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Cloud-based multitemporal shoreline change analysis using google earth engine and DSAS: A case study of Canggu Beach, Bali, Indonesia

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ABSTRACT

Canggu Beach, Bali, is a multifunctional coastal area facing increasing environmental pressures from erosion and rapid coastal development. This study analyzed shoreline changes during the period 2016-2024 using multitemporal Sentinel-2 imagery processed on the Google Earth Engine (GEE) platform. Shoreline extraction was employed the NDWI index and Otsu threshold method, with sea level stability was controlled using HYCOM data. Shoreline change analysis was conducted using Digital Shoreline Analysis System (DSAS) on 247 transects with Net Shoreline Movement (NSM) and End Point Rate (EPR) approaches. Results showed a dominant trend of accretion (NSM +16.61 m; EPR +2.26 m/year), with localized erosion (NSM –8.8 m; EPR –1.2 m/year), identified around estuary and structured areas. Spatial patterns of change were visualized in the form of multitemporal maps and statistical histograms, revealing uneven shoreline dynamics. The integration of GEE and DSAS proved effective for large-scale shoreline monitoring, and the results can provide a basis for adaptive coastal management in dynamic, multi-functional coastal areas.

Keywords: Canggu beach, shoreline change; remote sensing; google earth engine; DSAS

1 Introduction

As an archipelagic country with approximately 80.000 km of shoreline and a dominant maritime territory, Indonesia's coastal areas are vital centers of economic, social, and cultural activity [1], [2]. However, intensive exploitation of coastal areas has triggered various environmental problems, such as erosion, accretion, and damage to coastal protection structures [3]. Therefore, changes in the shoreline need to be monitored continuously as a key indicator in anticipating more serious ecological impacts [4].

Canggu Beach, Bali, is a multifunctional area combining global tourism, spiritual activities, and fishing livelihoods. However, this area faces ecological pressures due to erosion at a rate of 1.42–2.05 m/year, driven by infrastructure expansion and natural dynamics [5]. As a worldclass tourist destination that once ranked 39th among the top 100 beaches in CNN's 2013 list, Canggu Beach faces the risk of shoreline changes that could disrupt the sustainability of the ecosystem, the functions of the area, and its socio-cultural values [5]–[9].

Regular monitoring of shoreline changes is important for understanding coastal dynamics and their long-term impacts on the environment, economy, and spatial planning [10]. Conventional survey methods often have limitations because considered costly and inefficient [11] and are unable to capture rapid changes [12]. The land–sea boundary ambiguity often leads to interpretation errors [13], while historical data are difficult to obtain, causing long-term dynamics to be overlooked [14]. Therefore, remote sensing and DSAS-based approaches are increasingly adopted as they provide more accurate multitemporal shoreline monitoring [15]–[17]. In this context, cloud computing-based platforms such as Google Earth Engine further support large-scale geospatial data analysis with higher efficiency [18].

To address these limitations, cloud computing based approaches offer a relevant solution. Google Earth Engine (GEE) emerges as an innovative platform enabling large-scale geospatial data processing with high efficiency. With open access to global satellite image archives and advanced analysis algorithms, GEE supports remote sensing research that requires high spatial and temporal accuracy [18]–[20].

The use of Google Earth Engine-based remote sensing not only improves the accuracy of erosion and accretion detection [21], but also provides a scientific basis for the formulation of adaptive policies that integrate environmental mitigation with sustainable development needs [22]. Satellite based remote sensing is an efficient approach to obtain data in areas with limited time series field observations [23].

This study aims to analyze the multitemporal dynamics (2016–2024) of the shoreline at Canggu Beach by integrating satellite data processing using Google Earth Engine (GEE) and statistical analysis through the Digital Shoreline Analysis System (DSAS). The results of this study are expected to serve as a basis for developing adaptive technical recommendations for coastal protection, particularly for areas with dual functions such as tourism, spirituality, and fishing activities.

2 Data and Methods

2.1 Research Location

The research location is at Canggu Beach, which is located in Canggu Village, Kuta Utara District, Badung Regency, Bali, Indonesia **(Figure 1)**.

