait and are consequently exposed to relatively higher wave energy. In contrast, despite similarly facing open-sea wave action, several locations in Manggar and Lamaru Villages retain relatively intact mangrove vegetation cover, which attenuates wave energy and mitigates the rate of abrasion. This spatial pattern is consistent with the recorded disaster history in the sub-district, including the extreme wave event of 15 September 2022 in Manggar, which damaged three houses and affected sixteen residents [7], as well as the ongoing structural monitoring of abrasion-resistant infrastructure in Manggar Baru [8]. The alignment between field-observed hazard indicators and prior disaster records supports the reliability of the field dataset as an input for, and subsequent validation of, the CVI analysis.

Analysis of Coastal Vulnerability Index (CVI)

The level of coastal vulnerability was analyzed using the Coastal Vulnerability Index (CVI) method by integrating five physical parameters affecting coastal dynamics, namely geomorphology, shoreline change, coastal slope, significant wave height, and tidal range. Each parameter was classified according to its level of vulnerability using a score ranging from 1 (very low) to 5 (very high), based on the criteria presented in Table 2. The use of these five parameters aims to provide a comprehensive depiction of the physical condition of the coastal area of East Balikpapan District. Each parameter possesses distinct characteristics and a different degree of influence on coastal vulnerability. Therefore, the integration of all parameters through the CVI method enables a more holistic assessment than would be obtained through separate analysis of each parameter.

The parameters of shoreline change and geomorphology exhibit the most dominant influence on variations in the level of coastal vulnerability. Coastal segments experiencing a high rate of abrasion and dominated by sandy landforms tend to yield higher vulnerability scores. Conversely, areas retaining natural protection in the form of mangrove vegetation exhibit relatively lower vulnerability levels, as mangroves are capable of attenuating wave energy and mitigating erosion rates. Coastal slope likewise contributes to the level of vulnerability, as gently sloping beaches possess greater potential for inundation during peak tidal events. Meanwhile, significant wave height and tidal range display relatively minor variation across the study area, resulting in a comparatively uniform contribution to the overall CVI value. The integration of these five parameters produced varying CVI values across coastal segments. This variation indicates that the physical condition of the coast in East Balikpapan District is not homogeneous, but is instead shaped by local characteristics specific to each segment. Accordingly, the CVI analysis serves as the primary basis for identifying coastal areas requiring priority intervention and mitigation.

