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Analysis Of Coastal Changes In Lumajang Regency Over A 30-Year Period (1994-2024) Utilizing Remote Sensing And GIS Data

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Abstract— Coastal areas in Lumajang Regency, Indonesia, provide a variety of ecosystem services for coastal communities, including improving the region's economy in the trade, fisheries, and fishing sectors. In addition, it is a habitat for marine biodiversity, such as coral reefs, seagrass, and mangrove ecosystems. This study investigated coastal erosion and accretion patterns in Lumajang Regency, Indonesia, over three decades (1994-2024) using remote sensing and Geographic Information System (GIS) techniques. Landsat satellite imagery was analyzed using the Normalized Difference Water Index (NDWI) to extract shoreline positions, and the Digital Shoreline Analysis System (DSAS) was employed to quantify the rates of change. The results revealed that complex coastal dynamics are influenced by both natural processes and human activities. Accretion dominated the earlier decades, whereas erosion has become more prevalent in recent years. Significant erosion hotspots were identified near estuaries, particularly at the Bondoyudo and Kali Glidik Estuaries, highlighting the impact of fluvial processes on coastal morphology. Conversely, substantial accretion was observed in the Pasiran District, notably at the Watu Pecak and Dampar beaches. The End Point Rate (EPR) analysis showed an average shoreline change rate of 8.25 m/year (1994-2004), 9.69 m/year (2004-2014), and -8.06 m/year (2014-2024). The analysis of the LRR parameters revealed that the Lumajang Regency coast has tended to accrete at an average rate of 3.94 m/year over the past three decades. This study emphasizes the importance of continuous monitoring and the need for adaptive management approaches to address the challenges posed by ever-changing coastal areas.

Keywords—Coastal, Erosion and Accretion, DSAS, Remote Sensing, GIS

I. INTRODUCTION

Coastal areas are meeting places between land and sea that undergo dynamic changes. This area is important for natural life because it is a habitat for ecosystems such as coral reefs, seagrass beds, and mangroves [1]. In addition, coastal areas are beneficial in improving the region's economy, such as in the trade, fisheries, and fishing sectors, which are key to the lives of the coastal communities. Despite these benefits, coastal areas often experience rapid and continuous changes in their shape. These changes are caused by oceanographic factors such as strong currents, tides and wave phenomena that have exacerbated the situation, further eroding the coast and causing significant land loss [2]. The combination of these natural forces with the impact of sand mining creates complex dynamics that threaten beach stability. In addition, human activities such as natural resource exploitation and land use, as well as climate change, such as stronger coastal storm phenomena and rising sea temperatures, can accelerate the global trend of shoreline change. These changes have the potential to threaten ecosystems and reduce the benefits of coastal areas.

Previous studies have described one beach condition at TPI Beach in Lumajang Regency as having dynamic environmental challenges that require attention. Over the years, this beach has faced significant erosion, mainly due to anthropogenic factors such as excessive sand mining activities in the coastal area [3]. This sand exploitation activity has disrupted the balance of the natural sediment supply, which is crucial for maintaining the morphological structure of the beach, leading to a noticeable reduction in the shoreline. Bulurejo Village in Tempursari District has become a tangible form of chronic coastal degradation due to erosion caused by reduced sediment supply from the upper watershed and uncontrolled sand exploitation. The imbalance between the sediment supplied to the beach and the material eroded by ocean waves has resulted in increased sediment loss from the beach, further contributing to shoreline changes that are increasingly prone to continuous erosion and environmental degradation [4].

From a socio-economic perspective, Lumajang's coastal communities rely heavily on fisheries, wetland agriculture, and beach-based tourism, making it a strategic area that is also highly vulnerable to ecological disturbances [5]. Therefore, studies in this area are important to formulate sustainable ecosystem and disaster risk based coastal management strategies. Accurate and continuous monitoring of shoreline changes is essential for understanding these dynamics and designing effective mitigation strategies. Multispectral satellite imagery, such as Landsat with consistent temporal and spatial resolution since 1972, provides comprehensive historical data to analyze shoreline shifts, erosion, sedimentation and habitat degradation in a multitemporal manner [6]. This study used Landsat satellite image analysis to measure the rate of shoreline change in the coastal area of the Lumajang Regency. The findings are expected to provide a scientific basis for sustainable coastal management policies, the preservation of critical ecosystems, and community adaptation to the threat of environmental change.

