Omni-Akuatika, 21 (1): 34 - 51, 2025
ISSN: 1858-3873 print / 2476-9347 online

Research Article

journal homepage: http://ojs.omniakuatika.net

Exploring Coastal Green Infrastructure (CGI): A Promising Approach To Mitigating Climate Change-Related Disasters In West Java's Southern Coast, Indonesia

Muhammad Raka El Ghifari[1], Andhy Romdani[1,*], Fahmi Rahmat Amanulloh[1], Empung[1], Tryantini Sundi Putri[2], Mudatsir[3]

[1]*Department of Civil Engineering, Faculty of Engineering, Siliwangi University, Tasikmalaya, Indonesia*
[2]*Department of Civil Engineering, Faculty of Engineering, Halu Oleo University, Kendari, Indonesia*
[3]*Department of Medical, Faculty of Medical and Health, Muhammadiyah University of Jakarta, Indonesia*

**Corresponding author: andhyromdani@unsil.ac.id*

Received 18 October 2024; Revised 8 August 2025, Accepted 9 November 2025; Available online 5 December 2025, Published 5 December 2025

ABSTRACT

Coastal Green Infrastructure (CGI) is increasingly recognized as a nature-based solution to address climate-related challenges such as sea-level rise, coastal erosion, and flooding. However, there remains a lack of standardized and the implementation of CGI resolves the limitation of globally adaptable methods for identifying selecting optimal CGI implementation sites, particularly in tropical coastal regions with diverse environmental characteristics. This study aimed to develop an alternative assessment approach by constructing in assessing CGI potential, focusing on the CGI Coastal Protection Index and CGI Coastal Vulnerability Indices, specifically tailored to tropical coasts. The method incorporated ecological and physical indicators derived Index, with a specific emphasis on tropical coast. Using a comprehensive case study from remote sensing and the southern coast of West Java, the research combines literature review, spatial analysis and was applied to the southern coastal region of West Java, Indonesia, and decision-making frameworks to identify key indicators in developing these indexes. The findings reveal that this region is highly vulnerable to climate-induced coastal hazards, with insufficient existing protection and relatively low CGI implementation potential. By proposing a practical and location-sensitive assessment framework, this study fills a methodological gap in CGI research and offers. This study advances the nature-based coastal protection researches by providing a practical evaluation method of the CGI potential, addressing the existing research gap in tropical environments, and offering valuable insights for advancing coastal management strategies in tropical settings.

Keywords: Coastal Green Infrastructure (CGI), climate change, coastal protection, coastal vulnerability, southern coast of West Java

ABSTRAK

Coastal Green Infrastructure (CGI) semakin diakui sebagai solusi berbasis alam untuk menghadapi tantangan perubahan iklim, termasuk kenaikan muka air laut, erosi pantai, dan banjir pesisir. Namun, hingga kini belum tersedia metode baku yang dapat diterapkan secara global untuk mengidentifikasi dan memilih lokasi optimal bagi penerapan CGI, terutama pada wilayah pesisir tropis yang memiliki karakteristik lingkungan beragam. Penelitian ini bertujuan mengembangkan pendekatan penilaian alternatif melalui konstruksi Indeks Perlindungan Pesisir CGI dan Indeks Kerentanan Pesisir CGI yang dirancang khusus untuk pesisir tropis. Metode ini mengintegrasikan indikator ekologi dan fisik yang diturunkan dari data penginderaan jauh, tinjauan literatur, analisis spasial, serta kerangka pengambilan keputusan, dan diterapkan pada wilayah pesisir selatan Jawa Barat, Indonesia. Hasil penelitian menunjukkan bahwa kawasan ini memiliki tingkat kerentanan tinggi terhadap bahaya pesisir yang dipicu oleh perubahan iklim, dengan perlindungan eksisting yang belum memadai dan potensi implementasi CGI yang relatif rendah. Dengan mengusulkan kerangka penilaian yang praktis dan sensitif terhadap karakter lokasi, penelitian ini mengisi kekosongan metodologis dalam studi CGI. Temuan ini sekaligus memberikan kontribusi terhadap pengembangan upaya perlindungan pesisir berbasis alam di lingkungan tropis melalui metode evaluasi yang aplikatif dan relevan untuk mendukung strategi pengelolaan pesisir.

Kata kunci: *Coastal Green Infrastructure* (CGI), perubahan iklim, perlindungan pesisir, kerentanan pesisir, pesisir selatan Jawa Barat

http://dx.doi.org/10.20884/1.oa.2025.21.1.1207

1. Introduction

Global concern for climate change is growing rapidly, as evidenced by significant projections of SLR in the future sea level rise (SLR) (Mimura, 2013). According to the report of the IPCC (2014), the global mean sea level (GMSL) is expected to rise between 0.26 and 0.82 meters by 2100 for the RCP8.5 scenario. SLR is a significant hazard to coastal ecosystems due to saltwater intrusion, coastal flooding, alterations in sediment regimes, coastal erosion, and expanded inland impacts by tropical storm surges (Vitousek et al. 2017). These hazards may induce the migration of coastal communities owing to permanent damage to irrigated agriculture, freshwater supplies, property, and infrastructure. (Alexander et al. 2019). Consequently, socioeconomic losses have increased over the past century owing to the expanding areas of SLR impacts (Hadipour et al. 2020).

Indonesia, an archipelago consisting of 17,001 islands with an area of 1.892.410,09 km2 (Badan Pusat Statistik, 2023), is at risk for climate change disasters. Without adequate adaptation measures, over 4.2 million people living in coastal areas are facing the risk of permanent flooding by 2070−2100 (Asia Development Bank, 2021). For instance, the southern coast of Java Island experienced an average SLR of 1.4 mm/year from 1995 to 2014 (Uswatun et al. 2015). West Java Province's Southern Coastal Area, as a densely populated area and among the most popular tourism attractions in Indonesia, is now at risk of SLR. Therefore, mapping biophysical vulnerability and developing an appropriate coastal management strategy are crucial for tackling these challenges.

Coastal Green Infrastructure (CGI) is widely regarded as an environmentally friendly approach to mitigate the effects of climate change disasters. According to Conger and Chang (2019), the CGI is defined as a nature-based system that reproduces dynamic coastal topography, vegetation, and shoals. Typical CGI types encompass dynamic coastal landforms, such as sand, gravel, rocky beaches, barrier islands, and dunes (Ruckelshaus et al., 2016). The potential role of CGI protection benefits includes sediment capture, wave attenuation, and changes in coastal resilience as response mechanisms. Therefore, disruption of CGI response mechanisms can contribute to increased biophysical vulnerability (Feagin et al., 2015). Additionally, rapid increases in SLR and changes in local water levels resulting from anthropogenic activities that modify the coastal profile could intensify the CGI vulnerability (Duarte et al., 2013).

Conger and Chang (2019b) proposed an indicator-based approach to identify CGI potential in coastal areas. Their study identified relevant indicators from various sources to measure both CGI's coastal protection benefits and vulnerabilities of the CGI. These indicators were then organized into the CGI Coastal Protection Index and the CGI Coastal Vulnerability Index. The CGI Coastal Protection Index considers indicators that provide protection, such as the CGI, elevation, and geomorphology. Conversely, the CGI Coastal Vulnerability Index focuses on the biophysical and social vulnerability of the coast. Conger and Chang (2019b) adapted the Coastal Vulnerability Index (CVI) method developed by Gornitz and Kanciruk (1989). The overall CVI is calculated by combining indicator data using a hierarchical ranking methodology. Each indicator is assigned a rank within a 1-5 scale, with 5 indicating the most favorable rating. Although the CVI method has been used in environmental vulnerability studies, Conger and Chang (2019b) were the first to apply it to CGI coastal protection assessments.

Using a case study from the southern coastal region of West Java, this study aims to identify indicators for measuring CGI potential in tropical regions and organize them into indices, such as CGI coastal protection benefits and vulnerabilities. Additionally, the study sought to identify specific differences in CGI potential assessments for coastal areas and make necessary adjustments to fit the existing conditions of the study location. This new assessment approach will be applied to evaluate the CGI potential in the southern coastal region of West Java, resulting in a CGI Potential map. This study also suggests the most suitable CGI implementation for coastal areas. The findings may provide insights into CGI implementation in Indonesia and serve as basic information for policymakers to develop appropriate coastal management and disaster risk mitigation strategies.

2. Materials and methods

This research applies experimental methods and was carried out in Randusanga Wetan Village, Brebes Regency, Central Java from December 2022 to February 2023.

2.1. Study Area

This study focused on assessing the potential impact of climate change-related disasters on coastal vulnerability along the southern coastal areas of West Java Province, Indonesia. The study area encompasses the entirety of West Java Province's southern coastal areas, which are geographically located between 6°58'44.0"S−7°40'18.3"S and 106°23'50.0"E−108°48'02.2"E (see **Figure 1**), spanning approximately 379.35 km and administratively consisting of five regencies: Sukabumi, Cianjur, Garut, Tasikmalaya, and Pangandaran.

