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Coastal Morphological Characteristics and Environmental Factors Causing Abrasion at Moilong Beach Based on GIS Analysis

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Abstract
Coastal erosion is a major environmental problem in coastal areas resulting from the interaction of coastal morphology, oceanographic processes, and human activities. This study aims to identify the coastal morphological characteristics and environmental factors contributing to erosion at Moilong Beach, Banggai Regency, Central Sulawesi, using Geographic Information Systems (GIS) and field observations. The study integrated Landsat 8 imagery, the Indonesian National Digital Elevation Model (DEMNAS), geological, soil, bathymetric, watershed, land-use, and oceanographic datasets through spatial analysis. The results indicate that coastal erosion is primarily driven by the combination of a narrow sandy shoreline, unconsolidated Holocene alluvial deposits, gently sloping bathymetry that promotes longshore currents, reduced sediment supply from upstream watersheds, and land-use changes characterized by wetland conversion and mangrove degradation. Furthermore, the proximity of settlements and infrastructure to the shoreline significantly increases coastal vulnerability. The findings demonstrate that effective erosion mitigation requires an integrated coastal management approach involving mangrove restoration, sustainable watershed management, coastal spatial planning, and the implementation of both engineering-based and ecosystem-based protection measures to enhance long-term coastal resilience.
Keywords: *coastal erosion, coastal morphology, geographic information system, coastal mitigation, moilong beach*

Abstrak
Abrasi pantai merupakan salah satu permasalahan utama di wilayah pesisir yang dipengaruhi oleh interaksi faktor morfologi pantai, oseanografi, dan aktivitas manusia. Penelitian ini bertujuan mengidentifikasi karakteristik morfologi pantai serta faktor-faktor lingkungan yang menyebabkan abrasi di Pantai Moilong, Kabupaten Banggai, Sulawesi Tengah, menggunakan pendekatan Sistem Informasi Geografis (SIG) dan observasi lapangan. Data yang digunakan meliputi citra Landsat 8, DEMNAS, peta geologi, jenis tanah, batimetri, daerah aliran sungai, penggunaan lahan, serta data oseanografi yang diintegrasikan melalui analisis spasial. Hasil penelitian menunjukkan bahwa abrasi dipengaruhi oleh kombinasi morfologi pantai berpasir sempit, dominasi endapan aluvial Holosen yang mudah tererosi, batimetri landai yang memicu pembentukan arus sejajar pantai, berkurangnya suplai sedimen dari daerah aliran sungai, serta perubahan penggunaan lahan berupa konversi lahan basah dan berkurangnya vegetasi mangrove. Selain itu, keberadaan permukiman dan infrastruktur yang berada sangat dekat dengan garis pantai meningkatkan tingkat kerentanan terhadap abrasi. Penelitian ini menegaskan bahwa mitigasi abrasi memerlukan pendekatan terpadu melalui rehabilitasi mangrove, pengelolaan daerah aliran sungai, penataan ruang pesisir, serta penerapan perlindungan pantai yang mengintegrasikan solusi rekayasa dan berbasis ekosistem untuk meningkatkan ketahanan kawasan pesisir.
Kata Kunci: *abrasi pantai, morfologi pantai, sistem informasi geografis, mitigasi pesisir, pantai moiling*

1. Introduction

Coastal areas represent transitional zones between terrestrial and marine ecosystems that are characterized by highly dynamic environmental processes resulting from the interaction of oceanographic, geological, geomorphological, and anthropogenic factors. These interactions continuously alter coastal morphology through sedimentation and erosion processes. As regions with significant ecological, economic, and social value, coastal zones support various human activities, including settlements, fisheries, tourism, transportation, and trade. Consequently, they are highly vulnerable to environmental degradation if not managed sustainably [1],[4]. Furthermore, global climate change, characterized by sea-level rise and increasing wave and storm intensity, has substantially increased the risk of coastal erosion worldwide. It is projected that nearly 50% of the world's sandy coastlines may experience significant shoreline retreat by the end of this century if greenhouse gas emissions are not effectively mitigated [2].

Coastal erosion is the process of shoreline retreat caused by the continuous action of waves, currents, tides, and wind, leading to the gradual loss of coastal land. This phenomenon is influenced by the interaction of multiple factors, including coastal morphology, sediment characteristics, beach slope, shoreline orientation relative to incoming waves, sediment transport dynamics, and land-use changes within coastal regions [3]. An imbalance between sediment supply and wave energy accelerates the removal of coastal materials, resulting in progressive shoreline erosion. The impacts of coastal erosion extend beyond land loss, encompassing damage to infrastructure, degradation of coastal ecosystems, reduction of productive land, and increased vulnerability of coastal communities to coastal hazards [4]. As the world's largest archipelagic country, with more than 108,000 km of coastline, Indonesia faces serious coastal erosion problems in many coastal regions. According to the National Disaster Management Agency (BNPB), hundreds of kilometers of Indonesia's coastline have been affected by erosion, with the severity continuing to increase due to the combined effects of natural processes and human activities. This condition is further aggravated by intensive coastal exploitation, infrastructure development that neglects coastal dynamics, degradation of protective coastal vegetation such as mangrove forests, and climate change that contributes to sea-level rise and increased wave energy [4],[5]. Therefore, identifying the factors responsible for coastal erosion based on the physical characteristics of coastal environments is an essential first step toward developing appropriate coastal management and mitigation strategies.

