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Assessment of Coastal Vulnerability to Support Mangrove Restoration in the Northern Coast of Indramayu Regency

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ABSTRACT

Indramayu Regency, a low-lying coastal area in West Java, has experienced substantial mangrove deforestation. Climate change, worsened by global warming, which causes rising sea levels, has made coastal ecosystems vulnerable. Mangroves play an important role in preventing ecological imbalance in coastal ecosystems and play a role in securing local livelihoods. Considering the dense population on the Indramayu coast, it is imperative to conduct vulnerability mapping as a decision support for policymakers to implement sustainable coastal management in Indramayu. This study aimed to develop a Coastal Vulnerability Index (CVI) for the Indramayu coastal ecosystem using a geospatial analysis of multiple parameters: geomorphology, shoreline change rates, sea level rise, wave height, coastal slope, and tidal range. The methodology employed a grid-based approach (4×4 km²) along the coastline to identify priority zones for restoring mangroves. This study also included the Mangrove Vulnerability Index (MVI) assessment and combined it with relevant policy documents to provide recommendations for mangrove restoration efforts. The results indicate severe coastal vulnerability, with 37.14% of the area classified as highly vulnerable. In contrast, mangrove ecosystems showed greater resilience, with 77.14% of the grids categorized as having low vulnerability. These findings provide science-based recommendations for policymakers to prioritize resource allocation in mangrove restoration programs.

Introduction

Coastal areas that are sensitive to ecological changes are not immune to developments that affect all sectors of human life [1]. The anthropogenic activities of coastal areas are not the sole pressure factors; the oceanographics of waves, tides, currents, and the processes of sedimentation are additional, which, in the cumulative form, result in shifts in the shoreline area and deteriorating the quality of wetland ecosystems [2]. Among the coastal ecosystems that have been highly prone to such changes are mangroves, which play significant roles, including the prevention of saltwater encroachment, decreasing abrasion effects, and serving as a source of carbon deposits and sequestration that underpins climate change [3]. In addition to their ecological roles, mangroves are socio-economically useful, as they are a strategic ecosystem in sustainable development, especially in contributing to the realization of the Sustainable Development Goals (SDGs) point 14 [4].

Despite the numerous ecological, economic, and social benefits provided by mangroves, these vital ecosystems in Indonesia are increasingly threatened by human activities, particularly deforestation. As much

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as 6% of the country's total forest loss is caused by deforestation and this issue also affects mangroves. The function of the mangroves becomes weaker for supporting the biodiversity and protecting the coastal areas. When mangroves are lost, the carbon stored in the soil will be released into the atmosphere thus it increases the greenhouse gas emissions [5]. In fact, the additional pressure is from the inevitable climate change. It results in sea levels rising and storms that become stronger, more frequent, and salinity and temperature will follow to change. These conditions affect mangroves to become more vulnerable to damage or loss [6].

In Indramayu, a regency located on the northern coast of West Java, it has similar problems occurring where the coastline is quite long, around 114 km, thus it comes with strong potential for the mangrove development. However, many coastal areas are already degraded and it mainly occurs as the land is generally converted into aquaculture, agriculture, and settlements in Southeast Asia [7]. It is reported that the situation was exacerbated due to the coastal morphology and rising sea levels following the effect of climate change [8]. These conditions are sufficient data that shows that mangrove protection and restoration are urgent.

In the field, there have been several mangrove restoration programs been carried out in Indramayu. However, these efforts have not been fully evaluated in terms of the coastal vulnerability, and to examine this, several approaches such as Multi-Criteria Decision Analysis (MCDA), the Coastal Sensitivity Index (CSI), and the Coastal Vulnerability Index (CVI) can be used. The MCDA operates as it is setting priorities based on the selected parameters, but, it requires stakeholder involvement, which is also its challenge, thus the results can be subjective if the weighting process is not conducted carefully [9]. Another method is the Environmental Sensitivity Index, and it is used to map the sensitivity of the coastal areas especially to oil spill risks. It considers the physical and biological factors such as the wave energy, tidal range, slope, substrate, and productivity [10]. In Indonesia, the Coastal Vulnerability Index (CVI) is known to be the most commonly used approach.

The CVI was developed by Gornitz and Seeber [11] primarily used to see the level of vulnerability of coastal areas especially from the sea level rise and the shoreline change. In this study, the researchers used several parameters including geomorphology, shoreline change, slope, wave height, tidal range, and relative sea level rise. There is also the Mangrove Vulnerability Index (MVI), and it is basically an extension of CVI, but it adds the variables of mangrove density. Moreover, it also uses the supporting documents such as the Forest Area Map from the Ministry of Environment and Forestry, the 2021 Mangrove Potential Map, the Indramayu Regency Spatial Plan 2011–2031, and the West Java Spatial Pattern. Those would assist with the completion and process of the analysis. However, different from many previous studies, this method does rank the vulnerability from low to high, but it builds a spatial decision matrix as well which becomes its highlight. This matrix would directly connect each level of the vulnerability with suitable restoration techniques. And in many studies, mangrove vulnerability is only the final result, but in this approach, the CVI is combined with the biophysical aspects to separate areas. Some areas are found to be better for ecological restoration, then the others would need socio-economic approaches such as silvofishery or community-based protection. This kind of approach answers the need for location-specific adaptation strategies often mentioned but has not yet been applied in the Indonesian coastal policy. This method is expected to present more scientific recommendations that would help and improve sustainable mangrove restoration in the Indramayu.

Materials and Methods

Study Area

Indramayu Regency is located on the northern coast of Java Island and encompasses 11 coastal sub-districts. Topographically, the region has elevations ranging from 0 to 100 m above sea level, characteristic of low-lying coastal plains, which renders it highly vulnerable to floods, tidal inundation, flash floods, tornadoes, and coastal erosion [12]. The climate follows the Schmidt-Ferguson Type D classification, with humidity levels of 70–80% and temperatures ranging from 22.9°C to 30.0°C owing to its coastal position [13]. To obtain more comprehensive analysis results, the studied area focused on areas directly adjacent to the sea. The area directly adjacent to the sea was divided into 35 grids measuring 4 km × 4 km (Figure 1).

