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Simulation of High Wave Inundation at Payangan Beach Using Delft3D for Coastal Mitigation

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A B S T R A C T

The south coast of Indonesia has a high risk of high waves. The community around Payangan Beach was one of those affected by the high waves, which caused damage to various buildings and inundation. One of the disaster mitigations to reduce the impact that occurs is to do inundation modeling. This study aims to model inundation due to high waves on Payangan Beach using Delft3D software. Wind, bathymetry, and tide data are used as model input data. The model was created using Delft3D-FLOW for tides while Delft3D-WAVE for waves. After the program is executed, the height and area of the inundation and significant wave height will be obtained. The modeling results will be validated with existing condition data using the Root Mean Square Error (RMSE). The modeling results show that the inundation height is 1.96 meters, the significant wave height is 2.45 meters, and the inundated area is 300 meters from the coastline, with 100 houses potentially inundated with an area of 187.4 m2. The validation results show that the model is quite good, with an accuracy of 96.88%. From these results, the Government of Jember was able to make a mitigation map for the inundation area on Payangan Beach and build a Sea Wall. So that in the future, high-wave disasters can be minimized.

1. Introduction

Indonesia is the largest archipelagic country in the world, with a coastline of 99,093 km [1]. One of the beaches in Indonesia is on the south coast. This beach crosses from Serang Banten to Banyuwangi, East Java. The beach is vulnerable to coastal disasters such as high waves [2]. It was recorded that 1913 villages in Indonesia were affected by high waves in three years (2019-2021) [3]. Villages around Payangan Beach (south coast in Jember Regency) also experienced high wave disasters reaching 5.5 meters, recorded on 27 May 2020. These events caused tidal floods, damaged various houses and facilities, and caused inundation [4].

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This shows that high waves have the potential to increase the level of vulnerability to flooding in coastal areas. High waves will occur when the wind that blows above sea level is large. The stronger the wind, the bigger the waves are formed. In addition, the influence of the moon's gravity can also affect the formation of high waves [5]. High waves can occur suddenly and are dangerous for human life [6], [7]. Therefore, mitigation is needed to reduce the impact of high waves, one of which is by modeling inundation [8]. Inundation modeling cannot deal with high waves directly but can assist in planning the right coastal infrastructure to reduce the impact of the damage caused [9]. In addition, inundation modeling can also assist in planning an appropriate early warning system [1].

Inundation modeling can be done using several software such as HEC–RAS [10], MIKE Flood [11], and Delft3D [12]. Inundation modeling using the integration between Delft3D, WaveWatch III-SWAN, and SOBEK can produce flood inundation models in Jakarta and provides good accuracy [1]. In addition, Delft3D can simulate and predict the water level that causes beach inundation in the coastal area of Medan Belawan with a correlation of 0.92 and an RMSE of 0.39 meters [13]. Apart from inundation, Delft3D can also model tsunamis caused by earthquakes [14], [15]. Delft3D is widely chosen in hydrodynamic modeling because it can simulate various processes, including eutrophic, waves, tides, seawater intrusion, and water quality [16]. Utilizing Delft3D, inundation on Payangan Beach can be modeled, considering that no research has focused on this.

This study aims to model inundation due to high waves on Payangan Beach using Delft3D software. From the modeling, you will get the height of the inundation, the significance of the high waves, and the area of the inundated area. These results are expected to be used as mitigation for high-wave disasters in the future in order to minimize their impact.

2. Research Method

The research begins with identifying the problem of inundation in Payangan Beach, and then a literature review is carried out. After that, data collection (primary and secondary) was carried out. Some data, such as wind data, bathymetry, and tides, must be processedt before creating an inundation model in Delft3D [17]. Finally, each data processed will be used as an input model. While inputting all data into the model, the parameter will be set. The running simulation can start after all this process has been done. The simulation can be visualized on graphics and figures after completing the running process. The output of this model shows wave height and inundation area on the location. This result is being compared with the primary data to validate using Root Mean Square Error calculation [18].

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2.1 Research Location

The inundation simulation was located at Payangan Beach, Ambulu District, Jember Regency. The study location was inundated due to high waves on 27th May 2020. The observed areas are the location of the stalls and lobster warehouses which were damaged by high waves, as shown in **Figure 1.**

Source: Google Earth.

