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Mapping of Geomorphological Zones and Benthic Habitats Using PlanetScope Imagery with Google Earth Engine on Leti Island, Maluku Province

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Abstract: The shallow marine ecosystem of Leti Island, Southwest Maluku, Indonesia, which is rich in biodiversity but lacks data, was mapped using 3-meter spatial resolution PlanetScope imagery processed in Google Earth Engine with the Random Forest algorithm for hierarchical classification of geomorphological zones (10 classes) and benthic habitats (6 classes), integrating radiometric correction, ArcGIS Pro mosaicking, and training samples from field data. The results show the dominance of coral/algae (621.25 ha, 38.27%) and seagrass (536.77 ha, 33.07%) habitats, followed by rock (389 ha, 23.96%), reflecting erosion-sedimentation dynamics and the potential for biodiversity and fisheries conservation, while the geomorphological zones are led by the terrestrial reef flat (705.40 ha, 40.03%) and outer reef flat (228.71 ha, 12.98%), with reef slopes and lagoons serving as adaptive transitions to local hydrodynamics and non-volcanic tectonics. The results of this study emphasize the ecological implications for resilience to climate change and human activities, recommending field validation, predictive spatial modeling via lidar/sonar, and the use of these thematic maps as a basis for the sustainable management of Indonesia's outermost marine conservation areas.

Keywords: Benthic Habitats, Geomorphological Zones, Google Earth Engine, PlanetScope

1. Introduction

Shallow marine ecosystems, particularly coral reefs and seagrass beds, are fundamental assets for global biodiversity and ecosystem services of high economic value (Jamieson et al. 2020). However, this ecosystem faces increasing anthropogenic pressure and the impacts of climate change, requiring continuous and accurate monitoring (Lucatelli et al. 2020). In remote areas like Leti Island, the scarcity of field data often hinders conservation efforts and coastal spatial planning. Therefore, to comprehensively map the biophysical conditions of the area, we need an efficient marine resource inventory approach (He et al. 2023).

Mapping geomorphological zones and benthic habitats is crucial because both provide an understanding of the physical structure and biological distribution of the seabed (Rifai et al. 2025). Geomorphological zones determine the hydro-oceanographic energy dynamics, while benthic habitats reflect the ecological health of a body of water (Lozano et al. 2020).

Conventional mapping using the dive transect method has limitations in terms of spatial coverage and cost, especially for large island regions (An et al. 2023). In this context, remote sensing becomes a cutting-edge solution for providing synchronous and repetitive spatial data over complex shallow marine areas (Ahmed, Mutua, and Kenduiywo 2021).

The development of satellite technology has now shifted toward the utilization of high-spatial-resolution imagery, such as PlanetScope. Unlike conventional satellites (e.g., Landsat or Sentinel-2), PlanetScope offers 3-meter resolution with daily revisit frequency, enabling more detailed detection of microscale objects on the seabed (Van An et al. 2023). The use of PlanetScope in recent literature studies has been proven to minimize the effects of spectral mixing in heterogeneous habitats, thereby improving classification accuracy compared to medium-resolution sensors (Ariasari et al. 2024).

The integration of Google Earth Engine (GEE) as a cloud-based processing platform has revolutionized geospatial analysis (Zapata-Ramírez et al. 2023). GEE allows for the parallel processing of large datasets without requiring high hardware specifications on the user side (Mutanga and Kumar 2019). Machine learning algorithms available in GEE, such as Random Forest (RF) or Support Vector Machine (SVM), can be optimized to perform geomorphological zone and benthic habitat classification with significant time efficiency (Ahmed, Mutua, and Kenduiywo 2021). This approach is very effective in addressing the challenges of atmospheric and water column correction in satellite imagery (Rifai et al. 2025).

Leti Island has unique water characteristics, but there is still limited scientific research on mapping its underwater habitats. The varied geomorphological characteristics, ranging from coral reefs to steep slopes, make this island an ideal location to test the integration performance of PlanetScope and GEE. This study aims to fill the knowledge gap regarding the effectiveness of utilizing a constellation of micro-satellites (PlanetScope) for mapping shallow water zones in Indonesia's outermost regions, which face significant logistical challenges.

Through this approach, this research aims to develop a robust classification model and generate accurate thematic maps as a spatial database (Wicaksono et al. 2023). The results of this mapping are expected not only to contribute theoretically to the field of marine geoinformatics but also to provide practical recommendations for policymakers in the sustainable management of marine conservation areas on Leti Island. The integration of high-resolution sensors and cloud computing is a step forward in accelerating the achievement of sustainable development goals related to marine ecosystems.