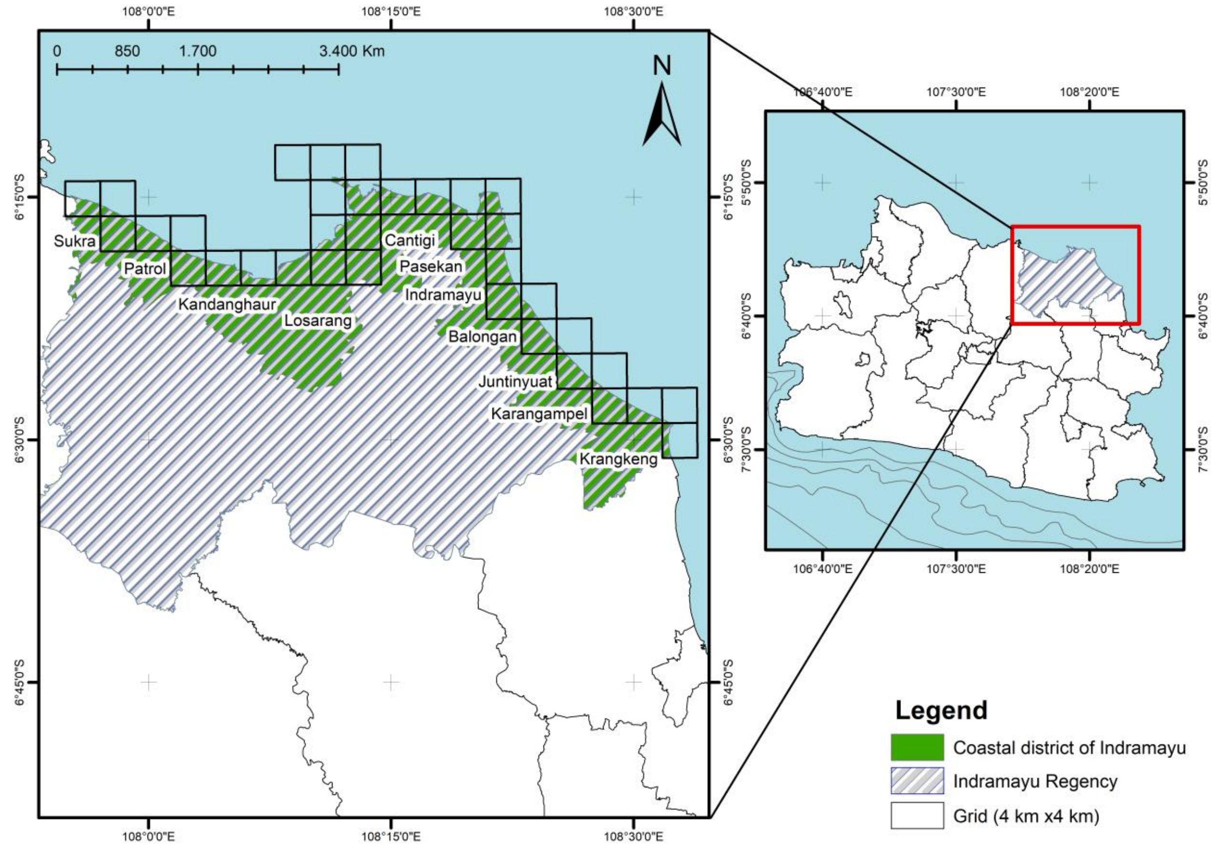

Figure 1. Map of the study area. The map shows the coastal districts of Indramayu Regency (the area in dark green), including Sukra, Patrol, Kandanghaur, Losarang, Cantigi, Pasekan, Indramayu, Balongan, Juntinyuat, Karangampel, and Krangkeng. A 4 km × 4 km grid system (CVI/MVI Grid) is overlaid on the map to represent spatial units for coastal vulnerability assessment.

Data Processing

The analysis of coastal vulnerability and mangrove dynamics in the study area was conducted using a multitemporal geospatial approach. The Coastal Vulnerability Index (CVI) was used to identify the vulnerability level of the coastal area in five classes according to the parameters of coastal geomorphology, change in shoreline, coastal slope, relative sea level rise, average wave height, and tidal level under the vulnerability index mentioned by Bappenas in 2018 [14]. In addition to the CVI, the Mangrove Vulnerability Index (MVI) was calculated, which can be used to assess the resilience of mangrove ecosystems to a spectrum of threats or to relate information to the vulnerability status. The parameters used in the MVI were set to be comparable to those used in the CVI, but with more parameters, including bathymetry and mangrove density. These data were resampled and placed into 4 km × 4 km grids, which were then assigned vulnerability rankings. Shoreline extraction, grid generation, and CVI and MVI analyses were performed using ArcGIS software. In 2021, 35 grids were examined to determine the degree of risk for each grid based on its respective variables. The individual variable scores within each grid were summed to obtain the total CVI and MVI scores for the study site.

Landsat 5 TM, Landsat 7 ETM, and Landsat 8 OLI/TIRS Top-of-Atmosphere (TOA) images were used in analysing land cover change, with the help of Google Earth Engine. The Google Earth Engine is a cloud-enabled platform that provides easy access to high-performance computing facilities for massive-scale calculations [15]. The classification used supervised techniques to classify five land-cover classes: mangrove, aquaculture, water bodies, built-up areas, and non-mangrove land. This evaluation was conducted between 1991 and 2001, 2001 and 2011, and 2011 and 2021.

The shoreline change in this study was taken from the Landsat images, with same data source, using the coastline records from 1991 until 2021, and the analysis used the DSAS tool in ArcGIS. First, the shoreline was digitized, then the system calculated the rate of change over time with a baseline measurement approach.

