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Hydrodynamics Analysis of Sanur Port Construction on the Sanur Beach Area

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***Abstract*—Coastal construction can alter the landscape. The port's construction at Sanur Beach has affected sediment deposition on the northern breakwater. Satellite data shows an accretion rate of 61.8 meters from 2021 to 2022. This research analyzes the influence of hydrodynamic factors on Sanur Beach before and after port construction. To ensure the accuracy of our findings, we employed a meticulous research methodology, using Flexible Mesh modeling with a Coupled model to understand the dynamics of the hydrodynamic factors that occur. It was found that the dominant winds arise in the east and southwest directions, with the most significant percentage being east winds, which cause current directions with dominant intensity from north to south. Simulations show that after the construction of Sanur Port, bed level changes will occur in the western season of 2022 in the form of an increase in the depth of the bottom of the waters with an average of 1.00-1.25 m and the east season 1.25-1.50 m. Before the construction of the port, changes in the bottom of the waters tended to be lower, with an average change of around 0.16-0.32 m in the east season and 0.05-0.30 m in the west season. The simulation results showed that Sanur Port's construction caused sediment accretion at its southern end and erosion at the northern end. This research is essential for coastal management, providing insights into the effects of port development on coastal dynamics.**

***Keywords*—Bed level change; Sanur beach; sedimentation modeling; Sanur Harbor Bali; accretion; beach morphology.**

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I. INTRODUCTION

The marine environment is inherently dynamic, influenced by the movement of currents. These currents facilitate various chemical reactions that lead to the dissolution of materials, resulting in the corrosion of adjacent underwater structures and contributing to sedimentation in specific areas. This phenomenon poses significant challenges for structures such as bridges situated over water. Consequently, conducting hydrodynamic and chemical-hydrodynamic analyses is essential to understand these impacts better [1], [2].

Bali's coastline decreased by 6.05 km (3.76 mi) from 2016 to 2021 due to human activities and wave circulation at an average rate of -1.21 meters (3.97 feet) annually [3]. As an island with beach tourist visits, supporting facilities are essential in the beach area [4], [5], [6], [7]. Development in coastal areas generally tends to cause an impact and threat to the continuity of the function of coastal use because development activities increase over time, resulting in problems in coastal areas [8], [9], [10], [11], [12]. Problems on beaches that generally occur are in the form of accretion and erosion, which are characterized by changes in the coastline caused by sedimentation processes that occur or changes in morphology [13], [14]. One of the locations where changes in beach morphology occurred on the island of Bali that attracted attention occurred at Sanur Beach.

Sanur Beach is a beach that is used as a tourist attraction and is a crossing location that is often used as access for tourists to cross Nusa Penida [15]. To support these activities at Sanur Beach, complementary facilities have been built to support tourism activities, including Sanur Harbor. Sanur Harbor is located in Pakraman Sanur Kaja Village in Denpasar City; the coordinates are 8°40'13.1"S 115°15'40.0"E [16]. There are coastal changes at Sanur Harbor, including 31.2 m of accretion in the north and erosion in the south after port construction on Sanur Beach [17]. Therefore, this research investigates the impact of construction on current sedimentation issues.

The pattern of transport of sediment material in waters can be influenced by tidal patterns [18]. Tidal changes in water bodies can produce tidal currents [19]. This flow causes the movement of water circulation, which carries sediment material at the bottom of the water. This sediment movement is related to flow speed and sediment particle size. The flow velocity required to carry sediment particles is in line with the particle size, so the more significant the particle size, the higher the flow velocity required to transport the sediment material [20]. Moving sediment in waters depends on ocean currents and other oceanographic factors that have a significant impact, such as waves [21], [22]. As a wave approaches the shore, it will break into shallow water due to the change in depth [23]. These wave breaks will stir up coastal sediments, resulting in sediment movement at the bottom of the seas. Continuous sediment movement can result in sedimentation or erosion in the waters [24]. Therefore, studies on mitigating the impact of changes in the coastline at Sanur Harbor due to sedimentation are critical. The aim is to mitigate the impact of the construction of a building in a coastal area such as Sanur Harbor on changes in the contour of the bottom of the waters and changes in morphology over a certain period. This information has strategic value for those who manage the port in making decisions regarding area management on Sanur Beach [25].

Thus, research and analysis must include bottom sediment movement patterns through a modeling approach. Factors such as currents and waves are identified as the main influences in the sediment transfer process used as a basis for determining appropriate mitigation [26]. This sediment transfer modeling was carried out to understand the changes in the waterbed level that occurred in the waters of Sanur Harbor, Sanur Beach, Bali.

II. MATERIALS AND METHODS

The method stages in processing the data that has been collected along with other supporting data are carried out by processing the data to create a simulation of a sediment material transport model from the data that has been processed. The stage begins with collecting tidal data in the Sanur Harbor area. After obtaining tidal data in the Sanur Harbor area, the tidal data is then processed by processing the tidal data into the MIKE 21 software using the Time Series module [27]. The second data is bathymetric data, which is processed using the ArcGIS program to be converted into points to create boundaries. The following process is digitizing the port and coastline around the port using Sentinel-2 Satellite imagery as in Figure 1 to obtain softcopy data on port maps carried out in the years before and after the construction of Sanur Port. The digitized data must be converted into (.xyz) format so the MIKE 21 flow modeling processing software can read the port digitization results.

The processed data is in the form of data in (.xyz) format and then imported into the MIKE 21 software using the mesh generator module. The first step in processing sedimentation modeling is creating a mesh. Boundary conditions must also be determined to distinguish between ocean and land. After that, the mesh is interpolated and exported into (.mesh) file format. The sedimentation model simulation in this study uses the MIKE 21 auxiliary program with a timestep of 1 month in each of the dominant wind seasons, namely west and east in the year under review, namely 2020 and 2022.

