Shoreline Dynamics in Makassar from 1973 to 2025: A Remote Sensing Analysis Using Landsat Imagery

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Abstract: *Coastal zones are highly dynamic environments shaped by both natural processes and significant anthropogenic influences. In rapidly urbanizing areas like Makassar, Indonesia, monitoring shoreline changes is critical for sustainable coastal management. This study aims to quantitatively analyze the long-term shoreline dynamics in Makassar through multi-temporal analysis of Landsat satellite imagery from 1973 to 2025, with a focus on estimating the extent of shoreline retreat and advancement during this period. A time series of annual median Landsat imagery was utilized to extract yearly shoreline positions, while for 2025, the analysis was based on a composite image up to August. The methodology adopted in this study relied solely on manual interpretation for the earlier shorelines (1973, 1978, and 1981). For shorelines after 1990, a semi-automatic approach was applied in combination with manual interpretation for correction. This approach involved cloud-filtered preprocessing, annual median value extraction, calculation of the Modified Normalized Difference Water Index (MNDWI), waterline extraction using Canny edge detection, and morphological processing, with manual refinement further applied to ensure the generation of accurate shoreline vectors. The Digital Shoreline Analysis System (DSAS) was used to quantify the rate of change (Linear regression rate (LRR) & End point rate (EPR)) of the Makassar shoreline. The results reveal that between 1973 and 2025, the Makassar shoreline underwent significant changes, mainly due to large-scale reclamation projects like Citraland CPI and Makassar New Port, causing shoreline advancement rates of up to 38.1 m/year and 31.7 m/year, respectively. Shoreline retreat occurred in limited areas—such as Tanjung Layar Putih, Indah Bosowa Beach, and east of the Tallo River outlet—due to coastal abrasion and disrupted sediment supply. Mangrove dynamics also influenced shoreline changes, particularly in the northeast. Overall, the Makassar coastal area gained about 617 hectares of land and lost 27 hectares in the 1973 - 2025 period. These findings provide critical, evidence-based data to support sustainable coastal planning and management strategies, highlighting the profound impact of urban development on the coastal landscape.*

Keywords: *Shoreline dynamics, remote sensing, DSAS, Landsat, Makassar*

Introduction

Coastal areas are highly vulnerable to a range of natural hazards (mostly driven by climate change), including tsunamis, storms, tidal floods, erosion, and sea-level rise. In some densely populated coastal areas with unconsolidated sediment, where groundwater extraction is excessive, the risk of land subsidence further increases these coastal vulnerabilities (Arjasakusuma et al., 2022).

Shoreline represents the transitional boundary between the mainland and the ocean, characterized by highly spatial dynamic and continuous change, influenced by tides, waves, sea-level fluctuations, sediment supply, erosion, and also anthropogenic activities (Sun et al., 2023). Based on National Reference Data for Indonesian Marine Area *(Data Rujukan Kelautan Wilayah Indonesia)*, Indonesia, as an archipelago country, has 17,504 islands and a 108,000 km long shoreline, making Indonesia the second country in the world with the longest shoreline after Canada. With 60 percent of the total population, or 150 million people, living in the coastal area (Rudiarto et al., 2018). This underscores the necessity of shoreline monitoring as an integral component of coastal planning and management strategies. Through long-term monitoring, it becomes possible to identify and mitigate risks that may pose threats to coastal communities. However, Indonesia's long shoreline also makes the monitoring a challenge to conduct.

The combination of the abundance of remote sensing data and the availability of a cloud computing platform (Google Earth Engine) could provide an efficient way to conduct shoreline change monitoring, by providing a collection of comprehensive time-series remote sensing imagery data, less time-consuming data processing, and a large regional scale of monitoring area. Integration with the Digital Shoreline Analysis System (Himmelstoss et al., 2024) could give even more comprehensive information regarding the quantitative rate of shoreline change in a certain time period. Many recent studies have demonstrated the applicability of the integration of Google Earth Engine and DSAS to provide long-term, comprehensive shoreline change observation and rate of change quantitative analysis. Surbakti (Surbakti et al., 2025) investigated long-term shoreline change in Banyuasin Estuary, South Sumatra, from 1989 to 2019 using Landsat 5,7, and 8. Arjasakusuma (Arjasakusuma et al., 2022) also integrated GEE and DSAS to identify long-term shoreline dynamics in the East Java north coastal region, from 2000 to 2019, using multisensor satellite imagery. The primary methodology used in this study involves the extraction of shorelines from annual satellite imagery using MNDWI and manual delineation for earlier year shorelines, followed by manual correction to align the extracted shorelines more closely with actual shoreline positions, and statistical analyses conducted using the Digital Shoreline Analysis System (DSAS), to estimate shoreline retreat and advancement in the 1973 - 2025 time period.