II. Study Area

Lumajang Regency, located on the southern coast of East Java Province with coordinates 112º-53'-113º-23' E and 7º-54'-8º-23' N, is an area with ±53 km of coastline stretching from Tempursari District to Yosowilangun District. A coastal location map of Lumajang Regency is shown in Figure 1. Oceanographically, the coastal waters of Lumajang are directly adjacent to the Indian Ocean, which is known for its high waves and strong currents [7]. The coastal area of Lumajang has dynamic geomorphological characteristics, a combination of sandy beaches, estuaries, and volcanic moorlands influenced by the activities of Mount Semeru. Geotectonically, Lumajang is located in an active subduction zone between the Indo-Australian and Eurasian plates. This puts the area at a high tsunami risk, with estimated tsunami heights in Lumajang reaching up to 3 m, posing a significant risk to coastal communities[8].

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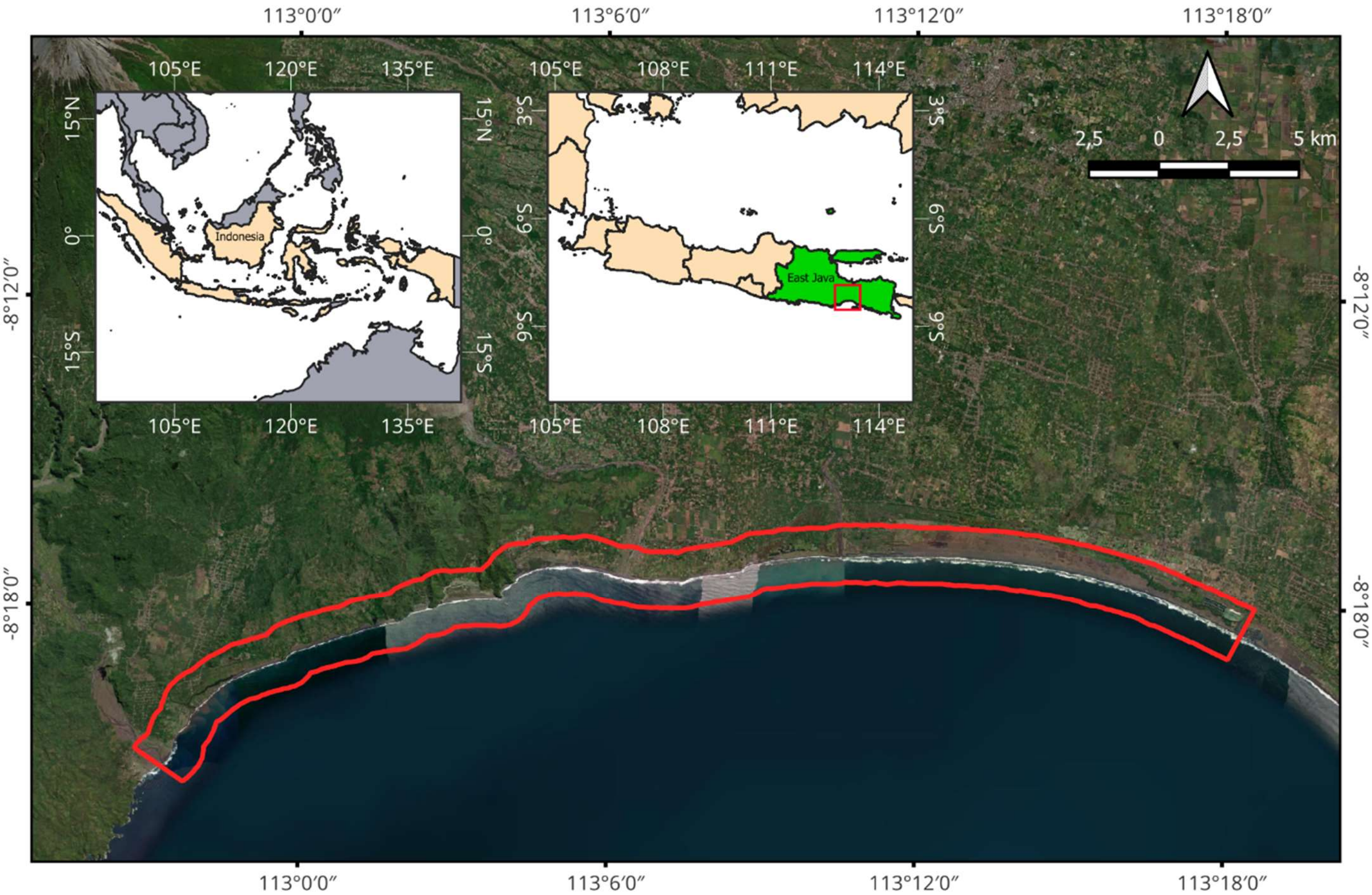

