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Article

Assessing Coastal Multi-Hazards in the Randangan River Mouth Area, Tomini Bay, Indonesia

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Abstract: This study aims to provide a preliminary assessment of coastal hazards in the Randangan River Mouth Coastline, Tomini Bay, Indonesia, using the Coastal Hazard Wheel (CHW) framework. The assessment focuses on key parameters such as geomorphology, wave exposure, tidal range, vegetation cover, sediment balance, and storm climate across a 14.46 km coastal stretch. Results reveal high levels of vulnerability, with ecosystem disruption, gradual inundation, and coastal erosion each posing very high to high risks along 8.35 km of the coastline, particularly in sediment plains and deltaic zones with minimal vegetation. Saltwater intrusion affects nearly the entire coastline (13.91 km) at moderate risk, while flooding presents a high risk across 13.54 km, indicating the limited buffering capacity of existing natural features. Despite data limitations, the CHW approach effectively identifies and maps multi-hazard exposure, providing a valuable tool for early-stage planning. The findings underscore the need for integrated coastal zone management, including ecosystem-based interventions and improved data collection, to support long-term resilience and adaptive strategies in vulnerable coastal settings.

Keywords: coastal hazard; coastal risk; multi-hazard mapping; Randangan River Mouth; Tomini Bay

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1. Introduction

Tropical coastal areas are critically important due to their rich biodiversity, which supports livelihoods, cultural practices, and sustainable development (Singh *et al*., 2021). However, these regions face significant threats, particularly from coastal erosion, flooding, and saltwater intrusion, which can severely disrupt ecosystems and human activities. For instance, coastal erosion, exacerbated by sea level rise (SLR), leads to habitat loss and increased vulnerability to storms (Adewumi *et al*., 2018; Bagheri *et al*., 2019; Saleh *et al*., 2022). Additionally, saltwater intrusion poses a major risk to freshwater resources and agricultural activities, threatening both ecosystems and food security (Callistus *et al*., 2024).

Coastal zone management in tropical regions, particularly in Indonesia, faces multifaceted challenges. Rapid urbanization is a significant concern, leading to ecosystem degradation and pollution, profoundly impacting local fisheries and diminishing coastal biodiversity (Safitri *et al*., 2023). Urban expansion often intensifies conflicts over resource use and exacerbates coastal erosion, with reports indicating that roughly 40% of Indonesia's coastline is affected by erosion (Pattipawaej, 2024). Furthermore, climate change elevates sea level and increases storm frequency, further stressing coastal areas and complicating management efforts (Cahyadi Ramadhan *et al*., 2022).

Sustainable practices, such as mangrove reforestation, are increasingly recognized as central to mitigating coastal erosion and enhancing ecosystem. However, the implementation of these strategies is impeded by the physical vulnerability of coastal zones and the significant time required for newly planted mangroves to mature—typically several years before they can provide effective protection (Herbenita *et al*., 2022). Additionally, integrated coastal zone management (ICZM) is hindered by fragmented governance structures across various stakeholders and sectors, complicating coordinated responses to environmental changes (Singh *et al*., 2021). The combination of these factors necessitates innovative and resilient approaches to ensure sustainable coastal management in Indonesia.

The Coastal Hazard Wheel (CHW) has proven valuable for hazard assessment in regions with limited field data. (Stronkhorst *et al*., 2018) showed that global open-access data could be effectively integrated through the CHW to assess erosion hazards in Colombia. (Micallef *et al*., 2018) applied the CHW to the Maltese coast, identifying multiple hazards such as erosion, ecosystem disruption, and saltwater intrusion. Similarly, (Su *et al*., 2021) demonstrated the CHW's adaptability in the Guangdong-Hong Kong-Macao Greater Bay Area, even under changing environmental conditions. These studies underscore the CHW's versatility and effectiveness in synthesizing diverse data for multi-hazard assessments in data-scarce regions.