Figure 1. Research Location.

2.2 Data

Primary data is obtained through observation location and interview surveys at Payangan Beach. The results of field surveys and interviews with residents around Payangan Beach are the primary data used. Primary data is used to validate the inundation results of coastal flooding against the results of modeling inundation. Secondary data includes wind data, bathymetry data, and tidal data. The data obtained are as follows:

- Wind Data

  Wind speed data is obtained by making measurements directly above sea level or on land close to the location of the wave forecast [18],[19]. The wind data for hindcasting is wind data above sea level at the generation location. Wind speed data is measured at 10 meters above sea level in the hindcasting process. If the wind is not measured at an elevation of 10 meters, it is necessary to calculate the height correction. Daily wind data has been obtained from the official website of the BMKG Banyuwangi Station for ten years, from September 2011 until September 2021.

- Bathymetry Data

  Bathymetry data were obtained from the Badan Informasi Geospatial (BIG) official website. Bathymetry data is used as input for sea depth elevation data. Bathymetry data input is done by entering the coordinates of the research location in the QGIS program [20]. The

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bathymetric coordinates were used at the 2 points of the maximum and minimum latitude-longitude areas shown in **Table 1.**

Table 1. Bathymetry Location Coordinates.

Latitude	Longitude
8° 24' 47.04"	113° 32' 12.26"
8° 29' 55.49"	113° 37' 22.52"

Source: Research Method.

- Tidal Data

Tidal data was obtained from the official website of the Badan Informasi Geospatial (BIG) and taken at one coordinate point of the research location. The tidal duration of the modeling was used for 49 hours (26^{th} May 2020 at 00:00 to 28^{th} May 2020 at 00:00). The tides included in the modeling contain water level elevation data during the period under review.

2.3 Wind Data Analysis

The wind speed obtained on land must be converted to wind speed above sea level through location correction. In order to determine the wind speed correction based on the height, location, and wind stress factors, the following equation is used:

$$U(10) = U(y)(\frac{10}{y})^{1/7} \tag{1}$$

$$R_L = \frac{U_W}{U_L} \tag{2}$$

$$U_A = 0.71U^{1.23} \tag{3}$$

Where U(10) is wind speed measured at the height of 10 meters; U is wind speed corrected; y is elevation; R_L is the relationship between the wind speed on the sea and the land; U_W is wind speed on the sea; U_L is wind speed on the land; and U_A is wind speed corrected by a wind stress factor.

The generation of waves in the ocean due to the wind is affected by the fetch length. In wave formation, wave generation is influenced by wind direction and various angles to the wind direction. For determining the length of fetch, the following equation is used:

$$F_{eff} = \frac{\Sigma X_i \cos\alpha}{\Sigma \cos\alpha} \text{ [18]} \tag{4}$$

Where F_{eff} is the mean fetch length effective; X_i is the length of fetch segment measured from wave observation point up to the end of fetch; α is a deviation on both sides of the wind direction using the addition of multiple angles of 6^o on both sides of the wind direction. Forecasting the height and period of significant waves is carried out by the hindcasting process [21]. The hindcasting process used wave forecasting equations and nomogram graphs.

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2.4 Delft3D Modeling

Delft3D-FLOW and Delft3D-WAVE are used for wind wave modeling at Payangan Beach. Delft3D-FLOW is used to model tides, while Delft3D-WAVE is used to model waves generated by wind. By modeling the inundation, the Delft3D-FLOW model and the Delft3D-WAVE model will be run simultaneously in the coupling model process. The program is run, and a significant wave height and inundation area will be obtained.

2.5 Inundation Model Validation

Observation points to measure the height of the inundation on the mainland. Then, the validation process compares the inundation height from the field survey observations and the model inundation height using Root Mean Square Error calculation [22]. The equation of Root Mean Square is:

$$RMSE = \sqrt{\Sigma_{i=l}^{N}(\frac{x_i - y_i}{N})^2} \quad [23] \tag{5}$$

X_i is the existing value, y_i is the model value; and N is the data amount. Furthermore, the model inundation area is compared with the inundation area from the observation location. In determining the inundation area from the modeling, the results of the image plot in Delft3D are entered into Google Earth. Then, the image is overlaid, and the flooded area is calculated [24].