Figure 1. Research Location Map

III. Materials and Method

Shoreline change analysis was conducted over a period of 30 years from 1994 to 2024. The initial stage involved selecting satellite image data every 10 years. This study used Landsat satellite images for data processing. The types of Landsat data used included Landsat-5 Thematic Mapper (TM), Landsat-7 Enhanced Thematic Mapper Plus (ETM+), and Landsat-8 (OLI/TIRS) images (obtained from the Google Earth Engine datasets). The type of Landsat imagery used varies according to the time required for recording and analysis. Landsat satellite images were chosen as the main database in this study based on considerations of optimal spatial, temporal and spectral resolution for the analysis of shoreline dynamics. The 30-meter spatial resolution of the multispectral channel (Landsat TM/ETM+/OLI) enables precise and accurate identification of land-sea boundaries, especially on sandy beach and estuary features that are dominant in coastal areas [9]. Meanwhile, the 16-day temporal resolution (revisit time) of the Landsat satellite series provides consistent temporal coverage for monitoring shoreline changes in a multidecadal manner [10]. To process Landsat images, a combination of multispectral channels enabled the extraction of information from the coastline. Shoreline extraction was performed using the Normalized Difference Water Index (NDWI) algorithm. NDWI is used to enhance the contrast between water and non-water objects in Landsat satellite images [11]. This index is calculated using the green band (Green) and near-infrared band (NIR) using the following formula:

$$NDWI = \frac{Green - NIR}{Green + NIR}$$

The next step was to analyze the results of the shoreline extraction to determine the level of abrasion and accretion every year. The Digital Shoreline Analysis System (DSAS) is an effective tool for quantitatively and systematically analyzing shoreline changes [12]. This method enables a comprehensive statistical calculation of the rate of shoreline change based on a series of historical shoreline data collected from the time period of 1994 to 2024. The DSAS allows the identification of areas of significant coastal erosion and locations where active sedimentation occurs. In addition, this method can reveal patterns of shoreline change that may not be detected through visual observation alone.

One of the parameters produced in the processing of shoreline changes with dsas is the EPR. Where EPR is the endpoint rate, which describes the rate of shoreline change between two different time points. Positive EPR values indicate accretion or land gain, whereas negative values indicate erosion or land loss. EPR analysis helps in quantitatively understanding the dynamics of shoreline change by detecting nonlinear patterns of shoreline dynamics, revealing significant differences in erosion and accretion rates influenced by physiographic features and human activities, and can be used as a basis for more effective planning and management of coastal areas [13]. The Linear Regression Rate (LRR) method is also used in shoreline change analysis to determine long-term change trends. This method calculates the rate of shoreline change based on all the available historical data. This method uses a simple statistical approach by analyzing the shoreline position data series over time using linear regression. The slope of the resulting regression line represents the average rate of shoreline change for each segment. LRR is considered more stable in the face of short-term temporal variations or data noise than other methods, such as EPR, because it utilizes all data points equally. EPR is used in short-term shoreline research with limited data, whereas LRR is appropriate for long-term analysis where more data are available [14].

IV. Results and Discussion

The results of coastline extraction using the NDWI method showed an effective ability to separate water and land areas based on their spectral characteristics. NDWI utilizes the reflection of green bands and the absorption of near-infrared (NIR) waves by water; thus, water areas tend to have positive index values, while land is negative or close to zero. This pattern results in a relatively clear delineation of the coastline, particularly in areas with a high contrast between the water surface and dry land. After shoreline extraction, statistical calculations were performed using the DSAS. In the initial stage of analyzing shoreline change, it is necessary to establish a baseline that is used as the point of origin in plotting transects, which are required for shoreline measurement. This baseline is useful to ensure that measurements of any shoreline dynamics are carried out consistently and accurately in each analysis time period [15]. The next step was to create 430 transects, which were used as reference points to observe the changes. The transects were evenly spread along the coastline under study. Each transect was of equal length and positioned perpendicular to the shoreline. Transect arrangement was done by determining the distance interval between transects of 100 m, while the transect length was determined to be 1500 m long, so that the transect could cover each shoreline change for three decades. The results of the transect creation based on the shoreline conditions on the coast of Lumajang Regency are shown in Figure 2. Shoreline change analysis was conducted by comparing the position of the shoreline at each transect at different times. The results were processed by analyzing the EPR parameters every 10 years from 1994 to 2024. This comparison allowed the identification of areas of significant erosion or accretion. The rate of shoreline change was calculated based on the distance the shoreline shifted at each transect divided by the observation time interval. The results of this analysis were then mapped to provide a visual representation of the dynamics of shoreline change in the study area over a 30-year period.

