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Analysis of Coastline Changes with the Utilization of Geospatial-Based Sentinel Imagery

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ABSTRACT

Coastline is a dynamic phenomenon influenced by natural forces such as waves, currents, tides, and human activities such as coastal resource extraction and infrastructure development. Using Sentinel-2 imagery and geospatial technology, this study seeks to examine the changes in the coastline in the coastal areas of Lais, Air Besi, and Air Napal Districts, North Bengkulu Regency. The approach used includes image processing with geometric correction, *Normalized Difference Water Index* (NDWI), coastline digitization, and accuracy testing using a fusion matrix. The results of the analysis show that between 2019 and 2024 there will be considerable changes in the coastline, with an average erosion rate of 1,71 Meters per year. Some areas, such as Pasar Bembah 2.39 meters per year, Pal-30 2,182 meters per year, and Air Padang Village 3,293 meters per year, have experienced significant erosion. Air Padang Village is among the areas most affected by abrasion. Limiting human activities in areas prone to abrasion, planting coastal vegetation, and building sea walls are important strategies that can be used to reduce the impact of abrasion and shoreline changes.

Keywords: Abrasion, Mitigation, Geospatial, NDWI, Sentinel-2, coastline.

Introduction

Geographically, Bengkulu Province stretches for 500 kilometers, with its west coast facing directly to the open sea [1], the location of the study was carried out on the coast of the region, Lais District, Air Besi District, and Air Napal District, North Bengkulu Regency. Coastal is a land area along the sea that is still affected by marine conditions, such as tides and seawater seepage to land [2]. Meanwhile, the beach is an area located on the edge of the water, which is influenced by the rise and fall of sea water due to tidal waves and tides, the coastal area functions as a border between the land and the sea waters [3]. There is a phenomenon that causes the study area to undergo significant changes such as what happened in the village of Air Padang. Shoreline changes are natural phenomena that continue to occur due to various factors, both natural and anthropogenic [4]. Natural factors that affect this change include waves, ocean currents, tides, and erosion that occur due to the interaction between the sea and the land, so that study areas such as Air Padang Village experience eruptions.

Coastal erosion is an impact due to sea level rise on sandy beaches or muddy beaches in a form of balance of the coastal profile resulting in a shift in the coastline [5], Coastal erosion occurs due to an imbalance in sediment transport in a coastal area [6]. This process is the result of hydraulic work, which is the force of water in the form of waves or currents that slowly erode the coast [7], One of the most

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obvious impacts of shoreline changes is coastal abrasion, there has been quite worrying abrasion in some study areas.

Abrasion is a phenomenon that causes the coastline to regress, abrasion is a significant problem faced by ecosystems and settlements in coastal areas [8], which is the process of land erosion by waves and ocean currents that constantly hit the coast, causing a reduction in the area of coastal areas. The erosion that occurs on the land of the coastal area causes sediment transport to move from its place of origin and down the direction of incoming waves, thus affecting changes in the coastline [8]. Abrasion can occur naturally, but human activity often speeds up this process. In addition, the overexploitation of beach sand also reduces the amount of sediment that acts as a natural protector of the beach from abrasion. Therefore, the updating of the map of coastline changes needs to be carried out continuously. In addition, it also plays a role in the protection of the coastal environment and sustainable development planning in coastal areas [9].