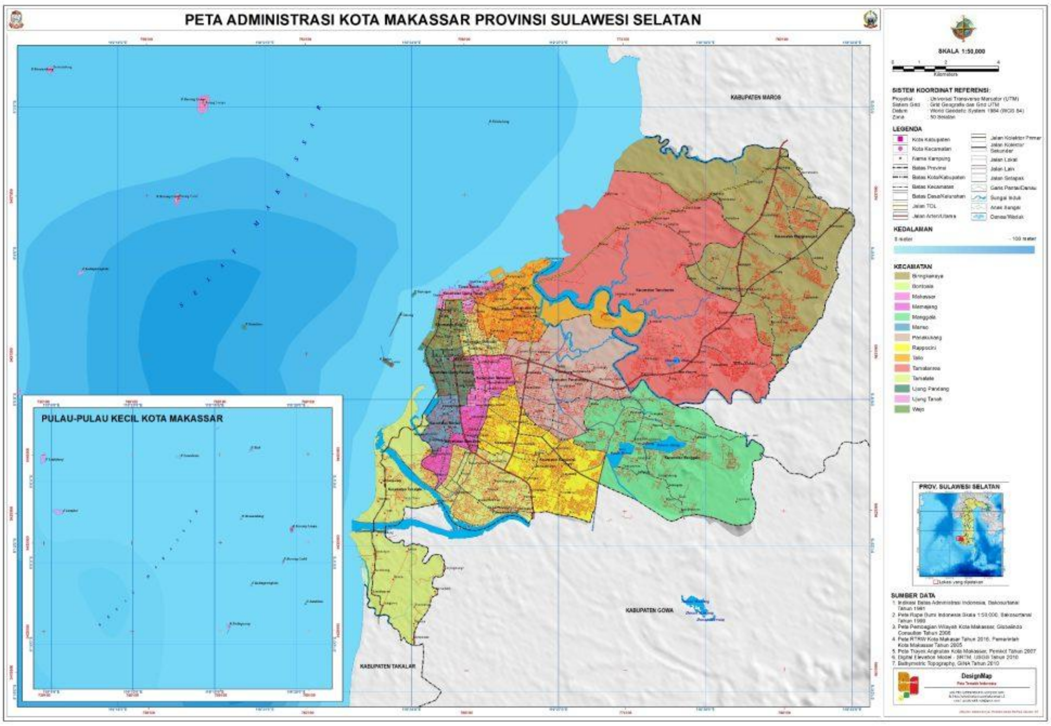
Makassar, as the capital of South Sulawesi, has undergone rapid urban expansion, with several large-scale developments concentrated in the coastal area. Prominent examples are the massive reclamation and development of The Citraland CPI and the Makassar New Port, which are significantly altering the shoreline of Makassar City. This study on long-term shoreline monitoring in Makassar (1973 - 2025) is conducted to better understand the increasingly complex dynamics of coastal change, due to the anthropogenic influence and also the natural processes. The objective of this study is to:

1. Identify and conduct a quantitative analysis of the long-term shoreline dynamics in Makassar (1973–2025) using the collection of Landsat satellite imagery data
2. Estimate the extent of changes in the Makassar shoreline area due to shoreline retreat and shoreline advancement from 1973 to 2025.

Methodology

a. Study Area:

The study area for this research is the shoreline of Makassar City, located in South Sulawesi, Indonesia. The northernmost part of the shoreline lies along the administrative boundary between Maros Regency and Makassar City, delineated by the Bone Tanjore River. Meanwhile, the southernmost area of the administrative boundary between Makassar City and Gowa Regency is directly bordered by the Jeneberang River. Makassar City was selected as the study area for this research due to its sedimentation processes influenced by major rivers, particularly the Jenebrang River in the south, Tallo River, and the Bone Tanjore river in the Northeast, as well as significant anthropogenic pressures, these include extensive reclamation activities, such as the Citraland City CPI Makassar development and the construction of the Makassar New Port Container Terminal. The large-scale reclamation projects in Makassar are still ongoing, with the South Sulawesi Provincial Government still targeting 4,000 hectares of reclamation by 2034 in the coastal area and also on small islands (Asy'Ari et al., 2023). This emphasizes that, Makassar shoreline is still expected to undergo significant changes in the future.



Source: https://makassarkota.go.id/peta-wilayah-administrasi-kota-makassar/

Figure 1: Makassar Administration Area

b. Data Sources:

This study used multi-temporal Landsat surface reflectance data from 1973 to 2025. Landsat satellite imagery was selected for this study due to its long availability, which is essential for analyzing long-term shoreline changes. All imagery was accessed and pre-processed using the Google Earth Engine (GEE) platform. For each target year, composite images were generated using the median reflectance of all available scenes, while for 2025, the composite was derived from scenes acquired up to August. Shoreline positions were extracted for the years 1973, 1978, 1981, 1990, 1995, 2000, 2005, 2010, 2015, 2020, and 2025. However, due to data limitations, Landsat imagery was not available for the years 1970, 1975, 1980, and 1985. It is also worth mentioning that a limitation of this study lies in the lower spatial resolution of Landsat 1 and Landsat 4 imagery (60 meters), in comparison to the higher spatial resolution data provided by Landsat 5 and later (30 meters). This discrepancy may introduce some degree of error in shoreline delineation, particularly in earlier years.