2. Methods

This research was conducted in the waters of Leti Island, Southwest Maluku Regency, Indonesia (Figure 1). The study utilized PlanetScope satellite imagery data, officially downloaded from Planet Labs: https://www.planet.com/explorer/, recorded on January 11 and 12, 2026. The initial stage of this research focuses on the acquisition and preprocessing of remote sensing data using PlanetScope satellite imagery with a spatial resolution of 3 meters acquired in 2026. The selection of PlanetScope was based on its daily temporal resolution capability and high spatial resolution, which are crucial for mapping complex structures on Letti Island. The entire image scene covering the study area was combined into a coherent mosaic using ArcGIS Pro software, applying radiometric and atmospheric corrections to ensure consistency of reflectance values across channels.

After the mosaic process is complete, the dataset is uploaded to the Google Earth Engine (GEE) cloud-based platform for large-scale data processing. Within the GEE environment, feature extraction and data annotation are performed through a process of visual interpretation enhanced with ground control points (GCP) to determine training samples. The use of GEE allows for computational efficiency in handling complex algorithms and facilitates the integration of various vegetation or water indices if necessary to improve the accuracy of separating terrestrial and marine objects.

Figure 1. Study Location, Leti Island, Southwest Maluku Regency, Indonesia

The classification process was carried out by applying the Random Forest (RF) algorithm, an ensemble learning method proven to be highly effective in handling non-linear data and having high accuracy in benthic habitat mapping. The RF algorithm was configured by determining the optimal number of trees and predictor variables to minimize out-of-bag error (Lyons et al. 2024). This approach allows for the automatic and objective identification of spectral patterns for seabed substrates along the coast of Letti Island.

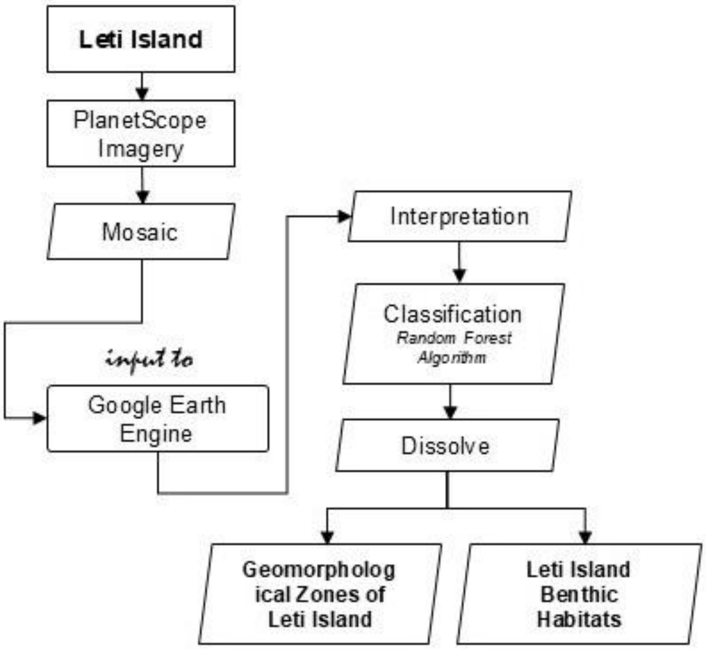

Figure 2. Workflow

The final outputs of this study are two main thematic maps: a geomorphological zone map and a benthic habitat map. The classification scheme was performed hierarchically to separate the geomorphological zones, which consist of 10 classes, including shallow lagoon, deep lagoon, inner reef flat, outer reef flat, reef crest, terrestrial reef flat, sheltered reef slope, reef slope, plateau, and back reef slope, as well as 6 benthic habitat categories, including sand, rubble, rock, seagrass, coral/algae, and microalgal mats. The workflow of this research can be seen in Figure 2.

3. Results and Discussion

3.1. Leti Island Benthic Habitat Distribution

The distribution of benthic habitats on Leti Island reflects the rich diversity of marine ecosystems, with the total area dominated by hard habitats and underwater vegetation. Coral/algae habitat is the largest, covering 621.25 ha, or 38.27% of the total area, followed by seagrass at 536.77 ha (33.07%). This composition highlights the crucial role of coral reefs and seagrass as supporters of high biodiversity in the Maluku Islands region. The distribution of benthic habitats can be seen in Figure 3, and their area can be seen in Table 1.

