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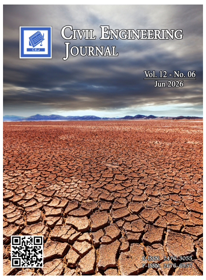

# Eco-Levee Coastal Corridors for Integrating Nature-Based and Hybrid Solutions in Coastal Resilience

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**Abstract**

Coastal settlements in low-lying tropical regions are increasingly threatened by tidal flooding, coastal erosion, and ecosystem degradation driven by climate change and rapid urbanization. *Objectives:* This study aims to develop and evaluate the Eco-Levee Coastal Corridor (ELCC) as a multifunctional spatial adaptation model that integrates coastal protection, ecological restoration, and social functions. Methods/Analysis: The research employs an integrated spatial analysis combining coastal hazard mapping, morphological assessment, and socio-spatial analysis of settlement patterns, supported by a design-based research approach to formulate the ELCC framework. The analysis focuses on coastal settlements in South Sulawesi, Indonesia, representing both urban and rural contexts with high vulnerability to tidal flooding and abrasion. *Findings:* The results demonstrate that ELCC enhances coastal resilience by combining hybrid engineering structures with Nature-Based Solutions, including vegetated buffers and edible forest systems, while simultaneously accommodating mobility corridors and community-based activities. This integrated configuration reduces exposure to coastal hazards, improves environmental quality, and supports local livelihoods. *Novelty:* The novelty of this study lies in reconceptualizing the eco-levee not merely as a defensive infrastructure but as a multifunctional coastal corridor that aligns technical engineering design with socio-spatial dynamics, offering a scalable and adaptive model for sustainable coastal development in vulnerable tropical coastal settlements.

*Keywords:* ELCC; Coastal Resilience; Nature-Based Solutions; Hybrid Engineering; Climate Adaptation.

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## 1. Introduction

### 1.1. Background

Coastal flooding, particularly tidal flooding, has become an increasingly severe threat to low-lying coastal settlements worldwide. Driven by sea-level rise, land subsidence, and extreme tidal fluctuations, tidal flooding results in seawater intrusion that disrupts daily life, damages infrastructure, and progressively reduces habitable land in coastal communities [1, 2]. These impacts are especially pronounced in Southeast Asia, including Indonesia, where coastal livelihoods are strongly dependent on fisheries and maritime activities, making communities highly sensitive to climate-induced disruptions [3]. Climate change accelerates these risks through rising ocean temperatures, polar ice melt, and the intensification of storm surges and wave energy. Empirical studies indicate that increased wave intensity significantly amplifies coastal erosion, undermining shoreline stability and degrading coastal infrastructure and public

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spaces [4, 5]. Concurrently, widespread degradation of coastal ecosystems—particularly mangrove loss—has weakened natural coastal defenses, further increasing vulnerability to tidal flooding and erosion [6].

Existing literature consistently highlights the interlinked roles of climatic drivers, geomorphological processes, and ecosystem degradation in shaping coastal vulnerability, emphasizing the need for integrated adaptation strategies. In response, coastal adaptation strategies have increasingly shifted toward ecosystem-based approaches and Nature-Based Solutions (NBS). Research demonstrates that coastal vegetation and hybrid ecological–engineering systems can effectively attenuate wave energy, reduce erosion, and enhance ecosystem services [7, 8]. Hybrid coastal infrastructures combining hard structures with ecological elements have gained attention, particularly in densely populated coastal areas where land scarcity and safety requirements coexist [9, 10]. Beyond physical protection, social dimensions—such as community participation and governance capacity—are also recognized as critical factors in strengthening coastal resilience [11, 12]. However, while these studies provide valuable insights into ecological performance, engineering efficiency, and governance frameworks, they tend to examine these dimensions separately rather than as an integrated socio-spatial system.

### 1.2. Review of Previous Research and Research Gap

Despite the growing body of research on eco-levees, hybrid coastal infrastructure, and Nature-Based Solutions, existing studies predominantly conceptualize these interventions as technical or ecological defense mechanisms. The majority of the literature emphasizes wave attenuation performance, structural efficiency, or ecosystem services, while giving limited attention to how such infrastructures function as integrated socio-spatial systems within everyday coastal life. This reveals a critical gap in the literature regarding the spatial and social embeddedness of coastal defense infrastructures, particularly in densely populated and informal settlements.

Specifically, three key gaps can be identified. First, there is insufficient integration between coastal protection infrastructure and spatial functions, such as mobility corridors, public access, and livelihood-related activities, particularly in informal and densely populated coastal settlements. Second, although community participation is frequently discussed in policy-oriented studies, few design-based frameworks explicitly embed local social structures and kinship-based settlement patterns into the spatial and technical configuration of coastal defense systems. Third, existing eco-levee models rarely address the need for multifunctional adaptability, where a single infrastructure simultaneously delivers protection, ecological restoration, and socio-economic benefits under long-term climate uncertainty. These gaps indicate that current approaches remain largely sectoral, overlooking the potential of coastal infrastructure to operate as an integrated platform for resilience, everyday use, and socio-economic adaptation.

Addressing these gaps, this study proposes ELCC as a multifunctional and spatially integrated adaptation model. ELCC reconceptualizes the levee not only as a protective barrier against tidal flooding and erosion, but also as an ecological and social corridor that supports mobility, livelihood activities, and community interaction. By integrating Nature-Based Solutions within a hybrid engineering structure and aligning them with local socio-spatial dynamics, ELCC advances a more holistic and transformative approach to coastal resident.

Research on coastal resilience and eco-levees has explored various approaches, including ecosystem-based services, NBS, and socio-ecological resilience analysis. Several studies highlight the role of ecological barriers in disaster mitigation and environmental protection [8], while others focus on adaptation strategies to sea-level rise and urbanization [9, 13]. Economic and policy-driven approaches in coastal management have also evolved, including the potential for financing through blue carbon markets [14] and cost-benefit analyses of coastal embankments [15]. Material innovations, such as biopolymers, have been investigated to enhance levee resilience against erosion and runoff [16]. Nature-based and hybrid infrastructure solutions demonstrate the effectiveness of coastal vegetation in wave attenuation and environmental resilience [7, 17]. Studies in Japan following the 2011 Tohoku tsunami also indicate public preference for hybrid infrastructure solutions [10]. From a social perspective, community empowerment has been found to significantly enhance disaster resilience [12], while interactions between hard and soft infrastructure contribute to urban resilience [11].

While most research has focused on eco-levees primarily as coastal defense structures, this study advances the concept of a multifunctional eco-levee that serves not only as a coastal protection measure but also as an integrated regional corridor supporting transportation, socio-economic activities, ecology, and recreation. This comprehensive approach delivers broader benefits to coastal communities, promoting resilience and sustainability beyond conventional flood mitigation strategies.

### 1.3. Problem Formulation and the Need for a Multifunctional Eco-Levee Solution

- How can coastal vulnerability to tidal flooding and erosion, driven by climate change and urbanization, be reduced through sustainable infrastructure?
- How can the integration of NBS and hybrid infrastructure in eco-levee development enhance coastal resilience?

- How can an eco-levee function as a safe and accessible interregional corridor to improve connectivity in coastal areas?
- How can an eco-levee contribute to the socio-economic well-being of coastal communities by fostering coastal-based enterprises and promoting ecotourism?
- How can an eco-levee support ecological sustainability and climate change mitigation through coastal vegetation restoration as a natural buffer and blue carbon sink?

### 1.4. Research Objective

This study aims to develop a multifunctional eco-levee that serves not only as a coastal defense against tidal flooding and erosion but also as an integrated system that incorporates transportation, socio-economic, recreational, and ecological functions within a sustainable framework. The concept is designed to enhance coastal resilience by combining NBS and hybrid infrastructure, thereby reinforcing regional connectivity through the provision of safe and accessible transportation routes.

Furthermore, the eco-levee is expected to support economic sustainability and social well-being by creating opportunities for coastal-based businesses and fostering ecotourism development. From an ecological perspective, this system contributes to climate change mitigation by restoring coastal vegetation, which acts as a natural buffer against extreme weather events and functions as a blue carbon sink. By integrating these multiple dimensions, the eco-levee is envisioned as an innovative and holistic solution that enhances coastal resilience across physical, social, economic, and environmental aspects in a sustainable manner.

## 2. Research Methodology

This study employs a combination of Geographic Information System (GIS) technology and hydrodynamic modeling to analyze coastal dynamics, particularly those related to shoreline change, tidal flooding, erosion, and oceanographic patterns. The methodology is designed to identify land-use transformations, map high-risk flood-prone zones, and evaluate the effectiveness of natural and engineered coastal protection strategies.

### 2.1. Spatial and Hydrodynamic Analysis Framework

### 2.1.1. GIS-Based Mapping and Land Use Change Analysis

- Shoreline Change Analysis is conducted using GIS techniques to assess erosion and accretion patterns. Data sources include:
    - Satellite imagery from United States Geological Survey (USGS) and Environmental Systems Research Institute (ESRI) for multi-temporal coastline mapping.
    - Google Earth historical imagery to identify land-use and functional changes in coastal areas.
- Flood Vulnerability Mapping utilizes spatial data from Indonesia Disaster Risk Index (InaRISK) Badan Nasional Penanggulangan Bencana (BNPB)/ National Board for Disaster Management, which includes:
    - Projection: Universal Transverse Mercator (UTM)
    - Grid System: Geographic Grid System
    - Horizontal Datum: World Geodetic System (WGS) 84, Zone 50S

### 2.1.2. Hydrodynamic Modeling

To simulate and analyze ocean dynamics affecting the coastal region, a hydrodynamic model is employed to evaluate:

- Tidal fluctuations;
- Wave height and direction;
- Ocean current velocity and direction.

Key data inputs include:

- Tide and Sea-Level Data: Provided by BMKG (Meteorology, Climatology, and Geophysics Agency of Indonesia)
- High Tide Reference Station:
    - Station Name: Paotere Maritime Meteorological Station;
    - World Meteorological Organization Identification Number (WMO ID): 97182;

  - ○ Latitude: -5.11375;
  - ○ Longitude: 119.41983;
  - ○ Elevation: 5 meters above sea level.

### 2.2. Climate and Rainfall Pattern Analysis

To understand hydrometeorological drivers of flooding, this study incorporates:

- Daily Climate Data from BMKG Paotere Station, focusing on rainfall patterns during the peak rainy season (December–February).
- Rainfall Distribution Mapping using:
  - ○ CHIRPS (Climate Hazards Group InfraRed Precipitation with Station Data) imagery for spatial-temporal rainfall intensity.
  - ○ GADM (Global Administrative Areas) data for geospatial referencing of administrative boundaries.

### 2.3. Data Collection Approach

### 2.3.1. Quantitative Data Collection

- Remote Sensing and Satellite Imagery:
  - ○ Google Earth (land use)
  - ○ USGS & ESRI (shoreline change)
- Oceanographic Data:
  - ○ Current, tide, and wave data from BMKG and international marine datasets
- Climate Data:
  - ○ Daily precipitation from BMKG Station Paotere (WMO ID: 97182)
  - ○ CHIRPS precipitation raster data for peak rainfall mapping

### 2.3.2. Qualitative Data Collection

- Photographic Documentation and Field Observation:
  - ○ To illustrate structural adaptations in coastal settlements impacted by tidal flooding.
- Coastal Function Assessment:
  - ○ Evaluates the social, residential, and economic functions of the coastline for the local community.
- Comparative Case Studies:
  - ○ Reviews the design and effectiveness of various coastal protection measures, such as conventional seawalls, breakwaters, and hybrid eco-levees.
  - ○ For the collection of qualitative data, the research team received valuable assistance from the village head and local families who served as key informants, possessing in-depth knowledge of the village's socio-environmental conditions. Additional support was provided by village staff, particularly in facilitating access to respondents and organizing the data-gathering process. The local informants were long-term residents whose families had inhabited the area for generations, ensuring rich historical and contextual insights.

Prior to conducting interviews with informants and community members, the researchers clearly explained the objectives and purpose of the study, as well as the type of data expected from the interviews. All participants expressed their understanding and consent, acknowledging the relevance and significance of the research. They also noted that their village had frequently been visited by researchers and recognized that the findings of this study could serve as a valuable reference for local government in addressing coastal challenges and improving community resilience.

### 2.4. Integrated Analysis

By synthesizing spatial (GIS), dynamic (hydrodynamic model), and field-based data, this study aims to:

- Delineate and prioritize high-risk zones exposed to tidal flooding and erosion.

