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Sea Surface Temperature and Sea Level Rise Impact on Coastal Dynamics in Makassar, South Sulawesi, Indonesia

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***Abstract*— Makassar City in South Sulawesi (Indonesia) is located at a low elevation of about 0-25 meters, while the coastal area is only 1-5 meters above sea level and is composed of alluvial deposits. The western boundary is directly adjacent to the Makassar Strait. These conditions make Makassar City highly vulnerable to the impacts of ocean dynamics and coastline changes caused by erosion or sedimentation, posing significant threats to infrastructure and livelihoods. This study aims to quantify sea-level changes that potentially cause coastal disasters in Makassar by detecting temporal variations in sea surface temperature (SST) and coastline changes. This study utilized remote sensing technology from AQUA MODIS, Landsat 7 ETM+, and Landsat 8 OLI/TIRS. The in-situ sea temperature measurements were conducted using a conductivity-temperature-depth (CTD) hydrographic device. In addition, the coastline verification was performed using a traverse of a global positioning system (GPS) device. Image processing was done using the SST extraction and band ratio methods to detect sea surface temperatures and coastlines, respectively. According to the AQUA MODIS data, the maximum SST increased from 28.84°C to 30.69°C from 2004 to 2024 with the highest temperature occured in 2024. The increase of SST agreed to the increase of sea level and coastlines. The evidence of the coastline changes presented by sedimentation and erosion is about 3.47 hectares and 32.89 hectares, respectively. The geological factors that play a role in coastal sedimentation and erosion originate from river sedimentation supply and increased sea level.**

Keywords— SST, Landsat, coastline, sea-level rise, remote sensing, hazard mitigation

I. INTRODUCTION

As global temperatures rise, melting glaciers and the thermal expansion of seawater cause a continuous rise in sea level, which poses serious risks to lowland island nations, including coastal erosion, flooding, and saltwater intrusion into inland areas. This immediate threat not only endangers the safety of the population and the integrity of the ecosystem but also adversely affects infrastructure, housing, the national economy, and social progress [1] [2].

During the period 1993–2002, the sea level rise in the Makassar Strait reached 7.5 cm, while based on simulations, it is estimated that the sea level rise in Makassar will reach 88.16 cm in 2025, 1.14 m in 2050, and 1.44 m in 2100 [3]. This condition exceeds the estimated global sea rise of 1.5 mm/year. Moreover, Makassar City is a lowland region that is located at an altitude between 0-25 meters above sea level. The western area directly adjacent to the sea is about 1 to 5 meters above sea level, while the eastern and northern parts are about 6 to 25 meters above sea level. Because of this natural condition, Makassar City often experiences flooding during the rainy season, especially when it rains along with the rising tide. For example, on February 13, 2023, the flood that hit parts of Makassar City was triggered by sea waves that had risen 4 meters because of water flow from settlements meeting sea tides [4].

Rising sea levels potentially flood the coastal region of the northern region. The potential flooded area are about 76.82 hectares in 2025, and increase to 681.05 hectares in 2075, including industrial areas, open land, mangrove forests, ports, and educational areas. Furthermore, settlements, reclaimed areas, wilderness, weirs, and even agricultural areas could also be affected in 2100 [5]. Moreover, the erosion that occurred at the Monument on Layar Putih Beach and sediment that resulted from abrasion that was transported by currents and sea waves towards Losari Beach generated a sedimentation process in the area are clear physical evidence of impacts manifested by sea level rise [6].

Observations from the 20th century show that the world's coastlines have been eroded and it is still unclear if this is because of more local factors or sea level rise linked to climate change [7] However, it is projected that the rising sea level caused by ongoing global warming will render many low-lying and heavily populated coastal locations increasingly susceptible in the coming decades [8]. Likely, the rising sea level will soon become a significant threat to a sizable portion of the human population [9]. Therefore, this study was conducted on temporal changes in sea surface temperature to determine the relationship between climate change and sea level rise by analyzing changes in sea surface

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temperature as an object affected by climate change in Makassar City. In addition, sea level rise is associated with stronger storms and unpredictable precipitation patterns, increasing the vulnerability of coastal areas [10]. Therefore, this study also analyzed temporal coastline changes to determine the types of changes that occur and the geological factors that influence them. The results of the analysis of coastline changes were expected to be a reference for researchers and the community in raising awareness of the negative impacts of upcoming climate change. They could be used as a basis for land use management and future mitigation of the coastal areas.

Remote sensing and geographic information systems, including sea surface temperature as crucial input data for coastal research, are becoming feasible and appealing for application in coastal ecosystem studies and management due to technological advancements and cost reductions [11]. One of the common applications of remote sensing technology is monitoring sea surface temperature (SST) using the Aqua MODIS satellite. This satellite is capable of providing SST data at wavelengths of approximately 4 and 11 μm under cloud-free conditions, offering broader temporal and spatial coverage [12] and high sensitivity [13]. In the context of Makassar City, the SST AQUA MODIS data were used to detect changes in ocean temperature over time, which is crucial for analyzing the long-term impacts of climate change in coastal areas. Previous studies detect coastline changes using satellite imagery data from Landsat 7 ETM+ and Landsat 8 OLI/TIRS.that have been conducted in various regions around the world [14], [15], [16], [17], [18], [19].

II. METHOD

A. Location

Makassar City has a total area of about 175.77 km² divided into 15 sub-districts. The city's geographic coordinates are 119°18'27,97"-119°32'31,03" East Longitude and 5°00'30,18"-5°14'6,49" South latitude. Makassar is the capital of the Indonesian province of South Sulawesi. The city is located on the southwest coast of Sulawesi Island (Figure 1), facing the Makassar Strait. It is known as the Waterfront City, with three rivers flowing into the sea termed as Tallo, Jeneberang, and Pampang Rivers. Makassar City is the gateway to Eastern Indonesia and the intersection between West and East Indonesia, Australia and Asia.

