# TSUNAMI HAZARD ASSESSMENT IN MOZAMBIQUE COAST

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## ABSTRACT

The purpose of this study is to assess tsunami hazard in Mozambique coast, specifically to estimate tsunami heights as well as tsunami arrival times considering near-field and far-field tsunami source models. The softwares used for the study were TUNAMI-N2 code and Tsunami Travel Time (TTT) for near-field tsunami, TUNAMI-F1 for far-field. Tsunami propagation was calculated by using GEBCO one arc-minute bathymetry grid data. We used 2 tide gauges and 20 assumed stations positioned along the Mozambique coast as outpoints. For near-field tsunami simulations, we considered normal-fault type events in the Mozambique channel. The seven source locations were assumed with two magnitudes (Mw 7.0 and Mw 8.0) and three depths (0, 5 and 10 km), totalizing 42 cases. For far-field tsunami simulations, six tsunami sources with the size of Mw 8.0 to Mw 9.3 were adopted. We found that for all the source models with Mw 7.0 the calculated tsunami heights do not exceed 0.4 m and due to that, the coast would not be at high risk if events of this size happened. Regarding the source models with Mw 8.0, the maximum tsunami heights were of 3 m or 2.5 m for some regions. The minimum travel times of tsunami to reach the coastal area are less than 10 min for some regions near the source. If events of this size happened, the coastal area of Mozambique would be in risk of damages. For far-field, the coast of Mozambique could be at risk if the event located in south Sumatra with Mw 9.1 (slip amount of 13 m, fault length and width of 550 km and 175 km, respectively) or with Mw 9.3 (slip amount of 15 m, fault length and width of 900 km and 175 km, respectively) took place, because the tsunami which its height of 2 m to 3 m could cause some damages to the coastal region. The time of 9 hours, that the tsunamis took to reach the first region in the coast of Mozambique, can allow people to evacuate.

**Keywords:** Tsunami hazard, Mozambique coast, Tsunami simulation, Travel time, Fault model.

## 1. INTRODUCTION

Due to its geographical location, Mozambique is crossed by the rift valley system at the central region. Most of this region is prone to seismic activities, because a great part of the domestic territory seats in tectonic faults. It can bring negative impacts on the social and economic development, as hazards for the country.

The extent of coastline is about 2600 km, allows the country to play a major role in transportation and communication along the southeast African continent due to many natural harbors along the coast zone. It is necessary to study the tsunami hazard assessment in the coastal area of Mozambique to ensure the risk that the coastal area people and infrastructure are facing. It will be a great help for developing appropriate hazard mitigation strategies. The possibility of damage caused by tsunamis originating from less-than-optimally oriented regions cannot be excluded without some investigation, for near-field as well as for far-field tsunamis.

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## 2. METHODHOLOGY

### 2.1. Tide Gauge Stations and Bathymetry Data

For this study, 22 tide gauges stations (TG1 to TG22) were used as output points of tsunami simulation, along the coast of Mozambique. Among those 22 tide gauges stations, 20 represented by red triangles in Figure 1, are assumed in this study and 2 represented by yellow triangles are operated by National Institute of Hydrograph and Navigation (INAHINA). Two different bathymetry data (GEBCO and ETOPO1), which are globally available, were used for simulations. The eventual comparison of simulation results was made to decide which bathymetry would be used and the GEBCO bathymetry data was selected to be used for this study.

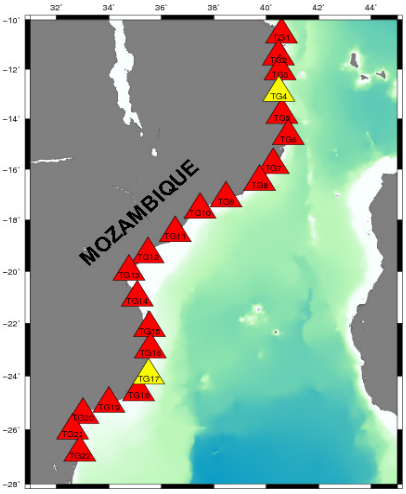

Figure1. Location of tide gauges stations.