3. Results and Discussions

3.1 Wind Data

The recapitulation of wind direction and speed data is shown in **Table 2.**

Table 2. Recapitulation of Maximum Wind Speed and Direction for 10 Years.

Direction	Maximum Wind Speed (m/s)				Total Wind Data
	0-3	4-7	8-11	12-38	
North	33	129	6	0	168
North East	84	363	23	1	471
East	143	227	9	1	380
South East	294	686	6	0	986
South	299	502	4	1	806
South West	173	228	3	0	404
West	76	90	1	2	169
North West	16	19	0	0	35

Source: BMKG Banyuwangi Station.

Table 2. shows that the primary wind direction dominates in the south direction. The maximum wind speed that occurs in the south is 13 m/s. The spread of the wind based on its direction and speed is shown in **Figure 2**.

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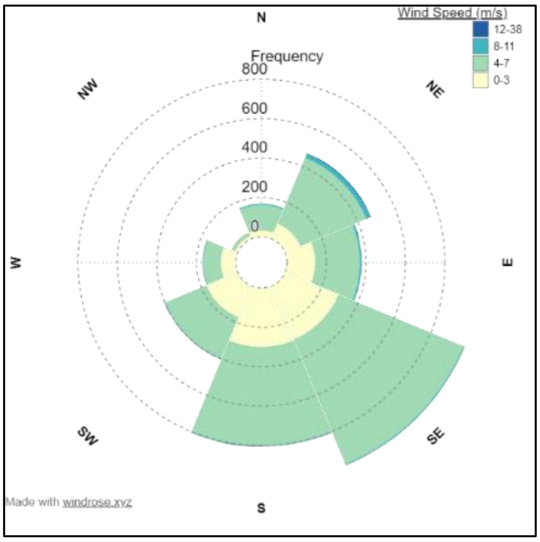
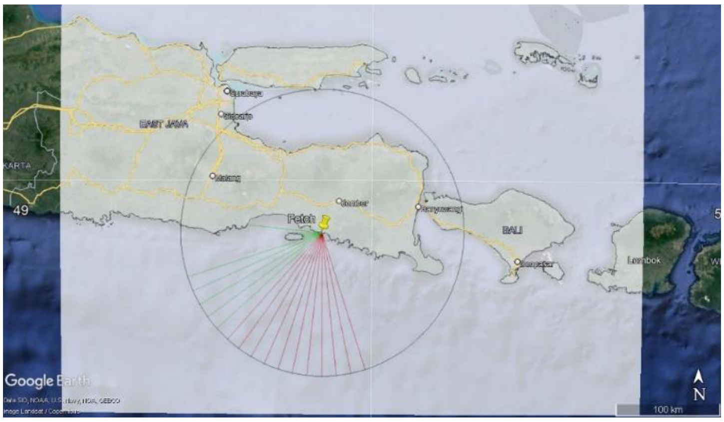


Source: Windrose.xyz.

Figure 2. Windrose.

Based on **Table 2**, the south direction is the dominant primary wind direction with a maximum wind speed of 13 m/s. Therefore, to carry out wave modeling, wind data on land must be changed and corrected to become wind data over sea level. The corrected wind data results in a wind speed of 14.8 m/s.

The determination of the wave fetch length is carried out at a radius of 120 km. Fetch is taken at 0° angle starting from the south. The effective fetch length is obtained by measuring the line length from the observation point to the right and left at 6° intervals [25], as shown in **Figure 3.**



Source: Google Earth and Author Analysis.

Figure 3. Fetch Length.

Based on **Figure 3.** the effective fetch length is 102,3008 km. Through the calculation of wind data analysis, the maximum wind speed is 14,8 m/s, and the length of fetch effective is 102,3 km. The wind factor produces a significant wave height (Hs) of 2,45 meters and a peak wave period (Ts) of 7,2 seconds.