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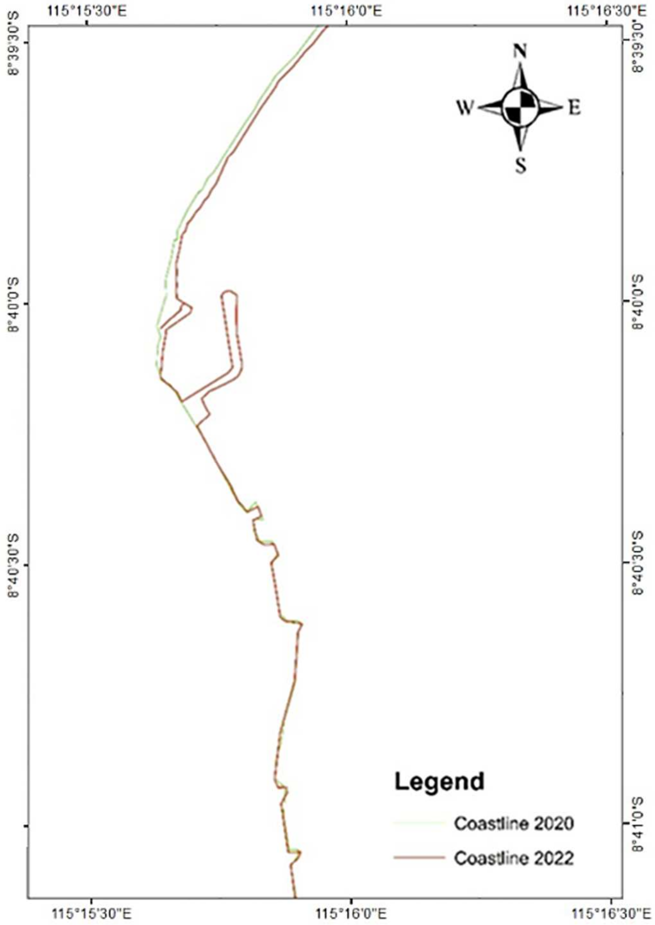

Fig. 1 Coastline Changes in 2020 and 2022 with the Sentinel-2 Satellite

The parameters entered are tidal data and harbor pool bathymetry. Other physical parameters such as density, eddy viscosity, tidal potential, and Coriolis forcing are entered as default values. In the sediment transport model simulation, parameters of sediment characteristics were used, namely sediment grain size and downstream recharge of the Ayung River of 2.93 m^3/second, data obtained from BWS Bali-Penida. The output of the sediment transport model simulation is the area series. The regional distribution pattern of sediment material transport is analyzed at the analysis stage. Analysis was carried out on bed-level sediment changes in the harbor pool. The method used to analyze sediment movement in the Sanur Harbor area is described by applying Sand Transport (ST) modeling techniques using MIKE 21 software. The ST model in the MIKE 21 tool is a tool that studies sediment movement with non-cohesive properties [28], [29]. For its implementation, the ST model is applied simultaneously (couple) with the MIKE 21 Flexible Mesh (HD FM) Hydrodynamic model [30].

The advantages of the MIKE 21 HD FM model compared to the MIKE 21 HD Classic model include the ability to create grids flexibly, especially in dealing with the complexity of the domain contour, which can be described in its entirety. This model shows a good correlation for bases that have high Manning number values (32 $m^{1/1/3/s}$) and is suitable for areas where sediment transport is mainly influenced by waves so that the combined wave and current model provide more realistic results [31], [32], [33].

A. Coastal Hydrodynamics Analysis

After learning about the pattern of changes in the coastline at Sanur Beach, the next step is to conduct an in-depth analysis of coastal hydrodynamics, the dominant factor in these changes. This analysis involves evaluating several main factors that influence coastal conditions according to [34], [35] namely wind, wave, sedimentation, and ocean current factors. First, wind factor analysis was carried out by considering wind speed, wind direction, and wind patterns in the Sanur Beach area. Historical data on winds collected over the past few years are used for a deeper understanding of how winds can influence water flow and sediment movement on these beaches [36], [37].

Furthermore, wave factor analysis is an essential component in understanding coastal hydrodynamics. Wave height, wave frequency, and wave direction are evaluated to identify their impact on shoreline changes [38], [39]. Accurate data collection and ocean wave measurements are the first steps in analyzing this factor. Sedimentation factors must also be investigated, considering that the movement of sediment, such as sand and gravel, is an essential element in forming coastlines [17]. Sedimentation analysis includes understanding sediment resources, changes in sediment supply, and redistribution of sediment along the coast [40], [41].

Lastly, analysis of ocean current factors will include understanding local ocean currents, flow direction, and intensity. This factor plays a role in directing sea water and sediment movement along Sanur Beach. All these analyses help in detailing the factors that contribute to shoreline changes, which in turn can help in designing more effective coastal management strategies [42], [43].

B. Mitigation

Mitigation is carried out by adopting a series of actions adapted to the pattern of changes in the coastline and the base layer on Sanur Beach while considering the prevailing hydrodynamic patterns of the coast. These measures are designed to create an accurate representation of coastal environmental conditions to protect coastal morphology and maintain the operational continuity of Sanur Harbor [44]. First, in the context of shoreline change, mitigation can include coastal restoration efforts such as planting coastal vegetation, building coastal protective structures such as levees or seawalls, or even removing infrastructure threatened by coastal erosion [45], [46]. This action aims to stop or slow the rate of change in coastlines and maintain stable coastal conditions.

Furthermore, in the face of changes in the base layer, mitigation may involve surveying and better understanding of the characteristics of the base layer around Sanur Harbor. This can lead to planning or modifying port designs to suit the situation. Figure 3 shows the sedimentation pattern in the east season of 2022 in the Sanur Harbor area. Sediment movement tends to resemble the west monsoon towards the harbor pool or south. However, there were more significant changes in depth in the breakwater area, where the highest change reached 1.25-1.50 m within one month.

changing bed conditions over time. Routine maintenance and monitoring of the base layer can also be an essential part of mitigation [47]. Regarding coastal hydrodynamic patterns, mitigation may involve current management or planning to deal with specific wave surges. This can include the use of protective structures such as groynes or breakwater, which can reduce the impact of currents and waves that can damage coastlines or port infrastructure [48].