One of the coastal regions experiencing severe erosion is Moilong Beach, located in Moilong Village, Moilong District, Banggai Regency, Central Sulawesi, Indonesia. Coastal erosion in this area has persisted for several years and has intensified, particularly during the west monsoon season when high waves and maximum tidal conditions occur. Field observations indicate that wave action has eroded hundreds of meters of shoreline, damaged simple coastal protection structures constructed by local communities, and threatened residential areas located along the coast. Although the Provincial Government of Central Sulawesi has constructed coastal protection structures to reduce erosion, shoreline retreat continues to occur, suggesting that the underlying causes of erosion have not yet been comprehensively understood from a scientific perspective. Coastal morphology is one of the primary factors determining the vulnerability of coastal areas to erosion. Shoreline configuration, beach slope, elevation, sediment characteristics, and the presence of coastal vegetation influence the capacity of coastal environments to dissipate wave energy. In addition, environmental factors such as wave height, current direction, land use, and changes in vegetation cover also affect the equilibrium of coastal systems. The relationship between coastal morphology and these environmental factors can be comprehensively analyzed using a spatial approach based on Geographic Information Systems (GIS). The integration of satellite imagery, Digital Elevation Models (DEMs), and field observations enables more accurate identification of erosion patterns and controlling factors than conventional analytical methods [6],[7].

The application of Geographic Information Systems has become increasingly important in coastal research because it enables the integration of various spatial datasets into comprehensive information regarding coastal morphology and shoreline dynamics. GIS-based spatial analysis facilitates the identification of areas with high erosion susceptibility through the mapping of beach slope, shoreline configuration, land-cover changes, and the relationships between physical and oceanographic variables. Such information provides a valuable scientific basis for developing adaptive and sustainable coastal zone management strategies. Although numerous studies on coastal erosion have been conducted in Indonesia, research integrating coastal morphological characteristics and environmental factors using a GIS-based approach at Moilong Beach remains limited. Most previous studies have focused primarily on shoreline change analysis or the evaluation of coastal protection structures, whereas the interactions between coastal morphology and environmental factors as the principal drivers of erosion have not been comprehensively investigated. Therefore, this study aims to identify the coastal morphological characteristics and environmental factors contributing to coastal erosion at Moilong Beach using Geographic Information Systems and field observations. The findings are expected to provide a scientific foundation for developing more effective, adaptive, and sustainable coastal erosion mitigation and coastal management strategies.

2. Material and Methods

Study Area

The study was conducted at Moilong Beach, located in Moilong Village, Moilong District, Banggai Regency, Central Sulawesi, Indonesia. The study area was selected because it has experienced continuous coastal erosion that threatens coastal settlements and infrastructure. This research focused on identifying coastal morphological characteristics and environmental factors contributing to coastal erosion through field observations and Geographic Information System (GIS)-based spatial analysis.

Research Materials

This study employed both primary and secondary data. Primary data consisted of field observations of shoreline morphology, beach slope, sediment characteristics, coastal vegetation, shoreline conditions, and geographic coordinates collected using a handheld Global Positioning System (GPS). Secondary data included Landsat 8 satellite imagery, Digital Elevation Model Nasional (DEMNAS), geological maps, soil maps, bathymetric data, watershed (DAS) data, land-use maps, and supporting oceanographic information such as wave, tidal, and current characteristics. These datasets were integrated to characterize coastal morphology and identify environmental factors associated with coastal erosion.

Data Collection

Field observations were conducted at representative locations along the Moilong coastline to document geomorphological conditions, sediment types, shoreline characteristics, and coastal vegetation. GPS coordinates and photographic documentation were collected at each observation point to validate the interpretation of satellite imagery. Secondary spatial datasets were obtained from government agencies and publicly available geospatial databases. Landsat 8 imagery was used to interpret shoreline and land-cover conditions, while DEMNAS and thematic maps provided information on topography, geology, soil characteristics, bathymetry, and watershed conditions.

