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To cite this article: Lilik Kartini *et al* 2020 *IOP Conf. Ser.: Earth Environ. Sci.* **437** 012022

Two-dimensional numerical simulations of tsunamis on Puger beach, Jember

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Abstract. On June 3, 1994, an earthquake located 200 km south of the island of Java triggered a devastating tsunami and caused losses of life and materials around beaches in the Jember, Lumajang, and Banyuwangi Regencies. It is highly important to study the process of tsunami occurrences, especially at Puger Beach, Jember. Thus, the main purpose of this study is to understand the mechanism of tsunamis in Puger Beach. Tsunami numerical simulation was performed using the Delft3D model to calculate the propagation of possible future tsunamis. Bathymetric data obtained from GEBCO_08 were utilized in this study. The tsunami model was validated using the survey data of the tsunami on June 3, 1994. Tsunami simulations were successfully performed in this study. From numerical simulations, it was shown that the fault model characteristics utilized in the model directly affected the tsunami height. Just after the initial surface elevation, the wave height decreased and the tsunami propagated at sea. As the wave propagated from offshore to shallower area, the tsunami height increased until reaching the maximum tsunami height in coastal areas such as Puger Beach. Tsunami mechanisms are clarified from both numerical simulations.

Keywords: Tsunami, numerical modelling, Delft3D, Puger Beach

1. Introduction

At the southern parts of the island of Java, the Indo-Australian plate penetrates underneath the Eurasian plate. Subduction zones of the Earth's plates that cross the southern part of Java become the main triggers of earthquakes that are stronger than 7 Mw. This type of earthquake would initiate devastating tsunamis. One such event was in the year 1994, when an Indian Ocean tsunami was triggered by an earthquake 200 km south of Java with a strength of 7.9 Mw.

A survey on the 1994 Banyuwangi tsunami was conducted by Maramai and Tinti [1]. They stated that the 1994 Banyuwangi tsunami caused losses of life and material around the coastal areas of Jember, Lumajang, and Banyuwangi. The modelling of the tsunami had been performed by Maemunah *et al*. [2] and Pribadi *et al*. [3]. In 2006, the Pangandaran tsunami also caused a three-meter tsunami on the south coast of Java that destroyed houses and caused casualties of at least 668 people dead and 65 missing [4].

It is highly important to understand the mechanisms of tsunamis, especially at Puger Beach, Jember. Thus, the main purpose of this study is to understand the tsunami threat in the southern part of the island of Java, specifically in the area of Puger Beach in Jember Regency. This study is accomplished

IOP Conf. Series: Earth and Environmental Science **437** (2020) 012022 doi:10.1088/1755-1315/437/1/012022

using numerical simulations to calculate the propagation of possible future tsunamis. The research was performed by utilizing the Delft3D model developed by Deltares.

2. Research Materials and Methods

2.1. Research materials
The materials of the research consist of bathymetric data obtained from GEBCO_08, a global 30 arc-minute interval grid. Scenario 1 was designed to model the 1994 Banyuwangi tsunami, and thus a fault model [2] was used for tsunami simulation while slip values for both scenarios were taken from Pribadi *et al*. [3] (Table 1). Validation data of Scenario 1 were obtained from the observational results of the 1994 Banyuwangi tsunami from Maramai and Tinti [1].

Since the 2006 Pangandaran tsunami is one of the largest tsunamis in south Java, Scenario 2 was designed to simulate the 2006 Pangandaran tsunami in the same location as Scenario 1 (Banyuwangi). In Scenario 2, earthquake characteristics were taken from Aeda *et al*. [5] except the slip value as stated above.