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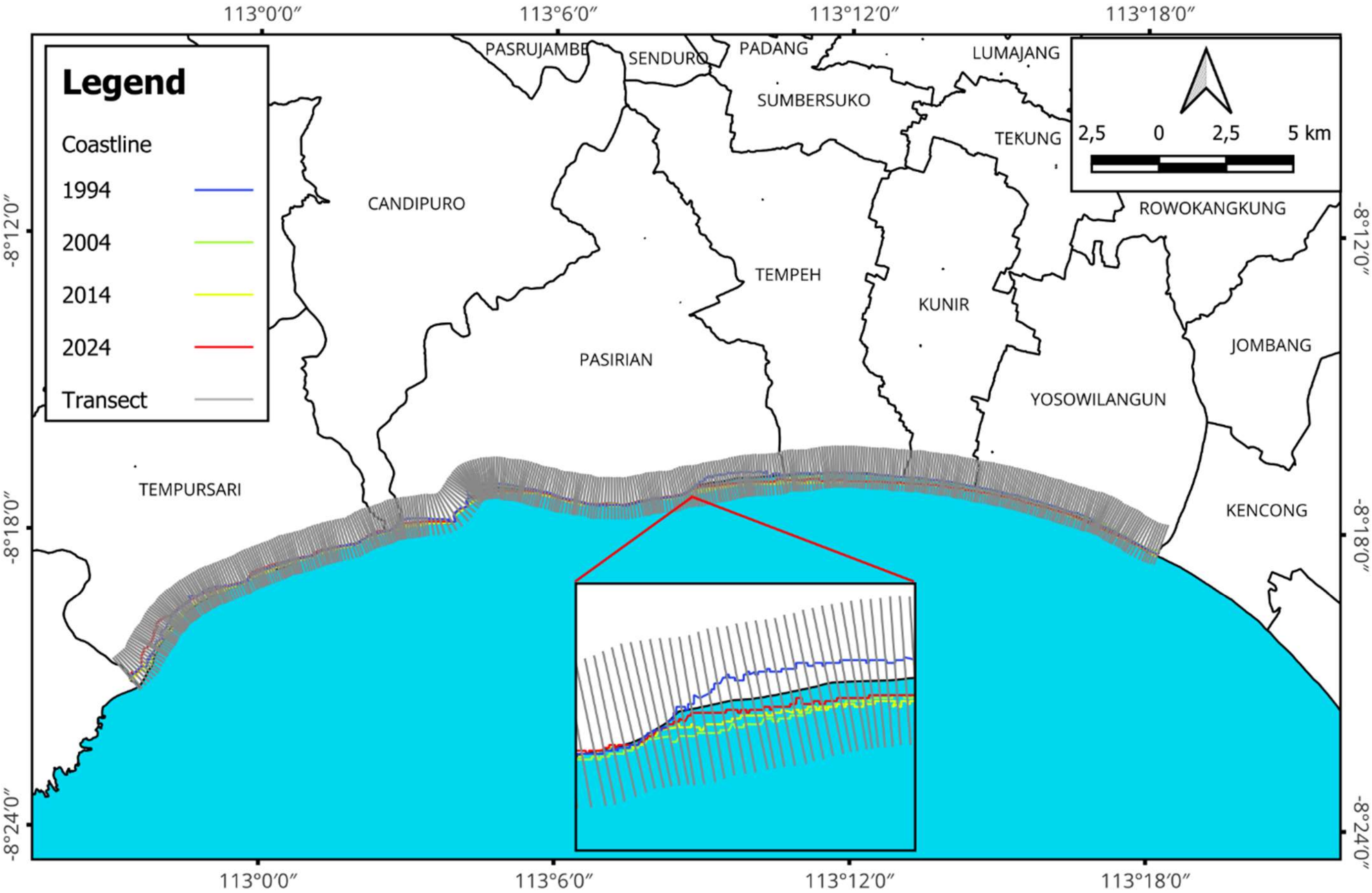

