Designing the Layout of Offshore Protection Structures at Tugu Beach, Air Bangis (Indonesia) using Numerical Simulation

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Abstract: Tugu Air Bangis Beach, located in West Pasaman Regency, has experienced severe coastal erosion caused by wave energy from the Indian Ocean. This condition has resulted in the collapse of several structures along the shoreline and threatens the remaining coastal infrastructure. Mitigation measures are therefore required to maintain shoreline stability and prevent further damage. This study aims to design the layout of coastal protection structures for Tugu Air Bangis Beach using numerical simulations to reduce the impact of wave- and current-induced erosion.The data used in this study include satellite imagery, wind data, tidal elevation data, Digital Elevation Model (DEM) data, and aerial photographs. Tidal flooding (rob) occurred in Padang City and Air Bangis from December 3 to 5, 2021, and the tidal elevation data used for the simulation were obtained from realtime measurements recorded at the Teluk Bayur Station, Padang, between December 1 and 9, 2021. Numerical simulations were performed using the CMS-Wave and CMS-Flow modules in the Surface Water Modelling System (SMS) version 10.1.The simulations were conducted in two stages. The first stage employed the existing structure layout, simulated for 216 hours of model time (equivalent to 36 hours of computer running time). The results indicated that the incoming waves approach the shoreline perpendicularly, suggesting that a breakwater is the most appropriate coastal protection structure. In the second stage, two breakwaters of equal length (200 meters each) and equal distance from the original shoreline (100 meters) were added. The numerical model results showed that this configuration effectively mitigates erosion, as indicated by sediment accumulation along several shoreline segments and the initial formation of a tombolo behind the breakwaters.

Keywords: Abrasion; Shore protection layout; Breakwater; Numerical simulation; Tombolo.

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1. Introduction

Air Bangis City, situated on the coast, has maintained its urban status since the era of the Inderapura Kingdom, making it a historical and contemporary urban center. It has also established itself as a prominent beach tourism destination within West Pasaman Regency [1]. Popular tourist attractions in Air Bangis include Tugu Beach, Panjang Island, Harimau Island, Unggeh Island, Toluo Island, Pangkal Island, Pigago Island, Tamiang Island, Marando Hilltop, Lanang Bisai Park, and Rumah Gadang (Figure 1). Of these, Tugu Beach (0.215215°, 99.366025°), located near the Tugu monument, is the most frequently visited by tourists. A 2019 monitoring assessment of Tugu Beach revealed the presence of several concrete gazebos, enhancing its appeal to visitors. These gazebos are situated 36 meters inland from the shoreline (Figure 1), offering visitors a relaxing space to enjoy the scenic vistas.

Furthermore, Tugu Beach boasts a variety of culinary delights, including shark curry and crab soup.

Unfortunately, in 2020, the shoreline at Tugu Beach experienced significant landward movement, resulting in the collapse of a concrete gazebo (Figure 1). This phenomenon is known as shore erosion [2]. Continuous erosion poses a significant threat to shore infrastructure, damaging existing buildings and potentially endangering those that remain intact. This erosion is primarily driven by the forces of waves and currents, a process also referred to as abrasion [3].