Then, transects were made every 5 m along the coast. After that, the End-Point Rate (EPR) method was applied to get shoreline change values (m/yr). Positive values mean accretion, negative values show erosion both from natural processes. For the geomorphology, the data came from the Geospatial Information Agency Geoportal (https://inaland.big.go.id/map) and it was grouped based on the vulnerability level. The coastal area in each study site was divided into grid sections approximately 4 km along the shoreline, and these delta areas were found to be quite dynamic with marine ecosystems, alluvial plains, and water bodies.

The coastal slope data was taken from DEMNAS and also from the Geospatial Information Agency Geoportal (https://tanahair.indonesia.go.id/portal-web/unduh/demnas), with 0.27" resolution. Then the slope calculation used spatial analyst tools in ArcGIS and they were classified into five classes using the natural breaks method. The wave data, especially significant wave height from 1991–2021 was obtained from the ECMWF Interim (ERA5). The data was processed in Ocean Data View, then interpolated using IDW in ArcGIS, then the tidal range was calculated using the MIKE 21 model, based on coordinates around the north coast of Indramayu. MIKE 21 is a software for numerical modeling of waves including regular and irregular wave conditions in coastal areas such as in sand mining zones [16]. The formula used was TR = HHW - LLW, and for the sea level rise rate it was calculated from multi-satellite altimetry data (TOPEX/Poseidon/Jason/Envisat) from 1993 to 2021. In fact, changes in sea level would affect coastal morphology and would eventually increase coastal damage thus this results in the decision that areas with high rates of sea-level change are classified as highly vulnerable.

Regarding the bathymetry data in this study, it was taken from the Geospatial Information Agency Geoportal (https://tanahair.indonesia.go.id/portal-web/unduh/) with 6" resolution, then it was resampled into 4 km scale. The assumption used was quite simple with nearshore areas with gentle slopes considered more vulnerable, and the areas farther from the coast with steeper slopes are classified as less vulnerable. As for the ranking, the shallow coastal waters were given rank 5, and the deeper waters were given rank 1. Then, the mangrove density was calculated from land cover data in 2021 with grid size of 4 km × 4 km, and for the analysis the researchers used zonal statistics and raster calculator in ArcGIS to get the percentage of mangrove cover in each grid. The grids with higher mangrove density were given higher vulnerability rank (rank 5) since the potential loss was also higher compared to the areas without mangroves. The use of 4 km × 4 km grid was a compromise, since it had to keep the spatial detail and the analysis had to remain manageable. Although this decision also affected the results, that the larger grid size can smooth small variations in geomorphology, shoreline change, and mangrove distribution, thus it would not be completely clear to observe several of the local vulnerability hotspots. The materials used in this study are listed in Table 1.

Table 1. Materials used in this research. This table presents nine variables (geomorphology, coastal slope, mean tidal range, significant wave height, shoreline change and land cover change, sea level rise, bathymetric, and mangrove density) along with their respective data sources, spatial resolution, and temporal coverage.

Variable	Data	Source of Data	Resolution	Period
Geomorphology	Land System BIG	Geospatial Information Agency Geoportal (https://inaland.big.go.id/)	1:50.000	
Coastal Slope	GDEM	National Digital Elevation Model for Coastal Applications (http://tanahair.indonesia.go.id)	8 m	2021
Mean tidal range	Mean Sea Level	Model prediction using MIKE 21		1991–2021
Significant wace height	Sea Surface wave	Climate Copernicus (https://cds.climate.copernicus.eu /datasets)		1991–2021
Shoreline change and land cover change	Landsat 5, Landsat 7 ETM, Landsat 8 OLI	*Google Earth Engine*		1991–2021
Sea Level Rise	*Mean Sea Level Product*	Climate Copernicus (https://cds.climate.copernicus.eu /datasets)	0.25° × 0.25°	1993–2021
Bathymetric	BATNAS	Geospatial Information Agency Geoportal (http://tanahair.indonesia.go.id)	6"	2021
Mangrove density	Land cover change data for 2021	*Google Earth Engine*		2021

Data Analysis

The coastal vulnerability index (CVI) was calculated using a semi-quantitative approach incorporating six parameters: geomorphology, shoreline change, coastal slope, rates of sea-level rise, significant wave height, and mean tidal range, following established methodologies. Subsequently, the mangrove vulnerability index (MVI) was derived by integrating additional parameters, namely bathymetry and mangrove density [17,18]. The analytical procedure involved parameter ranking, in which each variable was classified into five vulnerability categories (very low to very high) based on the Bappenas classification system [14]. Subsequently, the parameters were calculated using the following formula (Equation 1 and 2).

$$CVI = \sqrt{\frac{a.b.c.d.e.f}{6}} \quad (1)$$

$$MVI = \sqrt{\frac{a.b.c.d.e.f.g.h}{8}} \quad (2)$$

The variables are defined as follows: a = geomorphology, b = rate of shoreline change, c = rate of sea level rise, d = significant wave height, e = coastal slope, f = bathymetry, g = mean tidal range, and h = mangrove density.

Upon all variables in each grid were given ranks, the CVI and MVI values were calculated then they were compared along all the coastal areas in the study. The ranking system and calculation details are shown below in Table 2. Then, the restoration priority was decided by using the overlay analysis between vulnerability index results and several official maps, such as the 2021 forest area map, 2021 habitat potential map, as well as the Indramayu spatial plan (RTRW) 2011–2031.

Table 2. Vulnerability rank of the variable. This table presents vulnerability ranking criteria for nine physical and environmental variables (geomorphology, shoreline ero. sion/accretion, coastal slope, sea level rise rate, significant wave height, mean tidal range, bathymetry, mangrove density, CVI, and MVI), each classified into five categories from "Very low" to "Very high".