III. RESULTS AND DISCUSSION

The analysis was carried out using the results of calculations and model simulations of hydrodynamic factors regarding changes in the coastline that occurred before and after the addition of the Sanur Harbor structure.

A. Bed Level Change Simulation

In Figure 2, the condition of the Sanur Harbor area is shown in the western season, namely January 2022. In this picture, you can see changes in sedimentation around the Sanur Harbor area within one month. Changes in sedimentation can be observed from the sediment movement towards the harbor pool. The picture shows that the sediment is moving toward the harbor pool, with the highest change in layer thickness reaching 1.00 - 1.25 meters. This shows the area's accretion or sediment accumulation for one month.

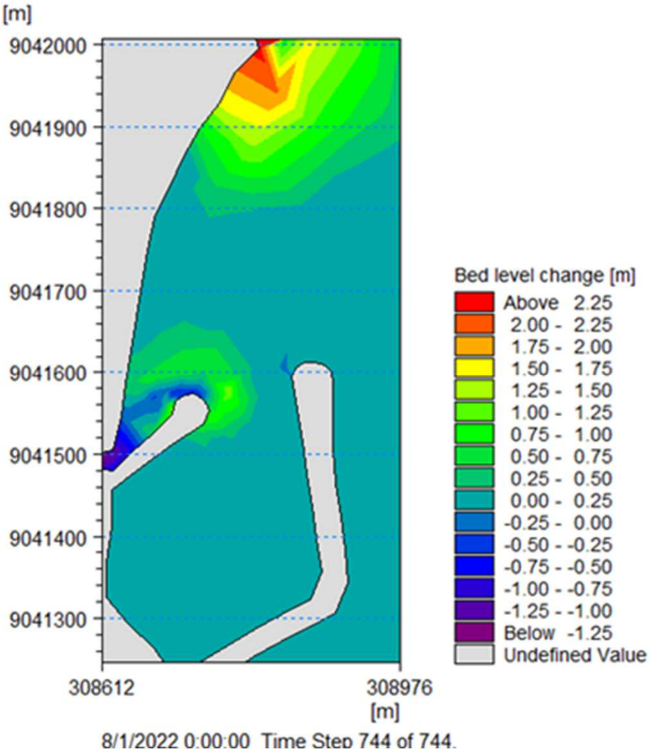

Fig. 2 Bed Level Change West Wind Season

Additionally, sedimentation movement can be seen north of the Sanur Harbor area. This movement causes changes in the base layer with a height above 2.25 meters. This indicates higher sediment accumulation in the area during the same time. Thus, the visualization results in Figure 2 provide information about changes in sedimentation that occur around

Sanur Harbor for one month during the western season. This information can be used to understand sedimentation dynamics in harbor areas and estimate changes in coastal morphology associated with these processes. However, sedimentation patterns need to be compared to the conditions of the east monsoon in the same year, namely 2022.

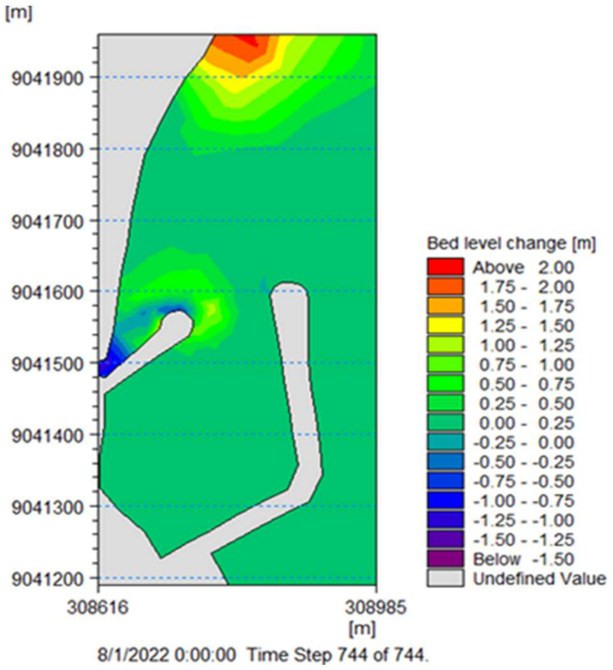

Fig. 3 Bed Level Change 2022 East Wind Season

Additionally, sedimentation patterns can be seen from the north with more significant changes, reaching more than 2.00 m. Based on these results, it can be concluded that the sedimentation pattern at Sanur Beach tends towards the south. However, the results obtained before mitigating the direction of bed level change tendencies require an analysis of the coastal hydrodynamics that occur at Sanur Beach.

B. Coastline Changes

Based on the results obtained, the direction of sedimentation is towards the south. If the process continues continuously, accretion will occur in the northern part of the port and erosion in the southern part. This is proven by analysis using Sentinel-2 imagery in 2021- 2022 and 2022-2023. Based on the pattern in Figure 4, the blue part is indicated to have experienced accretion. In contrast, the red is shown to have experienced erosion, resulting in a significant accretion in the northern part of Sanur Harbor, as shown in Figure 4. The highest accretion was located just north of the breakwater with a respective rate of change of 39.34 m, 54.76 m, 61.8 m, 48.53 m, and 26.58, and the respective areas are 1625.33 m, 1445.382 m, 933.50 m, and 357.34 m. Meanwhile, the southern part of the port is experiencing erosion on the south side of the port at a rate of 2.55 m.

Furthermore, an analysis was carried out in the following year, namely 2022-2023, to prove that the trend of change that occurred was continuous, changes as in Figure 6 in 2022-2023 obtained the results of the dominant changes that occurred in 2022 to 2023 based on the overall pattern of changes in the advance or retreat of the coastline. some changes are similar to the previous year, namely accretion in the northern part of Sanur Harbor and higher erosion, namely a maximum of -2.05 m average erosion rate with a maximum change of -9.91 m in the southern part of the harbor. Overall, the dominant change continues to experience accretion, with the highest total shoreline increase right in the northern part of Sanur Harbor, as in Figure 6.