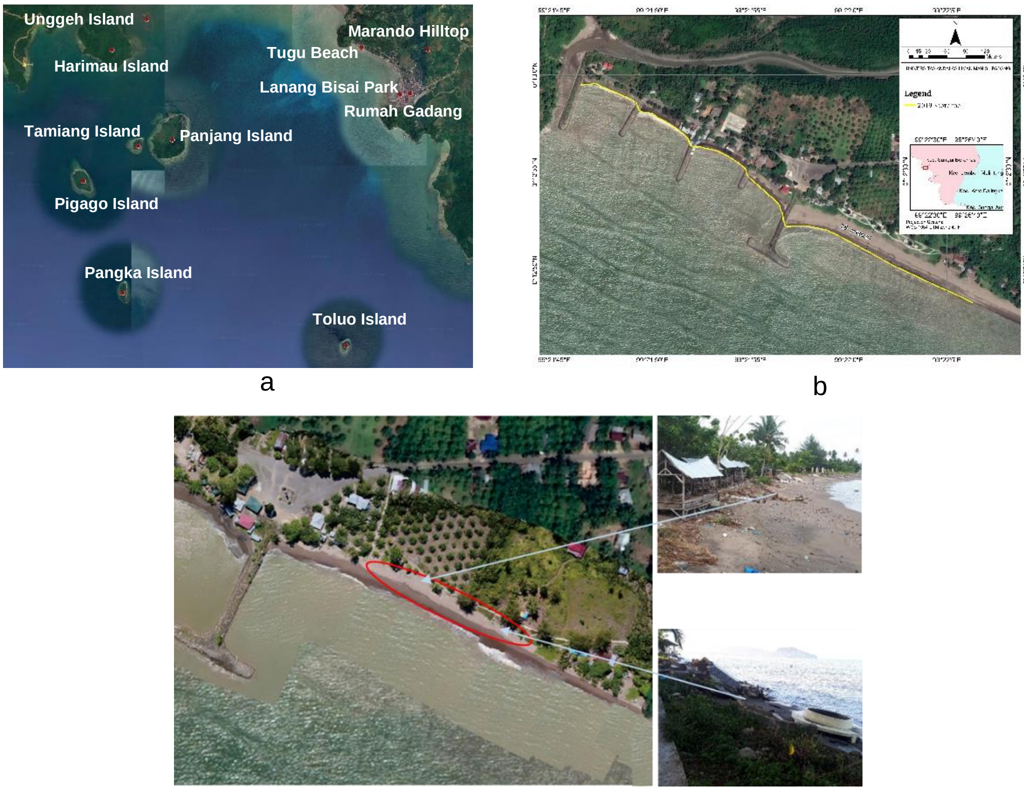

Figure 1. (a) Popular tourist spots in Air Bangis City; (b) Satellite Image Map of Tugu Air Bangis Beach from Google (2019); (c) Aerial Photograph 2023 and Collapsed Structures

Analysis of Google Earth imagery from 2019 to 2023 reveals that shore abrasion has resulted in shoreline retreat of up to 20 meters at Tugu Beach. This significant erosion poses a serious threat to the coastal environment of Air Bangis.

Mera and Chrisnatilova [4] conducted a numerical simulation study to determine the effectiveness of groynes and breakwaters at Gandoriah Beach, Pariaman City. Subsequently, Hariatama and Mera [5] carried out a similar study focusing on the effectiveness of groynes and breakwaters through numerical simulation, but at a different location — Ketaping Beach, Pariaman City. Both studies employed the Surface Water Modeling System (SMS) versi 10.1 and utilized maximum daily wind data obtained from BMKG. In the present study, the author also used SMS 10.1; however, the research was conducted at Tugu Beach, Air Bangis, using hourly wind data derived from the Climate Data Store (CDS) [6]. This study focuses on designing a safe layout for Tugu Beach, Air Bangis by employing numerical simulations to mitigate shore erosion driven by currents and waves.

The benefit of this study is to provide an alternative solution for relevant agencies in the protection of Tugu Air Bangis Beach.

2. Methods

2.1. Field Site

The research area encompasses the coastal zone around the Air Bangis Monument. It extends approximately 250 meters leftward from the T-groin located in the center of Air Bangis City (0.213879°, 99.368016°) to the end of Tugu Beach (0.216666°, 99.362827°) (Figure 2).

Figure 2. Field site

2.2. Data Collection Site

The secondary data used in this study consist of several types of datasets. The satellite imagery of Air Bangis was obtained from Google Satellite, while the Digital Elevation Model (DEM) data of Air Bangis were obtained from DEMNAS (2023) [11]. The wind data used are hourly maximum daily wind data recorded over a 20-year observation period, from 2001 to 2020. These wind data include two main parameters: the horizontal wind velocity component directed eastward at a height of 10 meters (10 m U-Component) and the horizontal wind velocity component directed northward at a height of 10 meters (10 m V-Component). The wind data were obtained from CDS (2021) [12] with the station coordinates located at Satpol Air (0.1975°, 99.37611°).

The tidal elevation data were obtained from the Geospatial Information Agency (BIG). These data represent realtime tidal elevation measurements recorded from December 1 to 9, 2021 [13], at the Teluk Bayur Station, Padang. Due to the limitation of measurement data, the influence of the Batang Aie Tompek River estuary was not considered in this study. Therefore, the sediment transport simulated in the model only accounts for contributions originating from the ocean.

Primary data collection included wave direction data obtained through a field survey and aerial photography data acquired using a drone in August 2023.

2.3. Data Processing and Analysis

This study analyzes shoreline changes by comparing digitized shorelines from 2019 and 2023, derived from [14,15,16] and aerial photography [17]. It determines Net Shoreline Movement (NSM) to identify areas of erosion (movement inland) and accretion (movement seaward) [2,18]. *Bathymetry* data is generated from a Digital Elevation Model (DEM) with a 1-meter elevation interval [19]. Wind data is processed in three stages to predict wave height and period offshore. First, wind speed and direction are calculated using vector operations. Second, a wind rose, a graphical representation of wind frequency and direction, is created [20]. Finally, the Sverdrup-Munk-Bretschneider (SMB) method is applied to forecast wave height and period [21,22]. Model verification is conducted by simulating the Tugu Beach area using wind direction, bathymetry, tides, and extreme waves. The simulation is a two-stage process: first, using the CMS-Wave module for wave propagation without currents [23], and second, incorporating both wave and current interactions with the CMS-Flow module [24,25]. An advanced simulation is then performed by adding offshore rubblemound breakwaters to the existing protection system [22]. A new layout's effectiveness is determined by its ability to predict the formation of a tombolo, which is a key indicator of an optimal design. A tombolo is a sedimentary deposit that connects the coastline to a breakwater [26].