C. Shoreline Extraction and Change Rate Quantitative Analysis Method.

The methodological framework of this study combined a manual approach, applied primarily for the 1973, 1978, and 1981 shorelines, with a semi-automatic approach for shorelines after 1990. The latter was largely adapted from the method proposed by Ding (Ding et al., 2021) for delineating and analyzing multi-decadal shoreline dynamics using satellite remote sensing data, with several modifications introduced. The overall workflow is presented in Figure 2, which summarizes the sequential stages of pre-processing, shoreline extraction *(red dot line: using Google Earth Engine)*, post-processing, and statistical analysis *(blue dot line: using DSAS)*. Each stage is described in detail below.

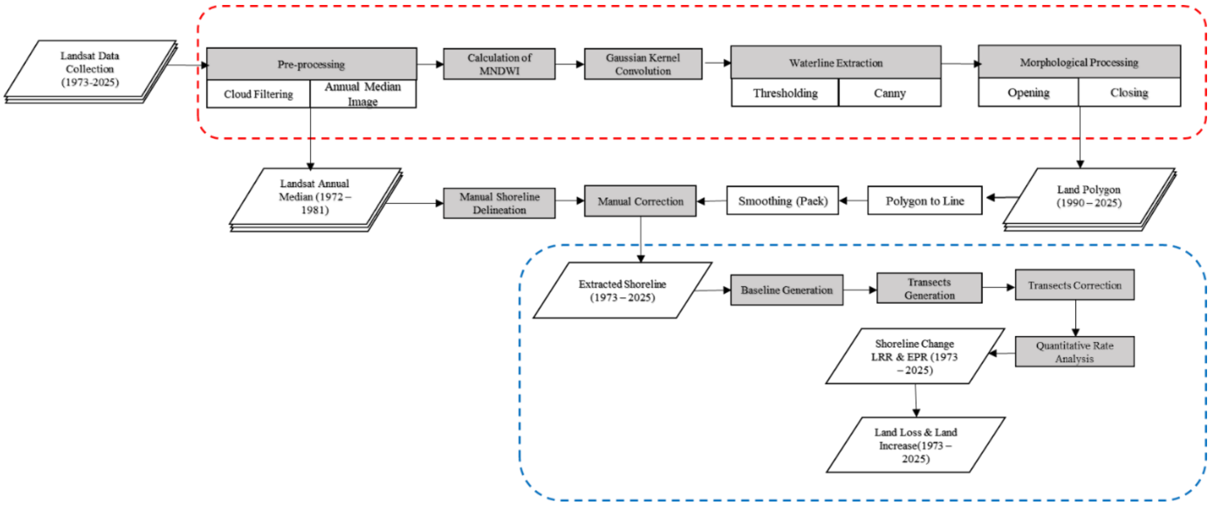


Figure 2: Workflow used in this study

1. Pre Processing

   The pre-processing phase was designed to ensure the integrity of the input imagery before shoreline delineation. The preprocessing phase in this study involves two main steps: cloud filtering to remove cloud and shadow interference, and the generation of annual median composites. Atmospheric factors such as cloud cover and shadows are the main sources of misclassification in optical data; therefore, a cloud filtering procedure was applied. Landsat quality masks were used to detect and remove cloud-contaminated pixels, while scenes with a high percentage of cloud coverage were excluded from the analysis.

   The median value was then selected across multiple scenes in the same period for generating annual composite images, as it effectively reduces noise and minimizes the influence of outliers. In addition, the median mitigates spatial misalignments by limiting the impact of temporally inconsistent pixel values, thereby producing a more stable and representative composite (Kathiroli et al., 2025). This approach has been widely applied in multi-temporal remote sensing studies to ensure consistency and reliability in long-term analyses. For the year 2025, the annual median composite was generated using a collection of images acquired up to August. This approach is acceptable because the selected time frame corresponds to the dry season in Indonesia, when cloud cover is minimal. Moreover, the annual median values across all years are primarily derived from dry-season imagery, thereby ensuring consistency and comparability among the annual composites.

2. Manual Delineation

   Initially, the same semi-automated approach was applied to earlier Landsat 1 MSS (1973) data and Landsat 3 MSS (1978, and 1981); however, the shoreline extraction results based on semi-automated approach were unusable. This was likely due to significant noise and image artifacts present in the Landsat MSS data from that period. The manual delineation was conducted solely based on visual interpretation on False color composite image.

3. Water Index Calculation

   To distinguish between water and non-water surfaces, the Modified Normalized Difference Water Index (MNDWI) developed by Xu (Xu, 2006) was used in this study. The MNDWI formula is calculated as follows:

$$MNDWI = \frac{Green - SWIR}{Green + SWIR}$$

   In this study, MNDWI was utilized to differentiate between water and non-water features. According to Xu (Xu, 2006), the substitution of the Near-Infrared (NIR) band with the Short-Wave Infrared (SWIR) band in the NDWI can effectively reduce noise caused by built-up land cover, thereby enhancing the separation between water bodies and non-water areas in densely developed coastal regions, like Makassar.