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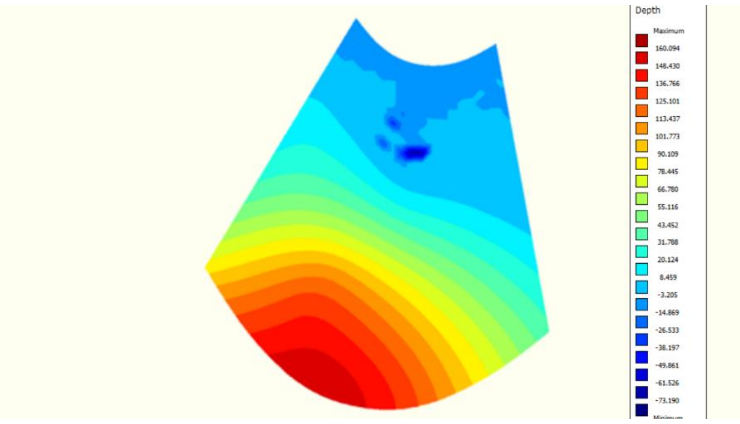
3.2 Bathymetry Data

The bathymetric data input entered into the Delft3D model is shown in **Figure 4.**



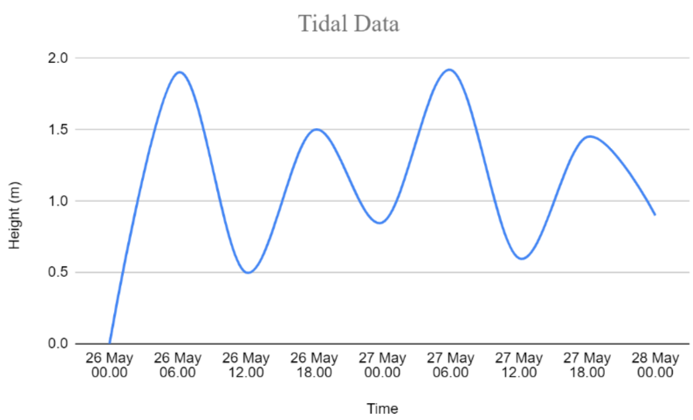
Source: Delft 3D Model.

Figure 4. Bathymetry Data.

The bathymetry data reveals that the maximum sea depth is 160.094 m.

3.3 Tidal Data

The tidal data obtained is illustrated in **Figure 5.** below.



Source: BIG Website.

Figure 5. Tidal Data.

Based on the graph, the height reached 1,9 meters, while the lowest height was 0.5 meters. This data will be used as modeling input in Delft3D.

3.4 Water Level

Inundation modeling using Delft3D shows changes in water level elevation that occur at point A. Point A is a monitoring location with coordinates 8°26'34,62" S and 113°34'38,50" E, shown in **Figure 7**. The function of these points is to monitor water level changes for 49 hours. The change in water level at point A is shown in **Figure 6**.

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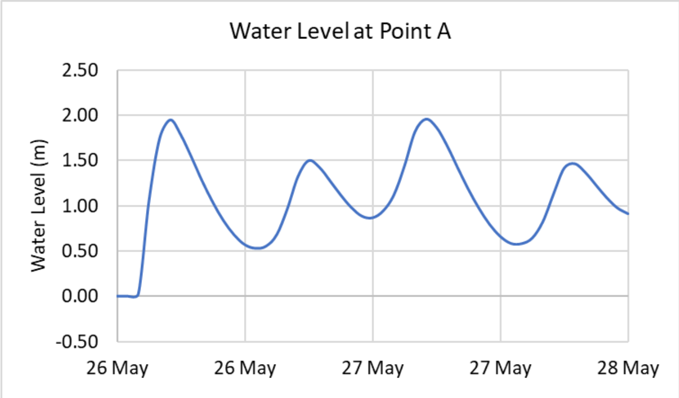
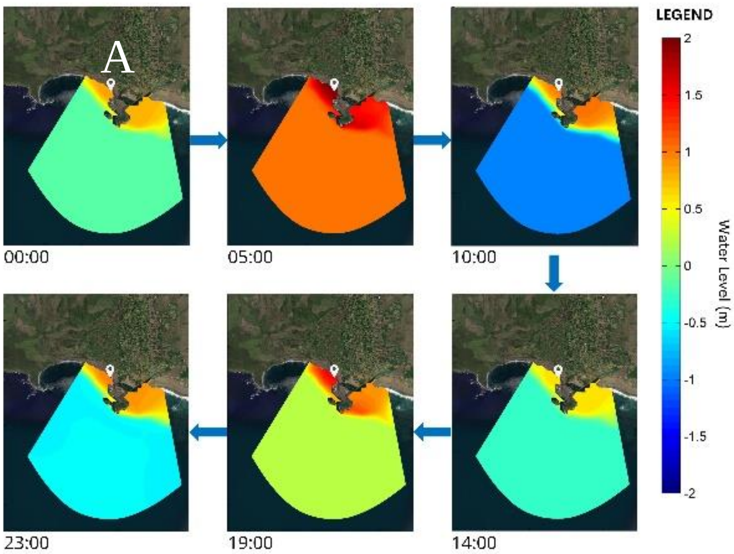