### 2.2. Tsunami Source Models

To study the hazard assessment in the coastal region of Mozambique it is important to consider two kinds of tsunami source, (1) near-field tsunami and (2) far-field tsunami. Two sizes of event were used for near-field tsunami, of which one source with Mw 7.0 and another source were assumed with Mw 8.0. We set three depths of 0, 5 and 10 km for each magnitude. There are 7 assumed scenarios for each size and the parameters for each source model were calculated by using scaling law, empirical equations as function of magnitude (Utsu *et al.*, 2001). The equations of the scaling law, seismic moment (*Mo*) and moment magnitude (*Mw*) are expressed as follows:

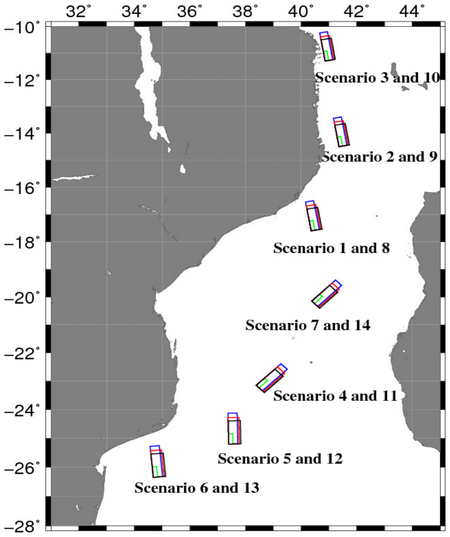

Figure 2. Tsunami source models for Mw 7.0 (green rectangles) and Mw 8.0 (blue, red and black rectangles for depths of 10, 5 and 0 km, respectively).

$$\log L = 0.5Mw - 1.8 \tag{1}$$

$$W = \frac{L}{2} \tag{2}$$

$$\log D = 0.5Mw - 3.3 \tag{3}$$

$$Mo = \mu DLW \tag{4}$$

$$Mw = \frac{\log Mo - 9.1}{1.5} \tag{5}$$

where $L$, $W$, $D$ and $\mu$ are fault length, width, slip amount and rigidity, respectively.

The same locations were considered for scenarios 1 and 8, 2 and 9, 3 and 10, 4 and 11, 5 and 12, 6 and 13, 7 and 14 (Figure 2). The strike angles are based on trench alignment of Davie ridge (DR) and Mozambique ridge (MR), conjugated with Quathlamba seismic axis, that connect the two ridges, DR and MR, in north and south region respectively (Stamps *el al.*, 2008).

The type of focal mechanism occurring in this area is generally pure normal fault (Grimison and Chen, 1988). For this reason, for source models with Mw 8.0, the fault widths are assumed corresponding to the top depths of fault and the bottom of seismogenic layer. We assumed the thickness of seismogenic layer as 40 km from Shudofsky *et al*. (1987) and CMT solutions. We used equation (4) to calculate the fault length by keeping the values of seismic moment and slip amount.

For far-field tsunami simulation, the source models parameters and the hypothetical scenarios used were based on the study of Okal and Synolakis (2007). Four events with six scenarios were selected (Figure 3). We calculated the seismic moment and obtained the moment magnitude for each scenario by using equations (4) and (5), assuming the rigidity of 3.0 x $10^{10}$ N/m$^2$. Those parameters are listed in Table 1.

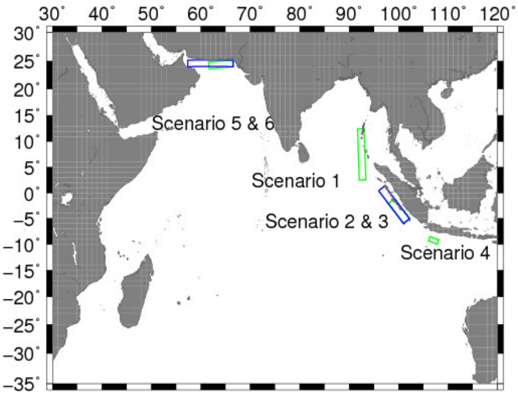

Figure 3. Tsunami source models for far field.

