Application of Remote Sensing Analysis for Shoreline Change as a Basis for Coastal Abrasion and Erosion Disaster Mitigation on the Selayar Limestone Formation, South Sulawesi Province Indonesia

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ABSTRACT

The coastal area of Bulukumba area, in South Sulawesi Province is composed of carbonate sedimentary rocks, particularly limestone. In this region, limestone tends to be relatively fragile and easily eroded, making the area highly vulnerable to coastal abrasion and erosion. This study aims to analyze shoreline changes over the past 10–15 years using remote sensing methods, including the use of satellite imagery such as Landsat and Sentinel-2, the Normalized Difference Water Index (NDWI), the Normalized Difference Moisture Index (NDMI), and shoreline change analysis through the Digital Shoreline Analysis System (DSAS). Additionally, geological interpretation of the coastal area, particularly the limestone lithology, was conducted to examine its correlation with the pattern of shoreline change. This research is expected to produce shoreline change maps, abrasion and erosion zonation maps, and coastal geological vulnerability maps. The information obtained can serve as a reference for formulating disaster mitigation strategies related to coastal abrasion and erosion in the study area.

Keywords: *shoreline change, remote sensing, abrasion, erosion, mitigation*

1. Introduction

A. Background

Indonesia has a large coastal area with a coastline that continues to change due to abrasion and accretion processes. These changes are influenced by natural factors such as waves, currents, and tides, as well as human activities in coastal areas. These conditions can have an impact on the coastal environment, including damage to ecosystems and infrastructure, so it is necessary to conduct studies to understand the dynamics of coastline changes as a basis for coastal disaster mitigation.

Bulukumba Regency is one of the coastal areas in South Sulawesi Province that has suffered damage due to abrasion, such as damage to flood retaining embankments and public facilities along the coast. This condition poses a threat to community settlements around the coastline. Based on this, this study was conducted to analyze changes in the coastline in Bulukumba Regency by utilizing remote sensing technology as an effort to support the mitigation of coastal abrasion and erosion.

B. Research Objectives

The objectives of the research to be carried out are as follows:

1. Analyzing the pattern of coastline changes in the research area in the last 9-year interval.
2. To know the influence of lithology on the research area in the change of coastline.
3. Knowing the mitigation strategies for the victims in the research area.

C. Problem Limitations

This study focuses on the analysis of changes in the coastline of the coastal area of Bulukumba Regency which is composed of limestone and agglomerates. The analysis was carried out using satellite imagery data for the past nine years using *the Normalized Difference Water Index* (NDWI) method for shoreline extraction and *the Digital Shoreline Analysis System* (DSAS) to calculate the rate of change, as well as examining the relationship between lithology and shoreline change patterns.

2. Research Methods

A. Data Collection

This study used sentinel imagery obtained from Google Earth Engine to visually observe shoreline changes. The satellite image data processed is in 2017 and 2025. Additional data in the form of hydro-oceanographic data including wave, tide, and flow data from the research area from 2017 and 2025 is sourced from the Geospatial Reference System (SRGI) and the Meteorology, Climatology and Geophysics Agency (BMKG).

The image data obtained is stored in a geodatabase, which serves as a source for the transects generated and analyzed through the *Digital Shoreline Analysis System* (DSAS).

The purpose of this is to determine the position of the coastline segment and combine the coastline patterns into one for the calculation of the rate of change.

B. Data Processing

Data processing uses ArcMap software to digitize the coastline that appears in the image, modeling the changes in the coastline using the DSAS add-in. Then the coastline data is *overlaid* to obtain the zones of change in the coastline.

Analysis of the rate of shoreline change using ArcMap software with the help *of the Add in Digital Shoreline Analysis System* (DSAS). The 9-year coastline vector digitized from satellite imagery was used as a variable of coastline change. The incorporation of the coastline is used as a *baseline* with the buffer method of the coastline. The 2017 and 2025 coastline vectors and *the baseline* were then used in the creation of transects perpendicular to *the baseline* to divide the coastline by the transect. The result of the transect will result in a change in the coastline.