GIS-Based Spatial Analysis

Spatial analysis was performed using ArcGIS software to integrate field observations with geospatial datasets. Image preprocessing included geometric correction, radiometric correction, image clipping, and shoreline digitization before generating thematic spatial layers. Coastal morphological parameters, including geology, soil type, beach morphology, bathymetry, watershed characteristics, and land use, were analyzed together with environmental variables such as coastal vegetation and shoreline conditions. Spatial overlay analysis was subsequently applied to examine the relationships between these parameters and the observed distribution of coastal erosion. The resulting thematic maps were interpreted to identify the dominant factors controlling erosion at Moilong Beach, while field observations were used to verify the accuracy of the spatial analysis.

3. Results and Discussion

Coastal Morphology Characteristics

The coastal morphology of Moilong Beach is characterized by a narrow sandy shoreline, a gently sloping beach, and a relatively narrow coastal plain directly adjacent to residential areas. Interpretation of satellite imagery and field observations showed that settlements have developed parallel to the coastline with minimal setback distance, while two small river mouths located at the northern and southern parts of the study area function as sediment transport pathways connecting terrestrial and marine systems. Land cover behind the shoreline is dominated by coconut plantations and mixed coastal vegetation, although parts of the southern coastal zone have been converted into aquaculture ponds. These geomorphological characteristics indicate that shoreline dynamics in Moilong are controlled by the interaction between coastal landforms, sediment supply, and anthropogenic land-use changes. Coastal morphology plays a fundamental role in determining shoreline stability because beach slope, sediment characteristics, and coastal configuration directly influence wave transformation and sediment transport processes [8],[9].

Geological analysis further revealed that the study area is entirely composed of Holocene alluvial deposits and alluvial soils, consisting of unconsolidated sand, silt, clay, and gravel that are highly susceptible to erosion. These materials possess low shear strength and weak particle cohesion, making the shoreline vulnerable to wave attack and longshore currents. Bathymetric analysis also indicated a gently sloping seabed, allowing waves to undergo gradual shoaling and generating longshore currents capable of redistributing sediments along the coast. Consequently, shoreline changes in Moilong are controlled by the balance between sediment supplied by river systems and sediment removed through coastal hydrodynamic processes. Similar findings have been reported in recent studies showing that unconsolidated coastal sediments, gentle bathymetric gradients, and active sediment transport strongly influence erosion and accretion patterns in tropical coastal environments [8],[10].

Land-use conditions further increase the vulnerability of the Moilong coastline. Field verification confirmed that settlements occupy areas immediately adjacent to the shoreline, while mangrove vegetation is limited to small patches and several coastal wetlands have been converted into aquaculture ponds. The reduction of natural coastal vegetation has diminished the capacity of the coastline to attenuate wave energy and retain sediments, thereby increasing exposure to coastal erosion. Overall, the morphological characteristics

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of Moilong Beach demonstrate that coastal erosion results from the interaction of natural factors—including geology, bathymetry, and sediment dynamics—with human-induced land-use changes. These findings provide an important scientific basis for developing integrated coastal management strategies that combine structural protection with ecosystem-based approaches such as mangrove restoration. This interpretation is consistent with recent studies emphasizing that maintaining coastal ecosystems and strengthening coastal resilience are essential for mitigating shoreline erosion and enhancing the adaptive capacity of coastal communities [10],[11],[12].

Fig.1. (a) before the construction of the seawall (b) erosion basin (c) shoreline retreat (d) loss of coastal areas (Source: Public Works and Spatial Planning Agency, 2023)

Geological and Soil Characteristics

The geological characteristics of the Moilong coastal area indicate that the study site is situated within the Banggai-Sula tectonic region, which was formed through complex plate interactions involving the collision of the Banggai-Sula microcontinent with the Sulawesi Island Arc. However, geological overlay analysis shows that the coastal plain of Moilong is predominantly composed of Holocene alluvial deposits (Qa) consisting of unconsolidated gravel, sand, silt, and clay derived from fluvial and marine sedimentation processes. Soil classification further confirms that the entire study area is dominated by alluvial soils, reflecting the accumulation of young sediments on the coastal plain. These findings suggest that the present coastal morphology is controlled more by recent depositional processes than by the underlying regional bedrock, making the shoreline highly dynamic under continuous coastal processes. This finding is consistent with recent studies indicating that unconsolidated alluvial deposits are highly responsive to shoreline evolution because they are easily reworked by waves, tides, and coastal currents [13],[14].