The objective of this study is to conduct a preliminary coastal hazard assessment using secondary data through the Coastal Hazard Wheel (CHW) framework, as develop by (Appelquist and Halsnæs, 2015). This approach aims to establish an initial understanding of the multi-hazard characteristics affecting the coastal area. Specifically, the study focuses on identifying potential risk zones along the Randangan River Mouth coastline by analyzing key biophysical parameters, including geomorphology, wave exposure, tidal range, and vegetation cover. The insights gained from this assessment are expected to support the formulation of more effective coastal management strategies and mitigation efforts in the study area.

2. Materials and Methods

2.1. Research location

Tomini Bay is strategically situated at the intersection of North Sulawesi, Central Sulawesi, and Gorontalo provinces. It encompasses approximately 6,000,000 hectares, making it a significant ecological and socio-economic zone (Arham *et al*., 2023). The bay features nutrient-rich waters due to its semi-enclosed nature, serving as a vital spawning, nurturing, and fishing ground for various marine species, including commercially important fish like Selaroides leptolepis (Pasisingi *et al*., 2020).

Randangan River Mouth is located in the Tomini Bay area, Pohuwato Regency, where the Randangan River meets the bay along the 14.46 km coastline. This coastal zone features sediment-rich plains and deltas, supporting vital ecosystems such as mangroves and seagrasses. These ecosystems help stabilize the coastline and are crucial for local livelihoods, including fishing and agriculture. However, the area faces significant coastal hazards and land use change, compounded by limited data and inadequate natural barriers. Despite these challenges, the Randangan River Mouth remains an important area for sustainable management due to its ecological and socio-economic value.