C. Analisis dan Interpretasi Data

Shoreline change analysis is carried out using *the Digital Shoreline Analysis System* (DSAS), which is an add-on to ArcMap developed by the *United States Geological Survey* (USGS) to automatically calculate shoreline change statistics based on the shift in shoreline position over time. Some of the parameters that can be calculated include *Shoreline Change Envelope* (SCE), *Net Shoreline Movement* (NSM), *End Point Rate* (EPR), and *Linear Regression Rate* (LRR). In this study, NSM and EPR parameters were used to determine the magnitude and direction of shoreline change, both abrasion and accretion, by calculating the distance between the longest and most recent years' coastlines. In addition, coastal hydrodynamic analysis was also carried out to identify the influence of waves, currents, and other marine processes on changes in the coastline in the study area.

3. Results and Discussion

Geology Research Area

Geomorphology of Research Areas

Geomorphologically, the research area is included in the southern coastal landscape of South Sulawesi which shows morphological variations from coastal plains to volcanic hills.

This variation in land form is controlled by lithological conditions, geological structure, and denudation and sedimentation processes that have taken place from the Miocene to the present.

The coastal plain unit occupies the western to southern part of the Basokeng area with elevations ranging from 0-50 meters above sea level (above sea level) and a slope of <5°. This unit is composed of alluvial deposits, coastal sand, and fine sedimentary material resulting from the weathering of the surrounding rocks.

Figure 1 Appearance of Coastal Areas in the Research Area

Lithology of Research Areas

The main constituent rocks in the study area include the Walanae Formation, the Selayar Member of the Walanae Formation, and the Volcanic Walanae Formation.

The Selayar Members of the Walanae Formation (Tmps) are limestone units that develop in the southern part of the research area, especially on Selayar Island and the coast of Basokeng. It is composed of coral limestone, solid limestone, and calcarenite, with napal inserts and gampingan sandstone. The thickness of this rock unit reaches ±2,000 m. Stratigraphically, the rocks of the Selayar Members are closely related to the Walanae Formation and are indicative of the transition of environmental change from clastic to carbonate.

The Volcanic Walanae Formation is a unit resulting from volcanic activity that occurred in the Late Miocene to the Pliocene. Its lithology consists of andesite lava, basalt, volcanic breccia, and tufa. Volcanic rocks have high compactness so they are relatively more resistant to marine abrasion than limestone. These formations are found in the western and northwestern parts of the study area, forming low to moderate hills with elevations of 150–400 m.

(A) (B)

Figure 2 Lithology in the research area: A. Limestone of the Selayar Member of the Walanae Formation, B. Agglomerate of the Volcanic Walanae Formation.

Structure of the Research Area

The geological structure in the study area is controlled by the Walanae Fault, which is the main fault that extends from north to south in the western part of South Sulawesi. This fault was instrumental in forming the Walanae Basin, which was the center of sedimentation from the Middle Miocene to the Pleisocene. Tectonic activity in this system repeatedly affects the process of deposition, rock deformation, and coastal morphological evolution in the Basokeng area.

The combination of geological structures results in a pattern of low undulating morphology in the coastal area of Basokeng and sloping hills in the interior. The coastline in this area tends to follow the general direction of the fault (N–S), signifying strong structural control over the shape of the shoreline. The regularity of the coastline pattern with the direction of the fault shows a spatial relationship between tectonic activity and the evolution of modern beaches. This reinforces the assumption that the coastal morphology of Basokeng is not only controlled by marine processes, but also by active structural deformation since the Late Miocene.

Shoreline Changes

A beach has a balance or stability of sediment transport. Changes in coastline are affected by the ingress and exit of sediment on the beach. An imbalance in coastal sediment transport will cause the coast to lose sediment (abrasion) or the beach to acquire sediment (accretion).

