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Tsunami Mitigation Strategy at Watu Ulo Beach Based on Numerical Modeling Using Delft3D-Flow

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ABSTRACT

The coastal area of Watu Ulo Beach in Jember has great resource potential but also the potential for major disasters, such as a tsunami. Tsunamis can cause casualties and destroy buildings. Thus, it is important to assess the possibility of future tsunami disasters. This study aims to simulate a tsunami at Watu Ulo Beach using Delft3D-Flow to analyze the possibility of affected areas. The tsunami modeling is based on two simulations, namely Scenario 1 as model validation using the characteristics of the 1994 Banyuwangi earthquake. Model validation calculation uses the MAPE method <10%. Scenario 2, modeling the southern Java megathrust earthquake, was analyzed to obtain the time and wave height as well as tsunami run-up and inundation, visualizing the area affected by Watu Ulo Beach. The simulation results show that the tsunami wave height at Watu Ulo Beach reached 12.57 m with a travel time of 29 minutes. The run-up elevation was 9.21 m, and the inundation distance was 2.38 km from the Watu Ulo coastline, indicating that the tsunami caused substantial damage. As an area affected by the tsunami, Sumberejo Village has an inundation area of 634.68 ha, and Sabrang Village has an area of 250.03 ha. The temporary evacuation location for Watu Ulo Beach is set at Tanjung Papuma Street via the shortest route of 0.57 km from the assembly point. Based on the results of this study can be used as a reference for determining temporary evacuation routes and locations for tsunami disaster mitigation in coastal areas.

1. Introduction

Jember Regency is one of the regencies on the south coast of East Java, with several beautiful beach destinations. One of the beaches in Jember with tourism potential with panoramic beauty is Watu Ulo Beach. This beach is unique, a coral reef with a scaly structure on the coast that elongates to the sea like a snake statue [1]. Besides, access to the location of Watu Ulo Beach is also relatively easy, so almost throughout the year, this tourist destination located in the Sumberejo Village, Ambulu District, has been visited by tourists, especially on holidays and national days [2].

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Coastal areas have great resource potential, but they also have great disaster potential, such as tsunamis. A disaster in water bodies will affect other nearby locations, including estuary and coastal areas. When a tsunami occurs at sea, the inundation will rise to the river and affect the land around the watershed [3]. Watu Ulo Beach is a beach that has a curvy shoreline shape. Thus, it amplifies the tsunami waves when entering a narrow area. This coastal area experienced the tsunami disaster on 3 June 1994, 01.17 West Indonesia Time, with the epicenter located in the Hindia Ocean [4][5]. The Meteorology, Climatology, and Geophysics Council data shows that the earthquake had a magnitude of 7.2 Ms at a depth of 18 km, followed by a tsunami with wave heights of up to 7 meters [6][7]. The event caused casualties and destroyed buildings and fishing villages [8]. The proximity of residential areas on the shoreline also caused this impact, and coastal communities still have insufficient knowledge of tsunami disasters.

Learning from disasters that have occurred, it is essential to study the possibility of a tsunami disaster occurring in the future, especially for disaster mitigation. Disaster mitigation is an effort to reduce the risk of disasters, such as mitigation planning, awareness, and capacity to face disaster threats that are useful in minimizing the occurrence of damage and losses caused. This effort must be made as well as possible because poor disaster mitigation planning can significantly impact. One such study is to simulate tsunami waves using numerical models with high spatial and temporal resolution in seconds to hours of computing time (shorter than real-time), such as Delft3D [9]. Delft3D is open-source software that solves non-linear shallow water equations from Deltares with various and complex water application areas [10][11]. This model also provides the facility for arranging resolutions with minimum distortions that can run in the cluster without changing the configuration [12].

Tsunami simulation has been conducted on some research in Jember beach using different parameters of the tectonic earthquake. For example, Widiyantoro [13] stated that the South Coast of Java Island has a high slip deficit zone that can produce a 9.1 Mw megathrust earthquake with a tsunami height of up to 20 meters. Pratama [14] simulated the Watu Ulo Beach tsunami using the earthquake parameter from Monte Carlo modeling with a strength of 8.9 SR. The highest setup height from the observation point is 5.52 meters, and the traveling time is 34 minutes. While Rikarda et al. [15] modeled the Puger Beach tsunami using Delft3D with the combination of earthquake resource characteristics in Southern Java and resulted in a tsunami height is 22.34 meters in the time of 40 minutes. These studies only analyzed the tsunami wave propagation without conducting run-up and inundation elevation analysis. In contrast, this study conducts run-up and inundation analysis of tsunamis for the affected areas.