Table 1. Fault Characteristics

Scenario	Long. (*)	Lat. (*)	MW	Depth (Km)	Strike (*)	Dip (*)	Slip (*)	D (m)	L (Km)	W (Km)
1	113.14	-10.547	8.0	10	100	15	85	4.7	130	70
2	113.14	-10.547	7.7	20	290	10	85	15	140	20

D: Dislocation (metres)
L: Length (km)
W: Width (km)

2.2. Research methods
This study utilized the case study research method with quantitative analysis, which is performed numerically. The study location was determined based on observations of the 1994 Banyuwangi tsunami in three locations that were considered acceptable to represent the study area. The locations are Tanjung Pelindu, Puger Beach, and Watu Ulo. Numerical modelling was performed by Delft3D-Flow [6], a hydrodynamic module that solves shallow water equations.

Figure 1 shows the overall stages of the study beginning with the setting of parameters and validation using data from the 1994 Banyuwangi tsunami. A simulation of the tsunami in south Java then followed.

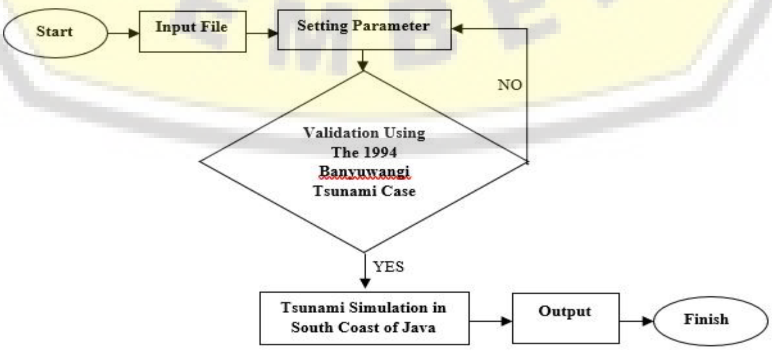

Figure 1. Framework of research

Figure 2 shows the stages of numerical modelling starting with the application toolbox on the Delft3D Dashboard. This toolbox calculates the properties of an underwater earthquake-induced tsunami. The preparation stage is the construction of rectangular grids with a resolution of 0.005 degree arc length and interpolated with bathymetry and topographic data. The tsunami toolbox was used to construct fault lines by inputting the parameter data of the earthquake. Flow was also used for another input for simulation parameters. In the numerical parameters setting, the standard cyclic method was applied. Numerical simulation was conducted using Delft3D-Flow. The output can be seen on the Quickplot after the successful running of the simulation.

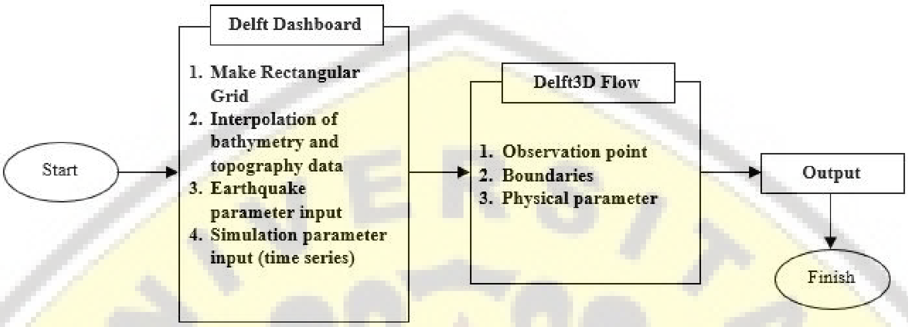

Figure 2. Framework of numerical modelling

3. Results and Discussion

In this section, the initial condition, the tsunami height time-series, the maximum tsunami height, and the time of the maximum tsunami height of each scenario are discussed. The three observation points are located in Tanjung Pelindu, Puger Beach, and Watu Ulo.

3.1. Scenario 1

Scenario 1 was simulated based on the 1994 Banyuwangi earthquake, with an epicentre of -10.547 South Latitude and 113.14 East Longitude and a strength of 8.0 Mw.