Figure 2. Map of Shoreline Extraction Results and Transect Distribution in Coastal Lumajang Regency from 1994 to 2024

Analysis using DSAS in the coastal area of Lumajang Regency revealed significant variations from 1994 to 2004 in shoreline change in the EPR parameter, which is a key indicator of shoreline dynamics. The EPR value for 10 years shows an average rate of 8.25 m/year. This indicates that accretion dominates erosion. Then in the calculation of the average erosion rate of -4.18 m/year and the calculation of the average accretion rate of 10.78 m/year. The highest erosion hotspots were identified in several districts, one of which was most significant at the border of Yosowilangun and Kencong Districts, where the two districts are bounded by the Bondoyudo River. The Bondoyudo Estuary had one of the highest erosion rates at -11.91 m/year. Estuaries that directly face the Indian Ocean are vulnerable to the influence of high waves and tidal forces, which result in sediment transportation. Coastal upwelling occurs on the south coast of Java due to monsoon winds and regional climate anomalies, including the El Niño Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) phenomena. IOD has a more significant influence on the intensity of upwelling events and other oceanographic parameters than ENSO [16]. Upwelling events can influence coastal erosion, sediment accretion patterns, and marine ecosystem dynamics. Sea-level rise influences changes in the coastline because the coastal location of Lumajang Regency is directly adjacent to the Indian Ocean, making it very vulnerable. Sea-level rise affects erosion events [17]. .This is also added to the factor of the magnitude of river discharge, which can significantly change the coastline [18]. Accretion hotspots are dominantly found in the Pasiran District, especially at Watu Pecak Beach, with an accretion rate of 54.84 m/year. The contrasting dynamics of erosion and accretion from 1994-2004 highlight the complex interactions between natural forces and human activities. The results of analyzing the rate of shoreline change with the EPR parameter analysis are shown in Figure 3. For example, erosion at the Bondoyudo Estuary threatens the local ecosystem and impacts nearby settlements, potentially causing displacement and loss of livelihood. In contrast, the observed accretion at Watu Pecak Beach suggests the potential for land reclamation and habitat restoration, which could be harnessed to enhance local tourism and fisheries.

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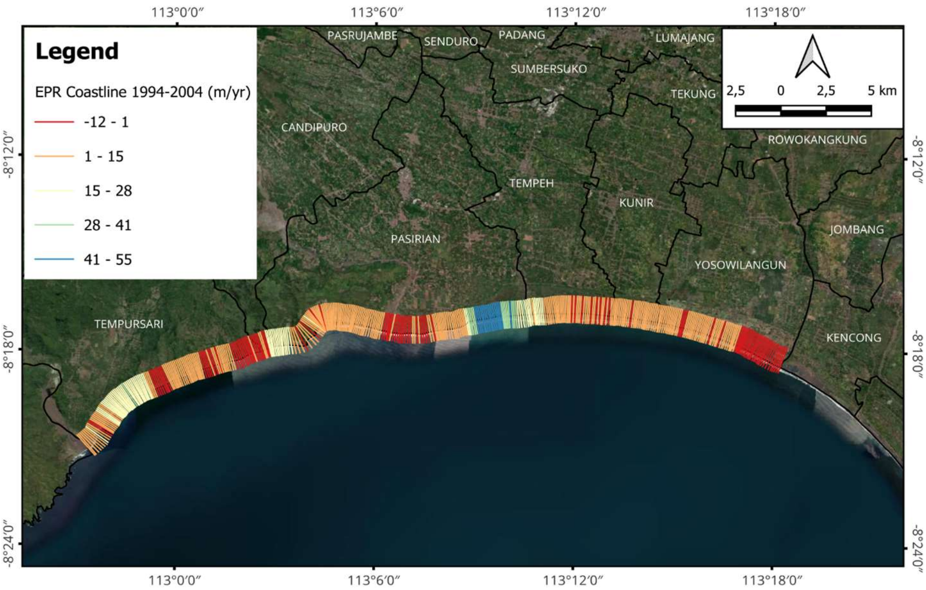

