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Statistical Analysis of Short-Term Shoreline Change Behavior Along The Southern Cilacap Coasts of Indonesia

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Abstract

There is a threat of extreme waves and a moderate risk level of coastal erosion in Bunton Village. Based on the preliminary assessment, there is huge erosion of the shoreline and visible changes in the shoreline temporally. However, there is no statistical data on short-term shoreline change behavior in this area. Hence, this research aims to analyze statistically the short-term shoreline change behavior to understand the conditions and phenomena that occur on the coast of Bunton Village. Landsat images spanning the years 2002 to 2022, with recording intervals of 5 years each, were used to identify the shoreline data, which was later analyzed using the Digital Shoreline Analysis System (DSAS). Statistical analyses of short-term shoreline change behavior were obtained using the End Point Rate (EPR) and Net Shoreline Movement (NSM) approaches. Over a 20-year period, the Bunton coastal area experiences dynamic changes that are primarily due to erosion, with an average distance change of -255.5 meters and an average speed of -14.6 meters per year (very high erosion). The existence of the electric steam power plant (ESPP) in Adipala, which built a breakwater in 2012, has been proven to increase the erosion process. Shoreline change in this area can affect various landuses and tourism activities as well as trigger environmental problems in the Bunton coastal area.

1. Introduction

Coastal areas serve as an intermediary region between the land and the water, making them susceptible to influences and forces from both environments (Bird, 2008; Marfai et al., 2020). Human activities on land, such as establishing communities and building infrastructure, engaging in agriculture, and exploiting natural resources, can lead to alterations in the shape and structure of coastal areas (Mutaqin, 2017; Marfai et al., 2022; Widantara & Mutaqin, 2024). In coastal environments, tides, waves, and human activities like the use of marine resources can all affect shorelines (Rangel-Buitrago & Neal, 2018; Mutaqin et al., 2021a; Ningsih & Mutaqin, 2024).Pinto (2015) states that tides and waves exert influence on the marine occurrence referred to as coastal erosion, which in turn affects coastal regions. Furthermore, both human activity and natural processes have an impact on the configuration of beaches in coastal areas (Bird, 2008; Rangel-Buitrago & Neal, 2018; Marfai et al., 2022). Coastal erosion refers to the wearing away of land in coastal regions, a process that is impacted by climate change factors such as increasing sea levels (Ningsih & Mutaqin, 2024; Widantara & Mutaqin, 2024). This leads to the shrinking of coasts and has a detrimental effect (Mutaqin, 2017; Rangel-Buitrago & Neal, 2018). Climate change, which encompasses sea level rise, alterations in sea water temperature, heightened wind intensity, and more frequent storm occurrences, has the potential to impact both the frequency and intensity of coastal erosion (Gornitz, 1991; Appelquist & Balstrøm, 2015; Micallef et al., 2018; Ningsih & Mutaqin, 2024; Widantara & Mutaqin, 2024).

High population growth in coastal areas is also a serious problem. The increase in population causes an increase in land requirements, especially for settlements (Arjasakusuma et al., 2021; Alwi et al., 2023). The development of human settlements can reduce the size of the buffer zone on the coast, making this area more vulnerable to erosion (Widantara & Mutaqin, 2024). The impact of coastal erosion is very significant, both from an environmental and economic perspective. Damage to the coastal environment impacts the lives of coastal communities that rely on coastal resources for their livelihoods (Mutaqin, 2017). Apart from physical impacts such as loss of land and habitat, coastal erosion can also disrupt the social and economic life of the community, including in Indonesia. The following authors have documented these changes in the Indonesian coastal area, i.e., East Java Province, north of Bali, Karimunjawa Islands, southern part of Yogyakarta, and Denpasar city of Bali: Arjasakusuma et al. (2021), Marfai et al. (2022), Alwi et al. (2023), Ningsih & Mutaqin (2024), and Widantara & Mutaqin (2024).

One of Indonesia's coastal areas is Cilacap Regency, Central Java Province, which is located in the south of Java Island so that it directly faces the Indian Ocean, which has the characteristic characteristics of large waves, high water salinity, and diverse sediment substrate composition (Budiadi, 2020). This position makes Cilacap Regency have the potential for floods, landslides, tsunamis, and coastal erosion disasters in coastal areas. Based on the 2017–2022 Regional Medium Term Development Plan of Cilacap Regency, the target for disaster-resilient villages in Cilacap Regency has only reached 7.04% of the total villages. The threat of coastal erosion in Cilacap Regency occurs in five sub-districts, one of which is Adipala District. It is further specified that there is a threat of extreme waves and a moderate risk level of coastal erosion in 23 villages, one of which is Bunton Village. Based on a preliminary visit and an interpretation of the satellite imagery in Google Earth, it can be seen that there is huge erosion of the shoreline and visible changes in the shoreline temporally (Figure 1).