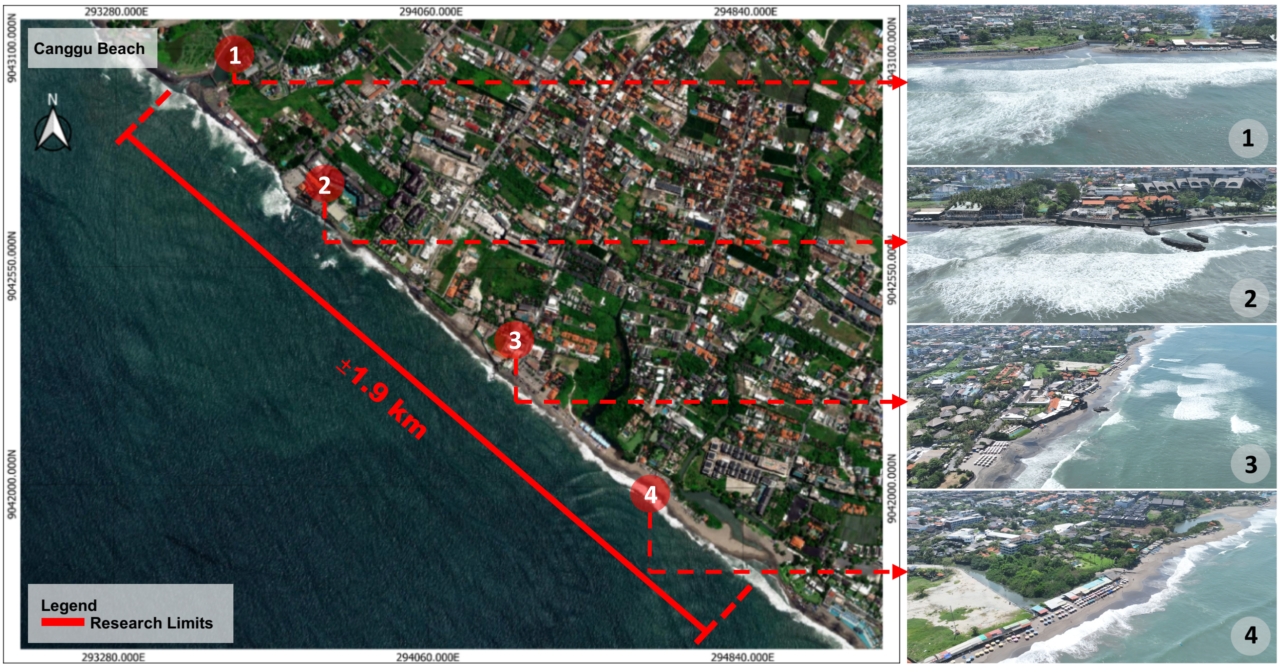


Figure 1. Map of the study area and drone documentation photos of Canggu Beach

2.2 Data Sources

This study utilized multitemporal Sentinel-2 satellite imagery accessed from the Google Earth Engine (GEE) platform to analyze changes in the shoreline of Canggu Beach during the period 2016–2024 **(Figure 3)**. The selection of image acquisition dates it was conducted based on two main criteria: (1) cloud-free atmospheric conditions, and (2) sea level stability within a range of 0.4–0.6 meters. However, the accuracy of satellite image classification results can be affected by sensor quality, processing algorithms, and atmospheric conditions such as aerosols and air turbulence, which can cause spatial distortion and reduce the accuracy of shoreline extraction [24], [25].

Sea surface elevation data were obtained from the Hybrid Coordinate Ocean Model (HYCOM) system, which provides satellite-based tidal information. With technological advancements, remote sensing enables widespread and periodic sea surface measurements, making it an essential tool for monitoring coastal area changes [26].

Figure 2 presents a graph of sea surface elevation fluctuations at Canggu Beach from 2016 to 2024 based on HYCOM data. The horizontal line within the 0.4–0.6 m range indicates the stable elevation range used as a reference for selecting Sentinel-2 image acquisition dates for shoreline change analysis.