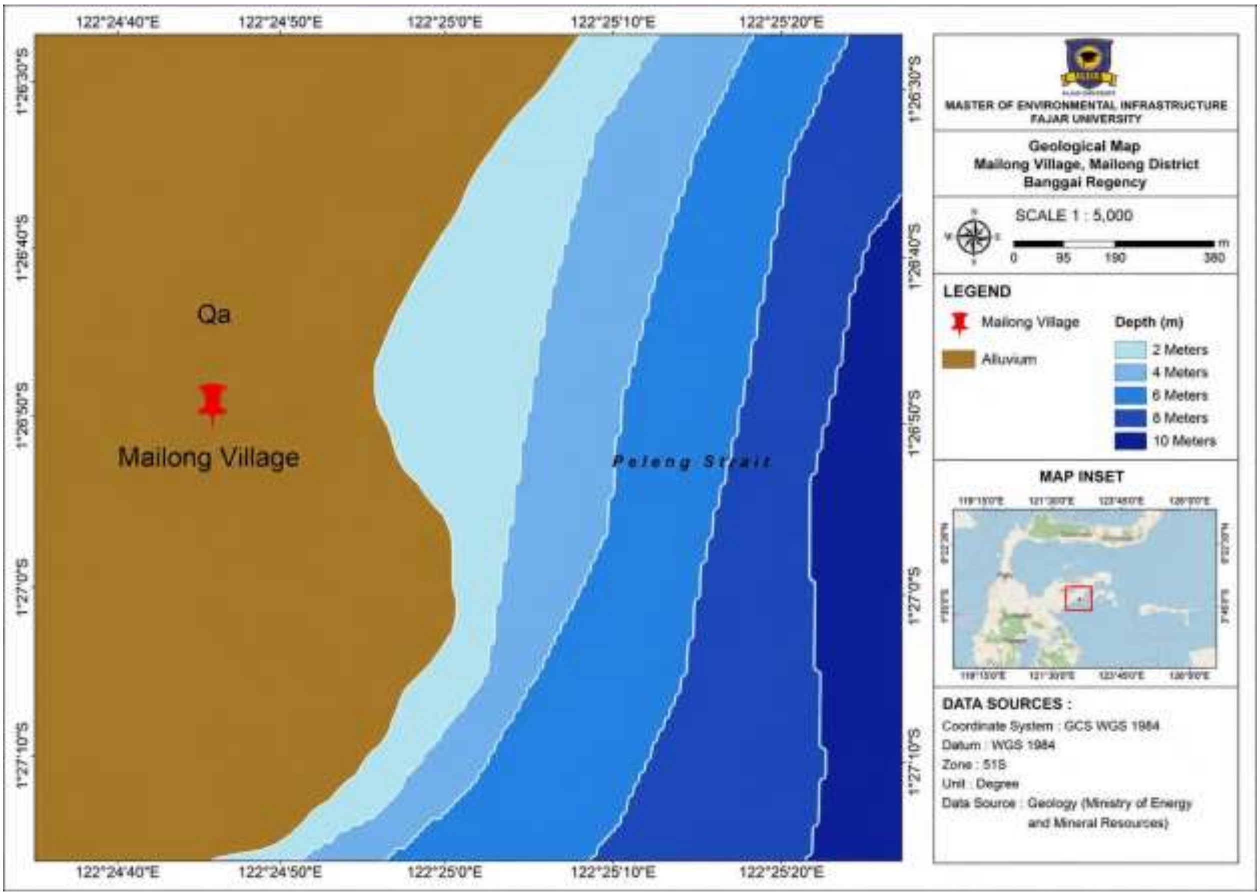

Fig.2. Geological Map of Moilong Village, Moilong District, Banggai Regency (adapted from Supandjono & Haryono, 1993)

From a coastal engineering perspective, the dominance of unconsolidated alluvial materials significantly increases shoreline susceptibility to erosion. The loose sediment structure exhibits relatively low shear strength and weak inter-particle cohesion, allowing sediments to be more readily removed under continuous wave action and longshore currents. Consequently, the balance between sediment supply from terrestrial sources and sediment loss through marine processes becomes the principal factor controlling shoreline stability in Moilong. Similar relationships have been reported in tropical coastal environments, where geological characteristics strongly influence erosion rates and sediment redistribution under varying hydrodynamic conditions [15],[16].

Overall, the geological and soil characteristics of Moilong Beach provide the fundamental physical setting governing coastal dynamics. The combination of Holocene alluvial deposits, alluvial soils, and active sedimentary processes creates a naturally erosion-prone coastline, particularly when coupled with intense wave activity and increasing anthropogenic pressures. Therefore, geological conditions should be considered as a key parameter in coastal vulnerability assessment and shoreline management, since they determine the intrinsic resistance of coastal materials to erosion and influence the long-term effectiveness of coastal protection measures [2],[17]. These findings reinforce that geological and pedological conditions constitute one of the primary controlling factors of shoreline change in the Moilong coastal area.

