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NUMERICAL MODELING OF THE 1998 PAPUA NEW GUINEA TSUNAMI USING THE COMCOT

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ABSTRACT

The Papua New Guinea tsunami of 1998 is a unique phenomenon because the source of the tsunami propagation has been speculated. There was a 7.1-magnitude earthquake on July 17, 1998, at 18:49 WIT before the tsunami hit the Aitape area. However, previous studies have shown that the leading cause of the tsunami was not the earthquake but a submarine landslide. One of the steps to simulating the event is to do tsunami modeling. A tsunami propagation simulation will be conducted using Cornell Multi-grid Coupled Tsunami (COMCOT). This simulation was carried out with three scenarios to see which had the most significant effect on the tsunami event. The first scenario uses a tsunami source from a 7.1 magnitude earthquake, the following scenario is carried out using avalanche parameters, and the last scenario is a scenario with a combined source of earthquake and avalanche. The results of this study indicate that underwater landslides are the source of a tsunami similar to the original event.

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1. INTRODUCTION

A tsunami has three stages: generation (source), wave propagation, and inundation. The ocean's bathymetry and beach type affect these three stages [1]. Tsunamis may also be caused by volcanic eruptions, underwater landslides, earthquakes, and the impact of a large meteorite plunging into an ocean [2].

One area that was hit by the enormous tsunami was Papua New Guinea (PNG). On July 17, 1998, at around 18.49 local time, an earthquake with a magnitude of 7.1 SR shook the Sissano Lagoon area, west of Aitape on the north coast of PNG [3]–[5]. This event was so important because it became the most significant landslide tsunami recorded in modern times. According to observed data, the PNG tsunami reached a maximum height of 15 m [6], and caused a lot of casualties, more than 2100 people died, 12.000 people lost their homes, and three villages suffered severe damage along the 45 km coastline [7], [8].

Large tsunamis are rare in PNG. Only two known tsunamis in recorded history reached wave heights equivalent to this 1998 catastrophe. Six tsunamis hit the Aitape – Vanimo coastline in the last century, three of which caused damage. [9]. The PNG tsunami event astonished researchers when they found that a minor earthquake could cause significant damage, so the PNG tsunami became an area of concern for tsunami research and was studied by many authors [7], [10], [11].

Based on Newman and Okal [11], the tsunami height reached 10 to 15 m. Even though there is no evidence that a tsunami caused by an earthquake caused the incident. Based on the E/M0 discriminant comparison, the earthquake that occurred did not have the characteristics that could generate the most enormous tsunami. Reviewed from the location epicenter of the quake, Sissano Village should have been the location hit by the tsunami runoff shortly after the earthquake occurred. However, according to local witnesses, there was a ~20-minute lag after the quake before the tsunami reached the coastal areas [12]. The distribution of this wave propagation also shows that there are other factors apart from the earthquake that caused the tsunami in the PNG region [13].

The suspected cause is the Submarine Mass Failure (SMF) or underwater landslide. However, at that time, SMF was still a rare case to be studied because it had never been proven to produce a tsunami height and its destructive impact. After doing a lot of research on model simulations, it was found that SMF was the main factor causing the tsunami in PNG, which claimed many lives. According to Watts et al. [14], the deformation of the underwater landslide is caused by the movement of the center of mass of the SMF itself. Previous studies showed that the maximum tsunami wave height reached 15 m, similar to the observed data [3], [15]. Both studies applied shallow water equations to their model. One of the studies used the FUNWAVE model, which used SMF as a source tsunami model [3]. Satake and Tanioka (2008) [16] used different source mechanism; long angle fault (earthquake) and submarine slum with a maximum elevation is 6.1 m. A different result comes from another study [14] using a Boussinesq model with the result of tsunami elevation maximum is 10 m. The tsunami hit the shore after 60 seconds after the landslide [15].

The PNG tsunami is a unique case to study. Therefore, in this study, three simulations of the PNG tsunami with three different sources were carried out using the Cornell Multi-grid Coupled Tsunami Model (COMCOT). The first source scenario is the earthquake, landslide, and both earthquake and landslide scenarios. The differences in results from the three models will determine which scenario fits with the observed data. Moreover, the tsunami propagation of each model will be analyzed to understand the differences between tsunami landslides, earthquakes, and combined. The parameters used to run this simulation are based on the literature [3], [14].

2. RESEARCH METHODS

Landslides that occur on the seabed can cause seawater disturbances that can produce tsunamis. Earthquakes that cause perpendicular movements in the layers of the earth can cause the seabed to rise and fall suddenly so that the balance of seawater above it is disturbed [17].

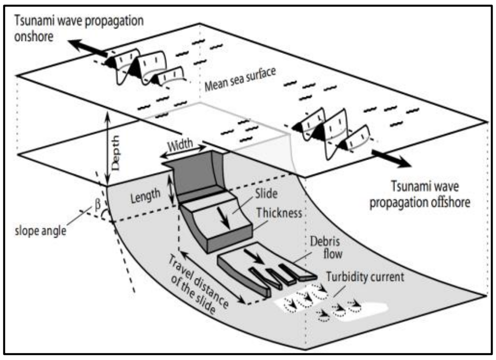


Figure 1. Formation of the Tsunami Submarine Landslide [2]

North Papua New Guinea (PNG) **Figure 2** is located on the border between the Australian and Pacific plates **[18]**. These borders are varied and complex. To the west, the border runs along the Papua New Guinea Trench, and the Pacific plate (Caroline segment) sinks southward under PNG. To the east is a complex microplate, and convergence divides on the north coast between the Bismarck North Sea Line, a sinistral east-west transformation, and the northward Ramu Markham fold. The convergency along this last fold tapers off westward **[19]**.