There are two types of rock formations in Makassar City: Camba Volcanic and Alluvium Deposit. The Camba Formation consists of marine sedimentary rocks mixed with volcanic rocks, and the alluvial deposit is a mixture of unconsolidated gravel, sand, clay, mud, coral, and limestone [20]. These alluvial deposits include present-day coastal, river, and swamp deposits along Makassar City's coast, which are significantly influenced by the marine dynamics along the coast.

B. Sea Surface Temperature (SST) Data

The Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA Earth Observing System satellites Terra and Aqua includes a 36-band sensor that spans the spectral range from 0.4 to 14.4μm, as well as two with wavelengths centered at 10.8 μm and 12.0 μm, the classic "split window" pair that can be used to extract SST (https://oceancolor.gsfc.nasa.gov).

This paper focuses on the Aqua MODIS SST products, which have a viewing swath width of 2,330 km and image 21 of the earth (https://oceancolor.gsfc.nasa.gov). Daily and yearly SST data are derived from the Aqua MODIS level 3 Standard Map Image, collected from 2003-2024 to study SST variability in the study area. Table 1 summarizes the information for SST Images from AQUA MODIS data used in this study.

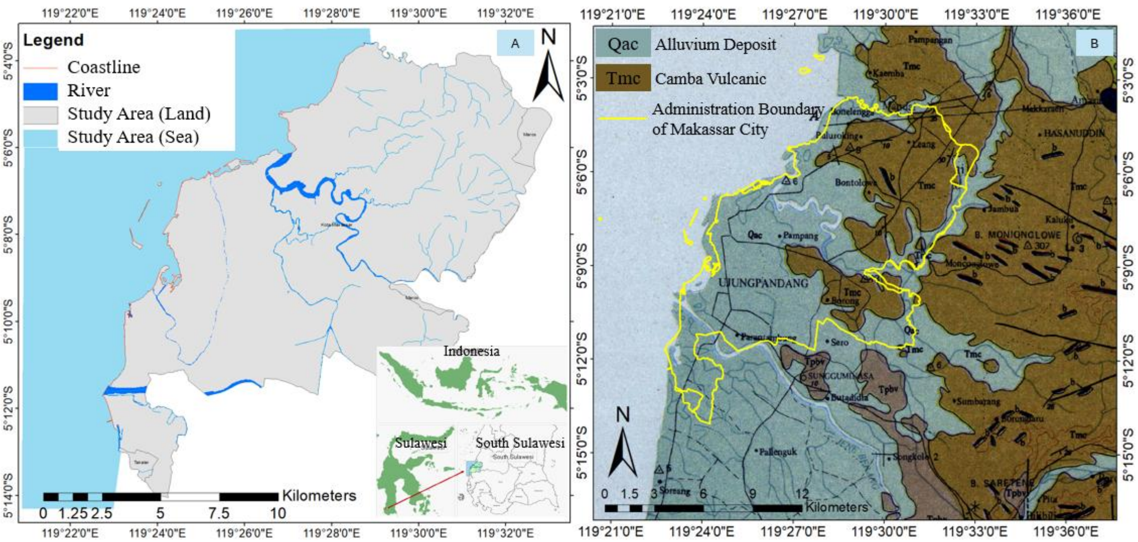

Figure 1. The study area presented by the blue (sea) and the grey (land) areas is located in Makassar City (South Sulawesi), enhanced with inset maps offering a regional perspective of Sulawesi, Indonesia (A) and geological maps depicting the research location, particularly in the coastline area, which is mostly formed by alluvium deposits.

TABLE 1.
SST IN THE STUDY AREA BASED ON AQUA MODIS IMAGES.

Data Description	Time of Satellite Image			Quality of Image
	Year	Month	Date	
Satellite: AQUA MODIS Data Type: SST Level 3 Orbit Orientation: Ascending Temporal Resolution: Daily Spatial Resolution: 4 km	2004	9	16	Good
	2006	9	19	Best
	2011	8	31	Best
	2014	10	20	Best
	2018	10	1	Good
	2021	9	14	Good
	2024	9	12	Good

TABLE 2.
DETAILS OF LANDSAT IMAGES USED IN THIS STUDY.

Sensor	Band	Path/ Row	Acquisition Date	Scene Center Time
Landsat-7 TM/ETM+	1, 2, 3, and 4	114/64	2003-05-26	01:59:20.3196982Z
Landsat-8 OLI/TIRS	2, 3, 4, and 5	114/64	2013-04-27	02:12:23.5593320Z
		114/64	2016-09-10	02:10:51.9842720Z
		114/64	2020-08-20	02:10:42.1297890Z
		114/64	2024-08-15	02:10:18.6173509Z

The in-situ SST measurements for validation purposes were conducted in mid-September 2024, which was included in the dry season in Indonesia, concordance to the images from the same month were selected to analyze ten years from 2004 to 2024. In addition, the available data qualities are divided into five types: no data, bad, questionable, good, and best. Only those of best and good qualities are analyzed to obtain high quality data. Therefore, the selection of the year and month was also based on the availability of data with these qualities, considering that August, September, and October fall into the dry season.

C. Landsat Data

In this study, the coastline changes were detected using Landsat 7 TM/ETM+ satellite imaging data and Landsat 8 OLI/TIRS data downloaded from the USGS Data Center (http://earthexplorer.usgs.gov, accessed June 11, 2024). These images were acquired during the dry season with less than 10% cloud cover. Table 2 provides a complete list of the Landsat images used in this study. Landsat 7 ETM+ and Landsat 8 OLI/TIRS satellite data were used to analyze changes in the coastline in Makassar City from 2003 to 2024. Before analysis, the multispectral images were radiometrically and atmospherically corrected. These corrections reduce the influence of haze, other atmospheric scattering particles, and sensor anomalies [21], [22], [23].