(a)


(b)

Source: Bachtiar Mutaqin, 2023

Figure 1. a) The Traditional Breakwaters and Hard-Structures that are Broken due to Erosion; and b) A Broken Jogging Track Following The Erosion

Therefore, it is important to carry out studies regarding the statistical analysis of short-term shoreline change behavior to understand the conditions and phenomena that occur on the coast of Bunton Village. The use of remote sensing technology can provide precise information spatially and temporally to monitor changes in shorelines and coastal ecosystems more efficiently. The acquired results can serve as valuable information for stakeholders in making informed decisions regarding the most suitable management approach to mitigate the adverse effects of coastal erosion threats in the future.

2. Data and Methods

Bunton Village is located in the southernmost part of Adipala District, directly bordering the Indian Ocean, and flanked by the Adiraja River (east) and the Serayu River (west) (Figure 2). These two rivers are the natural boundaries of the Bunton coast, with various unique physical and biotic characteristics. This position is enough to make Bunton Village vulnerable to disasters that occur on the coast. Located on the southern highway (JJLS), Bunton can be accessed by buses on the Yogyakarta-Cilacap-Jakarta route, while the distance between the village hall and the edge of Bunton Beach is 1.6 kilometers. The road that stretches from north to south from the beach to the Adipala Terminal is approximately four kilometers long. This route is the main evacuation route for the people of Bunton Village when a marine disaster occurs, such as a tsunami or tidal wave.