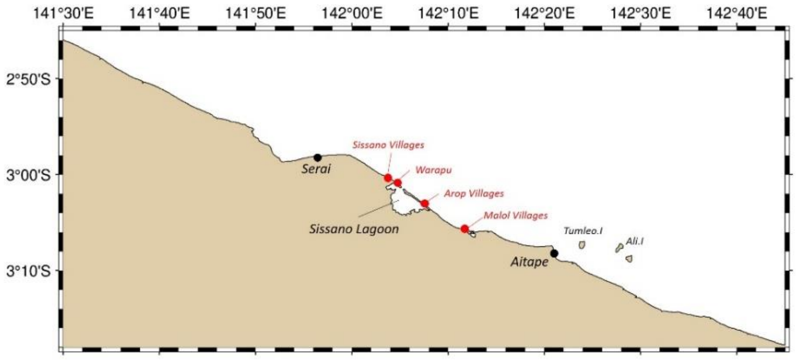


Figure 2. Papua New Guinea Region

2.1 Governing Equations

The model used to carry out the simulation is the COMCOT model. COMCOT model has been widely used in several real events with different tsunami sources, such as the 2004 Indian Ocean tsunami **[20]**, South Java Tsunami (2006) **[21]**, Tohoku Tsunami (2011) **[22]**, Chile tsunami (2014) **[23]**, Tonga volcanic tsunami (2022) **[24]**, and Palu landslide tsunami (2018) **[25]**.

The basis of the COMCOT model governing equations consists of the equations for the conservation of mass and momentum in the form of flux. The numerical method uses the leapfrog method (explicit leapfrog finite difference method). This numerical scheme counts time and space with the second order of the central difference equation. It means that the water level is calculated in the middle of the grid cell, while the flux is calculated on the sides of each grid cell based on the COMCOT manual **[26]**.

In COMCOT, the fundamental governing equation is a discussion of the mass-momentum equations in terms of fluxes. The linear terms from the governing equations are adequate for the tsunami's deep-water propagation. The following **Equation (2)** and **Equation (3)** in cartesian coordinates can be used to solve the two-dimensional problems:

$$\frac{\partial \eta}{\partial t} + \left\{\frac{\partial P}{\partial x} + \frac{\partial Q}{\partial y}\right\} = -\frac{dh}{dt} \tag{1}$$

$$\frac{\partial P}{\partial t} + gh\frac{\partial \eta}{\partial x} - fQ = 0 \tag{2}$$

$$\frac{\partial Q}{\partial t} + gh\frac{\partial \eta}{\partial y} + fP = 0 \tag{3}$$

In the same way, the governing equations with nonlinear terms in Cartesian coordinates area:

$$\frac{\partial \eta}{\partial t} + \left\{\frac{\partial P}{\partial x} + \frac{\partial Q}{\partial y}\right\} = -\frac{dh}{dt} \tag{4}$$

$$\frac{\partial P}{\partial t} + \frac{\partial}{\partial x}\left(\frac{P^2}{H}\right) + \frac{\partial}{\partial y}\left(\frac{PQ}{H}\right) + gH\frac{\partial \eta}{\partial x} + F_x = 0 \tag{5}$$

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{PQ}{H}\right) + \frac{\partial}{\partial y}\left(\frac{Q^2}{H}\right) + gH\frac{\partial \eta}{\partial y} + F_y = 0 \tag{6}$$

where:

g	: gravity acceleration [m/s^2}
P	: flux discharge in x- direction (West – East) [m^2/s}
Q	: flux discharge in y- direction (South – North) [m^2/s]
f	: Coriolis force coefficient [-]
R	: radius of earth [m]
h	: water depth [m]
η	: water surface elevation [m]
H	: total water depth [m]
Ω	: rotation rate of the earth [$7{,}2921 \times 10^{-5}$ rad/s]
F_x, F_y	: bottom friction in x and y direction
n	: Manning roughness coefficient [s/m$^{1/3}$]
u	: current velocity in x direction [m/s]
v	: current velocity in y direction [m/s]

The values of Manning roughness coefficient can be determined for different bottom conditions [27]. Numerical methodology solving **Equations (1) – (6)** in COMCOT is an explicit leapfrog finite difference method.

2.2 Parameters of the Earthquake and Landslide

The parameters of the earthquake and landslide used in the model were obtained from previous literature studies based on [3], [14] with details of the scenario parameters as follows:

Table 1. Earthquake Scenario Parameters

Earthquake Parameters	
Focal Depth (m)	10000
Length of Source Area (m)	40000
Width of Source Area (m)	20000
Width of Source Area (m)	20000
Strike Direction (m)	112
Dip Angle (°)	4
Slip Angle (°)	261
Epicenter	
Latitude (°)	142.16
Longitude (°)	-2.88

***Data Source:* [14]**

Meanwhile, the parameters used for the source of underwater landslides are indicated in **Table 2**.

Tabel 2. Landslide Scenario Parameters

Landslide Parameters	
Start Time (s)	0
Ending Time (s)	32
Typical Slope Angle Along Sliding Path (°)	12
Length of Sliding Volume (m)	4200
Width of Sliding Volume (m)	4500
Thickness of Slide Volume (m)	750
Epicenter	
X Start	142.282
Y Start	-2.8791
X Stop	142.2546
Y Stop	-2.861

***Data Source:* [3]**

The domains used in tsunami modeling are shown in **Figure 3**, with a domain size of $7000\ m \times 7000\ m$. The bathymetry data is retrieved from GEBCO with a resolution of 60 seconds. Meanwhile, the simulation time is 1800 seconds or 30 minutes with an interval of five seconds.