D. Detecting and Field Verification of SST Changes

The SST data from AQUA MODIS acquired between 2004 and 2024 were used to analyze changes in sea temperature in the study area. The data was downloaded through the Ocean Color website and processed using SeaDAS software developed by NASA. SeaDAS is a comprehensive software package for processing, displaying, analyzing, and quality controlling remote-sensing Earth data (https://seadas.gsfc.nasa.gov/about/). The data extraction process was carried out to produce a map of SST distribution with a spatial resolution of 4 km. The results of this temperature maps provide information about the temporal and spatial variations in ocean temperatures that occurred over 10 years. The resulting maps were then compared to identify patterns of changes in ocean temperature at the research site. Figure 2 shows the methodological process applied to SST change analysis using SST map Level 3 from AQUA MODIS in global and regional.

Sea temperature verification using the CTD (Conductivity, Temperature, Depth) tool is widely used in marine research to measure sea temperature directly [24], [25], [26], [27]. Using the CTD, sea temperature measurements are carried out from the surface to a depth of 20 meters according to the specified coordinate points (Figure 3A). The data obtained from the CTD tool can be used to verify sea surface temperature (SST) data obtained from satellites, such as AQUA MODIS, to ensure the accuracy of the results obtained from satellite imagery [18].

In this study, the CTD tool was used to measure sea temperature at the research site along the coast of Makassar City. Temperature measurement points are carried out randomly but representative of the research area to obtain data that includes variations in ocean temperature at a certain depth. The data obtained were then compared with SST data from AQUA MODIS taken simultaneously (Figure 3B). This verification process is important to ensure that satellite data, despite having a wide range of space, can reflect accurate ocean temperature conditions and match the reality on the ground. SST MODIS also shows the importance of field verification [28] using CTD tools to ensure the accuracy of ocean temperature measurements from satellite images [29]. The correlation between the SST AQUA MODIS data and the sea temperature measurement from the CTD device was carried out to see how strong the relationship between the two was. One of the parameters used to measure this relationship is the determination coefficient R^2 which indicates the extent to which satellite data models can explain the variability of ocean temperatures in the field [30]. If the R^2 is greater than 0.8, it indicates a model with a good fit for many practical applications [31].

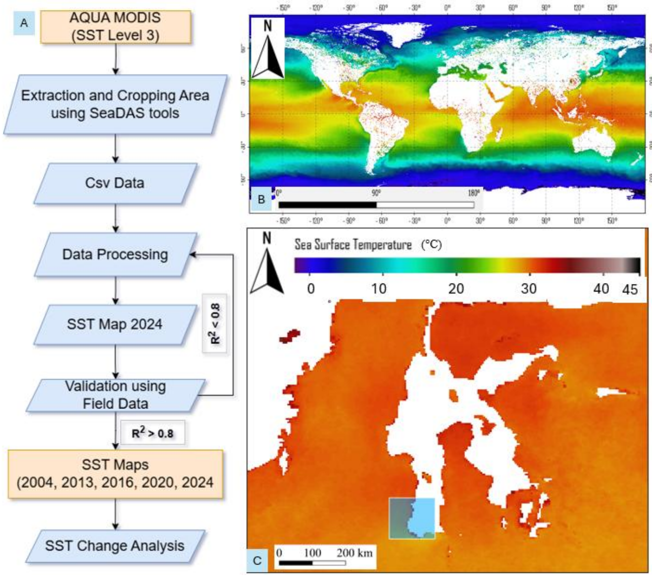

Figure 2. The methodological process applied to SST change analysis from AQUA MODIS (A) in global (B) and regional view (C).

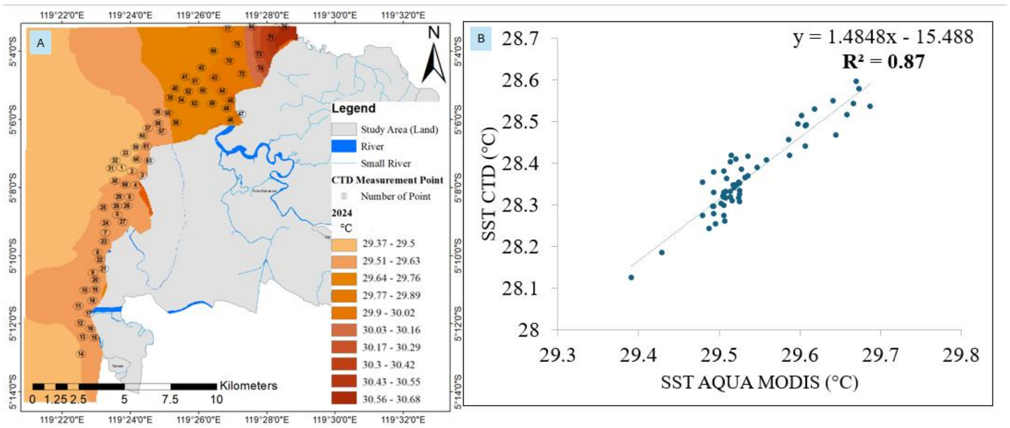

Figure 3. The map of the measured SST using CTD (A) and the correlation with SST from AQUA MODIS shows a R^2 of 0.87 (B).

This highlights the importance of a high R^2 as a key indicator of the reliability and accuracy of satellite-derived SST data in representing actual sea temperature conditions measured in the field.