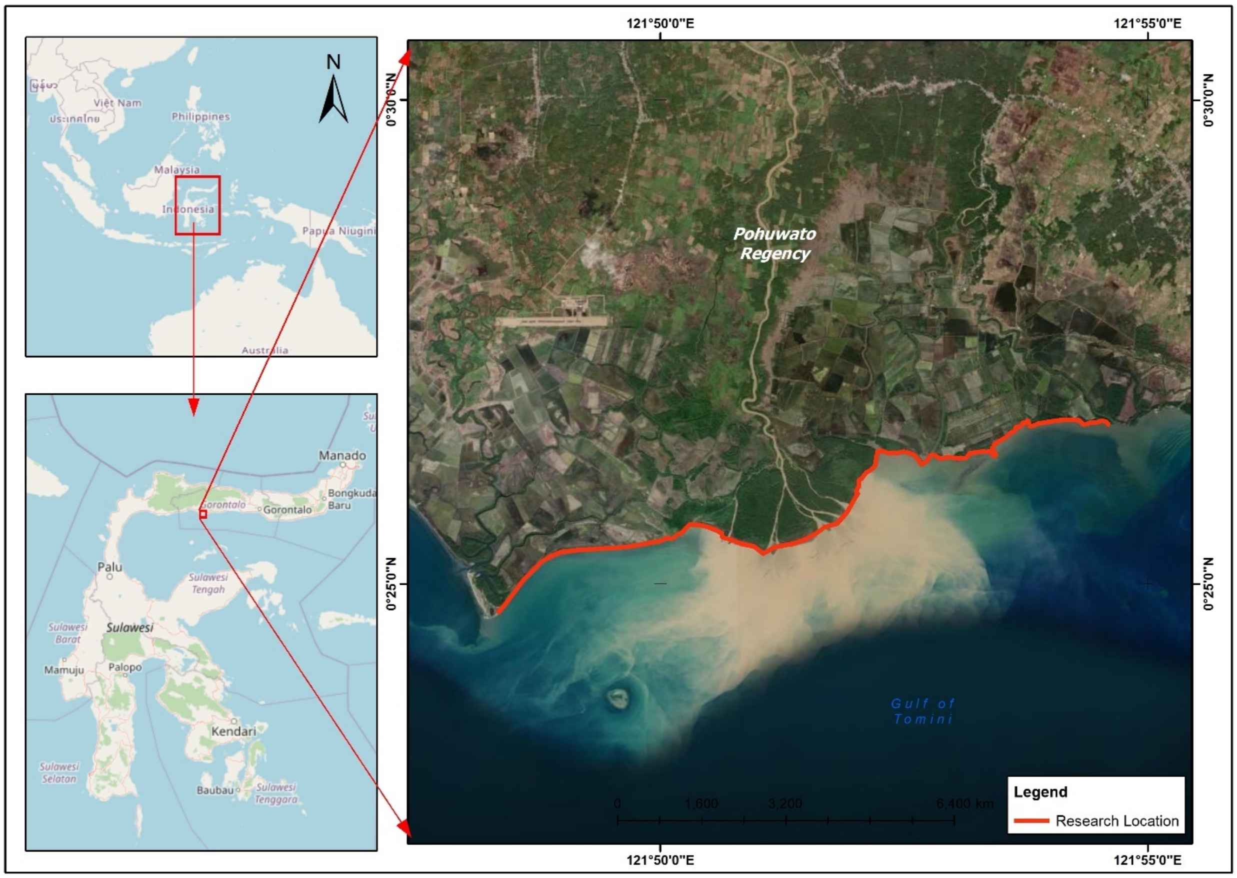

Figure 1. This research location in Randangan River Mouth, Tomini Bay based on Open Street Map and ESRI Imagery basemap

2.2. *Data sources*

This study employed the Coastal Hazard Wheel (CHW) method developed by (Appelquist and Halsnæs, 2015), which incorporates several variables including geological layout, wave exposure, tidal range, flora/fauna, sediment balance, and storm climate (see Table 1). The identification and analysis of climate change-induced multi-hazard classes were conducted through the following steps:

1. The geological layout was delineated using a geological map and interpreted from satellite imagery of the study area at a 1:50,000 scale.
2. Wave exposure data were obtained by averaging the significant wave height values from the study area, sourced from the BMKG website (https://maritim.bmkg.go.id/inawis).
3. Tidal range data were derived from sea level measurements processed by the Indonesian Geospatial Information Agency (https://srgi.big.go.id/tides).
4. Flora and fauna information was extracted through satellite imagery interpretation using Google Earth Pro, based on imagery dated November 1, 2024.
5. Sediment balance was assessed by analyzing shoreline accretion and erosion levels. This analysis used two shoreline datasets from different years (1997 and 2024), interpreted from Landsat imagery. The data were processed using the Net Shoreline Movement (NSM) statistical method within the Digital Shoreline Analysis System (DSAS) add-in for ArcGIS version 10.4.
6. Due to limited availability of storm climate data in the study area, information from the Global Wave Environment analysis by Appelquist *et al*. (2015) was used as a proxy. This alternative was considered appropriate given the extensive impacts of tropical cyclones.

2.3. Coastal Hazard Wheel for multi-hazard assessment

Appelquist and Halsnæs (2015) provided classification criteria for each variable (Table 1). The categorized variable data were then integrated into the shoreline dataset. The shoreline was segmented based on the classification of each variable, and the corresponding data were assigned to the attributes of each segment. The multi-hazard classes were identified by matching the variable characteristics of each segment with the CHW diagram. The assessment followed a concentric approach, beginning with the innermost variable (geological layout) and proceeding outward to the outermost (storm climate), as illustrated in Figure 2.

The seventh ring of the CHW diagram presents the levels of potential multi-hazards such as ecosystem disruption, gradual inundation, seawater intrusion, erosion, and flooding on a scale from 1 to 4, representing low, medium, high, and very high hazard levels, respectively. These scores were not calculated using a mathematical formula but were derived through a visual classification method by following a concentric assessment from the innermost to the outermost ring of the CHW, each shoreline segment was assigned a hazard level based on the combination of variable characteristics. The final multi-hazard score was obtained by matching the observed variable classes with the predefined hazard classification in the outer ring of the CHW diagram.

Coastal management types were identified by linking variable data to the first six rings of the CHW diagram and interpreting the hazard levels from the seventh ring. The outermost part of the diagram provides coastal management codes for each shoreline segment. These codes were then matched with the management type table developed by Appelquist and Halsnæs (2015) to determine the most appropriate coastal management strategies for each segment.

