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Integrated land–sea spatial planning for disaster risk reduction in Tanah Laut Regency, South Kalimantan, Indonesia

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Abstract

This research examines the potential of integrated land–sea spatial planning as a strategic approach to disaster risk reduction in Tanah Laut Regency, South Kalimantan province, Indonesia. Specifically, it aims to (a) assess spatial overlaps between terrestrial–marine land use patterns and hazard zones, (b) evaluate coastal typologies and their corresponding vulnerabilities, and (c) formulate subdistrict-specific spatial planning recommendations to enhance regional resilience. A mixed methods design was adopted combining quantitative spatial techniques and qualitative descriptive analysis. Disaster potential in coastal regions is examined through an integrated assessment of terrestrial disaster risks and marine-based coastal vulnerability index (CVI) analyses. Terrestrial disaster susceptibility was assessed by using the Regional Development Planning Agency's 2021 disaster risk assessment, while coastal vulnerability was evaluated by using CVI parameters and overlaid with terrestrial and marine spatial planning categories. The spatial analysis shows a strong convergence between high terrestrial disaster risk and land use categories associated with intensive human modification—notably, food crop agriculture (23,610.53 ha), plantations (19,718.99 ha), aquaculture, and urban and rural settlements. Protected areas such as mangrove ecosystems, wildlife reserves, and natural tourism parks are located in high-risk coastal belts, while parts of marine conservation reserve areas and capture fisheries areas fall within high and very high CVI classes. Land rights overlays demonstrate that high tidal flood risk coincides with ownership rights and unregistered parcels. Overall, the research demonstrates that sustainable coastal development in Tanah Laut Regency cannot be achieved by treating land and sea as separate planning arenas. Risk-sensitive, typology-based integration of terrestrial and marine spatial plans—as supported by ecosystem-based zoning, mangrove restoration, relocation from high-risk zones, and strengthened marine conservation and fisheries management—is essential to enhance disaster resilience and long-term spatial sustainability in Tanah Laut Regency.

Keywords: spatial planning, disaster risk reduction, coastal vulnerability, coastal typology, terrestrial and marine spatial planning

Introduction

Coastal regions represent inherently complex and dynamic ecosystems that serve as critical hubs for economic, social, and ecological functions (Dahdouh-Guebas et al., 2000). Economically, these areas support vital sectors, such as fisheries, tourism, and maritime trade (Teh et al., 2013). From a societal standpoint, they are home to millions of inhabitants and play a key role in sustaining cultural heritage and traditional practices (Adger et al., 2005). Ecologically, coastal zones are characterized by

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high biodiversity and provide essential ecosystem services, including shoreline stabilization, flood regulation, and carbon sequestration (Barbier et al., 2011). However, their geophysical positioning at the land–sea interface heightens their vulnerability to natural hazards, such as coastal erosion, tidal flooding, tsunamis, and extreme storm events (Nicholls et al., 2007). The expansion of coastal infrastructure, including residential and tourism developments, often proceeds without a sufficient assessment of disaster risk or environmental carrying capacity (Marfai & King, 2008; Purbani et al., 2020). This is particularly evident in the construction of infrastructure within high-risk zones (Godschalk, 2003), such as erosion-prone coastlines and tsunami-vulnerable areas, heightening risks to structural integrity and human safety.

Within this research, Tanah Laut Regency in South Kalimantan province, Indonesia, with a coastline extending 72 km (Bakri et al., 2023), faces increased exposure to coastal disasters, posing significant risks to infrastructure, economic stability, and human safety (Kharisma et al., 2024). Spatial planning in the coastal region of Tanah Laut Regency encounters substantial challenges in integrating terrestrial and marine components, exacerbating vulnerability to disasters and environmental degradation (Djalante & Thomalla, 2012). Land use modifications in upstream areas, particularly deforestation for oil palm cultivation, amplify erosion rates and downstream sediment accumulation in coastal zones (Carlson et al., 2013). Excessive sedimentation results in the shallowing of estuarine systems, creating transitional brackish water environments at the freshwater–seawater interface (Lee et al., 2023), which adversely affects mangrove ecosystems and exacerbates the frequency and severity of tidal flooding (Steward et al., 2024). Given these vulnerabilities, the integration of disaster risk reduction (DRR) into coastal spatial planning is imperative for risk mitigation and the advancement of sustainable development (Arifin et al., 2023). Effective mitigation strategies should extend beyond reactive postdisaster measures, such as evacuation and reconstruction, to prioritize preventive and proactive interventions through systematic spatial management (UNISDR, 2009). Key components of this approach include hazard identification and geospatial mapping, the establishment of protective zones (e.g., coastal buffers and conservation areas), and the implementation of stringent resilient construction standards (Godschalk, 2003).

While the concept of integrated terrestrial and marine spatial planning has been extensively explored in academic literature (Douvere & Ehler, 2009), there remains a paucity of research specifically addressing disaster mitigation within the context of Tanah Laut Regency. Existing studies have primarily examined discrete elements, such as coastal vulnerability assessments (Kharisma et al., 2024; Theocharidis et al., 2024) and coastal resource management strategies (Adger et al., 2005; Meng et al., 2024). Although broader spatial planning frameworks have been investigated (Shabrina et al., 2026), few studies have undertaken a holistic analysis that integrates spatial planning, DRR, and the distinct socioenvironmental conditions of Tanah Laut Regency. With its extensive coastline and diverse coastal ecosystems, Tanah Laut Regency presents a strategic case study for examining the integration of terrestrial and marine spatial planning rooted in disaster mitigation principles (Bakri et al., 2023). In addressing these issues, this research investigates the effective integration of disaster mitigation-based spatial planning across terrestrial and marine domains in Tanah Laut Regency, employing a mixed methods approach that combines qualitative and quantitative methodologies.

The study addresses three research questions. First, it quantifies the spatial overlap between terrestrial disaster risk classes, coastal vulnerability index (CVI) classes, and designated terrestrial and marine zoning categories, and identifies which land and sea use categories account for the largest exposed areas at the regency scale. Second, it identifies the most prominent zoning–risk mismatches, defined as the coincidence of high or very high terrestrial risk or high or very high CVI with intensive-use zones, including settlements, agriculture/plantations, aquaculture, industrial/transportation zones, and key marine use zones, and examines how these mismatches vary across coastal typologies. Third, it prioritizes coastal subdistricts for risk-sensitive land–sea planning interventions by synthesizing risk levels, CVI classes, and affected terrestrial and marine zoning categories to derive subdistrict-specific planning recommendations.

Integrated land–sea spatial planning is operationally defined in this research as a geographic information system (GIS)-based risk-sensitive alignment of terrestrial disaster risk classes, CVI-derived coastal vulnerability classes, land rights (LR) regimes, and terrestrial and marine spatial-plan zoning categories, evaluated through overlay-based consistency (match/mismatch) and subdistrict disaggregation by coastal typology.

This research examines the potential of integrated land–sea spatial planning as a strategic approach to DRR in Tanah Laut Regency. Specifically, it aims to (a) assess spatial overlaps between terrestrial–marine land use patterns and hazard zones, (b) evaluate coastal typologies and their corresponding vulnerabilities, and (c) formulate subdistrict-specific spatial planning recommendations to enhance regional resilience. Furthermore, the research provides targeted policy and planning interventions to improve the adaptive capacity and disaster resilience of Tanah Laut Regency's coastal zones in response to future climate and hazard risks. The novelty of this research lies in its integrated land–sea approach to disaster risk-informed spatial planning in Tanah Laut Regency. Unlike previous studies that treat coastal vulnerability, land use, or marine planning separately, this research simultaneously overlays terrestrial disaster risk, legal LR regimes, and CVI-based coastal vulnerability with terrestrial and marine spatial plans and then disaggregates the results at the subdistrict level by coastal typology. This integrated framework generates operational place-specific zoning and governance recommendations that offer a potentially transferable analytic workflow for risk-sensitive land–sea planning in other disaster-prone coastal regions. However, transferability is not formally evaluated here. Instead, the research positions the framework as context grounded and replicable in principle, subject to local hazard data availability, legal institutional settings, and coastal typology comparability.

Materials and methods

Research area

The research area is situated within the coastal zone of Tanah Laut Regency, South Kalimantan. Geographically, the research area extends approximately from 3°30′–4°10′ S and 114°30′–

115°20′ E, covering terrestrial and marine spaces of the regency. A prominent cape projecting into the Java Sea bifurcates the coastline into western and southern sectors. More details can be seen in Figure 1.