E. Detecting and Field Verification of Coastline Changes

Coastline detection using the Landsat 7 ETM+ and Landsat 8 OLI/TIRS data were processed using two indices: Modified Normalized Difference Water Index (MNDWI) and Normalized Difference Vegetation Index (NDVI). The MNDWI was developed as a development or modification of the NDWI to overcome the limitations of NDWI in detecting and separating water features from the surrounding environment [32], [33]. The NDWI was proposed by McFeeters (1996), which uses a combination of green and near-infrared (NIR) channels to improve the contrast between water bodies and land, especially vegetation. However, NDWI has significant drawbacks, especially in areas with non-water features such as buildings, open ground, or surfaces with high reflectivity that can produce like those of water bodies, thus decreasing the accuracy of these indices under certain conditions[34], [35]. The detailed methodology and indices applied to this study are presented in Figure 4.

To overcome this weakness, [33] introduced the MNDWI by replacing the near-infrared (NIR) channel in the NDWI with a short-infrared channel (SWIR). The combination of green channels and SWIR in the MNDWI makes this index more effective in reducing the interference effects of artificial surfaces, such as roads, concrete, or other structures often found in urban or reclaimed areas [36]. The MNDWI can improve the detection of water features in complex environments, such as urban or coastal areas experiencing reclamation [37]. The MNDWI was calculated as follows:

$$MNDWI = \frac{Green - SWIR\ 1}{Green + SWIR\ 2} \tag{1}$$

The Normalized Difference Vegetation Index (NDVI) is a typical vegetation index that allows us to generate an image for evaluating relative biomass in each area [38]. To produce a more accurate coastline, coastline retrieval using the NDVI and the MNDWI indices combined using a high-resolution satellite image map from Google Earth Pro (10-meter resolution) with the same acquisition time. The map resulted after preprocessing using the NDVI and the MNDWI, presented in Figure 4. The NDVI is calculated using the comparatively high reflectance of plants in the near-infrared band (NIR) and chlorophyll absorption in red

[39]. The derived output of the NDVI approach is a single-band dataset that solely exhibits greenery. The index returns between -1 and +1, while +0.1 representing flora and near to zero representing rock and barren soil, while Negative NDVI correspond to water, snow, and clouds [40]. An increase in the positive NDVI indicates greener vegetation. NASA scientists created this method and popularized it as the Normalized Difference Vegetation Index (NDVI), which is determined by the following formula:

$$\mathrm{NDVI} = \frac{\mathrm{NIR} - \mathrm{Red}}{\mathrm{NIR} + \mathrm{Red}} \quad (2)$$

In the context of coastline analysis, the NDVI helps distinguish between land areas with vegetation and open areas such as sand or water. After the primary segmentation, the normalized differential vegetation index (NDVI) was used to distinguish vegetated and non-vegetated areas. The NDVI is more suitable for digitizing the coastline in the southern part of Makassar City, which is dominated by sandy beaches. Sand has low reflectance in the near-infrared spectrum, so the NDVI in these areas are low or near zero. Conversely, vegetation such as coastal plants that are present around the area showed higher NDVI than the surrounding non-vegetated areas, allowing for better differentiation between vegetated and non-vegetated coastal zones.

Coastline verification using Global Positioning System (GPS) is an effective method to obtain accurate spatial data regarding the position of the coastline in the field [41]. In this study, the GPS is used to acquire points along the coastline (Figure 5). Using GPS, we marked the points directly at the location being studied, ensuring that the data obtained is highly relevant to actual conditions in the field. The data obtained from the GPS is then used to validate the results of coastline detection using Landsat 7 ETM+ and Landsat 8 OLI/TIRS.

The process of collecting coastline data is carried out by tracking along the coast and plotting GPS points every 10 to 20 meters, depending on the access area. These measurements are carried out to obtain an accurate and even representation of the position of the coastline in the field. By plotting these points, we observed and measured the extent of the difference between the position of the coastline recorded in the field and the satellite image. We ensured that the detected coastline using satellite images was valid.

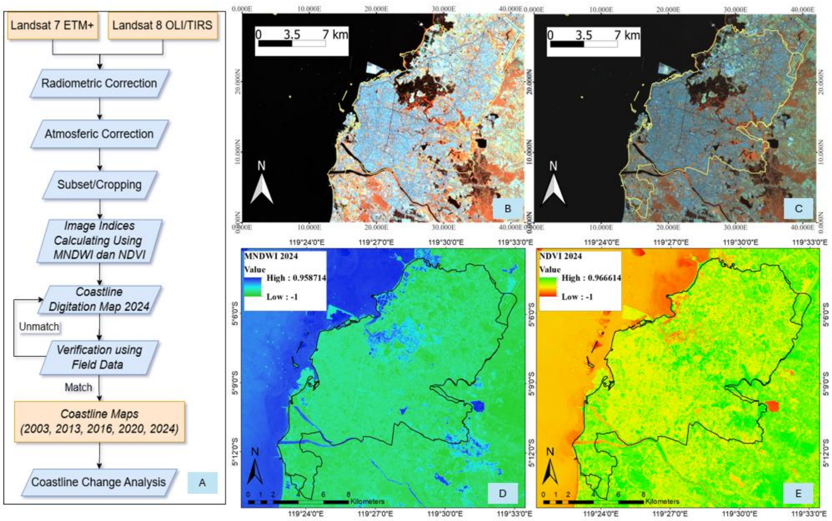

Figure 4. The workflow of the coastline changes detections (A), Landsat 7 ETM+ image acquired on August 2020 and the study area inside the yellow border (B) and after radiometric and atmospheric correction (C) shows images sharper than previously. The MNDWI shows the contrast between land and water (D), and the NDVI shows the contrast between high and low vegetation areas (E).