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Therefore, this research aims to simulate a tsunami at Watu Ulo Beach using Delft3D-Flow to analyze the possible affected areas. Model validation is carried out using observation data of the 1994 Banyuwangi tsunami from previous research and analyzing run-up elevation and tsunami inundation from the simulation. The model will generate several components, such as wave height, arrival time, run-up, and tsunami inundation. Tsunami arrival time is related to evacuation time, while wave height, run-up, and tsunami inundation indicate vulnerable areas potentially affected by tsunamis with a specific wave height. Based on the results of this study, it can be used as a reference for tsunami disaster mitigation in coastal areas.

2. Research Method

This research uses a type of quantitative research, a case study research method that is analyzed numerically. Tsunami simulation is conducted by performing modeling using Delft Dashboard and Delft3D-Flow. This research started by collecting the data required for the simulation. First, a grid of the numerical simulation domain is created using the Delft Dashboard. This research uses different grid sizes in the coastal and offshore areas by adjusting two bathymetry data with different resolutions. The tsunami modeling in this research used two simulation scenarios. The simulation of these two scenarios generates water surface elevation, which is analyzed to obtain the height and arrival time of tsunami waves at each predetermined observation point. Meanwhile, the run-up and inundation elevations of the tsunami are obtained from the analysis of the maximum water surface elevation that floods the land area to determine the affected areas in the coastal area of Watu Ulo Beach.

2.1 Modeling

The resolution of the grid essentially determines the accuracy and efficiency of the results [16]. Many grid cells with high grid resolution will require high computing time and power [17]. Thus, the proper grid resolution is necessary to obtain stable results and efficient computation time. After the simulation domain was prepared, the fault parameter of the defined earthquake was put into the Delft Dashboard toolbox to generate a tsunami. The process of interpolation, parameter setting, model running, and display of model results using Delft3D.

2.2 Scenario

2.2.1 Scenario 1

This scenario is a validation model. The tsunami simulation using the characteristics of the 1994 Banyuwangi earthquake. The earthquake characteristics data used in this scenario were obtained from the USGS and are shown in **Table 1.**

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Table 1. Characteristics of Earthquakes

Name	Lon. (°)	Lat. (°)	Mag. (Mw)	Depth (Km)	Strike (°)	Dip (°)	Slip (°)
Tsunami Banyuwangi 1994	112.835	-10.477	7.8	11.5	97	83	91
South Java Megathrust	112.655	-10.779	9.1	44	278	16	90

Source: USGS and Widiyantoro et al.[13]

Table 1. shows the earthquake characteristics used as input parameters in the Delft Dashboard tsunami tool to generate a tsunami in the simulation. Longitude and latitude are the coordinates of the epicenter of the earthquake. Magnitude is the earthquake strength, depth is the depth of the hypocenter, and strike, dip, and slip are the direction of motion of the fault.

Earthquake magnitude is one of the most critical aspects of earthquake source parameters that can be directly measured and quantified. Generally, at the onset of an earthquake, magnitude is the first source parameter to be quantified to determine earthquake strength [18]. The magnitude can be utilized to study the pattern of earthquake occurrence [19]. The empirical relationship between fault area, fault length, and fault width can be obtained using a regression approach, which are empirical regression equations that relate fault dimensions to earthquake magnitude [20][21]. Hence, the calculation of fault length, fault width, and dislocation in this model used the regression equation from Wells and Coppersmith [22].

For Scenario 1, the simulated tsunami wave height was compared with the tsunami wave height from the Maramai and Tinti field observations in 1994 to determine the observation point for scenario 1 [6]. These include Watu Ulo Beach, Puger Beach, Cape Pelindu, Sukamade Beach, Rajegwesi Beach, Pancer Beach, and Pulau Merah Beach. This validation is calculated using MAPE (Mean Absolute Percentage Error), shown in equation [23].

$$MAPE = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{X_{oi} - X_{pi}}{X_{oi}}\right| x\ 100\%$$

While n is the total number of observations, X-oi, and X-pi. Are height of observation and simulation waves. The interpretation of the MAPE value is classified into four categories: <10% is considered highly accurate, 10-20% is considered good, 20-50% is reasonable, and >50% is inaccurate [24]. Thus, the validation percentage determined in this model is less than 10%.

2.2.2 Scenario 2

Scenario 2 is a tsunami simulation with the possible worst scenario. In this simulation, observation points are focused on Jember Beach, namely Watu Ulo Beach, Puger Beach, and Cape Pelindu. The simulation in Scenario 2 was carried out by changing the input data on

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tectonic earthquake parameters. The earthquake parameters used in this scenario are the South Java megathrust earthquake data obtained from Widiyantoro [13], which can be seen in **Table 1.** Based on **Table 1.**, the magnitude in this scenario is 9.1 Mw, which can also be referred to as a possible earthquake in the worst-case scenario and potentially cause considerable impact. Inundation analysis is conducted in the predetermined research area, namely Watu Ulo Beach, to analyze the height and arrival time of the waves. Then the determination of temporary evacuation sites and routes refers to reports from the Meteorology, Climatology, and Geophysics Agency and the Regional Disaster Management Agency [25].