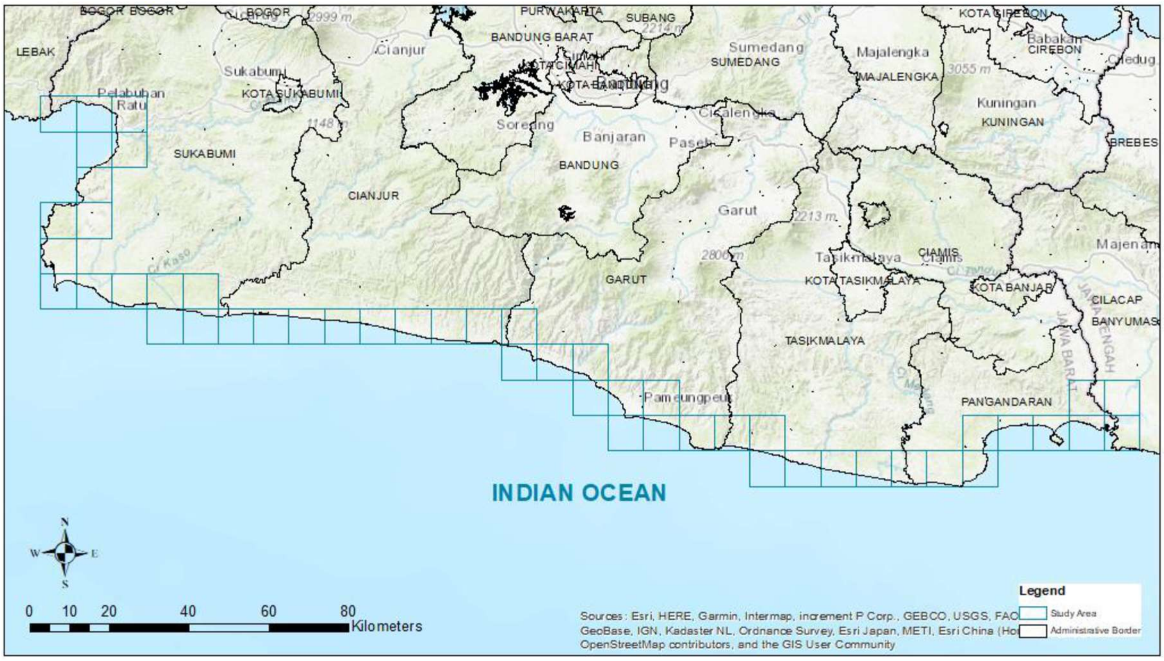

Figure 1. Location of the study area, West Java, Indonesia

The southern coast of West Java exhibits diverse geographical and ecological characteristics shaped by both natural processes and human activities. This region features distinct coastal vegetation, including mangrove ecosystems—primarily Avicennia species—that stabilize shorelines and support marine biodiversity (Solihuddin et al., 2019). The region experiences mixed tides, predominantly semi-diurnal, with tidal ranges from 1.78 m to 3,32 m, classified as micro and meso tides (Mutaqin & Ningsih, 2023). In addition, the coastal zone is exposed to the strong wave energy from the Indian Ocean, resulting in significant coastal erosion (Mutaqin & Ningsih, 2023).

The southern coastal areas of West Java Province, which lack coastal protection infrastructure and directly face the Indian Ocean, are prone to disasters such as SLR, erosion, and coastline changes owing to high wave exposure (Nurlatifah et al., 2021). For instance, Pangandaran is projected to lose approximately 105 hectares of coastal land by 2100 under a worst-case scenario, including around 32 hectares of residential areas and 14-16 hectares of agricultural land (Dwi Dasanto & Boer, 2022). The southern coast of Java has also been affected by sea level rise, with an average increase of 1.4 mm/y recorded between 1995 and 2014 (Uswatun et al., 2015). Furthermore, coastal regions such as Bantul, Cilacap, and Tasikmalaya have experienced significant shoreline changes driven by both intensive erosion and accretion processes (Amanulloh & Romdani, 2024; Dewi et al., 2020; Gumilar et al., 2023; Mutaqin et al., 2024).

2.2. Methods

This study follows a modified approach based on Conger & Chang (2019) to assess the potential of Coastal Green Infrastructure (CGI) in tropical coastal areas. The methodology consists of five main steps aligned with the research objectives. First, a systematic literature review was conducted to identify indicators relevant to CGI in tropical coastal regions. The review focused on ecological functions (e.g., mangroves, coral reefs), social benefits, and vulnerability factors commonly used in previous studies. Second, the identified indicators were grouped into two indices: the Coastal Protection Index and the Coastal Vulnerability Index. These were developed using content analysis and simple scoring methods based on frequency and relevance in the literature. Third, to reflect local conditions along the southern coast of West Java, the indices were adjusted using local environmental and socio-economic information. This involved qualitative analysis to tailor the indicators and their weights to the study area. Fourth, the indices were mapped using GIS-based spatial analysis. A weighted overlay method was used to combine the two indices, resulting in a CGI Potential Map that shows areas with different levels of suitability for CGI implementation. Finally, recommendations for CGI implementation were developed using the CGI Potential Map and a multi-criteria evaluation approach. Local policy context and regional development plans were also considered to support practical decision-making.

2.3. Literature Review

A literature search was conducted using Google Scholar and Research Gate to identify the parameters related to CGI's role of CGI in coastal protection and vulnerability. Numerous studies on CGI topics have been identified using the following keywords: coastal protection, nature-based coastal protection, coastal protection by vegetation, coastal protection from erosion, and sea-level rise. References were published in a time frame of ten-years (from 2013 to 2023) to ensure that this study covered the most current CGI studies. A total of 140 literature references met the search keywords and were selected for review. A total of 89 out of the 140 literatures analyzed met the requirements, namely containing specific parameters related to the role of CGI in coastal protection and vulnerability, with the publication periods ranged from 2013 to 2023, and originating from journals indexed by Scopus or SINTA.

2.4. Content Analysis

To determine the parameters associated with CGI's role of CGI in coastal protection and vulnerability, a content analysis was conducted manually on all 89 qualified studies. The parameters were comprehensively listed and systematically organized into thematic categories based on shared functional, ecological, or spatial characteristics. The categories were not chosen in advance, but were formed based on repeated ideas and themes that appeared in the studies. For example, parameters related to mangroves, kelp forests, seagrass, marsh or dune vegetation, and other vegetation were grouped under the theme of 'CGI Characteristics'. Similarly, estuaries, beaches, dunes, cliffs, and human-made coasts were then grouped under the 'Geomorphology' theme. Other parameters were grouped based on their relevance to coastal protection and vulnerability, as detailed in **Table 1**.

2.5 Development of CGI Indices

A CGI dataset was developed based on the thematic categories identified in the previous subsection. Publicly available data were collected from multiple databases to support this analysis. Based on six selected themes—CGI characteristics, geomorphology, sea-level change, tidal range, wave patterns, and coastal land use—eight corresponding indicators were available to use. However, three indicators—habitat zone, sedimentation, wave exposure, and erosion/shoreline change—were excluded due data unavailability and related limitations. Thus, the final dataset includes eight indicators that together reflect the physical composition of coastal areas and the interactions between natural landforms, built environments, and coastal processes. The full list of themes, indicators, and their corresponding 8 indicators and data sources is presented in **Table 1**.

Table 1. CGI themes, indicators, and their data sources

Category	Themes	Indicator	Data source
Protection Benefit	CGI characteristic	- CGI characteristic	Earth Explorer by USGS (2024), and Google Earth (2024)
Protection Benefit	Geomorphology	- Coastal type (i.e., estuaries, beaches, dunes, cliffs, and human made costs) - Elevation (m)	Land use data by BIG (2019), Digital Elevation Model by BIG (2019), and Google Earth (2024).
Vulnerability	Sea-level change	- Sea level changes (cm) in the past 100 years	ERA5 hourly data on single levels from 1940 to present dataset by ECMWF (2023).
Vulnerability	Tidal range	- Tidal range (m)	ERA5 hourly data on single levels from 1940 to present dataset by ECMWF (2023)
Vulnerability	Wave patternsCoastal land use	- Significant wave height (m) - Wind fetch (m)- Coastal land use (i.e., Green (5) to gray (1) scale that refers to the use of the costs where green refers to mostly agricultural and gray refers to mosly commercial and infrastructure use)	Land use data by BIG (2019).Marine Copernicus EU
Vulnerability	Coastal land use	- Coastal land use (refers to the use of the costs where green refers to mostly agricultural and gray refers to mosly commercial and infrastructure use)	ERA5 hourly data on single levels from 1940 to present dataset by ECMWF (2023), Land use data and geology map by BIG

The chosen indicators were categorized into two indices: the CGI Coastal Protection Index and the CGI Vulnerability Index. The CGI Coastal Protection Index assesses the ability of the CGI to attenuate wave height, flooding, and erosion, while the CGI Coastal Vulnerability Index measures the risk of CGI to environmental changes, which may result in a decreased protection benefit (Conger & Chang, 2019).