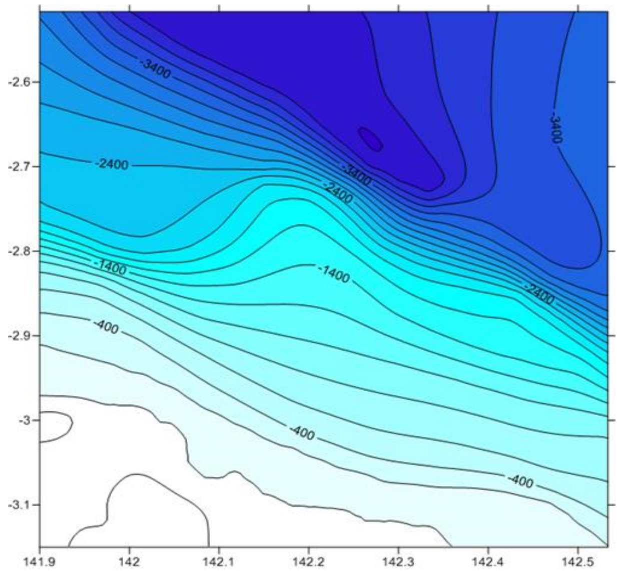


Figure 3. Domain and Bathymetry Used in Research, Line Contour is the Water Depth in Meters.

3. RESULTS AND DISCUSSION

3.1 Scenario with Source from Earthquake and Landslide

The modeling results using both parameters (landslides and earthquakes) after 30 minutes of running show at the 5th second, the waves have yet to develop. At 55 s after the submarine landslide (0–32 seconds), the formation of waves began to form. As time progresses, it is possible that the waves, which have a height range of 5 to 6 meters, may hit the shore at 05.55 minutes. The model findings obtained after 16.45 minutes, no longer observable tsunami wave propagation **Figure 6**. The graph shows that the tsunami wave at point 3, **Figure 4**, and **Figure 5** has a maximum height of 6.5 m. **Figure 8** shows the initial tsunami elevation height resulting from the earthquake, with the maximum height being 2 m located close to the coast. The tsunami's start height during the simulation of the avalanche scenario is shown in **Figure 9**. The earthquake-caused tsunami, which was 15 m high and located about 1 degree north of the coast, was much smaller than it.

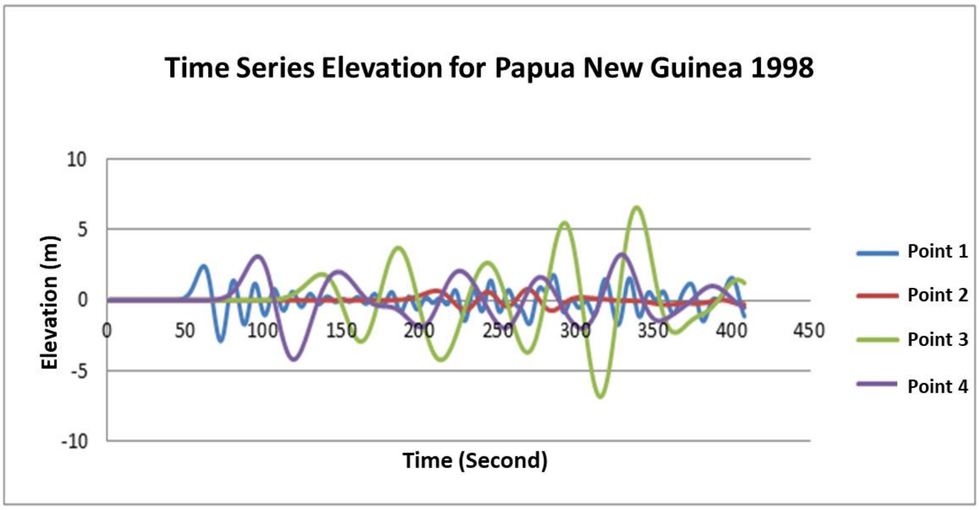


Figure 4. Time Series of Wave Elevation for Papua New Guinea 1998 Caused by Earthquake and Landslide