The coastal belt includes six coastal subdistricts—Bumi Makmur, Kurau, Takisung, Panyipatan, Jorong, and Kintap—which constitute the primary focus of this research. The landward boundary of the research area is delineated by geomorphological features that remain influenced by marine processes. In contrast, the seaward boundary extends to 12 nautical miles offshore, in accordance with Law No. 32/2014 on maritime affairs (Suhaidi et al., 2018).

Research design and analytical framework

This research examines disaster potential in coastal regions through an integrated assessment of terrestrial disaster risks and CVI-based coastal vulnerability. A mixed methods design was adopted, combining quantitative spatial techniques and qualitative descriptive analysis (Mackiewicz, 2018). The research was conducted in Tanah Laut Regency, South Kalimantan, from August to November 2024. The analytical framework links three main components: Terrestrial disaster risk assessment, coastal vulnerability analysis, and the evaluation and integration of terrestrial and marine spatial plans. It incorporates disaster risk levels (Djalante & Thomalla, 2012), coastal typologies (Dahdouh-Guebas et al., 2005; Lehmann et al., 2021), and comparative spatial planning directives that are systematically tabulated to derive process-based integration strategies (Tocco et al., 2024).

Operationally, the framework proceeds in five sequential stages, as depicted in Figure 2. First, potential disaster identification is carried out by combining disaster risk data (terrestrial hazard maps and disaster records) with CVI-based coastal vulnerability to characterize multihazard coastal risks. Second, these hazard indicators are linked to land space and LR (e.g., ownership, cultivation, settlements, productive land uses) and to marine space (e.g., fisheries, aquaculture, conservation zones), producing an integrated picture of exposure in both domains. Third, the analysis incorporates spatial data and space

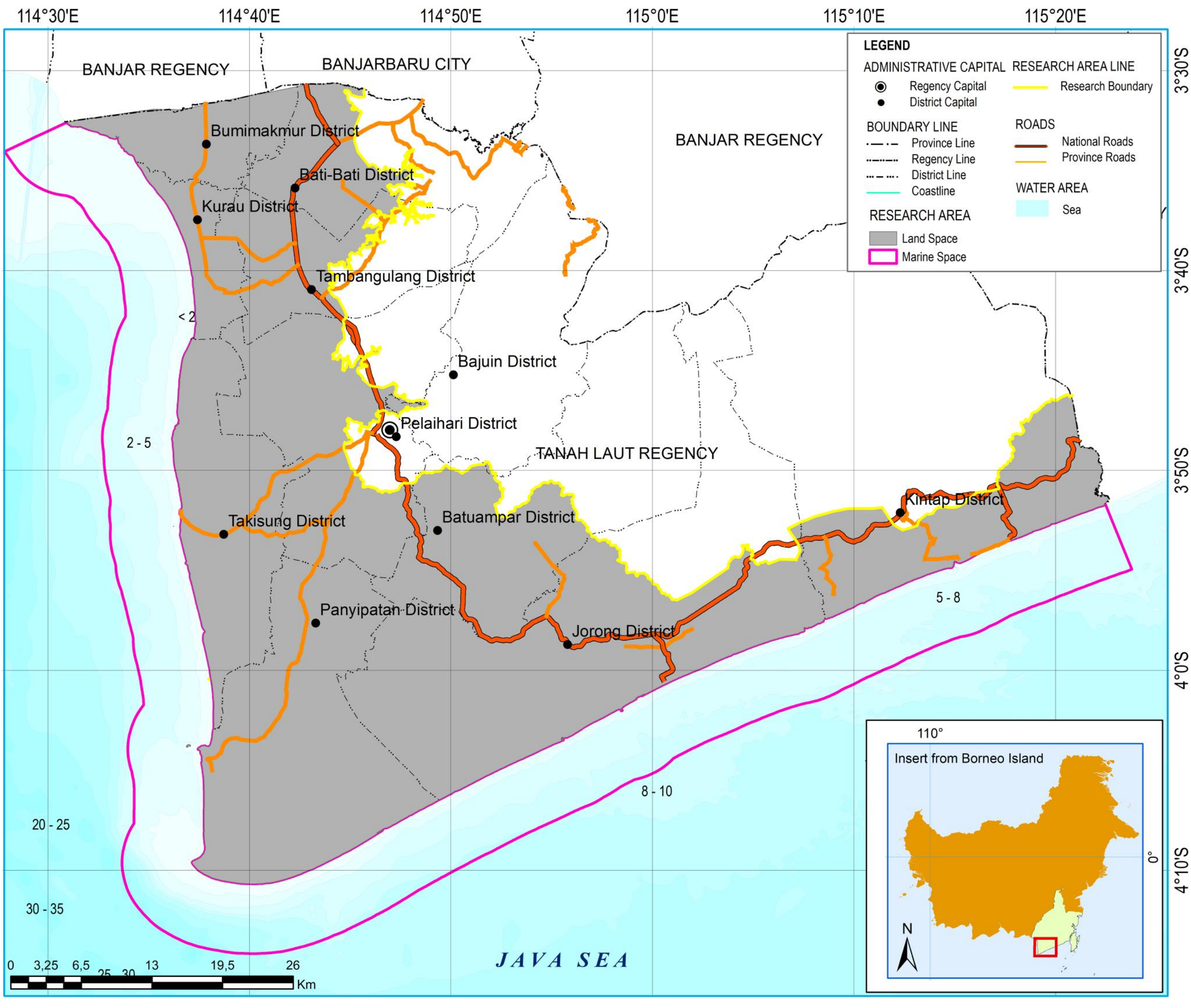

Figure 1 Research area map: Coastal and marine spatial integration in Tanah Laut Regency, South Kalimantan.

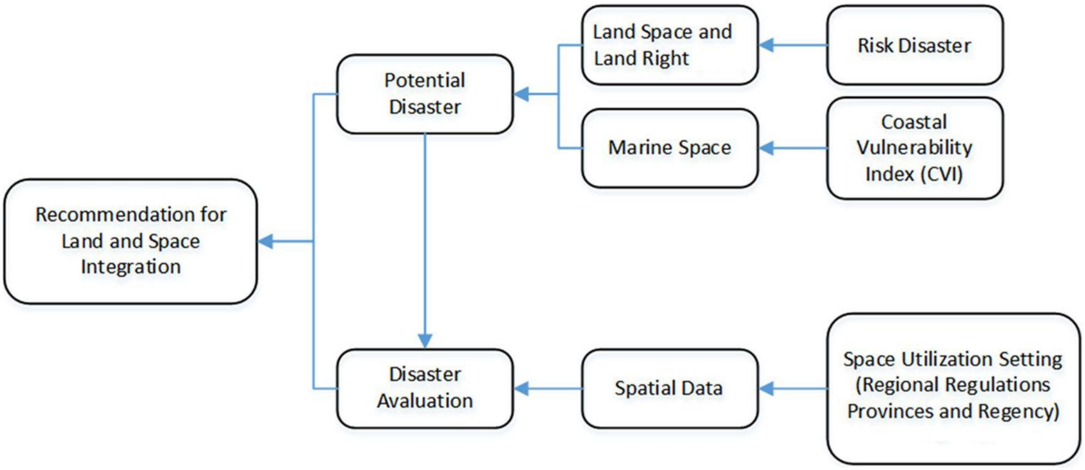

Figure 2 Analytical framework for integrating disaster risk assessment into land and marine spatial planning in coastal regions.

utilization settings derived from regional and spatial planning regulations, enabling a comparison between existing zoning arrangements and identified hazard levels. Fourth, on this basis, a disaster evaluation is performed to assess the consistency or conflict between current spatial allocations and disaster risk and coastal vulnerability patterns. Finally, the results are translated into recommendations for land and marine space integration, formulating zoning adjustments, protection priorities, and adaptation measures tailored to the specific conditions of Tanah Laut's coastal subdistricts. The stepwise analytical framework for integrating disaster risk assessment into land and marine spatial planning in coastal regions is summarized in Figure 2.

Data collection

Secondary data were obtained from relevant government agencies and existing planning documents.

- Terrestrial disaster risk maps and datasets, particularly the disaster risk assessment compiled by the Regional Development Planning Agency (RDPA) in 2021
- The Regional Spatial Plan of Tanah Laut Regency and South Kalimantan province, encompassing zoning regulations, land use allocations, and designated protection and cultivation areas
- Marine spatial planning documents, including marine zoning schemes and records of marine space utilization, compiled in accordance with established marine spatial planning protocols (Ehler & Douvere, 2009)
- Auxiliary spatial data, such as land use/land cover maps, administrative boundaries, shoreline data, and bathymetric information.