Table 1. Source parameters used for far-field tsunami simulations.

| Scenario | Mw | Length L (km) | Width W (km) | Depth d (km) | Strike ø (°) | Dip δ (°) | Rake λ (°) | Slip D (m) |
|---|---|---|---|---|---|---|---|---|
| 1 | 9.2 | 1100 | 150 | 10 | 359 | 8 | 110 | 15 |
| 2 | 9.1 | 550 | 175 | 5 | 322 | 12 | 90 | 13 |
| 3 | 9.3 | 900 | 175 | 5 | 322 | 12 | 90 | 15 |
| 4 | 8.0 | 200 | 100 | 5 | 290 | 10 | 102 | 6 |
| 5 | 8.1 | 450 | 130 | 5 | 265 | 7 | 89 | 10 |
| 6 | 9.2 | 850 | 130 | 5 | 270 | 7 | 89 | 10 |

### 2.3. Numerical Simulation of Tsunami Propagation

For near-field tsunami simulation, TUNAMI-N2 software developed by Disaster Control Research Center (DCRC) of Tohoku University in Japan, were used. This software solves the non linear shallow water long wave equations numerically. The computation region used for all scenarios extends from 31ºE to 45ºE and from -31ºS to -10ºS, with grid points of 840 and 1080 along the longitude and latitude, respectively. Using the GEBCO bathymetry data, the computational domain of 1 arc minute grid spacing is adopted for the computation region. The initial deformation of sea surface is given to the numerical simulation as an initial value, assumed identical as the deformation of sea floor. For the initial condition, static deformation of the sea floor, Okada (1985), was calculated using the parameters of the two source models. The integration time step $\Delta t$ is equal to 3.0 s, while computation time is equal to 6.5 hours, the total number of time steps for computational time is 7800, the maximum depth is 4822.43 m, the grid interval $\Delta x$ and $\Delta y$ are 1754.59 and 1844.6 m, respectively. We confirmed that the condition of CFL's stability is satisfied because the value of $\Delta t$ is less than the quotient between $\Delta x$ and $\sqrt{2gd}$ which is equal to 6.02 s. Snapshoot is taken in interval of 1 min, to make an animation (Figure 4).

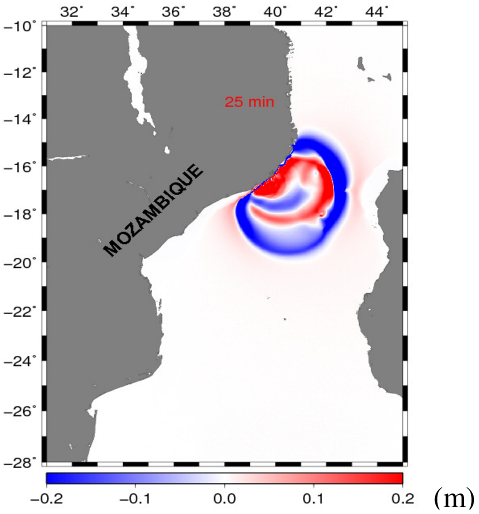

Figure 4. Snapshoot of tsunami propagation for scenario 8 of near field source model.

For far-field tsunami simulation, we used TUNAMI-F1 (linear theory of tsunami propagation in the spherical coordinate) code developed by DCRC, Imamura et al. (2006). In the governing equations, the effects of Coriolis force are taken in consideration because the tsunami propagates through long distance. The computation region is from 30ºE to 120ºE and from -35ºS to 30ºS, with grid points of 5401 and 3901 along the longitude and latitude, respectively. The integration time step is equal to 3.0 s, while computation time is equal to 17 hours, the total number of time steps is 20400. We also confirmed that the CFL's stability condition was satisfied.

### 2.4. Calculation of Tsunami Travel Time (TTT)

The Tsunami Travel Time software, originally developed by Paul Wessel (Georware, http://www.geoware-online.com), uses Huygens principle to calculate tsunami travel time by applying it on geographic latitude and longitude grid. By using the software provided by National Geophysical Data Center (NGDC) and International Tsunami Information Center (ITIC), the times required for the waves to propagate toward the places where the tide gauge stations are located were calculated for all near field scenarios. Travel times from the tsunami waveforms were also obtained and comparison of the two methods was made. Results obtained from the comparison shows a negligible difference between the two methods in the near field simulations.

## 3. RESULTS AND DISCUSSION

### 3.1. Tsunami Heights

For source models of Mw 7.0 with depth of 5 km, the following tsunami heights were obtained in 22 tide gauges for the 7 different scenarios. The highest tsunami of 0.35 m was calculated at Nampula (TG5) for scenario 2, followed by 0.26 m at Inhambane (TG15) and Maputo (TG22) for scenario 4 and 6, respectively (Figure 5). For the rest of scenarios the calculated tsunami heights were less than 0.2 m. The results by using other depths (0 km, 10 km) show small difference among them. For the case of source models of Mw 8.0 (Figure 5), at depth of 5 km, the tsunami height is of 3.8 m at Cabo Delgado (TG1), 2.9 m at Inhambane (TG15) and 2.3 m at Nampula (TG5). For the rest of scenarios the tsunamis reached less than 2 m. For depth of zero km, the tsunami reached 3 m at Cabo Delgado (TG1) for scenario 10 and more than 2.5 m at Nampula province (TG5 and TG8) for scenarios 9 and 14 respectively. For depth of 10 km the obtained results show 3 m at Inhambane (TG17), 2.7 m at Cabo Delgado (TG1) and 2.4 m at Nampula (TG5).