2.3 Hydrodynamic Modeling

Delft3D-FLOW model, a multidimensional (2D or 3D) hydrodynamic simulation program developed by Deltares used to simulate tsunamis based on the two determining scenarios. This research conducted the two-dimensional computation with the same horizontal components (two-dimensional depth-averaged calculations) because for tsunami simulation, the horizontal length and time scale are significantly more significant than the vertical scale. The equation governing Delft3D-FLOW is shown as follows:

Momentum equation for x and y:

$$\frac{\partial u}{\partial t}+\frac{u}{\sqrt{G\xi\xi}}\frac{\partial u}{\partial \xi}+\frac{v}{\sqrt{G\eta\eta}}\frac{\partial u}{\partial \eta}+\frac{\omega}{d+\zeta}\frac{\partial u}{\partial \sigma}-\frac{v^2}{\sqrt{G\xi\xi}\sqrt{G\eta\eta}}\frac{\partial\sqrt{G\eta\eta}}{\partial \xi}+\frac{uv}{\sqrt{G\xi\xi}\sqrt{G\eta\eta}}\frac{\partial\sqrt{G\xi\xi}}{\partial \xi}-fv=-\frac{1}{\rho 0\sqrt{G\xi\xi}}P\xi+F\xi+\frac{1}{(d+\zeta)^2}\frac{\partial}{\partial\sigma}\left(\nu v\frac{\partial u}{\partial\sigma}\right)+M\xi$$

$$\frac{\partial u}{\partial t}+\frac{u}{\sqrt{G\xi\xi}}\frac{\partial u}{\partial \xi}+\frac{v}{\sqrt{G\eta\eta}}\frac{\partial u}{\partial \eta}+\frac{\omega}{d+\zeta}\frac{\partial u}{\partial \sigma}+\frac{uv}{\sqrt{G\xi\xi}\sqrt{G\eta\eta}}\frac{\partial\sqrt{G\eta\eta}}{\partial \xi}-\frac{u^2}{\sqrt{G\xi\xi}\sqrt{G\eta\eta}}\frac{\partial\sqrt{G\xi\xi}}{\partial \eta}-fu=-\frac{1}{\rho 0\sqrt{G\eta\eta}}P\eta+F\eta+\frac{1}{(d+\zeta)^2}\frac{\partial}{\partial\sigma}\left(\nu v\frac{\partial u}{\partial\sigma}\right)+M\eta$$

2D depth-averaged continuity equation:

$$\frac{\partial\zeta}{\partial t}+\frac{1}{\sqrt{G\xi\xi}\sqrt{G\eta\eta}}\frac{\partial((d+\zeta)U\sqrt{G\eta\eta})}{\partial\xi}+\frac{1}{\sqrt{G\xi\xi}\sqrt{G\eta\eta}}\frac{\partial((d+\zeta)V\sqrt{G\xi\xi})}{\partial\eta}=(d+\zeta)Q$$

After input files are prepared, boundary and initial conditions are determined. The equation governing Delft3D-FLOW is used in the first step in hydrodynamic calculations until the simulation is completed. After calculating the equations, tsunami wave height at every node for all time steps could be obtained.

In Eq. governing Delft3D-FLOW, there are several terms explained below. U and V are defined as depth-averaged velocities [26]:

$$U=\frac{1}{d+\zeta}\int_d^\zeta u\,dz=\int_{-1}^0 u\,d\sigma$$

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$V = \frac{1}{d+\zeta}\int_d^{\zeta} v\, dz = \int_{-1}^{0} v\, d\sigma$

Q is a contribution of each unit area because of the water wasting or withdrawal, precipitation, and evaporation [26]:

$Q = \int_{-1}^{0}(q_{in} - q_{out})d\sigma + P - E$

$P\xi$ and $P\eta$ represent pressure gradient, vv is a vertical eddy viscosity coefficient (m^2/s). Meanwhile, $F\xi$ and $F\eta$ represent the horizontal unbalanced of Reynold pressure (m/s^2), $M\xi$ and $M\eta$ represent the external resource contribution or momentum inundation. f is a Coriolis parameter (inertia frequency) (1/s), u is a flow seep toward x (m/s), v fluid speed toward y (m/s), and ω speed toward z (m/s). Furthermore, ζ is water surface elevation with t as time and d as depth (m), $\sqrt{G\eta\eta = R}$ and $\sqrt{G\xi\xi} = R\cos\phi$ as ϕ is latitude. R is the radius of the Earth (6378.137 km, WGS 84). Also, ξ and η is horizontal curves coordinate, q_{in} and q_{out} represent the local sources and sinks of water per unit of volume [1/s], P is water rain, and E is non-local inundation because of evaporation.