Source: Research Result

Figure 6. Water Level Changing in 49 Hours.

The water level at point A indicates the inundation caused by waves entering the mainland. Based on the graph of changes in water level shown in Figure 5, the maximum water level at point A occurred at 05:00 WIB with a height of 1,96 meters. Within 49 hours, the maximum water level changes occurred on 26th May 2020 and 27th May 2020. The water level reached 1,95 meters and 1,96 meters, respectively. The wave height at Payangan Beach is quite high and can be dangerous for the surrounding community. Figure 6 shows the chronology of changes in water level caused by high waves on 27th May 2020.



Source: Research Result.

Figure 7. Water Level Changing on 27th May 2020 Using Delft3D.

The red areas are areas that have the potential to be hit by high waves of up to 2 meters, while the green to blue areas indicate regions experiencing low sea levels. The inundation modeling shows that the time that has the potential to be threatened by high waves is 05:00 WIB.

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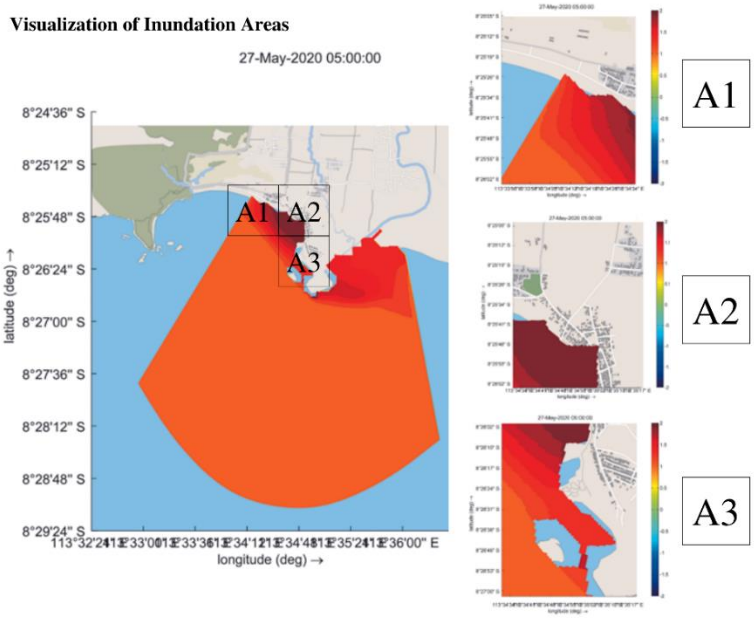
3.5 Inundation Visualization

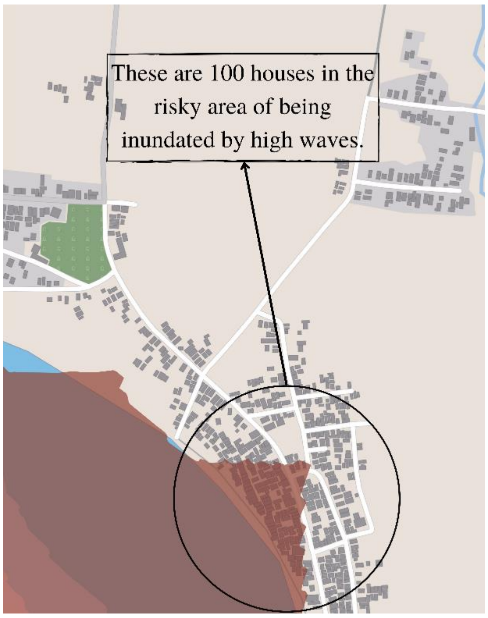
The results of the inundation modeling show that there is a water level of 1,96 meters that enters the residential area. Therefore, it is necessary to visualize inundation from the Delft3D model. Potentially inundated areas are shown in **Figure 8.**



Source: Research Result.