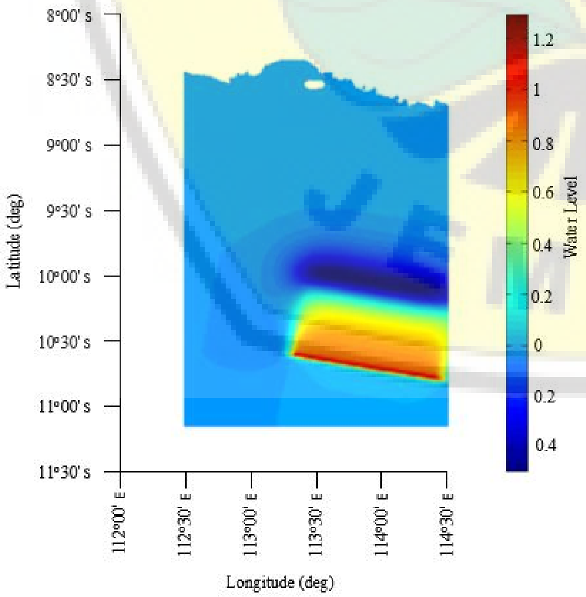

Figure 3. Initial surface elevation of Scenario 1

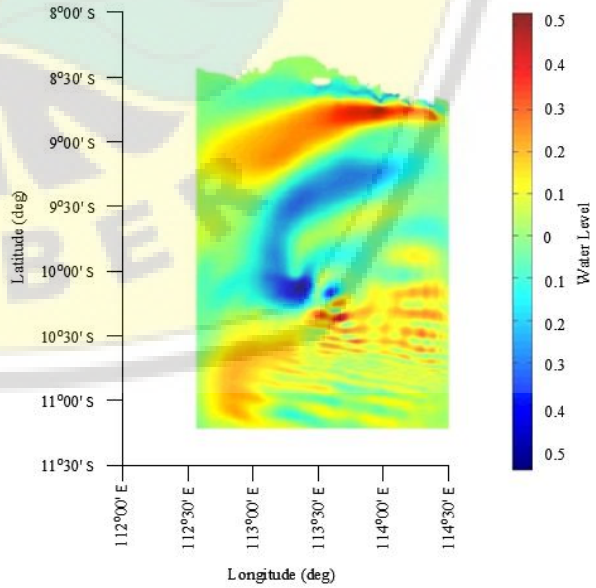

Figure 4. Tsunami height at minute 20 (Scenario 1)

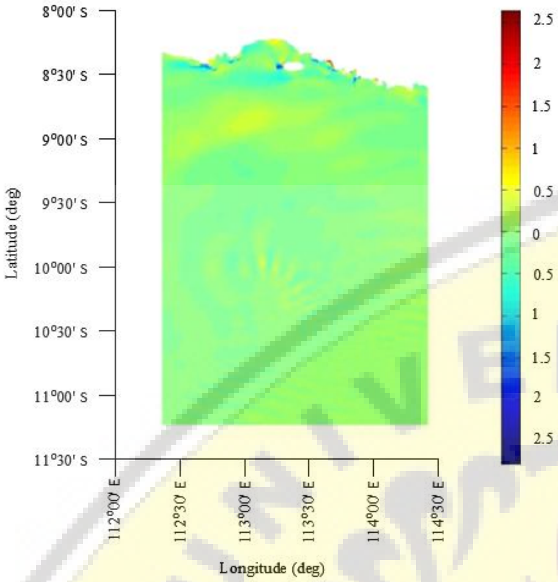

Figure 5. Tsunami height at minute 40 (Scenario 1)

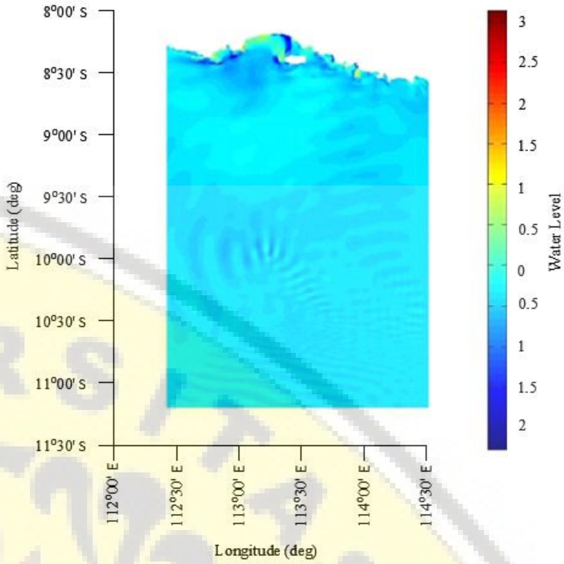

Figure 6. Maximum tsunami height at minute 55 (Scenario 1)