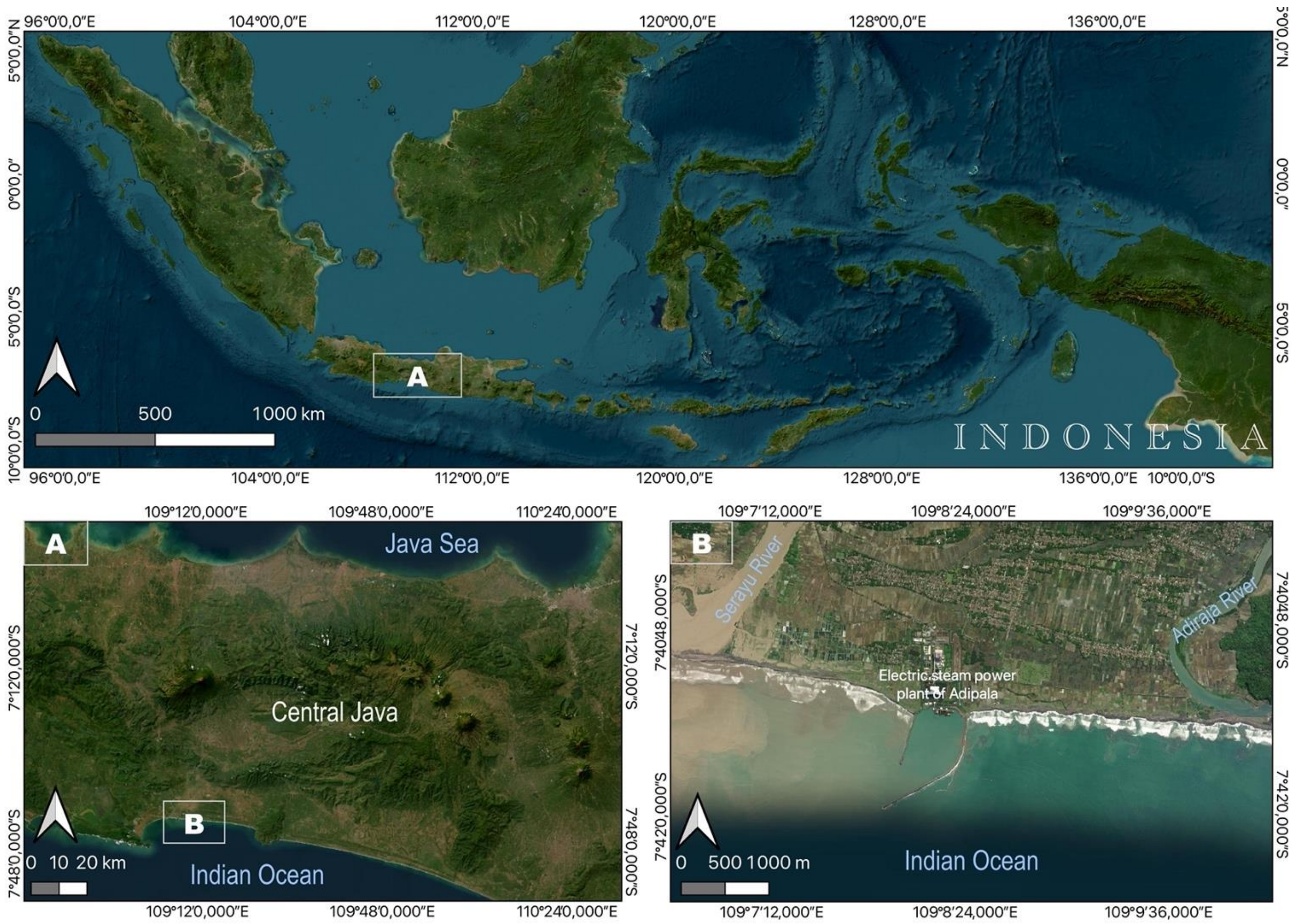

Figure 2. Study Area in the Bunton Coastal Area, Cilacap Regency

Quantitative description is employed as the methodology, utilizing remote sensing techniques and geographic information systems. Descriptive research is a method that attempts to describe the object or subject being studied according to the real condition, with the aim of systematically describing the facts and characteristics of the object being studied accurately (Sukardi, 2008). The main dataset utilized for input consists of Landsat images spanning the years 2002 to 2022, with recording intervals of 5 years each, specifically 2002, 2007, 2012, 2017, and 2022. The year 2012 was selected as the midpoint between the pre- and post-development of the electric steam power plant in Adipala. Furthermore, the selection of the image depicting the year 2022 was made in order to acquire the most recent data sources, which are readily available at no cost and exhibit little cloud cover (Pribadi et al., 2020; Septiangga & Mutaqin, 2021; Alwi et al., 2023).

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The visual interpretation of the five satellite images was thereafter conducted in order to ascertain the presence of the shoreline. In addition, the process of manual digitization was conducted by utilizing the editing feature within the QGIS software in order to get shoreline data. The shoreline data acquired was subsequently subjected to analysis utilizing the Digital Shoreline Analysis System (DSAS). Prior to conducting any additional analysis, it is necessary to record the five shoreline vectors in a database as a single feature class file (Himmelstoss et al., 2021). Additionally, the feature class was enhanced by incorporating a new information column through the utilization of the attribute Automator function. This additional column includes information about the time at which data sources were acquired and the values of uncertainty. The values of uncertainty serve as a means to ascertain the precise location of the intersection point between the shoreline and the transect by providing information on the distance surrounding the shoreline (Arjasakusuma et al., 2021; Himmelstoss et al., 2021; Alwi et al., 2023).

Furthermore, it is imperative to establish a feature class baseline, which will serve as the initial reference for delineating the transect line (Ningsih & Mutaqin, 2024; Widantara & Mutaqin, 2024). The process of establishing the baseline might be facilitated by utilizing the buffer function inside the 2002 shoreline data, which is considered the oldest shoreline (Mutaqin, 2017; Marfai et al., 2022; Alwi et al., 2023). It is also important to provide a new column in the feature class baseline that includes ID, group, and search information. The baseline is grouped using ID and group information, while the length of the transect line is determined using search information as a reference value (Himmelstoss et al., 2021). Subsequently, it became imperative to allocate various options within the default parameter function based on the data stored in shoreline and baseline attributes. After that, the compute rates function was used to find the shoreline change distances after the cast transects function was run (Marfai et al., 2022; Alwi et al., 2023; Ningsih & Mutaqin, 2024; Widantara & Mutaqin, 2024).

Statistical analyses of short-term shoreline change behavior were obtained using the End Point Rate (EPR) and Net Shoreline Movement (NSM) approaches. The NSM approach is employed for quantifying the extent of alteration in shoreline displacement between the most ancient and the most recent shorelines (Mutaqin, 2017; Marfai et al., 2022; Alwi et al., 2023). The EPR technique is employed for the computation of the shoreline rate of change, wherein the temporal dimension is divided by the distance between the oldest shorelines and the most recent shorelines (Mutaqin, 2017; Arjasakusuma et al., 2021). The DSAS statistical data is utilized to determine the distance between the oldest shoreline, specifically 2002, and the most recent shoreline, specifically 2022 (during a span of 20 years). A positive value (+) denotes accretion, whereas a negative value (-) signifies erosion. In order to assess land use and environmental issues, an examination of field conditions is conducted through the utilization of cross profiles (cross sections) and visual observations. In the research area, cross-sectional profiling is modified to align with topographic maps and digital elevation model (DEM) data.