2.6. Index Formatting

Six indicators from the CGI database were used to develop the CGI coastal protection and vulnerability indices. First, indicators from **Table 1** were assigned to either the protection or vulnerability index based on their role. A rule-based method was then applied to rank each indicator on a scale of 1 (very low) to 5 (very high). Following this ranking, the indices were computed using a methodology adapted from Gornitz and Kanciruk (1989). This method, used to create the Coastal Vulnerability Index (CVI), involves ranking indicators from 1 to 5 and calculating the square root of the geometric mean divided by the total number of variables:

$$CVI = \sqrt{\frac{a^1 x a^2 x a^3 x \ldots x a^n}{n}} \quad (1)$$

where a represents an individual indicator and n signifies the total number of indicators used. Indicator values derived from spatial analysis (**Table 2**) were categorized into four categories (very low, low, medium, and high) based on the data distribution histogram. Lastly, GIS was used to map the spatially linked data. Since it is a method based on relative quantities, it does not directly show specific physical coastal processes and effects. However, it can help pinpoint which areas are most at risk from rising sea levels by acting as a diagnostic tool.

2.6.1. Remote Sensing and CGI Identification

This study proposes an initial approach for identifying CGI using a combination of satellite data, Spectral Vegetation Indices (SVIs), and bathymetric depth. Landsat 8 OLI data from USGS Earth Explorer (2024) were chosen along with the Normalized Difference Aquatic Vegetation Index (NDAVI) and bathymetric depth to analyze CGI cover in the specific coastal area.

NDAVI was selected due to its superior performance compared to other SVIs in identifying CGI elements. Accurately classifying species within CGI presents challenges due to biases and ambiguity in the analysis process. High NDVI values can be misleading as they may reflect the influence of ocean waves, rocks, or even trees. Furthermore, discrepancies between elevation data and satellite imagery added complexity to the analysis.

Given these limitations and considering the absence of a reliable CGI classification method, this study opted against using the combination of NDVI and bathymetric depth. Instead, this study employed visual observation on Google Earth, supplemented by researcher judgment, to assess CGI potential. However, this approach has inherent limitations: relying solely on visual observation and judgment can be subjective and prone to inaccuracies due to the absence of established methods and limited data availability.

Table 2. CGI Coastal Protection and Vulnerability Indices

Indicators	Very low	Low	Moderate	High	Very High
	1	2	3	4	5
COASTAL PROTECTION INDEX					
CGI Characteristic	No Vegetation	Seagrass	Dune Vegetation	Mangroves	Coral Reefs
Geomorphology	Sand, gravel, and mudflats	Human to made	Estuaries, lagoons, and dunes	Rocky beaches	Rocky cliffs and platforms
Elevation (m)	0 to 5	5.1 to 10	10.1 to 20	20.1 to 30	>30.1
COASTAL VULNERABILITY INDEX					
Sea-level changes (mm/year)	≤-1.1 Land rising	-1.1 to 0.99 Land rising	1.0 to 2.0 Within range of eustatic rise	2.1 to 4.0 Land sinking	≥ 4.1 Land sinking
Tidal range (m)	≤ 0.99 Microtidal	1.0 to 1.9 Microtidal	2.0-4.0 Mesotidal	4.1-6.0 Macrotidal	≥6.1 Macrotidal
Significant Wave Height (m)	<2.0	2.1 to 4.0	4.1-5	5.1-6.0	>6.1
Effective fetch	<1	1 to 10	10 to 50	50 to 500	500 to 1000
Coastal land use	Mostly green	Mostly green with agriculture	Mixed green and gray (residential)	Mixed green and gray (commercial)	Mostly gray

2.6.2. Fetch Analysis

The study used GIS software equipped with the Windfetch extension to calculate fetch length. The calculation followed the Shore Protection Manual (SPM) method by USACE (1984), which considers eight wind directions. The main line was aligned with the dominant wind direction—195 degrees—based on Copernicus EU data (2023). Additionally, seven supplementary lines were drawn at 3-degree intervals on either side of the main line, covering directions of 183, 186, 189, 192, 198, 201, and 204 degrees.

2.7. Synthesizing the Indices

After creating and calculating the CGI coastal protection and vulnerability indices, a 2 × 2 matrix was used to synthesize the results. The CGIs were categorized based on their combinations as follows: low coastal protection benefits and high vulnerability, low benefits and low vulnerability, high benefits and high vulnerability, and high benefits and low vulnerability (**Table 3**). These categories were spatially mapped using GIS (Conger and Chang, 2019b).

2.8. Model Validation

Due to the reliance on existing data and the absence of fieldwork, a sampling method was designed specifically for model validation. This method extracts the necessary values from relevant indicators (elevation, coastal land use, coastal vegetation, etc.) to validate the model based on the agreement between user observations and the model's output. The Fitzpatrick-Lins (1981) equation was employed to determine the appropriate sample size for the chosen spatial area.

$$N = \frac{Z^2 pq}{E^2} \qquad (2)$$

where N is the total sample, p is the expected percent accuracy, q = 100 - p, and E is the allowable error. From this formula, this study employed a sample size of 390 to ensure a high confidence level and an acceptable margin of error (E = 5%) in the absence of a known expected proportion. These 390 sampling points were randomly distributed across 39 segments (10 x 10 km grids) along the Southern Coastal Area of West Java Province, with a buffer distance from the coastline varying based on the specific indicator being measured.

Therefore, the kappa coefficient of agreement is utilized to assess image classification accuracy and determine the suitability for qualitative items (Lillesand et al. 2015). This method has used in this study to measure agreement between user interpretation of CGI characteristics from Google Earth imagery and the expected field conditions. The kappa coefficient (K) was calculated using Cohen's method using the provided equation.

$$K = \frac{P_o - P_c}{1 - P_c} \qquad (3)$$

The letter "K" measures agreement between observed and chance classifications. It ranges from -1 to +1, but usually, only positive values matter, as negatives suggest no agreement. "P_o" stands for observed agreement, and "P_c" for chance agreement. If the Kappa coefficient indicates poor results, then the analysis is considered irrelevant to the actual situation.

Results

Quantitative and qualitative data from eight key indicators were used to develop the CGI Coastal Protection and Vulnerability Indices. These indicators include CGI characteristics, geomorphology, elevation, sea-level change, tidal range, significant wave height, effective fetch, and coastal land use. Each factor was evaluated using a five-point Likert scale, where values from 1 (very low) to 5 (very high) represent the relative level of coastal protection benefit or vulnerability (see Table 3). This classification reflects relative differences withinNote that this scale does not show an absolute low to high protection level, but rather the relative CGI coastal protection benefits and vulnerability in the study area, rather than absolute protection levels.

To ensure relevance to local conditions, the indicators were adjusted based on the specific geomorphological and environmental characteristics of the southern coastal region of West Java. These adjustments were made using visual interpretation from Google Earth and supporting spatial datasets. The resulting indices provide a context-sensitive assessment of current shoreline conditions, wave dynamics, and land use, forming the basis for identifying CGI potential under existing environmental circumstances.

Table 3. CGI typology matrix from Conger and Chang et.al. (2019)

		CGI coastal protection benefits	
		Very low/ low	Moderate/ high
CGI Vulnerability	Very low/low	Type-2	Type-4
	Moderate/high	Type-1	Type-3

3.1. CGI Coastal Protection Index

3.1.1. CGI Characteristics

The CGI classification system proposed by Narayan et al. (2016), which categorizes CGI based on wave-dampening abilities: no vegetation, seagrass, dune vegetation, mangroves, and coral reefs), was adopted in this study. While this framework does not explicitly include complex or mixed ecosystems (e.g., coral–seagrass–mangrove systems), it offers a simplified typology suitable for large-scale spatial analysis and vulnerability assessment. This differs slightly from the Conger and Chang (2019b) system, which uses salt marshes instead of mangroves. Although both wetlands are found in sheltered coastal areas, their geographic distribution varies. Salt marshes are common in tropical regions (Davidson-Arnott, 2017). However, mangroves are generally limited to protected tropical coastlines (Duke et al. 1998). Additionally, coral reefs were chosen over kelp forests because of their prevalence in tropical and subtropical regions, where kelp forests are scarce (Davidson-Arnott, 2017; Assis et al. 2024). Seagrass and dune vegetation remained unchanged in both classifications, as they are also found in tropical regions (Luisa Martínez and Psuty, 2008; Davidson-Arnott, 2017; McKenzie et al. 2020).

NDAVI was selected because of its superior performance compared with other SVIs for identifying CGI elements. Accurately classifying species within the CGI presents challenges owing to biases and ambiguity in the analysis process. High NDVI values can be misleading, as they may reflect the influence of ocean waves, rocks, or even trees. Furthermore, discrepancies between the elevation data and satellite imagery add complexity to the analysis.

Figure 2. This study investigated four types of CGI: (a) mangroves and (b) aquatic plants in Pangandaran; (c) mangroves in Garut; and (d) dune vegetation in Cianjur

Given these limitations and considering the absence of a reliable CGI classification method, this study opted to use a combination of NDVI and bathymetric depth. Instead, this study employed visual observation on Google Earth, supplemented by researcher judgment, to assess the CGI potential. However, this approach has inherent limitations: relying solely on visual observation and judgment can be subjective and prone to inaccuracies owing to the absence of established methods and limited data availability.