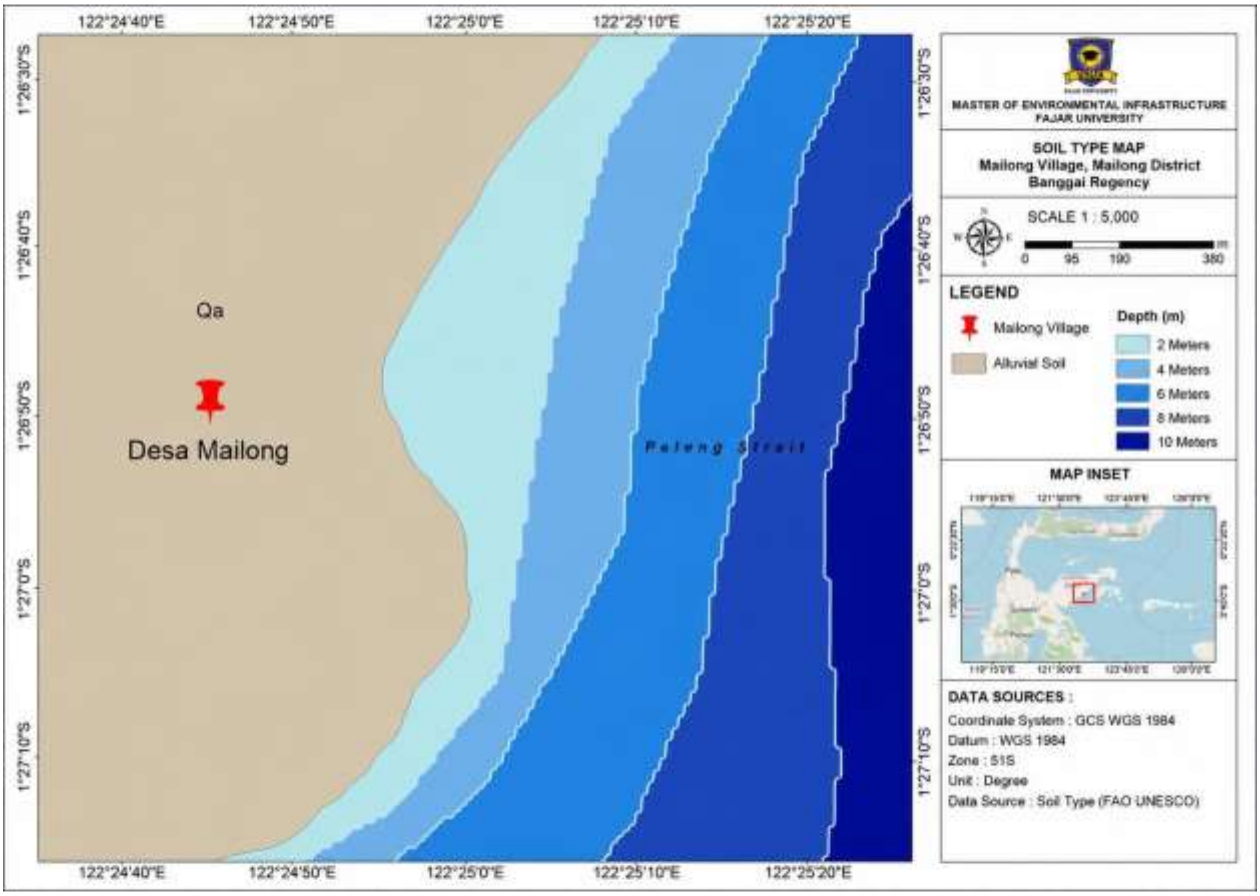

Fig.3. Map of Soil Type Moilong Village, Moilong District, Banggai Regency

Bathymetry and Coastal Processes

Bathymetric analysis indicates that the nearshore waters of Moilong Beach exhibit a gradual increase in depth from approximately 2 m near the shoreline to around 10 m at a distance of 800–1,000 m offshore, reflecting a gently sloping seabed toward the Peleng Strait. This morphology facilitates gradual wave shoaling before wave breaking occurs within a relatively wide surf zone. Consequently, wave energy is dissipated over a broader area, influencing the spatial distribution of coastal hydrodynamic processes and sediment transport. These findings demonstrate that bathymetry is a key factor controlling coastal processes and shoreline evolution in the study area. Similar bathymetric conditions have been reported to regulate wave transformation and nearshore sediment dynamics in tropical coastal environments ([18],[19].

The gently sloping seabed also promotes the formation of longshore currents that transport sediments parallel to the coastline, thereby creating alternating zones of erosion and deposition. Sediments eroded from one coastal segment may be redistributed and deposited elsewhere depending on wave direction, current intensity, and sediment availability. Such hydrodynamic interactions explain why shoreline changes along Moilong Beach are spatially heterogeneous rather than uniform. This pattern is consistent with previous studies demonstrating that coastal bathymetry strongly influences the balance between erosion and accretion through its control on wave energy dissipation and sediment transport pathways [20],[21].