Figure 3. End Point Rate (EPR) of Lumajang Regency Coast from 1994 to 2004

From 2004 to 2014, the average value of EPR along the coastal area of the Lumajang Regency was recorded at 9.69 m/year. Based on this value, it was confirmed that the influence of accretion was more dominant in shaping shoreline changes from 2004 to 2014. The average EPR value of accretion events at the research site was 13.23 m/year. The average value of the erosion rate was -5.43 m/year. The visualization results of the EPR Map from 2004 to 2014 are shown in Figure 4. Along the coastline, there are several hotspots of erosion events, where the most significant erosion event occurred in the Tempursari District at the exact location of the Glidik River estuary, with an erosion rate of -17.82 m/year. The Kali Glidik Estuary is the meeting point of the sea and rivers originating from Mount Semeru, one of the most active volcanoes in Indonesia. As part of a river system flowing from the mountainside, the estuary is characterized by carrying large amounts of volcanic material [19]. This phenomenon causes the dynamics of sediment transport at the Glidik Estuary to be very intense, resulting in the erosion of the surrounding coastline. The hotspot value of the accretion rate was 42.21 m/year, which occurred in the Pasiran District.

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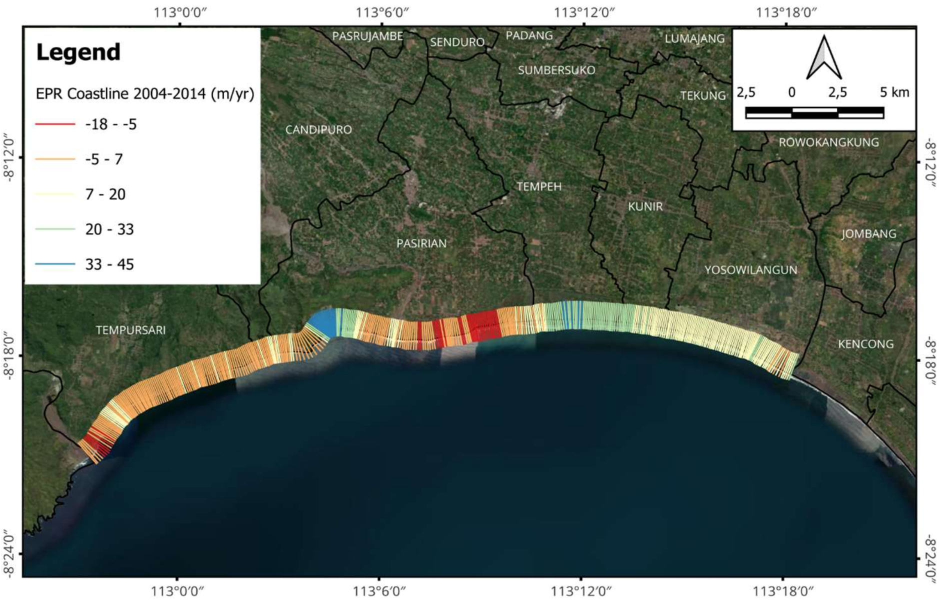

Figure 4. End Point Rate (EPR) of Lumajang Regency Coast from 2004 to 2014

Statistical analysis using the End Point Rate (EPR) method revealed an average shoreline change value from 2014 to 2024 of -8.06 m/year. The results of the EPR analysis in the form of map visualization are shown in Figure 5. The average erosion event that occurred was -10.03 m/year, while the average accretion event was 1.86 m/year. The location with the highest erosion rate of -55.87 m/year is located in Tempursari District, precisely at TPI Beach, which is the estuary of the Bulu Rejo River. The incident is the result of excessive sand mining activities on the riverbed, which disrupt sediment supply and cause an imbalance between sediment transport and erosion by sea waves from the Indian Ocean [4]. The highest accretion rate during this decade occurred in Pasiran District, especially at Banyu Adem Beach, with an accretion rate of 6.07 m/year.