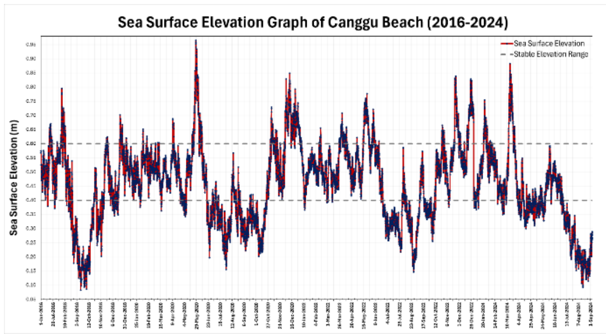


Figure 2. Sea surface elevation graph of Canggu Beach (2016–2024)

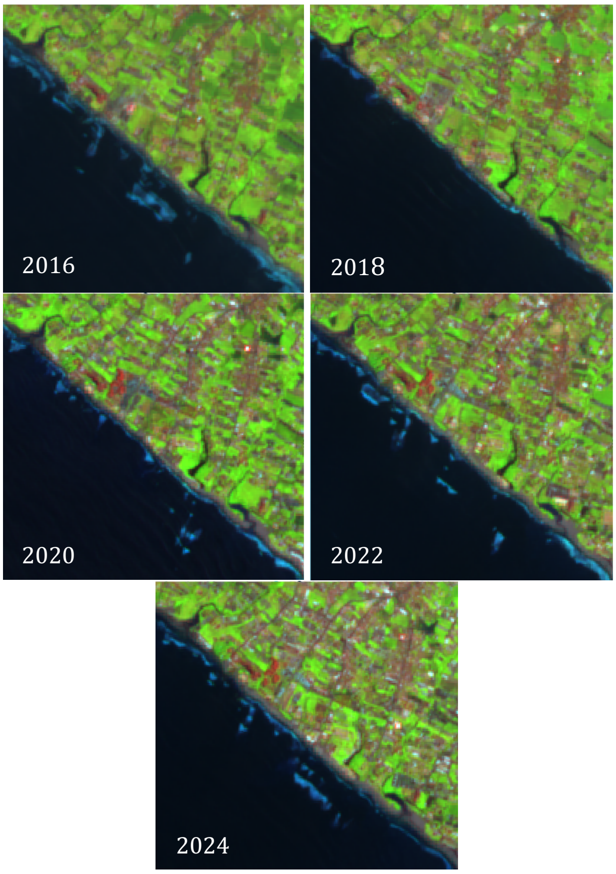


Figure 3. Sentinel-2 imagery of Canggu Beach (2016–2024)

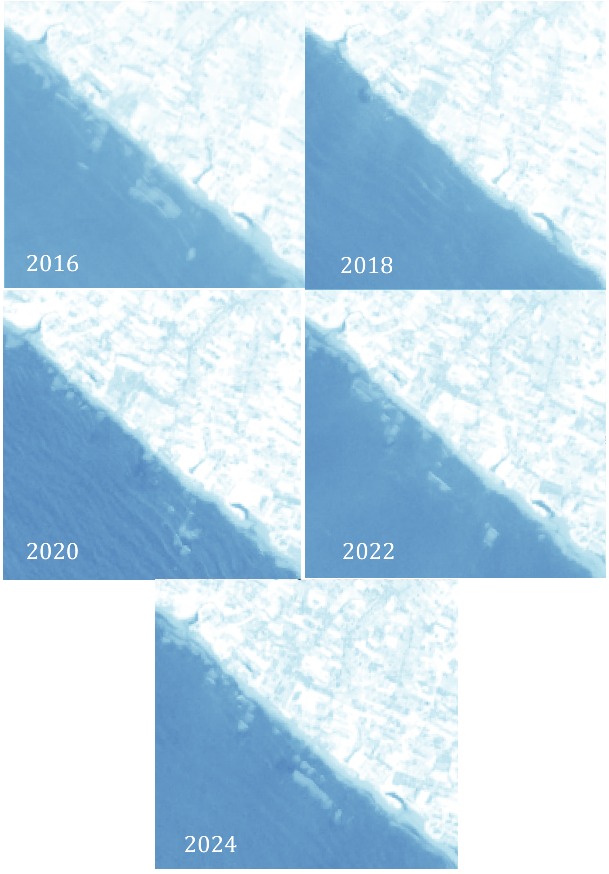


Figure 4. NDWI outputs for shoreline extraction (2016–2024)

2.3 Pre-Processing and NDWI Calculation

The Normalized Difference Water Index (NDWI) is calculated from green and NIR channels, because water reflects more green light and absorbs more of the NIR spectrum, making it easier to accurately separate water areas from land [27], [28]. The advantage of NDWI lies in its ability to distinguish between water and non-water areas, particularly in complex urban environments where built-up areas and water bodies often overlap spectrally [29]. This index has been widely used to monitor changes in water surfaces and support environmental analysis, including flood mitigation and natural resource conservation [30], [31]. NDWI is calculated using two spectral bands: the green (Green) band and the near-infrared (NIR) band. The formulation of the NDWI can be expressed using **Equation 1.** The NDWI output results for selected dates are visualized in **Figure 4.**

$$NDWI = \frac{Green - NIR}{Green + NIR} \quad (1)$$

This formula allows clear differentiation between water and non-water surfaces based on differences in reflectance, and has been used effectively in land/water boundary identification and shoreline monitoring [32].