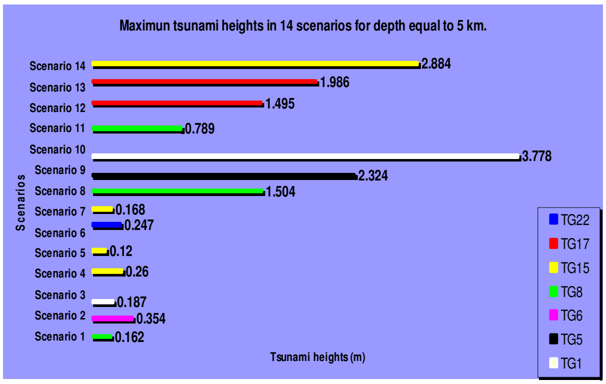

Figure 5. Near field maximum tsunami heights in 14 scenarios for depth of 5 km.

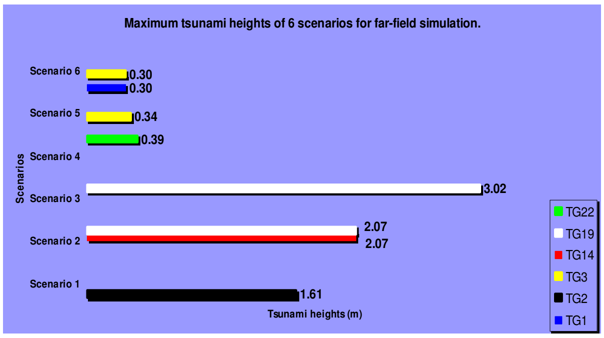

Figure 6. Far field maximum tsunami heights in 6 scenarios for depth of 5 km.

The results of far-field tsunami simulation (Figure 6), show that the maximum heights calculated in different scenarios were 3.02 m at Gaza (TG19), 2.07 m at Gaza and

Sofala (TG19 and TG14) and 1.61 m at Cabo Delgado (TG2), for scenarios 3, 2 and 1 respectively. The rest of scenarios (4, 5 and 6) the heights were less than 0.4 m. Despite the length of scenario 6 larger than the one of scenario 5, the tsunami heights for these two scenarios are nearly same, and the maximum reached only 0.3 m at Cabo Delgado (TG1, TG2 and TG3). Scenario 4 has the highest tsunami of 0.4 m at Maputo (TG22).

### 3.2. Tsunami Travel Times

Tsunami arrival times for source model with Mw 7.0 (Figure 7) for the depth of 5 km, indicate that the tsunami arrived first in the coasts of Nampula (TG6) and Cabo Delgado (TG1) for scenario 2 and 3, respectively in 0.2 hours (11.7 min). For depths of zero and 10 km, there is no big difference in the calculated travel times.

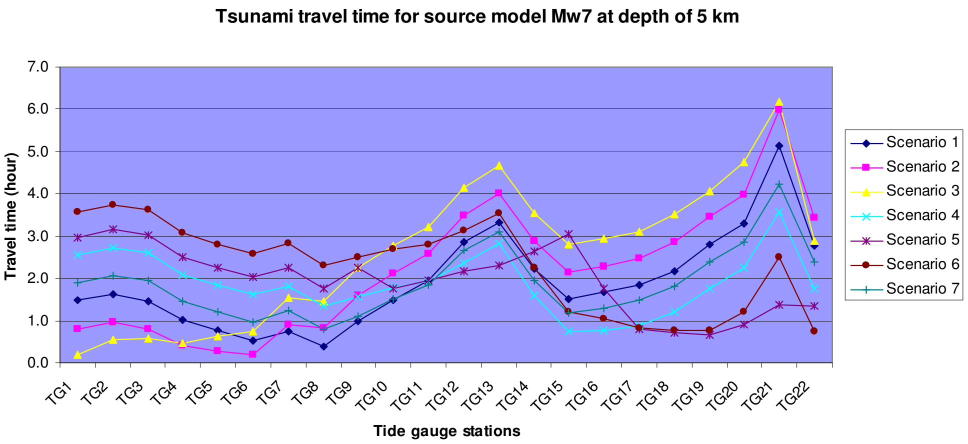

Figure 7. Tsunami travel times in 22 tide gauges for near field source models with Mw 7.0, for depth of 5 km.