- Quantify the protective role of coastal vegetation against shoreline retreat.
- Assess climate and rainfall influence on flood dynamics.
- Recommend adaptive, sustainable strategies including nature-based solutions (NBS) and hybrid engineering approaches for improving coastal resilience.

Rationale and Objectives for Integrating Quantitative and Qualitative Methods in Coastal Risk Analysis. This study adopts a mixed-methods approach, integrating both quantitative and qualitative data to gain a comprehensive understanding of coastal environmental changes, particularly in relation to tidal flooding, shoreline erosion, and their socio-spatial implications. The integration of these two methodologies is crucial in bridging the gap between large-scale environmental data and the localized, human-scale experiences and adaptive responses of coastal communities.

### 2.4.1. Objectives of Quantitative and Qualitative Analysis

The quantitative component of this research focuses on:

- Spatial and temporal analysis of coastal change, including shoreline retreat and land-use transformation, using satellite imagery and GIS-based mapping.
- Hydrodynamic modeling to simulate ocean currents, wave heights, and tidal fluctuations, incorporating oceanographic and climatic data from the Meteorology, Climatology, and Geophysics Agency of Indonesia (BMKG) and Paotere Maritime Meteorological Station.
- Flood vulnerability and risk assessment, utilizing flood hazard datasets from InaRISK BNPB, integrated with geospatial data (WGS 84, Universal Transverse Mercator Zone (UTM Zone) 50S) and high-resolution elevation maps.
- Rainfall trend analysis, especially during the peak monsoon season (December–February), by analyzing CHIRPS satellite data and ground-station records to understand the correlation between heavy rainfall and coastal inundation events.

The qualitative approach aims to:

- Document the socio-ecological impacts of tidal flooding through photographic evidence and systematic field observations of housing adaptations, infrastructure vulnerability, and daily disruptions in affected coastal settlements.
- Explore local perceptions and adaptive strategies, using interviews and participatory observations to understand how communities respond to and cope with chronic flooding and erosion.
- Assess the functional role of coastal zones as spaces for residence, economy, and social interaction, which are often underrepresented in purely physical or spatial analyses.
- Conduct comparative case studies to evaluate the design and performance of coastal protection structures (e.g., seawalls, vegetative buffers, hybrid levees) implemented in other regions, identifying best practices and context-specific applicability.

### 2.4.2. Integration Purposes and Added Value

The integration of these two methodological approaches serves several key purposes:

- To connect macro-scale environmental dynamics with micro-scale social experiences, allowing for a more nuanced interpretation of how physical changes affect human systems.
- To validate and contextualize spatial data by grounding remote sensing and model-based findings in the lived experiences and observational insights gathered from the field.
- To inform site-specific, adaptive solutions that are both technically sound and socially acceptable, ensuring that proposed mitigation strategies—such as nature-based solutions, multi-functional levees, or ecological buffer zones—align with community needs and spatial realities.
- To foster interdisciplinary insights, combining geospatial technologies, environmental sciences, and social inquiry to advance sustainable coastal resilience planning.

Through this integrated framework, the research not only identifies patterns of environmental vulnerability but also elevates local knowledge and adaptive practices as key elements in developing inclusive, scalable, and sustainable coastal management strategies (Figure 1).

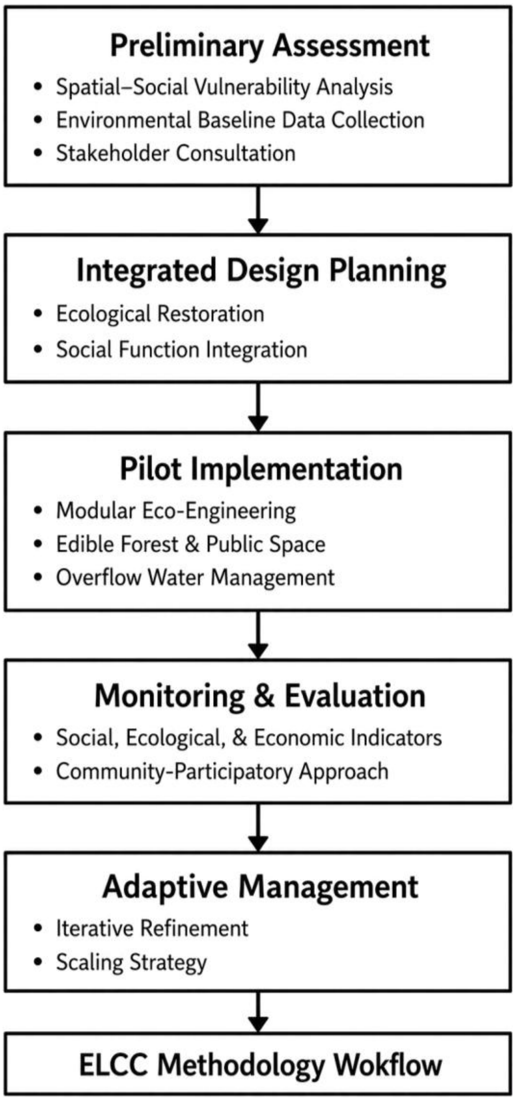


**Figure 1. ELCC Methodology Work Flow**

### 2.4.4. Research Location

The study will be conducted in rural coastal areas of Galesong Utara District, Takalar Regency, South Sulawesi (Figure 2). This region has been selected due to its direct exposure to the Makassar Strait and the increasing threats of:

- Erosion and abrasion;
- Tidal flooding (rob);
- Seawater intrusion;
- Declining environmental quality;
- Loss of protective coastal vegetation;
- Climate change and extreme weather events;
- Land-use conflicts;
- Unplanned urbanization and coastal development.

Given these pressing challenges, Galesong Utara presents an ideal case study for investigating sustainable coastal resilience strategies, particularly through the implementation of nature-based solutions and hybrid infrastructure approaches.

The research location is in Biringkassi Village, specifically in the Karamak and Ujung Kassi hamlets, which are adjacent to the coast (Figure 3). The area has a high-density settlement, with some houses even built on the beach. However, most houses are constructed at the highest tidal boundary, particularly in Middle Karamak and South Karamak, making them highly vulnerable to coastal erosion and tidal flooding (rob).