2.4 NDWI Thresholding Process Using the Otsu Method

NDWI images are classified into binary images using the Otsu automatic thresholding method, which globally determines the optimal threshold value to distinguish water and land pixels [33], [34]. The binary classification results based on Otsu thresholding are visualized in **Figure 5.** The advantage of the Otsu technique lies in its ability to perform unsupervised segmentation, making it efficient in water information extraction.

The combination of Otsu with NDWI and Sentinel data is effective in detecting flooded areas [35] and can improve extraction accuracy and speed when applied to radar images [36].

From the evaluation of various studies, it can be concluded that the Otsu method is a valuable tool in NDWI image processing, providing advantages in improving the accuracy of water body mapping, especially when applied to complex images where the interaction between water and non-water land dominates. The Otsu method, adopted in several other water extraction approaches, continues to prove its usefulness in addressing the challenges faced in accurately monitoring water resources [35]–[37].

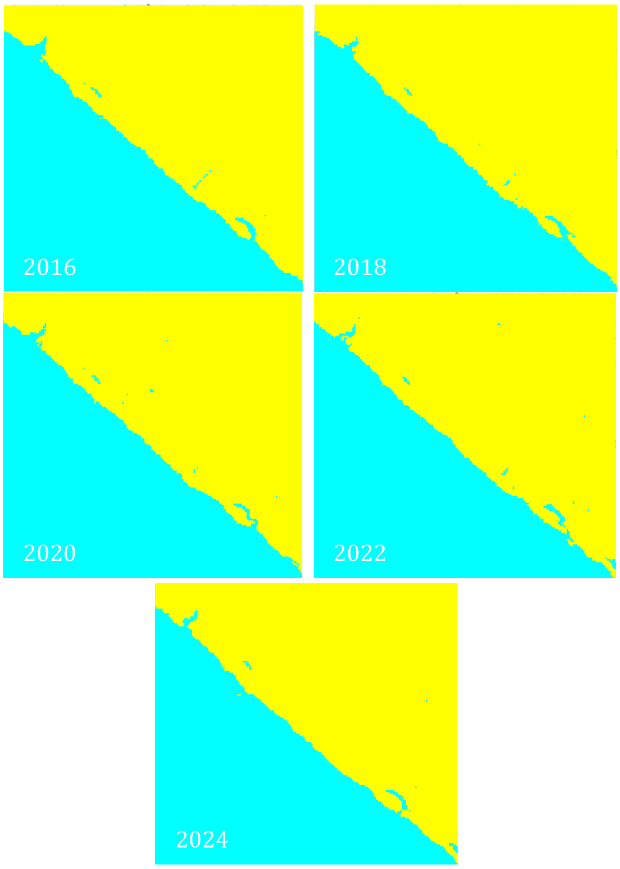
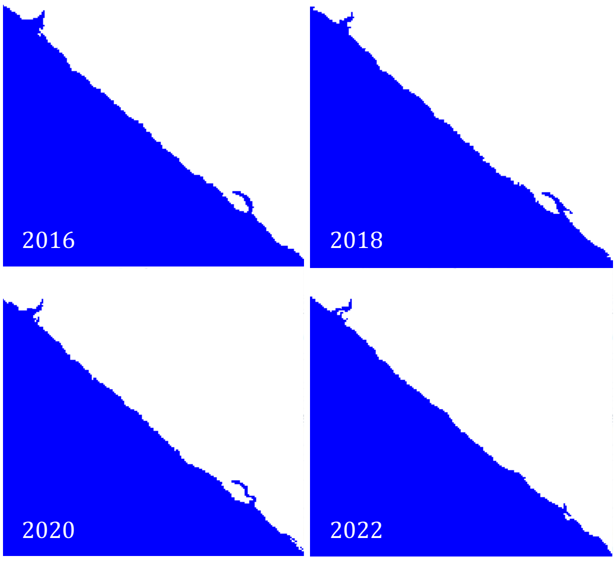