Remote sensing technology has great potential in the research of coastal change phenomena such as the research carried out by Putu Aryastana with the result, the average coastline change recorded in Gianyar Regency based on SPOT satellite images from 2009 to 2015 is around 22. 441 meters [4]. So it is clear that with the advantages of reaching a large area, the variety of resolutions that can be chosen, and the time efficiency offered, this technology is a very useful tool for understanding the dynamics of coastal areas [10]. By paying attention to this, spatial data through a remote sensing approach is needed to determine shoreline changes that have an impact on coastal land changes [11]. This technology provides accurate, comprehensive, and continuous data on shoreline conditions over various time periods, allowing for more systematic and efficient detection of changes [7]. In addition, satellite imagery plays a role in mapping erosion and sedimentation patterns along the coast, supporting coastal spatial planning, and helping to mitigate and adapt to abrasion impacts [12]. The data obtained can also be combined with other geospatial technologies, such as Geographic Information Systems (GIS) and hydrodynamic modeling, to produce more accurate and thorough analyses. Geographic Information Systems, or commonly abbreviated as GIS (*Geographic Information System*), is a computer-based information system designed to manage data with spatial information [13]. This system is capable of taking, inspecting, integrating, manipulating, analyzing, and displaying data that refers spatially to the conditions of the earth. Geographic Information Systems (GIS) consist of three main elements, namely system, information, and geography [14]. From these three elements, it can be understood that GIS is a type of information system that specifically emphasizes "Geographic Information" [15]. A map represents a geographic feature or other spatial phenomenon by graphically depicting information about its location and related attributes[16], Another advantage of satellite imagery technology is its ability to link shoreline changes in the long term without the need for intensive, high-cost field surveillance [17]. With this remote sensing technology, authorities can identify trends in shoreline changes more quickly, so that preventive measures can be implemented to reduce negative impacts on the environment and coastal communities [18]. Therefore, the use of satellite imagery is an effective and efficient solution in supporting better management of coastlines and abrasion.

Sentinel-2A satellite imagery has been used to analyse changes in coastlines in various locations, including in coastal areas [19]. The continuous availability of Sentinel data is a huge plus in the management of coastal areas. The data collected by these satellites is freely and openly accessible, making it an invaluable tool for researchers, coastal area managers, and authorities in coordinating and planning mitigation efforts against the impacts of coastline change and abrasion [20]. The advantages of Sentinel imagery in the analysis of shoreline changes and abrasion include high spatial resolution, high temporal resolution, wide area coverage, free data access, and continuous data. The use of Sentinel data in coastal management includes coastal erosion monitoring, shoreline change mapping, abrasion analysis, coastal spatial planning, and disaster mitigation [21]. Mitigation is a variety of preventive actions/efforts to minimize the negative impacts of environmental damage that are anticipated to occur in the future in a particular area, and is a long-term investment for the welfare of all levels of society [22].

This study aims to determine the interpretation of coastline with the use of sentinel imagery, measure shoreline changes using sentinel imagery, and analyze shoreline change mitigation strategies based on geospatial data.

Methods

This research was carried out in the coastal area of North Bengkulu Regency, precisely in Lais District, Air Besi District, and Air Napal District. Data was collected through field observations, interviews with coastal communities, and documentation in the form of archives, photos, and digital data. The main data used are Sentinel-2 satellite images for 2019 and 2024. The research process starts from image acquisition, cutting of the study area, combination of RGB bands (Band 2, 3, 4), to digitizing the coastline using ArcGIS software. The treated coastline was then analyzed to calculate changes and erosion rates using the image overlay approach in 2019 and 2024.

NDWI is a remote sensing index specifically designed to emphasize the presence of water by comparing light reflections in the near-infrared (NIR) and green spectrums [21]. as well as the average calculation per year. To distinguish land and water, the NDWI (Normalized Difference Water Index) index was used with a combination of Band 3 (Green) and Band 8 (NIR) [19]. Calculations:

NDWI=band Green - NIR tire / band Green + NIR tire ....(1)

The green band and near infrared band used are band 3 and band 8 of Sentinel-2A.

Validation of results was carried out using an accuracy test through a confusion matrix to assess the accuracy of image classification. The accuracy of the classification is considered valid if it reaches a value of more than 80%. This geospatial approach allows for precise spatial analysis of the dynamics of coastline changes, chaos, abrasion and erosion in the coastal area of North Bengkulu.

Results and Discussion

Normalized Difference Water Index (NDWI)

The processing stage is followed by the separation of land and sea or delineation using the *Normalized Difference Water Index* (NDWI) formula, NDWI values range from -1 to +1 and are divided into five categories, as follows.

Table 1. Classification (NDWI) *Normalized Difference Water Index*

Yes	Wetness Rate	Ndwi Value
1	Non Water Body	-0,6 – -0,3
2	Very Low Wetness	-0,30 – -0,1
3	Low wetness	-0,1 – 0,1
4	Moderate wetness	0,1 – 0,3
5	High wetness	0,3 – 1

This table presents a grouping of values *Normalized Difference Water Index* (NDWI) into various moisture categories, which aims to recognize the intensity of the level of water presence on the surface of an area. With this grouping, a high NDWI value generally indicates the presence of a water body such as a river, lake, or swamp, while a lower value usually indicates dry land or plants that have low moisture content [23].