3. Result and Discussion

Based on satellite images from 2002, 2007, 2012, 2017, and 2022, it is evident that coastal dynamics have significantly altered the shoreline in Bunton over the past 20 years (Figure 3a). Coastal erosion, one kind of coastal dynamics, is a disaster that is very detrimental to people's lives, especially those on the coast (Mutaqin, 2017; Arjasakusuma et al., 2021; Marfai et al., 2022). Coastal erosion is a natural phenomenon related to changes in sea level rise, climate, and ecosystems that are largely influenced by destructive human activities and result in many problems in coastal areas (Ningsih & Mutaqin, 2024; Widantara & Mutaqin, 2024). Based on Digital Shoreline Analysis System (DSAS) analysis with the NSM approach, 90 transects were identified with shoreline changes caused by erosion ranging from -5 meters (transect 47) to -657 meters (transect 11) with an average change in distance of -255.5 meters, while the shoreline changes caused by accretion range from +4 meters (transect 41) to +19 meters (transect 48) with an average of +12.8 meters (Figure 3b).

Based on EPR analysis (Figure 3c), changes in shorelines caused by erosion have an average speed of -14.6 meters per year, which is categorized as very high erosion according to Nassar et al. (2018). Meanwhile, changes in shorelines caused by accretion have an average speed of +0.6 meters/year, which is categorized as moderate accretion (Nassar et al., 2018; Alwi et al., 2023). The erosion process that occurs shows that closer to the electric steam power plant (ESPP) in Adipala, the erosion rate decreases. Compared to other Indonesian coastal areas that also have ESPPs, such as Pandeglang (Banten) and Buleleng (Bali), the closer to the ESPP, the erosion rate is also decreased, and somehow there is an accretion (Mutaqin et al., 2021b; Marfai et al., 2022).

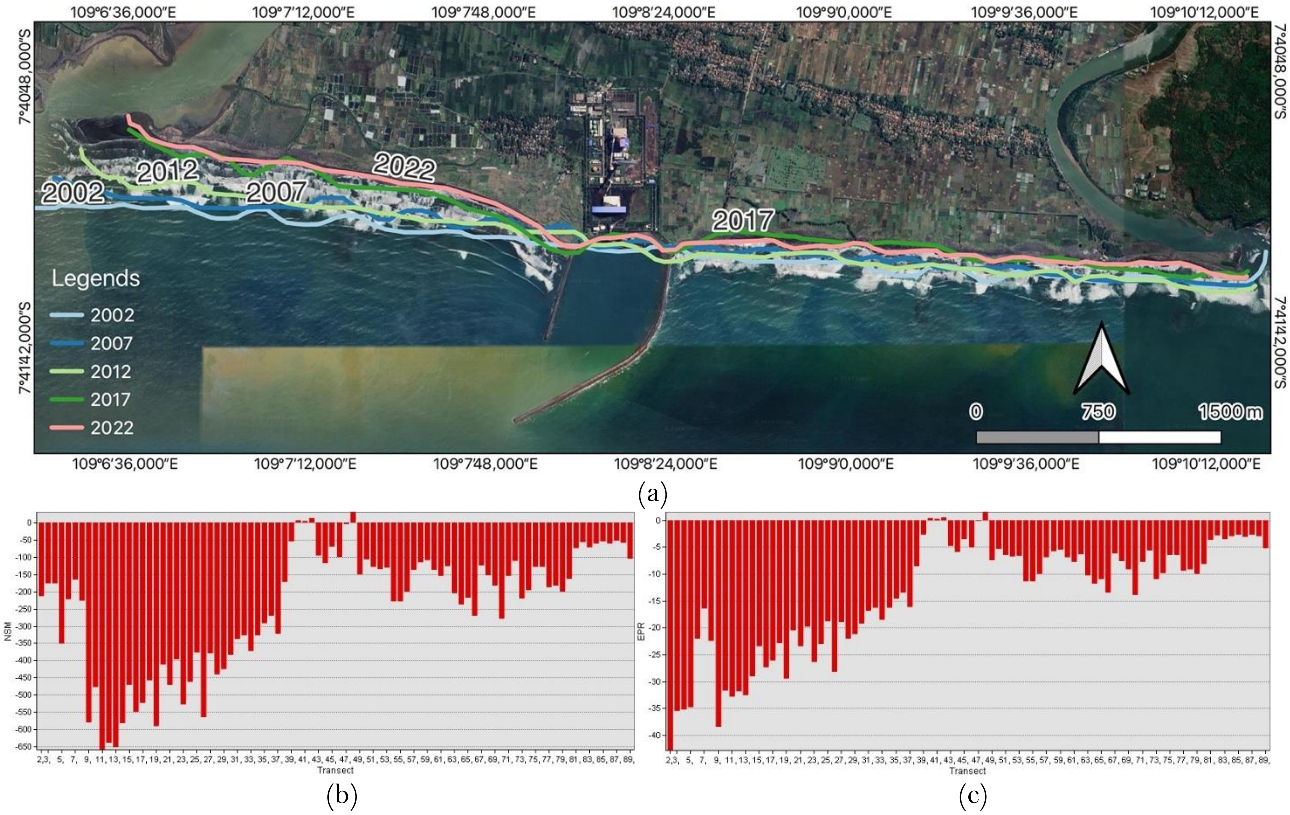
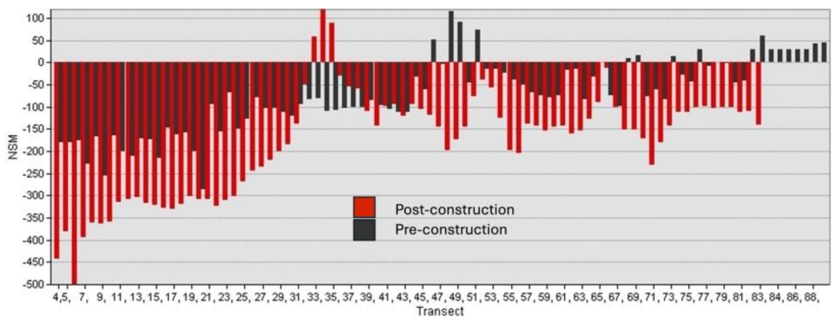