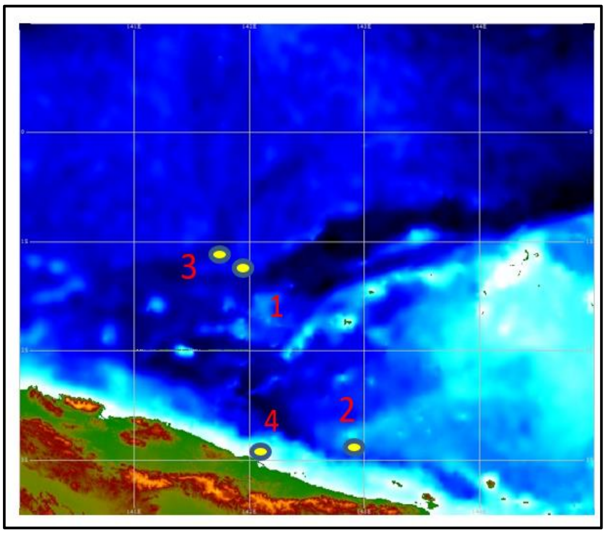


Figure 5. **Location of Maximum Height of Tsunami Wave Elevation**

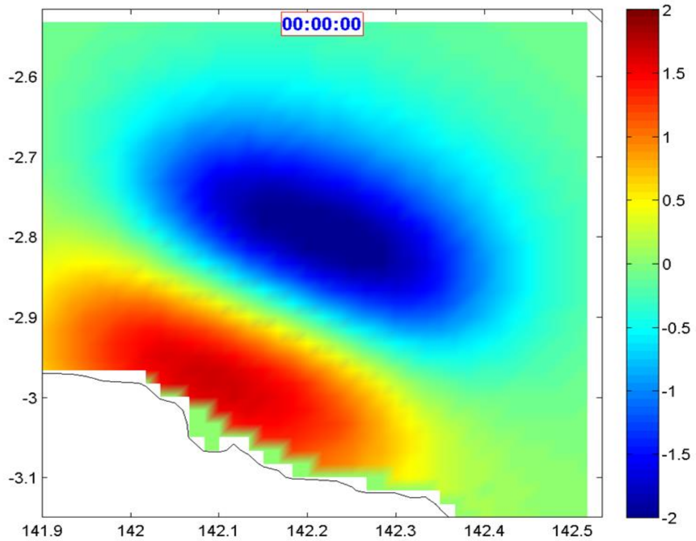


Figure 6. **Earthquake Scenario Tsunami Wave Initials**

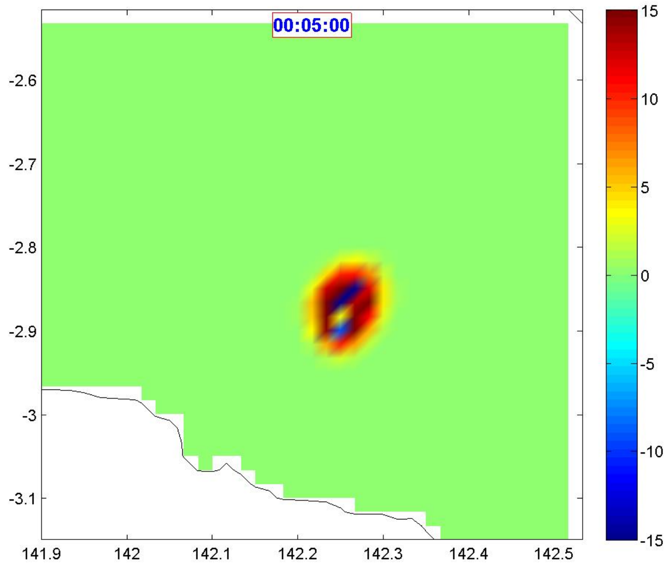


Figure 7. **Initial Tsunami Wave Landslide Scenario**

According to the FUNWAVE model's results by **[3]**, the height of the waves created is between 10 and 15 meters. The model results state that the first wave (tide) appears when a tsunami is more than zero, followed by an elevation with a negative value (ebb). The analysis of the tsunami waveforms conducted by

[7] states that there was a delay of 12 to 17 minutes in the formation of landslides compared to the time of origin of the main shock. This is also evidence of the landslide source that caused the tsunami in Papua New Guinea. Figure 9 shows the results of the Papua New Guinea Tsunami COMCOT model with an earthquake scenario.

Meanwhile, the model results for the combined earthquake and landslide scenario are shown in Figure 10. It is shown that in the earthquake scenario Figure 9, the tsunami first struck the coast at a positive elevation (red color), reaching a maximum height of roughly 2 meters. Over the next 110 seconds, the tsunami is primarily driven by a negative elevation. Additionally, the tsunami's propagation along the coast and northeast of the domain region is seen. This analysis also included a tsunami landslide scenario, the outcome of which is displayed in Figure 10. Although the maximum tsunami elevation is greater than the tsunami generated by an earthquake, it takes a lot longer to propagate to the coast. After five minutes, the landslide source, farther from the earthquake epicenter, brought the first wave of the tsunami to the shore. Almost the same length and speed are propagated in all directions.

Figure 11 shows the last possible scenario. The highest elevation of the wave is comparable to a landslide situation, and it takes less than two minutes to reach the coast. The propagation is shown to be essentially identical to a landslide scenario, albeit at a faster pace. The maximum observed tsunami height, according to earlier research, is between 10 and 16 meters. In this case, however, we found that the elevation reached 15 meters [4], [9], [28]–[30].