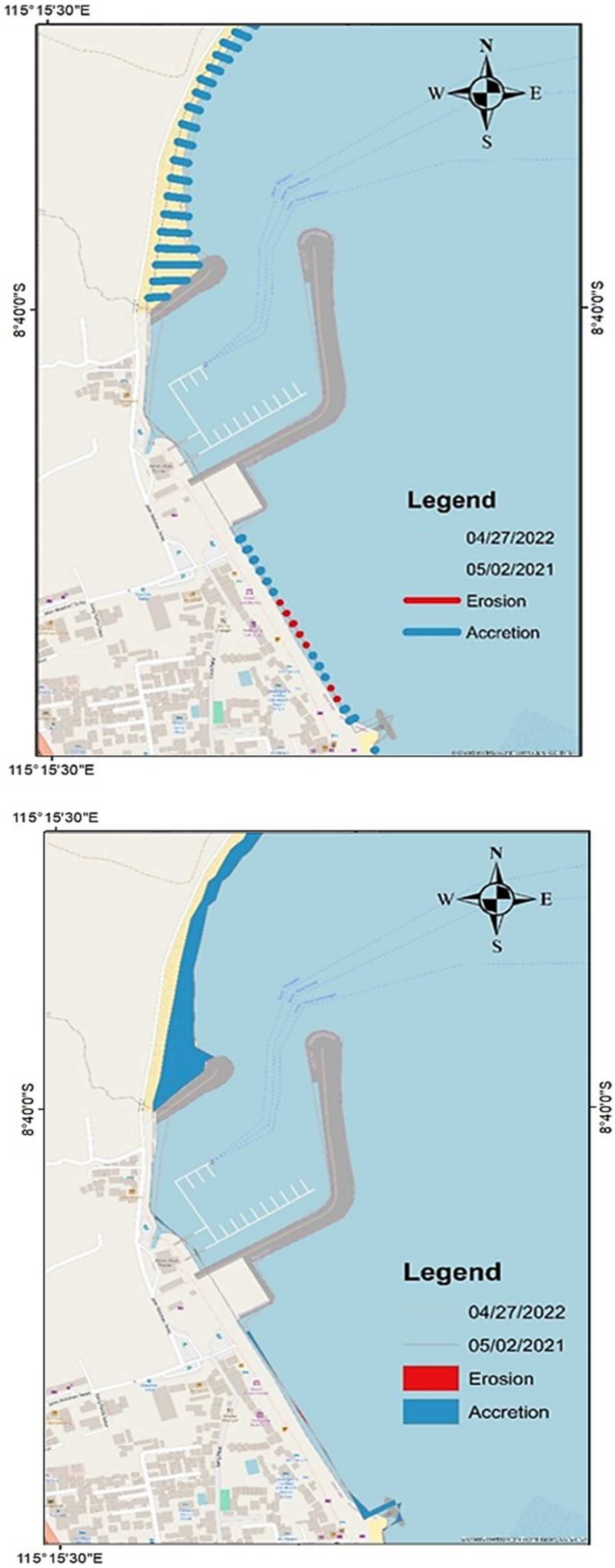

Fig. 4 Changes in Sanur Coastline in 2021-2022 in (m/year) (Left) and (m2) (right)