The numerical modeling begins with data input and parameter settings on the Delft3D-Dashboard. The data used in this modeling was National Bathymetry data with the six arc-second resolution (approximately 180 meters) obtained from the Geospatial Information Agency for the area close to the coastline. While in the offshore sea, the GEBCO_2021 data with 15 arc-second resolutions (approximately 450 meters) obtained from BODC (British Oceanographic Data Center) was utilized. According to the bathymetry resolution, the modeling domain used in this research was a rectangular grid of 0.005 x 0.005 degrees, equivalent to 500 x 500 meters for the offshore area, and 0.0025 degrees, equivalent to 250 meters for the coastal area. Next, the earthquake fault parameter was defined on the Delft Dashboard tsunamis toolbox based on the earthquake data in Table 1 to obtain the initial surface elevation. The simulation was run based on two predetermined scenarios. The model output from the simulation results can be visualized using Quickplot in Delft3D, which will display the water surface elevation for further analysis.

3. Results and Discussions

Two parameters from the simulation results of Scenario 1 and Scenario 2 were analyzed: tsunami height and wave arrival time from each predetermined scenario. In Scenario 2, the run-up elevation and inundation area due to the tsunami were analyzed to determine the affected area, which was focused on the Watu Ulo Beach area.

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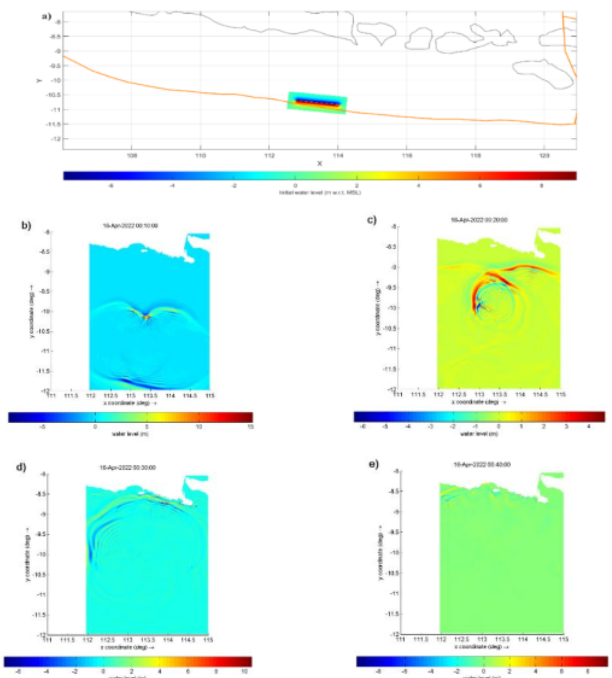
3.1 Numerical Modeling Scenario 1

The simulation in this scenario aims to validate the model used in the research. The simulation results will display the water surface elevation, used as an analysis parameter to obtain the wave height at each observation point. The description of the location of the observation point on the model is shown in **Figure 1.**

Source: modeling observation points on Delft Dashboard (2022).

Figure 1. Modeling Observation Points.

Figure 1. above shows the coordinates for the observation locations in the model illustrated in the Delft Dashboard. The creation of the model domain for tsunami simulation includes these locations. The tsunami parameters for Scenario 1 utilized the 1994 Banyuwangi tsunami event, resulting in the spatial water level elevations shown in **Figure 2 (a-e).**



Source: Author Analysis (2022).

Figure 2. Spatial water level elevation Scenario 1: a) initial elevation, b) 10 minutes, c) 20 minutes, d) 30 minutes, e) 40 minutes.