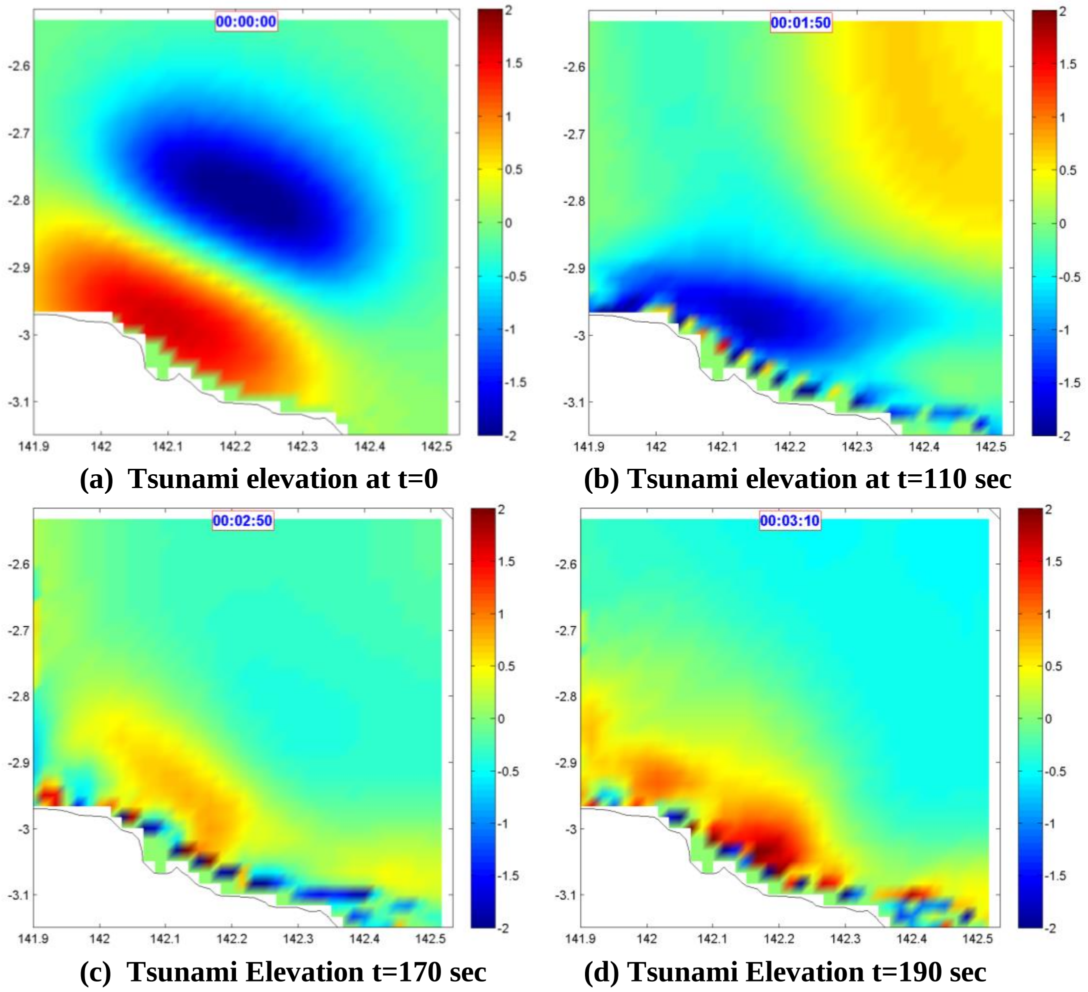
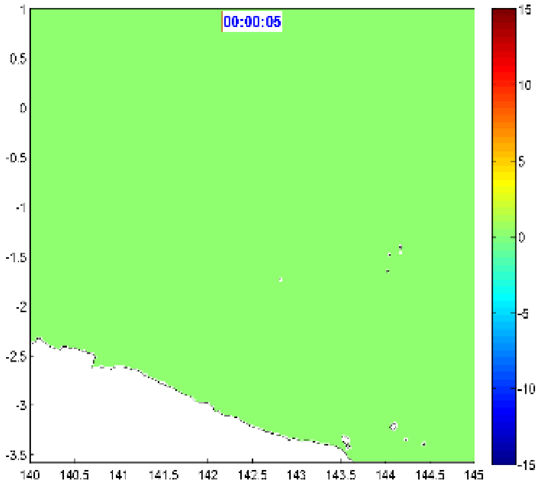
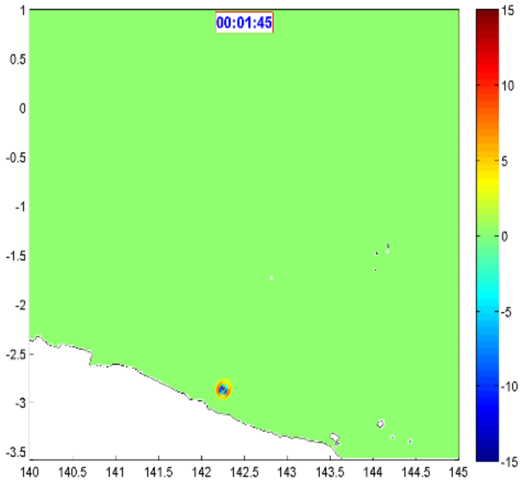


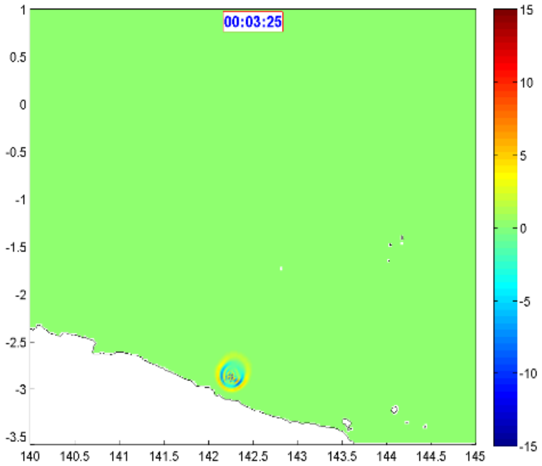
Figure 8. Result of Tsunami Propagation with Earthquake Scenario COMCOT Model (a) Tsunami Elevation at t = 0 sec, (b) Tsunami Elevation at t = 110 sec, (c) Tsunami Elevation at t = 170 sec and (d) Tsunami Elevation at t = 190 sec