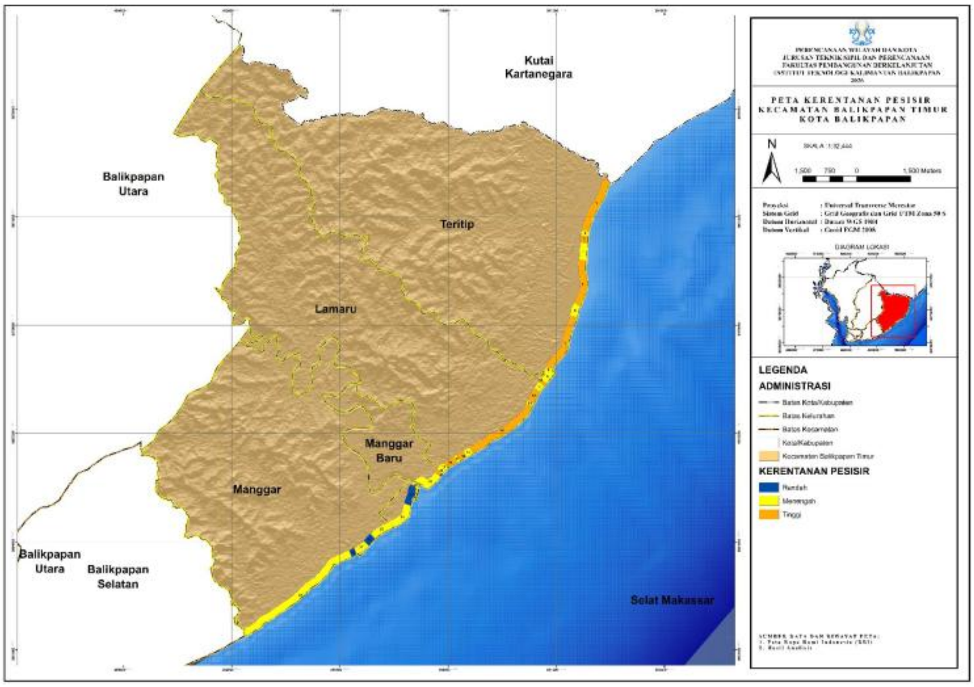

Figure 5. Map of Coastal Vulnerability Index (CVI) in East Balikpapan District

Based on the results of the Coastal Vulnerability Index (CVI) calculation, the level of coastal vulnerability in East Balikpapan District exhibits spatial variation influenced by the combination of five constituent parameters, namely geomorphology, shoreline change, coastal slope, significant wave height, and tidal range. Prior to the generalization process, 70 analysis segments were produced as units of analysis. Subsequently, a dissolved process was performed by merging adjacent segments sharing the same vulnerability class, resulting in 29 final segments. This process aims to simplify the spatial display without altering the underlying CVI value of the map. As shown visually in Figure 4, the level of coastal vulnerability is not evenly distributed along the coastline of East Balikpapan District. Some segments fall within the high vulnerability category, while others are classified as medium or low. These patterns indicate that the physical characteristics of the coastline vary across locations, resulting in differing levels of vulnerability. Such differences are primarily influenced by geomorphological conditions, the rate of shoreline change, and coastal slope, whereas wave height and tidal range contribute relatively uniformly across the study area.

Table 4. Classification of coastal vulnerabilities based on CVI values.

No	Sub Districts	Segments	High	Medium	Low	CVI Value
1	Teritip	8	4	4	0	8.4 – 10.9
2	Lamaru	11	5	6	0	8.4 – 10.9
3	New Manggar	6	1	4	1	4.3 – 10.9
4	Manggar	4	0	2	2	4.3 – 9.8
	Total	**29**	**10**	**16**	**3**	

Shoreline-change rate and geomorphology emerged as the most influential parameters, consistent with the theoretical basis of the CVI, which weights erodible, unconsolidated coastal material (sand, mud, mangrove fringe) as inherently more susceptible to wave-driven retreat than consolidated or cliffed coasts. Wave height and tidal range contributed comparatively uniformly across segments, reflecting the sub-district's relatively homogeneous exposure to the Makassar Strait rather than localized differences in these two parameters. Based on Table 4, the analysis results show that of the 29 segments formed after the dissolve process, 16 segments (55.17%)

are classified into the medium vulnerability category, 10 segments (34.48%) into the high vulnerability category, and 3 segments (10.34%) into the low vulnerability category. These results indicate that the coastal area of East Balikpapan District is generally dominated by medium vulnerability levels; however, a few segments still exhibit high vulnerability, thereby requiring particular attention in coastal management and mitigation efforts.

Segments with high vulnerability are generally located in coastal areas characterized by a combination of vulnerable geomorphological conditions, shoreline change dominated by abrasion, and relatively gentle coastal slopes. The combination of these parameters renders coastal areas more susceptible to erosion and shoreline change induced by wave and tidal action. In contrast, segments with low vulnerability exhibit more stable geomorphological conditions, relatively minor shoreline change, and physical characteristics better able to attenuate wave energy, resulting in lower CVI values. In terms of spatial distribution, segments with high vulnerability are predominantly found in Teritip Village and Lamaru Village, with a portion also present in Manggar Baru Village. The low vulnerability category, meanwhile, is found only in several sections of Manggar Village. The medium vulnerability category is distributed across nearly the entire coastal area of East Balikpapan District, making it the most dominant vulnerability class. This pattern indicates that the physical characteristics of the coast within the study area are heterogeneous and are shaped by local conditions specific to each coastal segment.

