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RESEARCH ARTICLE

Study of Coastal Morphological Changes by Tsunamis in Aceh (Indonesia) Using Satellite Images

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Abstract

This study identified the coastal morphological changes caused by tsunamis that occurred in Banda Aceh, Lampuuk-Lhoknga, and Meulaboh. The morphology of study areas was drastic changes during the 2004 tsunami and followed by the 2005, 2010, and 2012 tsunamis. Time series of Landsat satellite images and tidal data were collected during the period 1988-2020 and analyzed using DSAS (Digital Shoreline Analysis System) analysis method. The main aim of this study is to monitor recovery, trend development, and controlling factors of the coastal morphology before and after fifteen years of the 2004 tsunami.

In Banda Aceh, the shoreline shift in the 2004-2005 period shows an inland retreat trend, with an average NSM (net shoreline movement) value of -644.69 m. The EPR (end point rate) value for the 2005-2020 period reached 21.31 m/year, but the recovery of the 2020 shoreline position has not returned to the original position before the 2004 tsunami. The significant shoreline retreat and land loss with an average NSM value of -40.59 m in the period 2004-2005 occurred on the Lampuuk and Lhoknga beaches. The 2020 shoreline of Lampuuk beach underwent a recovery with accretion. Nevertheless, Lhoknga beach is still experiencing apparent erosion. The recovery of the Meulaboh east coast was fast as evidenced by the development of the annual growth of spit features. The coastal morphological changes are influenced by complex interactions between natural and anthropogenic processes. The 2004 tsunami was the major factor to change the coastal morphology in the study areas.

Keywords: Coastal morphological changes, Shoreline change, Tsunamis, DSAS analysis.

1. Introduction

In general, destructive tsunamis majorly occur in the Indian and Pacific Oceans, and Indonesia is one of the countries with a relatively high incidence of tsunamis. A tsunami can have a devastating impact on the coastal system. Some researchers have studied remarkable coastal morphological changes caused by the 2004 tsunami on Banda Aceh coast (Chen et al., 2005; Borrero, 2005; Meilianda et al., 2010, 2019; Griffin et al., 2012; Syamsiddik et al., 2015, 2016; Rasyif et al., 2019; Irham et al., 2021). According to Liew et al., (2010), Aceh coast was eroded on average by about 500 m during the 2004 tsunami event, except at the rocky headland. As a result, most accretional landforms, including beaches, dunes, and wetlands were severely destructed and lost. According to Meilianda et al., (2010), Ulee Lehue coast lost about 15% of the total sediment due to tsunami and land subsidence caused by the 2004 earthquake. Irham et al., (2021) studied coastal accretion and erosion from 2004 to 2017 around Lampudo beach and found a remarkable shoreline retreat in 2009 where breakwater, seawall, and port were rebuilt after the 2004 tsunami event. Syamsidik et al., (2015) revealed that Ujong Pancu and Ulee Lehue coasts recover naturally without artificial construction and other restoration projects.

On Lampuuk-Lhoknga coast, the erosion of the 2004 tsunami induced an average shoreline retreat of 500 m with a maximum of 2 km near the river month. The mean shoreline retreat from Lampuuk to Leupung was 60 m with a maximum of 150 m (Paris et al., 2007). According to Adela et al., (2019), Lampuuk coast underwent post-event net accretion from 2005 to 2018.

In Meulaboh, shoreline retreat was more than 1 km caused by the 2004 tsunami (Nugroho., 2013). While the tsunami removed the beach ridge, connected the streams directly to the sea, and flooded the swales (Liew et al., 2010). Research on the shoreline and coastal morphology changes in Meulaboh coast due to minor tsunamis in 2005, 2010, and 2012 have been very difficult to find in recent years.

Referring to the studies, the three coasts induced a devastating impact. Therefore, it is necessary to monitor the evolution of the shoreline and coastal morphology affected by tsunamis and caused by other factors.

This study focuses on the shoreline and coastal morphological changes caused by both major and minor tsunamis in the western part of Sumatra, Indonesia. The three coasts Banda Aceh, Lampuuk-Lhoknga, and Meulaboh were selected to investigate long-term coastal evolution (including erosion and accretion) patterns interrupted by tsunami events and other controlling factors of the shoreline and coastal morphological changes will also be discussed before and after the tsunami events.

2. Study Area

The study locations are occured on Banda Aceh, Lampuk – Lhokngaa and Meulaboh coast (Fig. 1). Banda Aceh is located on the northwestern end of Sumatra Island and is bordered by the Malacca Strait, the Gulf of Bengal, the Andaman Sea on the north, and the Indian Ocean on the west. According to Meilianda et al., (2010), Banda Aceh coast is characterized by a steep offshore gradient with a narrow continental shelf. Geomorphologically, it consists of Ujong Pancu headland, Krueng Raya Estuary, barriers, lagoons, and wetlands. The average elevation of the barrier was about 1.5 m above the mean low water level (MLWL). Ujong Pancu and Ulee Lehue coasts were recovered naturally, and no hard structure was introduced to restore the coastal land until 2009. However, the recovery of Pande coast was faster because of the construction of revetment structure (Syamsiddik et al., 2015). Irham et al., (2021) found a remarkable shoreline retreat in 2019 where breakwater, seawall, and port were rebuilt around the Pande coast.

Lampuuk and Lhoknga coasts are located on the west coast of the northwest tip of Sumatra Island, Indonesia, with the Reba River flowing in the between. They face the Indian Ocean with a relatively wide continental shelf. According to Irham et al., (2021) sandy beaches have a gentle slope. Sediments consist of moderately sorted medium sands.

Meulaboh is located in the southwestern part of the Aceh Province and is the capital city of the West Aceh district. Meulaboh coast has a gentle slope, which favors the height and speed of incoming tsunamis to increase.

Indonesia is a country well known for its active seismicity. In the last decades, devastating earthquakes and tsunamis occurred. There is the source of the earthquake on the subduction fault, strike-slip earthquakes on the Sumatra fault, and volcanic earthquakes. According to the Indonesian Meteorological Climatological and Geophysical Agency (or BMKG), a report entitled “Katalog Tsunami Indonesia per-wilayah” states that Aceh was hit by 13 tsunamis recorded between 1837 and 2012. This study focused on tsunamis in 2004, 2005, 2010, and 2012 (Table 1).

The Indonesian Archipelago lies on the equator, where a typical monsoonal climate occurs and converges the Inter-Tropical Convergence Zone (ITCZ). Seasonal changes in wind direction characterize the monsoon climate. The Southwest monsoon is directed from the southwest to northeast during June-September, and the Northeast monsoon is directed from the north and northeast to southwest during December-February (Rizal et al., 2012).

