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EVALUATION OF TSUNAMI SOURCE MECHANISMS ALONG THE TONGA TRENCH AND VOLCANIC ARC – Case Study: Earthquake and Tsunami of 29 September 2009

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Tsunami Society International

ABSTRACT

The present report provides an evaluation of the tectonics of the upper part of the Tonga Trench and Volcanic Arc Region. The overall tectonics of the region are dominated by the convergence of the Pacific and Australia plates. The active westward movement of the Pacific oceanic lithosphere underneath the Australian plate has formed an extensive tectonic boundary. The boundary consists of the Tonga-Kermadec Subduction Zone, marked by a great trench and its associated adjacent volcanic arc. The eastern edge of the Australia plate is a collection of smaller micro-plates that move with respect to each other, and with the Pacific plate and the interior of the Australia plate. Many earthquakes along the boundaries of these tectonic boundaries have generated relatively small tsunamis. However, on 29 September 2009 a major 8.3 Richter magnitude earthquake near the upper segment of the Tonga trench generated an unusually destructive tsunami. Large waves struck coastal villages and towns in Samoa, American Samoa and the island Kingdom of Tonga, causing extreme damage and many deaths at Pago Pago harbor, the village of Leone and elsewhere. The destruction by this particular event was unprecedented. A tsunami warning issued by the Pacific Tsunami Warning Center did not reach the affected region in time for people to evacuate. The following report documents the tectonics of subduction along the northern segment the Tonga Trench and Volcanic Arc, the source mechanism of the 2009 tsunami, and a brief history of past events. Furthermore, and in view of the tsunami generated by the 15 January 2022 eruption/explosion of the submarine volcano Hunga-Tonga-Hunga-Ha'apai near Tonga, the present report provides a preliminary evaluation of stresses along a cross-section in the middle segment of the Tonga trench from Pacific plate subduction along the spreading center of Lau Basin, for a report under preparation pertaining to tsunami generation mechanisms along the adjacent volcanic arc.

Key Words: *Tonga-Kermadec Subduction Zone*, *29 September 2009 Earthquake Tsunami*

1. INTRODUCTION

The overall tectonics of the Tonga-Kermadec subduction region are dominated by the convergence of the Pacific and Australia plates at an average rate of 86mm/year. The active westward movement of the Pacific oceanic lithosphere underneath the Australian plate has formed an extensive tectonic boundary. The boundary consists of the Tonga-Kermadec Subduction Zone - marked by a great trench - and its associated adjacent volcanic arc. The eastern edge of the broad Australia plate is a collection of smaller micro-plates that move with respect to each other and with respect to the Pacific plate and the interior of the Australia plate.

A major earthquake occurred on 29 September 29, 2009 in the Samoan Islands region (Fig. 1). A destructive tsunami struck coastal villages and towns in Samoa, American Samoa and the Tonga island Kingdom, causing extreme damage and many deaths. A tsunami warning issued by the Pacific Tsunami Warning Center, did not reach the affected region in time for people to evacuate. Severe damage and deaths occurred at Pago Pago harbor, the village of Leone and elsewhere. The following report documents this earthquake, past events in the region, and the tectonics of subduction along the northern segment of the Tonga Trench. Additionally, the report provides a preliminary evaluation of the tsunami's source mechanism.