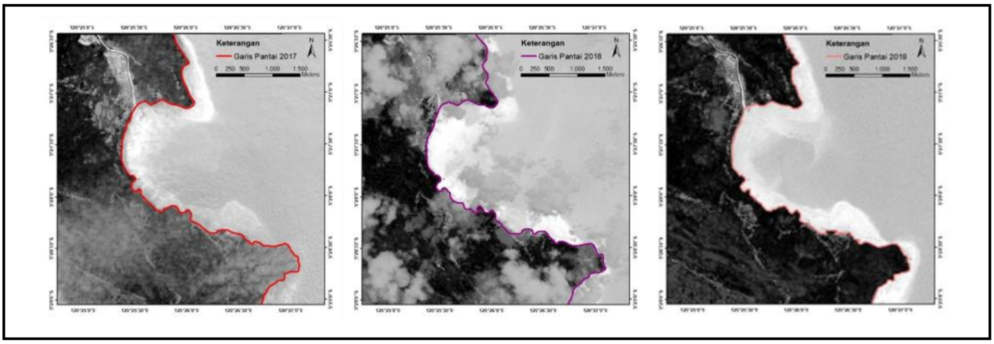


Figure 3 Results of the extraction of the coastline of the Basokeng District in 2017 - 2019

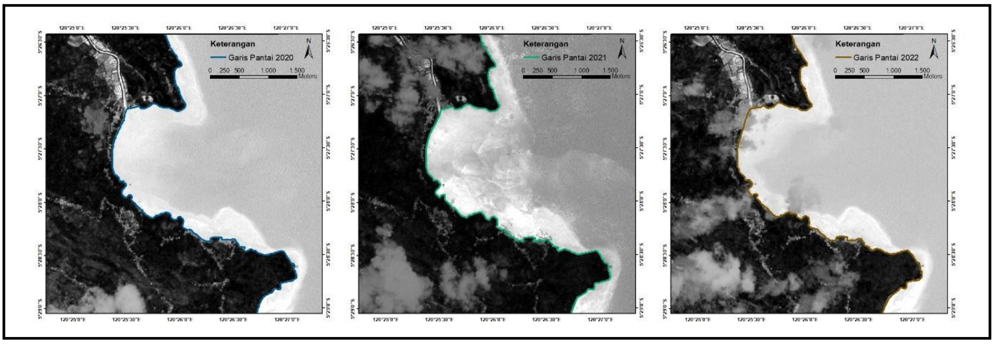


Figure 4 Results of the extraction of the coastline of the Basokeng District in 2020 - 2022

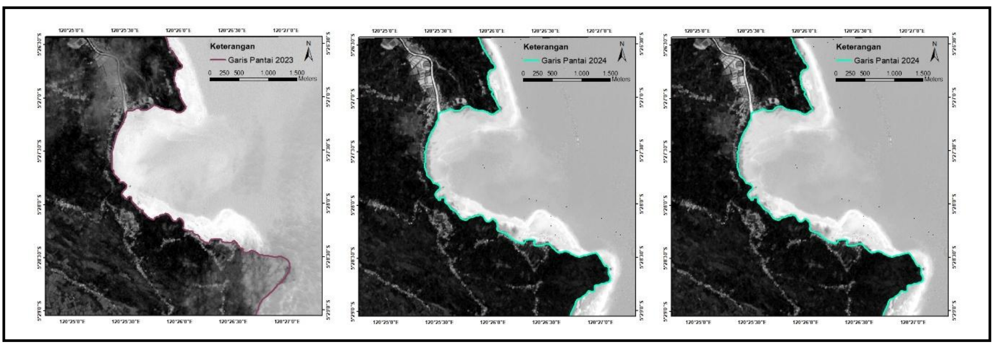


Figure 5 Results of the extraction of the coastline of the Basokeng District in 2023 - 2025

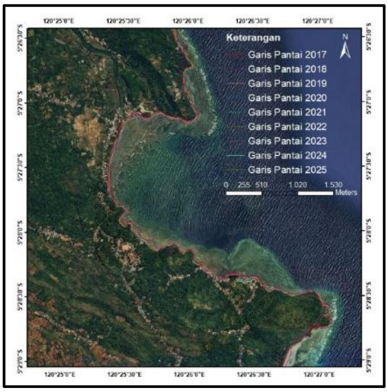


Figure 6 Basokeng County Coastline Overlay in 2017 - 2025

Table 1 Length of the coastline of the study area

Year	**Coastline Length (meters)**
2017	9,4
2018	9,6
2019	9,6
2020	9,6
2021	9,7
2022	9,5
2023	9,2
2024	9,5
2025	10

Based on the coastline length data in Table 1, it can be seen that there are dynamics of change. In 2017 – 2021, the coastline tended to experience a gradual change in addition from 9.4 meters to 9.7 meters with an increase rate of around 1-2% per year. However, in 2022 – 2023 there was a decrease of up to 9.2 meters, equivalent to a reduction of around 3% compared to the previous year.