The analysis revealed moderate-to-high CGI potential in the study area, with extensive mangrove presence in Pangandaran, Sukabumi, and Garut (**Figure 2**). Coral reefs are present in smaller parts of these regions, and their abundance is likely influenced by sedimentation levels. Coral reefs generally thrive in clear waters at temperatures between 18 °C and 30°C (Davidson-Arnott, 2017). High sedimentation, which is often found in estuaries, hinders coral growth. Therefore, areas with lower sedimentation in Pangandaran, Garut, and Sukabumi offer more suitable conditions for coral reefs and mangroves (Rivera-Monroy et al., 2017). This finding suggests a potential synergy between the coastal ecosystems in these areas, contributing to the moderate to high CGI potential

The limited dune vegetation identified in this study is primarily found in Cianjur. This scarcity is likely due to the study locations being within the tropical climatic regions (Luisa Martínez and Psuty, 2008). In addition, seagrass was not visually observed because of potential bias. Furthermore, significant CGI cover was lacking in some coastal areas, particularly Cianjur, Garut, and Tasikmalaya. Unknown aquatic plant species in estuaries and non-mangrove coastal plants have also been found in certain regions, raising uncertainties regarding CGI identification. These limitations are likely due to insufficient data and information about CGI in the study locations.

3.1.2. Geomorphology

Visual observations using Google Earth, combined with expert judgment, were employed to classify coastal types along West Java's southern regions. Five distinct categories were identified: sandy beaches and mudflats (Tasikmalaya, Cianjur, Garut); human-made coasts in residential and commercial areas (Pangandaran, Sukabumi); estuaries, lagoons, and dunes (scattered across Pangandaran, Tasikmalaya, Cianjur, Sukabumi); rocky shores (Tasikmalaya, Garut, Sukabumi); and rocky cliffs (eastern Pangandaran, mountainous areas near Pelabuhan Ratu, Sukabumi).

Coastal types significantly influence the wave energy. Rough surfaces, such as those found in estuaries with mangroves, beaches, dunes, and rocky platforms, attenuate wave energy more effectively through friction than smoother surfaces such as sand, gravel, and mudflats. Roughness further increases with features, such as sloped beaches, rocky coasts, and cliffs. While human-made structures offer some protection, their vertical alignment can cause wave overtopping and deterioration over time (Conger and Chang 2019).

Coastal elevation also plays a critical role in wave attenuation, which is influenced by the nearshore and beach slopes. Steeper slopes enhance wave dissipation, offering superior protection compared with gently sloping beaches (Davidson-Arnott, 2017). This study revealed a trend along the southern coast of West Java. Approximately 84.62% (320.99 km) of the area falls within the very low elevation category (0-5 meters above sea level) and primarily consists of sandy beaches and mudflats. In contrast, the western region of Pangandaran exhibited high elevations with cliffs, providing significantly stronger coastal protection.

Applying the CGI Coastal Protection Index, this study assessed over 379.35 km of the coastline along the southern coast of West Java. The index values are classified into four categories: red (very low protection), yellow (low protection), green (moderate protection), and blue (high protection). As shown in **Figure 3**, a significant proportion (56.4%) exhibited very low protection, followed by low protection (25.6%). Moderate protection was present on 10.3% of the coastline, whereas only 7.7% experienced high protection.

Analysis of the CGI coastal protection index revealed very low to low values across most of the southern coastline of West Java. This suggests that due to factors such as sandy beaches, low elevation, and limited existing CGI, CGI alone may be insufficient for comprehensive protection. Therefore, this study recommends prioritizing hard or hybrid structures for coastal protection in these areas. However, for specific areas with a high CGI potential, utilizing and enhancing the CGI approach could be a viable strategy.

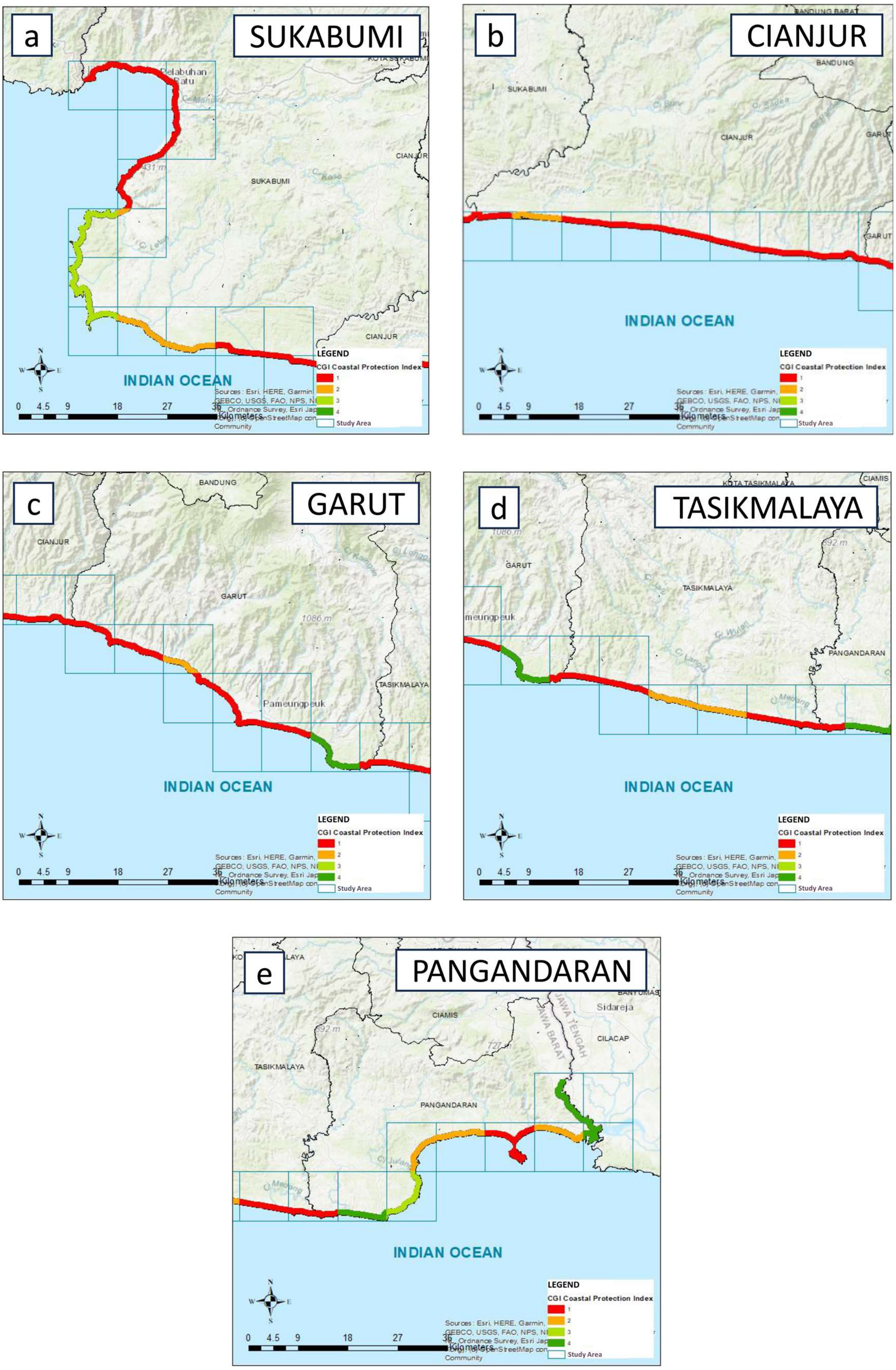

Figure 3. CGI Coastal Protection Index in: (a) Sukabumi; (b) Cianjur; (c) Garut; (d) Tasikmalaya; (e) Pangandaran

3.2. CGI Coastal Vulnerability Index

3.2.1. Tidal Range

The tidal patterns in the southern coastal areas of West Java are categorized as mixed-semidiurnal, which means there are two high tides and two low tides each day, with significant differences in their heights of these tides (Herrmann and Bucksch, 2014). The difference in elevation between high tide and low tide is called the tidal range, which controls the water level at the shoreline (Davidson-Arnott, 2017). The tidal range is categorized as microtidal (<2m), mesotidal (2-4 m), and macrotidal (>4m) according to the average tidal range during spring tides (Davies, 1964). Reanalysis of historical and future tide data from 13 stations along West Java's southern coast (Copernicus EU 2023) reveals a mean tidal range of 1.36 meters between 2021 and 2045, classifying it as microtidal. In microtidal areas, coastal geomorphology is shaped primarily by waves, whereas tides play a significant role in geomorphological changes in meso-to macro-tidal areas (Davis and Hayes, 1984). Coastal vulnerability assessments often label coastlines with high tidal ranges as highly vulnerable, because such ranges can lead to geomorphological changes in coastal areas by increasing erosion and sediment movement (Tano et al. 2018).