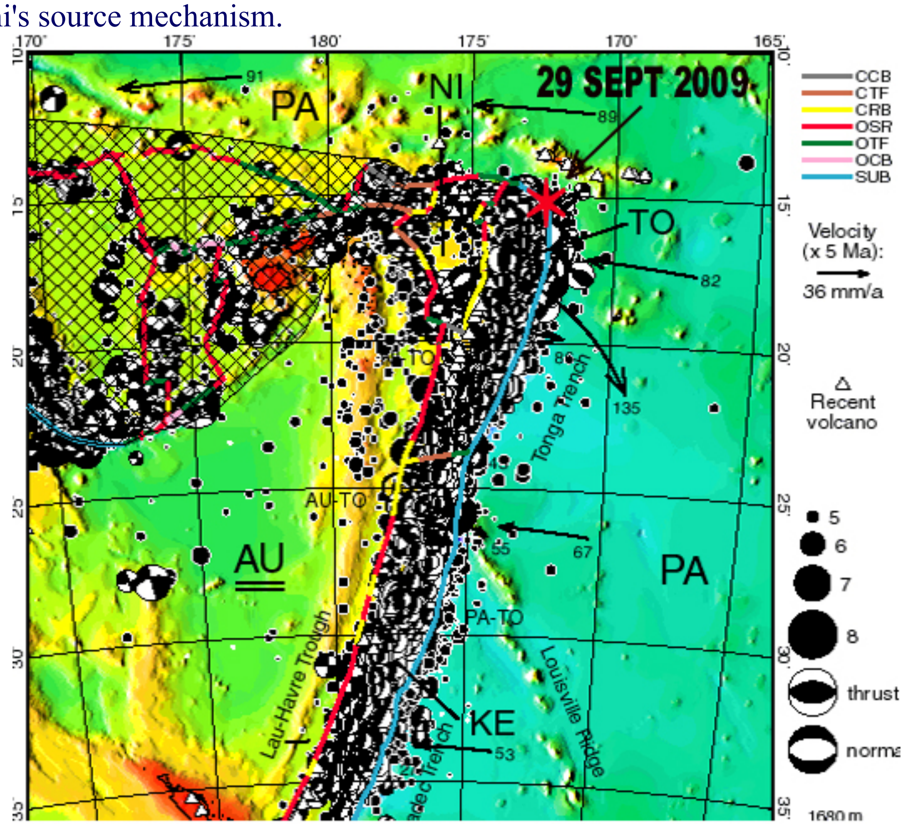

Fig. 1.The Tonga-Kermadec Trench and Arc. *Seismotectonics, Kinematics and Plate Boundaries of the Tonga subplate seismic activity along the Tonga Trench and its northern boundary near the region where the 29 September Earthquake occurred. TO-Tonga plate, PA-Pacific plate. KE-Kermadec plate, AU-Australian plate (modified graphic after Bird, P. (2003).*

2. TECTONIC SETTING OF THE TONGA-KERMADEC SUBDUCTION REGION

As shown in Fig. 1, the Kermadec-Tonga Arc is an intra-oceanic arc, one of the longest on earth, extending for almost 2500 km from New Zealand to Samoa. It is bounded on both sides by oceanic crust. The arc includes at least 100 volcanoes, most of them submarine (Baker, 2004). The Tonga-Kermadec Trench and Arc consist of two major segments. The Tonga (TO) segment is the northernmost half based of the presence of the Louisville Aseismic Ridge, located on the subducting Pacific plate, and the Kermadec segment (KE) in the southern half.

The earth's most active zone of mantle seismicity arises from the westward subduction of the Pacific plate beneath the Australia plate at the Tonga trench. Convergence rates across the trench increase northward to a maximum of 240 mm per year. The extraordinary seismic activity of the subducting slab is probably related to this unusually rapid subduction Bevis et al., 2002).

The intra-oceanic convergence tectonics along the Tonga Trench and the adjacent fore-arc between 14 S and 27 S Latitude is somewhat complicated and varies from North to South. The Pacific plate subducts westward beneath the northeast corner of the Australian plate at about 15 cm per year - which is quite high. Also the submarine morphology of the Tonga Trench indicates changes from relatively normal convergence in the north, to oblique convergence in the south. Anomalies are greater around 26 South latitude, which marks the boundary of the Tonga, and Kermadec fore-arcs. Furthermore, along the entire length of the Trench axis, there are numerous transform faults at right angles, which indicate that earthquakes in the region may be limited in rupture length.