The initial condition is shown in Figure 3. In this condition, the sea water level increased to 1.2 metres and the lowest sea water level was 0.4 metres. At minute 20, the sea water level decreased to 0.5 metres as the tsunami propagated along the sea (Figure 4). At minute 40, the tsunami started to reach the shallower areas and the sea water level increased to 2.5 meters (Figure 5). The tsunami reached the coastal area and the sea water level rose to the maximum of 3 meters at minute 55 (Figure 6).

Table 2 shows the tsunami travel time to each observation point, the maximum tsunami height, and the time of maximum tsunami height. At Observation Point 1, a maximum height of 1.83 m occurred 75 minutes after the initial condition, with a tsunami travel time of 32.4 minutes. At Observation Point 2, a maximum height of 0.8 m occurred after 35 minutes with a travel time of 21 minutes, while at Observation Point 3, the maximum tsunami height reached 0.95 m after 75 minutes with a travel time of 22.2 minutes. Among the three observation points, the highest maximum tsunami height occurred at Observation Point 1.

Table 2. Tsunami Travel Time, Maximum Height, and Time of Maximum Height

Observation Point	TTM (minute)	Hmax (m)	Time (minute)
1	32.4	1.83	75
2	21	0.8	35
3	22.2	0.95	75

TTM: Tsunami Travel Time; Hmax: Maximum Tsunami Height; Time: Time of Maximum Tsunami Height

3.2. Scenario 2

Scenario 2 was simulated to represent the characteristics of the 2006 Pangandaran earthquake with the epicentre of the 1994 Banyuwangi earthquake (-10.547 South Latitude and 113.14 East Longitude) and a strength of 7.7 Mw. The generated initial surface elevation during the earthquake is shown in Figure 7. In this condition, there was an increase in sea water level to 0.6 m and a decrease in sea water level to 0.2 m. At minute 10, the sea water level decreased to 0.3 metres (Figure 8) as the tsunami wave started to propagate along the sea. At minute 25, the tsunami started to reach the shallower areas and the sea water level increased to 1.2 metres (Figure 9). The maximum height of the tsunami was 2.5 metres at minute 55 after the wave reached the coastline area (Figure 10).