3.2.2. Sea-level change

Analysis result using the CMIP6 dataset from Copernicus (2022) projects a sea level rise of 5.00-5.15 millimeters per year from 2004 to 2044, resulting in a total increase of 0.203 meters by 2044 relative to 1986-2005. This is slightly higher than the IPCC (2019) GMSL projections for 2046 under RCP8.5, which estimates a rise of 0.22 meters. Furthermore, the projected rate of global mean sea level rise in 2044 shows a slight difference between CMIP6 ($\approx$ 0.72 mm/year) and IPCC ($\approx$ 0.7 mm/year). Additionaly, Nurlatifah et al. (2021) reported a historical increase of 4.7 mm/year in southern Java's sea level (1993-2018), exceeding the global average rise of 3.2 mm/year over the past two decades.

Seasonal monsoon variations significantly impact sea levels along the coast of Java, with higher levels observed during the northwest monsoon and lower levels observed during the southeast monsoon (Triana and Wahyudi, 2020). These seasonal fluctuations are further influenced by extreme events such as El Niño and La Niña. Beyond global warming, Fadlan et al. (2017) highlighted the role of interannual phenomena such as the El Niño Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) in driving SLR in the tropics. Consequently, sea levels in southern Java have experienced a continuous rise because of the combined effects of climate change, interannual variability (ENSO and IOD), and seasonal monsoons (Fadlan et al., 2017; Wirasatriya et al. 2017; Triana and Wahyudi, 2020).

Although earthquakes and landslides can temporarily impact sea levels through land elevation changes and tsunamis, climate change is the dominant driver over longer timescales. Climate change alters ocean water volume and land ice mass, influencing sea levels globally (Muis et al., 2022). The CMIP6 projection considers factors such as ocean warming, ocean circulation changes, contributions from ice sheets, and glacial landmass adjustments when calculating the SLR. In contrast, the IPCC projection incorporates these factors, along with rapid ice sheet dynamics and land water storage across various scenarios.

Coastal vulnerability assessments often link high SLR to a high vulnerability. Gornitz and Kanciruk (1989) categorized SLR into three categories: (1) land rising (less than -1.1 mm/year to 0.99 mm/year), (2) within eustatic rise (1.0 to 2.0 mm/year), and (3) land sinking (more than 2.0 mm/year). As sea levels rise, coastal areas experience more frequent and severe storm surges, increased flooding, and faster erosion (Feagin et al. 2008).

3.2.3. Wave Patterns

Reanalysis data from Copernicus EU ERA5 (2023) revealed average significant wave heights (SWH) in the southern coastal areas of West Java Province ranging from 1.84 to 3.46 meters in January and July 2023. This is lower than the findings of Barokah et al. (2023), who reported an SWH of 3–3.5 meters during the west wind season (December-February) and 4–5 m during the east wind season (June-August) from 2010 to 2021.

Howes et al. (1994) suggested utilizing the maximum fetch to assess wave exposure, with longer fetch indicating greater wave energy. While the southern coast of West Java generally faces open ocean with potentially unlimited fetch, localized variations—such as headland, embayment, and nearshore island—can shorten the effective fetch, reduce the wave energy, and offer protection (Cook et al., 2017). This study adopted Cook et al.'s (2017) classification based on the effective fetch for each coastal unit to reflect such variations. Analysis reveals a significant portion (79.49%) of the coastline was highly exposed, with fetches exceeding 500 m. An additional 12.82% were classified as semi-exposed, while only 7.69% were considered non-exposed.

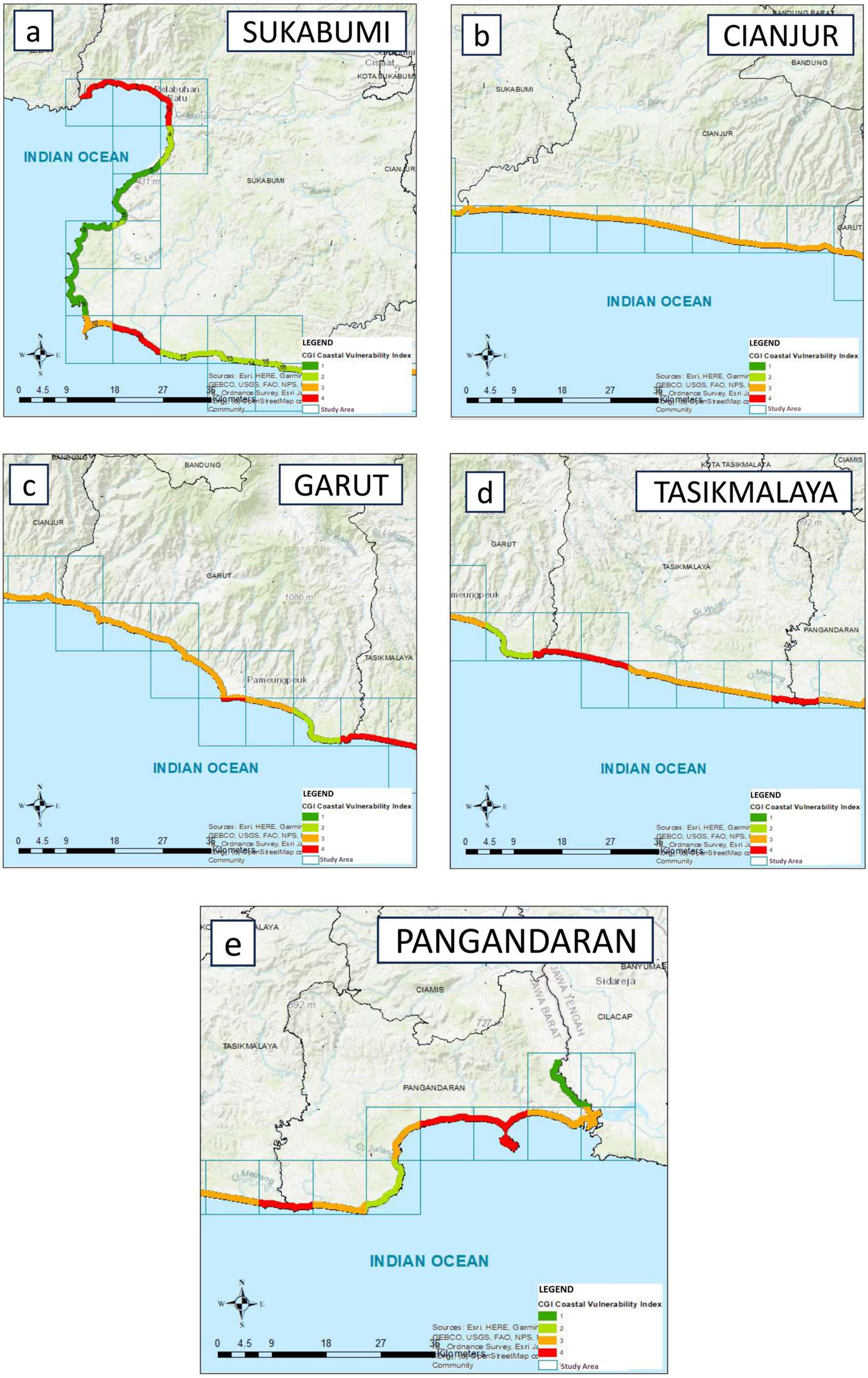

Figure 4. CGI Coastal Vulnerability Index in: (a) Sukabumi; (b) Cianjur; (c) Garut; (d) Tasikmalaya;