3. Result and Discussion

3.1. Wind Direction

Based on the field survey data, the prevailing wind direction is from the west. This westerly wind generates waves that approach the shoreline at a perpendicular angle. Based on the field survey data, the prevailing wind direction is from the west. This westerly wind generates waves that approach the shoreline at a perpendicular angle.

3.2. Bathymetry

Using ArcGIS, the DEM data was processed to generate bathymetric data with a 1-meter elevation interval, as illustrated in Figure 3.

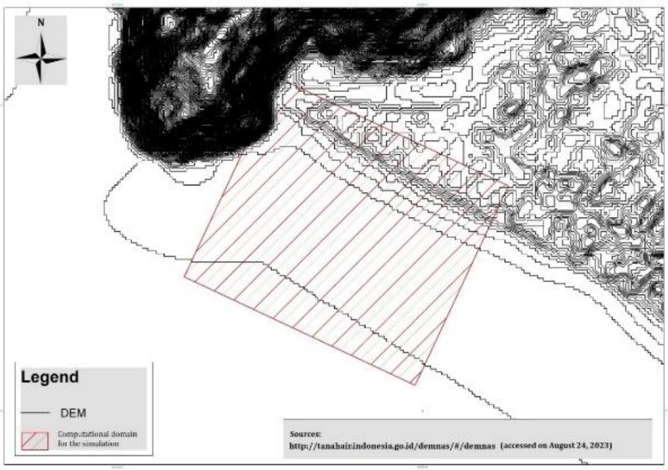

Figure 3. Visualization of bathymetric data [11]

3.3 Tide Elevation

Figure 4 illustrates the tide elevation data recorded at Teluk Bayur Padang Station from December 1 to 9, 2021, encompassing a period of 216 hours.

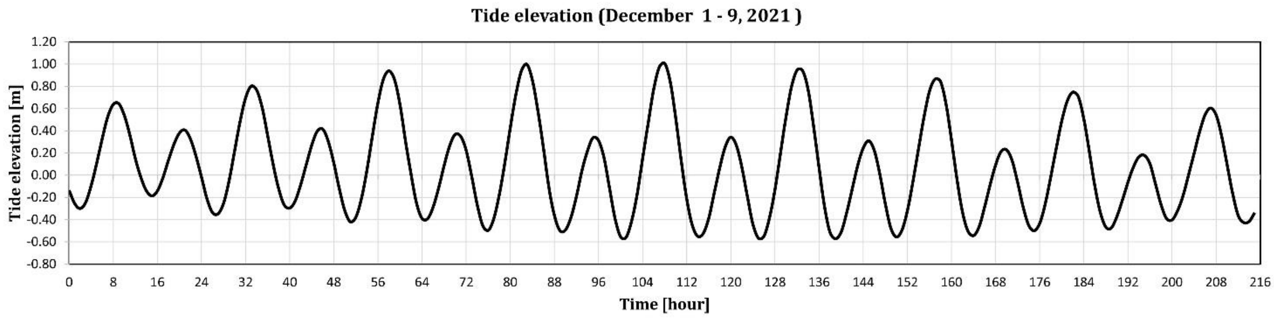

Figure 4. Tide elevation (December 1-9, 2021) - Real-time measurements by the Geospatial Information Agency [16]

Over the nine-day observation period, the highest recorded tide elevation was 1.01 meters on December 5, 2021. In contrast, the lowest elevation was -0.57 meters, with the average tide level for the period being approximately -0.02 meters.

3.4 Wind Rose

A total of 175,281 hours of maximum daily hourly wind data were analyzed, spanning the period from 2001 to 2020. The dataset encompasses a wide range of wind speeds, with a minimum of 0.004 m/s from the north, a maximum of 8.81 m/s from the northwest, and an average speed of 1.76 m/s. The analysis of this extensive dataset resulted in the creation of a wind rose, as depicted in Figure 5. This visualization provides valuable insights into the prevailing wind directions.