These datasets form the basis for the terrestrial and marine spatial overlays. Shoreline data were obtained from an Indonesian nautical chart referenced to World Geodetic System 84 titled "Kalimantan–South Coast, Tanjung Malatayur to Satui Passages, East Sheet," printed in 2024 and a nominal map scale of 1:200,000, and these data were used as the baseline shoreline reference for coastal segment generation and geomorphology interpretation. Bathymetric information was obtained from the General Bathymetric Chart of the Oceans 2024 Grid, provided on a 15-arc-second geographic grid, which was used to derive nearshore depth classes for the CVI parameterization and the marine overlay interpretation. Topographic elevation data were obtained from the Shuttle Radar Topography Mission 1 Arc-Second Digital Elevation Model acquired by the National Aeronautics and Space Administration in February 2000 with an approximate spatial resolution of 30 m.

Primary data collection involved systematic field observations and in-depth interviews with local communities and government officials in the six coastal subdistricts. Field observations documented (a) land use practices in cultivation areas (settlements, plantations, food crop agriculture, aquaculture, tourism, industrial zones, transportation corridors), (b) physical manifestations of disaster impacts (tidal flooding/rob, shoreline erosion, sedimentation, and inundation footprints), and (c) condition and management of ecological buffers such as mangrove forests and other protected areas.

In-depth interviews and qualitative discussions with community members and key stakeholders were conducted to (a) identify perceived drivers and impacts of coastal hazards, (b) document traditional ecological knowledge and local adaptation practices, and (c) understand implementation challenges and opportunities in integrating terrestrial and marine spatial planning. These qualitative insights support the interpretation of spatial patterns and inform the governance-oriented recommendations.

CVI assessment

Coastal vulnerability in Tanah Laut Regency was evaluated by the CVI method (Chacanza et al., 2024). The CVI integrates multiple biophysical parameters that influence the susceptibility of coastal zones to marine hazards. Key parameters included coastal geomorphology, beach slope, mean tidal range, sea level rise trends, erosion and sedimentation rates, significant wave height, bathymetry, and land use dynamics in nearshore areas. The shoreline was segmented into equal-length 500-m coastal segments by a linear referencing rule. The composite CVI used the square root CVI formulation (i.e., the square root of the geometric mean of ranked variables) with $n = 8$ and r ranked from 1 to 5 following the standard CVI definition (Thieler & Hammar-Klose, 1999) and recent CVI applications (Boumpoulis et al., 2025). The CVI values were classified into *very low* to *very high* by quantile breaks at the 20th, 40th, 60th, and 80th percentiles. Each parameter was reclassified into five ordinal vulnerability ranks (1 = *very low*, 2 = *low*, 3 = *moderate*, 4 = *high*, 5 = *very high*) and standardized before combination to generate a composite CVI score for each coastal segment. All input layers were sampled or summarized for each segment via GIS attribution procedures, including spatial join and extract-based sampling (Putra et al., 2023).

$$\text{CVI\_}i = \sqrt{((r1*r2*\ldots*rn)/n)}$$

In this equation, $r1$ through rn are the parameter ranks from 1 to 5 for that segment, and n is the number of parameters. In this research, $n = 8$.

All parameters were treated with equal weight. Ranks were combined directly in this equation. For map visualization and comparative summaries, ranks were also linearly scaled to a 0–1 range using $(r - 1)$ divided by 4, without changing the rank order. The sea level rise trend represents a long-term trend derived from multidecadal records from 1993 to 2023. Mean tidal range and significant wave height represent a multiyear climatology for 2014 to 2023. Erosion and sedimentation, as well as nearshore land use dynamics, were derived from the most recent decade-scale shoreline and land cover observations available for Tanah Laut for 2014 to 2024.

The final CVI values were classified into five classes from *very low* to *very high* using quantile breaks at the 20th, 40th, 60th, and 80th percentiles computed from the CVI distribution across all coastal segments. This ensures that class limits are fully reproducible from the CVI outputs.

The resulting CVI map distinguishes zones of high and very high coastal vulnerability, which are subsequently compared with marine spatial planning categories and coastal uses (e.g., capture fisheries, aquaculture, marine conservation reserves).

Terrestrial disaster risk assessment

Terrestrial disaster susceptibility in Tanah Laut Regency was assessed through the analysis of land-based disaster risk maps and associated spatial data, with particular reference to the RDPA 2021 disaster risk assessment. The analysis focused on (a) flood, tidal flood, landslide, and other relevant terrestrial hazards; (b) the spatial distribution of risk levels (low, moderate, high, very high) across subdistricts; and (c) the overlap of these risk levels with specific land use and zoning categories (e.g., food crop agriculture, plantations, urban and rural settlements, industrial zones, livestock areas, and transportation networks). This assessment produced terrestrial disaster risk layers that were subsequently overlaid with spatial planning categories, forming the basis of the integrated risk analysis.

Integration of terrestrial and marine spatial plans

GIS-based spatial overlay

The integration of terrestrial and marine spatial planning frameworks was carried out by GIS-based spatial analysis. Terrestrial disaster risk layers and CVI-derived coastal vulnerability maps were overlaid with terrestrial spatial plan categories (protected areas, cultivation areas, settlements, industry, transportation, defense and security zones, etc.) and marine spatial plan categories (marine conservation reserves, capture fisheries, aquaculture, shipping lanes, industrial maritime zones, and other designated marine uses).

All spatial layers were projected to a single working coordinate system, World Geodetic System 84/UTM Zone 50S (EPSG 32750), before overlay so that area calculations were consistent. The GIS overlay workflow used the following operations in sequence:

1) Project and clip were applied to harmonize spatial extents to the coastal belt and the 0- to 12-nautical mile marine boundary.
2) Intersect was used to compute polygon overlaps between terrestrial zoning and terrestrial disaster risk classes and between marine zoning and CVI classes.
3) Union was applied when multilayer overlays were needed so that all attribute fields were retained.
4) Spatial join attached subdistrict identifiers and coastal typology classes to each intersected feature.
5) Dissolve was performed by zoning category and risk class, as well as by subdistrict when required, before area summarization.

For Table 1, features produced by the intersection or union were dissolved by zoning category and hazard class. Polygon areas were computed by Calculate Geometry in square meters and converted to hectares as follows: ha = m^2/10,000. Summary statistics were then used to total hectares for each zoning category by risk class or CVI class. *Alignment* refers to zoning allocations that are consistent with risk reduction principles. Examples include protection or conservation zones overlapping high or very high hazard classes or high or very high CVI classes and cultivation, settlement, or industry allocated predominantly in low to moderate hazard classes. *Misalignment or conflict* refers to zoning that places intensive or exposure-sensitive uses, including settlements, food crop agriculture, plantations, aquaculture, industrial zones, and transport zones, within high or very high terrestrial risk classes or high or very high CVI classes. Misalignment also includes vulnerable coastal segments that lack an appropriate protection or buffer designation.

Interviews and field observations were used to validate and interpret the mapped overlays. This included confirming observed tidal flood footprints, erosion or sedimentation features,

Table 1 Overlay analysis of terrestrial and marine spatial plan categories with terrestrial disaster risk levels and CVI values in Tanah Laut Regency.

No.	Terrestrial and marine spatial plan	Terrestrial disaster risk, ha	CVI, ha	
		High	High	Very high
Protected areas				
1	Water bodies	863.92		
2	Mangrove ecosystem area	1,212.52		
3	Protected forest area	17.62		
4	Local protection area	647.97		
5	Wildlife reserve	1,930.52		
6	Natural tourism park	1,373.32		
7	Marine conservation reserve area		782.17	1,371.92
Cultivation areas				
1	Horticultural area	6.45		
2	Permanent production forest area	4,235.20		
3	Convertible production forest area	11.39		
4	Tourism area	267.38	18.24	
5	Power generation area	12.33		
6	Aquaculture area	3,202.84		
7	Capture fisheries area		834.02	174.10
8	Plantation area	19,718.99		
9	Rural settlement area	1,773.76		
10	Urban settlement area	3,618.10		
11	Defense and security area	428.22		
12	Industrial zone	664.78		
13	Livestock area	328.13		
14	Food crop agriculture area	23,610.53		
15	Transportation area	89.56	290.40	

Note. Data analysis results in 2024. Blank cells indicate *not applicable.* CVI = coastal vulnerability index.

and current land use practices and explaining governance or implementation constraints. Interview and observation evidence were not used to reclassify CVI ranks or disaster risk classes. Instead, it served as triangulation for the overlay results and to ground the policy recommendations.