Furthermore, the coastline will increase in 2024 and increase in 2025, reaching 10 meters as the highest value in the observation interval. Overall, the coastline experienced a change in the addition of a coastline of 0.6 meters or an increase of about 6.4% from the initial length.

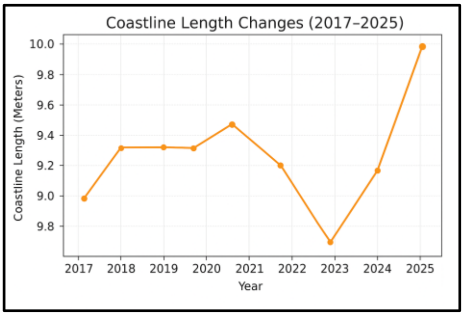


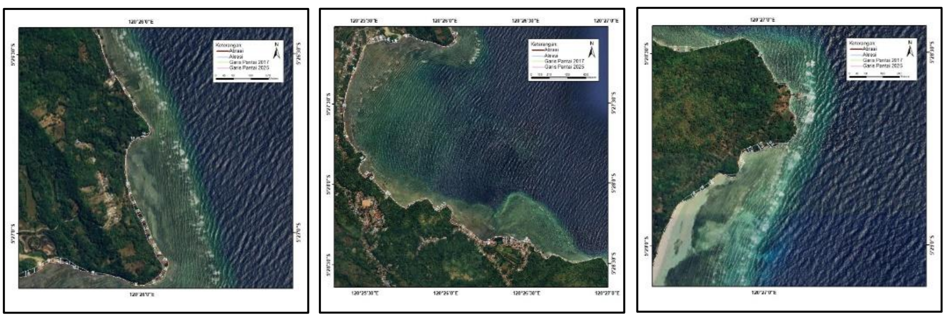
Figure 7 Graph of coastline change 2017 - 2025

Abrasion and Accretion

Table 2 Abrasion and accretion distance in the Basokeng Region in 2017 – 2025

Segment	Transect	Total Abrasion (m)	Average Abrasion (m)	Total Accresion (m)	Average Accresion (m)
A	1 – 34	-38,42	-5,49	391,8	13,99
B	35 – 158	-721,33	-14,14	1083,42	14,84
C	159 - 190	-198,24	-10,43	69,12	5,32

A negative value indicates a type of abrasion change, which indicates a retreat or erosion of the coastline towards the mainland. Meanwhile, a positive value indicates a type of accretion change, which indicates an expansion or addition of land around the coast. In the interval of 2017 – 2025, the coastal area of Basokeng has an average abrasion of 12.44 m, while the average accretion value is 13.55 m. These results provide a more detailed understanding of the dynamics of coastline change in the Basokeng Area (Table 2).



(A) (B) (C)

Figure 8 Coastline Map of Segments A, B, C

The results of the analysis that have been carried out also provide information on the total, average, maximum value, and minimum values of the SCE, NSM, EPR, and LRR variables related to changes in the coastline in the Basokeng Area. The data can be seen in table 4, which shows the value for each observed variable. By analyzing these tables, it is possible to identify extreme values, such as the largest and smallest changes that occur, as well as understand the overall distribution of shoreline changes.

Table 3 Results of the calculation of coastal changes in the Basokeng District 2017-2025

Value	SCE (m)	NSM (m)	EPR (m/thn)	LRR (m/thn)
Total	8.567,62	700,8	95,79	105,6
Average	45,09	3,68	0,5	0,55
Max	179,53	179,53	24,54	13,07
Min	12,65	-60,27	-8,23	-5,62

Based on the results of the *Shoreline Change Envelope* (SCE) analysis, the largest shoreline change reached 179.53 m, while the smallest change was 12.65 m. Positive values produced by SCE do not always indicate accretion until these two values can indicate both accretion and abrasion. In the Basokeng area, the average distance of the farthest and closest coastline shifts from *baseline* is about 45.09 m.