Figure 5. NDWI thresholding results using the otsu method (2016–2024)

2.5 Vector Processing and Land Separation

The binary image resulting from thresholding is converted into a vector and cleaned by removing land areas that are not part of water objects. This process aims to leave the boundary between water and land as a representation of the shoreline. The Otsu thresholding technique has proven effective in enhancing water segmentation accuracy by optimizing inter-class variance in NDWI images [38], [39]. The cleaned shoreline is visualized in **Figure 6.**



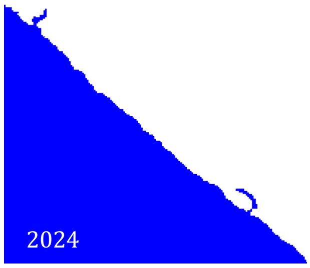


Figure 6. NDWI vector after land cleaning

2.6 Polygonal Shoreline Extraction Result

The binary classification results were then converted into vector features using QGIS software, resulting in a shoreline representation in the form of polygons. This representation serves as the basis for spatial and quantitative analysis of shoreline changes [40]. The final polygonal shoreline extraction result is visualized in **Figure 7.**

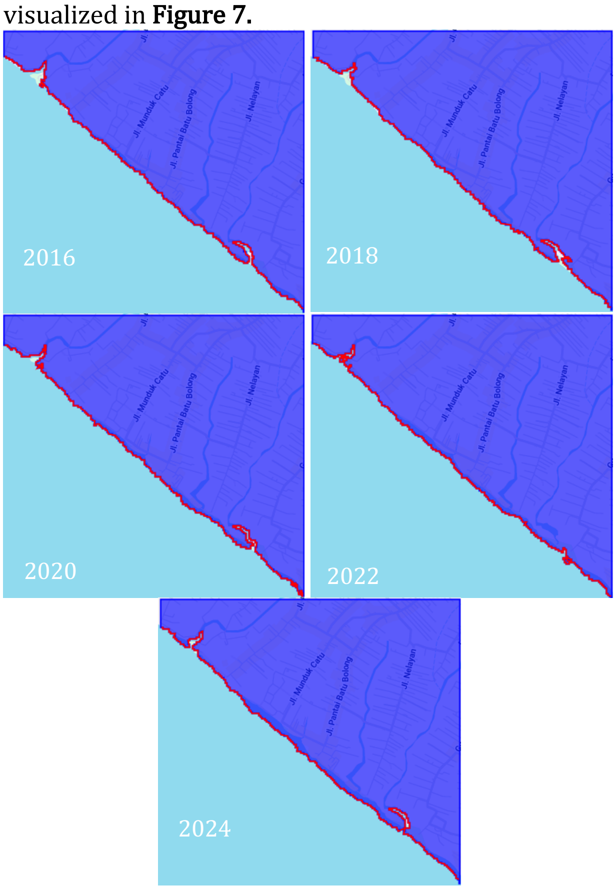


Figure 7. Polygonal shoreline extraction result

3 Results and Discussion

3.1 Existing Conditions of Canggu Beach

Canggu Beach is actively used for social, cultural, and economic purposes [41], including religious activities marked by temples **(Figure 8)** and traditional fishing activities with visible boats and landing sites **(Figure 9**).

From a tourism perspective, Canggu Beach features various supporting facilities **(Figure 10)**, reflecting its strong socio-cultural role and high economic value as an international tourist destination.

However, the area also faces physical issues, including seawall damage around Pura Batu Mejan due to wave pressure, as well as altered esstuary patterns and partial sedimentation, which could disrupt coastal dynamics **(Figure 11)**.

a. Pura Dalem Magada   b. Pura Batu Mejan   c. Pura Luhur Dalem Segara

d. Pura Batu Bolong   e. Pura Segara   f. Pura Segara

Figure 8. Spiritual area around Canggu Beach

Figure 9. Fishing base and supporting facilities at Canggu Beach

a. Beach Club   b. Café and Bar   c. Hotel

d. Surf School   e. Restaurant   f. Local Eateries

Figure 10. Tourism facilities and recreational areas in Canggu Beach

Figure 11. Seawall damage and changes in estuary flow direction

3.2 Multitemporal Shoreline Visualization

The shoreline of Canggu Beach was extracted from Sentinel-2 images for the period 2016-2024 using the Google Earth Engine (GEE) platform and the NDWI classification method. The extraction results were then spatially analyzed to map changes in the position of the shoreline over time.