Through this overlay analysis, the research identified (a) protected areas located within moderate to high terrestrial disaster risk zones and/or high CVI coastal segments, (b) productive and cultivation land uses (plantations, food crop agriculture, settlements, tourism, aquaculture, industrial zones) situated in high-risk terrestrial and marine zones, and (c) spatial patterns of alignment or misalignment between disaster risk distributions and existing zoning regulations.

Descriptive comparative and legal policy analysis

To evaluate the coherence between disaster risk distributions and spatial planning directives, a descriptive comparative analysis was conducted (Parthasarathy & Deka, 2021). This analysis compared (a) terrestrial disaster risk levels and coastal vulnerability patterns; (b) spatial plan designations in terrestrial and marine domains; and (c) regulatory provisions and planning principles stipulated in relevant legal frameworks, including Ministerial Regulations No. 28/2021 and No. 14/2021.

By juxtaposing the spatial configurations with these legal and policy instruments, the research identified areas where terrestrial and marine spatial plans are mutually reinforcing and where they conflict, particularly in high-risk cultivation zones and unprotected vulnerable coastal segments. These findings underpin the integrated governance recommendations articulated.

Subdistrict-level synthesis and typology-based recommendations

The integrated spatial datasets were disaggregated at the subdistrict level to derive context-specific analyses for Bumi Makmur, Kurau, Takisung, Panyipatan, Jorong, and Kintap. For each subdistrict, the research (a) characterizes terrestrial and marine land use configurations; (b) assesses the spatial coincidence of disaster risk levels, CVI classes, and spatial plan categories; and (c) relates these patterns to local coastal typologies (e.g., fluvial plains, fluviomarine plains, marine deposition coasts, volcanic coasts). Coastal typologies were assigned by geomorphological landform interpretation using the Rupa Bumi Indonesia topographic reference and Shuttle Radar Topography Mission-derived elevation and slope information, as supported by shoreline configuration and nearshore depth characteristics, and each coastal subdistrict was attributed to its dominant coastal landform type.

Land use change detection and disaster potential matrix

Land use change detection was conducted through a postclassification comparison of multitemporal land use/land cover maps for 2014 and 2024, which were reclassified into the coastal land use categories used in this research, then overlaid to quantify area changes and transition patterns within the six coastal subdistricts (Lu et al., 2004). A disaster potential matrix was constructed by cross-tabulating the terrestrial disaster risk classes from the RDPA 2021 layer with the CVI classes for each coastal segment and subdistrict, then computing an ordinal combined score as $S = R\_TR \times R\_CVI$, where R_TR is the terrestrial disaster risk rank (1 = *low*, 2 = *moderate*, 3 = *high*, 4 = *very high*) and R_CVI is the CVI class rank (1 = *very low*, 2 = *low*, 3 = *moderate*, 4 = *high*, 5 = *very high*). The resulting scores were reclassified into *low*, *moderate*, and *high* combined disaster potential based on the thresholds for interpretation—namely, *low* (*S* = 1–6), *moderate* (*S* = 7–13), and *high* (*S* = 14–20; United Nations International Strategy for Disaster Reduction, 2009).

Results

LR vulnerability to tidal flood hazards

The vulnerability of LR to tidal flood hazards in Tanah Laut Regency was assessed by an integrated quantitative and geospatial approach. The analysis focuses on five legal land tenure categories—ownership rights, cultivation rights, building rights, usage rights, and endowment rights—and considers parcels with no registered tenure (none). Together, these categories represent the formal and informal land systems exposed to coastal flooding in the six coastal subdistricts. More details can be seen in Figure 3.

Figure 3 shows the spatial distribution of different LR types overlaid with mapped disaster potential areas. Hatched zones indicate areas of tidal flood disaster potential that extend along almost the entire coastal belt, from Bumi Makmur and Kurau in the west to Jorong and Kintap in the east. These hazard zones intersect a mosaic of LR classes, with particularly dense overlaps in low-lying plains and estuarine areas. Large clusters of ownership rights, cultivation rights, and unoccupied parcels fall within hazard zones, especially in Bumi Makmur, Kurau, Jorong, and Takisung. This pattern reveals that formally titled lands and untitled or unutilized parcels are situated directly in coastal strips, suggesting that tidal flood risk considerations have been only partially incorporated into historical

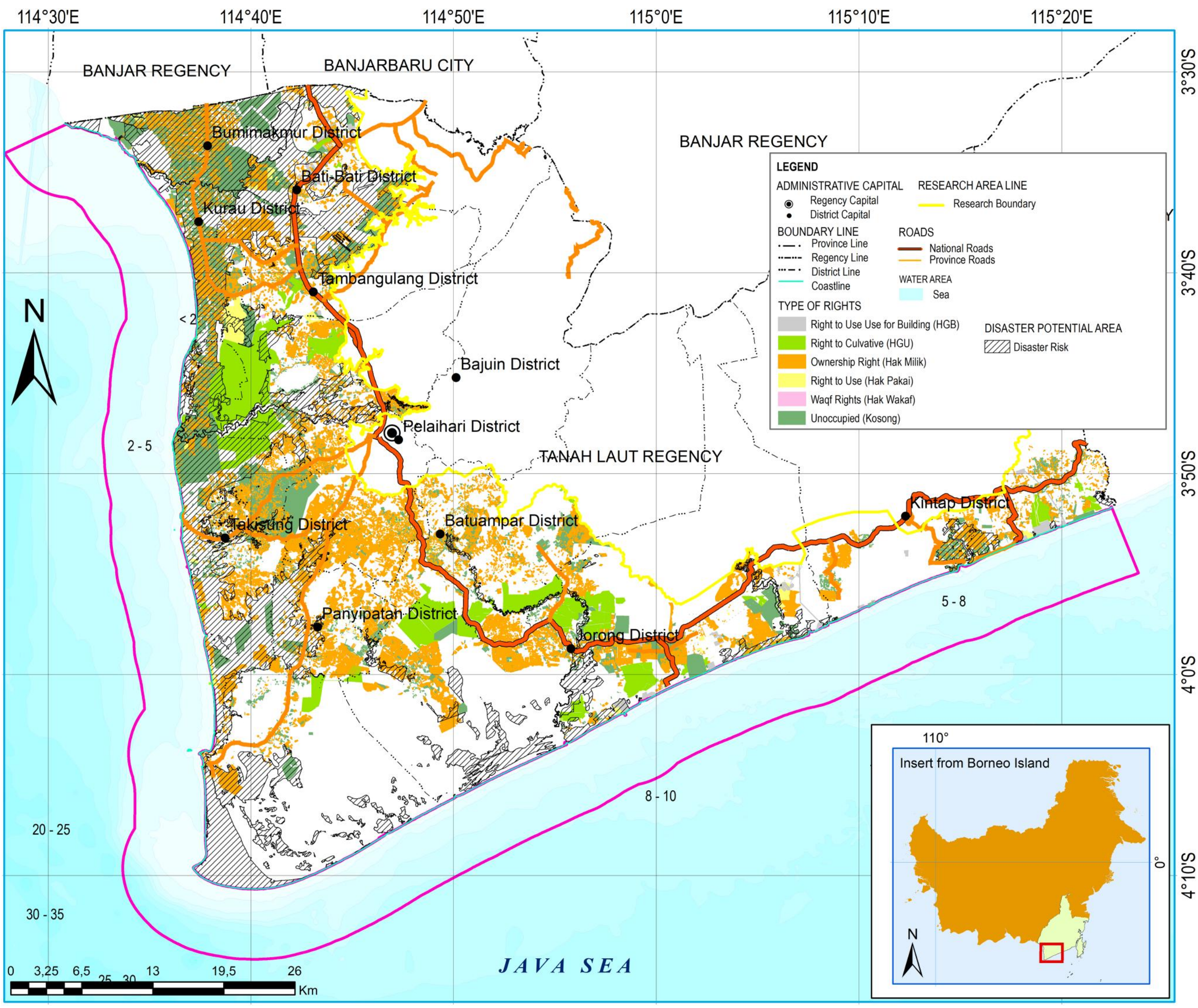

Figure 3 Spatial overlay of land rights categories and tidal flood–disaster potential zones in the coastal area of Tanah Laut Regency.