Overall, the bathymetric characteristics of Moilong Beach provide the physical framework governing coastal hydrodynamics and sediment redistribution. The interaction between gentle seabed morphology, wave transformation, and longshore sediment transport contributes significantly to shoreline dynamics and should therefore be incorporated into coastal vulnerability assessments and erosion mitigation planning. Integrating bathymetric information into coastal management strategies is essential to improve predictions of shoreline evolution and to support sustainable coastal protection under increasing environmental pressures [2].

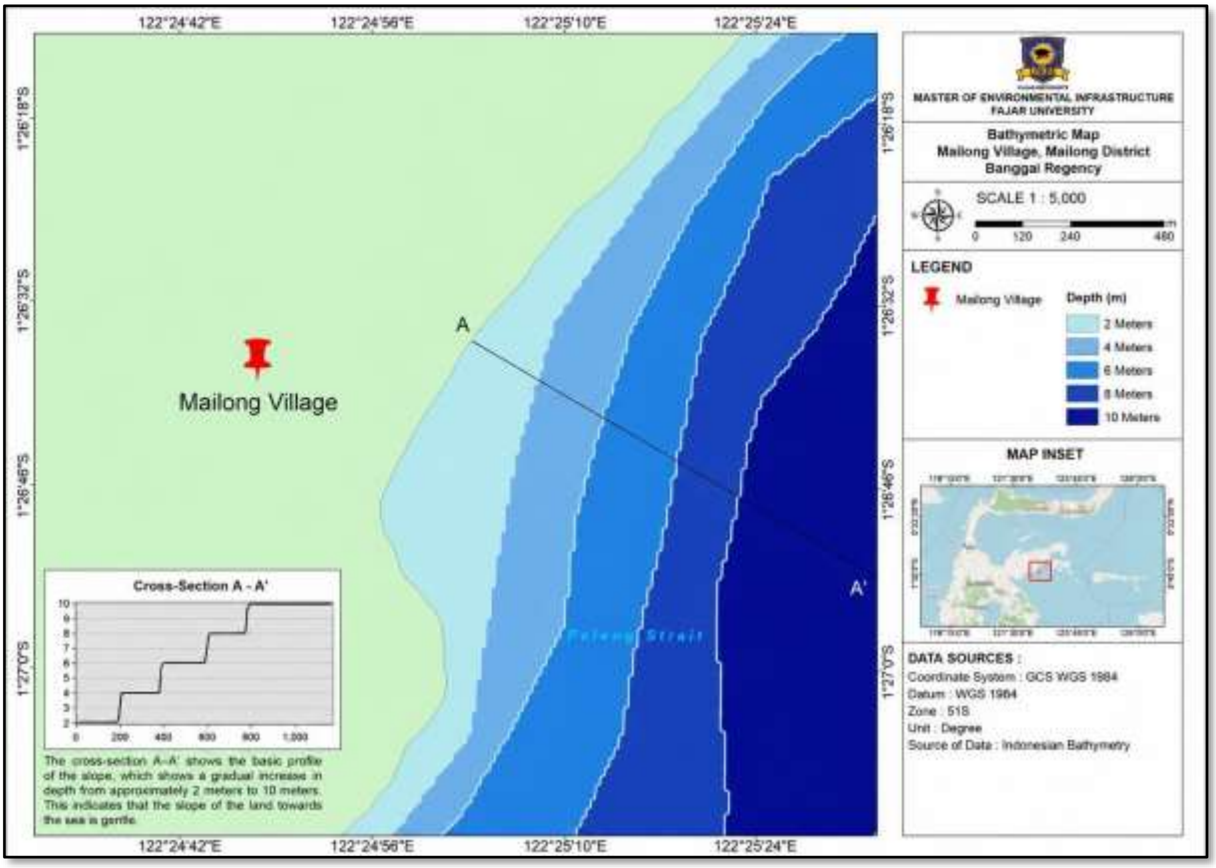

Fig. 4. Bathymetric Map of Moilong Village, Moilong District, Banggai Regency

Watershed and Sediment Supply

The watershed analysis identified one main river and a smaller tributary discharging into the coastal waters of Moilong Beach. These river systems function as the primary pathways transporting sediments from the upstream catchments to the coast, thereby maintaining the coastal sediment budget. Spatial observations indicate that the main river drains a larger catchment before reaching the Peleng Strait, whereas the tributary traverses the central settlement area and contributes additional sediment inputs to the northern coastal segment. These findings highlight the important role of watershed characteristics in controlling sediment availability and coastal morphology.