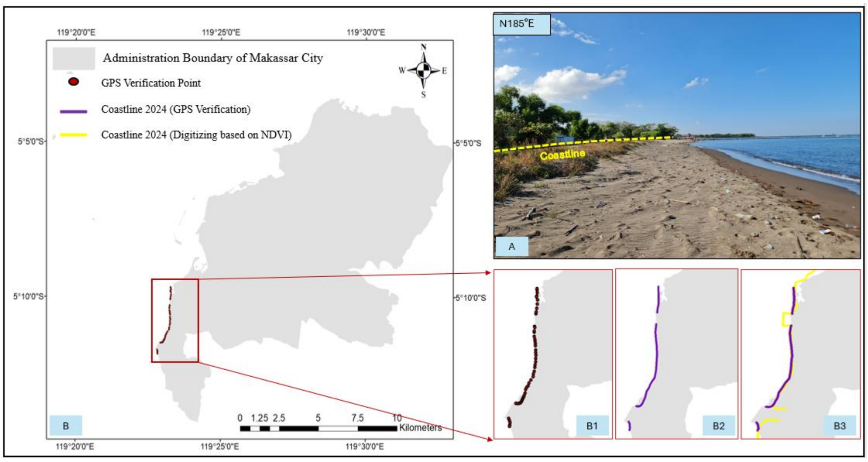

Figure 5. The image of the coastline (A) in the study area (B) verified using GPS (B1) to digitize the coastline (B2) and then overlayed with the digitized coastline based on NDVI shows that lines concordance each other (B3).

III. RESULTS AND DISCUSSION

The SST AQUA MODIS data that has been validated using in situ measurements with CTD (Conductivity, Temperature, Depth) was used to generate SST maps from 2004-2024. Therefore, based on the method used, it produced the sea surface temperature map generation on two decades as shown in figure 6. The colour represents the sea surface temperature ranging from 27.63°C – 30.68°C.

In addition, Table 2-3 presents Sea Surface Temperature (SST) based on the maps derived from MODIS AQUA satellite imagery on two decades (2004 to 2024). The data includes minimum, maximum, and average SST (in degrees Celsius) recorded on specific dates within each year.

Based on the data, in 2004, the SST exhibited an average of 28.44°C, with a minimum temperature of 28.13°C and a maximum of 28.84°C. A similar trend was observed in 2006, where the average SST slightly decreased to 28.33°C. Moreover, between 2011 and 2014, there was a slight increase in average SST, with recorded at 28.31°C in 2011 and 28.49°C in 2014.

However, in 2018, a significant decline in average SST was observed, dropping to 28.04°C. The minimum temperature for that year, 27.63°C, is the lowest recorded in the dataset. In subsequent years, particularly in 2021 and 2024, there was a notable rise in SST. In 2021, the average SST reached 29.80°C, while in 2024, it increased further to 29.57°C. The maximum temperature recorded in 2024, 30.69°C, is the highest in the dataset, highlighting intensified warming in the study area.

The graph illustrates an upward trend of Sea Surface Temperature (SST) in study area from 2004 to 2024 is shown in Figure 7. Based on the graph, In the early period (2004 to 2018), temperature changes were relatively stable, with averages ranging between 28.0°C and 28.5°C. However, starting in 2021, a sharper rise in temperature is observed, reaching over 30.69°C in 2024.

In addition, we compared the results of sea surface temperature detection using yearly average data. It shown that the sea surface temperature at Makassar Sea increased significantly from 2003 to 2024 as shown in Fig. 2-8 (A), with an initial of 28.81°C and reached 30.02°C at the end of the period. The highest temperature peak was recorded in 2022 with 30.35°C. This increasing of sea surface temperature indicates a real impact of increased concentrations of greenhouse gases in the atmosphere, which affects heat transfer from the atmosphere to the ocean in the study area [42], [43].

Furthermore, the data presented in Figure 8 (B) shows the correlation between the increasing sea surface temperature (SST) and its impact on the rise of sea levels in Makassar City. Based on the scatter plot, the coefficient of determination (R^2) shows a positive value, which is 0.52, between SST derived from Aqua Modis data and sea level rise for 2003 to 2009 in Makassar City based on previous study [44].

The correlation highlights the connection between increasing sea surface temperatures (SST) and sea level rise. Previous study presented that for every 1°C increase in sea surface temperature (SST) will rise global mean sea level by approximately 0.4 meters due to thermal expansion [45]. The sea surface temperature (SST) is a sign of hazard in the future especially for coastal ecosystems. Sea level rise (SLR) profoundly impacts coastline changes, driving erosion and sedimentation processes, intensifying inundation, displacing coastal boundaries landward, and degrading critical ecosystems like mangroves and aquaculture areas [46]. Furthermore, a study in Demak Regency highlighted that SLR contributes to significant erosion and land loss, emphasizing the urgent need for adaptive strategies to mitigate these impacts [47]. A review on monitoring coastline dynamics highlights the effectiveness of satellite remote sensing and GIS in tracking these changes globally, providing crucial insights into SLR's role in reshaping coastlines [48].

In this study, the coastline change that has been validated using GPS (Global Positioning System) was used to digitized coastline maps from 2003-2024. We used high resolution images from google earth pro to increase the precision on digitazion using the NDVI and the MNDWI indices as shown in figure 9.

An examination of coastline change analysis reveals that certain regions along the coast of Makassar City have experienced substantial deposition and erosion for two decades, from 2003 to 2024 (Figure 10). In this study area, coastline changes from 2003 to 2024 show the dominance of the coastal erosion process, covering an area of 32.89 hectares compared to coastal sedimentation of 3.47 hectares. This evidence demonstrates the widespread impact of sea wave erosion exacerbated by rising sea levels, a major driver of coastline retreat in various regions.