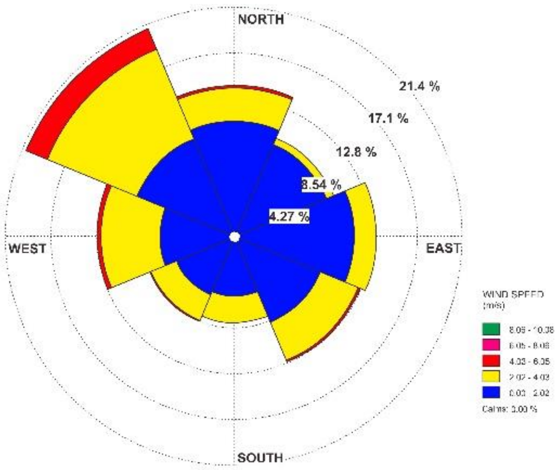

Figure 5. A Graphical representation of wind rose data (2001-2020)

Based on the frequency distribution of wind data, northwest winds are the most dominant, accounting for 20.94% of occurrences. This is followed by winds from the north (14.01%), east (13.18%), west (12.76%), and southeast (12.59%). The least frequent wind directions are from the southwest (8.53%) and south (8.06%).

3.5 Wave Height and Period

Utilizing the SMB method, the analysis revealed that the highest wave height (1.36 meters) and period (5.39 seconds) occurred on July 9, 2006, associated with an incident wave angle of 0° (west). These values will serve as crucial boundary conditions for the subsequent CMS-Wave parent grid (parent domain) simulation.

3.6 Shoreline Digitization

Figure 6 presents the results of the shoreline digitization.

Figure 6. Shoreline Digitization: Comparison of shoreline positions derived from Google Satellite Imagery (2019) and Aerial Photography (2023)

Analysis of the digitized shoreline image reveals erosion in segments I-I, II-II, and III-III, with Net Shoreline Movement (NSM) values of 25.99 meters, 5.97 meters, and 6.42 meters, respectively, as determined from map measurements.

3.7 Existing Layout: Model verification

To verify the SMS model, a numerical simulation was conducted using the existing shore protection structure layout and the corresponding pre-existing bathymetric conditions. The simulation results are presented in the form of predicted bathymetric morphological changes. Figures 7 depict the initial conditions, the simulation results at 120 hours (day 5), and 216 hours (day 9), respectively.