Despite the presence of these river systems, the amount of sediment effectively reaching the shoreline appears to vary considerably. The main river flows through areas experiencing substantial land-use changes and intensive human activities, which may reduce sediment delivery through channel modification, sediment trapping, and altered runoff processes. Consequently, sediment losses caused by wave action and longshore currents may exceed sediment inputs in the southern coastal segment, resulting in persistent shoreline erosion. In contrast, the smaller tributary drains areas with relatively lower anthropogenic disturbance, allowing a more continuous sediment supply that may contribute to localized shoreline stability or accretion. These observations agree with recent studies emphasizing that watershed conditions and sediment connectivity strongly influence coastal resilience and shoreline stability by regulating sediment flux from terrestrial to marine environments [22],[23].

Overall, the relationship between watershed characteristics and sediment supply demonstrates that shoreline evolution in Moilong is governed not only by marine hydrodynamic processes but also by upstream watershed conditions. Sustainable watershed management, including the conservation of river corridors and appropriate land-use planning, is therefore essential to maintain sediment delivery and reduce long-term coastal erosion. This integrated land–sea perspective has become a fundamental principle in contemporary coastal management, particularly for tropical coastlines where riverine sediment supply plays a dominant role in sustaining shoreline stability [24],[17].

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Fig. 5. River Flow Map of Moilong Village, Moilong District, Banggai Regency

Land Use and Coastal Vulnerability

The land-use pattern of Moilong Village is dominated by agricultural land in the inland area, while settlements are concentrated along the coastal road parallel to the shoreline. Coastal land cover consists of narrow wetland strips, small patches of mangrove forests, aquaculture ponds, and several vacant lands adjacent to the coast. This spatial configuration indicates that human activities are concentrated within the coastal zone, reducing the natural buffer between terrestrial and marine environments. The limited extent of mangrove vegetation and the conversion of coastal wetlands into aquaculture ponds further decrease the capacity of the coastal ecosystem to attenuate wave energy and retain sediments, thereby increasing shoreline vulnerability to erosion. These findings are consistent with previous studies demonstrating that land-use change and the degradation of coastal vegetation significantly increase coastal vulnerability by weakening natural shoreline protection [25],[26].

Field verification confirmed the reliability of the interpreted land-use map and revealed that dense settlements dominate the village center, whereas aquaculture ponds, wetlands, and open lands occupy the coastal fringe. An important finding is the occurrence of natural mangrove regeneration within abandoned ponds, indicating that ecosystem recovery has already begun in several locations. Nevertheless, the expansion of oil palm plantations and the gradual replacement of mixed vegetation with monoculture crops may alter watershed hydrology and sediment delivery to the coast, potentially accelerating erosion over the long term. These observations emphasize that sustainable land-use planning should integrate ecosystem conservation with community livelihood development to enhance coastal resilience. Similar conclusions have been reported by recent studies showing that mangrove restoration and integrated land-use management are among the most effective nature-based solutions for reducing coastal erosion and strengthening ecosystem resilience [27],[28]. Overall, the land-use characteristics of Moilong Beach demonstrate that coastal vulnerability results from the interaction between natural coastal processes and anthropogenic land conversion. The proximity of settlements to the shoreline, the limited distribution of mangroves, and the conversion of wetlands into aquaculture and agricultural land have collectively reduced the adaptive capacity of the coastal environment. Therefore, future coastal management should prioritize mangrove rehabilitation, protection of coastal wetlands, and the implementation of sustainable land-use policies to minimize shoreline degradation and improve long-term coastal resilience [29].