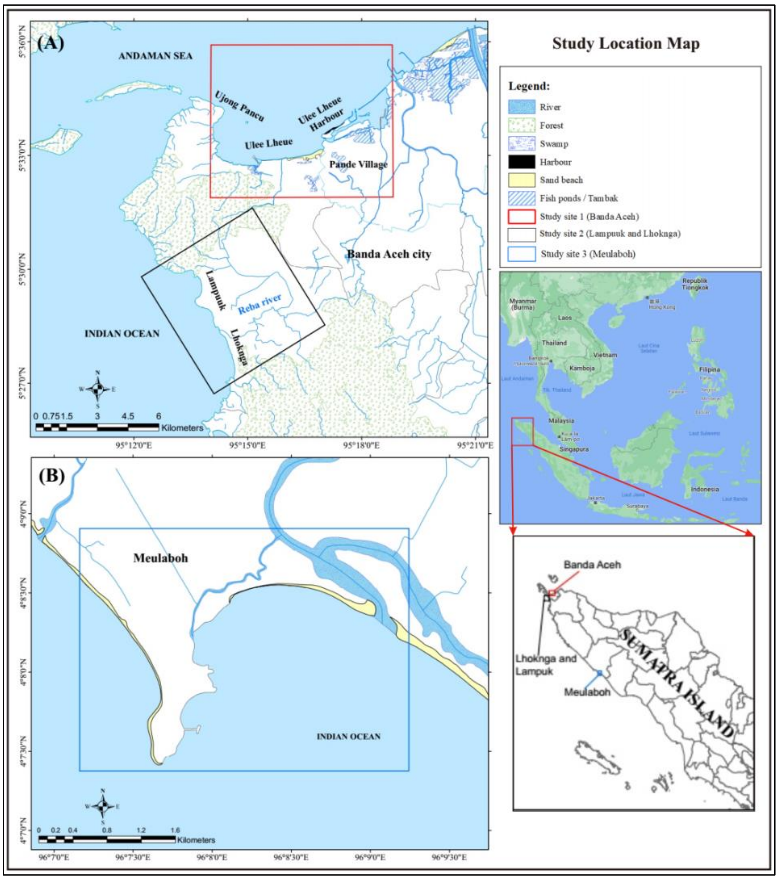

Fig. 1. Locations of study coasts at northwestern end of Sumatra Island in Indonesia. A) Banda Aceh and Lampuuk and Lhoknga, and B) Meulaboh.

3. Materials and methods

3.1 Satellite images correction

Satellite images of Aceh between 1988 and 2020 are used to analyze morphological and shoreline changes in response to tsunamis. The scenes of satellite images (Landsat-5 TM, Landsat-7 ETM+, and Landsat-8 OLI/TIRS) with a spatial resolution of 30 meters were freely downloaded from USGS https://earthexplorer.usgs.gov/. The data specification and acquisition date of all satellite images used and tidal information are listed in Tables 2 and 3. All images were employed to analyze the erosion and accretion rate and coastal recovery patterns. Three base maps of Banda Aceh, Aceh Besar Province, and West Aceh Province have been freely downloaded from the Indonesian geospatial information agency website https://tanahair.indonesia.go.id/portal-web. Radiometric calibration employed algorithms and processes to improve Landsat image quality and correct pixel values. It is done by converting the digital number (DN) values data to spectral reflectance. This is followed by the correction of atmospheric effects. This process is carried out using the FLAASH module on the ENVI environment software. The gaps in Landsat 7 scenes due to scan line corrector (SLC) failure were removed using two bands gap-fill method (SLC-on scenes and SLC-off scenes) in the ENVI software. The images are cropped based on the area of interest.

3.2 Shoreline extraction

Numerous methods exist for extracting the shoreline from images captured through remote sensing. Apart from utilizing advanced feature extraction algorithms for automatic shoreline extraction, several other techniques are commonly used. These techniques involve digitizing through visual inspection, spectral band ratios, edge detection, and classification using single or multiple bands. (White and El Asmar 1999; Li et al. 2003; Alesheikh et al., 2007: Pardo-Pascual et al., 2012; Claire et al., 2012; Suhana, 2016; Fan et al., 2019). Here, the extraction is employed spectral single band threshold, band ratios, and false-color composite red green blue techniques using ENVI software. The composite NIR and Green produce the boundary between land and sea in coastal areas covered by vegetation. Composite SWIR and Green will be obtained shoreline from the areas covered by sand and soil. To obtain a combination, the following algorithm 1 is used referring to Winarso and Budhiman., (2001). Then employed visual investigation and manual digitization is employed to extract the shorelines from raster to polygon in ArcGIS 10.5 software, to estimate the erosion-accretion rate and quantify the spatial distribution of the coastal area and its change.

If (B4/B2) ≥ 1 then 1 else if (B5/B2) ≥ 1 then 1else 2 (1)

3.3 Shoreline correction

The correction of the shoreline from the delineation of satellite imagery to the tides is carried out to produce land and sea boundaries that become shoreline features according to tidal conditions. Tidal data used based on the acquisition of satellite imagery from 1988 to 2020 was obtained from a download at the Indonesian Geospatial Information Agency website (https://tides.big.go.ig). The correction of the shoreline from the satellite image delineation to the tides is to calculate the slope of the coast. The coastal slope is calculated using an equation that refers to (USACE, 2003):

$$\tan \beta = \frac{d}{m} \quad (2)$$

Where:

tan β = coastal slope (°)

d = water depth (m)

m = the distance from the shoreline to water depth (m)

Furthermore, the distance of the shoreline shift from the correction to MSL is calculated using the equation based on (Suhana, 2016):

$$x = \frac{\eta}{\tan \beta} \quad (3)$$

Where:

η = Water level position during acquisition date (m)

x = the distance of shoreline shift as a result of the correction of the tides (m)

tan β = coastal slope (°)

To determine the correction for shoreline position, we consider whether the image was taken at high tide or if the sea level is above mean sea level (MSL). If the image was taken at high tide or the sea level is above MSL, the shoreline is shifted by a distance x towards the sea. Conversely, if the image was taken at low tide or the sea level is below MSL, the shoreline is shifted by a distance x towards the land. Therefore, to identify shoreline features using satellite imagery, relying on the theoretical approach of tidal correction is essential. This process generates a definitive boundary between land and sea, which can be considered a shoreline feature.