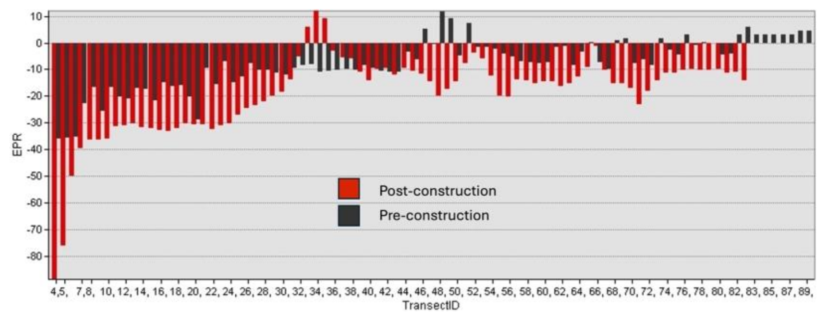
Figure 3. a) Coastal Dynamics have Significantly Altered the Shoreline in Bunton Over the past 20 years; b) NSM results in 90 Transects; and c) EPR Results along Bunton Coastal Area

Shoreline changes can occur naturally and be accelerated by human activities (Luijendijk et al., 2018; Vasconcelos et al., 2024). Based on observations in the field, Bunton is dominated by beach landforms with black sand materials. This material will more easily experience coastal erosion since most of the materials that make up the beach have not experienced compaction (Mutaqin, 2017; Arjasakusuma et al., 2021; Alwi et al., 2023; Ningsih & Mutaqin, 2024; Widantara & Mutaqin, 2024). Coastal erosion is the inability of coastal materials to reduce energy, including wave action (Bird, 2008). The wave energy that hits Bunton is a large wave that may trigger erosion. The wave propagates in a straight line without experiencing significant changes in its shape or speed over a fairly long distance and over a relatively long period of time until it hits the beach. Furthermore, the waters south of Java, including Bunton, generally have characteristics of a combination of strong local winds, especially during the east monsoon, as well as wave-tide dominated coasts (Mutaqin, 2017; Mutaqin & Ningsih, 2023).

Human or anthropogenic activities, like sand mining (Luijendijk et al., 2018), carried out by private companies and the community up until 2018, could potentially contribute to erosion in coastal areas. In addition, the presence of a breakwater from the ESPP may impact the coastal dynamics in this area (Luijendijk et al., 2018; Vasconcelos et al., 2024). The construction of the Adipala ESPP located in Bunton began in early 2012 and began operating at the end of 2015 until now. To determine the effect of the ESPP and its breakwater construction, we compare the distance and rate of change in the shoreline before and after the ESPP construction. The comparison graph of distance and change rate demonstrates that there was a difference in EPR and NSM before and after the construction of the breakwater by Adipala ESPP (Figure 4).



(a)



(b)

Figure 4. Comparison between Pre- and Post-Construction of ESPP in Adipala for: a) NSM results in 90 transects; and b) EPR results along Bunton coastal area

Before the Adipala ESPP was established, the average erosion distance was -106.34 meters in 10 years (2002–2012), with an average rate of -11.06 meters per year. After the construction of the Adipala ESPP, in 2012 there was an increase in the average erosion distance to -189.59 in 10 years (2012–2022) meters with an average rate of -20.03 meters/year. Meanwhile, accretion from pre-construction had an average accretion distance of +44.75 meters in 10 years, with an average rate of +3.94 meters per year. After the ESPP was constructed, it reached an average accretion distance of +89.69 meters in 10 years, with an average rate of +8.97 meters per year. The presence of a breakwater from ESPP may influence the movement of the dominant hydro-oceanographic parameters. Hydro-oceanographic parameters play an important role, namely as a medium for transporting sediment and erosion agents in coastal areas (Luijendijk et al., 2018; Nassar et al., 2018; Marfai et al., 2022; Vasconcelos et al., 2024).