Figure 12 shows a multitemporal shoreline visualization displaying five extracted lines in 2016, 2018, 2020, 2022 and 2024, with accretion trends, as well as local erosion in the estuary area and near coastal protection structures. These shifts reflect the interaction of natural factors such as currents, waves, and estuary dynamics, as well as anthropogenic factors such as coastal infrastructure development.

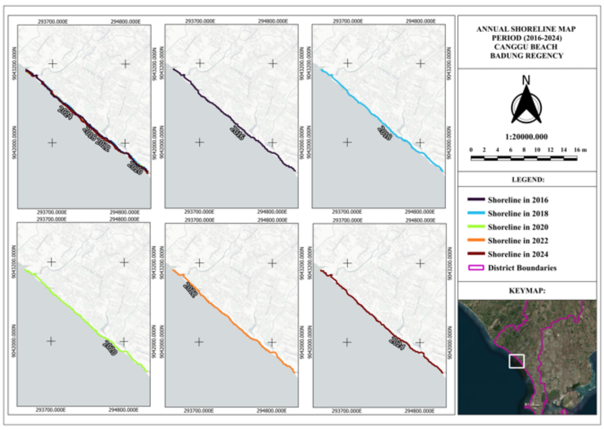


Figure 12. Annual shoreline map period (2016–2024) Canggu Beach Badung Regency

3.3 Statistical Analysis of Shoreline Changes

A total of 247 transects were analyzed using the Net Shoreline Movement (NSM) and End Point Rate (EPR) methods via the DSAS plugin. The results indicate that the Canggu shoreline generally experienced accretion, with an average NSM value of +16.61 meters and an EPR of +2.26 m/year. However, there are also segments experiencing erosion, with an average NSM value of –8.8 meters and an EPR of –1.2 m/year. This statistical distribution is presented in **Table 1**, while **Figure 13** and **Figure 14** provide its spatial visualization.

Statistically mapping shoreline changes not only provides a quantitative overview, but also provides an important basis for spatial assessments displayed on histograms of NSM (Figure 13) and EPR (Figure 14) values. This visualization makes it easier to identify areas with dominant erosion and accretion trends along the shoreline. Although changes generally tend to indicate accretion, eroding segments still need to be considered in coastal management planning. The extreme values found in both methods reflect significant coastal dynamics, making it important to incorporate these results into mitigation strategies and sustainable management of the area.

The highest accretion values occurred around Batu Bolong Beach and Nelayan Beach. This can be attributed to sediment accumulation due to longshore currents and changes in estuarine morphology that accelerate material deposition. Conversely, the highest erosion values were identified around estuary areas with damaged coastal protection structures. This suggests that anthropogenic activities are reinforcing the natural processes occurring in these areas.

This spatial pattern is in line with the results of previous research that found accretion trends in the central part of Canggu Beach and erosion around the estuary [5]. Similarly, research in the Batu Mejan area showed that the presence of coastal structures can trigger local erosion [7]. Thus, the results of this study not only confirm previous findings but also provide a more detailed quantitative and spatial picture of the intensity of shoreline change in Canggu.

Table 1. Global summary of shoreline change statistics (2016–2024)

Method	Unit	Min	Max	Mean	
				Erosion	Accretion
NSM	m	-21.5	47.6	-8.8	16.61
EPR	m/year	-2.9	6.5	-1.2	2.26

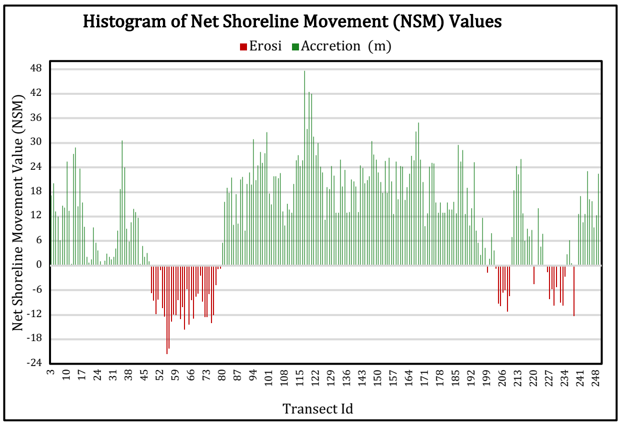


Figure 13. Histogram of the distribution of shoreline values (NSM)