3.4 Digital Shoreline Analysis Systems (DSAS)

In order to calculate changes in the shoreline, DSAS measures the gaps between its positions during specific periods. The objective is to examine the geometry indicators of the shoreline in order to evaluate the historical trend of shoreline changes. This study uses statistical parameters such as net shoreline movement (NSM), linear regression rate (LRR), and end point rate (EPR) to describe patterns of shoreline change. According to Himmelstoss et al, (2018), NSM is the distance between the oldest and the youngest shorelines for each transect. EPR is calculated by dividing the distance of shoreline movement by the time elapsed between the oldest and the most recent shoreline. A linear regression rate-of-change statistic can be determined by fitting a least-squares regression line to all shoreline points for a transect. LRR has comprehensive coverage and a recognized approach for calculating the extended period of shoreline changes (Crowell and Leatherman, 1999).

DSAS systems consist of different components: the baseline, historical shorelines, DSAS transects, measurement points, and measurement distances. The baseline serves as the starting point for all transects, while the historical shorelines are used to study specific periods. DSAS transects are created by casting from the baseline and intersecting different shoreline features. (Nguyen, 2017). This study established the baseline by buffering the shorelines from 2004, 2005, 2010, and 2012, following DSAS procedures (Himmelstoss et al., 2018). The three study areas were generated by specifying a distance of 1 meter. The number of transects employed in the Banda Aceh coastal area is about 12282 transects, in Lampuuk-Lhoknga coastal area about 7660 transects, and in Meulaboh about 7106 transects.

The analysis of the DSAS is calculated with the aim of knowing the changes in the shoreline associated with the tsunami that occurred. The NSM calculations are carried out to determine the distance of shoreline changes before the 2004 tsunami (1988 – 2004) and the distance of shoreline changes from 2004 – 2020. EPR analysis was calculated to determine the distance of erosion and accretion shoreline over time. In this study, the EPR calculation was carried out based on changes in the shoreline that were affected by tsunamis (as a tsunamigenic event). It is reported that Meulaboh coast was directly affected by the tsunami waves, while Banda Aceh and Lampuuk-Lhoknga coasts were not. However, it is still carried out at each research location to determine whether there is an effect due to the earthquake or tsunami that occurred. Except for the 2004 tsunami, others occurred in 2005, 2010, and 2012 respectively. Then the calculated LRR analysis for the long-term shoreline change from the 2004 – 2020 period.

Table 1. Catalog of earthquakes and tsunamis occurred around the Aceh area.

No	Area	Date	Magnitude	Depth (km)	Height of runup (m)	Category
1	Banda Aceh, Lhoknga (West Aceh), Meulaboh, Lhokruet (South Aceh), Krueng raya (Aceh besar), and Panteraja (East Aceh)	12/26/2004	9.1	30	Banda Aceh (9), Lhokgna (30), Lhokruet (10), Krueng raya (5), Panteraja (4.5), Meulaboh (4)	Earthquake and tsunami
2	Simeulue, Nias island, Aceh singkil and Meulaboh	3/28/2005	8.6	30	1	Earthquake and tsunami
3	Simeulue, Aceh singkil	4/6/2010	7.7	34	-	Earthquake and tsunami
4	Meulaboh	4/11/2012	8.4	12.9	0.8	Earthquake and tsunami

4. Result and Discussion

4.1 Spatial and Temporal Shoreline Changes

The spatial and temporal shoreline changes are captured in visual images from 1988-2020 at the study locations. The interpretation of the shoreline changes is carried out in Banda Aceh, Lampuuk-Lhoknga, and Meulaboh. The purpose of choosing the locations is that they were severely damaged by the devastating 2004 tsunami event and other smaller tsunamis. The result of these shoreline changes is based on DSAS analysis.

Banda Aceh Coast

The NSM of the Banda Aceh shorelines was measured from a series of satellite images over the period 2004-2005, and 2004-2020. The shoreline change in the 2004-2005 period generally shows a significant land loss for the entire coastal area (Fig. 2), with the average NSM value being -644.69 m. This period's minimum and maximum movement shifts are -2479.58 m and 18.63 m, respectively. The NSM values for the 2004-2020 period ranged from -0.05 m – (-1419.23 m) and 0 – 262.12 m. The shoreline seaward movement occurred locally at Ujong Pancu and the port in the Pande area. The shoreline change was primarily triggered by the 2004 tsunami which destroyed the barrier, resulting in severe erosion, with an average NSM of -321.37 m. Based on the result, the 2020 shoreline position has not returned to that in 2004 before the tsunami.

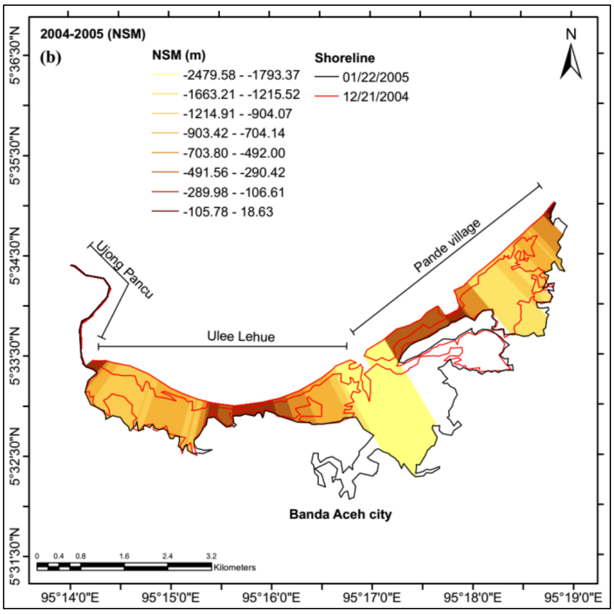

Fig 2. NSM map of Banda Aceh coast for the 2004-2005 period.

EPR calculation is divided into the damage caused by tsunamigenic events (2004-2005) and non-tsunamigenic events (2005-2020). The period 2004-2005 represented a change in shorelines directly affected by the 2004 tsunami. While the period 2005-2020 shows EPR values influenced by the non-tsunamigenic event. For shoreline change to be confidently detected must be positive (accretion) or negative (erosion). EPR values in the period 2004-2005 are known to experience very damaged erosion along Ulee Lehue and Pande coasts, with an average EPR value of -7536.88 m/year. The maximum landward and seaward shifts are -28987.89 m/year and 217.78 m/year, respectively. The 2004-2005 shoreline of 92.08% was characterized by statistically significant erosion and 7.92% by statistical accretion. The extreme EPR values resulted from large landward shoreline change in a short time with the loss of land. The shoreline change rate of non-tsunamigenic events revealed that the maximum and minimum EPR values amounted to 139.37 m/year and -9.09 m/year (Fig. 3). The result of the average EPR value is categorized as accretion, with an average EPR value of 21.31 m/year. It was indicated that 76.31% of shoreline was generally accretion during this period.