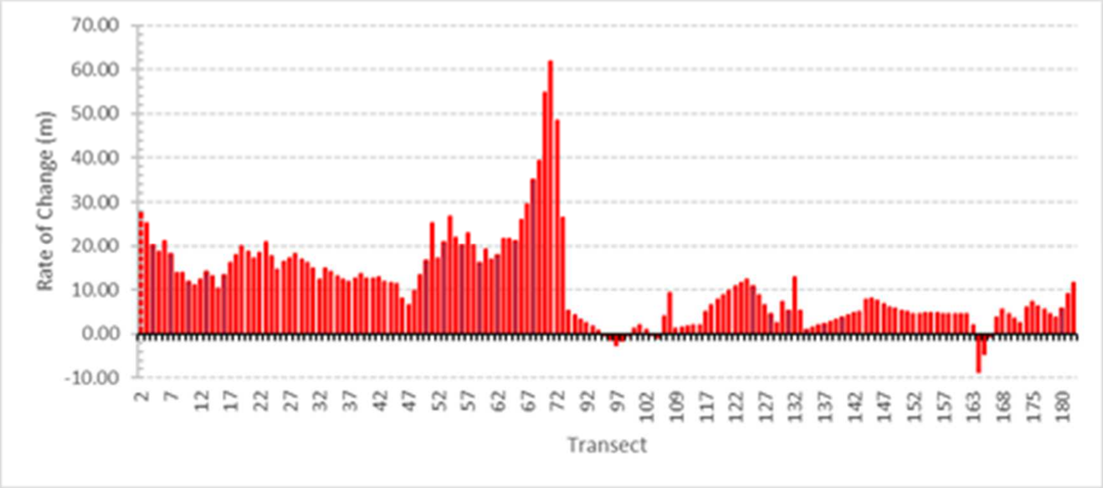

Fig. 5 Graph of Changes in Sanur Coastline 2021-2022

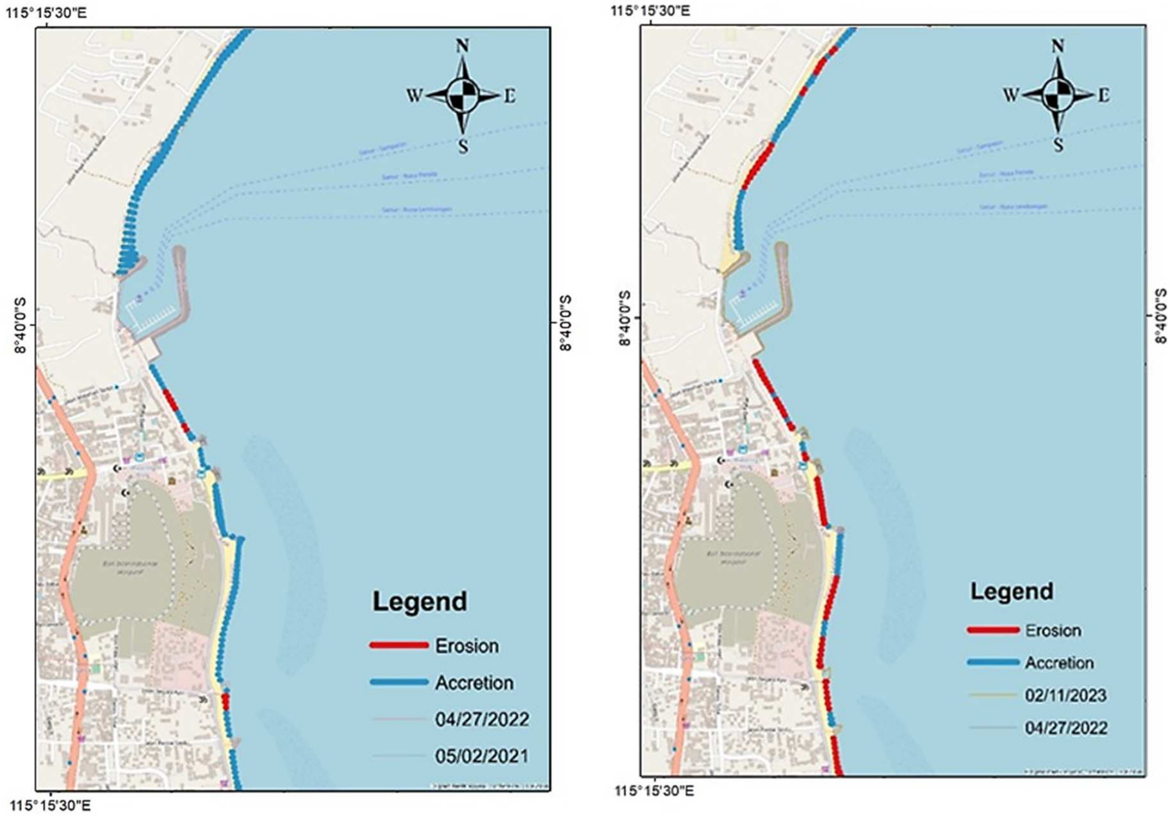

Fig. 6 Sanur Coastline Changes 2021-2022 and 2022-2023

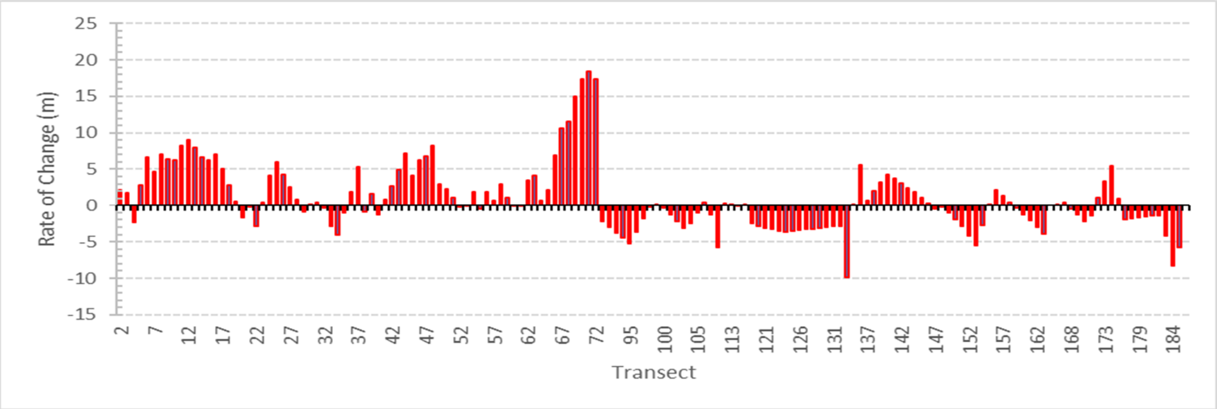

Fig. 7 Graph of Changes in Sanur Coastline 2022-2023

By obtaining results in the form of sedimentation tendencies from north to south based on previous bed level changes and proven by the results of analysis using satellite imagery that the tendency of sedimentation patterns results in morphological changes in the form of changes in the coastline in the northern part of Sanur Harbor in the form of accretion and the south of Sanur Harbor in the form of erosion, Next, an analysis of the hydrodynamics that occurs is needed to be used as a first step in determining appropriate mitigation.

C. Wind Direction and Speed

The hydrodynamic analysis begins with the wind factor, which occurs because wind influences the movement of sea waves; wind is one of the wave generation variables, while waves influence the sedimentation of a beach where the sedimentation process or sediment transport is based on wind data for 2018 - 2023, namely from the year before and after the construction of Sanur Harbor, a graph of wind speed and direction was obtained in Figure 8.

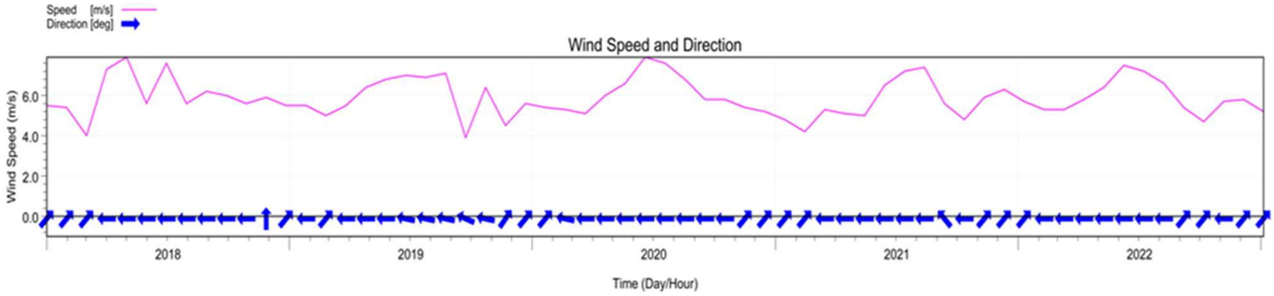

Fig. 8 Wind Recording Data at BMKG Ngurah Rai Station 2018-2023

In general, the characteristics of wind direction movement in the recording area, namely Denpasar City, blow from the East and Southwest with a frequency of 66.13% East with a highest speed of 7.9 km/hour and Southwest of 30.65% with the highest speed of 6.3 km/hour. Based on this data, it can be concluded that the East and West monsoons dominate the windy season for the Denpasar area.