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Figure 2 (a-e) shows the maximum water level elevation overall in the modeled domain. The water level overview in this study is set to be displayed every 10 minutes. Where x in the figure indicates the longitude coordinate area and y is the latitude coordinate. The earthquake triggered the initial water level of the tsunami, shown in **Figure 2a.** Based on the legend in the figure, the earthquake data obtained from the USGS generated an initial wave of 9 meters high. After 10 minutes (**Figure 2b**), the wave height becomes 15 meters. The wave height continually propagated toward the mainland area after 20 minutes. As a result, the wave height in **Figure 2c** decreased to 5 meters. As getting closer to the mainland area in 30 minutes, the tsunami wave in **Figure 2d** increased to 10.5 meters because as it is closer to the coastal area, the water surface in the sea is shallower, resulting in a higher wave. Consequently, in 40 minutes, the wave reached the beach, resulting in a high maximum wave of about 9.5 meters, as shown in **Figure 2e.**

Based on the overall water level elevation, an analysis was conducted to obtain the arrival time and maximum wave height at each predetermined observation point. These two parameters are obtained from the results of the Delft3D-FLOW hydrodynamic calculation through the momentum equation for x and y. Finally, these maximum wave heights validate the model by comparing them with the measured wave heights in the field observation. The percentage error was calculated using MAPE, and the results are shown in **Table 2.**

Table 2. Scenario 1 Modeling Validation Results

Location	Tsunami Wave Height (m) (Maramai and Tinti 1997)	Tsunami Wave Height (m) (Simulation Results)	Percentage Error (%)
Watu Ulo	6.5-7.5	7.28	2.88
Puger	4.88-5.85	4.99	14.73
Tanjung Pelindu	3.2	3.12	2.46
Sukamade	6.1-6.25	7.11	13.76
Rajegwesi	6.3-9.5	7.60	20.04
Pancer	4.55-4.7	5.03	7.11
Pulau Merah	4.35-6.15	6.12	0.46
		MAPE	**8.78**

Source: Author Analysis.

According to **Table 2.**, the average error percentage from all observation points was 8.78%. This rate complied with the validation provision, the MAPE rate, which is less than 10%. Therefore, this tsunami wave modeling can be accepted.

3.2 Numerical Modeling Scenario 2

This scenario represents the results of a tsunami simulation using the parameters of the South Java megathrust earthquake. The resulting output in the form of water surface elevation

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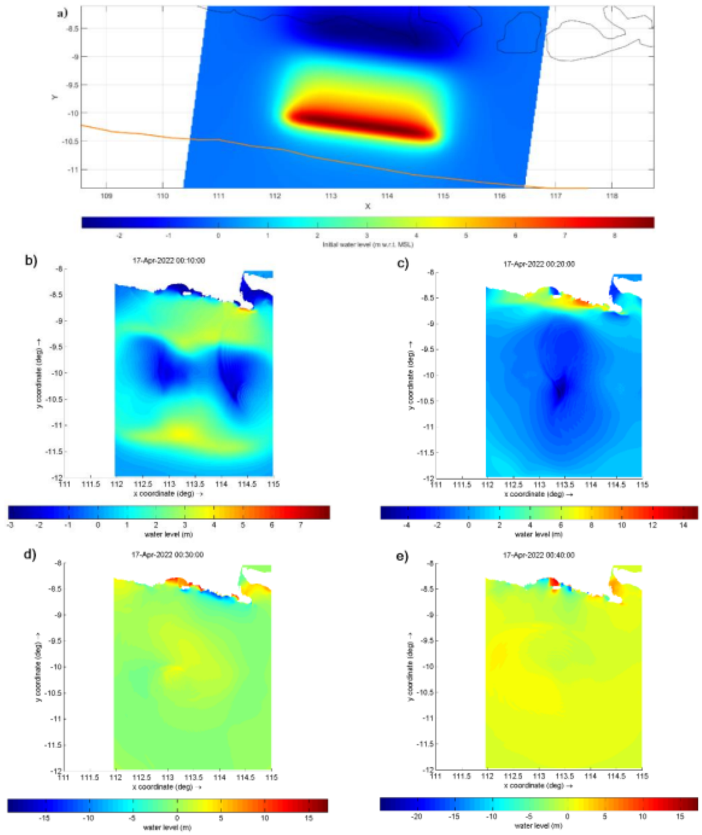
is analyzed to obtain the arrival time of tsunami wave heights at each predetermined observation point. Furthermore, the visualization of the results of the run-up and inundation analysis of the tsunami is also displayed in a spatial form focused on Watu Ulo Beach. **Figure 3(a-e)** shows the spatial condition of the water surface elevation from Scenario 2.



Source: Author Analysis (2022).

Figure 3. Spatial water level elevation Scenario 1: a) initial elevation, b) 10 minutes, c) 20 minutes, d) 30 minutes, e) 40 minutes.

Based on each legend of **Figure 3(a-e),** it can be seen that the overall maximum water surface elevation in the model reaches 8 to 17 meters, as this visualization is set to be displayed every 10 minutes where x is the longitude coordinate area and y is the latitude coordinate area. **Figure 3a** shows the water surface elevation of 8.8 meters. After 10 minutes, the maximum wave shown in **Figure 3b** resulted in an 8 m wave height. The earthquake in this scenario had an enormous magnitude of 9.1 Mw, so in 20 minutes, the wave in **Figure 3c** created a high wave reaching 15 meters. As time passed, the tsunami wave propagated toward the mainland, resulting in the higher wave in **Figure 3d** of 17 meters. As a result, in 40 minutes, the wave reached the mainland with an elevation of about 17.5 meters (**Figure 3e**).