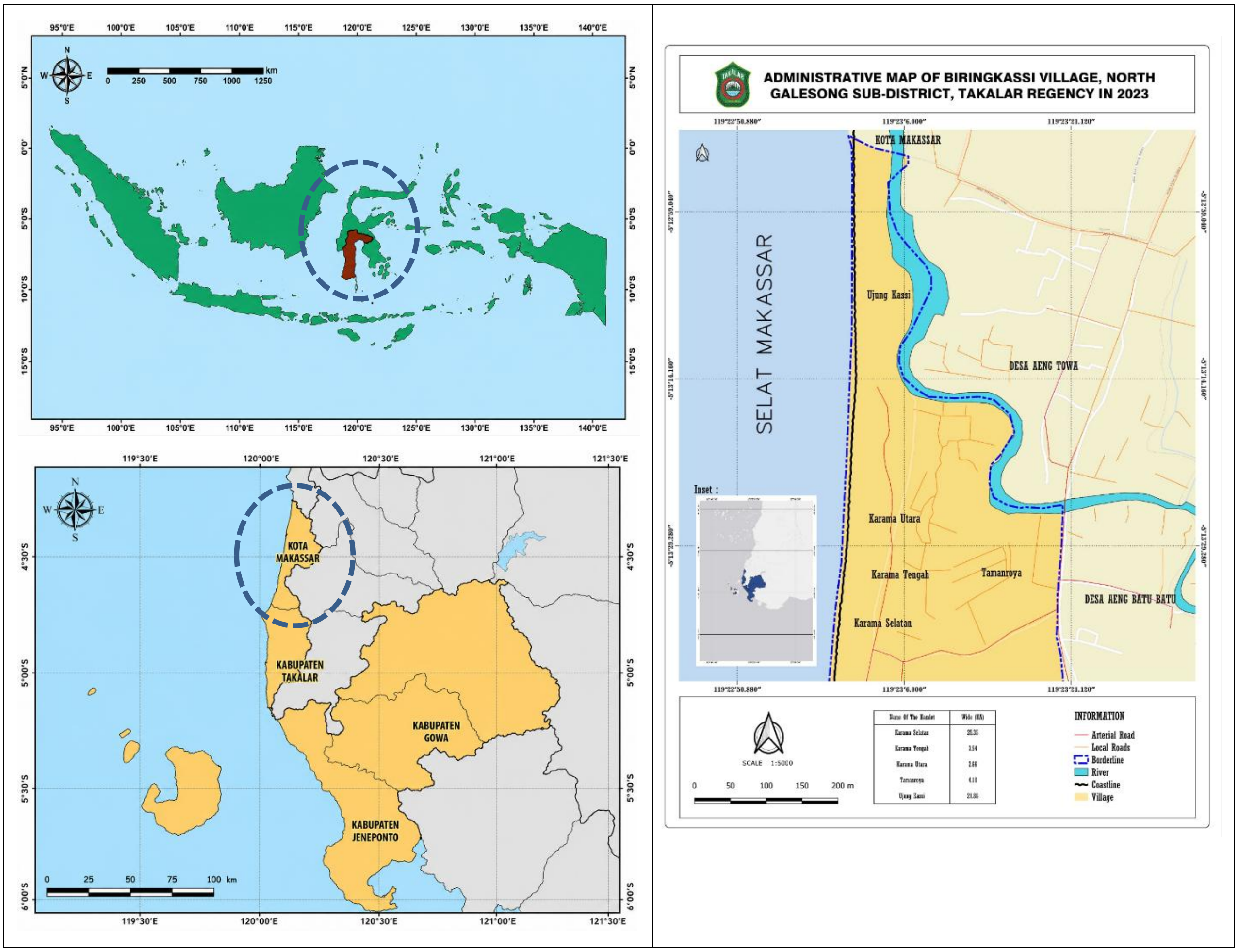


**Figure 2. Map of Indonesia, Takalar Regency, and North Galesong District**

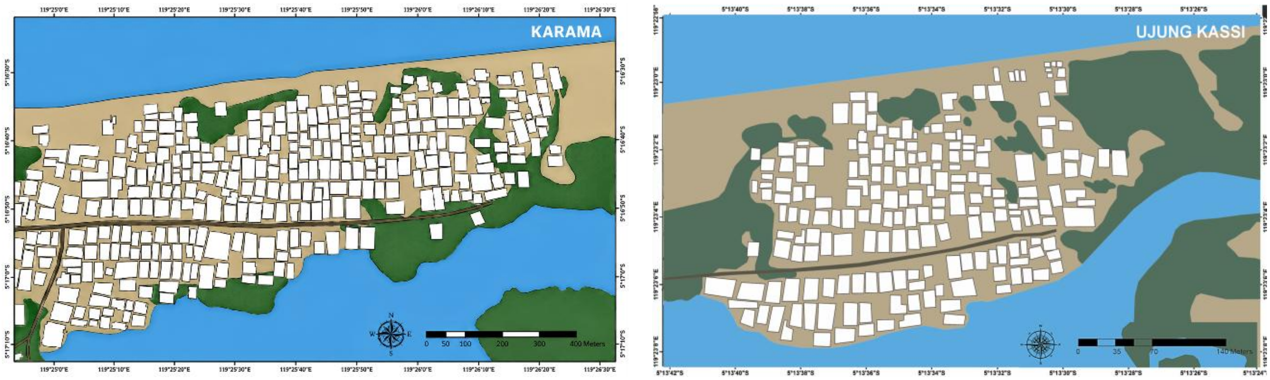


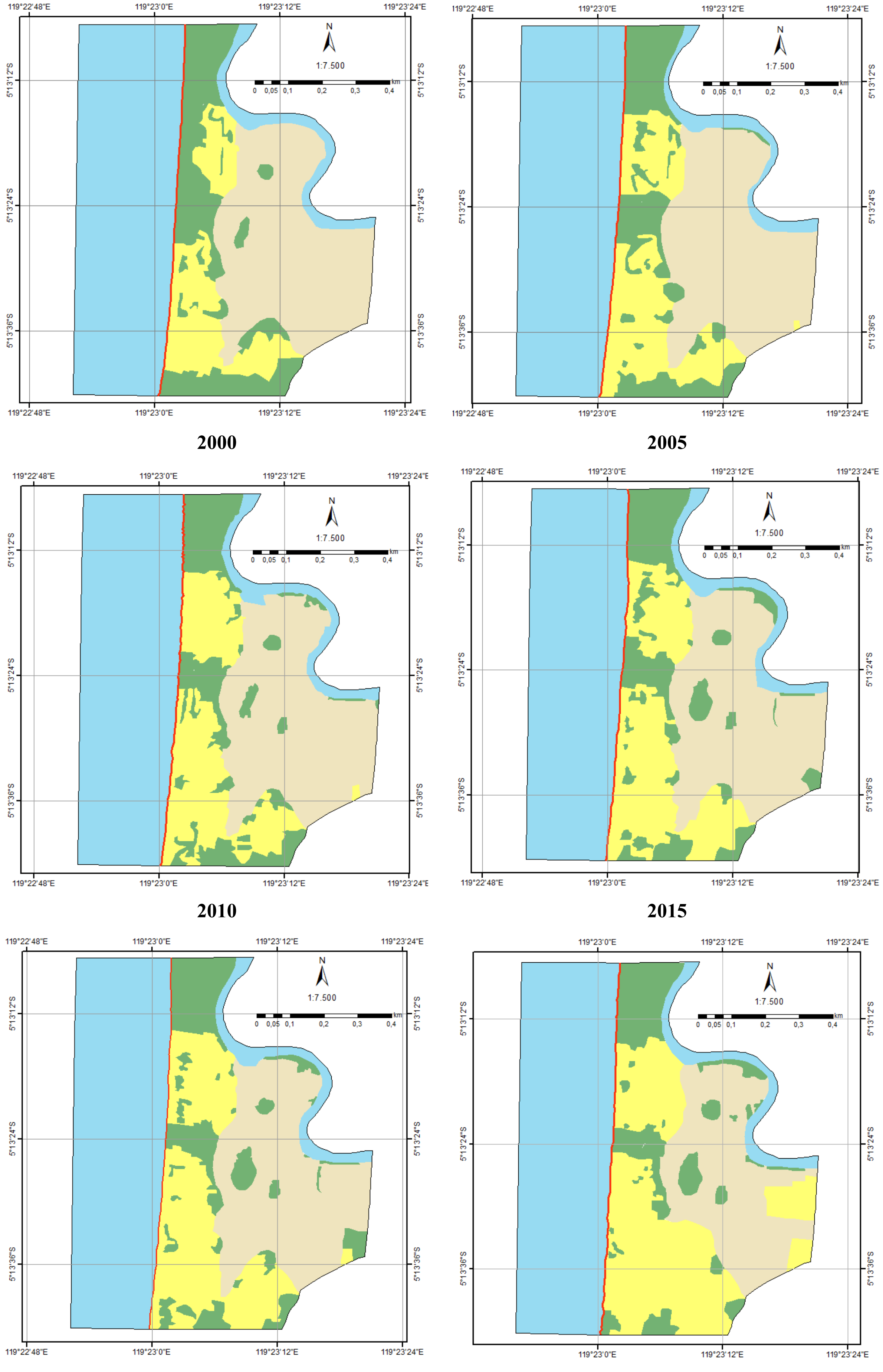
**Figure 3. Research Location: Biringkassi Village (Karamak Selatan, Karamak Tengah, Karamak Utara, and Ujung Kassi Hamlets)**

# 3. Results

## 3.1. Spatial Data and Analysis

The following section presents spatial data and analyses for Biringkassi Village, which is located along the coastline:

***Land Use Change:*** Spatial data and land use change analyses were conducted using multi-temporal Google Earth imagery covering the period from 2000 to 2025. The imagery was processed and analyzed using GIS techniques. Land use changes were visualized through color-coded maps, in which yellow represents residential areas, green indicates green open spaces and vegetation, brown denotes ponds or other water bodies, and blue represents river networks. The results reveal a significant transformation in land use patterns over time, characterized by the continuous spatial expansion of residential areas (yellow zones) and a corresponding reduction in green open spaces and vegetated areas (green zones). This pattern reflects the gradual conversion of ecological and open spaces into built-up environments, highlighting increasing anthropogenic pressure on coastal landscapes.



2000

2005

2010

2015

2020

2025

**Figure 4. Land use changes from 2000 to 2025**

Figure 5 illustrates the changes in land use over time. Residential areas have increased year by year, while green open space (vegetation) has decreased in volume. Likewise, ponds and water bodies have also diminished. Since 2022, residential developments and social function buildings, such as hospitals, have been constructed in former pond and water body areas. The following image shows changes in the coastline that have occurred from 2000 to 2025 (data from the Google Citra satellite only show this time span).

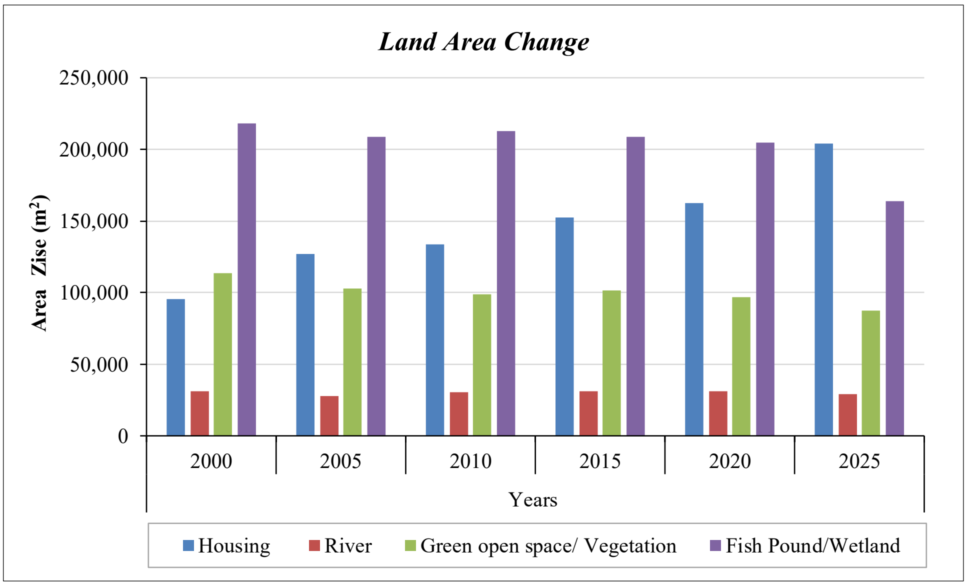
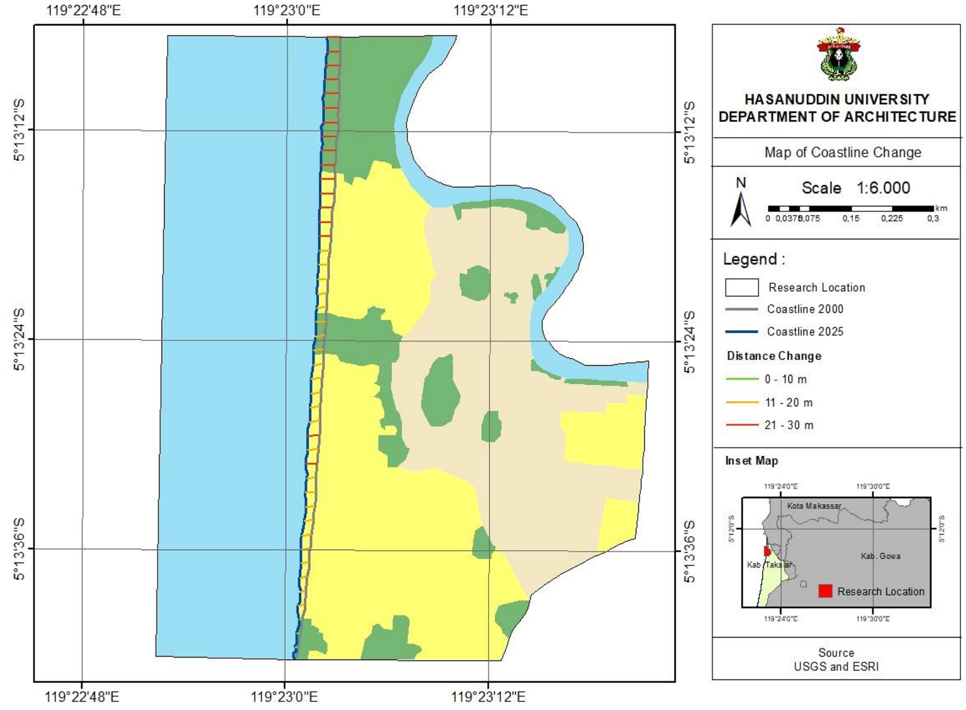


**Figure 5. Land Area Change and Land Use Change Graph**

The Biringkassi area, particularly Ujung Kassi and North Karamak, continues to experience sedimentation. However, South Karamak and middle Karamak have been affected by coastal erosion. According to several sources, including local residents and village officials, this erosion has intensified since sand mining began in the shallow waters near their settlement. Additionally, the construction of coastal embankments in neighboring areas has exacerbated the problem. The embankments, which were built only in adjacent regions and left incomplete at the border, have redirected strong waves toward unprotected areas. Previously, these waves primarily impacted the neighboring regions, but with the embankments in place, they are now striking South Karamak and Middle Kramak. As shown in Figure 6, the shoreline has retreated by approximately 0–10 meters in these areas, whereas Ujung Kassi and North Karamak have maintained their land expansion due to continued sedimentation.



Coastline Change from 2000-2025

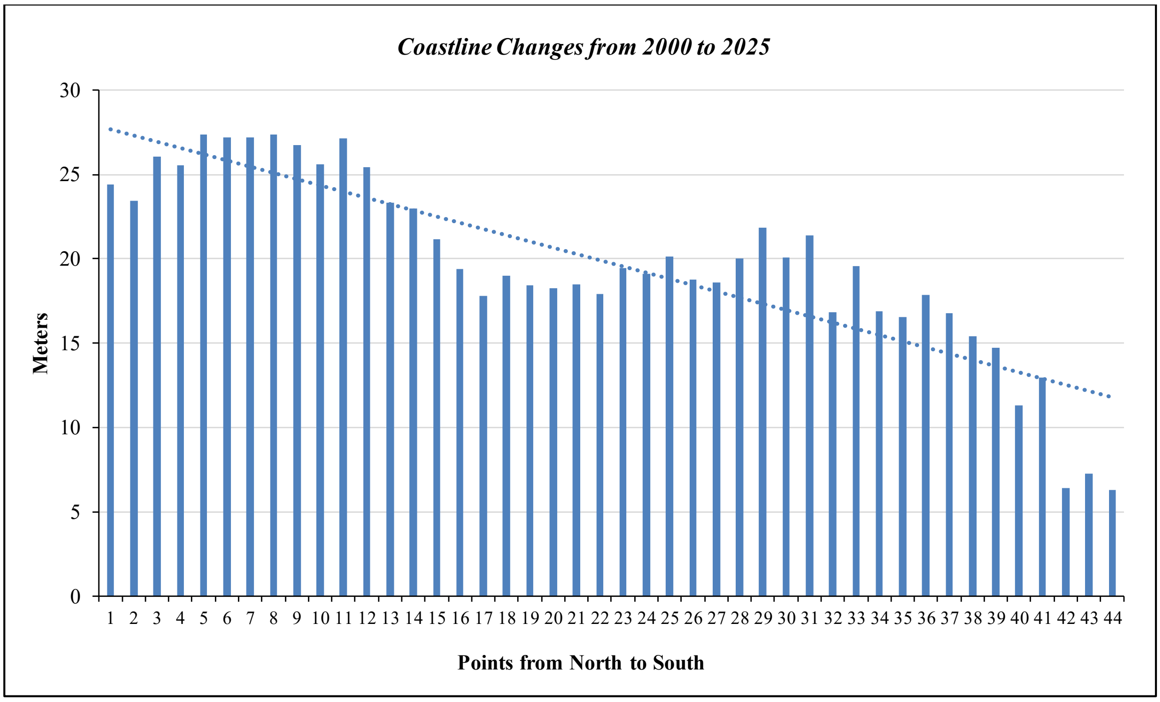
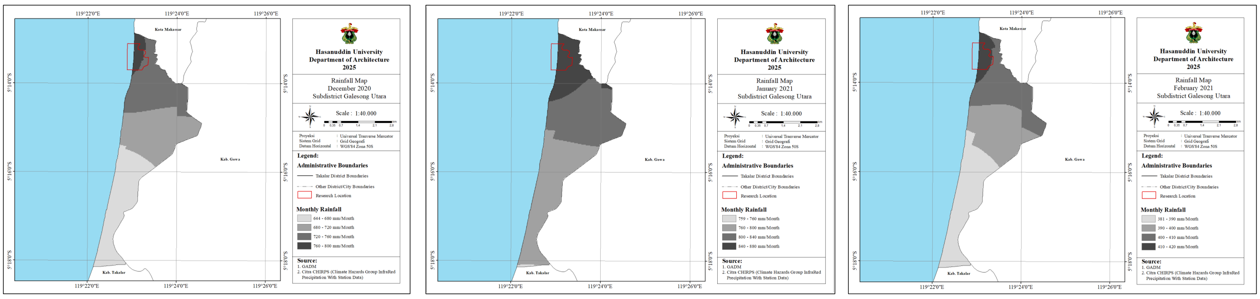
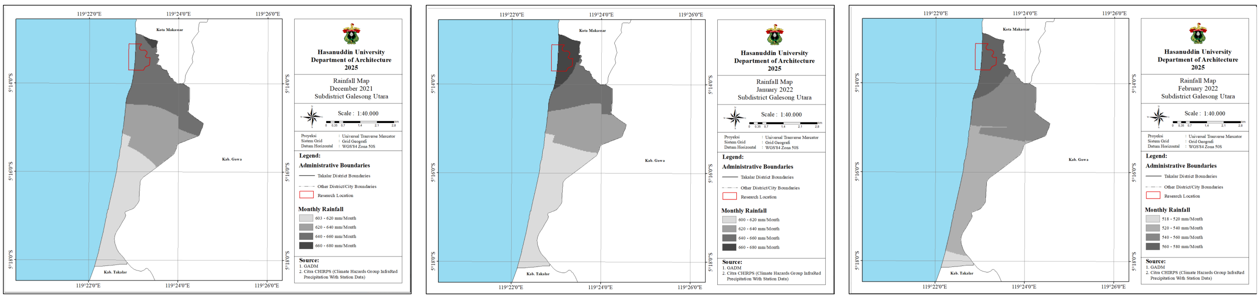