The results of this study show that the value of Net Shoreline Movement (NSM) measured in the Basokeng Area during 2017-2025 has a value range of -60.27 to 179.53 m. The lowest NSM values were found in segment B with a total of -721.33 m and an average of -14.14 m, indicating a significant abrasion process compared to other segments. Meanwhile, in the same segment, it also has a high NSM which can be concluded to be experiencing an accretion process.

The results of *the End Point Rare* (EPR) calculation show that there will be changes in the coastline in the Basokeng Area with a certain speed level in 2017-2025 with a maximum value of 24.54 m/year. The average rate of displacement of the farthest and closest coastline from baseline is about 0.50 m/year.

The results of the *Linear Regression Rate* (LRR) analysis showed that during 2017-2025 in the Basokeng Area, the largest value of the abrasion rate based on the LRR method was 13.07 m/year. The average rate of shift of the farthest and closest coastline from baseline is about 0.55 m/year, not significantly different from the results of the calculation of the rate of shoreline change based on *the calculation of End Point Rare* (EPR).

Causes of Shoreline Changes

Wind and Waves

Based on the calculation of the percentage of wind speed data, the dominant wind direction is from the North of 14% with a daily wind speed between 0.0 – 10.0 m/s, from the Northeast of 9% with a daily wind speed between 0.0 – 7.0 m/s, from the East of 10.5% with a daily wind speed of 0.0 – 6.0 m/s, from the Southeast of 8.8% with a daily wind speed between 0.0 – 6.0 m/s, from the South by 13% with a daily wind speed between 0.0 – 9.0 m/s, from the Southwest by 8.2% with a daily wind speed between 0.0 – 8.0 m/s, from the West by 4% with a daily wind speed between 0.0 – 6.0 m/s, and from the Northwest by 7% with a daily wind speed between 0.0 – 8.0 m/s.

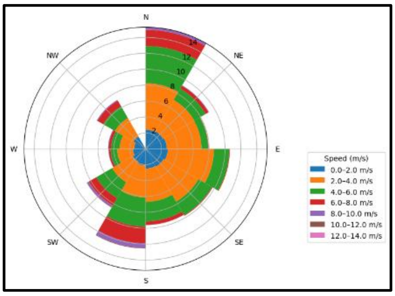


Figure 9 Wind Rose Diagram Year 2017 - 2025

From the results of the analysis of wind direction and speed in the study area for 9 years, the percentage shows that the wind blowing predominantly in the western season (the wind moves from the southeast to the northwest) is larger, with a speed of 0.0 – 9.0 m/s.

Based on the results of wave data processing obtained in table 5, it shows that the maximum wave height (Hmax) occurred in 2019 of 1.89 meters. The maximum period (Tmax) occurred in 2019 of 5.4 s. And the Amplitude (Amax) occurred in 2021 of 3.2 m.

Table 4 Wavelength, Period, and Amplitude in 2017 - 2025

Year	H Max (m)	T Max (s)	A Max (m)
2017	1,78993	5,2374	204,68794
2018	1,55061	4,915	209,25682
2019	1,88706	5,38661	204,30305
2020	1,29529	4,76946	19,08253
2021	1,71643	5,02227	301,02319
2022	1,25419	4,90777	27,48831
2023	1,43017	4,67402	208,25143
2024	1,63487	4,97722	205,97139
2025	1,33062	4,72714	205,92433

The waves in the study area have a wave height between 0.0 – 2.0 m that spreads mostly by wind and affects the amount of sediment transport from sea to land. The wave movement based on figure 14 is dominant in the Southeast – Northwest direction of 17.5% with a wave speed between 0.25 – 1.2 m/s.

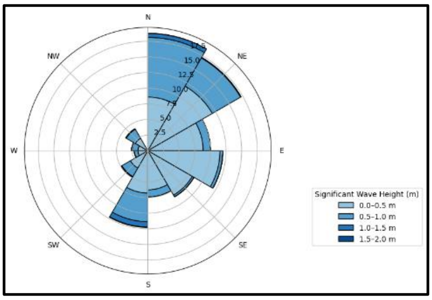


Figure 10 Wave Rose Diagram Year 2017 - 2025

Tidal

The data on the tidal component values of *High Water Level* (HWL), *Mean Sea Level* (MSL), and *Lower water Level* (LWL) were used to determine the type of tide at the research site in the form of a table that can be seen in the table below.