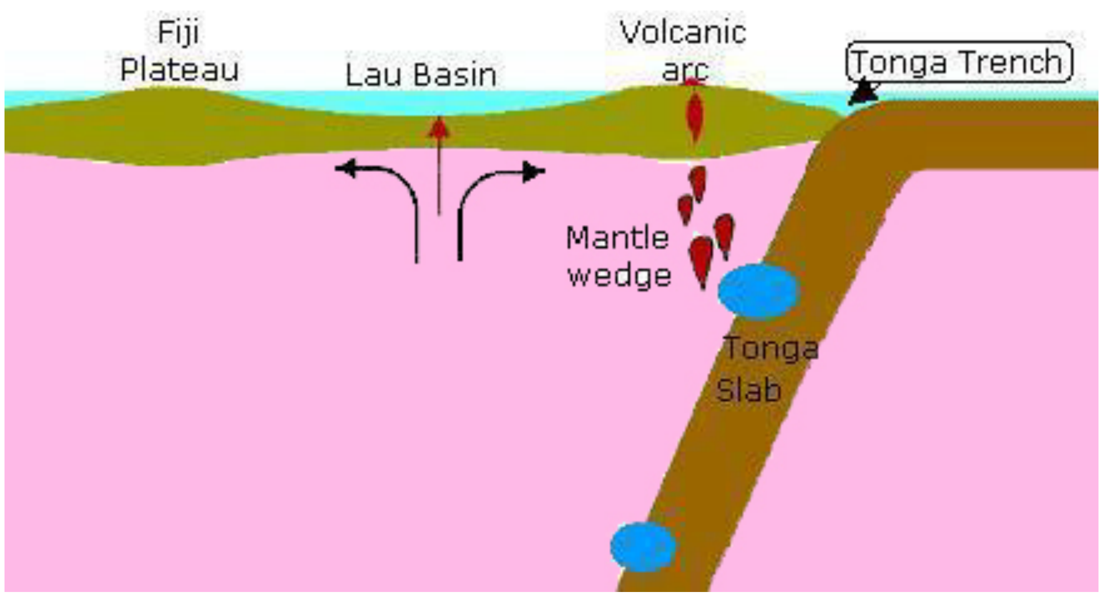

Fig. 2 Illustration of stresses along a cross-section in the middle segment of the Tonga trench from Pacific plate subduction and from the spreading center of Lau Basin (modified USGS graphic).

What is also significant in the central region is the high number of deeper earthquakes, along a rather steep subduction boundary on the east side. The adjacent cross-sectional chart across the middle part of the Tonga Trench, illustrates the tectonic complexity of this region the steepness of the subducting plate, the a lateral heterogeneity of structural features, and the stresses from both the spreading center of Lau Basin on one side of the Arc and the stresses from the subducting slab of the Pacific plate. The subduction along this central segment has created very deep bathymetry along the trench and an extensively deformed volcanic arc on the other side.

3. HISTORIC EARTHQUAKES AND TSUNAMIS IN THE TONGA-KERMADEC SUBDUCTION ZONE REGION

Extensive fracturing along the Tonga Trench, form natural asperities that often limits an earthquake's rupture length. Shorter ruptures and greater focal depths also limit the likelihood that tsunamis generated in this region will have a Pacific-wide impact. Most of the tsunamis generated in the past were local events. Yet, in spite of the obliquity of the southern portion of the Tonga Trench and fore-arc, a large magnitude earthquake could rupture two or more segments and produce a larger tsunami - although very infrequently. Most of the large magnitude earthquakes along the eastern boundary of the Tonga subduction zone occur at greater focal depths and - as already stated - none of the historical earthquakes in this region are known to have generated a significant Pacific-wide tsunami. The only exceptions may be the November 17, 1865 and the April 30, 1919 Tongan earthquakes, which generated tsunamis, that were visually observable at great distance. However, this is not the case along the northern segment where subduction changes direction and obliquity. Destructive local tsunamis can be generated. Pacific-wide tsunamis are also possible from this region, although they do not pose a significant, far field threat.

Review of historic records indicates that around 30 quakes of magnitude 7.0 or more have occurred along the Tonga plate boundary since 1900 (http://earthquake.usgs.gov/regional/neic). The most significant and largest of these in the northern segment was the magnitude 8.5 earthquake of June 26, 1917. It was an outer-rise earthquake on the northern end of the Tonga *Trench*, with epicenter at 15.500 S, 173.000 W. It generated a very destructive tsunami that had an observed local, maximum height of 12 meters (Pararas-Carayannis & Dong, 2980). Also the tsunami reached Japan and had at maximum recorded height at Kushimoto.

Another significant 7.5 magnitude earthquake occurred on April 14, 1957. Its epicenter was at 15.403 S, 173.129 W. (Pararas-Carayannis & Dong, 1980). A shallow 7.5 magnitude earthquake in the same region occurred on 1 September 1981, with epicenter at 15.112 S., 173.019 W.

Also there have been several significant earthquakes along the eastern subduction zone of the Tonga Trench and Arc. The largest to strike the Tonga region was a magnitude 7.2, deep (69km) event that occurred on 22 June 1977 (UTC). Its epicenter was considerably further south at 22.91 S., 175.74 W., approximately 190 km to the southwest of the islands of Tongatapu and Eua. The earthquake caused extensive damage to houses, public utilities, churches and many buildings, as well as to the Vuna Wharf in Nuku'alofa. There was no report that any tsunami was generated and none would have been expected given the depth of the hypocenter.

Another very deep focus earthquake occurred on March 9, 1994. This earthquake had a moment magnitude Mw= 7.6 and depth of 564 km - too deep to generate any tsunami. At least 50 strong but very deep aftershocks followed the main event.