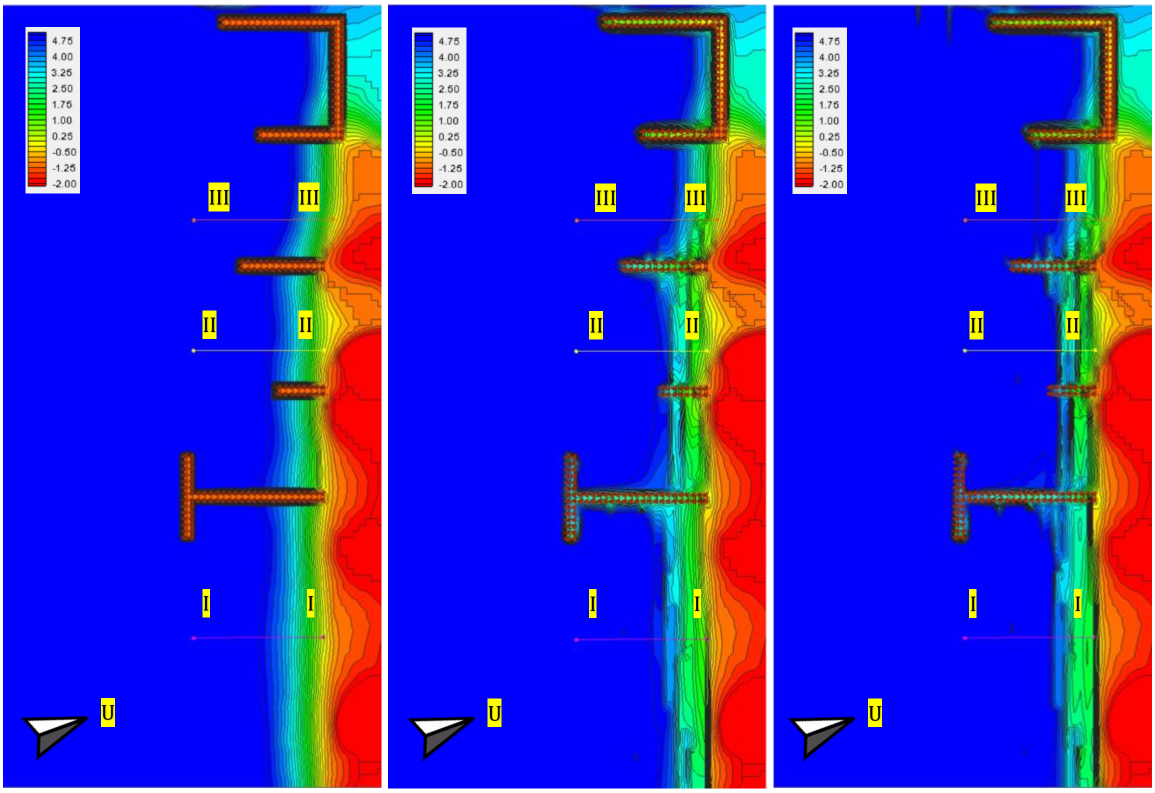

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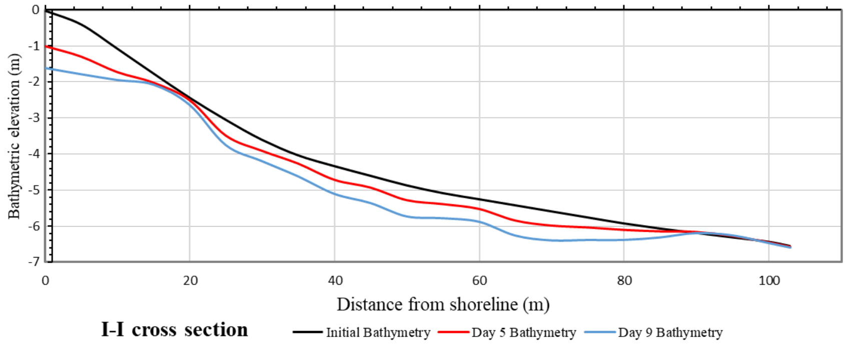
Figure 7. (a) Initial bathymetry and existing shore protection layout; (b) Day 5 bathymetry: impact of existing structures; (c) Day 9 bathymetry: impact of existing structures

Detailed bathymetric conditions resulting from the presence of existing shore protection are visualized in cross-sections presented in Figure 8.



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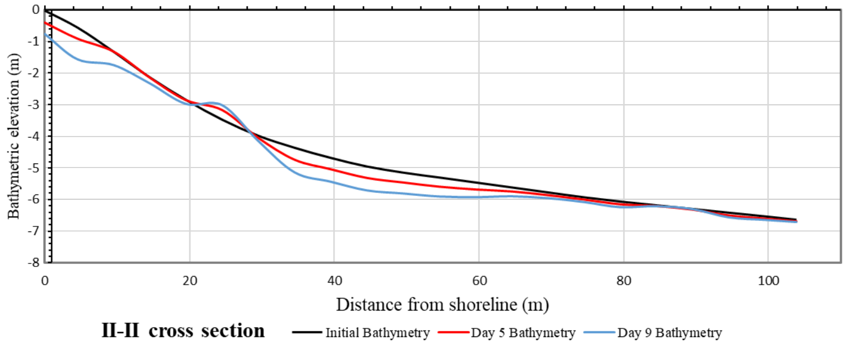

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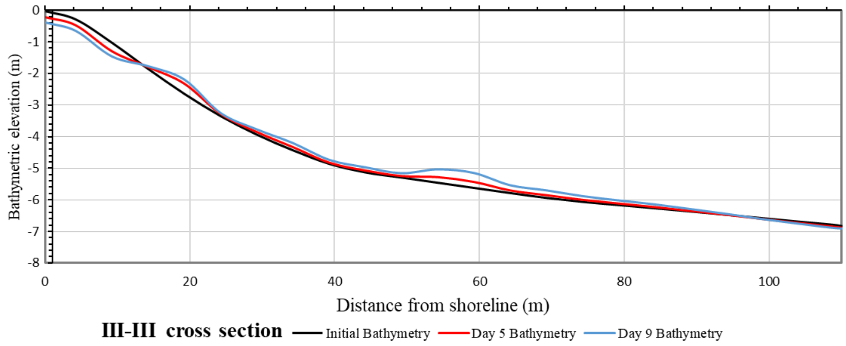

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Figure 8. (a) Bathymetric cross-section in section I-I; (b) Bathymetric cross-section in section II-II; (c) Bathymetric cross-section in section III-III illustrating the impact of existing shore protection

Analysis of the cross-section curves on Day 9 reveals distinct scouring patterns. In Section I-I, scouring occurred within the first 85 meters from the shoreline, reaching a maximum depth of 160 cm. Section II-II exhibited scouring in two zones: 0-20 meters and 30-85 meters, with a maximum scour depth of 99 cm. In Section III-III, scouring was observed within the first 15 meters, reaching a maximum depth of 43 cm.

Furthermore, Figure 8 demonstrates strong agreement between the simulated scouring and the shoreline digitization results presented in Figure 6. Both analyses indicate scouring within the same segments, validating the model's accuracy for the current domain and settings. This validated model can now be confidently applied to future scenarios or setups.