Table 5 Value of tidal components

Year	HWL (m)	LWL (m)	MSL (m)	Formzahl (F)
2017	0,83	-1,21	0	1
2018	0,92	-1,23	0	0,98
2019	0,95	-1,27	0	1,08
2020	0,75	-1,08	0	0,96
2021	0,78	-1,04	0	0,83
2022	0,91	-1,25	0	1,1,0
2023	1	-1,31	0	1,49
2024	0,72	-1,02	0	1,04
2025	1	-1,26	0	0,65

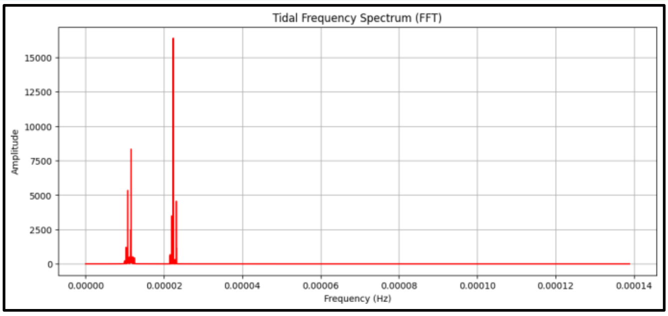


Figure 11 Tidal frequency graph

Based on the diagram above, it can be seen that the peak amplitude indicates the existence of ebb and flow at low frequencies, which is around 0.00002 Hz. The frequency value is equivalent to a period of about 12 hours, which shows the dominance of semi-diurnal components. In addition, there is another peak amplitude at around 0.00001 Hz, which represents a diurnal component with a period of about 24 hours. This suggests that the tidal type at the study site tends to be semi-diurnal, with two tides and two ebbs in one day.

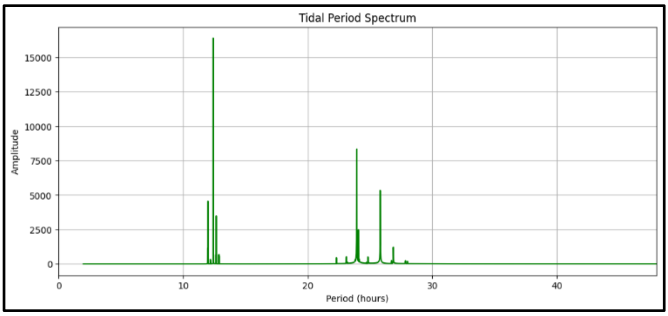


Figure 12 Tidal period chart

Based on the spectrum of tidal periods, the peak of the highest amplitude is seen in a period of about 12 hours which shows the dominance of semi-diurnal components. In addition, there is another peak around the 24-hour period that indicates the presence of a diurnal component. This shows that the type of tides at the study site is dominated by semi-diurnal tides, which occur twice in one day.

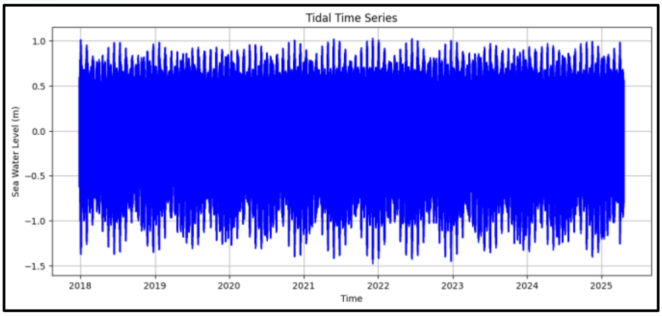


Figure 13 Tidal Chart for 2017 - 2025

Maximum tides and minimum tides affect changes to the beach. The coastline has an irregular position and can shift according to the influence of sea tides and the presence of coastal abrasion.