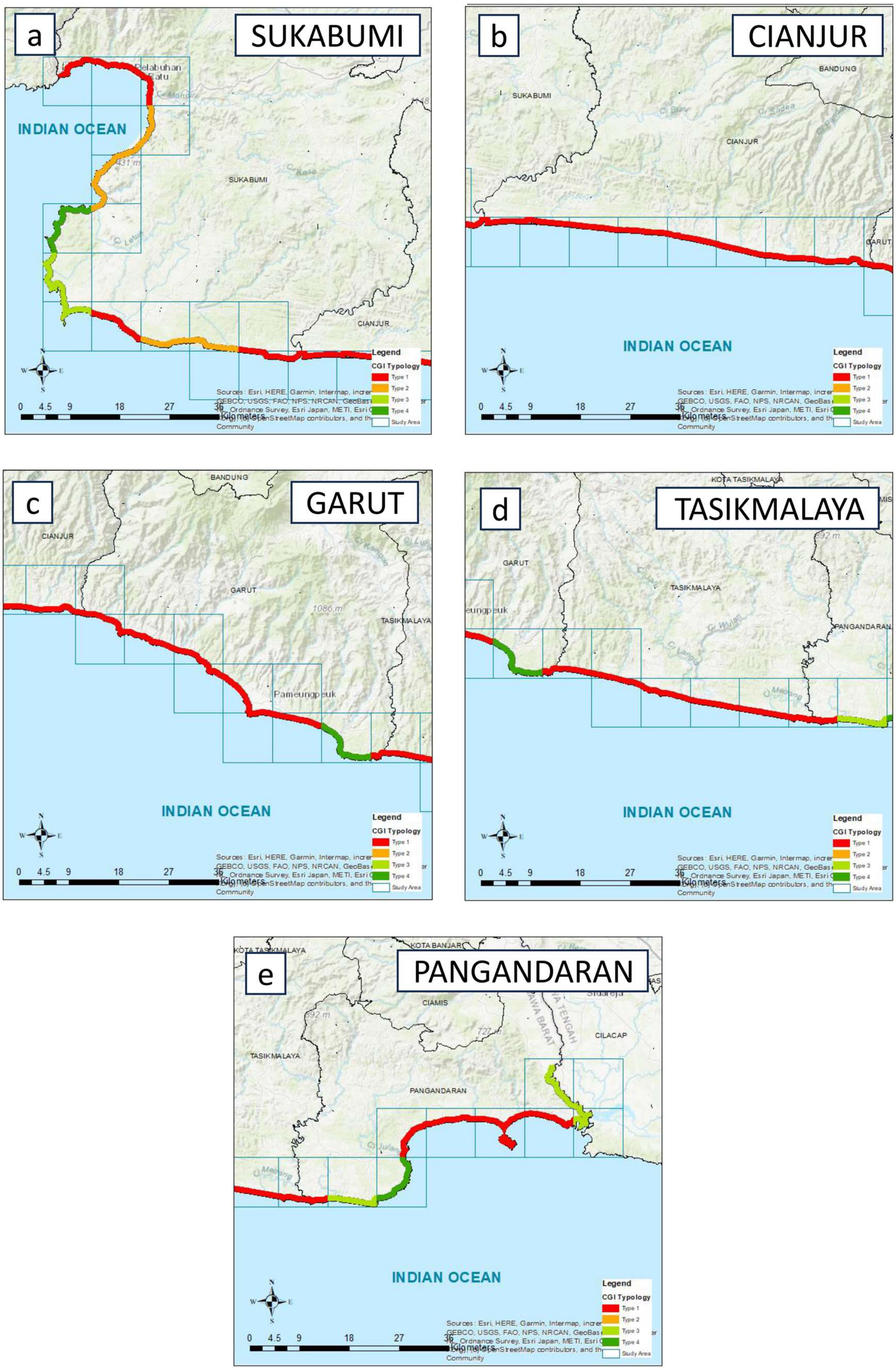

Figure 5. CGI Typology Map in: (a) Sukabumi; (b) Cianjur; (c) Garut; (d) Tasikmalaya; (e) Pangandaran

3.2.4. Coastal Land Use

Coastal land-use indicators are valuable for assessing infrastructure development, economic potential, community vulnerability, and potential disaster losses. To analyze land use characteristics along the southern coast of West Java, a Land Use/Land Cover (LULC) map was created using data from the Peta Rupa Bumi Indonesia (RBI) provided by BIG (2019). The analysis identified four main categories: (1) mixed green and gray areas for commercial purposes (23.08%); (2) similar areas for residential purposes (23.08%); (3) mostly green areas used for agriculture (51.28%); and (4) predominantly green areas (25.6%). Developed coastal areas are more susceptible to flooding, whereas green spaces and agriculture can mitigate wave energy and absorb floodwater (Conger and Chang, 2019b).

Using the CGI Coastal Vulnerability Index, over 379.35 km of shoreline along the southern coast of West Java Province was evaluated and mapped using the CGI Coastal Vulnerability Index. Index values range from 2.00 to 8.00, with lower values indicating lower vulnerability. As shown in **Figure 4**, over half of the coastline exhibited moderate vulnerability, whereas 23.08% exhibited moderate vulnerability. The remaining coastline was divided into low (17.59%) and very low (7.69%) vulnerability. The southern coast of West Java exhibits moderate overall vulnerability owing to a combination of factors, including SLR, low tidal range, low wave heights, long fetch, and the dominance of agricultural land use along the coast. However, this highlights the need for strategic coastal protection and prioritizing critical areas with high vulnerability.

3.2.5. CGI Typology

The evaluation and ranking process of CGI Typology covered over 379.35 km of shoreline along the southern coast of West Java (**Figure 5**). The CGI Potential was ranked from Type 1 (most suitable) to Type 4 (less suitable) according to the CGI Typology. Approximately 67% of patients were categorized as Type 1, while 15% were categorized as Type 2. The remaining coastline was categorized as type 3 (8%) or type 4 (10%). The analysis revealed that the southern coastal areas of West Java are predominantly classified as CGI Type 1, characterized by very low CGI protection benefits and moderate vulnerability. This suggests utilizing hard structures or developing hybrid structures in critical places with high vulnerability, particularly where existing hard structures are present. Coastal development should be restricted to essential purposes. Agricultural use is considered safe due to the low risk of coastal disasters in these communities. Restoration of coastal vegetation is also recommended as it is currently scarce.

4.Discussion

This study analyzed 89 relevant publications out of 140 global studies to identify key indicators and methods for assessing the potential of Coastal Green Infrastructure (CGI) in tropical coastal areas. Drawing from this review, three core indices were developed: the CGI Coastal Protection Index, the CGI Coastal Vulnerability Index, and the CGI Typology. The Coastal Protection Index identifies factors that enhance the protective capacity of CGI, such as vegetation type, tidal range, and wave attenuation, while the Vulnerability Index reflects site sensitivity based on biophysical and social characteristics. The CGI Typology then synthesizes these indices to classify coastal areas into categories of CGI potential, which serves as a basis for spatial planning and policy recommendations. This typology can be used to evaluate CGI potential in specific areas and inform the development of effective coastal protection strategies (see **Table 4**).

Applying this framework to the southern coast of West Java, the results show that many coastal areas have low protection index scores and moderate vulnerability, indicating limited CGI implementation potential under current conditions. Contributing factors include sparse existing CGI coverage (especially mangroves), low elevation, and the dominance of sandy beach geomorphology. These physical characteristics are further impacted by exposure to climate change hazards, including sea-level rise (SLR), high tidal ranges, long effective wave fetch, and significant wave heights. While the biophysical vulnerability remains relatively high, social vulnerability appears lower due to limited urban development and the prevalence of agricultural and green spaces. Exceptions include urbanized zones such as Pangandaran and Sukabumi, where population pressures elevate exposure risks.

Despite these challenges, CGI potential in tropical Indonesia remains promising. Studies have shown that mangroves are significantly more effective than other CGI types (e.g., salt marshes, oyster reefs) in wave attenuation and erosion control, particularly in tropical zones/ However, CGI adoption in Indonesia has been limited due to a lack of standardized frameworks, data availability, and institutional familiarity. Most previous studies focused narrowly on mangroves without incorporating broader CGI elements, such as coral reefs, seagrass beds, or dune systems.

Table 4. CGI types and policy advice

Type	Protection benefit	Vulnerability	Policy Advice
Type 1	Very low/low	Moderate/high	– Combining hard structures with CGI – Consider restricting coastal development to only essential purposes
Type 2	Very low/low	Moderate/high	– Restoring coastal vegetations – Developing hybrid structures (if hard structure exists there)
Type 3	Moderate/high	Very low/low	– Controlling coastal development – Cleaning and nourishment of the coastal area – Replacing hard structures with CGI – Developing hybrid structures
Type 4	Moderate/high	Very low/low	– Improving habitats – Removing hard structures – Replacing hard structures with CGI – Increasing the awareness of the coastal communities about the CGI

This study builds on the CGI index framework developed by Conger and Chang (2019) by applying a similar method to construct new indices. While the general concept aligns, this study was inspired by Carolina et al. (2023), who simplified these indices for their study in South Korea, focusing on clarity and avoiding ambiguity between the indicators. Nevertheless, this study significantly modified the CGI indicators compared to previous methods. The CGI ranking levels were updated based on Narayan et al.'s (2016) findings on coastal protection capacity. The salt marsh indicator was removed, with a greater emphasis placed on mangroves. Given the open-ocean nature of the study area, where wave fetch can exceed 1000 km, the original fetch thresholds from Conger and Chang (2019) were not well-suited for the study area. Therefore, this study has adopted the more regionally appropriate classification from Cook and Daley's (2017), which offers effective fetch ranges developed for high-exposure coastal environments. Similarly, the tidal range indicator was adjusted to focus on negative high-tide effects, neglecting the sediment transport benefits. The necessity for these changes underscores the adaptability of the CGI framework, allowing global application with location-specific adjustments. Future CGI research must account for geographical variations and research conditions, as they significantly influence both the methodology and outcomes. Tropical environments and climate variability can affect CGI characteristics, tidal ranges, and wave patterns. By considering diverse research circumstances, this study offers valuable contributions to coastal engineering, coastal management, and disaster mitigation strategies.