NDWI 2019 Results

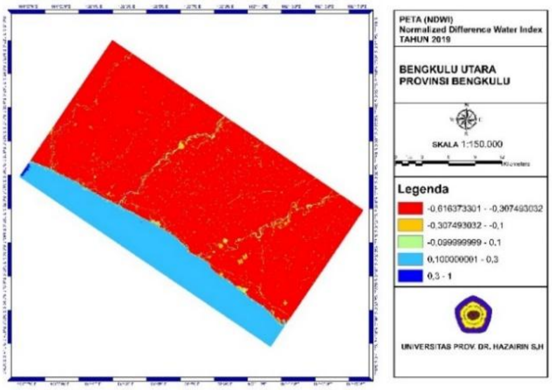

Figure 1. NDWI Map 2019
Source: researcher

The 2019 NDWI (*Normalized Difference Water Index*) map for the North Bengkulu area shows a dominance of red, which symbolizes a very low NDWI value, ranging from -0.616 to -0.307. This indicates that most areas have very minimal water content, often in the form of dry land with little moisture, such as settlements or open areas. The coastline has shades of light blue to dark blue, which indicates the presence of waters, such as the sea or river estuaries, although the distribution

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is still limited. In addition, river courses in the mainland are recognized as yellow to green, depicting the presence of a small amount of moisture although it is not significant enough to be categorized as a water area. Overall, the 2019 map reflects conditions in areas that tend to be dry with very few wet zones or waterlogged areas.

NDWI 2024 Results

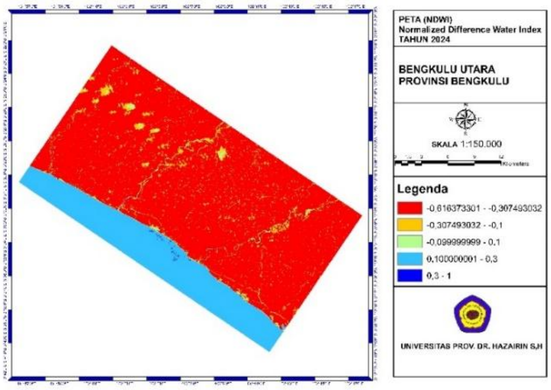

Figure 2. NDWI Map 2024
Source: researcher

The NDWI map for 2024 for the North Bengkulu region shows significant changes compared to 2019. Although the area dominated by red (which indicates a low NDWI value (between -0.616 to -0.307) is still very large, there is a noticeable increase in the distribution of yellow and green. This increase mainly occurs around river flows and some land points, indicating an increase in surface moisture or an increase in groundwater content.

Coastal water zones are also showing positive developments, with a more striking spread of light blue to dark blue compared to 2019. This indicates that there is indeed an expansion or increase of water bodies, such as the sea and river estuaries. Overall, although drylands still dominate, the 2024 map reveals clear signs of increasing humidity and water distribution in various areas in North Bengkulu.

Geometric Correction

Geometric correction was made to correct the inconsistency between the location coordinates of the image data and the actual location coordinates [24]. Some types of geometric correction include system, precision, and terrain corrections. Geometric correction is required to eliminate geometric distortion [9]. Here are the results of the image to map geometric correction.

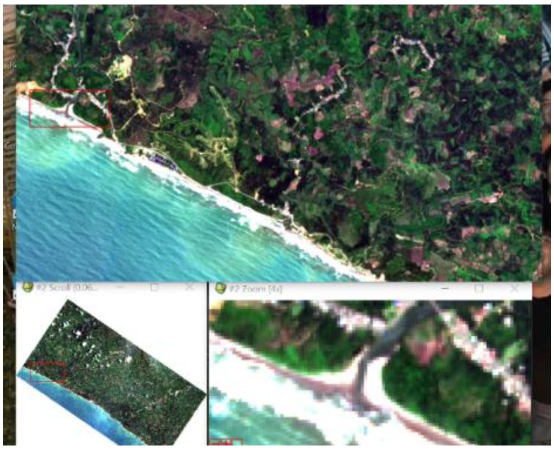

Figure 3. The image of 2024 has not been corrected (*Source: Researcher)*

This image is the result of initial processing of surface reflectance data (BOA Reflectance) at level 2A, but has not yet gone through the geometric correction process. From the visual appearance, it can be seen that some features on the surface, such as rivers, roads, and vegetation boundaries, are misaligned and distorted. The position of the object still refers to the coordinate system of the satellite sensor, so it is not entirely accurate when compared to reference maps or other spatial data.