4. Shoreline Extraction Workflow

   The shoreline extraction process consisted of several integrated operations aimed at accurately delineating the land–water boundary. The first step was the application of a Gaussian kernel convolution to the water index images. This filtering technique is based on the Gaussian (normal) distribution, where the maximum weight is concentrated at the center of the kernel and gradually decreases toward the periphery. In practice, each pixel is replaced by a weighted average of its surrounding neighbors, with weights determined by the Gaussian function relative to the central point. This produces a localized "blurring" effect, which smooths abrupt variations and reduces high-frequency noise in the image. As a result, the edge characteristics of water bodies are enhanced, making the subsequent contour extraction more accurate and stable.

Following convolution, shoreline extraction was performed using a combination of threshold segmentation and edge detection. Thresholding provided an initial classification of water and non-water pixels by applying a cutoff to the water index values. However, threshold segmentation alone often produces suboptimal results in complex regions, where water and land features overlap or exhibit spectral similarity.

To further refine the extracted boundaries, morphological operations were applied. Specifically, the opening operation (erosion followed by dilation) removed small, isolated patches caused by noise, while the closing operation (dilation followed by erosion) filled small gaps and connected fragmented shoreline segments. These refinements ensured that the shoreline vectors were continuous and geometrically coherent.

Finally, the complete shoreline extraction workflow, which includes Gaussian convolution, thresholding, Canny edge detection, and morphological refinement, was applied iteratively to all available Landsat imagery spanning the period from 1973 to 2025. This systematic repetition produced a consistent temporal archive of shoreline vectors, enabling reliable multi-decadal analysis of shoreline dynamics.

5. Post-Processing

The extracted shoreline vectors underwent post-processing to correct residual anomalies and ensure temporal consistency. The post-processing phase consists of conversion of the Polygon to a line feature, line smoothing, and manual correction. As the shoreline vectors were initially in polygon format, conversion to line features was essential. In this study, the conversion was performed using the Polygon-to-Line tool. The extracted shoreline initially exhibited a 'jagged' appearance due to the pixelated nature of the raster source. To enhance accuracy and produce a visually continuous representation of the actual shoreline, a smoothing process was applied using the PAEK (Polynomial Approximation with Exponential Kernel) algorithm (Bodansky et al., 2002), with a smoothing tolerance of 120 meters to reduce the pixelated 'jagged' appearances. The smoothing tolerance of 120 meters was determined through a trial-and-error approach. Tolerance values of 30, 60, 90, and 120 meters were tested, and 120 meters was found to provide the most visually accurate representation of the actual shoreline. Additionally, manual vector editing was then still performed to eliminate misaligned segments, address artifacts resulting from sensor limitations and harmonize shoreline positions across the time series. The temporal consistency must be achieved to obtain a more accurate result from statistical analysis. The cleaned shoreline archive was then prepared for quantitative analysis.

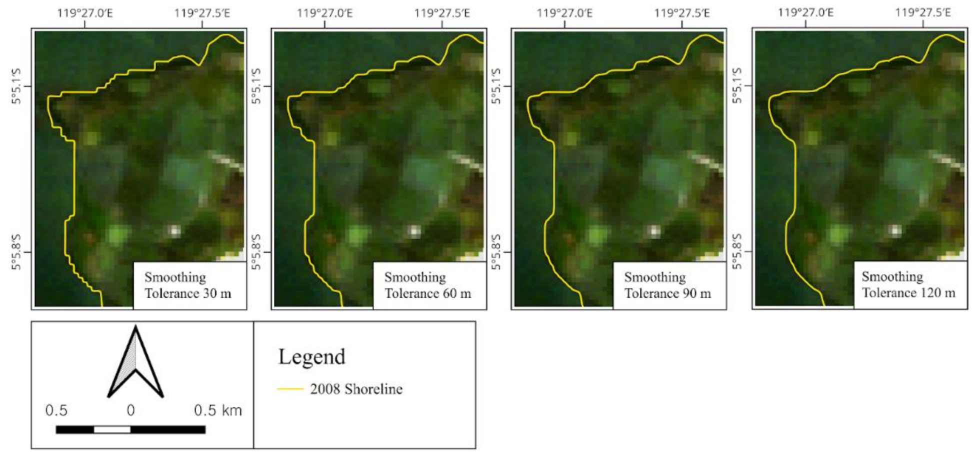


Figure 4. Example of the smoothing tolerance parameter in the PAEK algorithm. At lower smoothing tolerance values, the jagged appearance in the shoreline remains visible.