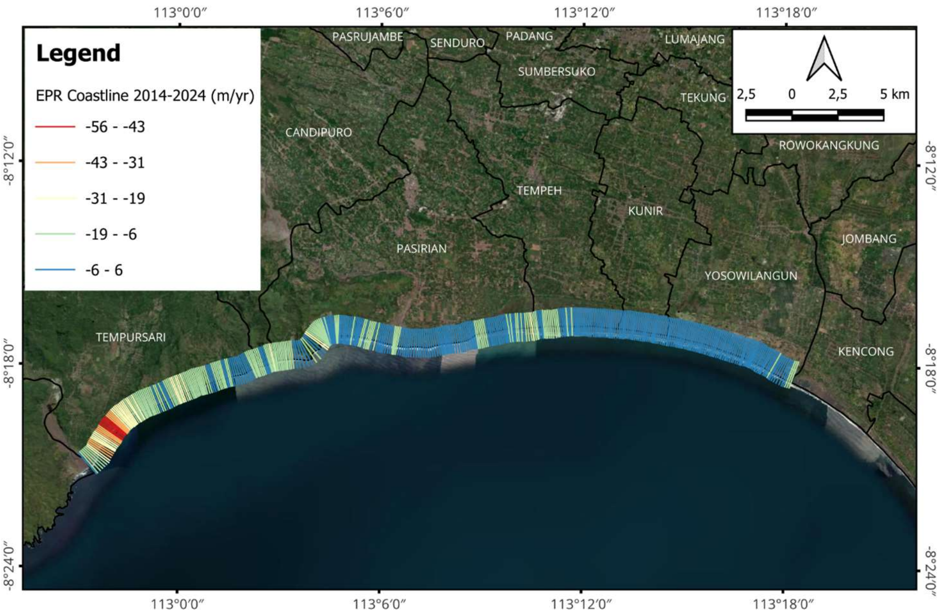

Figure 5. End Point Rate (EPR) of Lumajang Regency Coast from 2014 to 2024

The spatial distribution of the shoreline change shows significant variations along the coast of the Lumajang Regency. Coastal segments in the western part of the study area tended to experience more intensive erosion over the decades from the shoreline change analysis, whereas some locations in the central part showed accretion trends. Based on the results of the analysis of the rate of shoreline change carried out every 10 years for 30 years in the period 1994-2024, it shows that during the period 1994 to 2004, 80.23% of the coastal area of Lumajang Regency experienced accretion, while 9.53% of the coastal area experienced erosion. Each District evenly experienced accretion and erosion, but the accretion rate was more dominant during this decade. In 2004-2014, 79.53% of the coastline area experienced accretion and 15.35% experienced erosion. Meanwhile, in the last decade of the analysis–2014-2024, 6.51% of the coastline experienced accretion and 81.63% experienced erosion. The significant increase in erosion rates in the last decade is partly due to the south coast of Java experiencing sea level rise at a rate of approximately 4.7 mm/year, influenced by climatic phenomena such as the Asian-Australian monsoon and the Indian Ocean Dipole (IOD) [21].

Table 1. Variation of EPR Rates During 1994 to 2024 With Different Intervals Every 10 Years

Rate	**Period**		
	1994-2004	**2004-2014**	**2014-2024**
Average (m/year)	8.25	9.69	-8.06
Min (m/year)	-11.91	-17.82	-55.87
Max (m/year)	54.84	45.21	6.07
Erosion (m/year)	-4.18	-5.43	-10.03
Accretion (m/year)	10.78	13.23	1.86
Erosion Transect Index (%)	9.53	15.35	81.63
Accretion Transect Index (%)	80.23	79.53	6.51

To identify historical data on long-term shoreline change, it is necessary to apply the Linear Regression Rate method in the coastal district of Lumajang. LRR is a statistical method used to calculate the rate of shoreline change over time with a robust measurement of long-term change trends and allows the identification of persistent erosion and accretion trends [22]. The LRR is calculated by fitting a least-squares regression line to historical shoreline data points, which allows researchers to determine the rate of shoreline movement over time. This method is particularly effective for long-term assessments, as it provides a statistical basis for understanding how the shoreline has shifted due to natural processes and human activities [23]. The results of the analysis show that the average rate of shoreline change in the coastal area of Lumajang Regency is 3.94 m/year. Overall, for 30 years, the research location predominantly experienced accretion on the coastline.