3.8 Layout Modification

To mitigate incoming wave energy, the existing layout has been modified by incorporating an offshore breakwater positioned beyond the surf zone. This design is expected to facilitate the formation of a tombolo. Tombolo formed when $Ls/y > 1.5$ and $Ls/y > 2\,Lg/Ls$. Here, Ls represents the breakwater length, Lg denotes the distance between adjacent breakwaters, and y signifies the distance between the shoreline and the breakwater [24].

The breakwater is engineered to be parallel to the mean sea level (0 meters), ensuring it is submerged during high tide and becomes visible during low tide. This unique feature serves multiple purposes, including acting as a tidal marker, an educational tool for demonstrating tidal phenomena, and an aesthetic enhancement that adds to the visual appeal of the coastal area. The modified layout (Figure 11) was subsequently subjected to numerical simulation.

Figure 9. Proposed shore protection structure layout for Tugu Beach based on 2019 Google Earth imagery

The simulation results demonstrate changes in coastal bathymetry over time. These changes are visualized through a series of figures: Figure 10 depicts the initial bathymetric conditions prior to the simulation, presents the bathymetric conditions after 120 hours of simulation (Day 5), and illustrates the bathymetric conditions after 216 hours of simulation (Day 9).

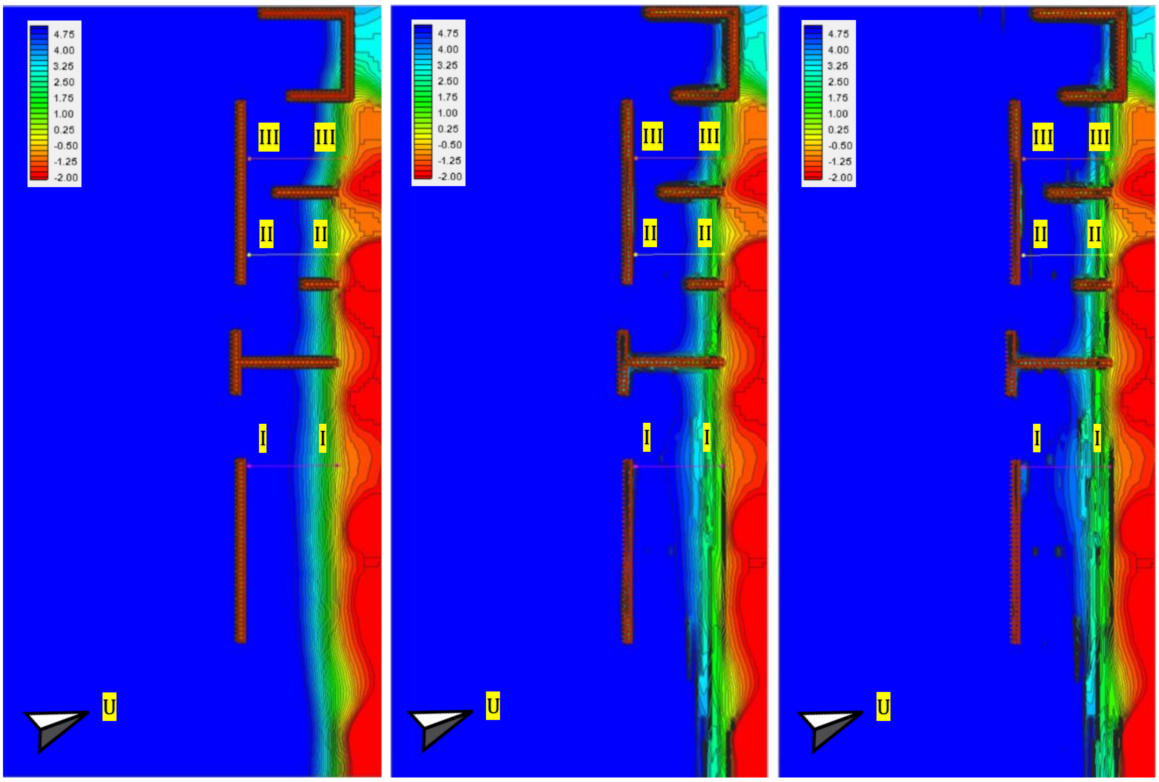

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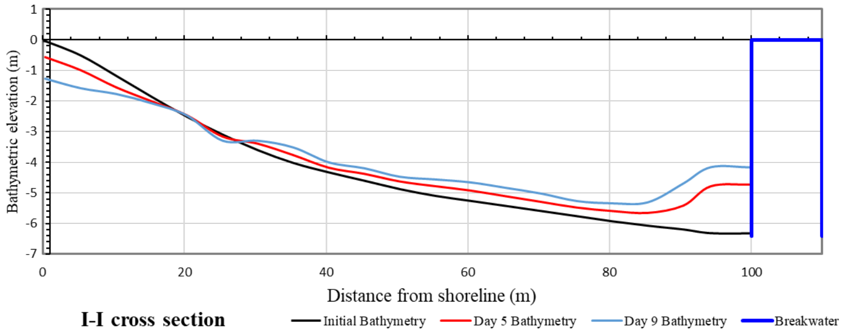
Figure 10. (a) Baseline bathymetry and proposed shore protection structure layout; (b) Bathymetric conditions after 5 days of simulation with modified layout ; (c) Bathymetric conditions after 9 days of simulation with modified layout