The coastal erosion identified in this study reveals the influence of ocean waves on relatively less consolidated coastal sediments. Wave erosion in alluvium material indicates the vulnerability of beaches to higher wave activity, especially during the westerly wind season. Similarly, studies in the Baltic Sea region have shown that strong winds and storm surges contribute to rapid coastal erosion, highlighting the susceptibility of alluvial coasts to such dynamic conditions [49], [50].

On the other hand, the process of sedimentation that covers a smaller area than erosion is influenced by the existence of the Jeneberang River as the primary source of sedimentary materials (See Figure 11 A). The sediment flows carried by these rivers accumulate in coastal areas (Figure 11 B), forming new landmasses (Figure 11 C) that can be observed through Landsat satellite imagery (Figure 12). The sedimentation dynamics in the Jeneberang watershed indicate ongoing natural processes, with variations over the years due to changes in river discharge and human activities.

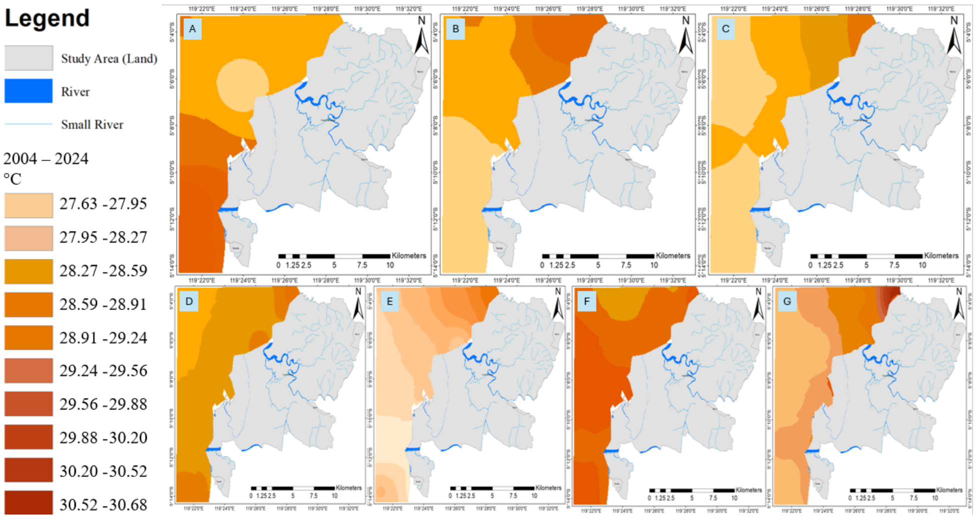

Figure 6. The SST image after preprocessing shows temperature changes in the study area in 2004 (A), 2006 (B), 2011 (C), 2014 (D), 2018 (E), 2021 (F), 2024 (G).

TABLE 3.
SST IN THE STUDY AREA BASED ON AQUA MODIS IMAGES.

Time of Satellite Image			Temperature (°C)		
Year	Month	Date	Minimum	Maximum	Average
2004	9	16	28.13	28.84	28.44
2006	9	19	28.15	28.63	28.33
2011	8	31	28.13	28.71	28.31
2014	10	20	28.31	28.80	28.49
2018	10	1	27.63	28.87	28.04
2021	9	14	29.64	29.91	29.80
2024	9	12	29.37	30.69	29.57

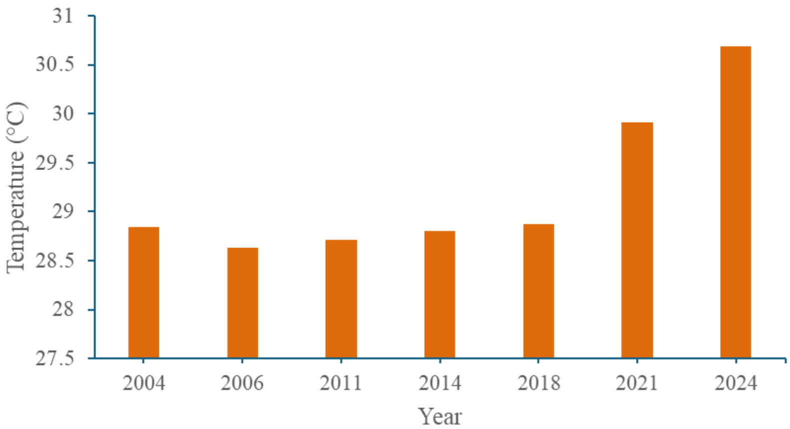

Figure 7. The average of SST in the study area using MODIS data show an upward trend in temperature on two decades.

GIS-based modelling in the Bili-Bili reservoir area within the Jeneberang basin emphasized the role of land use in sedimentation, reported that changes in land cover significantly affect sediment yield [51]. The result demonstrated significant erosion and sedimentation rates up to 717.48 tons/ha/year and 71.97 tons/ha/year respectively. highlighting the impact of land use on sediment dynamics [52]. Moreover, conservation efforts in the Mount Bawakaraeng area, part of the Jeneberang watershed, have been highlighted as crucial in mitigating erosion and sedimentation, indicating the importance of sustainable land management practices [53].

Geological factors play an important role in coastal deposition in the research area, especially the sedimentation process of materials carried by the Jeneberang River. The supply of sediment from the Jeneberang River is based on the river discharge ranges from 238.8 - 1.152 m3/second (annual average discharge of 33.05 m3/second) with a sludge level of 25-200 g/liter. However, the landslide on caldera Mt. Bawakaraeng in 2004 as presented by Figure 11 (D) increased the sediment supply to the Jeneberang River by 45,027,954 m3, with a total sediment flow volume from 2014 to 2018 of 65,652,098 m^3 [6].