Variable	Vulnerability ranking					Units
	Very low	Low	Moderate	High	Very high	
Geomorphology	Volcanic rocks and intrusive formations; slope gradient >5%	Volcanic rocks and intrusive formations; slope gradient 3–5%	Sedimentary rocks; slope gradient 2–3%	Uncon-solidated sediments; slope gradient 1–2%	Uncon-solidated sediments; slope gradient <1%	Qualitative
Shoreline erosion/accretion	>2.00	1–2	-1–(1)	-1.1–(-2)	>-2	m/year
Coastal slope	>5.00	3.00–5.00	2.00–3.00	1.00–2.00	<1.00	%
The rate of sea level rise	<0.73	0.73–0.74	0.74–0.75	0.75–0.76	>0.76	mm/year
Significant wave height	<0.75	0.75–1.00	1.00–1.25	1.25–1.50	>1.25	m
Mean tidal range	<1.00	1.00–1.50	1.50–2.00	2.00–4.00	>4.00	m
Bathymethry	<-15.70	-9.53–(-15.69)	-5.89–(-9.52)	-5.88–(-2.95)	>-2.94	m
Mangrove Density	0.0–9.17	9.18–28.27	28.28–48.14	48.15–71.45	71.46–97.44	
CVI	<2.5	2.5–3.0	3.0–3.5	3.5–4.2	>4.2	
MVI	<20	20–40	40–60	60–80	>80	

In this study, all parameters in the CVI and MVI were given equal weight, and this is considered a common way in coastal vulnerability studies, although there remains further explanation. The formula used the geometric mean, thus it took the square root from the multiplication of all the ranked variables, then they were divided by the number of parameters, thus the variables were treated as having the same contribution to vulnerability. This was selected as there was no strong data or theory that supports different weighting for the Indramayu coastline specifically. For the vulnerability classification, this study used the fixed thresholds from Bappenas, and it was not relative percentile, thus the results could be easier to read and compare. It has been known generally that if relative thresholds are used, it could create any misleading results, as it would for example show very high or very low vulnerability even if the real condition is not extreme. In addition to that, a sensitivity analysis could be considered to be added in order to check whether the equal weighting is stable thus the results could represent the real coastal conditions and risks, not entirely perfect but with better performance and results.

Results

Mangrove Area Changes from 1991 to 2021

The analysis conducted used Landsat 5 (1991), Landsat 7 (2001 and 2011), and Landsat 8 (2021) and referring to the data, the mangroves in Indramayu are found in 5 out of 11 coastal districts only in total. The changes captured over time are shown in Table 3. In 1991, the mangrove area was captured to be 1,443.74 ha, then the data shows that it dropped quite sharply to 833.07 ha in 2001. As can be seen, the biggest decrease is in Cantigi District, the numbers decreased significantly from 1,116.13 to 674.61 ha, and similar pattern is observed in Pasekan District as the numbers also decreased, from 139.21 to 42.63 ha. This decline is massive and tends to be caused by land conversion with data reporting the causes from activities of aquaculture and agriculture, as well as housing expansions [19]. The practice has been ongoing and keeps at it since the 1980s and the numbers are the evidence that it has had long-term impacts on the loss of mangrove cover in areas with high accessibility [20].

The trend shifted to recovery in the later period (2011–2021), with an increase in total mangrove cover of 167.03 ha (844.24 to 1,521.27 ha). The most intense recovery occurred in the Pasekan District, which increased from 79.71 ha in 2011 to 286.37 ha in 2021. The same has been observed in the Cantigi District, which had an increase in mangrove coverage from 706.78 ha to 1,065.21 ha. The trend indicates the success of some mangrove restoration and rehabilitation programs that have been launched in the middle of 2010, such as the appointment of Indramayu Regency as a western region mangrove development center by the Ministry of Environment and Forestry in 2015.

Table 3. Mangrove area on the northern coast of Indramayu. This table shows mangrove area changes (in hectares) from 1991 to 2021 across five coastal districts: Kandanghaur, Losarang, Cantigi, Pasekan, and Indramayu.

District	Mangrove area (ha)			
	1991	2001	2011	2021
Kandanghaur	7.29	1.73	2.21	1.13
Losarang	172.89	113.46	114.42	161.13
Cantigi	1,116.13	674.61	706.78	1,065.21
Pasekan	139.21	42.63	19.71	286.37
Indramayu	8.22	0.64	1.11	7.43
Total	1,443.74	833.07	844.24	1,521.27

Results of the CVI Parameters

The results of the analysis using the Coastal Vulnerability Index (CVI) are shown in Figure 3. The CVI calculations revealed the following distribution of vulnerability: 2.86% (1 grid) was categorized as very low vulnerability, 25.71% (9 grids) as low vulnerability, 2.86% (1 grid) as moderate vulnerability, 31.43% (11 grids) as high vulnerability, and 37.41% (13 grids) as very high vulnerability. The areas with very high vulnerability were in observation zone F3, located in the Pasekan District. This high vulnerability value was influenced by shoreline changes and a relatively steeper coastal slope than that of other observation zones. Conversely, observation zone K4, located in the Krangkeng District, had the lowest vulnerability value.

According to the analysis of geomorphological parameters, 48.57% or 17 grids fall under the very high vulnerability group due to the presence of a coastal land system feature in Indramayu, which directly opens to the open sea and features marine culture and alluvial land. The marine culture land system is principally used for activities such as fish farming, and it is very susceptible to floods because it lies close to water bodies.

The coastal areas of Indramayu Regency have slopes ranging from 1.55 to 7.30 percent. These findings align with data published by the National Disaster Mitigation Agency in 2021, which noted that the northern West Java coast is dominated by flat land with slope gradients of 0% to 5%. According to the data processing results, the primary coastal slope parameter corresponds to a low level of vulnerability, comprising 34.29% of the grids, or 12 grids out of 35 grids.