3. Results

3.1. Parameters biophysical

The assessment of coastal hazard in research study incorporated six primary biophysical parameters to reflect the area's ecological and geomorphological conditions (see Figure 3). The geological layout reveals that the shoreline is predominantly composed of sediment plains (8.72

km) and deltaic formations (5.74 km), both of which are inherently prone to morphological changes such as erosion, accretion, and inundation. Wave exposure is uniformly classified as protected along the entire 14.46 km coast, indicating minimal direct impact from large waves—likely due to offshore islands or coral reefs—yet the lack of wave energy limits sediment transport, heightening the risk of sediment buildup and flooding. Tidal range is categorized as micro-tidal, which, while minimizing vertical water fluctuation, also restricts natural flushing and can exacerbate issues like sediment accumulation, saltwater intrusion, and water quality degradation.

Table 1. Biosphysical parameters for asses the coastal multi-hazard

Parameters	Category	Description
Geological layout	Sediment plain	Soft rock; slope<20º
	Slope soft rock	Soft rock; slope≥20º
	Flat hard rock	Hard rock; slope<20º
	Rock	Hard rock; slope≥20º
	Delta/low estuary island	Sediment with slope<20º or≥20º
	Coral island	Mixed soft and hard rocks
	Barrier	Coastal area formed by low slope
	Tidal inlet/sand spit/river mouth	Landform associated with estuary
Wave exposure	Protected	<2 m
	Moderately exposed	2 – 4 m
	Exposed	>4 m
	Any	Any wave heights
Tidal Range	Micro	<2 m
	Meso	2 – 4 m
	Macro	>4 m
	Any	Any tidal ranges
Flora/fauna	Vegetated	There is vegetation
	Non-vegetated	There is no vegetation
	Swamp/Marsh	There is a swamp/marsh
	Intermittent marsh	Marsh within micro tidal range
	Mangrove	There is a mangrove ecosystem
	Intermittent mangrove	Mangrove within micro tidal range
	Tidal fat	low island within meso/macro tidal
	Coral reef	There is coral reef
Sediment balance	Balance/defcit	Shoreline moves towards the land
	Surplus	Shoreline moves towards the sea
	Beach	Coastal area with beaches
	No beach	Coastal area with no beaches
	Any	Any sediment balance categories
Strom Climate	Yes	There is a history of storm
	No	There is no history of storm
	Any	Any categories of storm climate

Source: Adopted from (Alwi *et al*., 2025)