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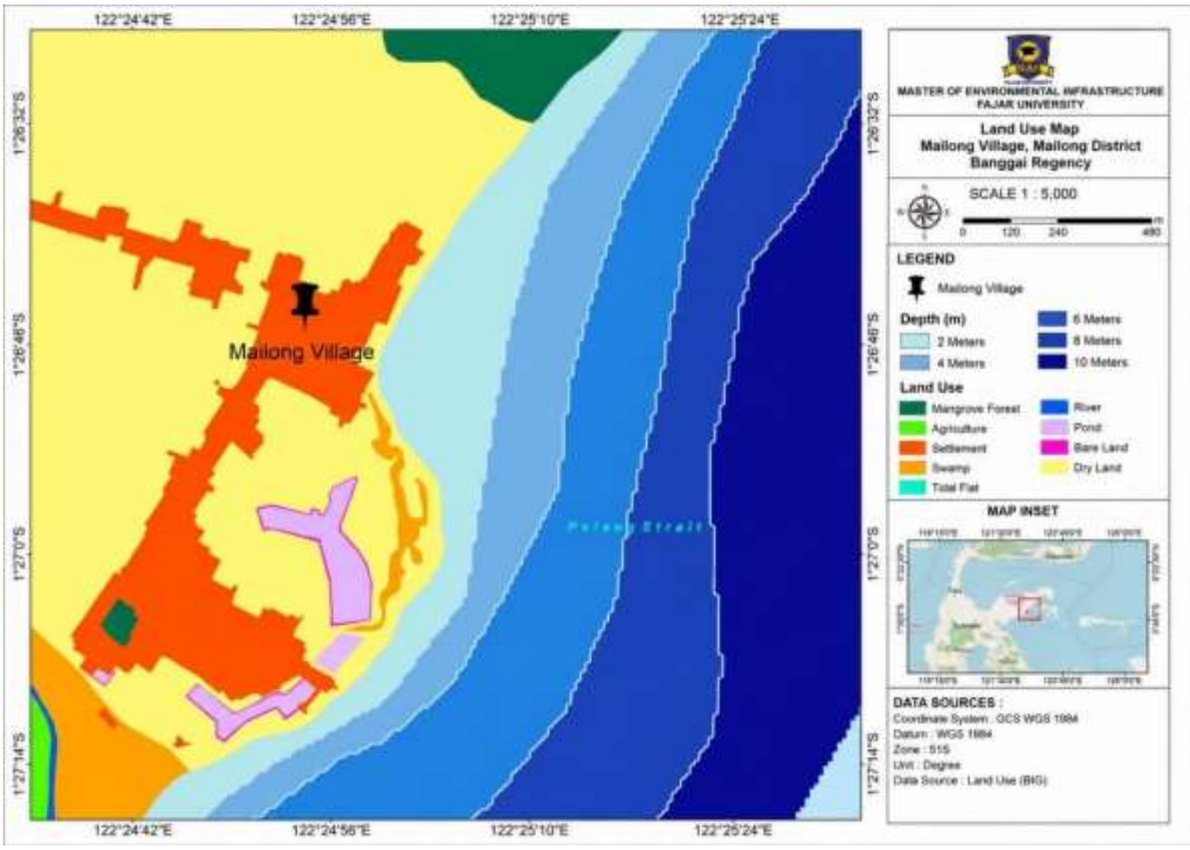

Fig. 6. River Flow Map of Moilong Village, Moilong District, Banggai Regency

Infrastructure and Coastal Exposure

The spatial distribution of settlements in Moilong Village shows a linear development pattern following the primary coastal road, with the highest building density located in the village center. This configuration has resulted in residential areas being established very close to the shoreline, increasing the exposure of communities and physical assets to coastal erosion. Although the existing road network provides adequate connectivity and may serve as an evacuation route during coastal hazards, the concentration of infrastructure within the immediate coastal zone substantially increases disaster risk when shoreline retreat occurs. Similar settlement patterns have been identified as major drivers of coastal exposure because infrastructure located within dynamic shoreline zones is highly vulnerable to erosion and sea-level rise [17],[30].

Field observations also revealed that structural coastal protection remains limited. The existing seawall protects only approximately 200 m of the 700 m shoreline investigated, leaving a large proportion of densely populated coastal segments without adequate protection. In addition, several public facilities and aquaculture ponds are located near the shoreline, increasing the potential for economic and social losses if erosion continues. These findings indicate that structural protection alone is currently insufficient to reduce coastal risk, particularly in areas where population density and infrastructure concentration are high. Recent studies similarly emphasize that the effectiveness of coastal protection depends on integrating engineered structures with ecosystem-based adaptation and appropriate spatial planning to reduce long-term exposure [31],[2].

Overall, the existing infrastructure and settlement pattern significantly contribute to the high coastal exposure of Moilong Beach. The close proximity of settlements to the shoreline, limited coverage of coastal protection structures, and increasing pressure from coastal development collectively heighten the vulnerability of both communities and infrastructure. Consequently, future coastal management should integrate shoreline setback policies, expansion of ecosystem-based protection measures, and strategic improvement of coastal infrastructure to enhance adaptive capacity and minimize the impacts of ongoing shoreline change [32].

4. Conclusion

This study demonstrates that coastal erosion at Moilong Beach is controlled by the interaction between coastal morphological characteristics and environmental factors identified through Geographic Information System (GIS)-based spatial analysis and field observations. The dominant factors contributing to shoreline erosion include the presence of unconsolidated Holocene alluvial deposits, a narrow sandy shoreline, gently sloping bathymetry that facilitates longshore sediment transport, reduced sediment supply from the watershed, degradation of mangrove vegetation, land-use changes, and the concentration of settlements and infrastructure along the coastline. These findings indicate that coastal erosion is driven by both natural coastal processes and anthropogenic pressures. Therefore, sustainable erosion mitigation should adopt an integrated coastal management approach that combines ecosystem-based measures, such as mangrove restoration and watershed conservation, with appropriate coastal spatial planning and engineering protection to enhance shoreline stability and long-term coastal resilience.

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