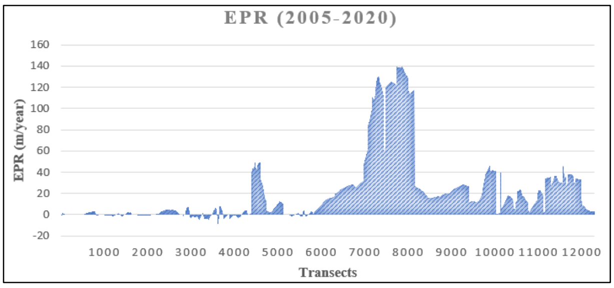

Fig 3. EPR values of Banda Aceh coast for the 2005-2020 period.

The LRR analysis for 2004-2020 revealed that two locations were still experiencing erosion, including the transects 2820-4372 in Ulee Lehue and the transect 10138-11513 in Pande. The minimum and maximum values of LRR indicate high erosion (-32.73 m/year) and high accretion (65.62 m/year). However, it is known that the average value of LRR is positive (3.69 m/year), which means the post-tsunami recovery process in the study area is slow in several locations.

Lampuuk-Lhoknga Coast

The NSM in Lampuuk – Lhoknga was calculated during the 2004-2005 and the 2004-2020 periods. The shoreline retreat occurred mostly along the Lampuuk and Lhoknga beaches, with the average NSM value being -40.59 m. There was a land loss in the Reba river mouth and slight accretion at Lampuuk beach (Fig. 4). The minimum and maximum shifts are -382.85 m and 46.76 m, respectively. The shoreline landward shift of the 2004-2020 period was more significant with the average NSM value being -16.98 m (erosion). During the 2004-2020 period, accretion was detected along 20.86% of the coast, while 79.14% of transects exhibited statistically significant erosion. Therefore, the shoreline change of Lampuuk-Lhoknga was dominated by erosion with the shoreline shifting landward.

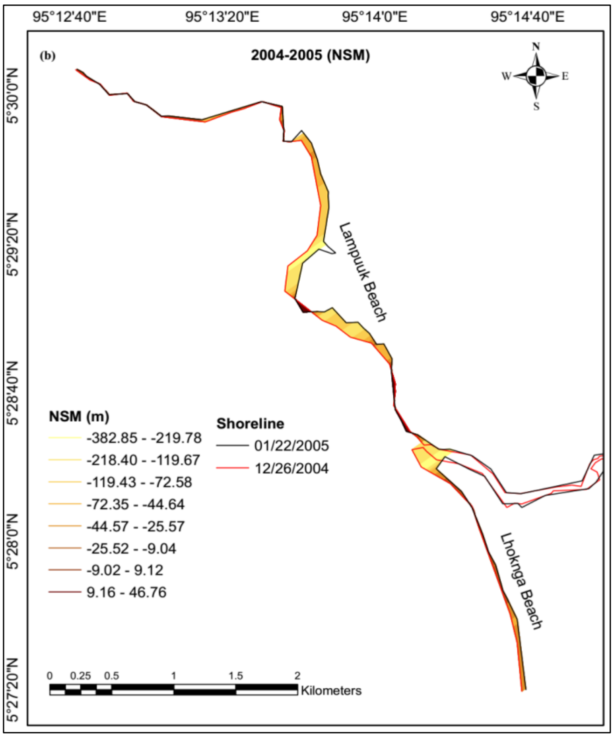

Fig 4. NSM map of Lampuuk-Lhoknga coast for the 2004-2005 period

EPR calculations are divided equally as in Banda Aceh, namely into the 2004-2005 period (tsunamigenic event) and the 2005-2020 period (non-tsunamigenic event). The average value of EPR for the period 2004-2005 is -557.36 m/year which indicates erosion along the shoreline. The calculated maximum and minimum EPR values reached 740.06 m/year and -4088.62 m/year, respectively. For the 2005-2020 period, the average EPR value was recorded positively at 1.62 m/year, with a maximum and minimum value of 19.94 m/year and -8.59 m/year (Fig. 5). The results of the average value of these two periods are inversely proportional. It shows the enormous influence of the tsunami waves on the shift of the shoreline.

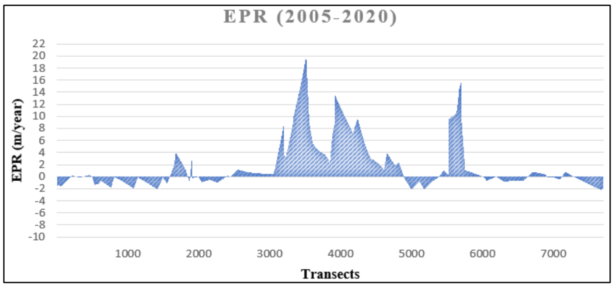

Fig 5. EPR values of Lampuuk-Lhoknga coast for the 2005-2020 period.

Analysis of LRR value for the period 2004-2020 revealed a relatively low erosion rate ranging from 0 – (-6.99) m/year locally, especially along the 1955-3081 transects were higher. The average value of LRR was recorded as positive (0.73 m/year).

Meulaboh Coast

NSM analysis at Meulaboh was calculated over 2004-2005 and 2004-2020. The shoreline change in the 2004-2005 period shows shoreline retreat at the Meulaboh beaches, with the average NSM value being -47.71 m and there was a land loss in the Suak Nihong river mouth (Fig. 6). This period's minimum and maximum shifts are -249.47 m and 0.44 m, respectively. The average NSM value for the period 2004-2020 is a positive value, amounting to 0.46 m. The maximum and minimum values amounted to 207.08 m and -188.34 m. The shoreline landward shift occurred only between transects 3-2663 for 2004-2020, the shoreline seaward shift occurred in transects 2667-4529 and 4544-5963 for the period 2004-2020. Thus, the 2020 shoreline position was still located landward of the 2004 shoreline position before the tsunami.