6. Statistical Analysis using DSAS

   Quantitative analysis of Shoreline change rate was conducted using the Digital Shoreline Analysis System (DSAS), developed by the U.S. Geological Survey (Himmeltoss et al., 2024). The finalized shoreline vectors were then used as input in the Digital Shoreline Analysis System (DSAS) to quantify the annual rate of shoreline change. DSAS was used in this study to estimate average shoreline change rates per year; End Point Rate (EPR), calculates the rate of change from the earliest to the most recent shoreline positions divided by the time difference; Linear Regression Rate (LRR), estimates the rate based on a linear regression of all available shoreline positions over time. LRR was utilized to use all available shoreline data to estimate the change rate; meanwhile, EPR only needed the latest and the earliest shoreline.

A baseline was first established using the earliest available shoreline (1973 shoreline), which was buffered by 1,000 meters with location *onshore*. This baseline served as the reference from which transects were generated to estimate the rate of shoreline change. In this study, the DSAS parameters were set with a transect spacing of 30 meters, a maximum transect length of 2 kilometers, and a smoothing distance of 500 meters. The transect position was also manually corrected to ensure more accurate measurements between the shorelines.

Results and Discussion

1. Annual Shoreline Extraction from Landsat Satellite Imagery

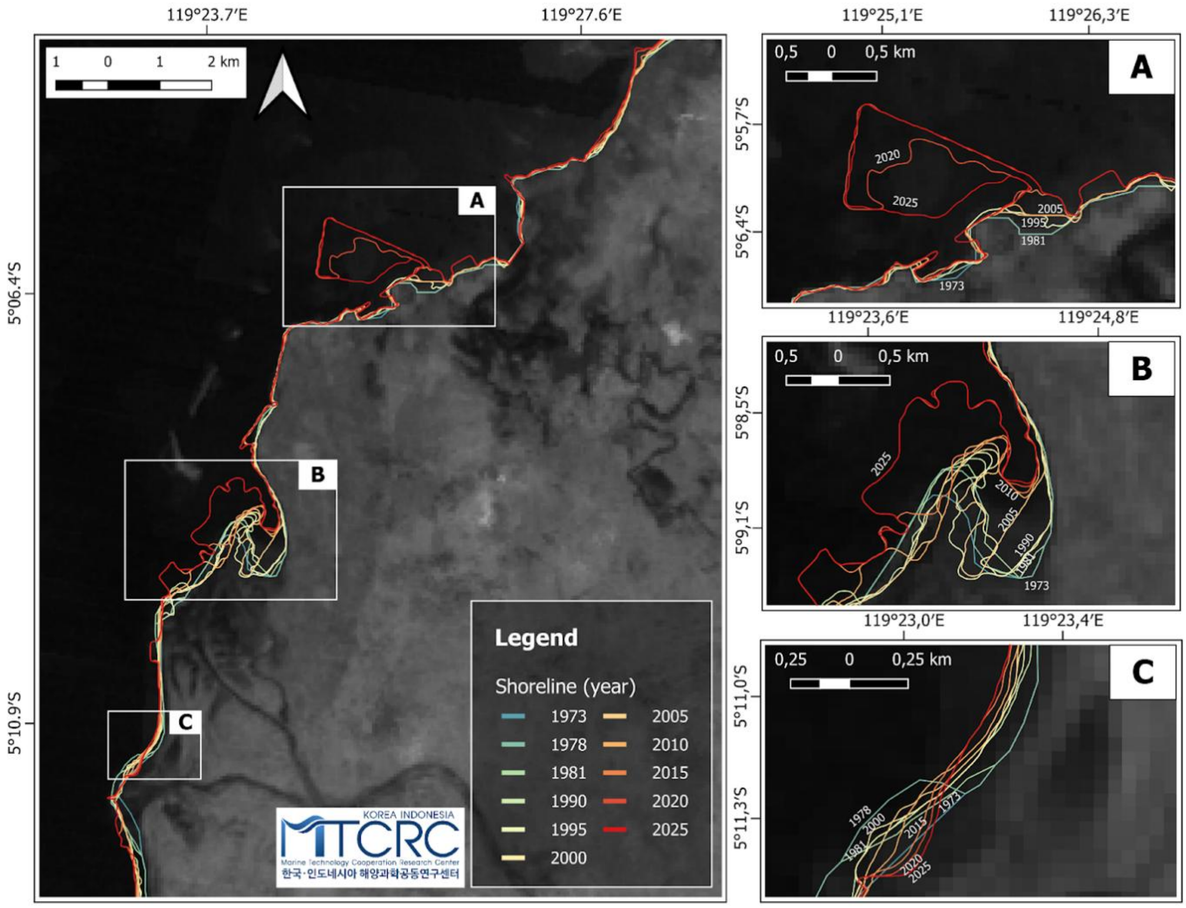


Figure 5. Corrected shoreline positions for each respective year over the 1973 annual median Landsat MSS single-band image as the background, accompanied by zoomed-in of Makassar New Port (A), Citraland CPI (B), and Tanjung Layar Putih Beach (C).