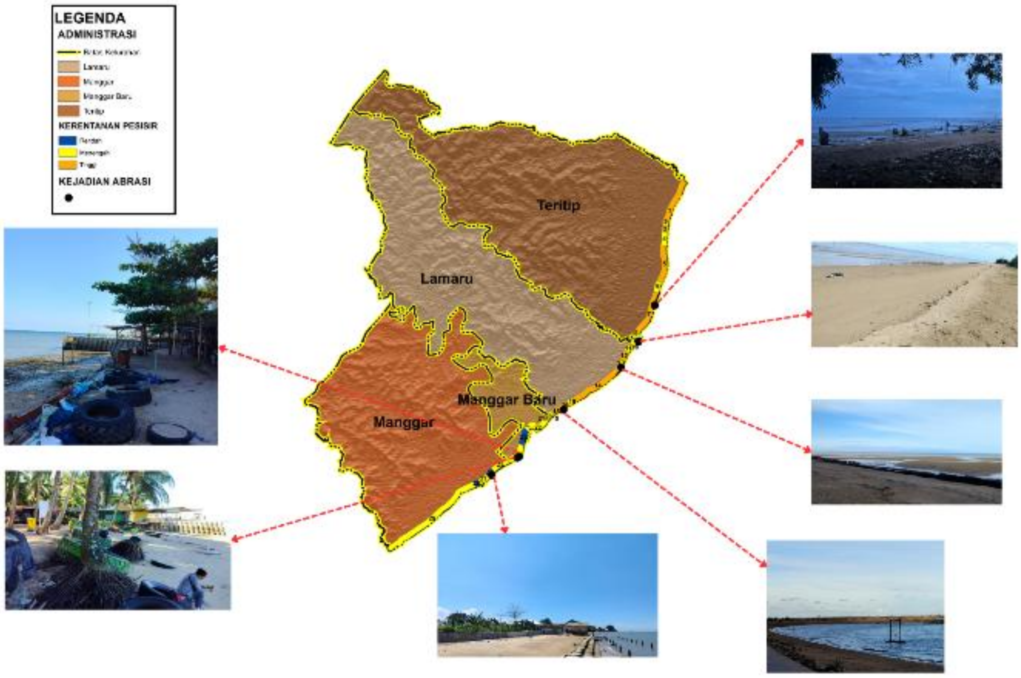

Figure 6. Coastal Vulnerability to Abrasion in East Balikpapan District

Based on Figure 5, most of the observed abrasion incidence points in the field fall within coastal segments classified as high or medium vulnerability. This finding indicates a general consistency between the results of the Coastal Vulnerability Index (CVI) analysis and actual field conditions. The distribution of abrasion points within segments exhibiting relatively high vulnerability values suggests that the parameters constituting the CVI are able to adequately represent the physical characteristics of coasts susceptible to abrasion. Nevertheless, several locations classified as medium vulnerability were still found to experience abrasion events. This indicates that the abrasion process is not solely governed by the physical factors analyzed within the CVI method, but may also be influenced by local conditions, such as specific coastal characteristics, vegetation cover, and anthropogenic activity in coastal areas. Accordingly, the results of this validation reinforce the applicability of the resulting coastal vulnerability map as a basis for further analysis, particularly at the overlay stage with land use, in order to determine mitigation priority areas within the coastal region of East Balikpapan District.

Overlay Analysis

Overlay analysis was conducted to examine the distribution of land use across coastal vulnerability levels in East Balikpapan District in Figure 7 and Table 5. The results indicate that each vulnerability class exhibits distinct land-use characteristics, reflecting varying degrees of exposure to coastal hazards. A notable finding is that high-vulnerability segments are not dominated by built-up land but instead coincide substantially with tourism infrastructure and mangrove ecosystems.