**Figure 6. Coastline Change and grafik from 2000-2025**

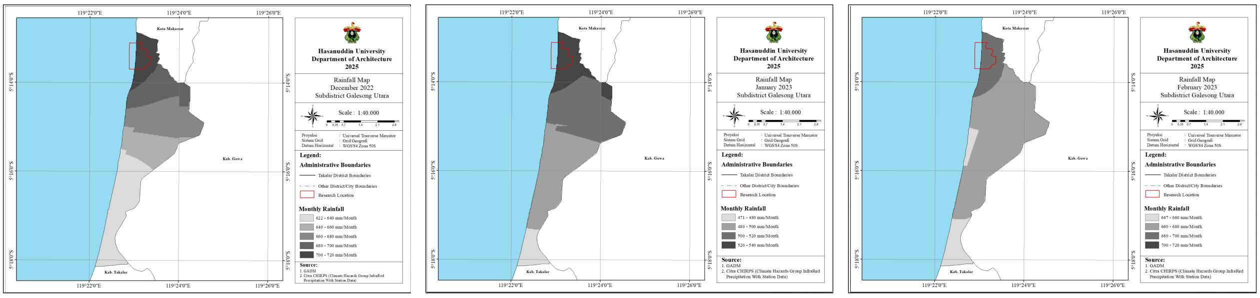
Figure 7 illustrates the highest rainfall recorded during the rainy seasons over the past five years. The rainy season in Indonesia typically lasts for approximately six months, from October to April, influenced by the Asian monsoon. The most intense and highest rainfall usually occurs in December, January, and February (DJF) [18-20].



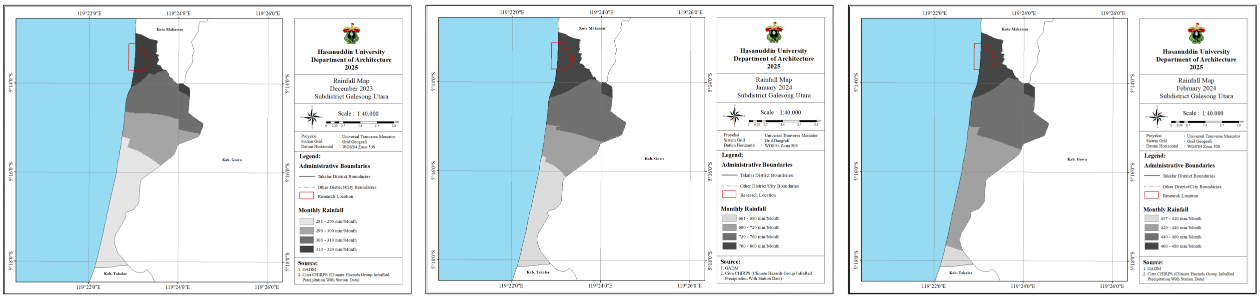
December 2020 January 2021 February 2021



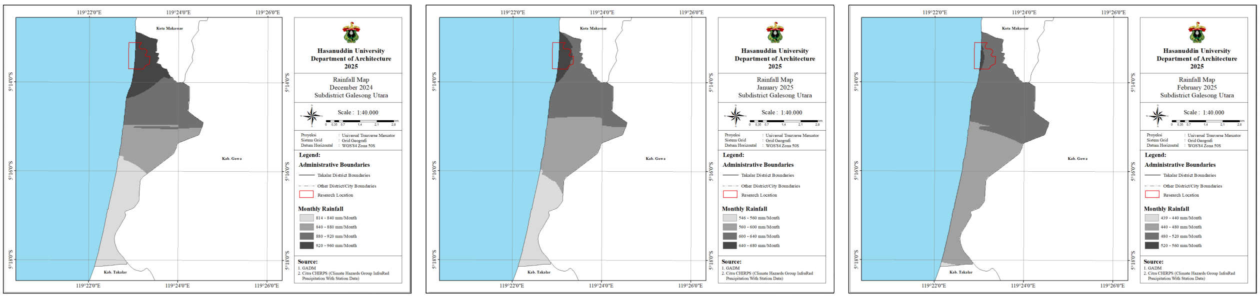
December 2021 January 2022 February 2022



December 2022 January 2023 February 2023



December 2023 January 2024 February 2024



December 2024 January 2025 February 2025

**Figure 7. Map of the highest rainfall during the rainy season**

The highest rainfall data were obtained from the GADM database and the CHIRPS dataset (Table 1). These data were subsequently analyzed using GIS to generate a spatial visualization depicting rainfall intensity gradients, represented through a color-coded map based on precipitation levels.

**Table 1. Graph of the highest rainfall when the peak of the rainy season begins**

| Moon-Years | Rainfall |
|---|---|
| December'20 | 720-800 mm/Month |
| January'21 | 840-880 mm/Month |
| February' 21 | 440-420 mm/Month |
| December'21 | 640-680 mm/Month |
| January'22 | 660-680 mm/Month |
| February'22 | 560-580 mm/Month |
| December' 22 | 700-720 mm/month |
| January'23 | 520-540 mm/Month |
| February'23 | 700-720 mm/Month |
| December'23 | 310-320 mm/Month |
| January '24 | 760-800 mm/Month |
| February'24 | 460-480 mm/Month |
| December'24 | 920-960 mm/Month |
| January'25 | 600-680 mm/Month |
| February'25 | 480-560 mm/Month |

Data resource: CHIRPS (Climate Hazard)

Data collected over five consecutive rainy seasons, specifically during December, January, and February, which are typically the peak months of the rainy season; indicate that North Galesong, particularly the Biringkassi area, experiences consistently high rainfall. The recorded average precipitation exceeds 700 mm per month, highlighting significant hydrometeorological challenges in the region.

Figure 8 illustrates the areas prone to flooding within Karamak and Biringkassi, providing a visual representation of flood-risk zones and their spatial distribution.

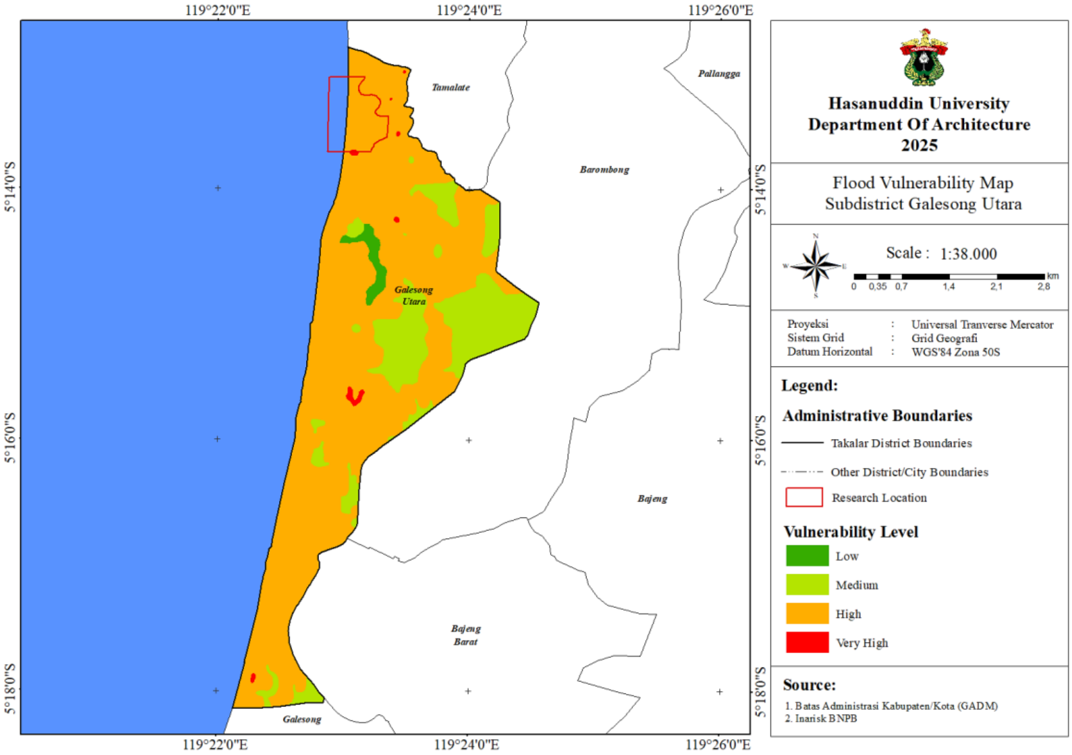


**Figure 8. Highest tide data in each rainy season from 2020-2025 (last 5 years)**

Take on the day when the highest tide occurred each month (in the peak month of the rainy season). The image indicates that nearly the entire North Galesong region, including Biringkassi village, is highly vulnerable to flooding.

Table 2 displaying the highest and lowest tidal levels on specific days during the peak months of the rainy season. This data provides critical insights into tidal fluctuations and their correlation with extreme weather conditions, which contribute to coastal flooding and inundation.

The data shows the highest tide data on the highest day in each month of December, January and February (complete data in the attachment). According to BMKG Agency of Indonesia, normal tidal fluctuations (0–1 meters) do not significantly impact coastal areas. However, high tides between 1–1.5 meters pose a risk of coastal flooding, while tides exceeding 1.5–2 meters or more are considered dangerous, potentially causing severe flooding.

Even at 1–1.5 meters, if tidal surges persist over time or coincide with extreme weather conditions (such as during peak rainy seasons) coastal hazards can intensify. These include tidal flooding, shoreline erosion, seawater intrusion, and ecosystem degradation [21-23].