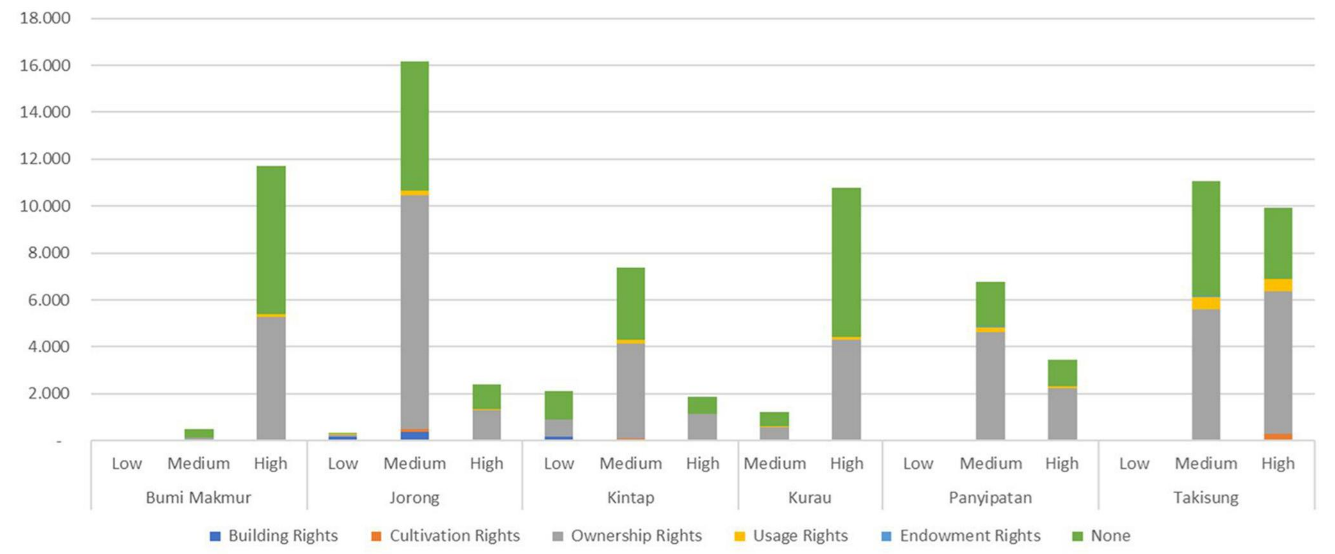

Figure 4 Land rights categories affected by low, medium, and high tidal flood risk levels across coastal subdistricts in Tanah Laut Regency.

land allocation and spatial planning decisions. More details can be seen in Figure 4.

Figure 4 quantifies these spatial patterns by disaggregating LR exposure by subdistrict and risk class. Across all coastal subdistricts, the largest exposed areas are associated with ownership rights and unoccupied land, while cultivation, building, usage, and endowment rights contribute relatively small fractions of the total. The greatest concentration of exposed land occurs in Jorong subdistrict, where medium-risk zones dominate and are largely composed of *ownership* and *none* categories. Substantial exposures are also evident in Bumi Makmur (primarily high-risk areas), Kurau (with large tracts in high-risk zones), and Takisung (medium and high risk combined). Kintap and Panyipatan show moderate but still significant LR exposure, again dominated by *ownership* and *none* categories. Very few LR parcels fall within low-risk classes, implying that most coastal lands already lie in medium to high hazard zones. Taken together, Figures 3 and 4 demonstrate that tidal flood vulnerability in Tanah Laut Regency is strongly shaped by the spatial configuration of LR regimes. The co-location of high hazard levels with ownership and unregistered (none) parcels suggests that risk-informed land use planning and tenure management have been limited and that future spatial planning revisions must explicitly integrate disaster risk considerations for formal and informal land tenure systems.

Spatial overlay of disaster risk in terrestrial and marine areas

The spatial overlay of disaster risk and LR categories (Figures 3 and 4) reveals marked disparities in exposure among subdistricts and suggests that local mitigation capacity and planning enforcement vary considerably. Across the six coastal subdistricts (Bumi Makmur, Kurau, Takisung, Panyipatan, Jorong, and Kintap), the mapped LR exposure patterns suggest variability in geomorphological setting, land use intensity, and the degree to which existing zoning provisions overlap hazard-prone coastal strips (Galderisi & Profice, 2011), although this research does not directly test these drivers. However, a detailed, context-specific assessment is required to fully understand the socioenvironmental drivers of LR susceptibility in each subdistrict. Consistent with the research objectives, the analysis proceeds by jointly evaluating terrestrial and marine disaster potential before their integration. Terrestrial vulnerability to coastal hazards is derived from the RDPA 2021 disaster risk assessment, while marine vulnerability is measured with the CVI, land use change detection, and a disaster potential matrix. Field surveys and in-depth interviews with community members and government officials are used to identify key drivers and impacts of coastal hazards and to ground-truth the spatial overlays. More details can be seen in Table 1.

Table 1 is presented for decision support and focuses on management hotspots by reporting only the high terrestrial disaster risk class and the high and very high CVI classes. The CVI classes (high/very high) reported here use the same quantile break thresholds (20th, 40th, 60th, and 80th percentiles) applied to categorize the composite CVI. Table 1 shows terrestrial and marine spatial planning classifications with terrestrial disaster risk (high) and coastal vulnerability (high and very high CVI). The results suggest a substantial convergence between high-risk zones and land use categories associated with intensive human modification. Across the terrestrial zoning categories reported in Table 1, cultivation and settlement-related uses total 57,670.11 ha, which represent 90.5% of the mapped area in the high terrestrial disaster risk class (63,698.36 ha). Food crop agriculture and plantations alone represent 43,329.52 ha (68.0% of the high-risk total). In the marine domain, marine conservation reserves and capture fisheries together account for 91.6% of the vulnerable marine area reported in high or very high CVI classes. Within protected areas, several categories are located in high terrestrial disaster risk zones, notably mangrove ecosystem areas (1,212.52 ha), water bodies (863.92 ha), wildlife reserves (1,930.52 ha), local protection areas (647.97 ha), and natural tourism parks (1,373.32 ha). Although these areas are legally designated for protection, their placement in high-risk coastal belts underscores their crucial role as ecological buffers against floods, landslides, and seawater intrusion (Dahdouh-Guebas et al., 2005). In the marine domain, marine conservation reserve areas occupy 782.17 ha and 1,371.92 ha in high and very high CVI classes, respectively, indicating that parts of the conservation network are themselves highly exposed to coastal hazards. In cultivation areas, the clustering of productive land uses in high-risk zones is even more pronounced. Food crop agriculture (23,610.53 ha) and plantation areas (19,718.99 ha) are the two most extensively affected categories, followed by urban settlements (3,618.10 ha), aquaculture areas (3,202.84 ha), and rural settlements (1,773.76 ha). Additional high-risk exposures are found in permanent production forests (4,235.20 ha), defense and security areas (428.22 ha), industrial zones (664.78 ha), livestock areas (328.13 ha), and transportation corridors (89.56 ha). On the marine side, capture fisheries areas are heavily concentrated in vulnerable zones, with 834.02 ha classified as high CVI and 174.10 ha as very high CVI, reflecting the high exposure of fishing grounds and associated livelihoods. Transportation areas also intersect high CVI classes (290.40 ha), indicating that coastal access and logistics infrastructure are simultaneously economic nodes and vulnerability hotspots. For decision support, Table 1 focuses on management hotspots and therefore reports only the high terrestrial disaster risk class and the high and very high CVI classes. These patterns yield several key insights, such as the following.

Protected areas and disaster risk. Many protected terrestrial zones—namely, mangroves, wildlife reserves, natural tourism parks, and water bodies—are located in high-risk coastal segments, reaffirming their importance as frontline defenses against hydrometeorological hazards while highlighting their own exposure to extreme events.

Productive land use in high-risk zones. Plantations, food crop agriculture, and rural and urban settlements are predominantly situated in high terrestrial risk zones. This spatial convergence reveals a structural conflict between economic development and environmental safety, calling for integrated zoning instruments that explicitly factor in hazard recurrence and ecological carrying capacity (Hietala et al., 2021).