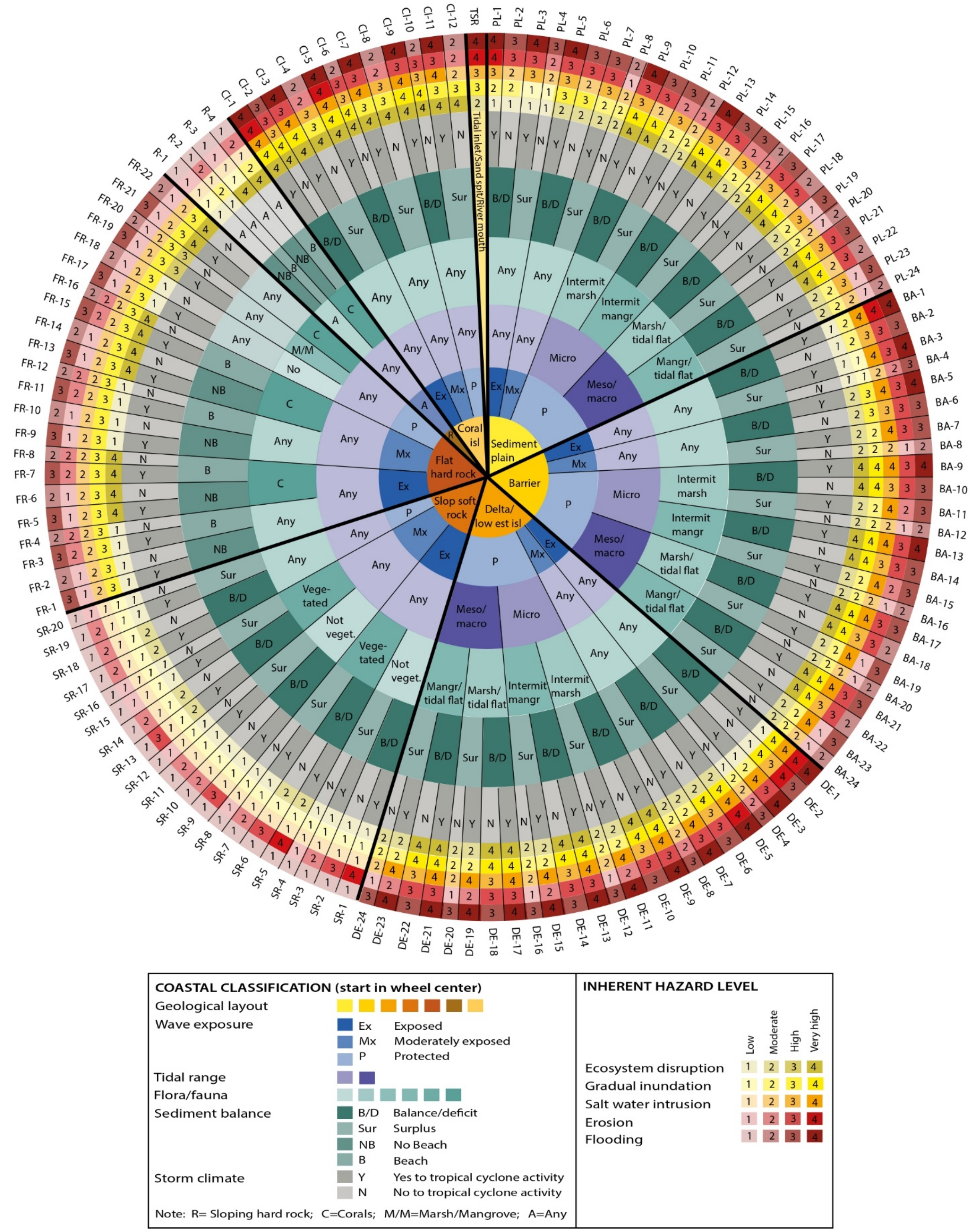

Figure 2. Coastal classification, associated multi-hazard level, and coastal management code, from Appelquist and Halsnæs (2015)

The coastal vegetation parameter shows a nearly balanced distribution between mangrove-covered areas (7.72 km) and non-vegetated zones (6.74 km). However, the latter are significantly more vulnerable to erosion and flooding due to the absence of natural buffers. A critical parameter, sediment balance, indicates a slight dominance of sediment-deficit zones (6.05 km) over surplus (6.11 km) in river mouth and balanced areas (2.29 km), pointing to disturbed sediment dynamics, potentially caused by altered fluvial input and anthropogenic interventions. Lastly, the storm climate assessment classifies the entire coastline as free from tropical cyclone influence, suggesting low climatic hazard but persistent vulnerability due to local non-climatic stressors. These parameters collectively underline the complex interplay between geomorphological features and ecological risks, emphasizing the need for integrative management strategies.

Figure 3. Six primary biophysical parameters conditions map

3.2. Coastal Hazard Exposure

The coastal hazard assessment along the 14.46 km shoreline of study area reveals varying levels of exposure to multiple types of coastal hazards (see Table 2). Ecosystem disruption poses a very high risk along approximately 8.35 km of the coast, primarily in areas characterized by sediment plains and deltas with minimal vegetation cover. Similarly, gradual inundation—indicating long-term sea level rise—also affects 8.35 km with a very high risk level, particularly in low-lying areas with sediment deficits and poor natural barriers. Saltwater intrusion shows a more widespread impact, with 13.91 km of coastline categorized as having moderate risk, suggesting that saline water penetration is a significant threat to groundwater and soil quality in nearly the entire study area. Coastal erosion presents a high risk along 8.35 km, mainly in zones lacking vegetative protection and suffering from sediment loss, while the remaining sections exhibit low to moderate risk. Finally, flooding emerges as a critical hazard, affecting 13.54 km of the coastline with high risk, including both vegetated and unvegetated areas, indicating that even existing mangrove stands may be reaching their functional limits under current hydrological pressures. Map of coastal multi-hazard exposure in Figure 4.