Figure 4. Image 2024 Geometric correction results (Source*: researcher)*

This figure is the result of a geometric correction process applied to similar data, where each pixel has been adjusted to its actual spatial position on the earth's surface. Thus, the resulting image becomes more accurate in terms of geographical position. Features such as rivers, roads, and land boundaries now look more aligned and reflect their original shape consistently. The coastline also appears smoother, and the zoomed in objects (with 4x zoom) look more precise and clear. The correction process is carried out without changing the reflectance value, so that the color and spectral information remain consistent with the initial image, but coupled with a much higher level of spatial accuracy.

The geometric correction value can be seen in the following figure:

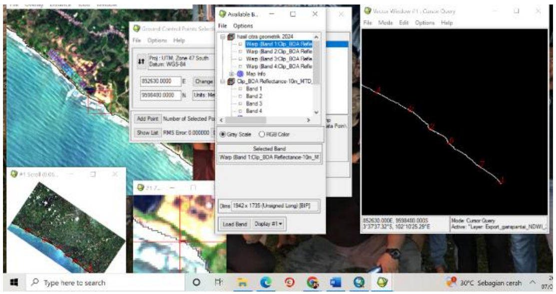

Figure 5. Image 2024 Geometric Correction Value Results (*Source: researcher)*

Matrix Fusion (Accuracy Test)

The final process of this study is to conduct an accuracy test, If the results of the confusion matrix calculation show a value above 80%, then the classification of the image is considered correct [25]. The calculation of the confusion matrix can be seen as follows [26].

Table 2. Error Matrix

		Field Conditions			Total
		Erosion	Stable	Sedimentation	
Result	Erosion	1	-	-	1
	Stable	-	25	-	25
	Sedimentation	-	-	2	2
	Total	1	25	2	28

Source: researcher

Accurate pixels = 25
Pixels involved = 28

Accuracy level =

$$\frac{\text{pixel accurate}}{\text{total pixels involved}} \times 100\% = \frac{25}{28} \times 100\%$$

= **89.29 %**

Shoreline Changes

Changes in the coastline that occurred in Lais District, Air Besi District, and Air Napal District, North Bengkullu. The coastline changes studied for the period 2019 to 2024 cover all coasts of Lais District, Air Besi District, and Air Na'pal District, North Bengkulu. The coastline per year that has been generated previously is displayed so that changes can be seen.

Figure 6. Map of coastline changes
Source: researcher

Table 3. Average Shoreline Change

Yes	Village Name	Average Coastal Gas Change (m)
1 .	Padang Water	16,468
2 .	Durian Leaves	5,318
3 .	Hamlet of Raja	8,690
4 .	Lais Market	8
5 .	Pal 30	10,911
6 .	Disclaimer	9,9
7 .	Kota Agung	5,665
8 .	Cliff Cage	6,685
9 .	Palik Market	7,977
10 .	Lubuk Tanjung	8,535
11 .	Tebat Market	9,967
12 .	Powder	7,9
13 .	Dry Chammock	7,57
14 .	Rare Gutters	6,74
15 .	Napal Water	6,41
16 .	Kerkap Market	9,3
17 .	Seafront	7,23
18 .	Waste Market	11,95
	Average	**8,621 m**

Source: researcher

Based on the value of the Average Table of Coastline Changes above, there are several areas that have experienced severe erosion such as Air Padang with an average change of 16,468 M, Dusun Raja with an average change of 8,690 M, Pal 30 with an average change of 10,911 M, Pentangkak with an average change of 9.7 M, Lubuk Tanjung with an average

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change of 8,535 M, Pasar Tebat with an average change of 9,967 M, Pasar Kerkap with an average change of 9.3 M, and Pasar Bembah with an average change of 11,621 M.