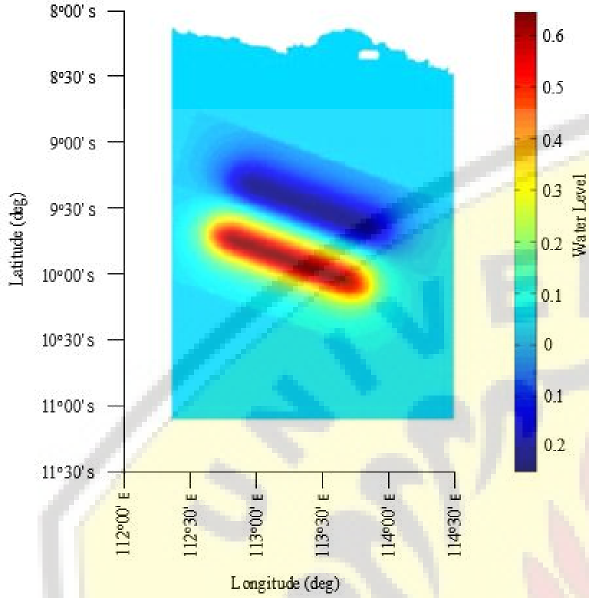

Figure 7. Initial surface elevation of Scenario 2

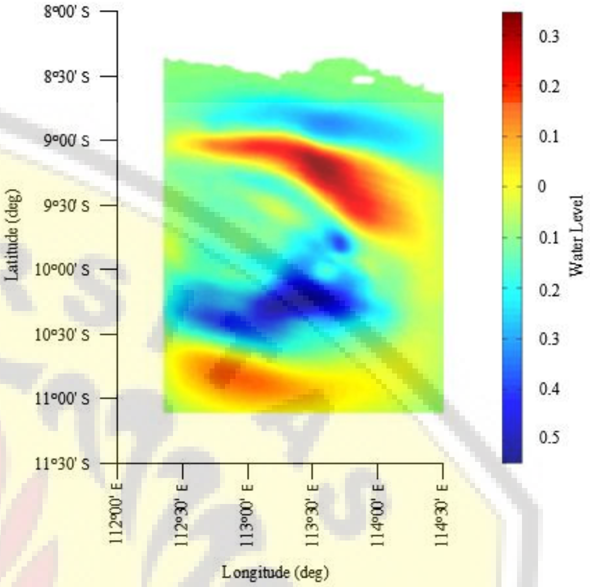

Figure 8. Tsunami height at minute 10 (Scenario 2)

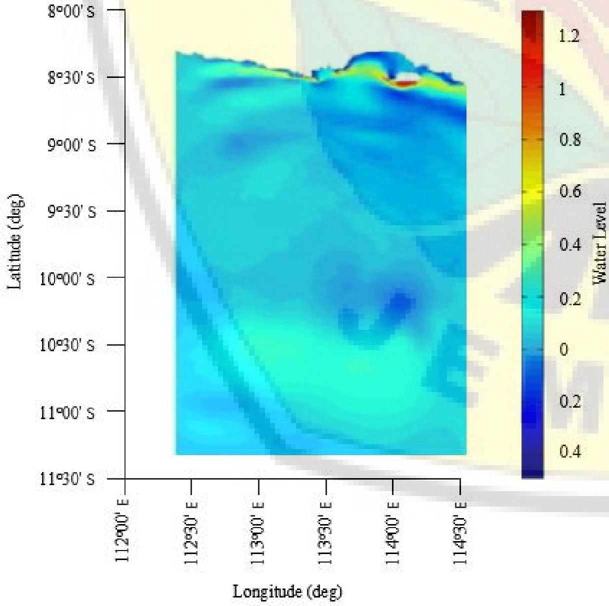

Figure 9. Tsunami height at minute 25 (Scenario 2)

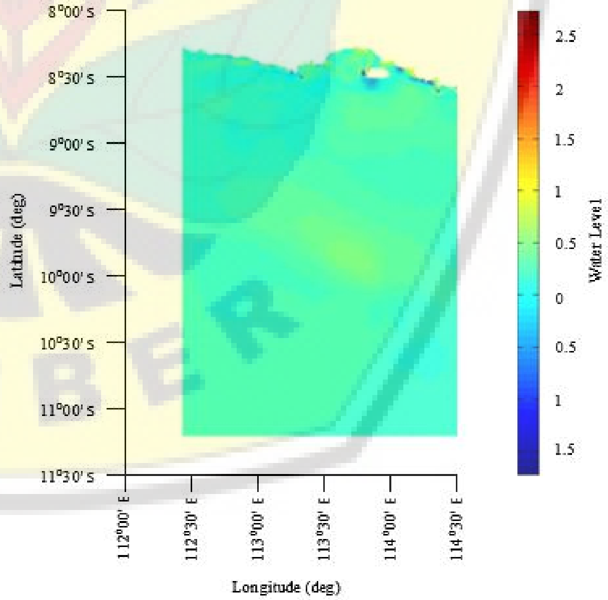

Figure 10. Maximum tsunami height at minute 35 (Scenario 2)

At Observation Point 1, a maximum height of 1.21 m occurred 70 minutes after the initial condition with a tsunami travel time of 10.8 minutes (Table 3). At Observation Point 2, a maximum height of 1.52 m occurred after 85 minutes with a travel time of 10.2 minutes, while at Observation Point 3, the maximum height reached 1.40 m after 95 minutes with a travel time of 13.8 minutes.