Table 2. Assessment levels of exposure to multiple types of coastal hazards

Hazard Type	Hazard Class (kilometers)			
	Low	Moderate	High	Very High
Ecosystem Disruption	-	6.11	-	8.35
Gradual Inundation	-	6.11	-	8.35
Saltwater Intrusion	-	13.91	0.55	-
Coastal Erosion	5.19	0.92	8.35	-
Coastal Flooding	-	0.92	13.54	-

Source: Analysis result (2024)

4. Discussion

The results of this study highlight a clear relationship between the biophysical conditions of the coastal area and the risk levels associated with various coastal hazards. The presence of sediment plains and delta landforms, which dominate the region, makes the area more susceptible to erosion, inundation, and saltwater intrusion. These landforms, being highly dynamic and subject to sediment deposition and removal, increase the vulnerability of the coast to multiple hazards. The analysis shows that areas with sediment deficit, such as delta and sediment plain regions, are particularly exposed to these risks. In contrast, areas with a surplus of sediment show a tendency for sediment accumulation, leading to significant changes in the shoreline and higher risks of flooding and ecosystem disruption. This imbalance in sediment dynamics is directly linked to the high levels of risk observed in the area.

Mangroves play a crucial role in mitigating coastal hazards, as evidenced by the spatial distribution of these ecosystems along the coastline of Randangan River Mouth. The study found that mangrove areas, which cover 7.72 km of the coastline, act as natural barriers against erosion and flooding by stabilizing the coastline with their root systems. Mangroves provide significant protection against wave energy, reduce sediment loss, and support the retention of water, thereby decreasing the likelihood of gradual inundation. However, the study also indicates that the distribution of mangroves is not uniform, with some areas lacking sufficient vegetation cover, which exacerbates the vulnerability to coastal hazards. This highlights the need for targeted mangrove restoration and conservation efforts in areas that are particularly vulnerable to erosion and flooding.