Rising sea levels due to global climate change can potentially expand the vulnerable coastal areas. According to data from CU SLR Colorado, the rate of sea-level rise in Indramayu Regency is 3.96 mm/year, which categorizes all the study locations as having very high vulnerability to this parameter. Additionally, rising sea levels exacerbate coastal erosion [21]. In fact, it is the local ecosystems that are at risk as the increase continues, and apparently it does not stop there yet as the infrastructure and livelihoods could highly face the risks as well. These conditions strengthen the need for mitigation for coastal communities that are in real threat of these pressures.

In Indramayu waters, waves are not as considered, and the pattern mostly follows the local wind conditions [22]. It can be seen as when examining the 30-year data, and it is revealed that the average wave height is noted to be only around 0.23 m. Therefore, all of the locations fall into very low vulnerability for the wave parameter, and this results in insignificant damage caused by waves in this area.

A different parameter, tides, also shows a similar pattern as observed using MIKE 21 prediction, the tidal range is about 0.17 m along the coast and with this small value, every coastal zone is placed in the very low vulnerability class. The influence of tides on coastal processes or flooding is limited even though in general tides are typically regarded as crucial in coastal systems. However, their impact was found minor in this context, thus the results show that they do not strongly affect the coastal stability in Indramayu.

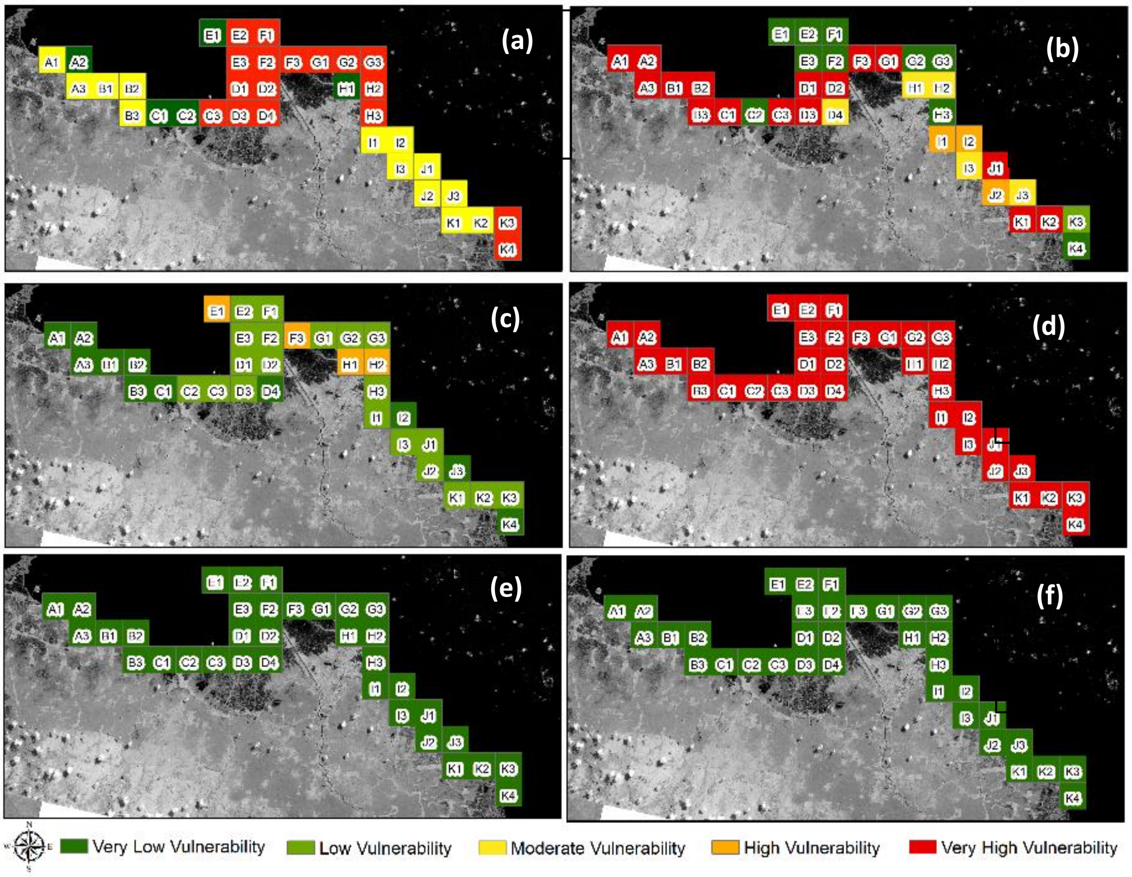

Figure 2. Parameters of CVI (a) Geomorphology (b) Shoreline erosion/accretion (c) Coastal slope (d) The rate of sea Level Rise (e) Significant Wave Height (f) Mean tidal range.

Coastal Vulnerability Index (CVI)

Figure 3 presents the CVI results and as can be seen, the pattern is uneven across grids with only 2.86% (1 grid) is very low, while as much as 25.71% (9 grids) fall into low class. Moderate is also found to be small, with a total only 2.86% (1 grid). The higher categories are more dominant with 31.43% (11 grids) in high and 37.41% (13 grids) in very high vulnerability. The most critical area is zone F3 in Pasekan District. It can also be observed here that the shoreline change and steeper coastal slope increase the vulnerability, but in contrast, zone K4 in Krangkeng District shows the lowest level compared to all of the observed areas.

In the field it has been reported that CVI is widely applied in Indonesia to indicate coastal risk as well as to support the management priority decisions. Local planners as well as many previous studies are reported to adopt this method since the method is regarded as relatively simple and practical to implement. One major aspect is that the CVI can be integrated easily with GIS and remote sensing and through these tools, CVI would be able to generate the shoreline vulnerability maps for large coastal regions. These advantages and strengths are beneficial for the process of ecosystem planning and restoration when it is combined with ecosystem-related variables.