Greater erosion occurred in the western part of the ESPP based on DSAS calculations after the construction of the ESPP, with an average rate of -29.8 meters per year compared to the eastern part, which reached -12.72 meters per year. Strong local winds and wave energy may impact this situation, especially during the east monsoon. Strong eastern waves have strong energy, which may cause the western part of the ESPP, due to wave deformation, to receive energy that is strong enough to cause more dominant erosion (Mutaqin, 2017). Wave breakers and wave deformation cause the eastern part of the ESPP to receive less wave energy. Furthermore, apart from wave energy, other factors, such as current patterns, may also influence erosion. Wave breakers have the potential to change the direction of longshore currents moving from east to west. Due to the slowing down of currents and the diversion of their direction by coastal structures, longshore currents slow down or become low in speed (Triatmodjo, 2012).

An analysis of shoreline changes in the Bunton coastal area from 2002 to 2022 can demonstrate the impact that erosion processes have on the environmental conditions near the Bunton coast in relation to landuse. We conducted field observations using a 100-meter cross-sectional profile analysis at six locations experiencing massive erosion to understand the potential impact of coastal erosion on land use, both currently and in the future (Figure 5). Cross-profile 1 (Figure 5a) is located to the west of the Adipala ESPP and is the final point of the western observation location. Based on the results of DSAS calculations as a whole for 20 years in the 2002–2022 period, cross-profile 1 is associated with transect 11, which experienced changes in the shoreline in the form of erosion. The erosion process occurs at a rate of -32.9 meters per year, with a change distance of -657.92 meters. At this location, there are 57 meters of undeveloped, unplanted land from the coast to the river. At high tide, seawater inundates the beach at this location (Figure 6a), potentially leading to environmental issues such as marine debris (Isnain & Mutaqin, 2023; Wahid & Mutaqin, 2024; Hibatullah & Mutaqin, 2024). Conditions near river estuaries cause changes in shorelines (both erosion and accretion) that are very dynamic because they depend on the amount of river water supply, transported sediment material, climate, wave activity, tidal waves, and currents (Bird, 2008; Ningsih & Mutaqin, 2024; Widantara & Mutaqin, 2024).

Based on the results of DSAS calculations, cross-profile 2 (Figure 5b) is associated with transect 23, which experienced changes in the shoreline in the form of erosion. The erosion process has a rate of -26.38 meters per year and a change distance of -527.51 meters. Cross-profile 2 has topography that tends to be gentle with low elevation differences and has empty land covered with vegetation for 45 meters, which is then bordered by a 12-meter asphalt road and a 7-meter river. Sloping conditions with low elevation differences may cause waves to hit the land further when the extreme waves occur (Mutaqin, 2017). At this location, various types of plastic waste were found along the shoreline (Figure 6b). Plastic in the aquatic environment will last for a very long time, and because it is light, the plastic will concentrate on the surface of the water, potentially affecting the quality of the coastal area (Lebreton et al., 2017; Noya & Tuahatu, 2021; Isnain & Mutaqin, 2023; Wahid & Mutaqin, 2024; Hibatullah & Mutaqin, 2024). Cross-profile 3 (Figure 5c) is the closest point to the ESPP, and it is associated with transect 33 with an erosion rate of -18.6 meters per year and a change distance of -371.86 meters. Cross-profile 3 has quite significant and varied elevational differences. Agricultural land situated near the beach and beach ridge is interspersed with 50 meters of empty land. The significant elevation difference between the beach and agricultural land in the form of a beach ridge (Figure 6c) may become a natural barrier for agricultural land during high and extreme waves (Dias & Kjerfve, 2009; Isla et al., 2023; Cescon et al., 2024).

Cross-profile 4 (Figure 5d) is the closest point to the ESPP in the east part. This cross-profile is associated with transect 54, which experienced shoreline changes in the form of erosion. The erosion process has a rate of -11.47 meters per year and a change distance of -229.41 meters. Locals use this area for tourism-related activities, i.e., to build temporary stalls to sell food and beverages (Figure 6d). Even though there were numerous pine plants (*Casuarina equisetifolia*) in this area, it cannot protect this area from coastal erosion since *Casuarina equisetifolia* is a wind barrier and not strong enough to face wave energy (Mutaqin, 2017). Ex-fishermen who switched careers because fishing was no longer profitable developed the agricultural land in this area. Due to extremely high coastal erosion in this area, the sustainability of tourism and agricultural activities was at risk, not only due to land loss but also due to the potential for seawater intrusion and coastal flooding (Ningsih & Mutaqin, 2024; Widantara & Mutaqin, 2024; Purnama et al., 2024).