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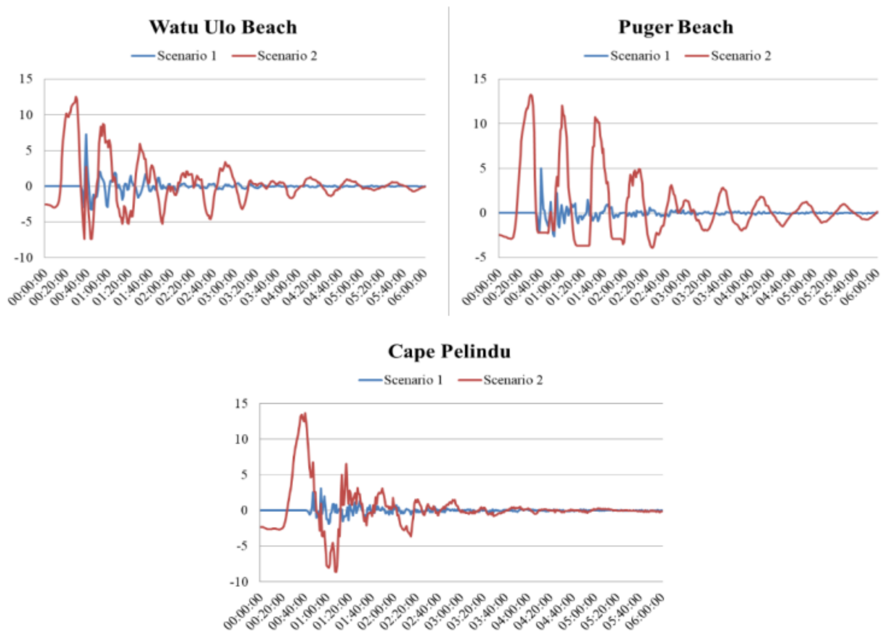
The time and wave height at each observation point were analyzed based on the overall maximum water surface elevation obtained in the simulation. The results of the analysis of wave height and arrival time at three coasts in Jember can be seen in **Table 3.**

Table 3. Tsunami Height and Arrival Time

Location	**Tsunami Height (m)**	**Arrival Time (minute)**
Watu Ulo	12.57	29
Puger	13.26	30
Tanjung Pelindu	13.67	40

Source: Author Analysis.

The tsunami due to the South Java megathrust earthquake based in **Table 3** resulted in a wave height of 12.57-13.67 meters, while the traveling time required by the tsunami to reach the coastal area was 29 to 40 minutes. Furthermore, the result compared the Scenario 2 simulation to Scenario 1 by determining the same three observation points. Comparisons between tsunami heights and arrival times for Scenarios 1 and 2 are shown in **Figure 4.**



Source: Author Analysis (2022).

Figure 4. Simulation Results of Scenario 1 and Scenario 2.

Based on the graphic shown in **Figure 4**, overall, the arrival time of the tsunami in Scenario 2 was faster to reach the coastline than in Scenario 1. The tsunami simulation results show that the shortest tsunami arrival time among the three observation points is at Watu Ulo Beach. In Scenario 1, the traveling time needed by a tsunami to propagate from the epicenter to

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Watu Ulo Beach was 39 minutes and in Scenario 2 was 29 minutes. Factors that influence the tsunami arrival time are the characteristics of the seabed and the distance between the observation point and the earthquake epicenter. Watu Ulo Beach's observation point is closer to the fault location than the other two observation points, so the tsunami arrival time in Watu Ulo Beach is the shortest among the three observation points.

In Puger Beach and Cape Pelindu, the tsunami arrived within 30 and 40 minutes for Scenario 2, while in Scenario 1, the arrival times were 40 and 54 minutes. The tsunami height resulting in Scenario 2 was higher than in Scenario 1. The maximum wave height in Cape Pelindu was 13.67 meters. Compared to Scenario 2, the earthquake characteristic in Scenario 1 has a shallower depth of epicenter than in Scenario 2. On the other hand, the earthquake characteristic of Scenario 2 had an enormous magnitude, so that this earthquake characteristic could cause a destructive tsunami. Besides, the position of the fault line in Scenario 2 was parallel and near the Southern Java plate line, and the lower dip rate resulted in the initial surface elevation closer to the mainland than in Scenario 1. They affect the wave arrival time in Scenario 2, which results in a faster arrival time with more significant potential damage.