Detailed bathymetric conditions resulting from the presence of modified shore protection are visualized in cross-sections presented in Figure 11.



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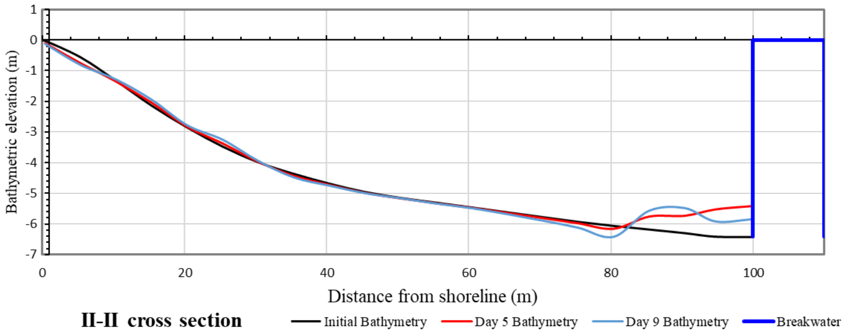

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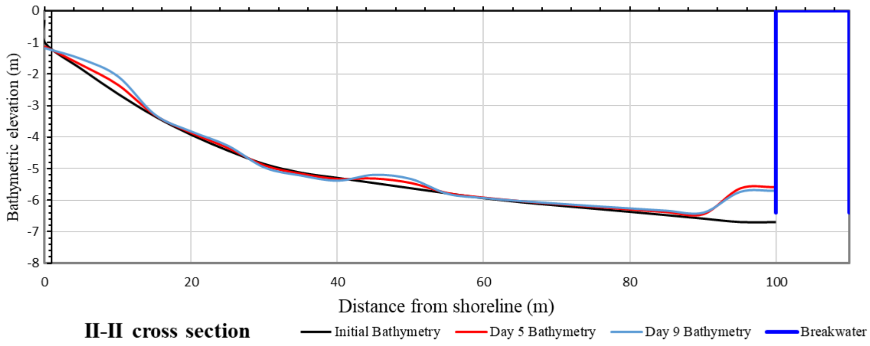

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Figure 19. (a) Bathymetric cross-section in section I-I; (b) Bathymetric cross-section in section II-II; (c) Bathymetric cross-section in section III-III illustrating the impact of added shore protection

Analysis of the cross-section curves on day 9 reveals that the most significant sedimentation occurred in section I-I, with an average sediment thickness of 68 cm between 30 and 100 meters. In sections II-II and III-III, sedimentation also occurred but with lower intensity, primarily within specific distance ranges.

4. Conclusion

The analysis indicates that the dominant wave direction at Tugu Beach, Air Bangis, is perpendicular to the shoreline (originating from the southwest), with the highest wave heights coming from the west. These conditions suggest that constructing a breakwater is an appropriate and effective solution to protect Tugu Beach from coastal erosion. Based on numerical simulation results, the proposed layout of coastal protection structures has proven to be effective in safeguarding and restoring the beach, even within the limited nine-day simulation period.

References

[1]. Perda. *Rencana Pembangunan Jangka Menengah Daerah (Regional Medium Term Development Plan) 2021-2026*. Peraturan Daerah Kabupaten Pasaman Barat (Regional Regulation of West Pasaman Regency) no. 2 tahun 2021. BAPPEDA of West Pasaman Regency: West Pasaman, 2021.

[2]. K. O'Brien, J. Stocker., J. Barret., and B. Hyde. Analysis of shoreline change in connecticut. Technical Report: Department of Energy & Environmental Protection, 2014, https://shorelinechange.uconn.edu/wp-content/uploads/sites/1897/2016/09/2014_CT_ShorelineChange.pdf.

[3]. L. H. Faza, and Y. N. Kurniadi. Desain bangunan pelindung pantai sebagai penanggulangan abrasi di Kawasan Pantai Ujung Jabung Provinsi Jambi (Design of shore protection structures as a means of preventing abrasion in the Ujung Jabung Beach, Jambi Province), *RekaRacana: Jurnal Teknik Sipil Itenas*, vol. 2, no. 2, 47 – 58, 2016.