Fast Erosion is calculated based on the average change in the coastline of a coastal area which is then averaged based on the year, as in the equation below:

Erosion rate: CR/ (2019-2024)= CR/5.........(2)

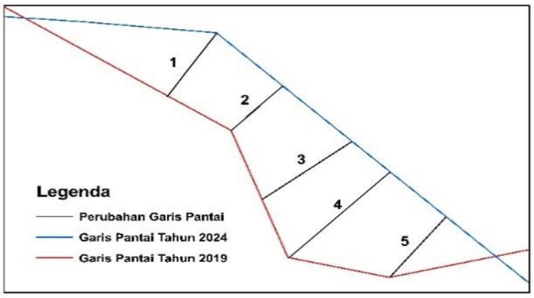

Figure 7. Calculation of average shoreline changes (*Source: researcher)*

Based on the value of the Average Coastline Change, it can be concluded that the average value of the Erosion Rate per year can be deduced, to see the value of the Erosion Rate can be seen in the table below.

Table 4. Average Erosion Rate

Yes	Village Name	Average Coastal Gas Change (m)	Average Erosion Rate Per Year (m/year)
1.	Padang Water	16,468	3,293
2.	Durian Leaves	5,318	1,063
3.	Hamlet of Raja	8,690	1,738
4.	Lais Market	8	1,6
5.	Pal 30	10,911	2,182
6.	Disclaimer	9,9	1,98
7.	Kota Agung	5,665	1,133
8.	Cliff Cage	6,685	1,337
9.	Palik Market	7,977	1,59
10.	Lubuk Tanjung	8,535	1,7
11.	Tebat Market	9,967	1,9
12.	Powder	7,9	1,58
13.	Dry Chammock	7,57	1,51
14.	Rare Gutters	6,74	1,34
15.	Napal Water	6,41	1,28
16.	Kerkap Market	9,3	1,86
17.	Seafront	7,23	1,44
18.	Waste Market	11,95	2,39
	Average	**8,621 m**	**1.71 m**

Source: researcher

Shoreline Change Mitigation Strategies

From the results of the analysis of changes in the coastline in several areas where changes occurred were categorized as high. The following are the areas that have undergone changes.

Air Padang Village

This village is located in the Lais District, North Bengkulu Regency. The following are mitigation strategies in the coastal area of Air Padang Village.

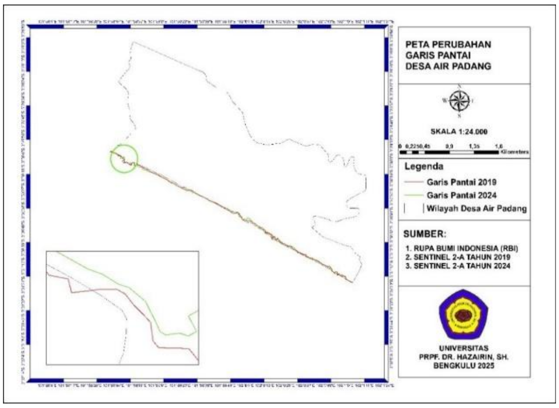

Figure 8. Map of Changes in the Coastline of Air Padang (*Source: researcher)*

Changes in the coastline in Air Padang Village are very high with an average change of 16,468 M, became one of the villages with the most extreme changes during the period 2019 to 2024.

Figure 9. Field Documentation
Source: researcher

The soil around the coastline looks eroded, even some coconut trees are in an alarming position, close to the side that has landslided. To handle this situation, the right mitigation strategy is needed so that the damage does not spread further and endanger the surrounding environment.

The initial steps taken in disaster mitigation can take several steps such as planting coastal vegetation. Plants such as sea spruce, beach grass, or even mangroves if conditions allow the tide of sea embankments can help break up high waves, strengthen soil structure and reduce the rate of abrasion caused by waves.

Figure 10. Concrete (riprap) → Concrete seawall (*Source: Artificial Intelligence)*

Dusun Raja Village

This village is also located on the coast of Lais district, Dusun Raja Juga Village is an area that has experienced a fairly high change in the coastline.