Some of the above factors cause the arrival time in Scenario 2 to be faster than in Scenario 1. In this case, Watu Ulo Beach produces the smallest wave height among the three observation points in Scenario 2. However, in this tsunami modeling, the arrival time at Watu Ulo Beach is faster and reaches the beach with a wave height of more than 10 meters. They may be caused by the sloping morphology of Watu Ulo Beach, consisting of fine sand and a lack of vegetation in the beach area. Therefore, this beach needs to be studied further through tsunami inundation analysis.

Furthermore, given that Watu Ulo Beach is a tourist destination that still attracts many tourists and still does not have tsunami mitigation planning both structurally and non-structurally, this computational can be used as a reference in determining such planning. In addition, the shape of the curvy Watu Ulo Beach line allows tsunami waves to get amplified when entering a narrowed area, with the resulting wave arrival time in Scenario 2 being relatively short. Therefore, this could cause considerable damage to the land area. Thus, this simulation analyzed the run-up and inundation elevations in the Watu Ulo Beach coastal area.

3.3 The Visualization of the Affected Areas

The run-up and inundation analysis in Watu Ulo Beach were conducted based on Scenario 2. The modeling resulted in the spatial distribution of inundation areas for the affected

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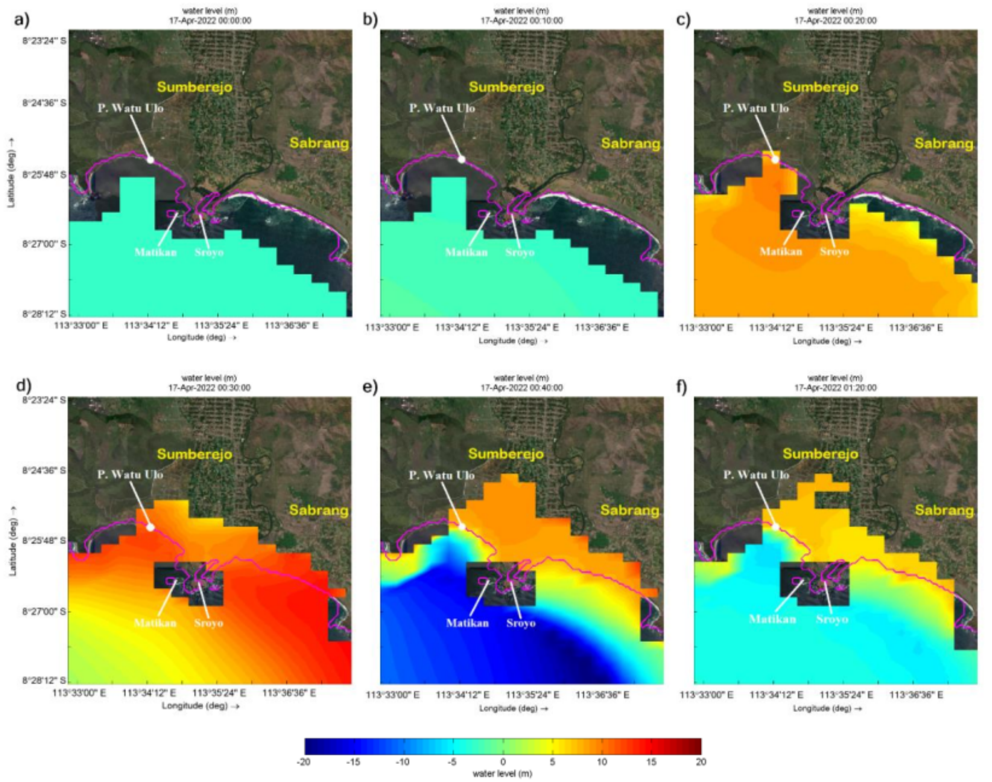
areas caused by a tsunami. The penetration of seawater to the mainland came step by step several times. **Figure 5.** shows a visualization of the seawater penetration to the mainland.



Source: Author Analysis (2022).

Figure 5. Spatial Distribution of Inundation on Land.

Figure 5a is the initial condition of seawater in the model. The initial phase of water penetration in the tsunami waves after 10 minutes (**Figure 5b**) did not result in a flood on the mainland. After 20 minutes (**Figure 5c**), the seawater started penetrating the mainland and reaching the coast. As time passed, the seawater spread and inundated the residential areas. Parts of Sumberejo Village began to be flooded by seawater after 30 minutes (**Figure 5d**).