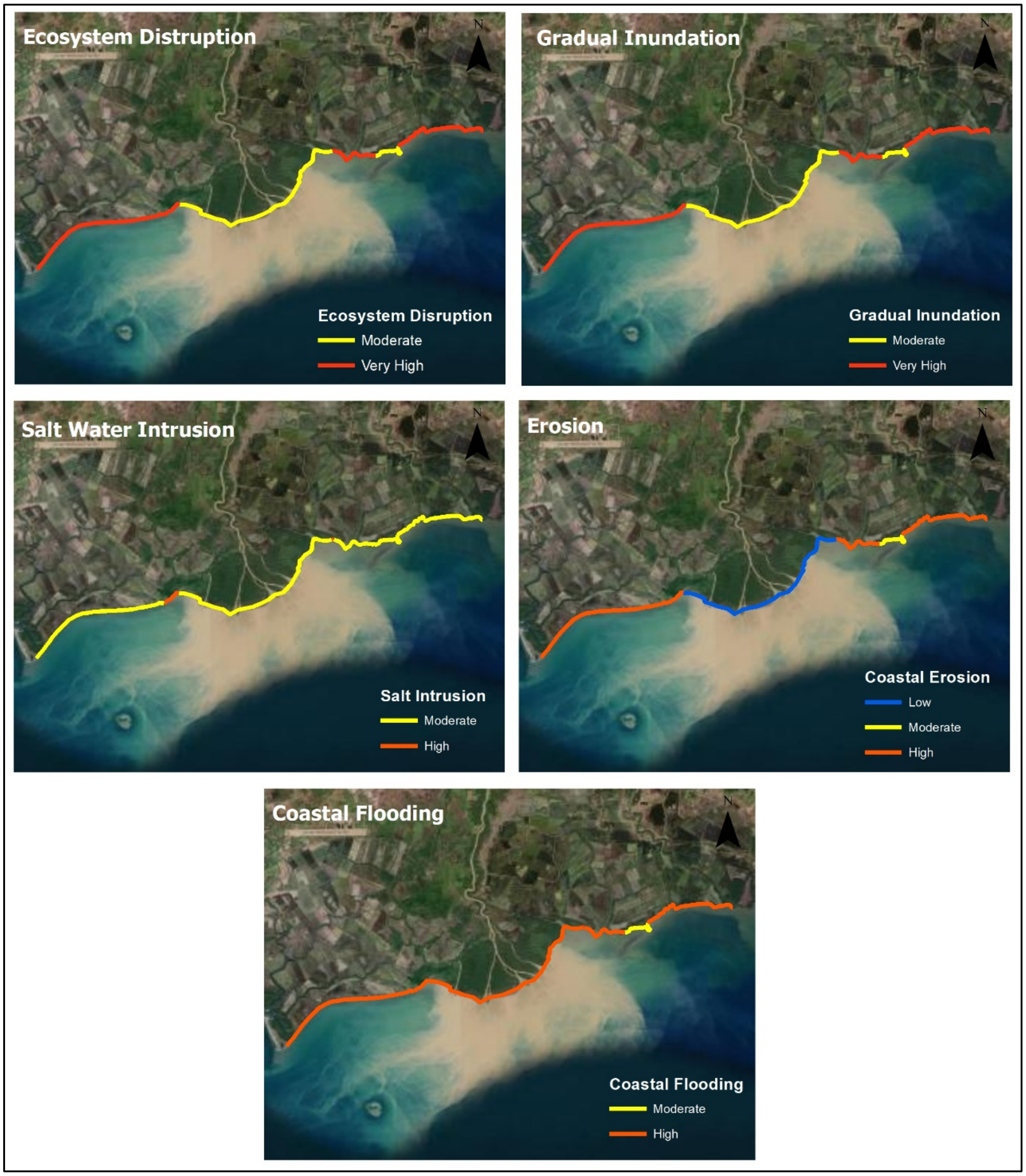

Figure 4. Map of the coastal multi-hazard assessment level exposure.

The sediment deficit observed in certain sections of the coastline is another critical factor affecting the morphological stability of the coastal area. The presence of sediment deficit (6.05 km) suggests that the natural sediment transport system is disturbed, either due to anthropogenic activities or natural processes, leading to erosion and the destabilization of coastal landforms.

Areas with insufficient sediment supply are more prone to coastal erosion, as the lack of sediment prevents the replenishment of eroded areas. This further exacerbates the risk of shoreline retreat and land loss, threatening both ecosystems and human infrastructure. Therefore, addressing sediment imbalances through effective sediment management and restoration strategies is essential to stabilize the coastal morphology and reduce the impacts of coastal hazards in Randangan River Mouth.

To address the high vulnerability of the coastal area, the following management strategies are recommended from CHW framework result. First, the establishment of a Coastal Management Zone (CMZ) is crucial for guiding sustainable development and resource use along the coastline. ICMZs aim to address fragmented management issues through systematic methodologies, promoting the sustainable use of coastal resources via effective planning and development strategies (Sun *et al*., 2018). Effective monitoring of coastline dynamics, incorporating geospatial analysis and remote sensing, is crucial for understanding coastal vulnerabilities and the impacts of human activities (Li *et al*., 2021; Sriyana *et al*., 2020). This approach can help mitigate the effects of coastal hazards, such as erosion, flooding, and saltwater intrusion, by ensuring that coastal activities are planned in harmony with the natural environment.