However, the CVI remains with several limitations as several important aspects might not be included, and the results could vary, based on the variable selection and weighting, as well as the data quality and spatial scale. In many applications, it is often observed that CVI methods emphasize the examination on physical and hydrodynamic parameters, with socio-economic vulnerability being excluded unless it is added separately. As a result of that, the overall risk assessment might become less comprehensive and different CVI formulations could produce different mapping outputs. Therefore, to avoid these unwanted conditions, there must be careful interpretation conducted before the results are applied for policy decisions. Then it can be drawn that when using unweighted CVI, there would be a possibility of overestimating or underestimating certain areas.

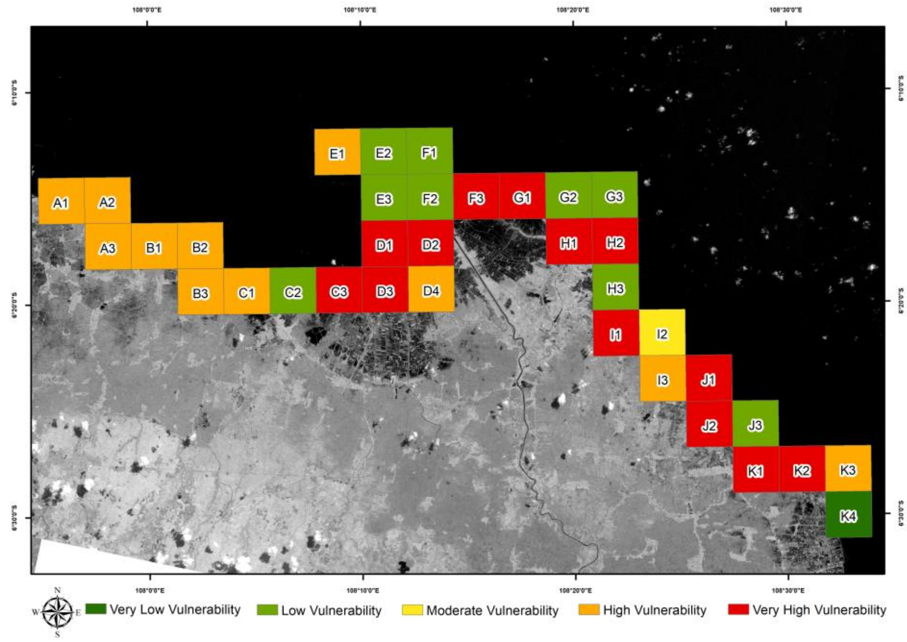

Figure 3. CVI analysis results. This figure presents CVI vulnerability ranking, each classified into five ranking from "Very low vulnerability" to "Very high vulnerability".

Relationship Between Mangrove and Coastal Vulnerability

The occurrence of mangrove degradation in Indramayu gives an indirect effect on the coastal vulnerability with specific link to climate change since if the mangrove cover decreases, the coastal areas would eventually become more exposed to environmental hazards. Referring to study findings, it indicates that mangrove loss would intensify the impacts of tidal flooding and saltwater intrusion [23] and referring to the overlay between CVI results and mangrove cover earlier, the areas with degraded mangroves tend to show higher vulnerability values. In fact this condition has been observed in Kandanghaur and Losarang Districts, and when mangroves are not as natural buffers, the impacts of tidal flooding, saltwater intrusion, coastal erosion, all those would become more severe. It is reported as well that the resilience of the ecosystem to sea-level rise is observed to decline [24].

The MVI was applied to support the decision-making in determining the priority areas for rehabilitation. The index would evaluate the capacity of mangrove ecosystems to withstand different threats but is also able to indicate their vulnerability level [17,18]. The parameters used are similar to the CVI, but in this method, it was applied with additional variables of bathymetry and mangrove density. Upon the results were gathered, a total of 27 grids are classified in the low vulnerability, while as many as 8 grids fall into the moderate category. This result is found to be contrasted with the CVI findings since most of the areas are categorized as very high vulnerability in the approach. According to these results it can be drawn that although several areas appear less vulnerable in the MVI assessment, the total coastal regions remain with considerable risks because the mangrove degradation is at place.

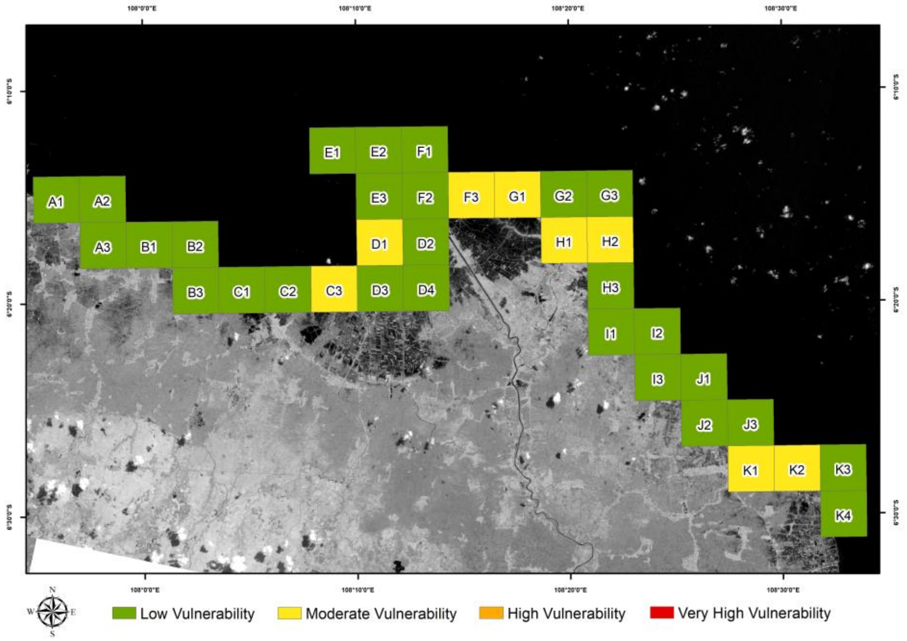

Figure 4. MVI analysis results. This figure presents MVI vulnerability ranking, each classified into five ranking from "Low Vulnerability" to "Very High Vulnerability".