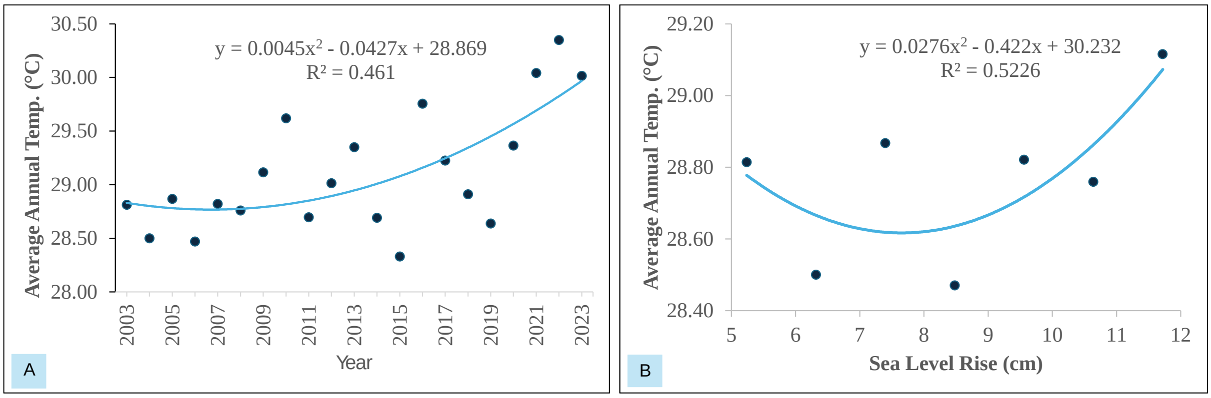

Figure 8. The sea surface temperature (SST) data from 2003 to 2023 obtained from Aqua MODIS shows an upward trend on two decades (A). The scatter plot comparing SST based on Aqua MODIS and sea level rise data based on Hidayat (2012) for the period of 2003 to 2009 in Makassar City demonstrates a coefficient of determination (R^2) of 0.52 when using a quadratic polynomial model (B).

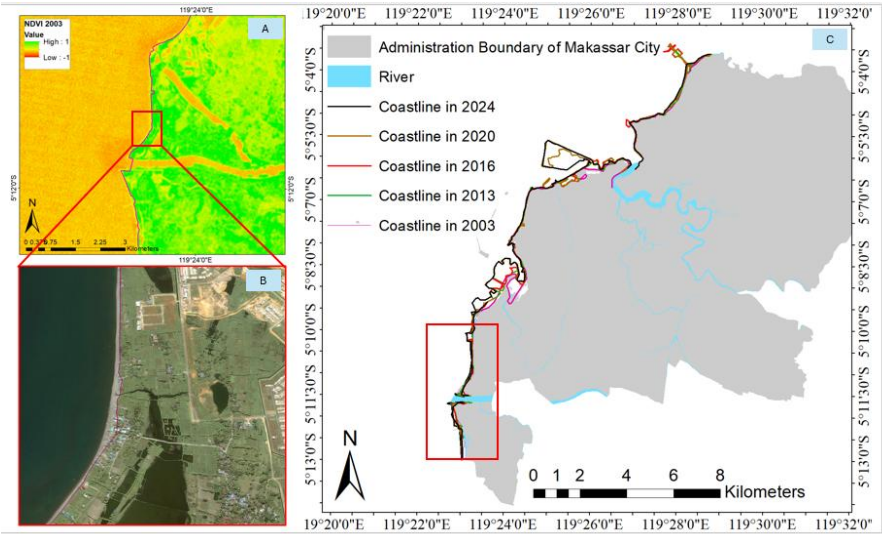

Figure 9. The coastline detection using NDVI (A) combined with a 10-meter resolution image from Google Earth Pro in 2003 shows very clear coastline boundaries (B) and detected coastlines from 2003 to 2024 (C).

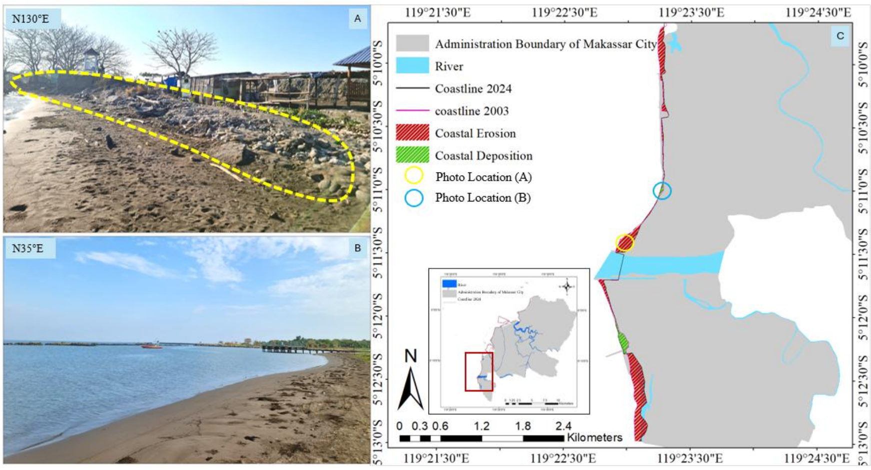

Figure 10. Photographs of coastal erosion (A) and coastal deposition (B) show that the influence of factors at the coastline changed from 2003 to 2024 in the Southern Region of study area (C).