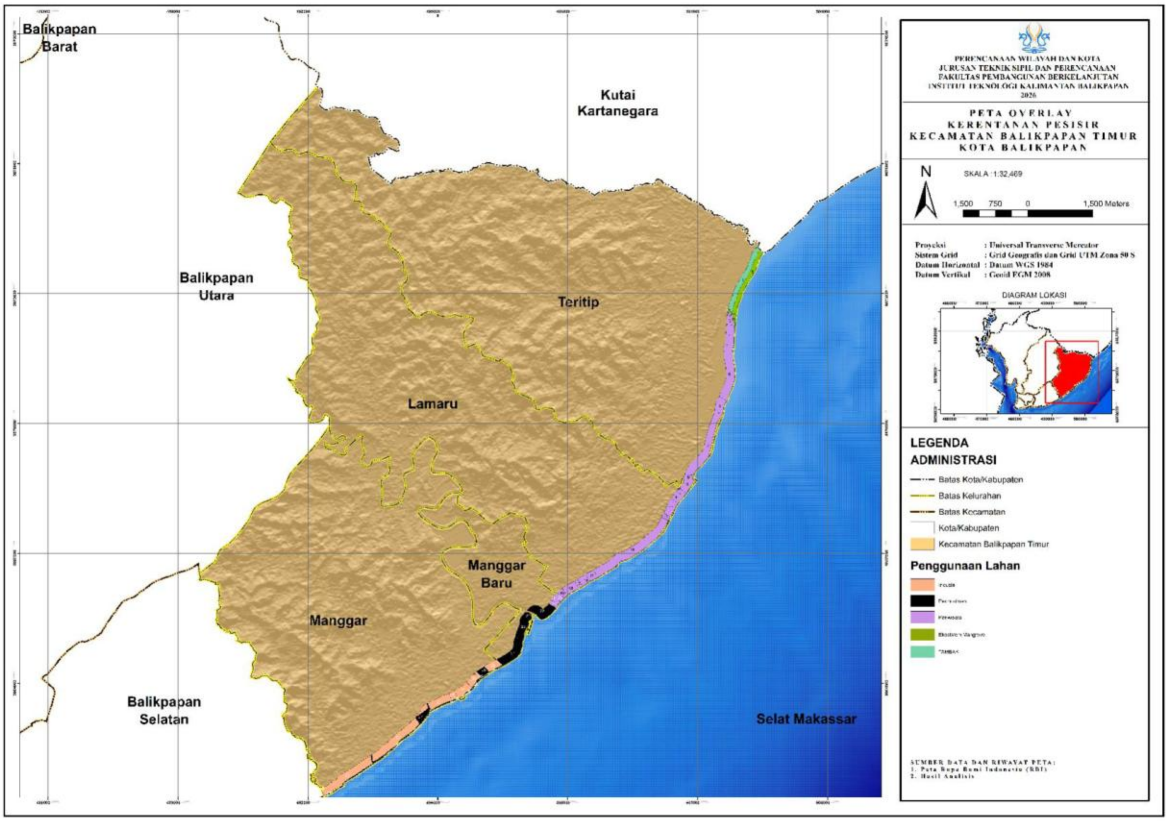

Figure 7. Overlay between CVI and LULC in East Balikpapan District

Table 5. Distribution of land use based on the level of CVI

No	Level	Segments	Dominant Land Use	Sub District
1	Height	10	Tourism, Mangrove Ecosystems, Ponds	Teritip, Lamaru, and Manggar Baru
2	Intermediate	16	Tourism, Settlements, Ponds, Mangrove Ecosystems, Industry	All sub-district
3	Low	3	Residential, Industrial	Manggar Baru, Manggar