**Table 2. High tide**

| ***Hour*** | **13/12/2020** | **30/1/2021** | **28/2/2021** | **3/12/2021** | **2/1/2022** | **1/2/2022** | **23/12/2022** | **23/1/2023** | **20/2/2023** | **13/12/2023** | **12/1/2024** | **11/2/2024** | **14/12/2024** | **31/1/2025** | **28/2/2025** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ***Height (m)*** | ***Height (m)*** | ***Height (m)*** | ***Height (m)*** | ***Height (m)*** | ***Height (m)*** | ***Height (m)*** | ***Height (m)*** | ***Height (m)*** | ***Height (m)*** | ***Height (m)*** | ***Height (m)*** | ***Height (m)*** | ***Height (m)*** | ***Height (m)*** |
| 0:00 | 0.97 | 1.03 | 0.90 | 0.98 | 0.89 | 0.82 | 0.94 | 0.91 | 0.78 | 0.98 | 0.97 | 0.93 | 0.92 | 1.02 | 0.85 |
| 1:00 | 0.87 | 0.91 | 0.81 | 0.89 | 0.76 | 0.69 | 0.81 | 0.77 | 0.66 | 0.86 | 0.83 | 0.82 | 0.80 | 0.90 | 0.76 |
| 2:00 | 0.78 | 0.78 | 0.71 | 0.79 | 0.63 | 0.56 | 0.67 | 0.63 | 0.54 | 0.73 | 0.69 | 0.70 | 0.69 | 0.77 | 0.66 |
| 3:00 | 0.68 | 0.66 | 0.61 | 0.68 | 0.50 | 0.43 | 0.54 | 0.49 | 0.42 | 0.61 | 0.55 | 0.58 | 0.57 | 0.65 | 0.56 |
| 4:00 | 0.58 | 0.53 | 0.51 | 0.58 | 0.39 | 0.33 | 0.41 | 0.37 | 0.34 | 0.48 | 0.40 | 0.46 | 0.47 | 0.52 | 0.48 |
| 5:00 | 0.51 | 0.43 | 0.45 | 0.52 | 0.30 | 0.24 | 0.32 | 0.27 | 0.26 | 0.39 | 0.31 | 0.38 | 0.40 | 0.43 | 0.42 |
| 6:00 | 0.45 | 0.34 | 0.38 | 0.45 | 0.22 | 0.15 | 0.23 | 0.18 | 0.19 | 0.31 | 0.21 | 0.30 | 0.32 | 0.33 | 0.36 |
| 7:00 | 0.40 | 0.26 | 0.34 | 0.40 | 0.16 | 0.10 | 0.17 | 0.12 | 0.15 | 0.24 | 0.13 | 0.24 | 0.27 | 0.26 | 0.33 |
| 8:00 | 0.39 | 0.22 | 0.33 | 0.39 | 0.15 | 0.10 | 0.15 | 0.09 | 0.16 | 0.21 | 0.09 | 0.21 | 0.27 | 0.21 | 0.34 |
| 9:00 | 0.41 | 0.26 | 0.35 | 0.41 | 0.20 | 0.14 | 0.18 | 0.12 | 0.21 | 0.23 | 0.11 | 0.23 | 0.31 | 0.22 | 0.37 |
| 10:00 | 0.47 | 0.33 | 0.39 | 0.47 | 0.29 | 0.24 | 0.26 | 0.21 | 0.30 | 0.29 | 0.17 | 0.28 | 0.39 | 0.26 | 0.42 |
| 11:00 | 0.54 | 0.42 | 0.45 | 0.53 | 0.39 | 0.34 | 0.36 | 0.32 | 0.39 | 0.39 | 0.28 | 0.36 | 0.48 | 0.34 | 0.47 |
| 12:00 | 0.61 | 0.42 | 0.50 | 0.60 | 0.52 | 0.48 | 0.47 | 0.44 | 0.52 | 0.49 | 0.39 | 0.44 | 0.58 | 0.43 | 0.54 |
| 13:00 | 0.71 | 0.52 | 0.59 | 0.70 | 0.68 | 0.63 | 0.62 | 0.60 | 0.66 | 0.63 | 0.55 | 0.56 | 0.72 | 0.54 | 0.62 |
| 14:00 | 0.81 | 0.65 | 0.67 | 0.80 | 0.83 | 0.79 | 0.78 | 0.77 | 0.80 | 0.77 | 0.71 | 0.68 | 0.85 | 0.67 | 0.71 |
| 15:00 | 0.91 | 0.78 | 0.75 | 0.90 | 0.99 | 0.95 | 0.93 | 0.93 | 0.94 | 0.91 | 0.87 | 0.80 | 0.98 | 0.79 | 0.79 |
| 16:00 | 1.01 | 0.90 | 0.84 | 1.00 | 1.11 | 1.06 | 1.07 | 1.07 | 1.03 | 1.06 | 1.03 | 0.92 | 1.08 | 0.92 | 0.87 |
| 17:00 | 1.08 | 1.01 | 0.90 | 1.07 | 1.21 | 1.17 | 1.17 | 1.18 | 1.13 | 1.15 | 1.14 | 1.00 | 1.17 | 1.02 | 0.92 |
| 18:00 | 1.15 | 1.09 | 0.96 | 1.14 | 1.30 | 1.25 | 1.27 | 1.28 | 1.19 | 1.25 | 1.25 | 1.08 | 1.24 | 1.11 | 0.98 |
| 19:00 | 1.20 | 1.17 | 1.01 | 1.19 | 1.33 | 1.27 | 1.32 | 1.33 | 1.21 | 1.33 | 1.33 | 1.16 | 1.27 | 1.18 | 1.02 |
| 20:00 | 1.21 | 1.21 | 1.03 | 1.21 | 1.31 | 1.25 | 1.33 | 1.32 | 1.19 | 1.33 | 1.33 | 1.15 | 1.26 | 1.21 | 1.04 |
| 21:00 | 1.19 | 1.21 | 1.03 | 1.20 | 1.25 | 1.19 | 1.29 | 1.27 | 1.13 | 1.30 | 1.30 | 1.13 | 1.21 | 1.21 | 1.03 |
| 22:00 | 1.13 | 1.17 | 1.01 | 1.15 | 1.16 | 1.11 | 1.20 | 1.18 | 1.06 | 1.23 | 1.22 | 1.08 | 1.12 | 1.16 | 0.98 |
| 23:00 | 1.06 | 1.10 | 0.95 | 1.07 | 1.07 | 1.02 | 1.11 | 1.09 | 0.98 | 1.14 | 1.13 | 1.01 | 1.03 | 1.09 | 0.93 |

Based on the daily climate data in Table 3, it is included in strong winds. Table 4 shows the Impact of Wind Speed on coastal areas.

**Table 3. Daily climate data**

| DATE | TN | TX | TAVG | RH_AVG | RR | FF_X | DDD_X | FF_AVG | DDD_CAR |
|---|---|---|---|---|---|---|---|---|---|
| 24-02-2020 | 25.6 | 33.5 | 28.8 | 81 | 5.6 | 11 | 130 | 3 | SW |
| 03-02-2020 | 26.2 | 32.7 | 28.8 | 82 | 8888 | 15 | 16 | 2 | NW |
| 09-12-2020 | 25 | 32.8 | 28.4 | 80 | 10.6 | 10 | 280 | 2 | E |
| 15-02-2021 | 24 | 28.6 | 24.7 | 93 | 24.1 | 13 | 270 | 2 | E |
| 24-02-2021 | 25 | 30.1 | 26.6 | 90 | 11.3 | 10 | 290 | 3 | E |
| 20-12-2021 | 26.4 | 31.2 | 28.4 | 82 | 8888 | 11 | 200 | 4 | NW |
| 30-12-2021 | 24.3 | 29 | 27.1 | 86 | 29.4 | 10 | 310 | 2 | NW |
| 15-01-2022 | 24 | 28.6 | 26.5 | 86 | 24.7 | 14 | 250 | 4 | E |
| 03-01-2023 | 25.6 | 31.9 | 26.3 | 89 | 9.6 | 10 | 280 | 5 | W |
| 22-01-2023 | 26 | 30.8 | 27.8 | 84 | 0.4 | 11 | 120 | 3 | NW |
| 08-02-2023 | 25.7 | 30.2 | 27.6 | 81 | 0.8 | 11 | 310 | 2 | N |
| 13-02-2023 | 24 | 27.8 | 25.3 | 94 | 200 | 10 | 270 | 6 | W |
| 14-02-2023 | 23.6 | 29.8 | 27.1 | 83 | 183 | 10 | 280 | 6 | W |
| 22-02-2023 | 24.8 | 30.2 | 27 | 88 | 25.7 | 10 | 250 | 3 | N |
| 26-02-2023 | 25.4 | 29 | 26.5 | 90 | 2.4 | 10 | 270 | 3 | W |
| 10-12-2023 | 24.2 | 31 | 26.2 | 87 | 8.2 | 10 | 330 | 3 | SE |
| 17-12-2023 | - | - | - | 88 | 0 | 10 | 290 | 2 | E |
| 11-01-2024 | 25.2 | 31.6 | 26.3 | 89 | 0 | 10 | 310 | 3 | E |
| 14-01-2024 | 23.4 | 27.3 | 25.6 | 92 | 26.9 | 10 | 320 | 3 | NW |
| 15-01-2024 | 24.6 | 28.9 | 25.9 | 93 | 8888 | 11 | 280 | 4 | W |
| 16-01-2024 | 24.6 | 29.1 | 25.4 | 92 | 33.2 | 12 | 310 | 3 | E |
| 22-01-2024 | 23.7 | 30.9 | 26.7 | 85 | 21.2 | 11 | 280 | 5 | NW |
| 23-01-2024 | 23.8 | 29 | 25.9 | 90 | 16.8 | 10 | 290 | 5 | NW |
| 24-01-2024 | 23.3 | 29 | 27.1 | 86 | 51.4 | 10 | 320 | 6 | NW |
| 26-01-2024 | - | - | - | 90 | 0 | 11 | 290 | 3 | E |
| 07-02-2024 | 22.8 | 26.9 | 24.4 | 92 | 42.8 | 11 | 280 | 3 | E |
| 11-02-2024 | 24 | 29 | 25 | 91 | 31 | 10 | 280 | 4 | E |
| 26-02-2024 | 22.8 | 30.2 | 25.2 | 87 | 43.6 | 10 | 280 | 3 | E |
| 06-12-2024 | 24.9 | 29.3 | 26.9 | 88 | 45.6 | 13 | 290 | 4 | NW |
| 20-12-2024 | 24 | 25.4 | 24.8 | 97 | 102.6 | 13 | 170 | 3 | E |
| 25-12-2024 | 24.7 | 29.6 | 26.4 | 89 | 11.8 | 10 | 290 | 3 | W |
| 14-01-2025 | 25 | 30.9 | 27.8 | 82 | 1.6 | 10 | 310 | 3 | E |
| 16-01-2025 | 25 | 29.6 | 26.6 | 86 | 11.4 | 11 | 280 | 3 | NW |

ID WMO : 97182
STATION NAME: PAOTERE MARITIME METEREOLOGICAL STATION
LATITUDE : -5.11375
LONGITUDE : 119.41983
ELEVATION : 5 Meter

| **Description** | |
|---|---|
| 8888: Unmeasured data | RR: Rainfall (mm) |
| 9999: No Data (no measurement taken) | FF_X: Maximum wind speed (m/s) |
| TN: Minimum temperature (°C) | DDD_X: Wind direction at maximum speed (°) |
| TX: Maximum temperature (°C) | FF_AVG: Average wind speed (m/s) |
| TAVG: Average temperature (°C) | DDD_CAR: Most wind direction (°) |
| RH_AVG: Average humidity (%) | |

**Table 4. The Impact of Wind Speed on coastal areas [9, 24, 25]**

| Wind Categories | Speed | Impact on Coastal Areas |
|---|---|---|
| Moderate strong winds | 8 – 10.7 m/s<br>(29 – 38 km/jam) | • Waves start to rise (0.5 – 1.5 m), risk for small boats.<br>• Beach sand starts to be carried by the wind, reducing visibility. |
| Strong winds | 10.8 – 13.8 m/s<br>(39 – 49 km/jam) | • Waves increase to 1.5 – 3 m, dangerous for small boats.<br>• Sand is blown more strongly, can damage coastal vegetation.<br>• Risk of coastal abrasion increases. |
| The wind is very strong | 13.9 – 17.1 m/s<br>(50 – 61 km/jam) | • Waves reach 3-4 meters, fishing boats are at high risk of sinking.<br>• The risk of tidal flooding increases if it coincides with high tides.<br>• Coconut trees and young mangroves can fall. |

In 2020, wind speeds in the region reached 15 m/s, classified as very strong winds. According to local residents, during this period, powerful waves transported massive amounts of driftwood, accumulating up to 2 meters along the shoreline of Aeng Batu Batu. The wave impact extended up to 40 meters inland from the highest tidal mark (Source: S. Dg. Bulan).

A similar situation occurred in January and December 2024, despite lower wind speeds. However, the prolonged duration of strong winds led to severe coastal flooding (rob), with waves reaching up to 20 meters beyond the highest tidal boundary. As a result, residential areas were inundated, with floodwaters rising to knee-deep levels for adults (Source: Local Residents). These observations highlight the increasing vulnerability of coastal settlements to extreme weather events, emphasizing the need for resilient coastal protection strategies. Following is qualitative data concerning the condition of settlements before and after the tidal flood, as well as the impact on construction of the tidal flood.

Figure 9 illustrates settlement conditions before and after tidal flooding and its impacts on coastal structures. Wave action directly strikes the shoreline, causing abrasion and structural damage to buildings located along the highest tidal boundary. Seawater inundation penetrates inland approximately 20–30 meters from the shoreline, disrupting settlement functions and weakening building foundations. Houses situated directly within the coastal zone experience more severe impacts, including partial structural failure and, in some cases, complete loss as they are swept away by waves. These conditions highlight the vulnerability of unprotected coastal settlements to tidal flooding and wave-induced abrasion.