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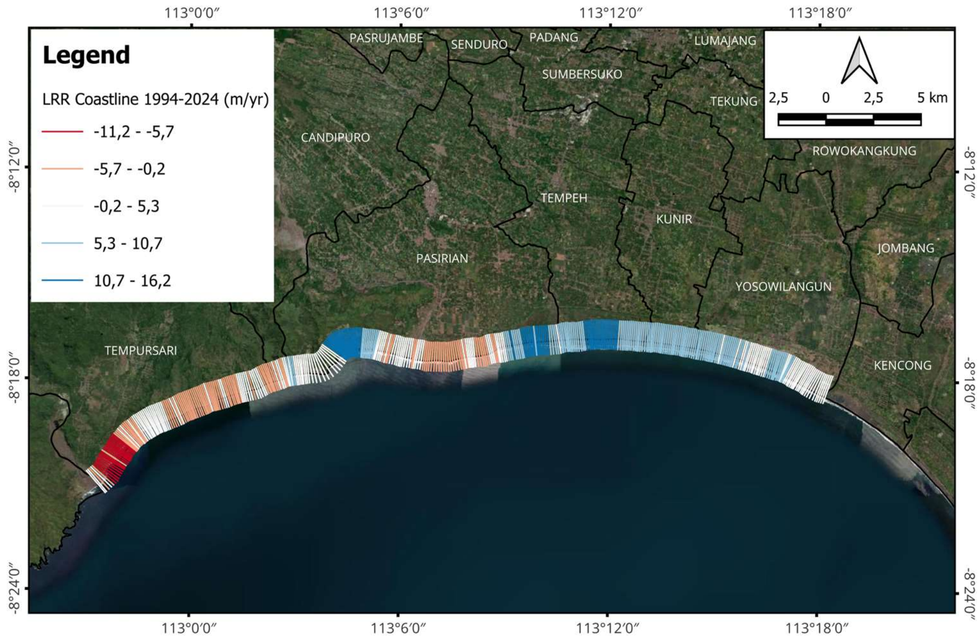

Figure 6. Linear Regression Rate (LRR) of Lumajang Regency Coast from 1994 to 2024

Table 2. Variation of LRR Rates During 1994 to 2024

Rate	Average (m/year)	Min (m/year)	Max (m/year)	Erosion (m/year)	Accretion (m/year)	Erosion Transect Index (%)	Accretion Transect Index (%)
1994-2024	3.94	-11.15	16.20	-2.28	6.47	27.67	70.70

The LRR measurement results showed that the average erosion rate was -2.28 m/year. In contrast, the LRR value for the average accretion rate was 6.47 m/year. Hotspot analysis was also conducted in the coastal Lumajang Regency, where certain areas were identified as erosion hotspots with significantly higher rates of land loss. The location with the highest erosion value was TPI Beach, Tempursari District, with an LRR value of -11.15 m/year. The location with the highest accretion rate of 16.20 m/year was Dampar Beach, Pasiran District. Based on the total transects along the coastline of the Lumajang Regency, 27.67% of the coastline experienced erosion, whereas 70.70% experienced accretion. Erosion and accretion events were evenly distributed along the coastline. As the shoreline continues to shift, ecosystems located at erosion sites have the potential to experience significant disruption, impacting on marine biodiversity and the livelihoods of communities dependent on coastal resources. In addition, increasing erosion rates at critical hotspots, such as TPI Beach, raise concerns about the vulnerability of infrastructure and ecosystems within them. The overall LRR results indicate that most of the coastlines in Lumajang Regency are experiencing landward expansion due to accretion processes in some coastal areas. This phenomenon can be caused by various factors, including river flows that transport sedimentary materials to coastal areas or changes in ocean currents and wave patterns.

V. Conclusion

The analysis of shoreline changes in Lumajang Regency over three decades (1994-2024) reveals complex coastal dynamics influenced by both natural processes and human activities. The study utilized the Normalized Difference Water Index method for shoreline delineation and the Digital Shoreline Analysis System for the quantitative analysis of erosion and accretion patterns. From the results of the EPR analysis conducted with variations over several decades, it was found that accretion phenomena dominated in some periods, and in recent years, shoreline erosion has become more frequent. Hotspots of erosion events were identified in areas adjacent to the estuary, especially around the Kali Glidik and Bondoyudo Estuaries, where erosion has been frequent over the past few decades. Areas with substantial accretion events were identified in the Pasiran District, particularly around the Panti Watu Pecak and Dampar beaches. The results of the trend analysis of the rate of shoreline change in the three decades showed an average EPR value during 1994-2004 of 8.25 m/year, 2004-2014 of 9.69 m/year and 2014-2024 of -8.06 m/year. An analysis was also conducted by identifying LRR parameters to determine the rate of shoreline change within 30 years more accurately. The results showed that the coast of Lumajang Regency experienced an accretion trend with an average rate of 3.94 m/year over a 30-year period. This research highlights the need for continuous monitoring and an adaptive management approach to solve dynamic coastal problems.

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