Marine protected areas and coastal vulnerability. The concentration of marine conservation reserves within high and very high CVI classes, coupled with the exposure of capture fisheries areas, indicates that current marine spatial planning only partially shields the most vulnerable coastal segments. Gaps remain where highly exposed areas lack adequate conservation or buffer status, raising concerns about the effectiveness and equity of marine management.

Industrial, livestock, and infrastructure exposure. Industrial and livestock areas, although smaller in extent than agricultural and settlement zones, still intersect high terrestrial hazard levels, and transport corridors overlap with high CVI values. These sectors therefore function as economic engines and potential amplifiers of disaster risk, especially if critical infrastructure is damaged.

Integrated risk management needs. The strong spatial correlation between high terrestrial disaster risk and high coastal vulnerability in plantations, food crop agriculture, settlements, aquaculture, and transport networks underscores the need for an integrated land–sea risk management framework in these hotspot areas.

Overall, the overlay analysis demonstrates that Tanah Laut Regency experiences substantial multihazard exposure across terrestrial and marine domains. The dominance of high-risk cultivation and settlement areas, combined with the vulnerability of key protected and marine conservation zones, highlights the urgency of harmonizing terrestrial and marine spatial planning with DRR and climate adaptation objectives. Enhancing disaster-informed spatial planning through ecological buffer preservation, relocation or retrofitting of high-risk land uses, and risk-sensitive zoning and permitting is essential to support resilient, equitable, and sustainable coastal governance in Tanah Laut Regency.

Subdistrict-level integrated spatial planning and integrated coastal spatial governance

A spatial analysis was conducted across selected coastal subdistricts within Tanah Laut Regency to examine how terrestrial and marine spatial plans are integrated at the local scale. This subdistrict-level assessment allows for a granular understanding of land–sea functional linkages, exposure to disaster risk, and spatial planning priorities. In Bumi Makmur and Kurau subdistricts, spatial plans reveal a multifunctional coastal belt dominated by fisheries, food crop agriculture, plantations, and linear settlements along collector roads. These land uses intersect with substantial tidal flood and coastal hazard zones, placing productive land and residential areas at high risk. To mitigate these vulnerabilities, integrated terrestrial–marine planning needs to prioritize the designation of marine conservation reserves and the rehabilitation of mangrove ecosystems suited to muddy coastal environments. The use of resilient mangrove species such as *Rhizophora mucronata* and *Avicennia marina* is recommended to enhance shoreline stability and wave attenuation (Farooqui & Siddiqui, 2014). On land, the concentration of settlements along key road corridors underscores the importance of clearly planned evacuation routes and designated shelter zones.

Takisung subdistrict shows the juxtaposition of protected forests and conservation areas with agriculture, plantations, fisheries, and rapidly expanding tourism. The sandy coastal geomorphology, coupled with proximity between settlements and the shoreline, increases susceptibility to tidal flooding (rob). Consequently, marine spatial plans should establish marine conservation reserves and locally managed coastal buffer zones that regulate development permits in high-risk strips. Community-driven spatial planning, especially for tourism facilities, needs to be strengthened to ensure local ownership and sustainable coastal management (Oktorie et al., 2025; Putra et al., 2026).

Panyipatan subdistrict shows a different risk configuration: inland areas exhibit high disaster risk, whereas coastal CVI values are relatively low. Dominant land uses include production forests, natural tourism parks, and wildlife reserves, while marine zones are primarily allocated for capture fisheries. This pattern highlights the necessity of integrating topographical and hydrological processes into spatial planning, particularly for watershed management and inland flood regulation. A culturally significant feature is Datuk Island, a religious tourism destination offshore from Tanjung Dewa Village, which underscores the need to harmonize DRR with the protection of cultural heritage sites.

In Jorong subdistrict, the land use composition is shaped by fisheries, transportation infrastructure, and extensive plantation agriculture. High-risk disaster zones cluster along rivers and estuaries, whereas coastal vulnerability ranges from low to moderate. Terrestrial zoning confirms Jorong's role as an industrial hub, incorporating the Jorong industrial zone and a collector port, while marine spatial allocations cover capture fisheries and maritime logistics, including coal terminal operations. Although sandy beaches and relatively steep coastal slopes reduce tidal flood susceptibility along parts of the coastline, escalating industrial activities call for stricter zoning regulations, environmental safeguards, and disaster-resilient design standards.

Kintap subdistrict shows that high terrestrial disaster risk is concentrated in mangrove ecosystems and aquaculture zones. Despite low to moderate marine vulnerability, zoning enforcement is inconsistent. Protected mangrove areas lack clear regulatory provisions, whereas aquaculture zones are subject to disaster-related rules. This mismatch indicates that current planning frameworks do not fully secure ecologically critical zones against land use conversion or unregulated aquaculture expansion. Taken together, the subdistrict maps demonstrate substantial overlaps among cultivation areas, settlements, plantations, aquaculture, industrial zones, and disaster-prone regions. Protected areas such as mangrove forests and nature reserves frequently border intensive economic activities, exacerbating ecological stress and complicating sustainability goals. Conversely, several highly vulnerable coastal segments remain without adequate protective status, particularly in marine zones lacking conservation or buffer designations. More details can be seen in Figure 5.

Figure 5 shows the terrestrial and marine spatial plans for all coastal subdistricts and overlays them with disaster risk and coastal vulnerability information. The zoning framework clearly differentiates functional land and marine areas while highlighting transition zones and connectivity along the coastal interface. Coastal fishery zones cluster in nearshore waters, whereas mangrove ecosystems and conservation forests form critical

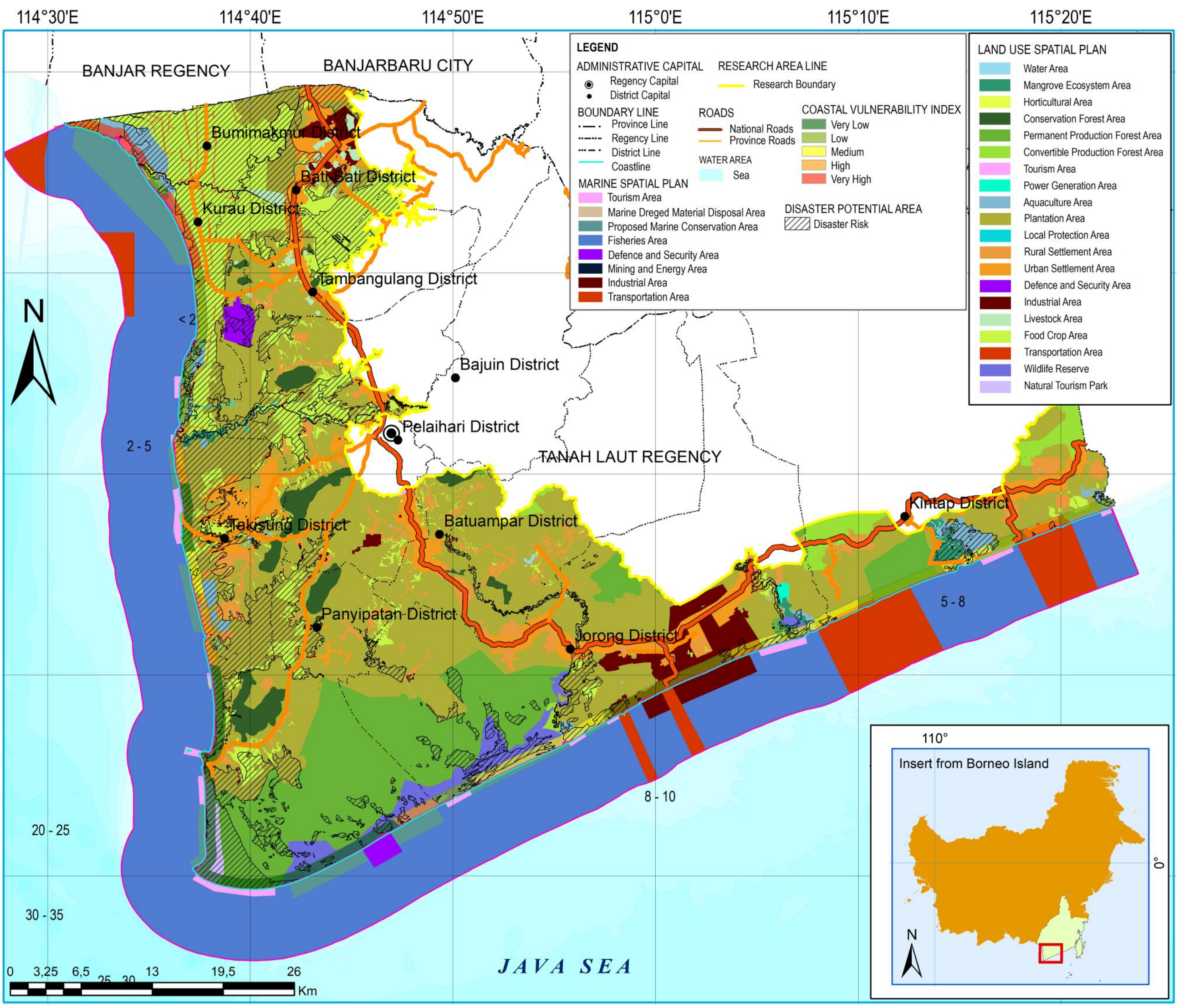

Figure 5 Integrated spatial plan map of terrestrial and marine areas in Tanah Laut Regency.

ecological buffers that mediate land–sea interactions and attenuate hazard impacts. The map also delineates key zones of terrestrial and marine resource abundance, illustrating how plantations, food crops, aquaculture, tourism, and industrial areas are distributed relative to high-risk coastal segments.