Visual observation based on Figure 5 indicates that the Makassar shoreline is very dynamic, characterized by massive land reclamation activities, particularly in the Citraland CPI (Figure 5B) and the Makassar New Container Port (Figure 5A). These processes not only alter the shoreline but also contribute to changes in the Makassar coastal landscape. Citraland CPI was originally the spit area *(Tanjung Bunga spit*), formed as a result of longshore sediment transport originating from sediment supplied by the Jeneberang River. Before significant human intervention, the Tanjung Bunga spit grew northward at a rate of up to 50 meters per year, as reported by Rochmanto et al., 1994. This is consistent with the findings of this study, which show that the spit extended by approximately 300 meters between 1973 and 1978 (Figure 5B). Land reclamation activities in this area have progressed significantly; Reclamation activities can be observed as early as 1990, starting in the southern part of Losari Beach and progressively extending northward. In the 2000 imagery, the construction of what is now the Metro Tanjung Bunga Road is also visible. Between 2015 and 2020, noticeable land expansion occurred. According to Asy'ari et al., 2023, the development of Citraland CPI was notably accelerated in 2017 and completed by 2018. A similar trend could also be observed in the development of the Makassar New Port (Figure 5A). An interesting pattern is seen at Tanjung Layar Putih Beach (Figure 5C). In general, this area has experienced shoreline retreat, possibly due to coastal abrasion. Interestingly, in 1978, the shoreline advanced compared to its position in 1973, before retreating relatively far in 1981, then some accretion was observed to have happened in 1990 - 2000, and the shoreline gradually retreated at a constant rate until 2025. The accretion that happened in 1978 suggests that during that period, sedimentation from the Jeneberang River, which carries sediment from Mount Bawakaraeng, was relatively high. In the northeastern region, shoreline changes are primarily influenced by mangrove forest dynamics, which, based on visual observation, appear to have generally increased over time.

2. Makassar Shoreline Change Quantitative Analysis

The results of the DSAS, linear regression rate analysis (Figure 6), indicate the average annual shoreline change from 1973 to 2025. The rate of shoreline increase is notably significant, with dominant land gain observed along the Makassar coast. In contrast, the rate of shoreline erosion is considerably lower, both in magnitude and spatial extent, with relatively limited areas along the Makassar coastline experiencing land loss.

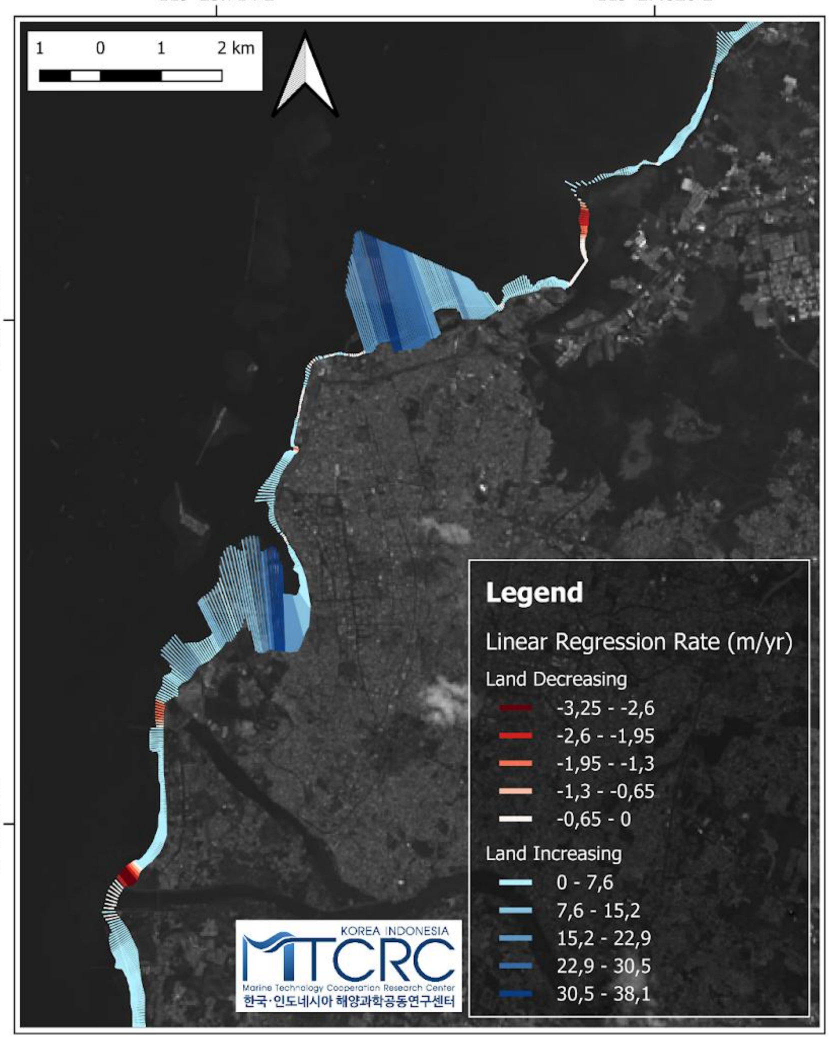


Figure 6. Results from the Digital Shoreline Analysis System (DSAS), showing the linear regression rate of shoreline change in Makassar from 1973 to 2025. Negative values indicate rates of change due to shoreline retreat, while positive values indicate shoreline advancement.