Restoration Strategies

The analysis of the restoration priority directions was conducted as the researchers integrated the results from the coastal vulnerability assessments by using the Coastal Vulnerability Index (CVI), the Mangrove Vulnerability Index (MVI), and other supporting documents needed in which they are included historical mangrove data, the Indramayu Spatial Plan (RTRW) 2011–2031, the Ministry of Environment and Forestry's Forest Area Map for 2021, the 2021 Mangrove Potential Distribution Map, and the West Java Spatial Plan (RTRP) 2022–2042. This approach has the aim to provide a scientific basis for the precise determination of mangrove planting locations, and it would also ensure that the policies implemented are measurable and sustainable. Referring to the data integration, the strategic recommendations were grouped into three priority categories as shown in Table 4 below, as well as presented in Figure 5 in clear visuals.

Table 4. Recommendation of strategies based on priority location. This table outlines three restoration priority levels (Priority I, II, and III), each linked to specific zone codes, a restoration target, and recommended approaches. These strategies are designed to provide a scientific basis for precisely determining where mangrove planting should occur.

Strategy	Zone	Restoration Target	Approach
Priority I	C3, D1, D2, D3 F3, G1, H1, H2	Protection of vulnerable areas	Ecosystem-based mangrove rehabilitation through replanting native mangrove species and restoring natural hydrology Application of hybrid engineering to enhance mangrove resilience to oceanographic stressors Strengthening protected area functions through regional regulations
Priority II	A1, A2, A3, B1, B2, B3, C1, C2, E2, E3, F1, F2, G2, G3, H3, I1, I2, I3, J1, J2 K1, K2, K3	Halt degradation, promote natural recovery	Community-based restoration Cross-sectoral planning
Priority III	E1, J3, K4	Maintain ecosystem resilience	Sapawarga app for damage reporting Educating local communities on the importance of mangroves Coastal vegetation (e.g., Casuarina and Pandanus) for erosion control.

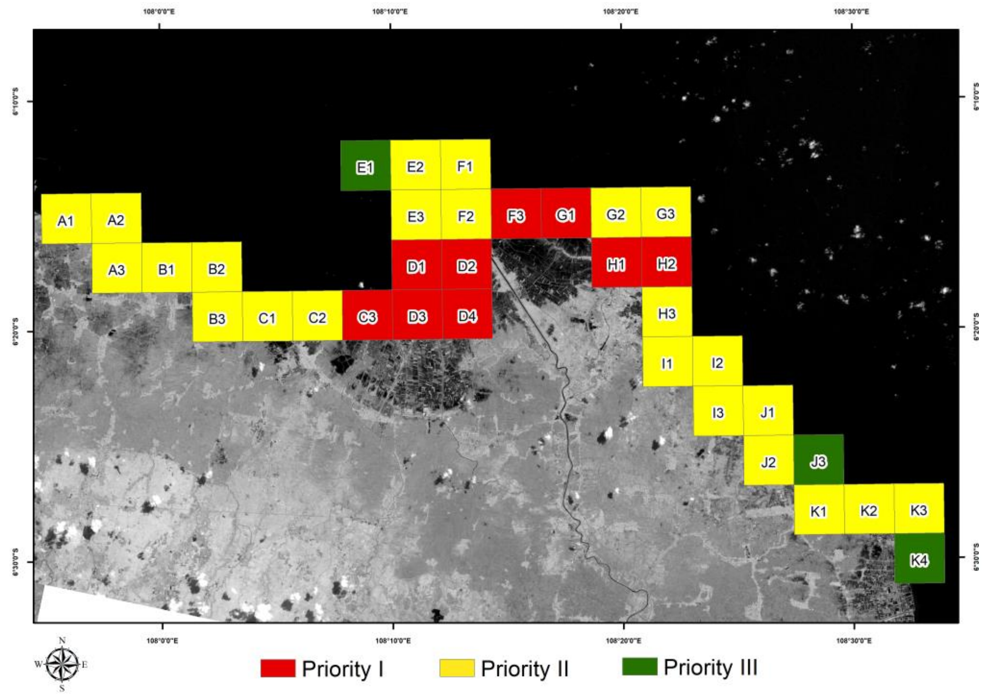

Figure 5. Priority locations for restoration. This map displays a grid system (cells labeled A1 through K4) over the coastal area with three restoration priority levels: Priority I, Priority II, and Priority III.

Discussion

The findings observed in Indramayu show that the mangrove change and coastal vulnerability are not simple as there is an interaction between several elements: the human activities, ecosystem condition, and the restoration efforts. Noted from 1991 to 2001, the mangrove area dropped significantly in number by 42.3%. In actuality, it is recorded that the pattern is similar to what happened in Southeast Asia where aquaculture contributed quite significantly with around 30–50% of mangrove loss during that period [25]. In Cantigi District, the loss reached 40.5%, and this number shows the sensitivity of the delta areas to land conversion. This data is in line with and supports Alongi's idea about the fragility of deltaic mangrove systems, but after 2011, the trend actually went through changes then shifted. The mangrove area increased by about 80.2% and this recovery is strongly related to restoration programs in Indonesia, one of which is the National Mangrove Rehabilitation Program in 2012 focusing on community involvement. Similar results are also found in other regions as the community-based restoration has been reported to give better ecological results. Positively, it is also found to also increase the local participation although not all areas automatically show improvement. In Kandanghaur District, the mangrove loss is observed to continue. The data results suggest problems in terms of governance, that is, in managing the protected areas, resulting in the need of more local-based strategies [20]. Aside from focusing on the ecological aspects, the restoration should also consider the social and political conditions.