Consistent with the initial hypothesis, effective integration of terrestrial and marine spatial planning requires regulatory alignment and complementarity to avoid conflicting zoning frameworks. In high-risk subdistricts such as Bumi Makmur, Kurau, and Takisung, where terrestrial and marine vulnerabilities are pronounced, spatial planning should strengthen DRR-oriented zoning for agricultural and residential areas, while marine plans prioritize conservation measures, particularly the designation of marine protected areas and the preservation of critical mangrove ecosystems that enhance coastal resilience (Bavinck & Vivekanandan, 2011). In Takisung and Panyipatan, where terrestrial hazards intersect with adjacent marine conservation zones, stringent regulatory controls are necessary to limit land use conversion and safeguard essential ecological functions. In Jorong and Kintap, where industrial and agricultural activities overlap with coastal hazard exposure, adaptive planning instruments such as zoning ordinances, minimum elevation standards, and disaster-resilient construction codes are essential to reduce risk. Overall, the integrated spatial analysis at subdistrict and regency scales provides a robust empirical basis for refining zoning policies, reinforcing risk mitigation strategies, and strengthening coastal spatial governance in Tanah Laut Regency.

Recommendations based on coastal typologies and disaster risk

To advance disaster-resilient and ecologically sustainable development in Tanah Laut Regency, terrestrial and marine spatial planning policies must be harmonized and explicitly calibrated to disaster risk levels and the distinct coastal typologies of each subdistrict. Building on the CVI–risk overlays and subdistrict spatial analyses presented in the previous sections, this research formulates context-specific spatial planning directives that align land–sea governance with local environmental dynamics. The proposed interventions are synthesized in Table 2, which combines (a) location-specific disaster risk levels, CVI classes, and coastal typologies; (b) marine spatial plan directives; (c) terrestrial spatial plan directives; and (d) recommended adaptation measures. These components define protection zones, optimize land use configurations, and prioritize risk reduction actions tailored to each coastal subdistrict. More details can be seen in Table 2.

Bumi Makmur and Kurau emerge as the most critically vulnerable subdistricts, with elevated risk across terrestrial and marine domains. Their fluvial and fluviomarine plains, characterized by muddy to muddy–sandy coastal formations, heighten susceptibility to tidal flooding and coastal erosion findings that are consistent with the CVI and disaster risk overlays. In these areas, mangrove ecosystem restoration is identified as a primary adaptation strategy. Species such as *Rhizophora mucronata* and *Rhizophora apiculata* are ecologically well suited to muddy intertidal substrates, making them optimal candidates for rehabilitation initiatives (Blasco et al., 1996, 2005). To improve seedling survival under high hydrodynamic energy, the use of reef ball structures is recommended to stabilize sediments and protect young mangroves (Perog et al., 2023). In parallel, community-based early warning systems that combine instrumental monitoring with traditional tidal knowledge are crucial for strengthening preparedness and response. The integration of local ecological knowledge into spatial governance can also reinforce long-term resilience.

In Takisung subdistrict, moderate to high coastal vulnerability and intensive tourism, agriculture, and settlement development along sandy coastlines generate significant exposure to tidal inundation. The directives in Table 2 therefore focus on the establishment of marine protected areas; zonation into core, limited, and utilization zones; and stricter enforcement of fisheries regulations. Complementary measures include strengthening mangrove ecosystem zones and coastal buffer areas, with the promotion of alternative livelihoods to reduce pressure on vulnerable fisheries.

In Panyipatan subdistrict, marine-related vulnerability is relatively low, but terrestrial hazards are significant, particularly within protected forest, wildlife reserve, and natural tourism park zones. The overlay analysis shows that high-risk areas coincide with environmentally sensitive and conservation-priority landscapes. Structural interventions such as seawalls, gabions, and riprap are therefore proposed to protect ecological integrity and adjacent settlements. Hard engineering measures are site specific and should be considered after ecosystem- or nature-based options where feasible, with monitoring of sediment transport, shoreline change, and erosion effects to avoid maladaptation. Given Panyipatan's strategic role in agriculture, fisheries, and ecotourism, strict conservation zoning and land use controls are essential (Handiani et al., 2022; Solihuddin et al., 2021). These engineered defenses must be combined with sustainable development practices to avoid transferring risk or degrading critical ecosystems.

Jorong subdistrict is characterized by intensive industrial and transport infrastructure adjacent to rivers and coastal waters, with high disaster risk driven by water body dynamics and low to moderate CVI values. The recommendations thus emphasize risk-conscious industrial development, such as protection zone designation around critical ecosystems and facilities. Integration of these zones into the spatial planning to avoid regulatory ambiguity, gradual relocation of settlements from flood-prone zones near industrial and port areas, and strict enforcement of disaster-resilient infrastructure standards.

In Kintap subdistrict, where high-risk zones coincide with mangrove ecosystems and aquaculture areas and CVI values are low to moderate, the priority is to build capacity within aquaculture-dependent communities. Recommended actions include community training on evacuation and early warning; promotion of integrated systems such as silvofishery that combine mangrove conservation with aquaculture production; diversification of commodities to reduce economic dependence on single high-risk sectors; and implementation of water–soil conservation measures, including organic fertilization, to maintain environmental quality under intensive use.

Across all coastal subdistricts in Tanah Laut Regency, Table 2 makes clear that high disaster risk and coastal vulnerability are closely associated with areas of intensive human use, particularly food crops, plantations, aquaculture, settlements, and

Table 2 Recommendations for the integration of terrestrial and marine spatial planning directives based on disaster risk levels and coastal typologies in each coastal subdistrict of Tanah Laut Regency.

Location, disaster level, and coastal typology	Spatial plan directives		Recommendations
	Marine	Terrestrial	
Bumi Makmur Disaster risk: High CVI: Very high Coastal typology: Fluvial plain (muddy coast)	• Marine conservation reserve area • Capture fisheries area	• Marine conservation reserve area • Local protection (coastal buffer zone) • Settlement area • Agriculture area • Aquaculture area (subject to special disaster risk regulations)	• Community-based mangrove restoration and conservation • Zoning of core, limited-use, and intensive-use areas • Development of mangrove-based ecotourism • Delineation of local protection zones based on vulnerability and ecological value • Enforcement of protection-zone regulations • Periodic environmental and biodiversity monitoring
Kurau Disaster risk: High CVI: Very high Coastal typology: Fluvial and fluviomarine plain	• Marine conservation reserve area • Capture fisheries area	• Marine conservation reserve area • Local protection (coastal buffer zone) • Settlement area • Agriculture area • Aquaculture area (subject to special disaster risk regulations)	• Relocation of communities from disaster-prone areas • Enforcement of disaster-resilient building codes • Community capacity building for disaster preparedness • Climate-adaptive sustainable agriculture and fisheries • Diversification of crop and fish commodities • Use of appropriate technologies to enhance disaster resilience
Takisung Disaster risk: High (tidal flooding) CVI: Moderate–high Coastal typology: Fluviomarine plain	• Marine conservation reserve area • Capture fisheries area	• Mangrove ecosystem area • Local protection (coastal buffer zone) • Settlement area • Tourism area • Agriculture area • Aquaculture area (subject to special disaster risk regulations)	• Establishment of marine protected areas based on biodiversity • Regulation of zoning (core, limited, utilization) • Law enforcement to protect marine ecosystems • Fishing quotas and size regulations • Seasonal and zonal fishery restrictions • Alternative livelihoods to reduce fishing pressure
Panyipatan Disaster risk: High (in protected areas) CVI: Very low Coastal typology: Marine deposition and volcanic coast	• Tourism area • Capture fisheries area	• Protected forest area • Natural tourism park • Wildlife reserve • Defense and security area	• Mangrove restoration considering high vulnerability and ecological function • Zoning for ecotourism, research, and sustainable use • Monitoring of mangrove sedimentation and growth • Detailed mapping of disaster-prone and ecologically valuable areas