Fluvial sediment management is another key strategy to address the observed sediment imbalance in the region. Strategies that enhance sediment supply, such as gravel augmentation, can restore channel morphology and improve ecological functions downstream, particularly in sediment-starved river systems (Chardon *et al*., 2022) Furthermore, understanding sediment connectivity within landscapes can facilitate more robust sediment management strategies by considering factors like vegetation cover and geomorphic conditions (Echevarria-Doyle *et al*., 2023). Such holistic approaches are essential for developing sustainable coastal management frameworks and mitigating adverse coastal processes influenced by sediment imbalances (Kasprak *et al*., 2024).

Finally, wetland restoration plays a vital role in improving the overall ecological health of the region and enhancing its resilience to coastal hazards (Ilhami *et al.*, 2022). Coastal wetlands contribute significantly to biodiversity, acting as natural infrastructures that mitigate storm surges and coastal erosion(Gittman *et al*., 2024; Lin *et al*., 2023). Utilizing beneficial uses of dredged material in wetland restoration projects combats sea-level rise and improves habitat conditions, as demonstrated in case studies like Mobile Bay (Runion *et al.*, 2021). Furthermore, sediment availability has been shown to be essential for successful restoration efforts, reinforcing the ecological stability of these ecosystems (Liu *et al*., 2021). A comprehensive wetland restoration program, including the active restoration of mangrove forests (Budiman et al., 2022), should be a central component of the management strategy for the Randangan River Mouth coastal area.

The Coastal Hazard Wheel (CHW) approach exhibits significant strengths in data-scarce areas by facilitating comprehensive hazard assessments with limited local data. It utilizes global open-access datasets to analyze coastal vulnerabilities, such as those seen in Colombia, where multiple biogeophysical variables were integrated using the CHW to create reliable coastal erosion assessments (Stronkhorst *et al*., 2018). This method has also been successfully applied to regions in Southeast India, indicating its adaptability to diverse coastal environments (Palpanabhan *et al*., 2023). Moreover, the CHW enables a multi-hazard assessment framework, as demonstrated in the Guangdong-Hong Kong-Macao Greater Bay Area, helping to classify and manage coastal hazards despite the lack of extensive local data (Su *et al*., 2021). Ultimately, its applicability in data-scarce regions is essential for developing adaptive management strategies in facing increasing coastal hazards.

Despite the valuable insights gained from using the Coastal Hazard Wheel (CHW) approach, this study has several limitations that should be addressed in future research. The reliance on secondary data, although practical may introduce uncertainties and reduce the precision of hazard assessments. As demonstrated in the measurement of tidal range and wave exposure, accurate coastal hazard analysis requires detailed primary data, such as direct sea level measurements processed with the Admiralty method and spatially validated wave exposure data using tools like Ocean Data View and Microsoft Excel (Ningsih and Mutaqin, 2024; Widantara and Mutaqin, 2024). Therefore, field validation is essential not only to verify findings but also to improve the reliability of classification outcomes. Moreover, incorporating socio-economic variables will enrich the analysis by highlighting the human dimensions of coastal vulnerability. Future studies are encouraged to adopt robust primary data collection methods and integrate socio-economic assessments to strengthen the analytical framework and enhance decision-making for sustainable coastal management.

5. Conclusions

The findings of this study reveal that the coastal area of Randangan River Mouth is highly vulnerable to various coastal hazards, including ecosystem disruption, gradual inundation, saltwater intrusion, erosion, and flooding. The use of the Coastal Hazard Wheel (CHW) as a preliminary assessment approach has proven effective in identifying and mapping risk zones in the region. The analysis highlights that factors such as sediment imbalance, areas lacking vegetation, and the dominance of delta and sediment plain landforms significantly contribute to the area’s vulnerability to these hazards. Moreover, the study recommends the integration of coastal zoning and mangrove conservation efforts to reduce the impact of these risks. Additionally, further research based on primary data and dynamic modeling is crucial to enhance the assessment framework and support more robust coastal management strategies. These future studies will help strengthen the decision-making process for sustainable and effective coastal management in the region.

Conflicts of Interest: The authors declare no conflict of interest.

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