[4]. M. Mera, and D. Chrisnatilova. Numerical simulation to determine the effectiveness of groynes and breakwaters as protective structures for Gandoriah Beach, Pariaman City. IOP Conference Series: Materials Science and Engineering, 1041, 012001: 1–12. IOP Publishing, 2020, https://doi.org/10.1088/1757-899X/1041/1/012001.

[5]. A. Hariatama, and M. Mera. Numerical Simulation to See the Performance of Groynes and Breakwaters as Shore-Protection Structures at Ketaping Beach, Padang Pariaman, Jurnal Talenta Sipil, vol. 8, no. 1, 2025, https:// doi.org/ 10.33087/talentasipil.v8i1.779.

[11]. Demnas, Tanahair Indonesia, 2023, https://tanahair.indonesia.go.id/demnas/#/demnas (accessed on August 24, 2023).

[12]. CDS. Climate Data Store. 2021. https://cds.climate.copernicus.eu/ (accessed on March 24, 2021)

[13]. BIG. Data pasang (tide data) Teluk Bayur Padang. Badan Informasi Geospasial (Geospatial Information Agency), May 2024, info@big.go.id (paid data).

[14]. S. Kermani, M. Boutiba., M. Guendoz, M. S. Guettouche, and D. Khelfani, "Detection and analysis of shoreline changes using geospatial tools and automatic computation: Case of jijelian sandy coast (East Algeria)", Journal Ocean & Coastal Management, 132, 46-58, 2016, https://doi.org/10.1016/j.ocecoaman.2016.08.010

[15]. E. L. Den Boer, Suntoyo, and A. C. Oele, "Determination of shoreline change along the East-Java coast, using digital shoreline analysis system", MATEC Web Conference, 177, EDP Sciences, 2018, https://doi.org/10.1051/matecconf/201817701022

[16]. N. A. Adnan, F. Q. B. S. Fadilah, R. M. A. Idzdihar, F. A. Mohd, A. R. A. Rasam, and E. S. Mokhtar, "Geospatial analysis of coastline erosion along Pulau Tuba, Langkawi", IOP Conference Series: Earth and Environmental Science, 620, 012017, IOP Publishing, 2021, http://dx.doi.org/10.1088/1755-1315/620/1/012017

[17]. R. Dolan, B. Hayden, and J. Heywood. A new photogrammetric method for determining shoreline erosion. *Journal Coastal Engineering*, 2, 21-39, 1978, https://doi.org/10.1016/0378-3839(78)90003-0

[18]. E. A. Himmelstoss, R.E. Henderson, M.G. Kratzmann, and A.S. Farris. Digital Shoreline Analysis System (DSAS) version 5.0 user guide, U.S. Geological Survey Open-File Report 2018–1179, 110, ISSN: 2331-1258, 2018, https://doi.org/10.3133/ofr20181179.

[19]. J. P. Rigol-Sanchez, N. Stuart, and A. Pulido-Bosch. ArcGeomorphometry: A toolbox for geomorphometric characterization of DEMs in the ArcGIS Environment. *Computers & Geosciences*, 85, A, 155–163, 2015, https://doi.org/10.1016/j.cageo.2015.09.020.

[20]. L. J. Thé, C.L. Thé, and M.A. Jhonson., WRPlot view user guide. Technical Report. Ontario, Kanada: Lakes Environmental Software, 2016.

[21]. CERC., *Shore protection manual*, US Army Corps Engineers, Washington, D. C., 1984.

[22]. B. Triatmodjo, *Teknik pantai (Coastal engineering)*, Yogyakarta: Beta Offset, 1999.

[23]. L. Lin, Z. Demirbilek, E. R. Greenblatt, S. S. Rice, and F. Buonaiuto. Numerical modeling of Shinnecock Inlet, New York, for coastal erosion control support and inlet sediment management, Coastal Engineering Proceedings, 37, 51, ISBN: 978-0-9896611-6-4, 2022, https://doi.org/10.9753/icce.v37.papers.51

[24]. SMS., *SMS user manual (v12.2)*, 2007 http://smsdocs.aquaveo.com/SMS_User_Manual_12.2.pdf.

[25]. A. Hariatama, Simulasi numerik untuk melihat kinerja bangunan pengaman pantai groin dan breakwaters di Pantai Ketaping, Padang Pariaman. *Master Thesis.* Department of Civil Engineeering, Universitas of Andalas, 2022

[26]. W. R. Dally, and J. Pope., Detached breakwater for shore protection. Technical Report CERC-86-1. US Army Corps Engineers, Vicksburg, MS 39180-6199, 1986, https://apps.dtic.mil/sti/pdfs/ADA171183.pdf.