We recognize here that for all scenarios the tsunami waves reaches the coast of Sofala (TG13) and Maputo (TG21) very late. For TG13, this behavior must be related with the wide area of shallower bathymetry from the coast toward ocean in this region. For TG21, this must be because of a process of interference that takes place in this region during the propagation of tsunami due to its geographical location inside the bay, which cause delay of the tsunami arrival. For event scenarios in the central part of channel (scenario 14), the wave arrive in 20 min at the coast of Nampula (TG8) but for the rest of tide gauges it reaches in 1 hour and later.

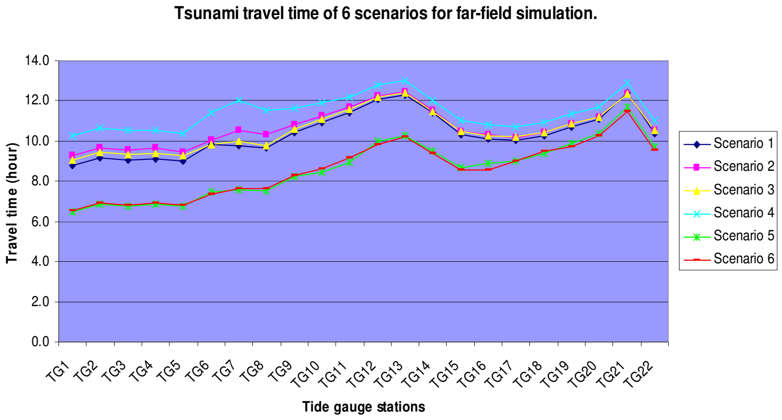

Figure 8. Tsunami travel times of 6 scenarios for far-field tsunami simulation.

For far field (Figure 8), scenarios 5 and 6, located in Makran, took 6.5 hours to reach the north coastal area of Mozambique channel and 9.5 hours to reach the south coast. Tsunami due to scenarios 1, 2 and 3 located off the coast of Sumatra, took 9 hours to reach the coastal area of north part of Mozambique channel and 10 to 12 hours to reach the south to central part. Scenario 4 took 10 to 11 hours to arrive at the north part and 12 to 13 hours to arrive at south part

## 4. CONCLUSION

We have assessed the tsunami hazard in the coast of Mozambique. For near field tsunami simulations, 42 normal-fault events were considered, with event sizes of Mw 7.0 and Mw 8.0, distributed along the Mozambique channel. For far-field tsunami simulation, six source models capable for generating transoceanic tsunamis were considered.

For near-field tsunami simulation, the coastal regions which are far from the source, in the channel of Mozambique, have the smallest tsunami height and the longest tsunami travel time compared with the coastal regions near the sources, which were affected by higher tsunami height in short time. For the cases in which the source is located in northern part of the Mozambique Channel, the regions in the southern part can have time for evacuation, if the warning system is efficient. By varying the depths of fault (0, 5 and 10 km), we notice that no significant difference between the computed tsunami heights. For source model with Mw 7.0 the coastal area would not be in risk while for source model with Mw 8.0 the coastal area would be in risk of suffering damages because the tsunami heights can reach 3 m.

For far-field tsunami, the coast of Mozambique could be at risk if the event located in south Sumatra with Mw 9.1 (slip amount of 13 m, fault length and width of 550 km and 175 km, respectively) and the other event located in south Sumatra with Mw 9.3 (slip amount of 15 m, fault length and width of 900 km and 175 km, respectively) took place because the tsunami heights can reach 2 to 3 m and it can cause some damages to the coastal region. The time of 9 hours that the tsunami takes to reach the first region, in the coast of Mozambique, can allow people to evacuate. For the event located in Makran zone with Mw 8.1 (slip amount of 10 m, fault length and width of 450 km and 130 km, respectively) and the larger event with Mw 8.9 (slip amount of 10 m, fault length and width of 850 km and 130 km, respectively), the coast would not have risk of damages because the tsunamis have small height of 0.4 m or less.

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