In terms of the coastal vulnerability, the results also show mixed conditions, as observed in the CVI that approximately 37.14% of the grids fall into very high vulnerability. One main reason is the sea-level rise that reaches 3.96 mm/yr, and this number is in fact higher than the Java Sea (3.3 mm/yr), and it is also above the global average [16]. This pattern is in line with climate models that show higher pressure in delta coastal areas [18] but even so, there is a difference between the MVI and CVI results. The MVI results show 77.14% in low vulnerability, and the CVI shows many of the areas fall within the high categories. This difference indicates that the mangroves still have some adaptive capacity, but they also have limits because once the mangrove cover drops significantly, the resilience would also decrease sharply, as explained by Mondal et al. [17]. For the restoration in coastal ecosystems, it needs to be done in a more integrated way if the goal is to reduce further damage [23] because if it is not carried out, the degradation will continue. Restoration itself can be regarded as one crucial effort among the other ones as this step has the aim to recover and more importantly to protect the coastal ecosystems that support marine biodiversity. In simple terms, restoration is supporting the damaged ecosystems to recover [24], and this process usually would be successful if the disturbances are reduced or removed.

This study proposes a three-level restoration framework combines biophysical, socio-ecological, and climate adaptation aspects, using evidence-based approaches. For the Priority I areas of zone F3, the selection is based on ecological suitability. For example, the tidal inundation between 0.17–0.76 m, which supports the mangrove growth [25], and slope around 1.55–7.3% that helps vegetation development [26]. Then in the Priority II areas, the focus was shifted to more about community-based approach, with the major aim to address any land conversion issues. In the field, it found that similar strategy has been applied in the Mekong Delta, Vietnam, and it is evident to have improved restoration success by around 35% [27]. As for the areas with strong erosion, actually it requires different approach in terms of the ecological as well as the engineering solutions. Several methods that have been proven to reduce wave energy by around 40–60% are known to be the hybrid methods which combine physical structures and biological elements as shown by Setyawan and Pamungkas [22] in similar coastal conditions.

These results are drawn and come to give some policy implications. First, spatial prioritization is important. Efficiency is in fact able to be improved by matching the restoration with the geomorphic units, for example focusing on alluvial plains instead of volcanic slopes, and the efficiency would increase by around 20–40% [28]. Second, the monitoring systems need to be improved as well, that can be done by integrating tools like Sapawarga to provide near real-time data. According to Murdiyarso et al. [5], this would likely reduce the response time to environmental damage by up to 60%. Third, the incentive systems. The payment for ecosystem services has shown good results, such as observed in the increasing mangrove cover by 22% in Demak, and more importantly the ability to maintain and even support local livelihoods [28].

There are still some gaps for future research as the use of 4 km grid is useful for regional analysis, but in fact, it is smaller scale (100–500 m) that would give better detail when faced with complex delta areas. Future studies can also include sediment parameters such as any organic content and redox potential to improve the habitat suitability models. In addition, it might be beneficial to calculate the blue carbon potential in order to support climate funding. These points are also highlighted in the IPCC Special Report on Oceans and Cryosphere [29]. The framework from this study can be used again in other areas, but the practical coastal adaptation planning can stay supported.

Referring to the discussion, it can be drawn that coastal restoration cannot use one general approach and it even needs to follow, taking into account the level of damage and using evidence-based strategies [30]. Certain ecosystems need more attention than others, and among the coastal ecosystems such as coral reefs, seagrass, estuaries, etc, mangroves in fact have been evident to have a strong position and positive effect. Supported by many studies, mangroves have been reported to efficiently act as natural protection against the storm surge and sea-level rise, and more importantly reduce the saltwater intrusion [29]. Interestingly, the case in Indramayu shows mixed conditions, as challenges are certainly present, but the opportunities for restoration are also visible to be acted upon. The findings also show that both climate change and human pressure have quite equal impacts, thus it needs better management, with scientific basis and community involvement. This kind of approach is required if the goal is to seriously maintain coastal resilience.

Conclusions

Upon conducting the analysis in the Indramayu context, the main issue was able to be clearly seen that it was the human activities regarding land conversion for aquaculture, agriculture, and settlements that are found to be the main cause of the mangrove loss. Those activities in fact contributed a huge number in reducing the natural protection of coastal ecosystems, and it resulted in making them more vulnerable to climate change in sea-level rise. The CVI and MVI methods were to identify the high-risk areas in a spatial way, and the results showed that more than 37% of the grids fall into high vulnerability in the areas with low slope and active shoreline change. These results can be regarded as sufficient data for targeted actions. The results also showed that although some of the areas were found with lower vulnerability, but the overall ecosystem resilience was still decreasing since the degradation continued, thus any integrated and ecosystem-based management might need to be started to be considered. In terms of the restoration planning, it can follow a three-level priority system based on the CVI and MVI results with the focus put to be protecting the vulnerable areas and stopping further damage. One more important point is on maintaining the ecosystem resilience. This approach is in line with coastal management and climate adaptation practices and in order to make the restoration more effective, several factors must be taken into account: the community participation, hybrid engineering methods, and most importantly, the fair and supportive government policy. To conclude this study, it must be noted that this study has several limitations since the remote sensing data might have resolution bias. Other points are visible in the vulnerability index that was relatively static with inability to fully capture the environmental changes over time, and the time range of the data that was limited resulting in the risk prediction. Future researchers conducting similar studies and topics are then advised to apply adaptive approaches with continuous monitoring and stakeholder engagement, thus the future coastal resilience strategies can be achieved

Author Contributions

NFZ: Writing - Original Draft, Visualization, Validation, Formal Analysis, Data Curation, Conceptualization; **YSW**: Writing - Review & Editing, Conceptualization, Supervision; **SBA**: Writing - Review & Editing, Supervision.

AI Writing Statement

During the preparation of this work, the authors used DeepSeek to help expand and refine their thinking, explore alternative perspectives, and enhance the clarity of expression. After using this tool, the authors carefully reviewed and edited the content as necessary and assume full responsibility for the content of the publication.

Conflicts of Interest

There are no conflicts to declare.

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