Areas with a high vulnerability level are dominated by tourism areas, mangrove ecosystems, and aquaculture ponds, found in Teritip and Lamaru. In Manggar Baru Village, high vulnerability is likewise found in tourism areas only. These conditions indicate that tourism activities and coastal ecosystems along the shoreline are highly exposed to abrasion and coastal dynamics, warranting particular attention in their management. In the intermediate level, land use is more diverse, comprising tourism, institutional areas, aquaculture ponds, mangrove ecosystems, and industry. This class is the most dominant and is distributed throughout the coastal area of East Balikpapan District, indicating that most space-utilization activities in the coastal zone remain potentially affected by shoreline change, albeit at a lower threat level than high-vulnerability areas. Management efforts for medium-vulnerability areas should therefore focus on risk reduction through the control of space utilization and regular monitoring of shoreline conditions. Land use in the low level is found only in residential and industrial areas in Manggar Baru and Manggar Village. These areas exhibit relatively more stable coastal physical conditions, resulting in a lower vulnerability level compared to other segments. Nevertheless, management efforts remain necessary to ensure that future land-use changes and development activities do not increase the level of coastal vulnerability.

The overlay analysis further reveals that high-vulnerability areas are not always dominated by built-up land but also encompass coastal ecosystems with important ecological functions, such as mangroves. Mitigation strategies should therefore address not only the protection of assets and community activities but also the preservation of coastal ecosystem functions as natural buffers against abrasion and wave action. The relationship between coastal vulnerability level and land use identified in this analysis provides the basis for formulating mitigation response in East Balikpapan District.

Design for Safety (DfS)-Informed Coastal Mitigation Recommendations

Mitigation recommendations were formulated based on the results of coastal hazard identification, the Coastal Vulnerability Index (CVI), the overlay analysis with land use, and the policy directions outlined in the RTRW (Regional Spatial Plan) of East Kalimantan Province for 2023–2042, tailored to the characteristics of each coastal segment in East Balikpapan District. These recommendations were developed through a triangulation of multiple information sources, so that the resulting recommendations account not only for the level of physical coastal vulnerability but also for land-use characteristics and relevant spatial policy directions.

Mitigation recommendations are differentiated according to the vulnerability level and dominant land use in each village. This approach is intended to produce mitigation strategies that are more targeted, consistent with regional characteristics, and capable of supporting the sustainable reduction of abrasion and flash-flood risk. A summary of mitigation recommendations for each village in East Balikpapan District is presented in Table 6.

Table 6. DfS-Informed Coastal Mitigation Strategy

No	Sub-District	CVI Level	Dominant LULC	Mitigation Strategies
1	Teritip	High - Medium	Mangroves, Ponds, Tourism	High vulnerability: mangrove rehabilitation, construction of coastal protection structures, and arrangement of tourist facilities in accordance with coastal boundary provisions. Medium vulnerability: mangrove conservation, control of space utilization in tourist areas, and strengthening of coastal vegetation as natural protection.
2	Lamaru	High - Medium	Tourism	High vulnerability: construction of coastal protection structures, protection of tourist areas, and rearrangement of tourist facilities along the coastline. Medium vulnerability: arrangement of tourist areas in accordance with coastal boundary provisions, control of new tourist-facility construction, and strengthening of coastal vegetation.
3	New Manggar	High - Medium - Low	Tourism, Settlements	High vulnerability: construction of coastal protection structures and arrangement of tourist areas. Medium vulnerability: settlement arrangement in accordance with coastal boundary provisions, control of coastal-area development, arrangement of tourist areas, and strengthening of coastal vegetation. Low vulnerability: control of space utilization, maintenance of coastal vegetation, and increased public awareness of coastal-area protection.
4	Manggar	Medium - Low	Industry, Settlement	Intermediate vulnerability: construction of coastal protection structures at abrasion-prone sites threatening industrial and residential areas, control of coastal-area development, and settlement arrangement in accordance with coastal boundary provisions. Low vulnerability: maintenance of coastal areas, control of space utilization, and increased public awareness of coastal-area protection.