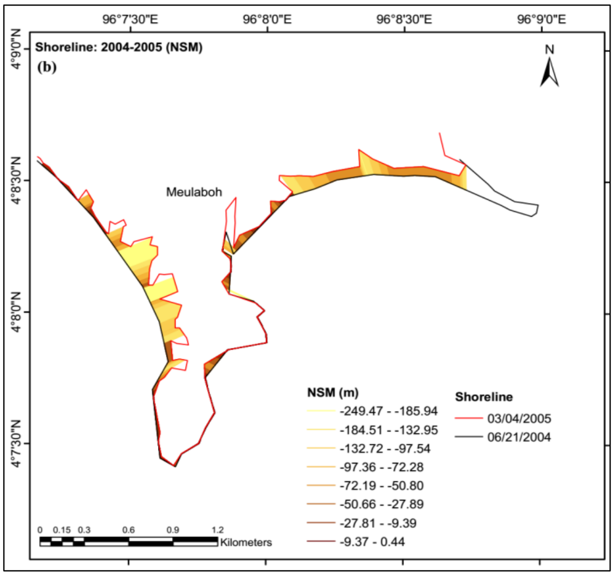

Fig 6. NSM map of Meulaboh coast for the 2004-2005 period

Erosion occurred along the shoreline due to the 2004 tsunami with an average EPR value of -67.06 m/year. The maximum and minimum EPR values reached 286.43 m/year and -356.99 m/year, respectively. The period 2005-2020 experienced uneven shoreline changes. The maximum and minimum EPR values were 870.8 m/year and -1241.97 m/year (Fig. 7), with an average EPR of -13.58 m/year. Shoreline recovery was slightly slow.

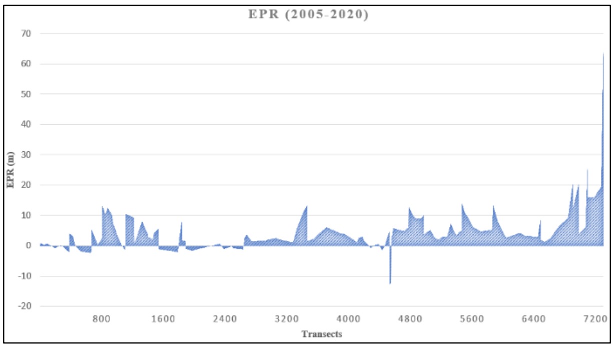

Fig 7. EPR values of Banda Aceh coast for the 2005-2020 period

LRR analysis in Meulaboh was recorded from 2004-2020 with an average value of 1.53 m/year. The erosion rate is relatively small, ranging from -0.01 to -6.44 m/year. The negative value of LRR was relatively high at -13.13 – (-13.47) m/year, in transects 4539, 4540, 4541, 4542, and 4543. The maximum LRR value reached 31.24 m/year.

4.2 Erosion and Accretion

Banda Aceh coast is divided into the southwest coast, occupied by Ujong Pancu and Ulee Lheue, while the Pande Village occupies the northeast coast. During the 1988-2004 period, erosion and accretion were recorded at 3.222 km^2 and 0.359 km^2. Accretion occurred in some areas of Ujong Pancu and at the Krueng Aceh river mouth. At the same time, the erosion process occurred in the Ulee Lheue area to the Pande Village. The net erosion was -2.863 km^2 with a rate of -178937.5 m^2/year. In the 2004-2005 period, the erosion reached 5.077 km^2 with a small accretion of 0.06 km^2. This high level of erosion was influenced by the 2004 tsunami. The net erosion value reached -5.017 km^2. The period 2005-2020 was carried out to determine the coast's recovery after the 2004 tsunami. The measured erosion was 0.12 km^2, and the accretion was 4.070 km^2. The net growth was recorded at 3.950 km^2 with a 263333.3 m^2/year growth rate. This high accretion value mainly occurred in the coastal part of Ulee Lheue and Pande Village, and erosion was still recorded at the tip of Ulee Lheue and part of Ujong Pancu (Table. 2). The slow recovery process was triggered only by natural processes without any hard structures built by human intervention, which is different from the artificial construction of a seawall and harbor in the Pande Village.

Lampuuk-Lhoknga coast is occupied by Lampuuk beach in the northwest and Lhoknga beach in the southeast. During the 1988-2004 period, the erosion and accretion were relatively low, with erosion of 0.059 km^2 and accretion of 0.096 km^2. Along the Lampuuk sand beach, there was a process of erosion and accretion. While erosion was relatively long on the Lhoknga sand beach, net growth was recorded at 0.037 km^2, with a 2312.5 m^2/year growth rate. In the 2004-2005 period, the erosion was 0.307 km^2, and the accretion of 0.016 km^2. Net erosion was calculated at -0.291 km^2. Erosion occurred almost along the Lampuuk-Lhoknga coast by the 2004 tsunami. The spit at the Reba River mouth was washed away by the tsunami waves. The 2005-2020 period was post-tsunami 2004 with a relatively high accretion of 0.211 km^2 and an erosion of 0.048

km². The net growth value reached 0.163 km² with a 10866.67 m²/year growth rate. The recovery process was fast during this period.

Table 2. The long-term erosion and accretion along the coast.

Coastal area	years	Erosion (km²)	Accretion (km²)	Net growth (km²)	Growth rate (m²/year)
Banda Aceh	1988-2004	3.222	0.359	-2.863	-178937.5
	2004-2005	5.077	0.060	-5.017	-
	2005-2020	0.120	4.070	3.950	26333.3
Lampuuk-Lhoknga	1988-2004	0.059	0.096	0.037	2312.5
	2004-2005	0.307	0.016	-0.291	-
	2005-2020	0.048	0.211	0.163	10866.67
Meulaboh	1988-2004	0.130	0.057	-0.073	-4562.5
	2004-2005	0.380	0.001	-0.379	-
	2005-2020	0.024	0.459	0.435	290000

In Meulaboh coastal area: the erosion was slightly high at 0.130 km² and accretion at 0.057 km² during the 1988-2004 period. The net erosion value was -0.073 km² with a -4562.5 m²/year growth rate. Erosion occurred almost along the coast of Meulaboh. It did not apply to spits that grew lengthwise over time. In the 2004-2005 period, erosion occurred almost along Meulaboh coast, the same thing as the period 1988-2004. the erosion reached 0.380 km², and the erosion was 0.001 km². The net erosion value was -0.379 km². However, this erosion was caused by the 2004 tsunami. The straight beach sand was washed backward by the tsunami waves. For the 2005-2020 period, the erosion value was at 0.024 km², and a high accretion value was at 0.459 km². Although the tsunami hit the Meulaboh coast again in 2005, 2010, and 2012, the recovery process for the Meulaboh coast was rapid. The net value knows of growth reached 0.435 km². Likewise, the spit was extended and widened every year.

4.3 The Evolution of Coastal Morphology

The December 2004 tsunami was very destructive along the studied coast. In Banda Aceh, the morphological features of the coast were occupied by cliff headlands, estuarine, lagoons, barriers, and wetlands. On the eastern coast of Banda Aceh, the Pande lagoon was separated from the open sea by the land barrier, keeping connection with the seawater only by a narrow tidal inlet near the Krueng River Mouth. The Krueng Aceh River separated the beach barrier system in Krueng Raya Estuary and Pande Village. Mangroves and fish ponds were lying behind the sheltered areas of beach ridges in Pande Village.