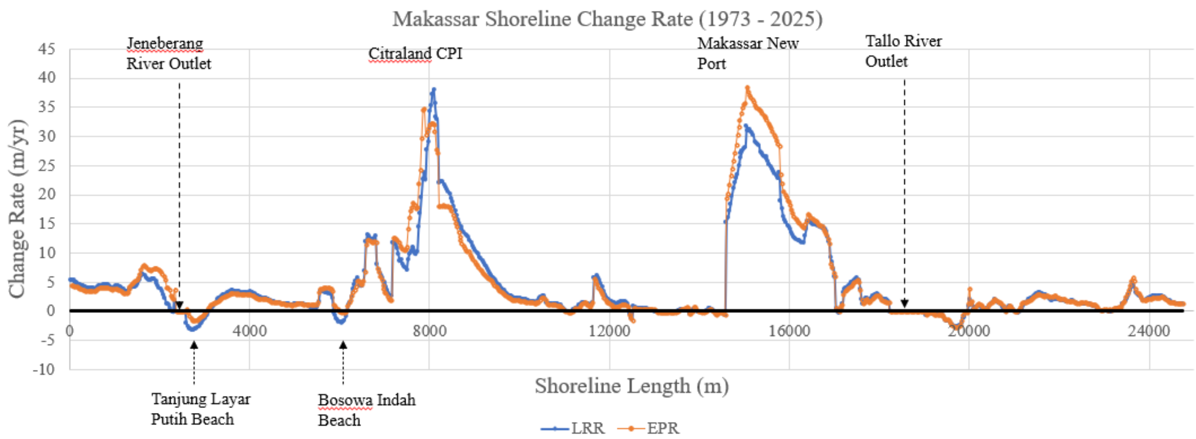


Figure 7: Linear Regression Rate of Makassar Shoreline change (1973 – 2025)

Further details on the rate of shoreline change are illustrated in the figure above (Figure 7). The measurement begins at the southwest region (south of the Jeneberang River), and extends to the final measurement point near the Bone Tanjore River in the northeast (before the Maros Regency administrative area). The graph demonstrates that the rates calculated using both the End Point Rate (EPR) and the Linear Regression Rate (LRR) are relatively similar. This indicates that the calculation of the End Point Rate (EPR) using only the earliest and most recent shorelines is generally sufficient to provide an overview of the rate of shoreline change in Makassar between 1973 and 2025. However, the Linear Regression Rate (LRR) offers a more accurate depiction of shoreline change trends in areas with relatively complex variations, particularly when at the same periods, both accretion and erosion occur. This indicates that, in general, shoreline changes in Makassar during the 1973–2025 period have been predominantly characterized by continuous land increase, primarily driven by large-scale human activities, especially land reclamation projects.

Overall, the data indicate a general trend of shoreline advancement in Makassar, with particularly rapid changes observed in areas undergoing large-scale reclamation, such as the Citraland CPI (LRR reaching up to 38,1 meters/year) and Makassar New Port (LRR reaching up to 31,7 meters/year). However, a relatively small shoreline retreat could be observed in Tanjung Layar Putih Beach, Bosowa Indah Beach, and in the Mangrove area, on the east side of the outlet of the Tallo River. The Linear regression rate for shoreline retreat at Tanjung Layar Putih LRR ranges from 0.57 - 3.25 meters/year; meanwhile, in Bosowa Indah LRR is 0.7 - 1.88 meters/year, and the mangrove forest in the outlet of Tallo River ranges from 0.93 - 2.57 meters/year.