Cross-profile 5 (Figure 5e) is associated with transect 70, which experienced erosion with a rate of -13.95 meters per year and a change distance of -279.01 meters. Hard rock structures that can withstand waves serve as a limit to the difference in beach elevation and empty land (Figure 6e). Even though the hard rock structure can withstand wave energy, coastal conditions directly facing the sea will become increasingly eroded, increasing the potential for seawater intrusion (Zamroni et al., 2021; Putriany & Sejati, 2023; Ningsih & Mutaqin, 2024; Widantara & Mutaqin, 2024; Purnama et al., 2024). Cross-profile 6 (Figure 5f) is associated with transect 89, which also experienced coastal erosion. This area has an erosion rate of -5.22 meters per year and a change distance of -104.34 meters. This area has almost the same conditions as cross-profile 1 (Figure 5a), which is dominated by empty land, but vegetation in the form of grass and *Casuarina equisetifolia* is found in the middle (Figure 6f). Apart from coastal erosion, other issues in this area include marine debris, which is also similar to environmental problems faced by Yogyakarta province (Isnain & Mutaqin, 2023; Wahid & Mutaqin, 2024; Hibatullah & Mutaqin, 2024). Shoreline dynamics in proximity to river estuaries are influenced by various factors, including the quantity of river water supply, transported sediment material, climate conditions, wave activity, tidal waves, and currents (Bird, 2008; Ningsih & Mutaqin, 2024; Widantara & Mutaqin, 2024). These conditions give rise to both erosion and accretion processes, which exhibit a high degree of dynamism.