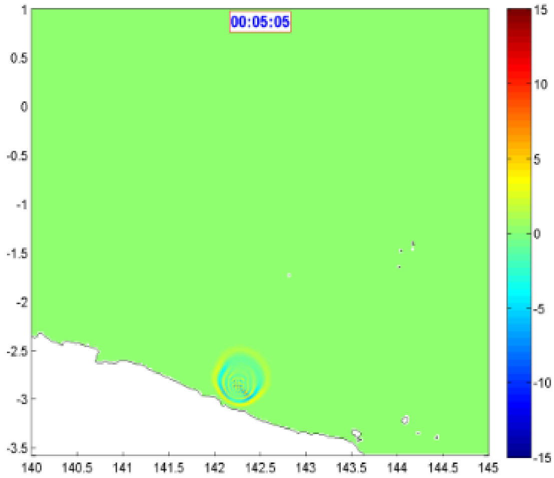
(a) Tsunami Elevation at=5 sec



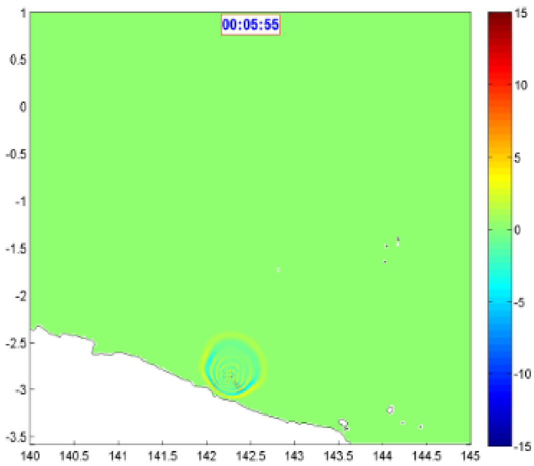
(b) Tsunami Elevation at t=105 sec



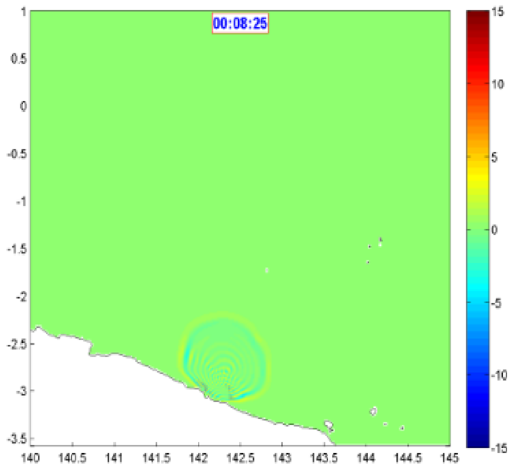
(c) Tsunami Elevation at t=205 sec



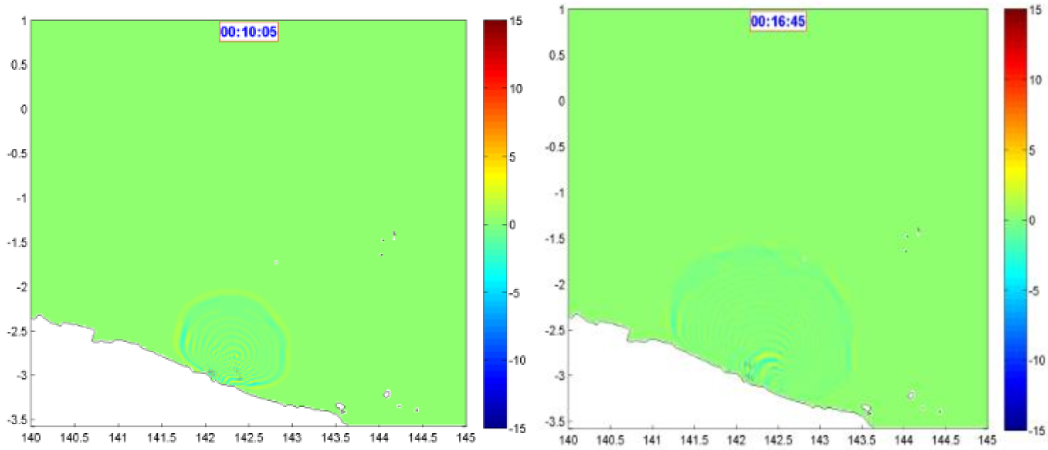
(d) Tsunami Elevation at t=305 sec



(e) Tsunami Elevation at t=355 sec

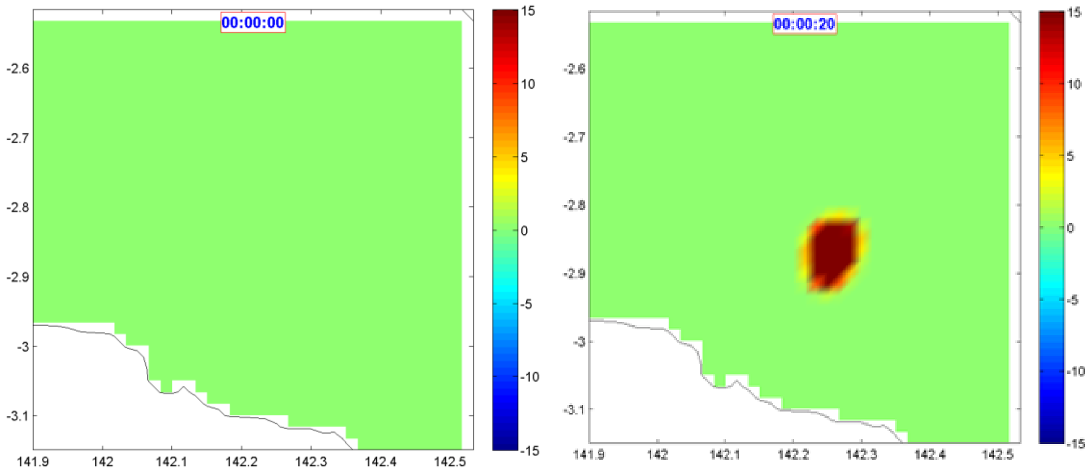


(f) Tsunami Elevation at t=505 sec

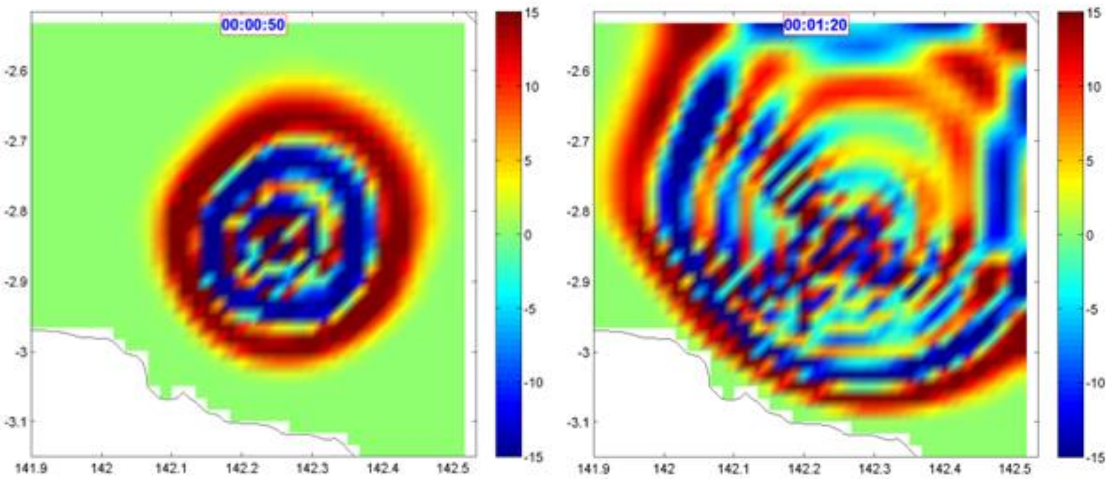


(g) Tsunami Elevation at t=605 sec **(h) Tsunami Elevation at t=1005 sec**

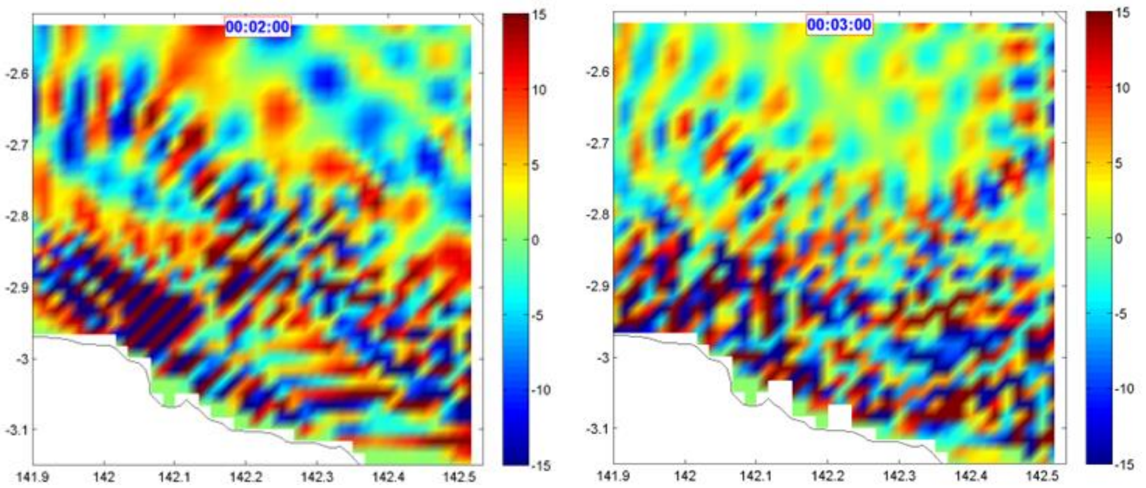
Figure 9. Result of Tsunami Propagation with Landslide Scenario COMCOT Model (a) Tsunami Elevation at t=5 sec, (b) Tsunami Elevation at t=105 sec, (c) Tsunami Elevation at t=205 sec, (d) Tsunami Elevation at t=305 sec, (e) Tsunami Elevation at t=355 sec, (f) Tsunami Elevation at t=505 sec, (g) Tsunami Elevation at t=605 sec, and (h) t=1005 sec



(a) Tsunami Elevation at t=0 sec **(b) Tsunami Elevation at t=20 sec**



(c) Tsunami Elevation at t=50 sec **(d) Tsunami Elevation at t=80 sec**



(e) Tsunami Elevation at t=120 sec (f) Tsunami Elevation at t=180 sec

Figure 10. Result of Tsunami Propagation with COMCOT Model of Earthquake and Landslide Scenario (a) Tsunami Elevation at t=0 sec, (b) Tsunami Elevation at t=20 sec, (c) Tsunami Elevation at t=50 sec, (d) Tsunami Elevation at t=80 sec, (e) Tsunami Elevation at t=120 sec, and (f) t=180 sec

3.2 Scenario with Source from Earthquake

Another option is to run each argument individually. According to the data, the earthquake only generated a wave height of around 2 m at the 300th second at point 3 **Figure 9**. Meanwhile, the tsunami height for the first wave at the four observation stations was less than one meter. At point 1, the tsunami arrived at the 220th second; at point 2, it appeared that no tsunami was coming; at point 3, it arrived at the 200th second; and at point 4, the tsunami arrived faster than the other sites, at the 130th second. Compared to the initial scenario, which includes both parameters, the wave height generated by this scenario is small.