After the 2004 tsunami, the land barrier and Ulee Lheue Harbor were destroyed, as the mangroves and fish ponds were behind it. Fifteen years of morphology observation (2005-2020), with the satellite images and the 2017 base map produced by the Indonesian government, established the recovery or development stages of the coastal lagoon in the eastern of Banda Aceh. The land barrier was breached, and the maximum landward extent of erosion was measured at 1 km. The beach recovery at the Pande Village had not been rebuilt through the natural deposition process and was partially replaced by the seawall as human intervention in 2009. Consequently, the wetlands were deposited with large amounts of sediment due to the effects of the construction that year. Furthermore, the narrow tidal inlet at the Krueng Aceh River mouth returns the only natural connection for seawater to the lagoon (Syamsidik et al., 2017) and the anthropogenic connection in the seawall (Fig. 8).

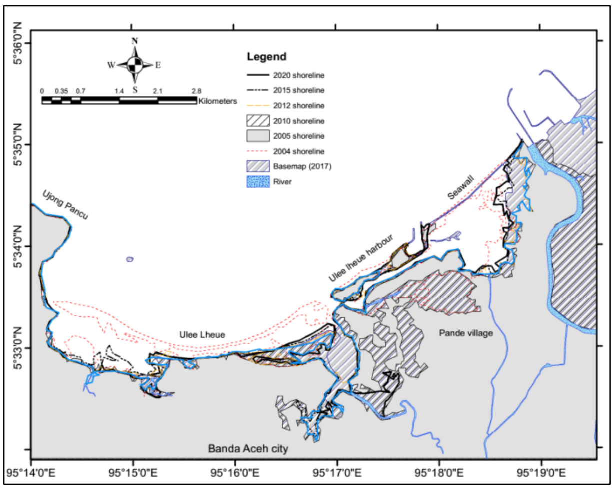

Fig 8. The shoreline and coastal morphological changes during 2004-2020 in the Banda Aceh area.

On the western coast of Banda Aceh, during the pre-tsunami event, the barrier beach system still existed. The mangroves and fish ponds existed behind the barrier beach, as shown in satellite images from 1988 to 2004. The coastal morphological changes in Banda Aceh have been discussed by Paris et al., (2009), Liew et al., (2010), Griffin, et al., (2013), and Syamsidik et al., (2017). The barrier land was destroyed after the 2004 tsunami. At the Krueng Raya Estuary, a sand barrier was rebuilt more than six years after the tsunami, with an accuracy of 343 m measured from January 2005 to April 2010. After fifteen years of the tsunami, the accretion was measured from 175 - 472 m. It had not yet returned to the form as before the tsunami. Even the shoreline erosion rate was still high after 15 years of the tsunami.

The morphological landform of the Lampuuk-Lhoknga coast was occupied by a cliff, sand beaches, bayhead, and spit. The shoreline was eroded by a tsunami along the Lampuuk-Lhoknga coast, with a maximum erosion value of 132 m. At Lampuuk beach, the width of the sand beach in 2020 exceeded before the 2004 tsunami event. The shoreline recovery measured approximately 300 m from January 2005 to June 2020. Despite the passing of 13 months, the beaches have been restored to their original position, complete with new berms and low dunes closely resembling their previous geometry and form (Liew et al., 2010). In contrast, the erosion rate during the 2005-2020 measurement was still high at Lhoknga beach. The erosion was affected by natural processes (wind, wave, and longshore current) and human intervention (jetty structure at Reba River mouth and sand mining). The coast underwent a significant morphological change after the 2004 tsunami at the Reba River mouth (Fig. 9). The sandspit was severely eroded. After fifteen years, the length of the sandspit reached 260 m measured from the 2005 sandspit. The spit extended outward from the earlier shore and perfectly aligns with the longshore sediment transport direction where supply sediments were derived from the Reba River and Lhoknga beach.

The coastal morphology features of Meulaboh were occupied by the straight beach, beach ridge, and spit. Based on satellite image observation, the growth of spits aligned with the direction of longshore sediment transport. The 2004 earthquake generated a series of extreme tsunami waves on Meulaboh coast, followed by small tsunami waves in 2005, 2010, and 2012 directly. The results of the EPR calculation show the 2005 and 2010 tsunami-affected shoreline changes on the east coast of Meulaboh. In contrast, was not affected beach in the western of Meulaboh. In the western of Meulaboh, the straight beach extends in a northwest-southeast direction. During the 2004 tsunami, the tsunami removed the beach, causing small streams connected to the sea directly and partially eroding the beach, then flooding the swamps. Based on Liew et al., (2010), the beach underwent reconstruction in 2006, which resulted in blocking the small streams. Even though vegetation started to grow back on the beach, the swamps were still inundated. The 2020 shoreline had not returned to the same pre-tsunami of shoreline position. The 2020 shoreline retreated inland at around 54 m from the 2004 shoreline. Morphological changes in the eastern of Meulaboh in the form of a beach ridge and sandspit at the Suak Nihong River. The tsunami waves cut off this sandspit. The growth of the beach ridge and sandspit was proportional to the increase in years. Even the length and width of the sandspit from the 2014-2020 period exceed the 2004 sandspit (Figs. 10). It was evidence that tsunamis were inhabited by beach ridges, spit growth, and the dynamics of the natural sedimentation process.

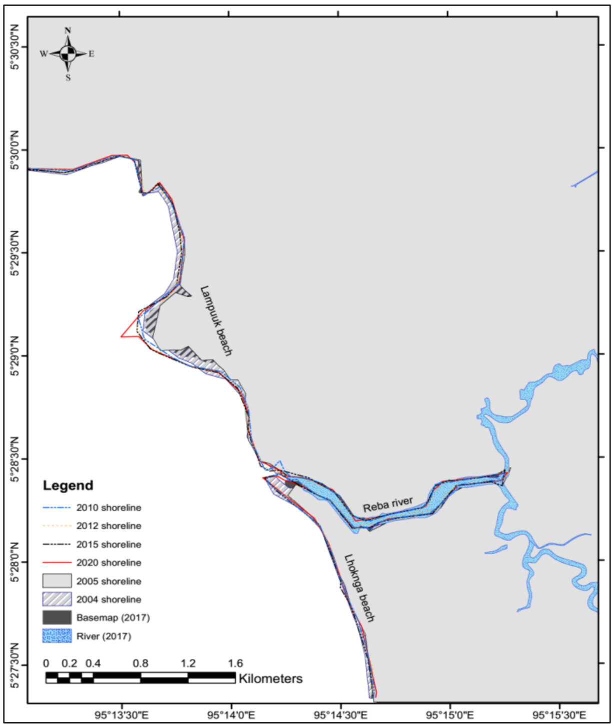

Fig 9. The shoreline and coastal morphological changes during 2004-2020 in the Lampuuk-Lhoknga area.