At the same time, some areas were not inundated; there were empty areas, as shown in the inundation results. These areas are small islands, namely Matikan Island and Sroyo Island, which have 25 and 102 meters of elevation height, in sequence, above the sea surface. These two islands have a higher elevation than the coastal elevation. Therefore, when a tsunami hits 12.57 meters, the islands can still withstand and are not inundated by the waves. Another factor was that the grid resolution is still quite large (250 m), causing the bathymetry data interpolation to be less close to these two islands and form a wide empty area.

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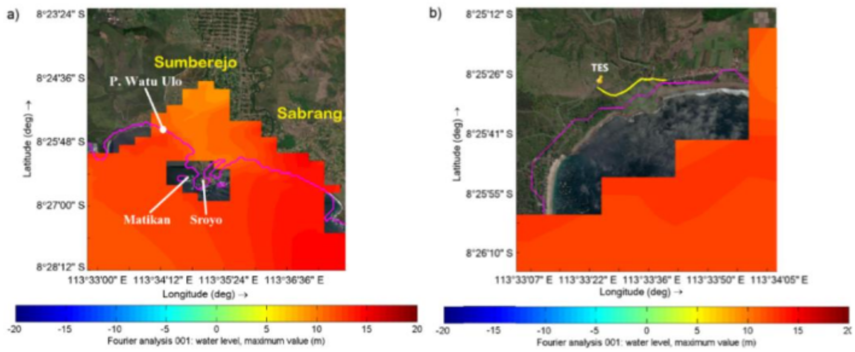
Inundation that started at Watu Ulo Beach continued to penetrate further into the village area. After 40 minutes, the tsunami inundated half of the Sumberejo Village area, resulting in a run-up elevation of about 7 to 9 meters (**Figure 5e**). Besides, the tsunami caused by the Southern Java megathrust earthquake also inundated part of Sabrang Village, located right beside Sumberejo Village. Furthermore, the seawater on the mainland started to recede and left inundations in some places after 80 minutes (**Figure 5f**). The visualization of maximum inundation in the mainland shows in **Figure 6.**



Source: Author Analysis (2022).

Figure 6. Tsunami Inundation at Watu Ulo Beach.

The wave inundation affected the tourist area and residential around Watu Ulo Beach (**Figure 6a**). The inundation distance caused by the tsunami was 2.83 kilometers from the Watu Ulo shoreline, so the wave run-up reached a height of 9.21 meters. The seawater that reached the mainland caused inundations, especially in Sumberejo Village, 634.68 ha, and the Sabrang Village area, 250.03 ha. This village which is part of Ambulu District, Jember Regency, is also located in the coastal area. The inundation area caused by the tsunami waves reached 884.71 ha.

The results of tsunami run-up and inundation caused by the South Java megathrust earthquake in **Figure 6a** can be used for tsunami mitigation planning, namely determining temporary evacuation routes and sites in Watu Ulo Beach (**Figure 6b**). The success of tsunami evacuation is highly dependent on the evacuation capacity and the speed of time to escape from tsunami waves. Therefore, the closer the evacuation site is to the residential areas in tsunami-prone areas, the more people can be saved. Assembly points that coastal communities can use are located in the western part of Watu Ulo Beach, where this location has a large area of vacant land. Meanwhile, the Temporary Evacuation Site (TES) is located on Tanjung Papuma Street, with an altitude of 68 meters above sea level. This location is safe from the tsunami of Watu Ulo Beach, with a height of 12.57 meters. Access to this location is also relatively easy because tourists commonly use this road to Papuma Beach, which is adjacent to Watu Ulo Beach. Furthermore, the distance between the assembly point and the TES is quite close at 0.57 kilometers, so the time to reach the TES is relatively short.

4. Conclusion

Tsunami wave modeling with the South Java megathrust earthquake characteristics creates higher tsunami waves and faster arrival with more significant potential damage. The tsunami wave height at Watu Ulo Beach created a high wave of 12.57 meters, with a wave arrival time from the epicenter to the coastal area of 29 minutes. The inundation distance caused by the tsunami is 2.38 kilometers from the Watu Ulo coastlines, resulting in a run-up as high as 9.21 meters in Watu Ulo Beach. Seawater rising to the mainland impacts several coastal areas, including Sumberejo Village, with an inundated area of 634.68 ha, and the Sabrang Village area was inundated by 250.03 ha of water. Then the Temporary Evacuation Site (TES) that coastal communities can use is on Tanjung Papuma Street, with an altitude of 68 meters above sea level. Then the assembly point is located in the western part of Watu Ulo Beach, where this location has a large empty land. The distance between the gathering point and the TES is 0.57 kilometers, so the time to reach the TES is relatively short. Based on the results of this study, it can be used as a reference for tsunami disaster mitigation in coastal areas.

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