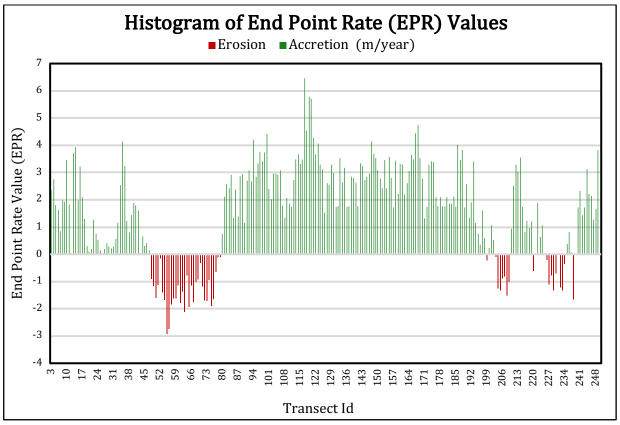


Figure 14. Histogram of the distribution of shoreline change values (EPR)

3.4 Spatial Distribution of Shoreline Changes

The results of the statistical classification of EPR and NSM are visualized spatially to illustrate the direction and intensity of shoreline changes. Each transect segment is grouped into three categories, namely:

- Accretion (shifting toward the sea),
- Erosion (shifting inland), and
- Constant (no change).

Figure 15 presents a map of shoreline change classification during the period 2016–2024. This map shows that accretion occurred predominantly in most areas, especially around Batu Bolong Beach and Nelayan Beach. However, erosion segments also appeared locally, especially at Batu Bolong Beach and around the estuary area.

This visualization clarifies the spatial distribution of shoreline changes and supports previous statistical results.

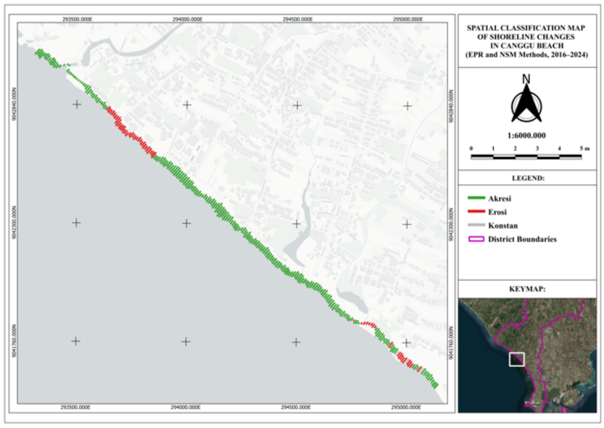


Figure 15. Spatial classification map of shoreline changes in Canggu Beach (EPR and NSM Methods, 2016–2024)

The distribution pattern of shoreline changes in the Canggu area is influenced by a combination of natural and anthropogenic factors. Naturally, the dominant wind direction, waves and longshore currents cause sediment redistribution [42]. In addition, the existence of estuary and changes in their channels can create local turbulence zones that accelerate the erosion and accumulation of sediments [43].

From an anthropogenic perspective, the rapid development of tourism infrastructure and coastal construction (such as seawalls and settlements near the shoreline) can disrupt the dynamic balance of coastal systems and trigger local erosion or accretion. Therefore, understanding these causes is important as a basis for formulating effective and sustainable coastal management strategies [44].

4 Conclusion

Google Earth Engine (GEE) and Digital Shoreline Analysis System (DSAS) proved effective in analyzing spatial and temporal shoreline changes in Canggu Beach during the period 2016-2024. The results of the analysis showed that most areas experienced an accretion trend with an average Net Shoreline Movement (NSM) of +16.61 meters and End Point Rate (EPR) of +2.26 m/year, while local erosion was identified around river mouths and areas adjacent to coastal structures.

These shoreline changes are influenced by natural factors such as currents, waves, and estuary dynamics, as well as anthropogenic pressures such as coastal infrastructure development. These findings are expected to be the basis for adaptive technical planning in the management of multifunctional coastal areas such as Canggu Beach.

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