Figure 3. Map of Benthic Habitat Distribution on Leti Island

Table 1. Benthic Habitat Area (Ha)

Benthic Class	Area (Ha)
Sand	31,28
Rubble	43,20
Rock	389,00
Seagrass	536,77
Coral/Algae	621,25
Microalgal Mats	1,80
Total Area	1.623,31

Hard habitats like rock dominate with 389.00 ha (23.96%), while rubble and sand are 43.20 ha (2.66%) and 31.28 ha (1.93%), respectively, indicating natural erosion and sedimentation dynamics on the island's seabed. The presence of very small microalgal mats, only 1.80 ha (0.11%), indicates that environmental conditions are less conducive to the accumulation of microalgae in sandy sediments. This distribution pattern is influenced by topographic factors, currents, and wave exposure, as observed in similar benthic habitat mapping in Indonesian waters (Teurupun et al. 2025). The presentation of the Leti Island benthic habitat areas can be seen in Figure 4.

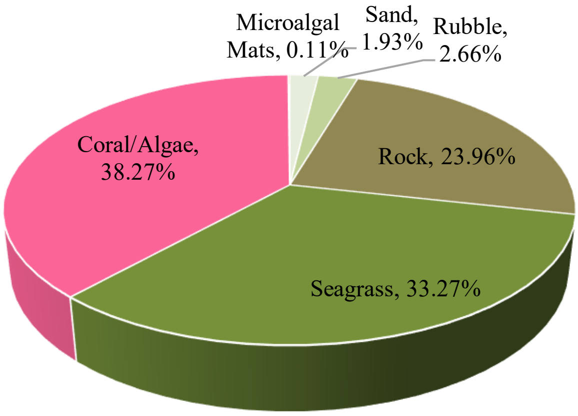

Figure 4. Benthic Habitat Area (%)

Understanding this distribution is crucial for analyzing the vulnerability of ecosystems to threats such as climate change and human activities. The dominance of coral/algae and seagrass offers potential as a priority conservation area, while soft habitats like sand and rubble serve as transitional zones supporting nutrient cycles. A satellite image-based mapping approach and field surveys are recommended for further data validation. The ecological implications of the benthic habitat distribution on Leti Island include significant contributions to local fisheries productivity and regional ecosystem resilience. Similar studies in the Indo-Pacific region confirm that such habitat diversity supports diverse benthic macroinvertebrate communities, which in turn strengthens the marine food web. Further research is needed to integrate spatial models to predict future distribution changes (Zhou et al. 2024).

3.2. Leti Island Geomorphological Zones

The distribution of geomorphological zones on Leti Island reflects the dynamics of coral reef formation, which is influenced by wave energy, water depth, and sedimentation processes in the Southwest Maluku Islands region. The Terrestrial Reef Flat Zone dominates with an area of 705.40 ha, or 40.03%, indicating a blend of land and fringing reefs exposed to freshwater flow and sediment. This zone is followed by the Outer Reef Flat, covering 228.71 ha (12.98%), which serves as a shallow platform with strong zonation due to the influence of open sea waves.

The reef slope zone, such as the Sheltered Reef Slope (221.77 ha, 12.59%) and the Reef Slope (201.49 ha, 11.43%), forms a transition to deeper waters. The former is characterized by protection from wind or currents, while the latter faces the prevailing wind. Additionally, the 93.37 ha (5.30%) plateau represents a stepped hard feature on the deeper seafloor. This composition indicates the influence of non-volcanic outer arc tectonics in the Leti region, as observed in the geological study of the Maluku Islands Geomorphological Zone, which can be seen in Figure 5, with its area shown in Table 2.