The average change in wind direction and speed for each month from 2018 to 2023 shows that the east dominates the wind direction from April to October with an average percentage of 57%, while in November, there is a transition between East and Southwest, for December until February the Southwest and West directions dominate it, then in March there is a transition between the West and East seasons. Based on these results, when compared with the position of Sanur Beach, which stretches between the Northeast to the Southwest direction and the confluence of the South to North direction, which is correct at the location of Sanur Harbor, then the dominant east and southwest winds can influence the direction of sediment transport from the sea to Sanur Beach, towards the Northeast and South West parallel sides in each wind season.

D. Wave Height and Period

The next hydrodynamic factor is the wave factor. Sea waves significantly influence coastline changes with the potential for erosion, sediment deposition, and the formation of coastal structures such as dunes, deltas, and spits [49], [50]. High wave energy can cause coastal erosion and accretion. Waves reaching shore can erode and carry sediment, resulting in a lowering of the coastline. However, waves can also cause sediment deposition when their energy is sufficient. The position of maximum accretion on Sanur Beach is influenced by the direction of the waves, which can move sediment horizontally.

In addition, the interaction of waves with the coast can also form coastal structures such as dunes, deltas, and spits. These can influence the shape of the coastline and patterns of change and sediment deposition around it. Wave analysis at Sanur Beach was conducted based on wind data to understand its impact on coastline change patterns and sediment distribution in the area.

Wave height and period significantly influence shoreline changes because they are closely related to sediment transport. Wind analysis data shows that the wave height at Sanur Beach ranges from 1,273 meters for a return period of 2 years with a wave period of 5,162 seconds and 1,588 meters for a return period of 100 years with a wave period of 5,537 seconds. Even though the wave height is still under 3 meters, which is considered high and has the potential to cause significant damage, the relatively short-wave period of under 6 seconds has high kinetic energy, which can affect coastal sediment erosion. Therefore, the wave period at Sanur Beach tends to be a factor that influences changes in the coastline.

TABLE I
WAVE HINDCASTING FISHER TIPPET TYPE I METHOD

Return period Tr (Year)	Wave Period (s)	Wave Height (m)
2	5.162	1.273
5	5.256	1.350
25	5.409	1.479
50	5.473	1.533
100	5.537	1.588

E. Sea Current

Plays a vital role in changes in coastlines and sedimentation in coastal areas. Ocean currents carry water along the coast and interact with the coast and sediments, having a significant impact. Currents can influence shoreline changes through two main mechanisms: transporting sediment and influencing sedimentation. It is essential to understand the characteristics of ocean currents, such as their speed, direction, and variability, through modeling and monitoring. An analysis of the direction of currents and the impact of the placement of Sanur Harbor will be carried out on Sanur Beach to understand the interaction between ocean currents, sediment, and changes in coastlines in the area.

Analysis of ocean currents after the construction of Sanur Harbor using data for 2022. Two windy seasons are used to run the model: the east season (July) and the west season (January). These two seasons are chosen at the time of the lowest tides and highest lowest tides. The highest tide will occur on January 1, 2022, and the lowest low tide will be on January 7, 2022. Meanwhile, in the east season in July, the highest tide will occur on July 13, 2022, and the lowest low tide will be on July 19, 2022.