Figure 8. Visualization of Inundation Modelling Area.

In **Figure 8**, three areas on land are threatened by high waves. Area A2 shows the entry of high waves into residential areas. At the same time, areas A1 and A3 show high waves entering the coast. The impact caused by high waves entering the land is shown in **Figure 9.**



Source: Research Result

Figure 9. Risk Area of Inundation Due to High Waves.

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Figure 9. shows high waves threatening around 100 inundated houses 300 meters from the shoreline. The red zone shows high waves that reach the land, potentially destroying the residential area. The area affected by inundation due to high waves is 187,4 m^2.

3.6 Inundation Model Validation

Model validation was carried out by comparing the results of the inundation model from Delft3D with the existing conditions in the field. Based on the field survey results, the inundation height that entered the settlement was 2 meters. Meanwhile, through the results of inundation modeling in Delft3D, the inundation height was 1,96 meters. The percentage of suitability from the inundation modeling with the inundation that occurred at the location is shown in **Table 3.**

Table 3. Inundation Validation

Item	Calculation
Observation Inundation Height (m)	2
Inundation Model Height (m)	1,96
RMSE (%)	3,12

Source: Research Results.

The percentage of inundation validation is calculated using the Root Mean Square Error equation [24]. From **Table 3**, the percentage of RMSE value is 3.12%. Because the accuracy is 96.88%, so the inundation modeling is stated according to the observed conditions. Figure 9 shows a lobster farm area damaged by high waves on 27th May 2020.

Source: Research Documentation.

Figure 10. Research Site Survey.

Inundation modeling using Delft3D shows that the area potentially threatened by high waves is 187,4 m^2. The field survey showed the location that occurred inundation on 27th May 2020 was 88,3 m^2. Therefore, the modeling can describe the inundation area quite well in the field. Figure 10 shows the modeled and observed inundation areas.

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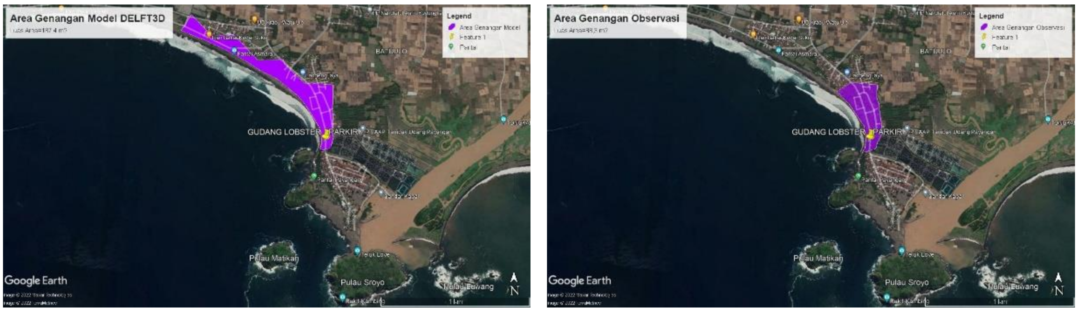

(a) (b)

Source: Research Result.

Figure 11. (a) Obtained Area of Inundation Model and (b) Inundation Area Based on Field Observation.

The purple zone shows the inundated area on the mainland. Figure 10 shows the potential area where high waves can inundate is 187,4 m^2. Areas that have the potential to be flooded by high waves are located in residential areas in Sidomulyo Village.

4. Conclusion

The inundation model in Delft3D shows that the inundation height at the observation point is 1.96 meters, and the significant wave height is 2.45 meters. The wave height is quite high and can be dangerous for the surrounding community. This inundation will damage 100 residents' houses with an area of 187.4 m2. The validation results show that the model is quite good, with an accuracy of 96.88%. This shows that wind waves make Payangan Beach very vulnerable to inundation. Through these results, the Government of Jember made a mitigation map for the inundation area on Payangan Beach and built a Sea Wall. So that in the future, high-wave disasters can be minimized.

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