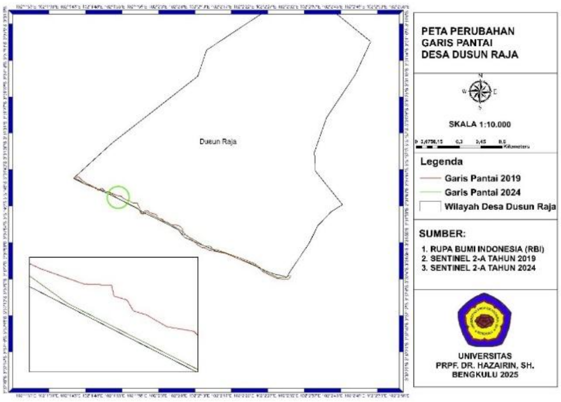

Figure 11. Map of Changes in the Coastline of Dusun Raja (*Source: researcher)*

Raja Hamlet has undergone significant changes in the coastline in recent years. Based on the analysis of the available maps, it can be seen that there is a shift in the coastline that is quite striking. The average change in coastline in this region during the period 2019 to 2024 was recorded at 8,960 meters. This figure indicates an intense coastal abrasion or accretion process, which has the potential to threaten the sustainability of the coastal environment as well as settlements and community activities around the area.

Figure 12. Field Documentation of Dusun Raja (*Source: researcher)*

Extreme abrasion that has caused the red earth cliff to collapse vertically, threatening the buildings of residents standing on the lip of the cliff so that it requires quick and thorough handling.

With the creation of physical structures to strengthen the bedside, such as multi-level guardrails using boulders or concrete, as well as the installation of gabions or ground ties to strengthen the slope from the inside. Moving buildings that are located too close to the cliff is also very important to do in order to avoid the possibility of loss of life if a landslide occurs again.

Pal 30 Village

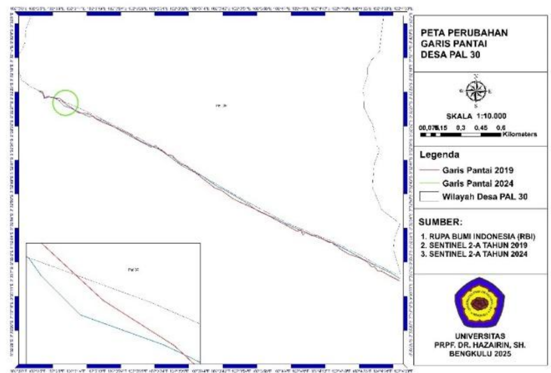

Figure 13. Field Documentation of Pal Village 30 (*Source: researcher)*

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The village of Pal 30 has undergone significant shoreline changes in the last five years. The average change in coastline between 2019 and 2024 was recorded at 10,911 meters. This value is in the very high category, which indicates the presence of extreme coastal dynamics, likely due to abrasion, land-use changes, or human activities that have a direct impact on coastal stability.

Figure 14. Field Documentation of Pal Village 30 (*Source: researcher)*

Given the damage to the road due to coastal abrasion, proper preventive measures are needed to avoid further damage as well as protect the infrastructure and the surrounding environment. Structurally, one of the main solutions is the construction of a coastal embankment that functions to prevent waves from directly hitting cliffs or roads. In addition, the installation of a breakwater in the sea can also reduce the strength of the waves before reaching the shore.

Planting coastal vegetation such as mangroves, sea spruce, or other plants with strong roots is also very effective in preventing soil abrasion naturally. Reinforcement of the road structure, including repairing the foundation and changing paths if necessary, needs to be considered, especially if the area is a zone prone to high abrasion. A good drainage system must also be implemented so that rainwater does not worsen erosion from the land.

Figure 15. Abrasion Resistance Requirements (*Source: Artificial Intelligence)*

Rogue Village

In addition to Air Padang Village, Penyangkak Village also showed significant changes to the coastline during the observation period. This change can be seen from the shift in the location of the coastline between 2019 and 2024.