Table 3. Tsunami Travel Time, Maximum Height and Time of Maximum Height

Observation Point	TTM (minute)	Hmax (m)	Time (minute)
1	10.8	1.21	70
2	10.2	1.52	85
3	13.8	1.40	95

TTM : Tsunami Travel Time
Hmax : Maximum Tsunami Height
Time : Time of Maximum Tsunami Height

The results from the simulations of Scenario 1 and 2 showed the maximum heights of the tsunami on the sea. When reaching the coastline, the waves experienced changes in speed, height, and direction. The changes from the sea to the coast are not shown in the calculations due to the lack of bathymetry data. Thus, the changes in tsunami height were calculated using Green's Formula [8] as shown in Eq. (1). For this study, it was assumed that there is no change in the width of the bay, as the research location is not a bay.

$$\frac{\eta_2}{\eta_1} = \left(\frac{h_1}{h_2}\right)^{1/4} \left(\frac{b_1}{b_2}\right)^{1/2} \tag{1}$$

η_2 = tsunami height in the coastal area (m); η_1 = tsunami height on the sea (m)
h_2 = water depth in the coastal area (m); h_1 = water depth on the sea (m)
b_2 = width of bay in the coastal area (m); b_1 = width of bay on the sea (m)

From calculations, the heights of the tsunami in the coastal area were obtained and are presented in Table 4 and Table 5.

Table 4. Tsunami Height – Scenario 1

Observation Point	Simulated tsunami height (m)	Corrected tsunami height (m)	Observed tsunami height (m)
1	1.8	3.63	3.2
2	0.788	3.08	4.88-5.85
3	0.94	1.95	6.5-7.5

After making corrections using Green's Formula, the wave height results became closer to the observation results. From the simulation of Scenario 1, a corrected tsunami height of 3.63 m at Observation Point 1 was reached. The simulation was able to reproduce a tsunami height close to the observed tsunami height (3.2 m). However, the tsunami heights at Observation Point 2 and at Observation Point 3 were still less than the observed tsunami height. It may be due to the accuracy of the bathymetry data [7] and the grid size that is relatively large (0.005 degree arc length).

Table 5. Tsunami Height – Scenario 2

observation point	Simulated tsunami height (m)	Corrected tsunami height (m)
1	1.21	2.44
2	1.52	5.94

3	1.40	2.90

From the simulation results of Scenario 2, it was found that the height of the tsunami on the coast reached 2.44-5.94 m. This shows the necessity to carry out mitigation strategies in the study area.

4. Conclusion

In this study, observation data of the 1994 Banyuwangi tsunami was validated using numerical simulations of Scenario 1. Scenario 2 was conducted using the characteristics of the 2006 Pangandaran earthquake by changing the fault location to be the same as that of the 1994 Banyuwangi tsunami. From numerical simulations, it was shown that the fault model utilized in the model directly affects the tsunami height. The tsunami height at Observation Point 1 of Scenario 1 is higher than that of Scenario 2. This may occur due to the higher magnitude of the earthquake in Scenario 1 than in Scenario 2. Moreover, in the case of fault model width, Scenario 1 is larger than Scenario 2. At the same time, the location of the fault model in Scenario 1 is shallower than that of Scenario 2.

After the earthquake occurs, initial surface elevation shows a difference in tsunami height. Just after the initial surface elevation, the wave height decreases and tsunami propagates quickly offshore. As the wave propagates from the offshore to the shallower areas, the tsunami height increases until reaching the maximum tsunami height in coastal areas, for example Tanjung Pelindu, Puger Beach, and Watu Ulo. Tsunami mechanisms are clarified from both numerical simulations.

Acknowledgments

This research is funded by the Ministry of Research, Technology, and Higher Education of Indonesia through the 2019 Master's Thesis Research Grant.

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