Before the ROB flood During the ROB flood

**Figure 9. The Impact of Abrasion and Tidal Flooding (Rob) on Residential Construction**

Tidal Flooding (Rob). *Top figures:* The condition of the Biringkassi village settlement during the peak of the rainy season in early January, when tidal flooding inundated residential areas. According to local residents, the water level reached approximately knee height for an adult. *Bottom figures:* A tidal flooding event in 2020 along the North Galesong coastline in Aeng Batu-Batu Village. During the peak of the rainy season combined with high tides, strong waves transported large volumes of driftwood toward the shore. Residents reported that the accumulated debris formed deposits of up to approximately 2 meters in height along the coastline (see Figure 10).

**Figure 10. The Impact of Flooding, Abrasion, and Tidal Flooding (Rob) on Settlements**

### 3.2. Physical, Social and Economic Impacts

Based on interviews with several residents living near the coastal area, the effects of tidal flooding and wave surges vary across different regions. In North Karamak, during the peak of the rainy season, seawater reaches only the highest boundary of the residential area. However, in Middle Karamak and South Karamak, wave surges extend 20 meters inland from the highest tidal boundary during the peak of the rainy season in January 2025. In contrast, during January 2024, wave surges reached 10 meters beyond the highest tidal mark. Similarly, in early 2023, the water reached 20 meters inland, mirroring the conditions of 2025. In January 2020, the situation was significantly more severe. According to residents, river water met the highest tidal surge, causing waves and floods to inundate up to 40 meters beyond the highest tidal boundary. Additionally, large waves carried tons of driftwood onto the shore. During this period, four houses built along the shoreline reportedly collapsed (see Figure 11).

Prior to the coastal erosion, which residents attribute to sand mining activities in the area, the settlement experienced sedimentation, making it possible for them to construct permanent houses along the coastline. However, following the commencement of sand mining, coastal erosion intensified, leading to severe damage to their structures.

From an economic perspective, fishing activities are severely affected during the rainy season, particularly in months with high rainfall and strong winds. During extreme weather conditions, fishermen are unable to go out to sea, resulting in a complete loss of income. On average, the daily income of fishermen is reported to be approximately Rp. 50,000 per day. According to residents, during extreme climate events, fishermen are typically unable to work for about a week, significantly impacting their livelihoods.

**Figure 11. Types of conventional seawalls built by the community to protect their homes from wave impact and coastal erosion**

According to residents, gabion walls filled with mountain stones are considered expensive, costing approximately Rp. 600,000 per unit with dimensions of 2×1×1 meters. In contrast, wave barriers made from sand-filled sacks are a more affordable alternative, but they lack durability and deteriorate over time. To support coastal protection efforts, the local government distributes 50 empty sacks per household, which residents then fill with sand collected from the beach. However, this practice leads to the formation of holes along the shoreline, which are later backfilled with waste materials.

Figure 12 shows the coastal edge functioning simultaneously as a physical barrier and a shared space for boat parking, fishing activities, equipment storage, social interaction, recreation, resting, and informal waste disposal.

**Figure 12. Multifunctional Use of the Coastal Edge in Daily Community Activities**

Figure 13 shows the existing coastal embankment in the northern Galesong area of Aeng Batu Batu Village, which operates as a conventional single-function structure primarily designed for wave retention and tidal flood protection. The embankment relies on a rigid structural form without integration of Nature-Based Solutions, drainage networks, or multifunctional spatial components. While effective in reducing direct wave forces, the structure does not accommodate ecological processes, adaptive water management, or additional socio-spatial functions. In contrast to the proposed ELCC, this conventional embankment demonstrates limited adaptability, minimal environmental integration, and higher long-term vulnerability to sedimentation, overtopping, and coastal dynamics under climate change conditions.

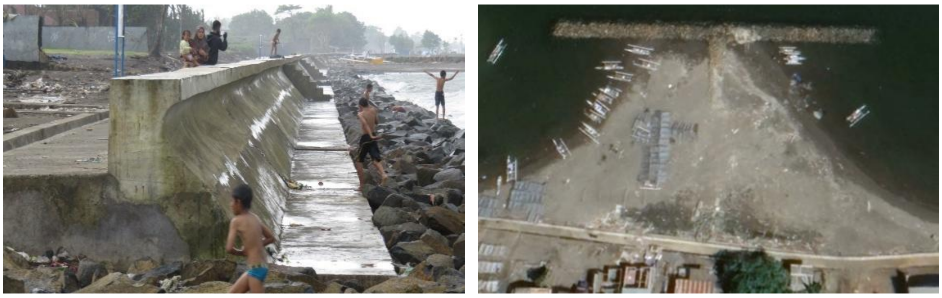


**Figure 13. Conventional Coastal Embankment in Northern Galesong**

## 4. Discussion

### 4.1. The Influence of Nature and Humans on the Decline in Coastal Environment and Community Quality

Figure 14 illustrates the conceptual framework of the Ecological–Living–Community Corridor (ELCC), demonstrating how social functions and community needs inform technical and ecological design decisions in coastal water management. This framework provides an interpretative lens to understand how intertwined natural processes and human activities jointly shape environmental degradation and spatial vulnerability in coastal settlements.

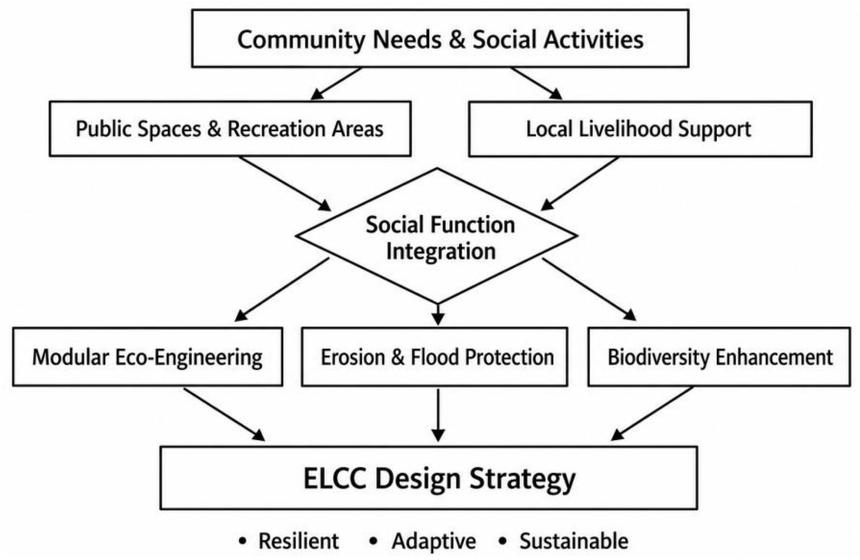


**Figure 14. illustrates the conceptual framework of the Ecological–Living–Community Corridor (ELCC), demonstrating how social functions and community needs inform technical and ecological design decisions in coastal water management**

Climate change and global warming have led to rising sea levels, which in turn accelerate coastal erosion, increase saltwater intrusion into freshwater sources, and destroy critical coastal habitats essential for ecosystem sustainability [26]. Additionally, changes in coastal geomorphology and hydrodynamics have worsened the degradation of shorelines (Figures 5 to 10). Natural erosion caused by ocean waves and currents becomes more severe when coastal vegetation, such as mangroves, is depleted due to human activities [27]. These combined pressures highlight the need for adaptive and nature-based spatial interventions, as conceptualized in the ELCC framework.

In several areas, communities have built their homes at the highest tidal boundary, with some even encroaching directly onto the beach, as depicted in Figures 3 and 7. The conversion of coastal land for residential, industrial, and tourism purposes has accelerated environmental degradation. This transformation not only reduces green spaces that act as natural wave barriers but also destroys habitats essential for coastal biodiversity [28]. The clearing of mangroves to expand aquaculture and coastal infrastructure has further intensified erosion while reducing the ecosystem's ability to absorb blue carbon, which plays a crucial role in climate change mitigation [29]. Such land-use practices demonstrate how social and economic drivers directly influence technical and ecological vulnerabilities in coastal systems.

Coastal pollution, particularly the accumulation of plastic waste and microplastics, has become a serious threat to marine life and beach ecosystems (Figure 12, bottom right). Plastics that accumulate in the ocean harm marine organisms, including fish and seabirds, which often mistake plastic debris for food [30]. Additionally, untreated domestic and industrial waste discharged directly into coastal waters further degrades environmental quality and undermines ecosystem services. These conditions reinforce the necessity of integrating environmental protection with community-based management strategies within coastal planning frameworks.

Unregulated infrastructure development also significantly impacts coastal environments. The construction of ports, concrete seawalls, and land reclamation projects often disregards ecological balance, disrupting natural coastal dynamics and accelerating erosion [31]. (Excessive groundwater extraction further contributes to land subsidence, increasing tidal flood risks [28]. Such engineering-dominated approaches illustrate the limitations of conventional coastal protection measures, supporting the argument for hybrid and adaptive solutions such as ELCC.

Rapid urbanization and changing lifestyles place additional pressure on coastal ecosystems, weakening community resilience [22, 27]. Low public awareness and limited participation in conservation efforts exacerbate environmental decline [32]. These social dynamics underline the importance of incorporating community needs and social functions into coastal design and management strategies, as emphasized in the ELCC framework.

Addressing coastal environmental degradation therefore requires ecosystem-based mitigation and adaptation strategies that integrate spatial planning, ecological restoration, and community participation. The ELCC framework responds to these challenges by bridging environmental processes, technical interventions, and social dynamics into a unified coastal resilience strategy.

## 4.2. Eco Levee Coastal Corridor: A Vision for Sustainable Coastal Development

The seawall constructed in the North Galesong region, specifically in Aeng Batu and Tamasaju villages—neighboring Biring Kassi—serves solely as a wave barrier to prevent coastal erosion, without additional functional integration (Figures 11 and 13). However, as shown in Tables 1 to 3, tidal flooding and erosion occur almost every rainy season due to extreme climatic conditions, such as heavy rainfall, strong winds, and high tides. This highlights the necessity of implementing ELCC, a hybrid infrastructure designed to integrate engineered structures with natural ecosystems. The initiative aims to balance ecological, social, economic, cultural, and environmental aspects within coastal settlements in North Galesong. By addressing critical challenges such as coastal erosion, tidal flooding, saltwater intrusion, and drought, while simultaneously improving the social and economic resilience of the community, ELCC seeks to provide both protective and developmental benefits.

ELCC functions as both an ecological and social corridor, incorporating natural vegetation, particularly edible forests, as a natural defense against coastal threats. Edible forests serve as an effective barrier against erosion and saltwater intrusion while providing spaces for social interaction and environmental education, fostering community participation in conservation efforts. Figure 12, along with Asmal et al. [33], highlights the significant amount of time coastal residents spend engaging in activities within public green spaces near the shore, emphasizing the importance of establishing such social corridors. Additionally, coastal vegetation offers economic benefits by allowing residents to utilize forest products such as fruits, medicinal plants, and handicraft materials, contributing to economic resilience [34, 35].

The Biringkassi coastal community predominantly consists of fishing families, a profession identified by Muslim et al. [36] as having one of the lowest income levels compared to other occupations. As increasing household needs are not matched by rising incomes, it is crucial to involve the community in finding alternative income sources. Edible forests provide a sustainable income diversification strategy, enabling residents to cultivate and harvest food resources while simultaneously contributing to coastal protection

### 4.2.1. The placement of the Eco Levee and Coastal Buffer Zone

The placement of the Eco Levee and Coastal Buffer Zone plays a vital role in ensuring coastal sustainability. Many coastal settlements are located near the highest tidal boundary, making them highly vulnerable to erosion, tidal flooding, and sea level rise. To enhance coastal resilience against climate change impacts, the integration of Nature-Based Solutions (NBS) and hybrid infrastructure is essential [37]. Improper placement of ELCC beyond the highest tidal boundary reduces its effectiveness in preventing erosion and tidal flooding [37], increases infrastructure damage risk [38], and negatively affects coastal ecosystems and economic activities [39]. Conversely, placing ELCC too far inland presents several major drawbacks:

- Reduced protection against tidal flooding and erosion [37].
- Disruption of natural hydrodynamic and sedimentation patterns [39].
- Reduced ecological benefits as a transition zone and blue carbon sink [38]
- Limited socio-economic benefits and restricted coastal connectivity [40].
- Non-compliance with coastal zoning regulations, leading to potential spatial conflicts [40].