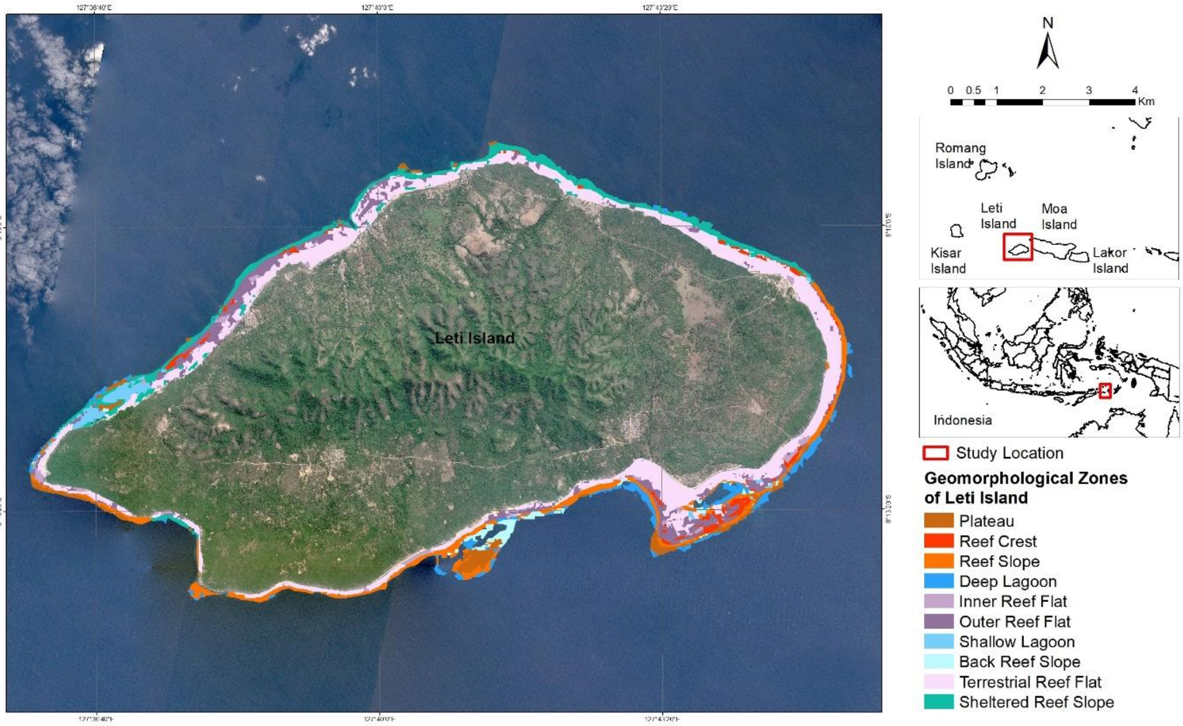

Figure 5. Leti Island Geomorphological Zones Map

Table 2. Geomorphological Zone Area (Ha)

Gomorphic Class	Area (Ha)
Shallow Lagoon	52.17
Deep Lagoon	103.70
Inner Reef Flat	50.61
Outer Reef Flat	228.71
Reef Crest	60.82
Terrestrial Reef Flat	705.40
Sheltered Reef Slope	221.77
Reef Slope	201.49
Plateau	93.37
Back Reef Slope	44.09
Total Area	1762.12

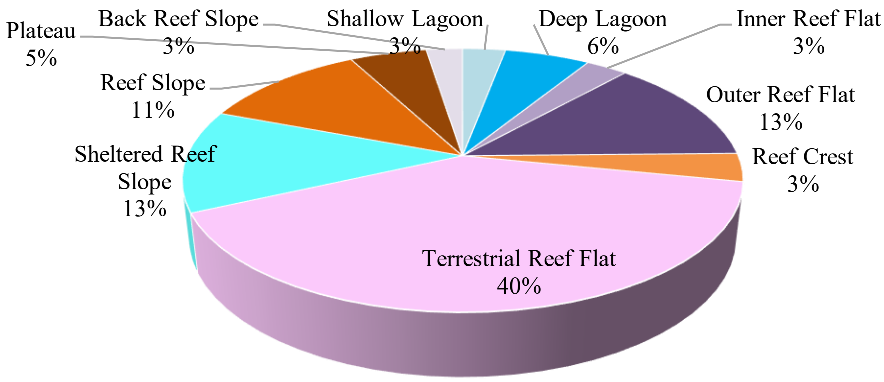

Figure 6. Geomorphological Zone Area (%)

Shallow lagoons (52.17 ha, 2.96%) and deep lagoons (103.70 ha, 5.88%) dominate the semi-enclosed areas with soft sediments from the reef, while the inner reef flat (50.61 ha, 2.87%), reef crest (60.82 ha, 3.45%), and back reef slope (44.09 ha, 2.50%) complete the internal zonation with low energy and sporadic coral outcrops. The presentation of the areas can be seen in Figure 6. This pattern reflects the morphological evolution of reefs, which adapt to local hydrodynamic conditions. Understanding the geomorphological zones of Leti Island is crucial in this study, particularly in analyzing vulnerability to climate change and biodiversity conservation. The dominance of the terrestrial reef flat and outer reef flat offers priority for monitoring coastal erosion, while the slope zone supports economically valuable fish habitats (Lyons et al. 2024). Further studies with lidar mapping or sonar surveys are recommended for spatial predictive models (Schill et al. 2021).

Conclusions

The distribution of benthic habitats on Leti Island is dominated by coral/algae (38.27%) and seagrass (33.07%), followed by hard habitats such as rock (23.96%), reflecting the rich diversity of marine ecosystems in the Maluku Islands influenced by topography, currents, and sedimentation. This is crucial for biodiversity conservation, fisheries productivity, and mitigating the threats of climate change. Meanwhile, the geomorphological zones are dominated by the Terrestrial Reef Flat (40.03%) and the Outer Reef Flat (12.98%), with the reef slope and lagoon serving as transitions. This indicates the dynamics of coral formation due to wave energy, depth, and local tectonics, which necessitates monitoring erosion, economically important fish habitats, and predictive spatial models based on satellite, lidar, or sonar data for regional ecosystem resilience.

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Conflicts of Interest
The authors declare no conflict of interest.

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