Lithology of Research Areas

Influence of Limestone Lithology on Coastal Hydrodynamics

Limestone in the study area has high porosity and is composed of calcite minerals formed in the shallow marine environment, so it has a great influence on coastal hydrodynamic dynamics. When the waves come perpendicular to the surface of the limestone, some of the energy is reflected and some form a *longshore current* that regulates the distribution of energy along the coastline. This condition triggers the formation of local abrasion and accretion zones as well as backcurrents that transport sediments to the sea. The results of the analysis showed that the coastal segment with limestone lithology had an abrasion rate (EPR) between –1.8 to –2.5 m/year, with the highest abrasion in areas directly exposed to waves and accretion in the protected part of the bay. Thus, limestone acts as a natural regulator of marine energy circulation that affects erosion and sedimentation patterns on Basokeng Beach.

Influence of Agglomerate Lithology on Coastal Hydrodynamics

The lithology of agglomerates in the study area showed an important role in controlling the abrasion and accretion processes of the coast. This rock is part of the Walanae Volcanic Formation which is composed of hard fragments (andesite–basalt) with a more fragile tufa matrix, so that high-energy waves are able to erode the matrix but the hard fragments remain, forming a rough and uneven surface. The results of the analysis showed that the NSM value ranged from 5–12 meters and the average EPR was 0.3–0.8 m/year, indicating a low to moderate abrasion level with a tendency to accretion. This resistance is due to the compactness of the rock and low porosity, so that agglomerates function as a natural barrier to abrasion as well as fine sediment accumulation areas from the erosion of the surrounding limestone.

Comparison of Limestone and Agglomerates Lithology to Abrasion – Accretion

The results of the comparison between Limestone and Agglomerates show a difference in resistance to coastal hydrodynamic forces and their implications for shoreline changes. Overall, limestone is easily eroded or soluble so the abrasion value is high, while agglomerates are resistant to erosion which makes the lithology more stable to shoreline changes and supports accretion. This difference shows that lithological variation is the main controlling factor for coastal hydrodynamics and sediment transport in the coastal area of Basokeng.

Mitigation Strategies

Based on the results of the analysis, mitigation strategies in the research area can be carried out through several main steps. First, conducting a mapping of abrasion-prone zones based on lithology, where areas with limestone are included in high-risk zones and are restricted from permanent development. Second, coastal spatial planning by focusing on the construction of facilities and settlements in agglomerate zones that are more stable against waves. Third, rehabilitation of coastal vegetation such as planting mangroves and sea fir to reduce wave energy and retain sediment in areas of light abrasion. Fourth, the construction of coastal protection structures based on geological and geotechnical data, taking into account the type of rock, the level of compactness, and the orientation of the cracks as the basis for *the design of the seawall* or *revetment*. Finally, it is necessary to periodically monitor shoreline changes using satellite imagery, for example every five years, to evaluate the effectiveness of mitigation measures and detect the dynamics of abrasion that occurs.

4. Conclusion

Based on the results of the study on "Application of Remote Sensing Analysis for Shoreline Change as a Basis for Coastal Abrasion and Erosion Disaster Mitigation on Limestone Selayar Members of the Walanae Formation and the Volcanic Walanae Formation Agglomerate, Bulukumba Regency, South Sulawesi Province", it can be concluded as follows:

1. Changes in the coastline in the study area during the period 2017–2025 show significant dynamics, with varying patterns of abrasion and accretion along the Basokeng coastline. Based on the results of the DSAS analysis, the value of coastline change (NSM) ranged from –60.27 m to +42.58 m, with an EPR value ranging from –2.5 m/year to +1.8 m/year.
2. Abrasion zones generally occur in areas with limestone limestone of the Selayar Members of the Walanae Formation, which are easily soluble and high porosity. The solution *weathering* process due to seawater interaction causes the intensive retreat of the coastline. Meanwhile, the accretion zone tends to develop in areas with the lithology of the Walanae Volcanic Formation Agglomerate. The high resistance of agglomerates to wave abrasion makes this area relatively stable and a place for sediment accumulation.
3. Understanding the geological aspects and dynamics of coastline change can be used as a basis for planning for disaster mitigation of abrasion, especially in determining vulnerable zones, coastal spatial planning, and the placement of coastal protective buildings that are suitable for the condition of bedrock materials.

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