To ensure optimal ELCC functionality, planning and design must consider elevation, hydrodynamics, soil stability, as well as socio-economic and ecological aspects. This approach maximizes protection, connectivity, and sustainability [38].

### 4.2.2. Implementation Eco Levee Coastal Corridor

ELCC is implemented as a comprehensive solution for coastal management, integrating ecological, socio-economic, and infrastructure aspects. Because the community has so far used the beach as a multi-functional space, its presence and function must be considered in the ELCC (Figure 9). It consists of a multifunctional seawall, an edible forest, and a grey water network. Several key elements are incorporated into ELCC implementation:

#### *Multifunctional Seawall: The Seawall within ELCC Serves as:*

- A connectivity corridor, featuring pedestrian paths, cycling lanes, recreational areas, and social interaction spaces. A coastal protection structure, incorporating Curved Concrete Wall technology, which dissipates wave energy by directing water back into the ocean, reducing erosion and backwash effects [41, 42].
- An adaptive structure, where the curved design evenly distributes hydrodynamic pressure, enhancing stability and reducing long-term maintenance costs compared to vertical seawalls [43]. Porous and adaptive materials are also integrated as toe protection, reinforcing coastal habitats and absorbing wave energy [43].

#### *Seawall as a Bridge Foundation*

Using the seawall as a bridge foundation is more efficient than constructing a massive four or five -meter-wide seawall, as it reduces material usage and construction costs [43]. The design includes:

- Curved Concrete Walls (1 meter wide on both sides), where the outer side functions as a wave breaker, while the inner side supports the elevated edible forest.
- A four or five-meter-wide bridge on top of the seawall, serving as a pedestrian and bicycle path as well as a social space [25]. The width is based on international standards for shared-use paths:
    - Jogging paths: 1.5–3 meters per lane [44, 45].
    - Bicycle lanes: 1.5–2.5 meters per lane [46, 47].
    - Combined pedestrian & bicycle paths: 3.5–4.5 meters (CROW: Centrum voor Regelgeving en Onderzoek in de Grond) Design Manual for Bicycle Traffic.
- Optimization of the space beneath the bridge for drainage and grey water networks, improving water management and environmental sustainability [48].
- A modular and adaptive structure, resistant to rising sea levels and sedimentation changes while maintaining coastal protection effectiveness [49].

#### *Edible Forest as a Coastal Green Belt*

The edible forest is developed as a blue carbon sink, supporting environmental, economic, and social sustainability [50]. Its width is determined by:

- Land availability and ecological needs, with an ideal minimum width of 10–20 meters for optimal function as a green buffer, ecosystem support, and sustainable food source.
- Ecological and social benefits, where a 10-meter width accommodates salt-tolerant trees, while 15–20 meters or more enhances biodiversity, prevents erosion, and improves carbon sequestration capacity.
- Community-based development, enabling edible forests to function as agroforestry zones, educational centers, and ecotourism areas, promoting environmental and economic benefits [50].

The proposed 10–20 m edible forest buffer width is based on an integrated, multi-criteria assessment combining empirical wave attenuation evidence, local hydrodynamic conditions, spatial constraints, and socio-economic considerations. Empirical studies in tropical and Southeast Asian coastal environments show that coastal vegetation can significantly reduce wave energy and flow velocity under low to moderate wave conditions within relatively narrow buffer widths [51-53]. In Indonesia, field observations indicate that vegetated buffers of 10–30 m can effectively mitigate daily tidal inundation and minor storm surges when combined with elevated coastal structures [54, 55].

BMKG data indicate that significant wave heights in the study area generally range from 0.1 to 1.25 m, with seasonal intensification during the west and south monsoons. These wave forces are further reduced by the elevated ELCC structure (approximately 1.5–2.0 m above beach level), allowing the edible forest buffer to function as a secondary energy-dissipation layer rather than the primary wave barrier. From a spatial and socio-economic perspective, buffer expansion beyond 20 m would risk residential displacement and disrupt fishing-based livelihoods, given the limited setback distance (75–140 m) between the shoreline and the village road. Therefore, the 10–20 m buffer represents a context-sensitive and technically justified compromise that balances ecological performance, engineering effectiveness, spatial feasibility, and social acceptability in dense tropical coastal settlements.

### *Grey Water Management System*

The grey water network, developed beneath the bridge, serves key functions:

- Capturing seawater overflow during high tides, preventing excessive flooding in the edible forest.
- Managing grey water drainage from residential areas, improving coastal sanitation and environmental quality.
- Enhancing ecological resilience, by channeling excess water efficiently and maintaining hydrological balance in coastal settlements [25].

Establishing an effective grey water management system is crucial, as Asmal et al. [56] report that these areas have long suffered from poor wastewater management. Untreated wastewater is often discharged into the coastline, streets, and residential yards, contributing to severe environmental degradation. Proper grey water infrastructure will significantly improve public health and ecological conditions.

In conclusion, ELCC represents an innovative coastal planning approach, balancing environmental conservation, infrastructure resilience, and socio-economic development. By integrating Nature-Based Solutions (NBS) with hybrid infrastructure, ELCC not only serves as a coastal defense system but also functions as a social and economic hub, enhancing the well-being of coastal communities. This model provides a sustainable and adaptive strategy for addressing climate change challenges in coastal areas, ensuring long-term resilience and inclusivity.

This matrix demonstrates that while previous studies have advanced coastal resilience through ecological and hybrid engineering solutions, ELCC extends these contributions by embedding spatial, social, and economic functions directly into the engineering design of the levee. The innovation of ELCC lies not in replacing existing approaches, but in synthesizing them into a multifunctional, adaptive coastal corridor that responds to both environmental hazards and everyday socio-spatial needs of vulnerable coastal communities.

## 4.3. ELCC as a Comprehensive and Integrated Architectural Design Concept

Biringkassi Village, as a coastal area, faces various ecological and social challenges, including coastal erosion, tidal flooding, seawater intrusion, and environmental degradation due to inadequate adaptive infrastructure. In response to these challenges, the ELCC emerges as a comprehensive and integrated architectural design concept aimed at mitigating these threats (Table 5). By adopting sustainable design principles, ELCC functions not only as a physical barrier against environmental hazards but also as a holistic system that harmonizes ecological, social, and economic aspects within coastal regions.

### *Integrating ELCC into Landscape Architecture and Coastal Urban Planning*

For ELCC to be effectively implemented, its integration into landscape architecture and coastal urban planning is crucial. The key strategies for ELCC implementation include:

### *Development of an Ecological Corridor*

ELCC connects urban green spaces with coastal vegetation, forming a natural buffer against erosion, flooding, and strong winds. Vegetation such as mangroves, beach she-oaks, and edible forests plays a vital role in absorbing blue carbon and enhancing biodiversity [57]. In Biringkassi Village, this approach is particularly relevant in addressing increasing coastal erosion caused by both human activities and climate change.

### *Utilization of Multifunctional Public Spaces*

ELCC is designed to transform coastal areas into multifunctional public spaces for recreation, sports, and social interaction. In addition to serving as a protective levee, the integration of pedestrian walkways and bicycle lanes enhances mobility and supports the local economy through eco-tourism development [58]**.** In Biringkassi Village, this approach can serve as a sustainable solution for improving community welfare by leveraging environmentally friendly tourism initiatives.

### *Adaptive Zoning for Climate Change Resilience.*

Coastal planning must be flexible and adaptive to address rising sea levels and extreme weather conditions. ELCC incorporates modular design principles, such as modern stilt houses and permeable materials, to enhance the structural resilience of settlements against hydrodynamic forces [43]. In Biringkassi Village, this strategy can be adapted to develop flood-resilient housing, ensuring greater protection against tidal flooding.

**Table 5. Matrix Comparison of Previous Coastal Resilience Studies and ELCC Framework**

| Aspect | Previous Studies | Key References | Findings of This Study (ELCC) | Analytical Advancement |
|---|---|---|---|---|
| Primary Function of Levee | Coastal defense focused on wave attenuation and flood protection | Masselink & Lazarus [9]; Mohamed [13] | Levee functions as a coastal protection system *and* a multifunctional spatial corridor | Expands levee role from single-function defense to integrated spatial infrastructure |
| Engineering Approach | Hard engineering or hybrid structures combining concrete with vegetation | Omori et al. [10]; Van der Meulen et al. [7] | Hybrid engineering combined with spatial layering for circulation, drainage, and ecology | Introduces spatial-functional engineering beyond structural performance |
| Nature-Based Solutions (NBS) | NBS mainly evaluated for ecological performance (wave reduction, erosion control) | Luo et al. [8]; Justine & Seenath [17] | NBS integrated as structural, ecological, and productive components (e.g., edible forests) | Shifts NBS from passive buffers to active, multifunctional systems |
| Socio-Spatial Integration | Social aspects discussed at policy or governance level | Pagano et al. [11]; Dushkova & Ivlieva [12] | Socio-spatial dynamics embedded directly in levee design and spatial configuration | Operationalizes social resilience at the design scale |
| Economic Considerations | Cost–benefit analysis and blue carbon financing | Peng & Song [15]; Eiselin et al. [50] | Local livelihood support integrated into infrastructure design | Moves beyond financial valuation toward spatially embedded economic resilience |
| Material Innovation | Focus on erosion-resistant materials and biopolymers | Ko & Kang [16] | Conventional materials combined with adaptive spatial and ecological systems | Prioritizes system adaptability over material novelty |
| Maintenance and Long-Term Adaptability | Often managed by centralized institutions | Masselink & Lazarus [9] | Community-supported maintenance aligned with local benefit structures | Enhances long-term sustainability in low-capacity coastal contexts |
| Application Context | Planned or formally developed coastal areas | van der Meulen et al. [7] | Informal, dense urban and rural coastal settlements | Extends applicability to highly constrained coastal environments |
| Overall Contribution | Incremental improvements in coastal defense performance | — | Integrated coastal corridor combining engineering, ecology, and socio-spatial functions | Represents a paradigm shift from defense infrastructure to adaptive coastal systems |

The grey water and overflow network integrated beneath the ELCC levee is intentionally designed to be simple and robust for rural coastal settings with limited technical capacity. Clogging risks are minimized through a large channel dimension (1.25 m × 1.25 m) and an episodic operational function, where the system is activated only during extreme events when wave levels exceed the levee crest, rather than for continuous wastewater conveyance. Maintenance is supported through strategically placed inspection and control points integrated into communal areas, allowing routine monitoring and debris removal using basic tools. Long-term management follows a community-based governance model, in which local residents are responsible for regular upkeep, motivated by direct benefits from the associated edible forest system. Periodic technical support and coordination are provided by local government institutions to ensure operational sustainability.

### 4.3.1. ELCC Solutions for Biringkassi Village

Biring Kassi Village faces major coastal challenges, including severe erosion, limited coastal green spaces, and insufficient infrastructure to mitigate climate change impacts. The implementation of ELCC provides practical solutions through:

#### *1. Reinforcement of Adaptive Levees*

The Curved Concrete Wall structure serves as both a wave breaker and a foundation for a coastal bridge, offering a cost-effective alternative to massive 3–5 meter-wide seawalls [59]. route, promoting sustainable urban mobility. The bridge constructed on top of the levee can also function as an environmentally friendly transportation

#### *2. Development of an Edible Forest*

Restoring coastal vegetation through the establishment of edible forests provides ecosystem protection while simultaneously benefiting local communities economically. With an optimal width of 10–20 meters, edible forests reduce coastal erosion and enhance local food security [49].

#### Socio-Economic Implications of ELCC Implementation

While livelihood diversification through edible forests and low-impact coastal tourism is discussed primarily in qualitative terms, indicative scenario-based estimates are introduced here to clarify its potential economic contribution. In a conservative scenario, edible forests integrated along the ELCC corridor—comprising salt-tolerant fruit trees and multipurpose vegetation—are expected to function as supplementary income sources rather than replacing primary livelihoods such as fishing. Evidence from small-scale coastal agroforestry systems suggests that mixed fruit production may contribute approximately USD 200–400 per household per year through a combination of subsistence use and limited local sales [60, 61].

Similarly, community-based coastal tourism linked to the educational, recreational, and ecological functions of the corridor may provide periodic income opportunities. Even under low visitor intensity, households engaged in guiding, small food stalls, or maintenance services could earn an additional USD 20–40 per month during peak periods, consistent with findings from nature-based tourism in rural coastal contexts [62, 63]. *These order-of-magnitude estimates are intended to support the development claims of the ELCC by illustrating plausible income diversification pathways, rather than serving as predictive economic models.* Further longitudinal and quantitative studies are required to refine these projections.