These recommendations directly address the research problem stated in Section 1: rather than issuing a single, undifferentiated mitigation strategy, results are matched to both hazard level and asset type, in alignment with the East Kalimantan RTRW 2023–2042. In practical terms, the findings imply that structural interventions (e.g., revetments, protective embankments) should be reserved for high-vulnerability segments containing ecologically irreplaceable assets, such as mangrove ecosystems, or high-value economic assets, such as tourism infrastructure, while non-structural measures (setback regulation, vegetation restoration, space-use control) are more cost-effective and ecologically appropriate for moderate- and low-vulnerability segments — an approach consistent with the non-structural mitigation principles emphasized in national coastal management policy [5] and prior CVI-based planning studies [19], [21].

Viewed through DfS, these recommendations follow an upstream risk-reduction sequence. Where practicable and consistent with spatial policy, the first priority is to avoid creating new exposure or to reconfigure development in the most vulnerable coastal segments; where exposure cannot be avoided, risk should be reduced at source through setbacks, ecosystem buffers, safer facility arrangement, and appropriately designed protective structures [22], [23], [24]. Residual risks should then be carried forward into detailed design, construction, operation, and maintenance planning. This interpretation is especially relevant to tourism facilities, settlements, and industrial assets because early siting and design decisions strongly influence their future exposure to erosion and tidal hazards.

Overall, the results demonstrate that integrating the CVI with land-use overlay analysis provides more spatially targeted mitigation guidance than a vulnerability map alone, thereby supporting the stated aim of this study and offering a replicable framework for other strait-facing coastal sub-districts in Indonesia with similarly heterogeneous land use, provided comparable physical and land-use datasets are available.

CONCLUSION

This study assessed coastal vulnerability in East Balikpapan Sub-district, Balikpapan City, using the Coastal Vulnerability Index (CVI) integrated with GIS-based spatial analysis, in line with the three objectives stated in Section 1. First, field observation confirmed that abrasion and tidal-flooding hazards remain active along the coastline, most pronounced in Teritip and Manggar Baru, which are directly exposed to the Makassar Strait. Second, the CVI analysis of five physical parameters: geomorphology, shoreline change, coastal slope, significant wave height, and tidal range, classified 29 coastal segments into three vulnerability levels: 10 segments (34.48%) high, 16 segments (55.17%) moderate, and 3 segments (10.35%) low vulnerability, with geomorphology and shoreline-change rate identified as the most influential parameters. This pattern is consistent with prior CVI applications in Indonesian coastal settings, reinforcing the validity of the method while also showing that the resulting vulnerability magnitude remains site-specific. Third, the overlay analysis between the CVI map and existing land use showed that high-vulnerability segments are dominated not by settlements but by tourism infrastructure and mangrove ecosystems, indicating that both economic assets and ecological buffers are simultaneously at risk. Based on this integration, mitigation recommendations were differentiated by vulnerability level and dominant land use for each village, ranging from mangrove rehabilitation and coastal protection structures in high-vulnerability areas to space-use control and vegetation strengthening in moderate- and low-vulnerability areas, consistent with the East Kalimantan RTRW 2023–2042. These findings confirm that vulnerability classification alone is insufficient for mitigation planning; integrating CVI results with land-use characteristics is necessary to produce spatially targeted, asset-specific recommendations. This integrated approach addresses the research gap identified in Section 1 and offers a replicable framework for other strait-facing, land-use-heterogeneous coastal areas in Indonesia. Future research is recommended to incorporate socio-economic vulnerability indicators and to validate the CVI classification against longer-term shoreline monitoring data, in order to strengthen the robustness of mitigation prioritization over time. The DfS perspective strengthens the practical contribution of the study by shifting the use of CVI from hazard description toward upstream risk-informed design and planning: vulnerability information can be considered early when deciding where development should be avoided or controlled, how coastal facilities should be arranged, and which natural or structural protections should be incorporated. Accordingly, DfS is applied here as a decision framework layered onto the CVI-LULC results, rather than as a replacement for the CVI methodology itself [22], [23], [24].

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