The sediment carried by the Jeneberang River, primarily comprising 73.43% sand, 18.05% silt, 7.56% gravel, and 3.47% clay, tends to settle in the river estuary due to calm wave conditions in the area, resulting in a sandy beach formation [54]. This sedimentation is facilitated by the small river discharge and low flow velocity of the Jeneberang River as shown in Figure 12, which cannot erode the deposited material effectively. Increased water discharge during the rainy season causes sediment accumulation in the estuary, blocking the flow of water to the sea and increasing the risk of flooding in the Jeneberang River estuary [54]. Activities in the river's upper reaches can affect sedimentation dynamics in coastal areas [55], [56], [57], [58].

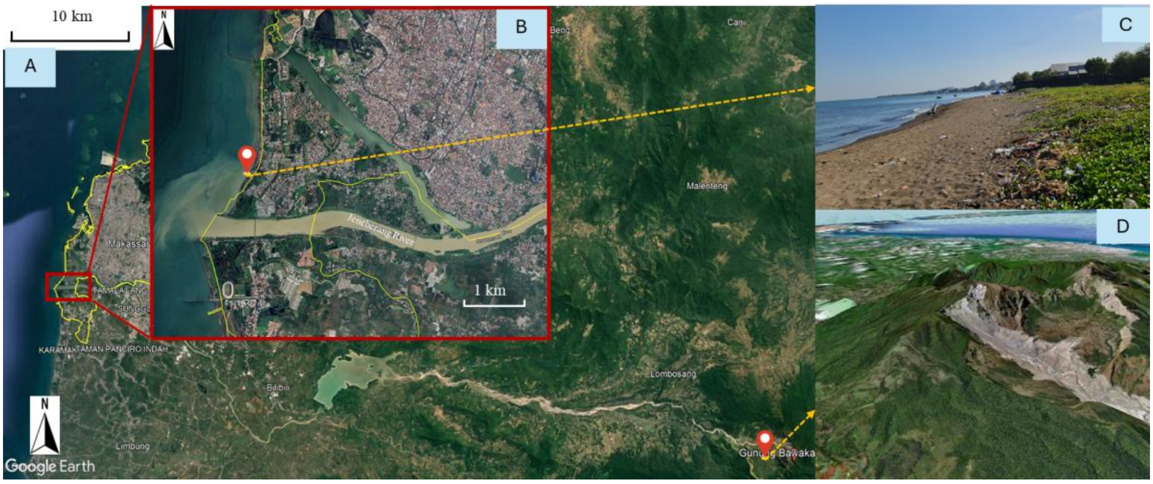

Figure 11. The study area presented by the yellow polygon of Makassar City overlaid on the Google Earth Pro image (A), subset of the Jeneberang River mouth bar (B) within the main source of sedimentary deposits in coastal areas (C), influenced by the 2004 Mount Bawakaraeng caldera landslide (D), which significantly increased sediment supply.

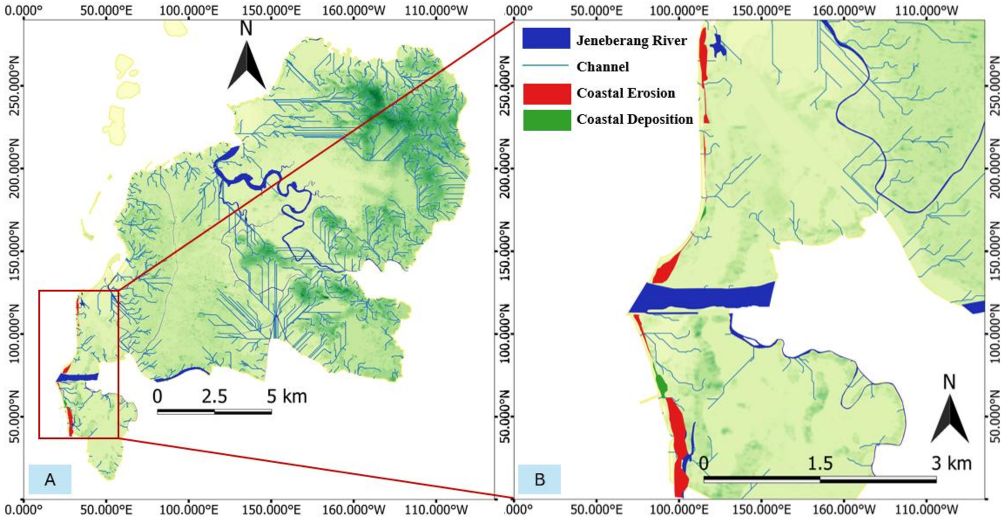

Figure 12. The river channels extracted using the digital elevation model national (DEMNAS) 9 m resolution in the study area (A) showed that the erosion role is higher than the sediment supply from river channels (B). The Jenebarang River is presented with a blue colour.

IV. Conclusion

Based on the analysis of sea surface temperature data from Aqua Modis, the maximum sea surface temperature from 2004 to 2024 increased by 1.85°C, rising from 28.84°C to 30.69°C, with the highest temperature recorded at the end of the period (2024). The increase in sea temperature and sea level rise showed a correlation coefficient (R^2) of 0.5, which subsequently influenced the wave reach, leading to coastal erosion in the study area. Changes in the coastline from 2003 to 2024 revealed that about 32.89 hectares of coastal erosion were recorded, indicating the impact of sea level rise. In addition, about 3.47 hectares of coastal sedimentation had occurred due to sediment deposition at the Jeneberang River mouth and excessive sediment supply from nearby river. Geological factors that contribute to coastal erosion include the presence of unconsolidated alluvial deposits, which make the study area more vulnerable to erosion. On the other hand, coastal deposition results from sedimentation processes, with materials originating from the collapse of Mount Bawakaraeng's caldera in 2004, leading to an increased transport of sediment downstream through the Jeneberang River.

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