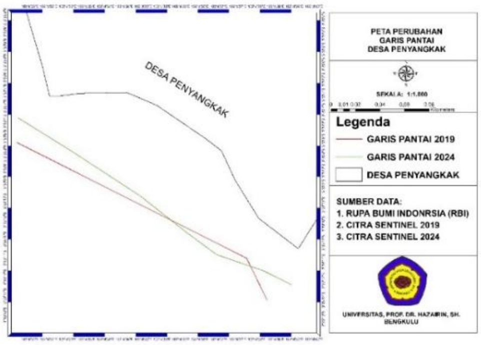

Figure 16. Map of Changes in the Coastline of Pentangkak Village (*Source: researcher)*

Based on the results of analysis and calculations, it is concluded that Penyangkak Village has experienced an average change of 9.9 meters in the 2019-2024 period, this figure is in the very high category.

Lubuk Tanjung Village

Changes in the seashore line are also seen in the coastal area of Dresa Lubuk Tanjung. Between 2019 and 2024, the region showed quite a significant shift, illustrating the ongoing dynamics of coastal ecosystems. To find out the level and pattern of change that occurs.

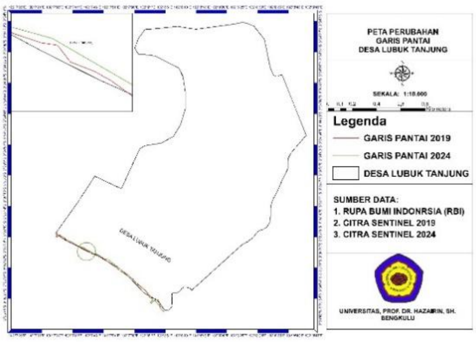

Figure 17. Map of Changes in the Coastline of Lubuk Tanjung Village (*Source: researcher)*

It was found that Lubuk Tanjung Village has experienced significant changes in the coastline. The average change in the coastline in this area during the period 2019 to 2024 was recorded at around 8,535 meters. Therefore, changes in the coastline in Lubuk Tanjung Village need to be immediately followed up with further research and the implementation of sustainable coastal management measures to prevent further damage.

Figure 18. Field Documentation of Lubuk Tanjung Village (*Source: researcher)*

There is an effort to reduce coastal abrasion by building a breakwater structure made of large rocks. This structure plays a role in reducing the strength of sea waves so that they do not directly hit the beach, so that it can slow down the occurrence of abrasion, Although this method is a fairly effective mitigation strategy structurally, additional steps are also needed such as planting coastal plants to strengthen the stability of the soil naturally, as well as regular maintenance of breakwater rocks so that they continue to function properly. In addition, community participation and the application of modern monitoring technology are also important elements in supporting the continuity of coastal area protection. The combination of technical and ecological approaches will create more comprehensive and responsive mitigation efforts to ongoing environmental changes.

Pasar Tebat Village

The transformation of the coastline in Pasar Tebat Village in the last five years illustrates that there are quite significant changes in the coastal area. Spatial data from 2019 and 2024 recorded a shift in the coastline that could be a sign of an abrasion process. This map displays a comparison of coastlines to support environmental studies and more sustainable coastal planning.

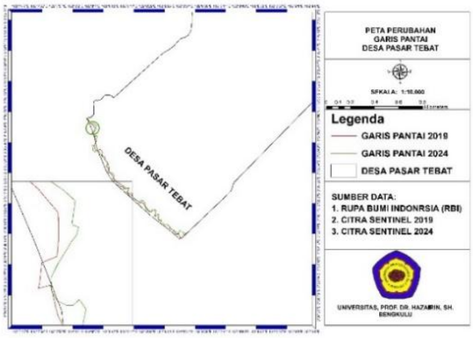

Figure 19. Map of Changes in the Coastline of Pasar Tebat Village (*Source: researcher)*

Based on the results of analysis and calculations, it is concluded that Penyangkak Village has experienced an average change of 9,967 meters in the 2019-2024 period, this figure is in the very high category.

Pasar Kerkap Village

Pasar Kerkap Village has also undergone changes to its coastline which has been very visible in the last five years. This change is a sign of natural processes and those caused by human activities that affect the dynamics in the coastal area of Kerkap Market Village.