3. Estimation of Land Area Increase and Decrease in Makassar

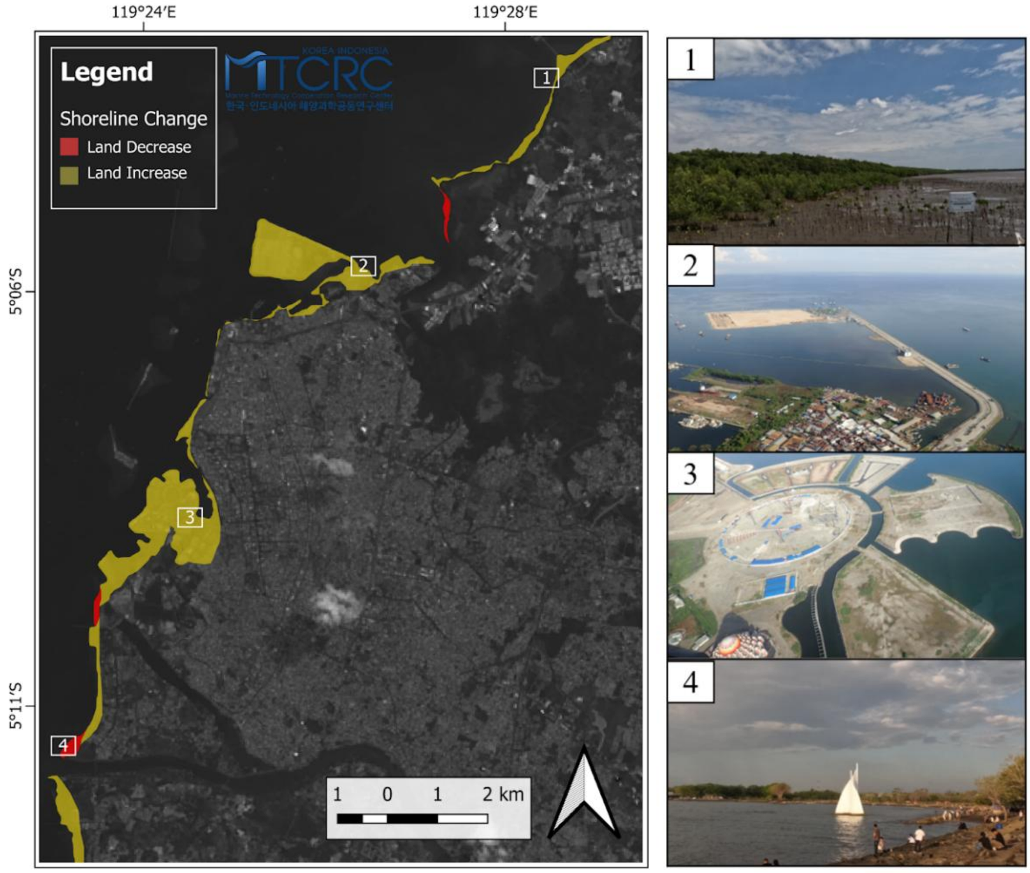


Figure 7: Makassar increasing land area (yellow) and loss land area (red) in 1973 - 2025 period; on the right side, actual latest photograph: taken in Untia region with photo direction to south taken in September, 2025 (1); aerial photograph of Makassar New Port area taken in June, 2021 (2); photograph of Citraland CPI area taken in June, 2021 (3); taken in Tanjung Layar Putih Beach with photo direction to northeast taken in September, 2025 (4)

Makassar shoreline has undergone significant changes over the 52-year period. The predominant trend is shoreline advancement, primarily driven by large-scale reclamation projects, notably the Citraland CPI and the Makassar New Port development. In addition, smaller-scale reclamation activities have also taken place along much of the Makassar shoreline. Shoreline advancement has not only resulted from reclamation but is also attributed to the expansion of mangrove forests, particularly in the northeastern coastal area near the Tallo River. On the other hand, notable shoreline retreat has been observed in some specific areas. One of the most significant erosion-affected areas is Tanjung Layar Putih Beach, where coastal abrasion appears to be the primary cause. The north of Layar Putih Beach, Indah Bosowa Beach, is also experiencing shoreline retreat. One contributing factor may be the closure of one of the Jeneberang River outlets for the construction of the Daeng-tata bridge; the water body later became Tanjung Bunga Lake. This may have halted the natural sediment supply to this region. As a result, sediment deposition has diminished, contributing to coastal erosion of Bosowa Beach and Tanjung Layar Putih. Meanwhile, in the northeastern region, shoreline changes are largely influenced by the dynamics of mangrove forest coverage. Our findings indicate a total land gain of approximately 6,170,757.24 m² (617 hectares) between 1973 and 2025, while the total land loss is estimated at 269,645.05 m² (27 hectares).

Conclusion and Recommendation

Between 1973 and 2025, the Makassar shoreline in general has experienced significant shoreline advancement, primarily driven by large-scale reclamation projects such as the Citraland CPI, with shoreline change rate (LRR) reaching up to 38.1 m/year and Makassar New Port up to 31.7 m/year. In contrast, shoreline retreat is limited but observed in specific areas, notably Tanjung Layar Putih and Indah Bosowa Beach, likely due to coastal abrasion and disrupted sediment supply following Jeneberang River modification and infrastructure development, and the mangrove area east of the Tallo River outlet, with LRR of retreat ranging from 0.57 to 3.25 m/year. Meanwhile, in the northeastern region, the shoreline change is mostly affected by the Mangrove forest dynamics, which mostly increase. In total, approximately 617 hectares of land were increased, while 27 hectares were lost.

To obtain more comprehensive insights into the acceleration or deceleration rates of shoreline change, quantitative analyses can be conducted over shorter and more discrete time intervals. This approach allows for a clearer identification of the main factors or phenomena that drive these shoreline changes. Moreover, analyses conducted before and after the reclamation activities would provide valuable insights into better understanding the natural processes of sedimentation and the associated changes in Makassar shoreline dynamics.

This study could be further developed by conducting a Coastal Vulnerability Index (CVI) assessment for Makassar. As is well known, Makassar has experienced significant land expansion in coastal areas due to ongoing reclamation activities, which are expected to continue. Assessing the vulnerability of Makassar's coastline is crucial, particularly in relation to natural hazards (especially driven by climate change) such as tidal flooding, land subsidence, sea level rise, coastal erosion, and accretion.

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