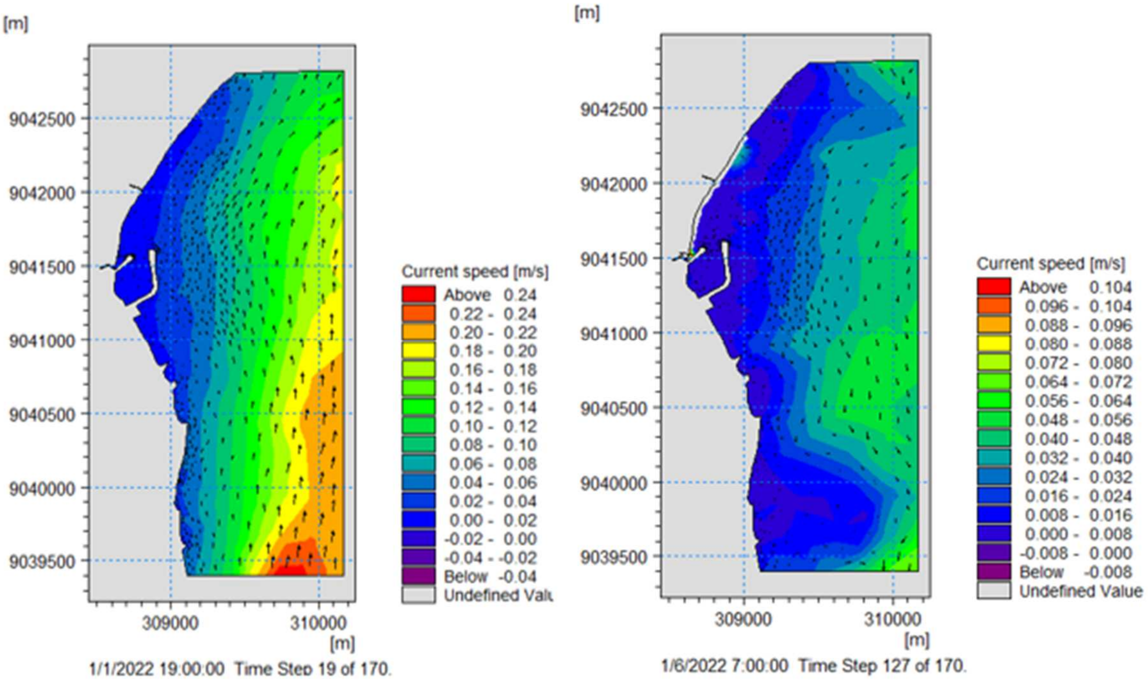

Fig. 9 Sanur Beach current pattern in the west season at the highest tide

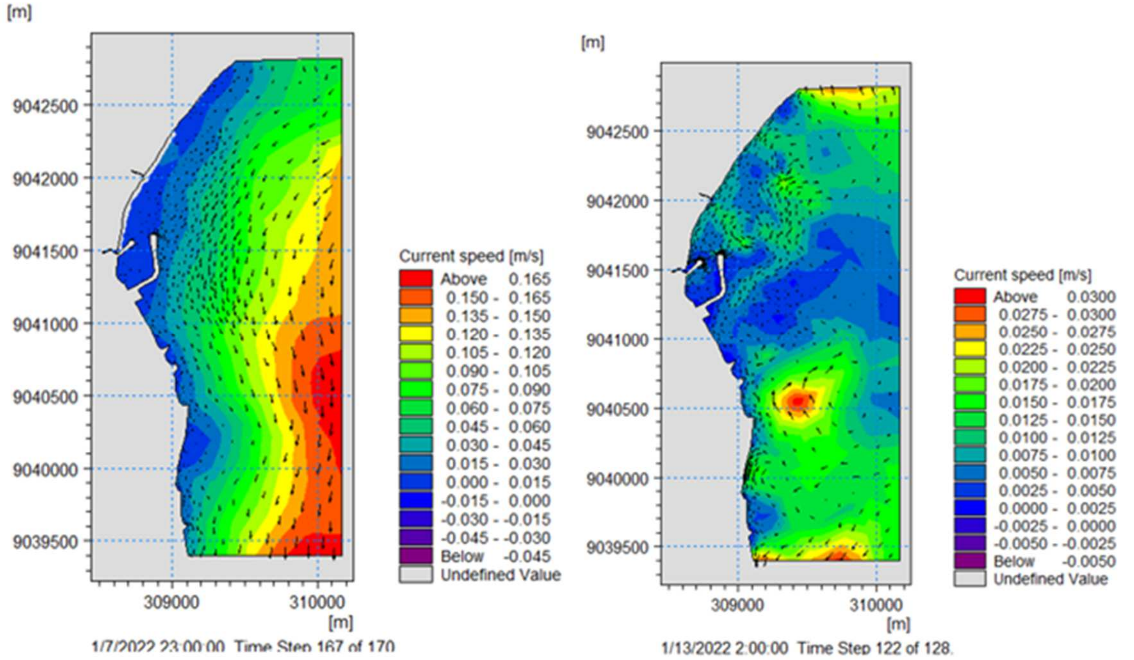

Fig. 10 Sanur Beach current pattern in the west season at the highest tide

Current trends from north to south. In the West season, both at the highest tides and lowest low tides, for a more comprehensive understanding, it is necessary to compare these results with the pattern of current direction in the East season. The east monsoon has a more extended dominance throughout the year, so current changes during this season must be considered. The model results of the current pattern during the east season at the highest tide (13 July 2022) and the lowest ebb (19 July 2022) are as follows.

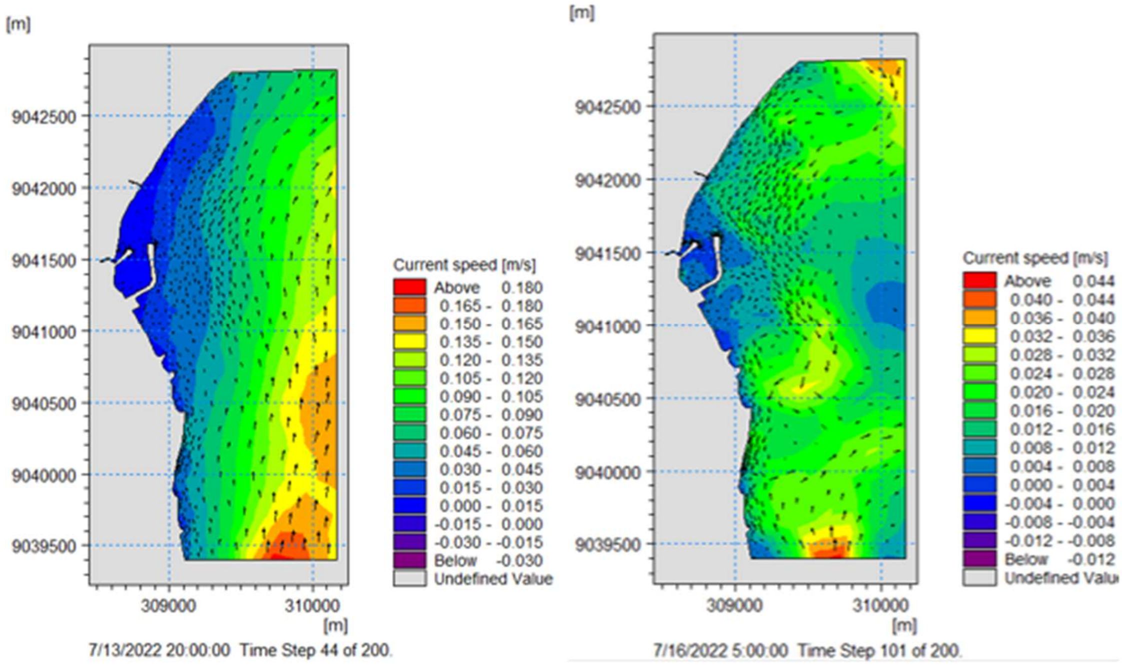

Fig. 11 Sanur Beach Current Pattern East Season at Highest Tide

Based on Figure 11, during the highest tide in the east season, the current pattern generally flows from south to north with varying speeds. The highest current speed reaches above 0.180 m/s, while the lowest speed ranges from 0.00 to 0.15 m/s. Some currents also move in the opposite direction at speeds of 0.00 to 0.030 m/s. The change in flow direction occurred on July 16, 2022, with a switch from south-north to north-south flow. The change in current direction at the highest tide is three days, from July 19, 2022, to July 16, 2022. These results need to be compared with the current pattern at the lowest ebb in the east season to determine the duration of the change in the current pattern at various speeds. Next, we explain the current pattern at the lowest low tide in the 2022 east season.