## *3. Implementation of a Grey Water Network System*

A drainage infrastructure system beneath the coastal bridge is designed to manage seawater runoff and residential grey water, preventing saltwater intrusion into the edible forest and ensuring optimal plant growth [25]. ELCC represents a landscape architectural solution that not only focuses on coastal protection but also supports economic and social development within local communities. In Biring Kassi Village, the ELCC framework can be applied to enhance environmental resilience through ecosystem-based approaches, improve community well-being through eco-tourism, and establish adaptive infrastructure for climate change resilience. By integrating nature-based solutions with hybrid infrastructure, ELCC serves as a sustainable and resilient coastal planning model for the future (Figure 15).

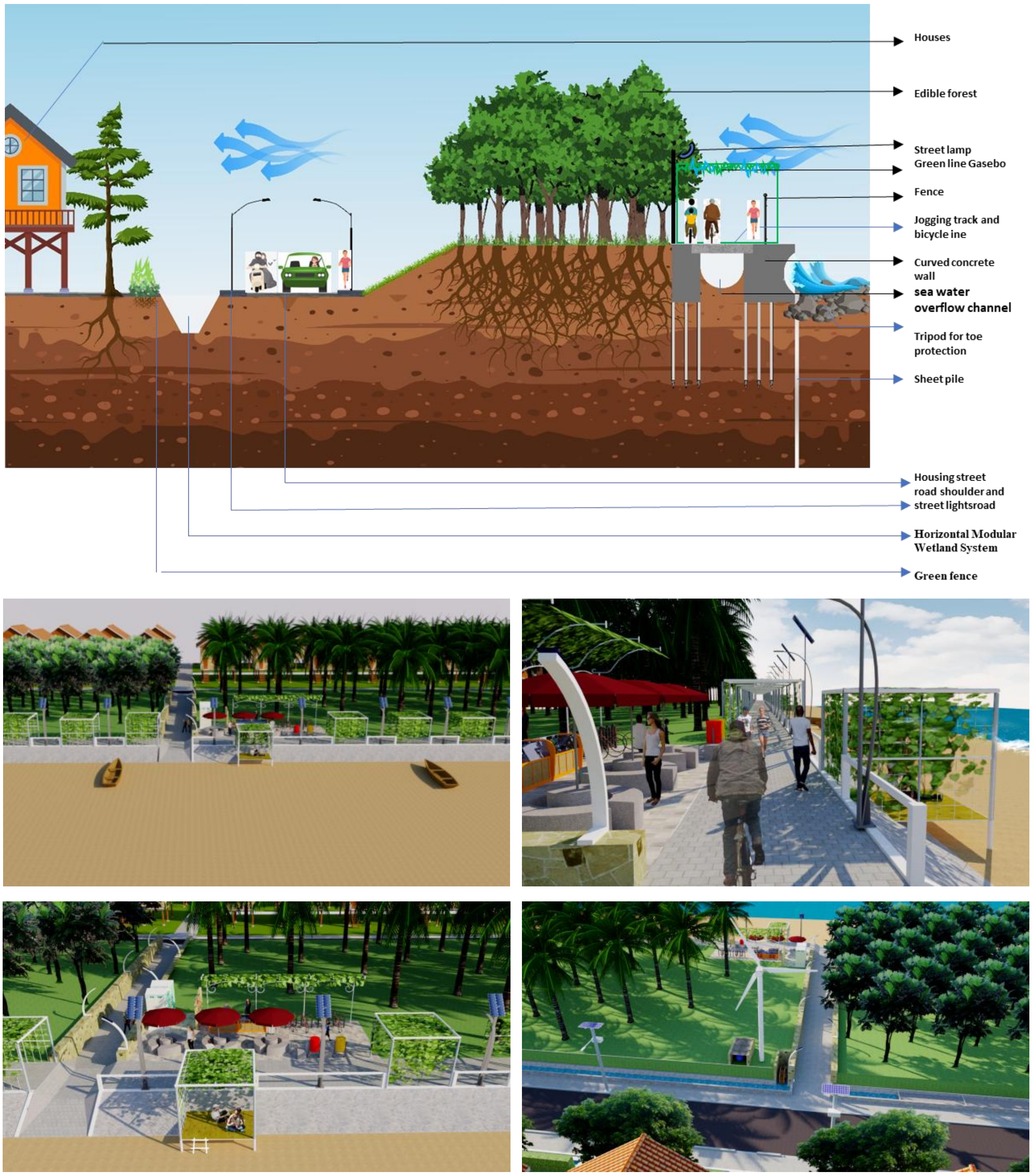


**Figure 15. Illustration ELCC**

The front section of the ELCC consists of a protective embankment with two main structures. The first embankment, located at the highest tidal boundary, functions as a wave breaker and coastal barrier against flooding. Additionally, it serves as the foundation for a pedestrian and cycling bridge, allowing visitors to walk, jog, and cycle along the coastline. The second embankment, positioned further inland, provides soil support and reinforces the Edible Forest, a green space with salt-tolerant fruit-bearing plants.

To manage excess seawater, a wave overflow channel is built beneath the bridge, directing water into the drainage system before safely returning it to the sea. The front section of the embankment also functions as a workspace for fishermen, preserving their traditional connection to the coastal area. Safety features include protective railings and streetlights to enhance visibility at night. Additionally, climbing plants are used as a gazebo roof, providing natural shading to increase comfort for pedestrians and cyclists.

Beyond the embankment lies the Edible Forest, which serves as a natural buffer zone, supporting biodiversity and food production. Every 200 meters, access pathways connect the beach to residential areas, equipped with rest areas, social spaces, bicycle parking, and public toilets [64-66]. Adjacent to this green space is the residential road, which integrates a Horizontal Modular Wetland System (HMWS) for household gray water management, improving wastewater treatment and environmental sustainability. Overall, the ELCC integrates coastal protection, sustainable mobility, and ecological resilience, creating a balanced and environmentally friendly coastal infrastructure.

### 4.3.2. Translating GIS and Hydrodynamic Outputs into ELCC Design Parameters

The extensive GIS-based spatial analysis and hydrodynamic assessment conducted in this study provide a quantitative foundation for determining the physical design parameters of the Ecological–Living–Community Corridor (ELCC). Rather than functioning solely as descriptive analytical outputs, these datasets were systematically translated into design decisions related to corridor height, width, and spatial placement.

Hydrodynamic modeling of tidal inundation and seasonal water level fluctuations was used to define the minimum elevation of the ELCC. Areas experiencing recurrent tidal flooding with water depths ranging from 50 cm to 1.0 m during peak events informed the establishment of a corridor base elevation at least 1.0 m above the ***Highest Astronomical Tide (HAT)***. This elevation threshold ensures functional continuity of the corridor during extreme tidal and rainfall events while maintaining structural resilience.

Spatial analysis of erosion intensity and shoreline retreat rates guided the determination of ELCC width. Zones identified as high-energy coastal segments required wider corridor sections to accommodate wave dissipation, vegetation buffers, and adaptive ecological components. In contrast, narrower ELCC segments were applied in low-energy zones and spatially constrained settlement edges, where modular and flexible configurations were prioritized.

The placement of ELCC segments was directly informed by GIS overlays integrating land elevation, greywater pollution hotspots, tidal inundation frequency, and the position of polluted clean water sources. Corridors were preferentially located along transitional zones between residential areas and the shoreline, where they could simultaneously function as protective buffers, ecological filters, and spatial mediators between human activity and coastal processes.

Through this translation process, spatial and hydrodynamic modeling outputs were operationalized into concrete design parameters, ensuring that ELCC implementation is not only conceptually robust but also technically precise and site-responsive. This explicit linkage enhances the methodological rigor of the study and demonstrates how analytical modeling can directly inform adaptive coastal infrastructure design.

**Key Features of ELCC Implementation in Biringkassi**

- Coastal Defense and Flood Resilience. The ELCC integrates an elevated levee system with bioengineered slopes and vegetated buffers to mitigate tidal surges, frequent flooding, and coastal erosion. By combining natural and engineered elements, the levee provides robust structural protection while promoting long-term shoreline stabilization.
- Edible Forest Integration (Food–Ecological Corridor). A core innovation of the ELCC is its function as an *edible forest*, planted with salt-tolerant, multi-use vegetation such as mangrove-associated fruit trees, medicinal plants, and traditional crops. These not only enhance local food security and nutrition but also generate income through harvest and small-scale trade. The edible forest supports biodiversity, carbon sequestration, and ecological stewardship, while functioning as a nature-based buffer.
- Social Infrastructure, Accessibility, and Local Livelihoods. The ELCC is designed as a multifunctional public corridor, integrating pedestrian and bicycle lanes, viewing decks, resting areas, and informal market spaces. These zones allow residents to sell local crafts, processed seafood, fruits, and traditional foods to visitors, creating *microeconomic hubs*. Elevated stilt houses along the corridor can be adapted as *homestays*, attracting tourists seeking immersive cultural and environmental experiences. This mixed-use framework boosts community-based tourism and strengthens the social economy.
- Water Management and Climate Adaptation. Rain gardens, bioswales, and freshwater retention pockets are embedded within the ELCC to manage surface runoff, prevent saltwater intrusion, and mitigate seasonal drought impacts. These features align with integrated water resource management principles and increase the village's adaptive capacity under changing climatic conditions.

- Community-Based Design and Maintenance. The ELCC's implementation is rooted in participatory planning. Local residents, youth groups, and traditional institutions are involved in species selection for the edible forest, corridor maintenance, and ecotourism management. This ensures cultural relevance, promotes shared ownership, and embeds the infrastructure within local governance practices.
- Scalable Prototype for Coastal Villages. As a modular and low-tech solution, the Biringkassi ELCC presents a scalable prototype for other Indonesian coastal villages facing sea-level rise, tidal flooding, erosion, drought, and saltwater intrusion. Its multifunctionality—combining defense, food systems, recreation, and livelihood—makes it both replicable and adaptable to diverse contexts.

In sum, the ELCC in Biringkassi redefines coastal protection by merging physical resilience with ecological productivity and socio-economic empowerment. It transforms a defensive structure into a regenerative, community-centered landscape, shifting coastal adaptation away from hard infrastructure toward hybrid, nature-based systems that deliver long-term sustainability.

## 5. Conclusion

This study demonstrates that the ELCC constitutes an integrated and adaptive coastal infrastructure model capable of addressing the complex environmental and socio-spatial challenges faced by densely populated tropical coastal settlements. Through the case of Biringkassi Village, the research reveals that conventional coastal protection approaches—such as rigid seawalls or single-function NBS—are insufficient when applied in environments characterized by tidal flooding, land subsidence, informal settlement patterns, and limited technical capacity. ELCC responds to these constraints by combining hybrid engineering structures with ecological systems and community-based management.

The findings show that ELCC functions simultaneously as a coastal defense system, an ecological buffer, and a socio-spatial framework. From an environmental perspective, the integration of edible forests and vegetated corridors enhances erosion control, supports blue carbon sequestration, and improves microclimatic conditions. The hybrid levee structure, designed as a curved concrete wall, provides effective protection against wave action and tidal inundation while maintaining structural efficiency and spatial flexibility. In addition, the subsurface greywater overflow network beneath the levee contributes to improved drainage performance and reduces the risk of saltwater intrusion, thereby safeguarding both coastal vegetation and groundwater quality.

Spatial analysis plays a critical role in the ELCC framework by informing the placement of infrastructure based on topography, inundation patterns, greywater pollution hotspots, and the location of polluted clean water sources. This evidence-based approach ensures that technical design decisions are context-sensitive and environmentally responsive. Importantly, the study highlights that long-term sustainability is reinforced through a kinship-based governance model, where local communities actively participate in maintenance and management, supported by local government institutions.

Overall, ELCC represents a scalable and context-adaptive model for sustainable coastal development. By integrating ecological restoration, hybrid engineering, and socio-cultural structures within a single spatial framework, ELCC offers a viable pathway to enhance climate resilience, environmental quality, and community well-being in vulnerable coastal regions facing accelerating climate change impacts.

## 6. Declarations

### 6.1. Author Contributions

Conceptualization, I.A.; methodology, I.A.; software, I.A.; validation, A.J.; formal analysis, I.A.; resources, I.A.; data curation, I.A.; writing—original draft preparation, I.A. and A.J.; writing—review and editing, I.A. and A.J.; visualization, I.A.; project administration, I.A.; funding acquisition, I.A. All authors have read and agreed to the published version of the manuscript.

### 6.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

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### 6.4. Conflicts of Interest

The authors declare no conflict of interest.

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