A key limitation of this study is its reliance on open-access data and their limited accuracy. While free satellite data provide a general overview for analysis, their lower resolution limits the extraction of detailed information needed for image classification. Similarly, digital elevation and bathymetry models from these sources may have lower accuracy, potentially impacting data processing and the interpretation of elevation and depth. Because of several constraints, field research and inspection were not feasible in this study. Consequently, Google Earth satellite imagery was used as the primary data validation source, utilizing a predetermined validation technique. However, this method relies on visual observations and the researcher's judgment, potentially leading to inconsistencies in qualitative analysis. Additionally, limitations in available data sources require indicators such as sedimentation, accretion, and habitat zones to be excluded from the analysis.

The absence of a well-established method for assessing CGI potential, likely because of the novelty of CGI research in coastal engineering, has also been one of the limitations (Kaskevich et al., 2024; Kim et al., 2024). Existing approaches often lack the ability to address the limited data availability. To address this gap, this study proposes a classification method using Satellite Vegetation Indices (SVIs) and water depths. However, this method is scientifically unproven and exhibits unsatisfactory results. Thus, it is substituted by visual observations in Google Earth with researcher judgment.

Despite these limitations, this study offers valuable insights for coastal management and disaster mitigation, particularly in Indonesia and other tropical regions. It expands our understanding of CGI and coastal management by considering diverse geographic settings, climate variations, data availability, and evolving approaches. This study provides practical solutions and can inform effective governmental strategies. Moreover, the framework can be adapted to assess CGI benefits and vulnerabilities across a broader range of contexts in future research.

5. Conclusion

Climate change intensifies coastal threats such as SLR and storm surge, increasing the vulnerability of coastal regions. To mitigate this problem, CGI offers a promising solution, gaining global recognition yet facing limited adoption and understanding in Indonesia. This study promotes the CGI's potential for Indonesian coastal management by introducing novel tools such as CGI coastal protection and vulnerability indices. These tools provide a practical means for assessing coastal protection benefits and vulnerability.

The Southern Coastal Area of West Java Province was revealed in this study to have low to very low CGI coastal protection benefits, resulting in high vulnerability to climate change disasters. This underscores the urgent need for comprehensive coastal management strategies that leverage the potential of CGI. In Indonesia, CGI can be implemented through mangrove restoration or conservation efforts as mangroves provide significant benefits to ecosystems. Furthermore, CGI's applicability of CGI can be extended globally to various ecosystems, both tropical and non-tropical, with adjustments made based on the specific study locations.

This study promotes the integration of CGI approaches into the national coastal management policies and practices. By embracing CGI principles and methodologies, the government can strengthen coastal resilience and mitigate climate change risk. Through collaboration and decision making, Indonesia can pioneer a more sustainable and resilient coastal future.

Acknowledgments

We wish to express our gratitude to the Rector of Siliwangi University, Dean of the Faculty of Engineering, and Head of the Department of Civil Engineering for their essential support and contribution to this research.

References

Alexander, M., Polimis, K. and Zagheni, E., 2019. *The Impact of Hurricane Maria on Out-migration from Puerto Rico: Evidence from Facebook Data*.

Asia Development Bank, 2021. *INDONESIA CLIMATE RISK COUNTRY PROFILE*.

Assis, J., Fragkopoulou, E., Gouvêa, L., Araújo, M.B. and Serrão, E.A., 2024. Kelp forest diversity under projected end-of-century climate change. *Diversity and Distributions*, 30(6), pp.1–11. https://doi.org/10.1111/ddi.13837.

Badan Informasi Geospasial Republik Indonesia, 2019. *Peta Rupabumi Digital Indonesia*. [online] Badan Informasi Geospasial Republik Indonesia. Available at: <http://tanahair.indonesia.go.id/portal-web/>.

Badan Pusat Statistik, 2023. *Statistik Indonesia 2023*.

Barbier, E.B., Hacker, S.D., Kennedy, C., Koch, E.W., Stier, A.C. and Silliman, B.R., 2011. The value of estuarine and coastal ecosystem services. *Ecological Monographs*, 81(2), pp.169–193. https://doi.org/10.1890/10-1510.1.

Barokah, N., Suarbawa, K.N., Putra, K. and Gunawan, A.A.N., 2023. Analysis of the Maximum Average Wave Distribution Map in the Southern Waters of Java Island during the Period 2010-2021. *Emerging Issues in Environment, Geography and Earth Science Vol. 1*, 5(1), pp.80–98. https://doi.org/10.9734/bpi/eieges/v1/7092a.

Bayraktarov, E., Saunders, M.I., Abdullah, S., Mills, M., Beher, J., Possingham, H.P., Mumby, P.J. and Lovelock, C.E., 2015. The cost and feasibility of marine coastal restoration. *Ecological Applications*, 26(4), pp.1055–1074. https://doi.org/10.1890/15-1077.1.

Bernini, E., Santos, C. de F.N. do R., Lage-Pinto, F., Chagas, G.P. and Rezende, C.E., 2014. Fitossociologia de lorestas de mangue plantadas e naturais no estuário do Rio das Ostras, Rio de Janeiro, Brasil Elaine. *Biotemas*, 27(1), pp.37–48.

Billah, M.M., Bhuiyan, M.K.A., Islam, M.A., Das, J. and Hoque, A.R., 2022. Salt marsh restoration: an overview of techniques and success indicators. *Environmental Science and Pollution Research*, 29(11), pp.15347–15363. https://doi.org/10.1007/s11356-021-18305-5.

Bosire, J.O., Kaino, J.J., Olagoke, A.O., Mwihaki, L.M., Ogendi, G.M., Kairo, J.G., Berger, U. and Macharia, D., 2014. Mangroves in peril: Unprecedented degradation rates of peri-urban mangroves in Kenya. *Biogeosciences*, 11(10), pp.2623–2634. https://doi.org/10.5194/bg-11-2623-2014.

Brown, J.M., Phelps, J.J.C., Barkwith, A., Hurst, M.D., Ellis, M.A. and Plater, A.J., 2016. The effectiveness of beach mega-nourishment, assessed over three management epochs. *Journal of Environmental Management*, 184, pp.400–408. https://doi.org/10.1016/j.jenvman.2016.09.090.

Burden, A., Garbutt, A. and Evans, C.D., 2019. Effect of restoration on saltmarsh carbon accumulation in Eastern England. *Biology Letters*, 15(1), pp.0–3. https://doi.org/10.1098/rsbl.2018.0773.

Church, J.A. and Gregory, J.M., 2019. Sea Level Change. *Encyclopedia of Ocean Sciences, Third Edition: Volume 1-5*, 1–5, pp.V6-493-V6-499. https://doi.org/10.1016/B978-0-12-409548-9.10820-6.

Conger, T. and Chang, S.E., 2019a. Developing indicators to identify coastal green infrastructure potential: The case of the Salish Sea region. *Ocean and Coastal Management*, 175, pp.53–69. https://doi.org/10.1016/j.ocecoaman.2019.03.011.

Conger, T. and Chang, S.E., 2019b. Developing indicators to identify coastal green infrastructure potential: The case of the Salish Sea region. *Ocean and Coastal Management*, 175, pp.53–69. https://doi.org/10.1016/j.ocecoaman.2019.03.011.

Cook, S., Daley, S., Morrow, K. and War, S., 2017. ShoreZone Coastal Imaging & Habitat Mapping Protocol December 2017. (December).

Davidson-Arnott, R., 2017. *Introduction to Coastal Processes and Geomorphology*. *Jurnal Sains dan Seni ITS*, .

Davies, J.L., 1964. A morphogenic approach to world shorelines. *Zeitschrift für Geomorphologie*, 8(5).

Davis, R.A. and Hayes, M.O., 1984. What is a wave-dominated coast? *Marine Geology*, 60, pp.313–329.

Duarte, C.M., Losada, I.J., Hendriks, I.E., Mazarrasa, I. and Marbà, N., 2013. *The role of coastal plant communities for climate change mitigation and adaptation*. *Nature Climate Change*, https://doi.org/10.1038/nclimate1970.

Duke, N.C., Ball, M.C. and Ellison, J.C., 1998. Factors influencing biodiversity and distributional gradients in mangroves. *Global Ecology and Biogeography Letters*, 7(1), pp.27–47. https://doi.org/10.2307/2997695.

Fadlan, A., Sugianto, D.N., Kunarso and Zainuri, M., 2017. Influence of ENSO and IOD to Variability of Sea Surface Height in the North and South of Java Islan. *IOP Conf. Series: Earth and Environmental Science*, 55. https://doi.org/10.1088/1755-1315/55/1/012021.

Feagin, R.A., Figlus, J., Zinnert, J.C., Sigren, J., Martínez, M.L., Silva, R., Smith, W.K., Cox, D., Young, D.R. and Carter, G., 2015. *Going with the flow or against the grain? The promise of vegetation for protecting beaches, dunes, and barrier islands from erosion*. *Frontiers in Ecology and the Environment*, https://doi.org/10.1890/140218.

Feagin, R.A., Sherman, D.J. and Grant, W.E., 2008. Coastal Erosion, Global Sea-Level Rise, and the Loss of Sand Dune Plant Habitats. *Bulletin of the Ecological Society of America*, 89(4), pp.310–313. https://doi.org/10.1890/0012-9623(2008)89[310:fie]2.0.co;2.