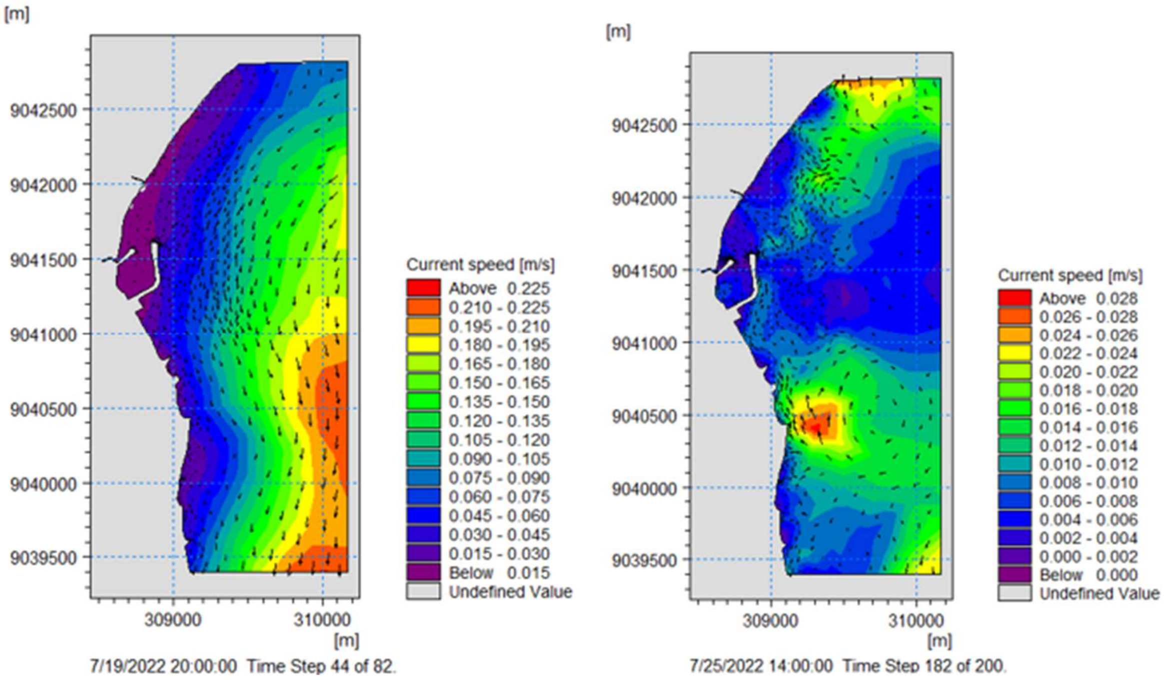

Fig. 12 Sanur Beach Current Pattern East Season at Highest Tide

The results in Figure 12 illustrate the current pattern during the lowest low tide at Sanur Beach in the east season. This current pattern tends to flow north to south or vice versa at the highest tide. The current speed varies, with the highest speed reaching 0.225 m/s and the lowest ranging from 0.015 to 0.030 m/s. This pattern occurs at the lowest ebb and about six days afterward, when there is a change in the current direction on July 25, 2022.

From these results, it can be concluded that the current from north to south takes around six days, which is longer compared to the highest tide conditions, which only take around three days. This indicates that the flow from north to south is more prolonged. In the context of Sanur Beach in 2022, with the structure of Sanur Harbor, especially the breakwater facing north, these results show that the dominant current direction with higher intensity is from north to south. This current pattern has the potential to influence sedimentation around the breakwater area, which can cause accretion or accumulation of sedimentary material in the northern part of the breakwater [51].

Based on hydrodynamic analysis and simulations of sedimentation and changes to the coastline with current conditions that tend from north to south and the amount of sedimentation, the pattern of morphological changes that will occur will tend to continue the same as in 2022, with accretion in the northern part of the port and erosion in the southern part of the port for the coming year.

Fig. 13 Sanur Beach Current Pattern East Season at Highest Tide

IV. CONCLUSION

Based on the research results related to changes in the coastline at Sanur Beach, it can be concluded that the construction of Sanur Harbor has had a significant impact on the dynamics of the beach. Before the construction of the port, Sanur Beach experienced erosion at an average rate of -2.75 m2 per year in 2018-2021. However, after the construction of Sanur Harbor in 2022, there will be a change in the trend toward accretion, with an average rate of 11.00 m2 per year in the 2021-2022 period. The main factor influencing changes in the coastline is the addition of the Sanur Harbor structure. The dominant east and southwest winds are essential factors, with the east wind having the most significant contribution. The port structure also influences the direction of currents and sediment transport, especially at the southern point of Sanur Harbor. The breakwater harbor obstructs sediment supply, resulting in accretion in the northern harbor and erosion in the southern harbor.

Future studies should focus on long-term monitoring and modeling of sedimentation and erosion patterns, especially after port construction and environmental changes. Research could examine climate change impacts on sediment transport and coastal dynamics at Sanur Beach, such as rising sea levels and increased storm intensity. Exploring natural and hybrid infrastructure solutions, like mangrove replanting with breakwaters, could offer sustainable coastal protection insights. Additionally, assessing the ecological impacts of sedimentation and erosion on local ecosystems would enhance the study's value. Comparative studies with similar coastal developments in Bali or elsewhere could provide a broader understanding of hydrodynamic patterns and their mitigation.

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