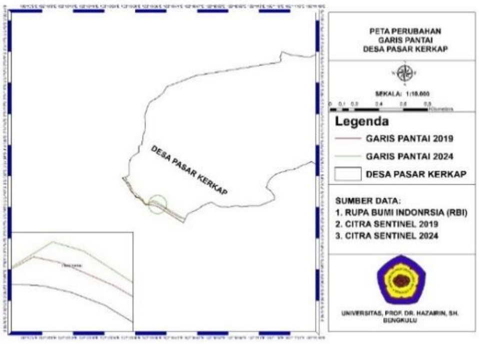

Figure 20. Map of Changes in the Coastline of Pasar Kerkap Village (*Source: researcher)*

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changes in the coastline in the form of coastal erosion with an average change of 9.3 meters during the 2019-2024 period.

Pasar Bembah Village

The change in the seashore in Pasar Bembah Village shows the coastal dynamics that continue to occur due to various influences, both from nature and from human actions. Monitoring the movement of coastlines is crucial to support mitigation and adjustment measures in this area. The image below shows a comparison of the coastline between 2019 and 2024 in the Pasar Bembah Village area, which can be seen in Figure 4.

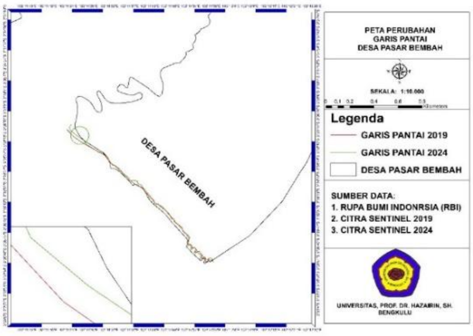

Figure 21. Map P Coastline of Pasar Bembah Village (*Source: researcher)*

The results of the 2019-2024 spatial data processing depict changes in the coastline that are concerned about the change in the average coastline at 11.95 meters during the period studied.

Figure 22. Field Documentation of Pal Village 30 (*Source: researcher)*

The coastal areas that can be seen show signs of quite serious abrasion, as seen from the cliffs eroded by the sea waves that hit continuously. Various systematic mitigation measures need to be implemented. One way that can be taken is to plant coastal vegetation such as sea cypress trees, sea pandanus, or mangroves in the appropriate area. These plants play a role in preventing erosion by binding the soil and dampening the force of the waves. In addition, the installation of protective structures such as breakwaters, retaining walls, or breakwater structures can also help reduce the impact of waves directly hitting cliffs. Coastal spatial planning is crucial so that development does not get too close to the coastline that is vulnerable to erosion.

Figure 23. Offshore Breakwater (Breakwater)- Revetment (Cliff Slope Coating)- Sea Wall / Retaining Wall (*Source: Artificial intelligence)*

This shift in coastline is triggered by two main factors, namely natural factors and human factors. Natural factors are related to the process of waves, ocean currents, and tides that constantly erode the coastline. On the other hand, anthropogenic factors include human activities such as infrastructure development on the coast, sand extraction from the coast, and irregular land use, which accelerate the abrasion process and have an impact on the environment and people's habitations. To deal with these changes in the coastline, this study recommends a number of mitigation strategies that are both technical and ecological in nature. The planting recommendations include coastal vegetation such as mangroves, sea firs, and seagrass to strengthen the soil structure naturally, as well as the construction of hard infrastructure such as sea embankments, gabions, and riprap breakwaters to protect the land from wave attacks. In addition, it is also important to regulate development activities in coastal areas by establishing protection zones so that infrastructure and settlements are not directly affected by abrasion. The use of Sentinel-2 imagery is sustainable, and it has a high spatial resolution that provides an advantage in periodic and efficient shoreline monitoring. The support of Geographic Information System (GIS) technology and remote sensing is proven to provide accurate data for decision-making related to abrasion mitigation and coastal area management. Thus, this research makes a significant contribution in supporting the development of data-driven policies for sustainable coastal protection and management.

Conclusions

The shift in coastline in Lais, Air Besi, and Air Napal sub-districts between 2019 and 2024 shows considerable changes due to abrasion. The average rate of erosion is 1.71 meters per year, and the average change in the value of the coastline is 8,621 meters. The communities of Air Padang, Pal 30, and Pasar Bembah are among the areas most affected by abrasion. Limiting human activities in areas prone to abrasion, planting coastal vegetation, and building sea walls are important strategies that can be used to reduce the impact of abrasion and shoreline changes.

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Conflicts of Interest

The authors declare that there is no conflict of interest in this research.

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