Fitzpatrick-Lins, K., 1981. Comparison of sampling procedures and data analysis for a land- use and land-cover map. *Photogrammetric Engineering & Remote Sensing*, 47(3), pp.343–351.

Gornitz, V. and Kanciruk, P., 1989. *ASSESSMENT OF GLOBAL COASTAL HAZARDS FROM SEA LEVEL RISE*.

Hadipour, V., Vafaie, F. and Kerle, N., 2020. An indicator-based approach to assess social vulnerability of coastal areas to sea-level rise and flooding: A case study of Bandar Abbas city, Iran. *Ocean and Coastal Management*, 188. https://doi.org/10.1016/j.ocecoaman.2019.105077.

Hein, M., McLeod, I.M., Shaver, E., Vardi, T., Pioch, S., Boström-Einarsson, L., Ahmed, M. and Grimsditch, G., 2020. Coral Reef Restoration as a Strategy to Improve Ecosystem Services - A guide to Coral Restoration Methods. *Ecological Engineering*, pp.345–364.

Herrmann, H. and Bucksch, H., 2014. *Coastal Tide*. *Dictionary Geotechnical Engineering/Wörterbuch GeoTechnik*. https://doi.org/10.1007/978-3-642-41714-6_32916.

Hersbach, H., Bell, B., Berrisford, P., Biavati, G., Horányi, A., Muñoz Sabater, J., Nicolas, J., Peubey, C., Radu, R., Rozum, I., Schepers, D., Simmons, A., Soci, C., Dee, D. and Thépaut, J.-N., 2023. *ERA5 hourly data on single levels from 1940 to present*. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). https://doi.org/Copernicus Climate Change Service (C3S) Climate Data Store (CDS).

Howes, D., Harper, J. and Owens, E., 1994. *Physical Shore-Zone Mapping System for British Columbia By*.

Jia, M., Wang, Z., Mao, D., Ren, C., Song, K., Zhao, C., Wang, C., Xiao, X. and Wang, Y., 2023. Mapping global distribution of mangrove forests at 10-m resolution. *Science Bulletin*, 68(12), pp.1306–1316. https://doi.org/10.1016/j.scib.2023.05.004.

Lillesand, T.M., Kiefer, R.W. and Chipman, J.W., 2015. *Remote Sensing and Image Interpretation*. 7th ed. Willey.

Luisa Martínez, M. and Psuty, N.P., 2008. *Coastal Dunes*.

McKenzie, L.J., Nordlund, L.M., Jones, B.L., Cullen-Unsworth, L.C., Roelfsema, C. and Unsworth, R.K.F., 2020. The global distribution of seagrass meadows. *Environmental Research Letters*, 15(7). https://doi.org/10.1088/1748-9326/ab7d06.

Mimura, N., 2013. *Sea-level rise caused by climate change and its implications for society*. *Proceedings of the Japan Academy Series B: Physical and Biological Sciences*, https://doi.org/10.2183/pjab.89.281.

Muis, S., Apecechea, M.I., Álvarez, J.A., Verlaan, M., Yan, K., Dullaart, J., Aerts, J., Duong, T., Ranasinghe, R., le Bars, D., Haarsma, R. and Roberts, M., 2022. *Global sea level change time series from 1950 to 2050 derived from reanalysis and high resolution CMIP6 climate projections.* Copernicus Climate Change Service (C3S) Climate Data Store (CDS). https://doi.org/Copernicus Climate Change Service (C3S) Climate Data Store (CDS).

Mukherjee, N., Dahdouh-Guebas, F., Koedam, N. and Shanker, K., 2015. *An interdisciplinary framework to evaluate bioshield plantations: Insights from peninsular India*.

Murdiyarso, D., Nurhati, I.S., Ambo-rappe, R. and Jompa, J., 2022. Rehabilitasi Kawasan Pesisir untuk Pembangunan Rendah Karbon. *CIFOR-ICRAF*, pp.1–4. https://doi.org/10.17528/cifor/008615.

Narayan, S., Beck, M.W., Reguero, B.G., Losada, I.J., Van Wesenbeeck, B., Pontee, N., Sanchirico, J.N., Ingram, J.C., Lange, G.M. and Burks-Copes, K.A., 2016. The effectiveness, costs and coastal protection benefits of natural and nature-based defences. *PLoS ONE*, 11(5), pp.1–17. https://doi.org/10.1371/journal.pone.0154735.

Nasution, M., Zakiah, K., Paramita, R., Christianingrum, R., Zahara, E.L., Kusumawardhani, R.T., Liana, D., Fitri, H., Bangun, O.V. and Mujiburrahman, 2022. Anggaran Hijau Indonesia dalam Menghadapi Perubahan Iklim. p.80.

Nurlatifah, A., Martono, Susanti, I. and Suhermat, M., 2021. Variability and trend of sea level in southern waters of Java, Indonesia. *Journal of Southern Hemisphere Earth Systems Science*, 71(3), pp.272–283. https://doi.org/10.1071/ES21004.

Powell, E.J., Tyrrell, M.C., Milliken, A., Tirpak, J.M. and Staudinger, M.D., 2019. A review of coastal management approaches to support the integration of ecological and human community planning for climate change. *Journal of Coastal Conservation*, 23(1), pp.1–18. https://doi.org/10.1007/s11852-018-0632-y.

Rivera-Monroy, V.H., Kristensen, E., Lee, S.Y. and Twilley, R.R., 2017. *Mangrove ecosystems: A global biogeographic perspective: Structure, function, and services*. *Mangrove Ecosystems: A Global Biogeographic Perspective: Structure, Function, and Services*. https://doi.org/10.1007/978-3-319-62206-4.

Ruckelshaus, M.H., Guannel, G., Arkema, K., Verutes, G., Griffin, R., Guerry, A., Silver, J., Faries, J., Brenner, J. and Rosenthal, A., 2016. Evaluating the Benefits of Green Infrastructure for Coastal Areas: Location, Location, Location. *Coastal Management*, 44(5), pp.504–516. https://doi.org/10.1080/08920753.2016.1208882.

Tano, R.A., Aman, A., Toualy, E., Kouadio, Y.K., François-Xavier, B.B.D. and Addo, K.A., 2018. Development of an Integrated Coastal Vulnerability Index for the Ivorian Coast in West Africa. *Journal of Environmental Protection*, 09(11), pp.1171–1184. https://doi.org/10.4236/jep.2018.911073.

Triana, K. and Wahyudi, A.J., 2020. Sea level rise in Indonesia: The drivers and the combined impacts from land subsidence. *ASEAN Journal on Science and Technology for Development*, 37(3), pp.115–121. https://doi.org/10.29037/AJSTD.627.

U.S Geographical Survey, 2024. *Earth Explorer*. [online] USGS Earth Explorer. Available at: <https://earthexplorer.usgs.gov/>.

Uswatun, I., Heliani, L.S. and Basith, A., 2015. *VARIASI PERMUKAAN LAUT PERAIRAN PULAU JAWA BERDASARKAN DATA SATELIT ALTIMETRI DAN PASANG SURUT*. Gadjah Mada University.

Vitousek, S., Barnard, P.L., Fletcher, C.H., Frazer, N., Erikson, L. and Storlazzi, C.D., 2017. Doubling of coastal flooding frequency within decades due to sea-level rise. *Scientific Reports*, 7(1). https://doi.org/10.1038/s41598-017-01362-7.

Vovides, A.G., Bashan, Y., López-Portillo, J.A. and Guevara, R., 2011. Nitrogen Fixation in Preserved, Reforested, Naturally Regenerated and Impaired Mangroves as an Indicator of Functional Restoration in Mangroves in an Arid Region of Mexico. *Restoration Ecology*, 19(201), pp.236–244. https://doi.org/10.1111/j.1526-100X.2010.00713.x.

Wirasatriya, A., Setiawan, R.Y. and Subardjo, P., 2017. The Effect of ENSO on the Variability of Chlorophyll-a and Sea Surface Temperature in the Maluku Sea. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 10(12), pp.5513–5518. https://doi.org/10.1109/JSTARS.2017.2745207.

Wolanski, E. and Elliott, M., 2015. Estuarine Ecohydrology: An Introduction: Second Edition. *Estuarine Ecohydrology: An Introduction: Second Edition*, (August), pp.1–321.

Zaldívar-Jiménez, M.A., Herrera-Silveira, J.A., Teutli-Hernández, C., Comín, F.A., Andrade, J.L., Molina, C.C. and Ceballos, R.P., 2010. Conceptual framework for mangrove restoration in the Yucatán Peninsula. *Ecological Restoration*, 28(3), pp.333–342. https://doi.org/10.3368/er.28.3.333.

Van Zanten, B.T., Brander, L.M., Gutierrez Torres, D., Uyttendaele, G.Y.P., Herrera Garcia, L.D., Patrama, D. and Kaczan, D.J., 2021. The Economics of Large-scale Mangrove Conservation and Restoration in Indonesia. *The Economics of Large-scale Mangrove Conservation and Restoration in Indonesia*. https://doi.org/10.1596/37605.