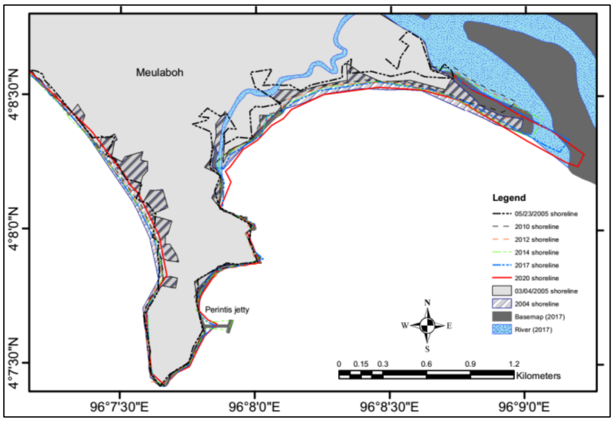

Fig 10. The shoreline and coastal morphological changes during 2004-2020 in the Meulaboh area.

4.4 Controlling Factors

The coastal morphological changes are influenced by complex interactions between natural and human-induced processes. In this study, natural processes were caused by geology and geomorphology, wave and wind climate, tidal currents, sediment transport and supply sediment, sea-level rise, subsidence, and the tremendous factor was tsunami (as a natural disaster event). In addition, the influence of human intervention in the form of artificial construction, consisting of seawalls, harbors, jetties, and fish ponds, together with recovering vegetation.

4.4.1 Coastal Geology and Geomorphology

Coastal geology and geomorphology play an essential role in developing and controlling shoreline changes. The study area encompasses a variety of coastal landform features, including estuaries, lagoons, sand barriers, beaches, wetlands, spits, headlands, and bays, all of which contribute significantly to shoreline changes. In Banda Aceh, the narrow continental shelf and steep offshore gradient have caused the deposition of eroded sediments offshore, which are challenging to remobilize (Melinda et al., 2010). Typically, the coastal areas encroached upon up to a distance of 1 km inland have low-lying topography, usually between -0.5 to 1 m above the mean sea level (Rasyif et al., 2019). Hence, the tsunami waves sweep far into the mainland of Banda Aceh. On the Lampuuk-Lhoknga coast, the coast was categorized as sandy beaches with a gentle slope. The study site consists of a cliff, sand beach, and river mouth. On the coast of Meulaboh, on the west part was a sandy beach with swales and other vegetation behind it, while in the eastern part, there was a sand beach and a spit bordered by a river mouth. The topography of the Meulaboh coast had a gentle slope, which causes the height and speed of the tsunami to increase.

4.4.2 Natural Causes

The tsunami event was one of the factors that cause changes in shoreline and coastal morphology. Tsunami waves had the capacity to change coastal morphology instantly, which can be categorized as temporary or long-term loss of land. As happened in the Aceh province, the Banda Aceh coastal area was included in coastal morphological damage for the long term. In contrast, the Lampuuk-Lhoknga and Meulaboh coast recovered quickly after the 2004 tsunami, and even the Meulaboh coast was hit again by tsunamis in 2005, 2010, and 2012, which were much smaller than the 2004 tsunami.

Natural processes and climatic conditions control the coastal development and recovery process. The natural and climatic processes were responsible for shoreline changes, erosion and accretion, and sediment transport. Climate, wave, and wind: littoral transport played a significant role in developing shoreline features like spits and bars and was causing considerable coastal erosion and accretion (King, 1972). Indonesia lies on the equator, where a typical monsoonal climate occurs. The monsoon climate is divided into the southwest (SW) monsoon that moves from SW to NE and the Northeast (NE) from north and NE to SW. During the SW monsoon, the direction of the current movement is dominated in the east of Banda Aceh, while on the north coast of Banda Aceh, it had little impact. Hence, the sediments on the Banda Aceh coast were only transported offshore, with slow energy of current movement. It caused the coastal morphological recovery on Banda Aceh coast to be relatively slow. The coast was not the recipient of the sediment discharge from the Krueng Aceh River, the main river in Banda Aceh (Meilianda et al. 2010). The Ulee Lheue coast was suitable as an example of slow post-tsunami recovery and high erosion rates. On the Lampuuk-

Lhoknga coast, the littoral longshore current from the southwest-northeast was following the coast during the SW monsoon. It could be evidenced by the spit extending straight to the northwest and the headland of the bay forming to the north; with the intense energy current from the sea and the Reba River, the sedimentation was faster than on the Banda Aceh coast. It was supported by Griffin et al., (2013) who stated the same description. While on the southern coast, the Lhoknga beach still experienced slight erosion during the non-tsunamigenic event. On the Meulaboh coast, the movement of sea waves was dominated by the SW monsoon; therefore, the sea waves lead to the coastal land, and it changed to the longshore current that moves towards the southeast to form a straight spit that grows every year. It was also influenced by sediment supply from the Suak Nihong River. The littoral sedimentation was controlled by marine hydrodynamics described by Stanica and Ungureanu (2010).

According to the Intergovernmental Panel on Climate Change (IPCC, 2007), the sea-level rise in Indonesian waters may increase to 0.2 - 0.6 cm/year. The subsiding of Ujong Pancu by about 2 cm/year due to tectonic activities worsens the situation (McKinnon, 2013). This rise in sea levels, caused by climate change, can gradually change the shape of the coast due to insufficient sediment transport capacity. It may cause the cost to remain non-equilibrium (Monecke et al., 2017). An earthquake can cause subsidence, the downward vertical movement of the Earth's surface. The 2004 tsunami caused subsidence on the coast of Banda Aceh, measured at 4.6 cm along the west coast of Banda Aceh and 17.2 cm in Lhoknga Bay (Subarya et al., 2006; Griffin et al., 2013). As a result, subsidence worsens erosion and land loss, but it does not fully explain the erosion and recovery patterns observed in the study locations.

4.4.3 Human Interventions and Anthropogenic Structures

Human intervention in shoreline changes occurred in research locations before the 2004 tsunami, especially on the Banda Aceh coast. Banda Aceh's shoreline was modified by several artificial structures like the Ulee Lheue harbor, fish and shrimp ponds, water breakers, and sea walls. The jetty and sand mining were rebuilt on the Lhoknga beach and then the constructed Perintis harbor was on the Meulaboh coast. The artificial structure certainly disturbs sediment transport. The entire artificial structures were destroyed after the 2004 tsunami. Even the mangroves were not strong enough to withstand the tsunami waves.