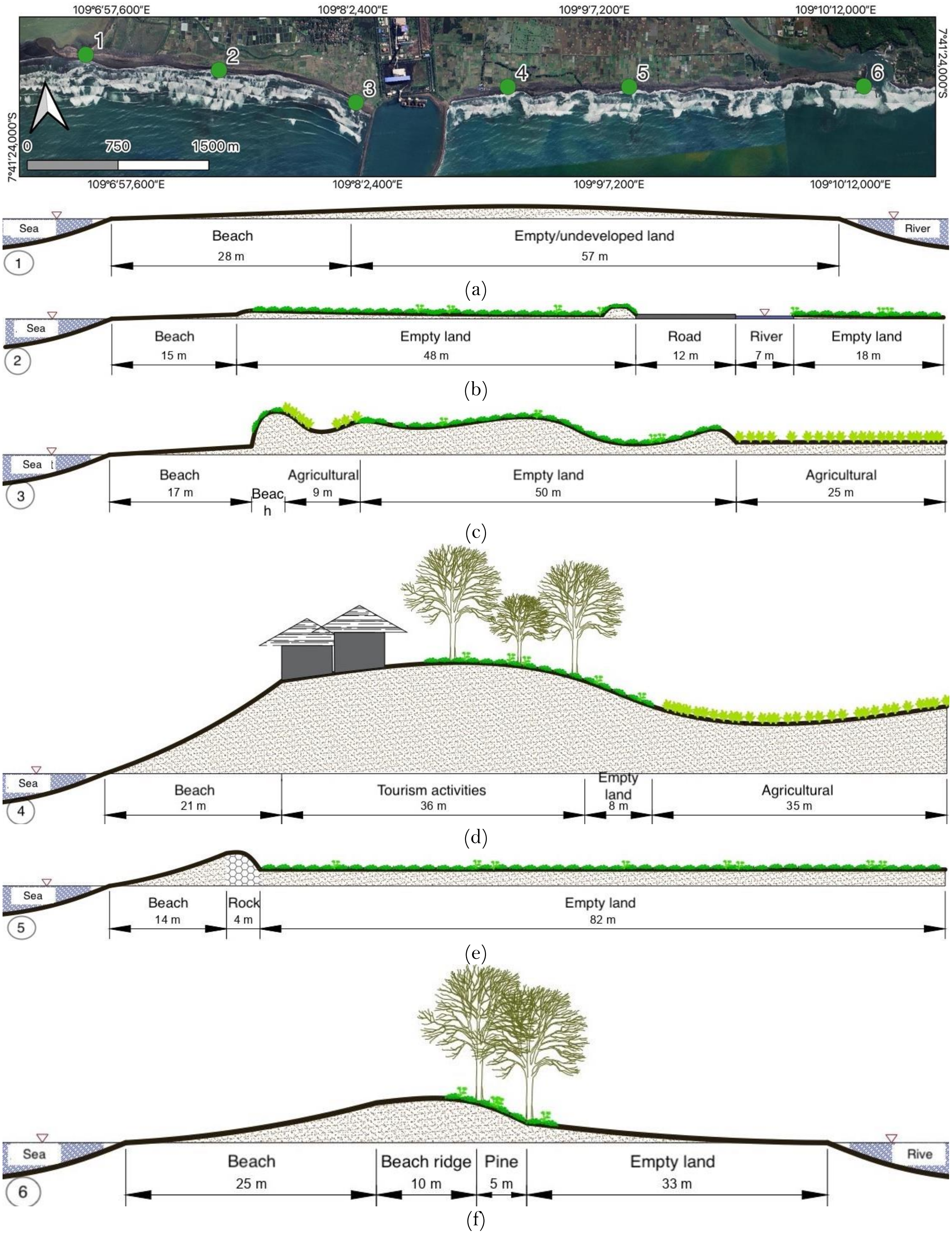


Figure 5. A 100-meter Cross-Sectional Profile Analysis at 6 Locations that Experience Massive Erosion Along Bunton coastal area (not-to-scale)

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(a) (b) (c) (d) (e) (f)

Source: Ariko V. Munandar, 2023

Figure 6. Present Condition Along the 100-meter Cross-Sectional Profile at Cross-Profile 1 (a) to 6 (f) that Experience Massive Erosion along Bunton Coastal Area

In the Bunton coastal area, the environmental problems that occur are quite serious, especially regarding the decline in land function due to coastal erosion, which has been going on for 20 years. Seawater may submerge tens of hectares of privately owned agricultural land due to extreme erosion and the effects of climate change (Ningsih & Mutaqin, 2024; Widantara & Mutaqin, 2024). This environmental damage in Bunton certainly threatens the sustainability of businesses and/or people's livelihoods. Moreover, the presence of marine debris in this area is quite high, and it may affect tourism activities and other coastal ecosystems (Isnain & Mutaqin, 2023; Wahid & Mutaqin, 2024; Hibatullah & Mutaqin, 2024). This is a very serious condition and requires exceptional action to address the problem immediately. Erosion, if left untreated, could lead to further consequences that not only harm agricultural land but also jeopardize water sources (Marfai et al., 2020; Purnama et al., 2024), causing disruption to the residents of the Bunton coastal areas. The environmental conditions and vulnerable coastal natural resources are impacting the socio-economic and socio-cultural aspects of the population living in this area (Mutaqin, 2017; Quesada-Román et al., 2023).

Each coastal area has different characteristics and problems depending on location, human activity, and how it is managed through the application of laws and regulations that apply in that area (Bird, 2008; Kay & Adler, 2005; Mutaqin et al., 2020). The Regional Disaster Management Agency and the Bunton communities are already aware that the very high level of erosion in the Bunton coastal area may exacerbate the existing problems. Even though several mitigation measures have been put in place, they still have not stopped coastal erosion because the communities are using simple materials without considering any detailed hydro-oceanographic conditions. Moreover, the existence of ESPP in Adipala may also accelerate erosion processes. To mitigate the impact of coastal erosion on human life, environmental damage, and its effects on social and economic problems, Bunton must implement sustainable management of coastal areas and mitigation plans for potential disasters (Bell et al., 2017; Luijendijk et al., 2018; Marfai et al., 2022; Alwi et al., 2023; Vasconcelos et al., 2024).

4. Conclusion

Over a 20-year period, from 2002 to 2022, the Bunton coastal area experiences dynamic changes that are primarily due to erosion, with an average distance change of -255.5 meters and an average speed of -14.6 meters per year, both of which are considered to be very high erosion. On the other hand, the accretion process, with an average distance change of +12.8 meters and an average speed of +0.6 meters/year, falls into the category of moderate accretion. The existence of the ESPP, which built a breakwater in 2012, had increased the erosion process. Before the construction of the breakwater, the shoreline changed due to erosion, with an average distance of -106.34 meters in 10 years (2002–2012) and an average rate of -11.06 meters per year. After the Adipala ESPP was established, the average erosion distance increased to -189.59 meters in 10 years (2012–2022), with an average rate of -20.03 meters per year. The environmental issues in the Bunton coastal region are highly severe, particularly over the deterioration of land functionality caused by ongoing coastal erosion for the past two decades. Due to severe erosion and the impacts of climate change, seawater has the potential to inundate tens of hectares of privately owned agricultural land in Bunton. Furthermore, there is a significant proliferation of marine debris in this region, which has the potential to impact tourism operations and other coastal ecosystems. In order to mitigate the adverse effects of coastal erosion in the Bunton coastal area, it is imperative to implement sustainable management strategies and develop mitigation measures for prospective disasters. Left untreated erosion may result in additional repercussions that not only damage agricultural land but also endanger water sources, therefore disrupting the lives of the inhabitants of the Bunton coastal regions. The ecological conditions and delicate coastal natural resources are affecting the socio-economic and socio-cultural dimensions of the inhabiting population in this region.

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