(continued)

Table 2 (continued)

Location, disaster level, and coastal typology	Spatial plan directives		Recommendations
	Marine	Terrestrial	
Jorong Disaster risk: High (water bodies) CVI: Low–moderate Coastal typology: Marine deposition coast	• Industrial zone • Shipping transportation area • Specialized coal terminal	• Industrial zone • Shipping transportation area • Specialized coal terminal	• Protection-zone designation (core, buffer, limited use) • Integration into the RTRW with clear zoning provisions • Gradual relocation of settlements from flood-prone zones • Enforcement of disaster-resistant infrastructure standards
Kintap Disaster risk: High (aquaculture areas) CVI: Low–moderate Coastal typology: Marine deposition coast	• Industrial zone • Shipping transportation area • Specialized coal terminal • Mangrove ecosystem area	• Capture fisheries area • Industrial zone • Shipping transportation area • Specialized coal terminal • Aquaculture area	• Community training on evacuation and early warning • Integrated farming systems (e.g., silvofishery) • Commodity diversification • Water and soil conservation and the use of organic fertilization

Note. Data analysis results, 2024. CVI = coastal vulnerability index; RTRW = *Rencana Tata Ruang Wilayah* (Regional Spatial Plan or RSP)

industrial or transport nodes. Synthesizing these patterns, the following cross-cutting strategies are proposed for Tanah Laut Regency.

Ecosystem-based zoning and mangrove restoration. Prioritize the designation and enforcement of protection zones for mangrove ecosystems and other critical habitats, with strong participation from local communities in planning, restoration, and monitoring.

Resettlement and disaster-resilient construction. Gradually relocate the most exposed communities from recurrent flood and tidal inundation zones, combined with strict enforcement of disaster-resilient building codes such as minimum elevation standards and structural reinforcement in high-risk areas.

Community-led ecotourism development. Promote ecotourism initiatives rooted in community stewardship and conservation ethics, particularly in areas with significant natural and cultural assets (e.g., Panyipatan and Datuk Island), ensuring that tourism expansion does not increase hazard exposure.

Marine protected areas and science-based fisheries management. Strengthen marine spatial planning through the designation of marine protected areas and the implementation of fisheries management regimes that include gear restrictions, catch quotas, and seasonal closures, especially in highly vulnerable nearshore zones.

Climate-smart and sustainable agriculture. Implement agricultural practices that enhance resilience, including crop rotation, diversification, agroecological methods, and climate-adaptive farming techniques, particularly in extensive food crop and plantation areas located in high-risk zones.

Sustainable industrial and infrastructure zoning. Consolidate "clean" industrial zoning backed by effective waste management systems, environmental safeguards, and disaster-resilient design standards, especially in industrial and transport hubs such as Jorong and Kintap.

Collectively, the directives and recommendations summarized in Table 2 operationalize the integrated land–sea planning framework outlined in the methods and empirically supported in the results. By reducing hazard exposure, strengthening adaptive capacity, and aligning spatial plans with coastal typologies and risk profiles, this framework advances the long-term resilience and sustainability of Tanah Laut Regency.

Conclusions

This research provides an integrated assessment of terrestrial disaster risk, LR exposure, and CVI in Tanah Laut Regency, South Kalimantan, which is explicitly linked to existing terrestrial and marine spatial plans. The spatial analysis shows that multihazard exposure is not evenly distributed but is concentrated in specific land use and tenure configurations. Cultivation areas—especially food crop agriculture, plantations, aquaculture, and rural and urban settlements—dominate the high terrestrial risk classes, while parts of the marine conservation reserves and capture fisheries zones fall within high and very high CVI categories. Protected terrestrial areas such as mangrove ecosystems, wildlife reserves, and natural tourism parks are simultaneously located in high-risk coastal belts, highlighting their dual role as ecological buffers and areas that are themselves exposed to risk. At the same time, several highly vulnerable coastal segments remain poorly protected, and large tracts of formal ownership rights and unregistered land are situated directly in tidal flood hazard zones, indicating that historical land allocation and spatial planning have been only weakly informed by DRR considerations. By combining CVI mapping, LR overlays, and comparative analysis of terrestrial and marine spatial plans, the research generates a subdistrict-differentiated set of recommendations that move beyond generic DRR prescriptions. Bumi Makmur and Kurau, which exhibit very high CVI values and muddy fluvial plains, require ecosystem-centered strategies that include mangrove rehabilitation using species suited to high-energy muddy coasts, reinforcement with reef-ball structures, the designation of local protection zones, and the development of community-based early warning systems. Takisung demands tighter regulation of tourism and settlement expansion along sandy coasts, stricter fisheries management, and the formalization of marine protected areas. Panyipatan, where inland hazards intersect with conservation landscapes and marine vulnerability is relatively low, calls for careful integration of structural protections with conservation zoning and ecotourism development. In Jorong and Kintap, where industrial and transport infrastructures intersect with water bodies, aquaculture, and mangroves, risk reduction hinges on the designation of protection zones, the application of resilient infrastructure standards, the gradual relocation of the most exposed settlements, the adoption of integrated farming systems such as silvofishery, and improved waste and resource management. Overall, the research demonstrates that sustainable coastal development in Tanah Laut Regency cannot be achieved by treating land and sea, or ecology and economy, as separate planning arenas. Instead, disaster-resilient and socially just outcomes depend on risk-sensitive land–sea integration that recognizes how tenure regimes, cultivation patterns, and coastal typologies jointly shape vulnerability. The integrated multiscalar approach developed in this research provides a practical governance template that is grounded in GIS analysis and is translated into concrete zoning and policy options that can be adapted to other disaster-prone coastal regions in Indonesia and beyond.

Supplementary material

Supplementary material is available at *Integrated Environmental Assessment and Management* online.

Data availability

The data supporting this study are available in the article and in the online supporting information. The supporting information includes GIS layers/shapefiles (ArcGIS map packages), CVI outputs, land–sea spatial overlays, and supporting summary tables.

Author contributions

Kiky P. Setiawan (Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing—original draft), Kasman (Conceptualization, Data curation, Formal analysis, Investigation, Visualization), Aprizon Putra (Conceptualization, Data curation, Formal analysis, Methodology, Supervision, Visualization, Writing—original draft), Budimawan (Conceptualization, Methodology, Writing—review & editing), Taslim Arifin (Conceptualization, Investigation, Supervision, Writing—review & editing), Yulius (Conceptualization, Investigation, Writing—review & editing), Muhammad Ramdhan (Data curation, Formal analysis, Methodology, Visualization, Writing—review & editing), Rinny Rahmania (Data curation, Formal analysis, Methodology, Visualization, Writing—review & editing), Hafidzuddin Fihrin (Data curation, Formal analysis, Visualization, Writing—review & editing), August Daulat (Writing—review & editing), Helfia Edial (Investigation, Supervision, Writing—review & editing), Ruzkiah Asaf (Investigation, Writing—review & editing), Admi Athirah (Investigation, Writing—review & editing), and Rudhy Akhwady (Data curation, Investigation)

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Conflicts of interest

The authors declare that they have no conflicts of interest, whether financial or nonfinancial, related to the research, authorship, or publication of this article.

Ethical statement and consent to participate

This research did not involve experiments on humans, animals, or plants. The research relied primarily on spatial analysis of existing disaster risk maps, coastal vulnerability indices, and official spatial planning documents, complemented by noninvasive field observations and in-depth interviews with adult stakeholders (local communities and government officials). According to the institutional and national guidelines applicable to the authors, formal approval from a medical or animal ethics committee was not required for this type of social and environmental research. Participation in interviews was voluntary, verbal informed consent was obtained from all participants, and no personally identifiable information was reported in this article.

Consent for publication

This article does not contain any person's data (including images, personal details, or case descriptions) in any form that would require explicit consent for publication.

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