Post-2004 tsunami, Ulee Lheue Harbor was rebuilt as soon as possible after the 2004 tsunami. Because the harbor was the leading marine transportation, the Lampudo port, sea wall, and floodway jetty construction on the eastern coast of Banda Aceh were rebuilt in 2009 to protect the mainland from sea waves. However, the consequence of the construction of the artificial structure was to interfere with natural longshore currents, sediment budgets, or sediment transport, resulting in an increased erosion rate. In the wetland, sediment accumulates in each subsequent year.

The Reba River mouth had rebuilt the jetty. The construction of this jetty played an essential role in erosion and accretion on the Lampuuk and Lhoknga beaches. The Reba River was the separator between Lampuuk and Lhoknga beach. The longshore current was from southeast to southwest direction. Therefore, the distribution of natural sediment by longshore currents leads to Lampuuk beach as an updrift sector, while the natural longshore current was blocked in Lhoknga beach to cause sediment starvation in a downdrift sector. The sand mining industry also influenced shoreline erosion.

In Ujong Pancu, there were no plants and fish ponds left after the 2004 tsunami. For several years, the shoreline has been restored through the construction of revetments and fish ponds with an area of approximately 0.2 km^2 (Syamsidik et al., 2015). The planting of coastal mangroves and fish ponds for the Ujong Pancu and Ulee Lheue coast was rebuilt in 2009 by NGOs and local people. Likewise, at Lampuuk Beach, mangrove or Casuarina vegetation was carried out in the same year.

The artificial construction impacted erosion phenomena in some coastal areas. In recent years, the implementation of the soft structure has been carried out because it has proven to be more effective and has a positive impact. Soft structural options reduce the impact of waves by emulating natural processes and preserving the picturesque beauty of the coast. These options include beach nourishment, dune construction, revegetation, and other methods that do not necessitate physical structures. This method can be applied at the study locations to reduce the impact of hard structures.

6. Conclusion

The DSAS analysis has calculated the distance of the shoreline shift after the 2004 Indian Ocean tsunami. The shoreline change in the 2004-2005 period generally shows a significant land loss caused by the 2004 tsunami for the entire Banda Aceh coastal area. Furthermore, the NSM value for the period 2004-2020 reveals that the recovery of the 2020 shoreline position has not returned to the 2004 shoreline position before the tsunami. The shoreline change analysis for the 2004-2020 period showed that statistical accretion was detected along 20.86% of the Lampuuk-Lhoknga coast, while 79.14% of transects exhibited statistically significant erosion. In Meulaboh, the shoreline shift for the 2004-2020 period is generally towards the sea but tends to move towards land on the west coast.

The calculation of the EPR value aims to determine shoreline changes that are tsunamigenic events and non-tsunamigenic events. In Banda Aceh, the average EPR value in the two calculation periods (the period March 2005-June 2005 and March 2012-April 2012) is positive (accretion) while the period October 2009-April 2010 is negative (erosion). Nevertheless, it was not the result of the tsunami but because of the construction of a sea wall on the east coast of Pande village. On the Lampuuk and Lhoknga beaches, there is a possibility of the 2010 and 2012 tsunami effects, with the average EPR value showing a negative value almost along the shoreline. Unlike the other two research sites, 2005, 2010, and 2012 tsunamis occurred in Meulaboh. As a result, the average value of EPR shows erosion in 2005 and 2010, but not in 2012. It is probably due to the small tsunami waves producing negligible erosion in the short term.

The erosion for 1988-2004 was more significant than the accretion in Banda Aceh and Meulaboh. In Lampuuk-Lhoknga, the erosion was lower than the accretion. The erosion for the 2004-2005 period in each study area was undoubtedly primarily due to the 2004 tsunami. The recovery after the 2004 Indian Ocean tsunami is seen in the 2005-2020 period. The accretion value is greater than the erosion value in each study area. In Banda Aceh, the net growth rate was 3.96 km2, with a 263,333.3 m2/year growth rate. Pande and Ulee Lehue villages in the east were the areas with the fastest recovery because there was human intervention in constructing sea walls and ports in Pande Village. Ulee Lehue and Ujong Pancu tend to have a slow recovery. The recovery process from 2005-2020 at Lampuuk Beach is more significant than the Lhoknga beach, with 10,866.67 m2/year, and the latter still experienced erosion in several places. The recovery and development along the Meulaboh coast are very rapid, with a growth rate of 290,000 m2/year as evidenced by the development of annual growth of spit features on the east coast of Meulaboh. The observations were made using satellite image data after fifteen years (2005-

2020), with the satellite images and the 2017 base map produced by the Indonesian government establishing the recovery or development stages of the coastal lagoon in the eastern part of Banda Aceh. The land barrier was breached, and the maximum landwards extent of erosion was measured at 1 km. In 2009, the beach recovery at the Pande Village was rebuilt through the natural deposition process and is now partially replaced by the seawall as human intervention. Consequently, the wetlands were deposited with large amounts of sediment due to the effects of the construction. Furthermore, the narrow tidal inlet at the Krueng Aceh River mouth returns the only natural connection for seawater to the lagoon and others in the seawall. After fifteen years of the tsunami, the accretion was measured from 175 - 472 m. It has not yet returned to the form as before the tsunami. During the evolution of the Lampuuk-Lhoknga coast from 2005-2020, the Lampuk beach underwent a recovery with accretion reaching around 300 m. In comparison, the Lhoknga beach is still experiencing apparent erosion due to natural processes and the sand mining industry around the beach. Then the spit at the Reba River mouth was reshaped after being destroyed by the 2004 tsunami. The spit extends outward from the earlier shore and is perfectly aligned with the direction of longshore sediment transport. In the eastern part of Meulaboh, the evolution of the beach ridge and sand spit is growing each year from 2014-2020. The rapid growth of the spit landform started in 2014 because there was no longer any influence from the tsunami that occurred.

Banda Aceh's shoreline is modified by several artificial structures like the Ulee Lheue harbour, fish and shrimp ponds, water breaker, and sea walls. The jetty at the Reba River mouth and sand mining is also rebuilt on the Lhoknga beach, and then constructing a Perintis harbour on the Meulaboh coast. Furthermore, the Lampudo port, sea wall, and floodway jetty construction on the eastern coast of Banda Aceh were rebuilt in 2009 to protect the mainland from sea waves. The Reba River mouth has rebuilt the jetty. The construction of this jetty plays an essential role in the erosion and accretion on the Lampuuk and Lhoknga beaches. The construction of hard structures causes erosion phenomena in some coastal areas. The soft structure method has been implemented in recent years because it has proven to be more effective.

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