The last scenario, which uses only the underwater landslide parameter, creates a tsunami wave height of roughly 6.5 m, as seen in **Figure 9** at point 3, similar to the first scenario when both variables are applied together.

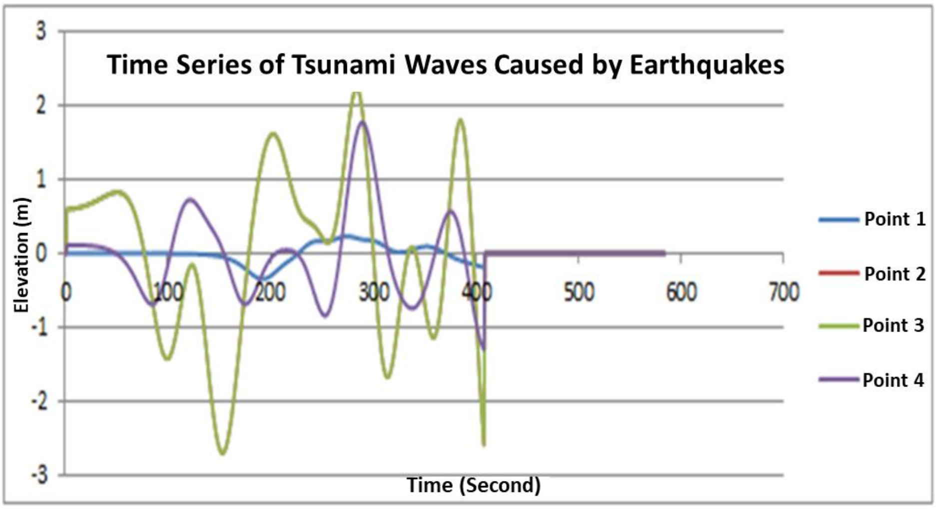


Figure 11. Time Series of the 1998 PNG Tsunami Wave Elevation Due to the Earthquake

3.3 Scenario with the Source Landslide

The difference in wave height obtained from the COMCOT model run and the previous researchers could be attributed to the inadequate accuracy of the bathymetry data used, resulting in divergent simulation results. Another scenario focuses solely on the avalanche's origin. **Figure 12** depicts the tsunami elevation propagation data at the four observation stations using this scenario, with a maximum height of more than 5 m at 330 seconds at point 3.

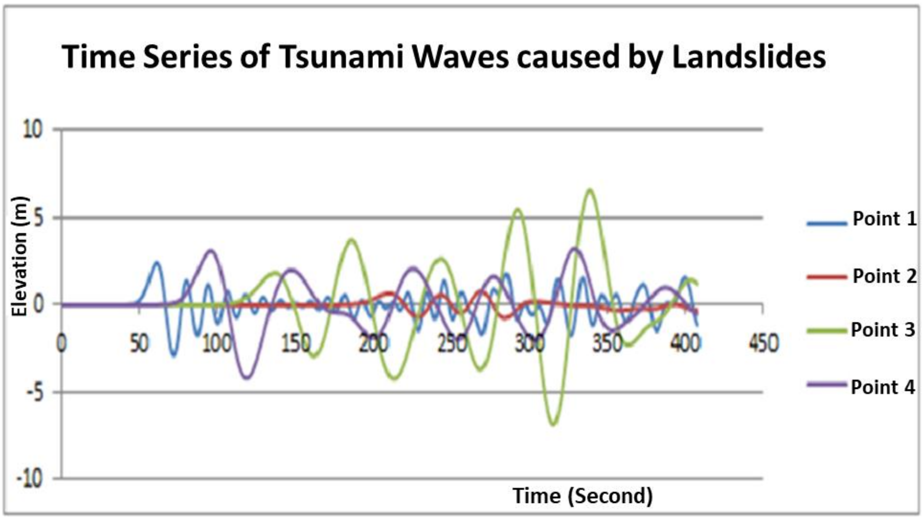


Figure 12. **1998 PNG Tsunami Wave Elevation Time Series Caused by a Landslide**

Aside from that, the time series graph shows that **Figure 4** and **Figure 12** have the same wave height values. According to this, the main factor influencing the magnitude of the tsunami wave height in Papua New Guinea in 1998 was the phenomena of submarine landslides, not earthquakes **[6]**.

4. CONCLUSIONS

This study examines the causes of the tsunami in PNG, which began with an earthquake of magnitude 7.1 Mw. However, previous studies have stated that landslides triggered the tsunami. Therefore, several scenarios containing a combination of earthquakes and submarine landslides were carried out to reconstruct the event. The results of this study are as follows:

a. The tsunami wave height using the first scenario (earthquake and submarine landslide) and the third scenario (submarine landslide) produced the same tsunami wave height of 6.5 m. The second scenario (only an earthquake) made a wave height of 2 meters.

b. The results of the study's analysis of the 1998 Papua New Guinea disaster indicated that submarine landslides were the principal source of the tsunami, despite the fact that an earthquake had earlier occurred in the same area. The seismic event (earthquake) had little effect on the propagation of the tsunami waves, although it did cause a landslide.

c. The difference between the previous results and the results of the COMCOT model is probably due to the low bathymetric accuracy factor. Because bathymetry (H) has an impact on the governing equation. So, an important lesson that can be learned from the 1998 Papua New Guinea tsunami is landslides can be triggered by relatively normal earthquakes, which can result in a regional tsunami hazard.

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