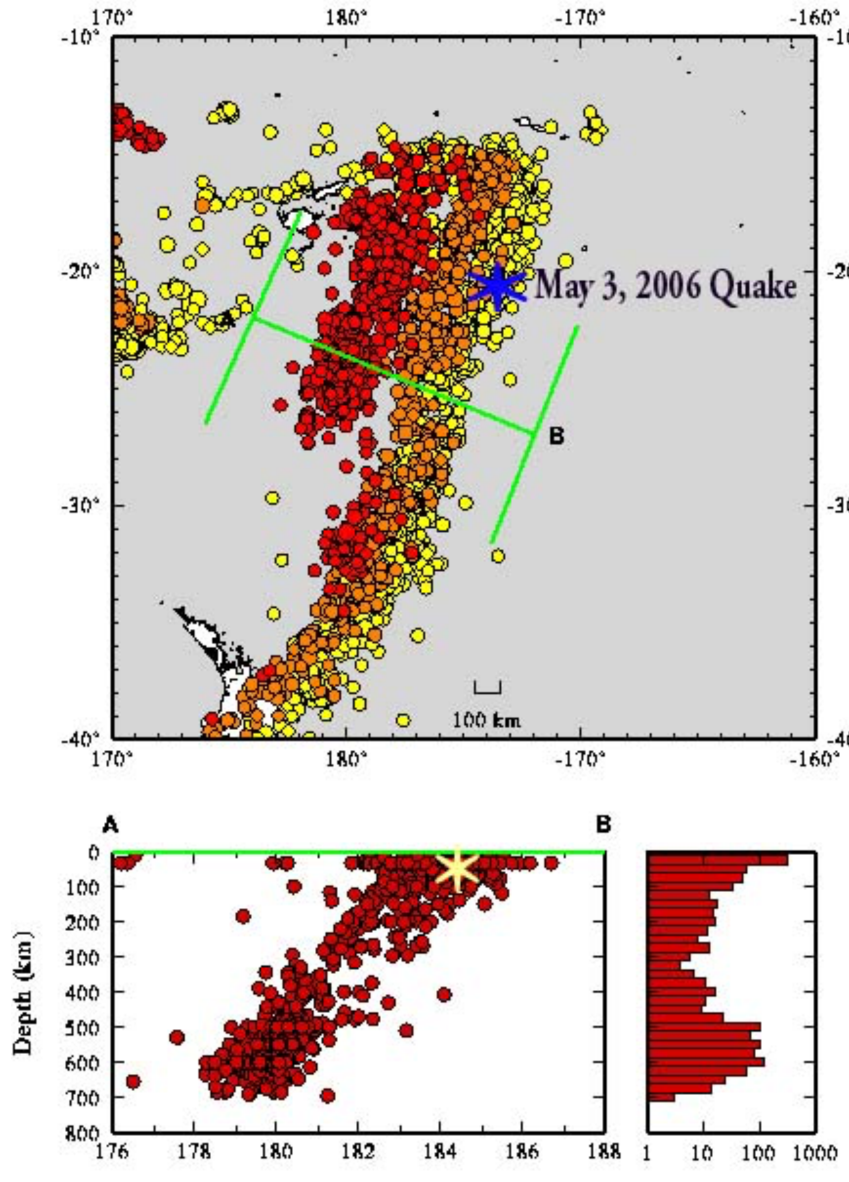

Fig. 3 Cross-section along the upper Kermadec-Tonga Arc, the epicenter of the 3 May 2006 earthquake, and variation in the number of earthquakes with focal depths (modified graphic from www.seismo.berkeley.edu)

On May 3, 2006, a magnitude 7.9 earthquake with focal depth of 55 km (34.2 miles) struck at 20.130 S, 174.164 W - about 160 km NE of Nuku'alofa (capital of Tonga), 165 km (100 miles) South of Neiafu, Tonga 465 km (290 miles) South of Hihifo, Tonga, and 2145 km (1330 miles) NNE of Auckland, New Zealand (see Fig. 3 above). This was the strongest felt earthquake in recent years. According to a report from Neiafu, 180 miles north of Nuku'alofa, the quake's strong motions lasted for about 90 seconds. The earthquake generated a small tsunami (Pararas-Carayannis, 2006).

Figure 3 shown above illustrates the horizontal and vertical distribution of earthquake epicenters on the surface, and of hypocenters along a cross-section that was taken on the Tonga segment of the trench by a recent study. The cross-section is somewhat south of the May 3, 2006 event, but the diagrams show the high incidence of deeper focus earthquakes in the region and the steepness of the downward bending Pacific oceanic plate beneath the Australian plate. The epicenter and hypocenter of the May 3, 2006 earthquake have been plotted on these diagrams.

3.1 The 29 September 2009 Earthquake and Tsunami on the Northern End of the Tonga Subduction Zone.

According to the U.S. Geological Service (USGS), at 17:48:10 UTC (06:48:10 AM local time) on 29 September 2009, a magnitude M 8.0 earthquake with focal depth of 18 km (11.2 miles) and epicenter at 15.509 South and 172.034 West (Fig. 4), occurred in the northern region of the Tonga Trench. The Pacific Tsunami Warning Center put the quake's magnitude at 8.3, and issued a tsunami warning.

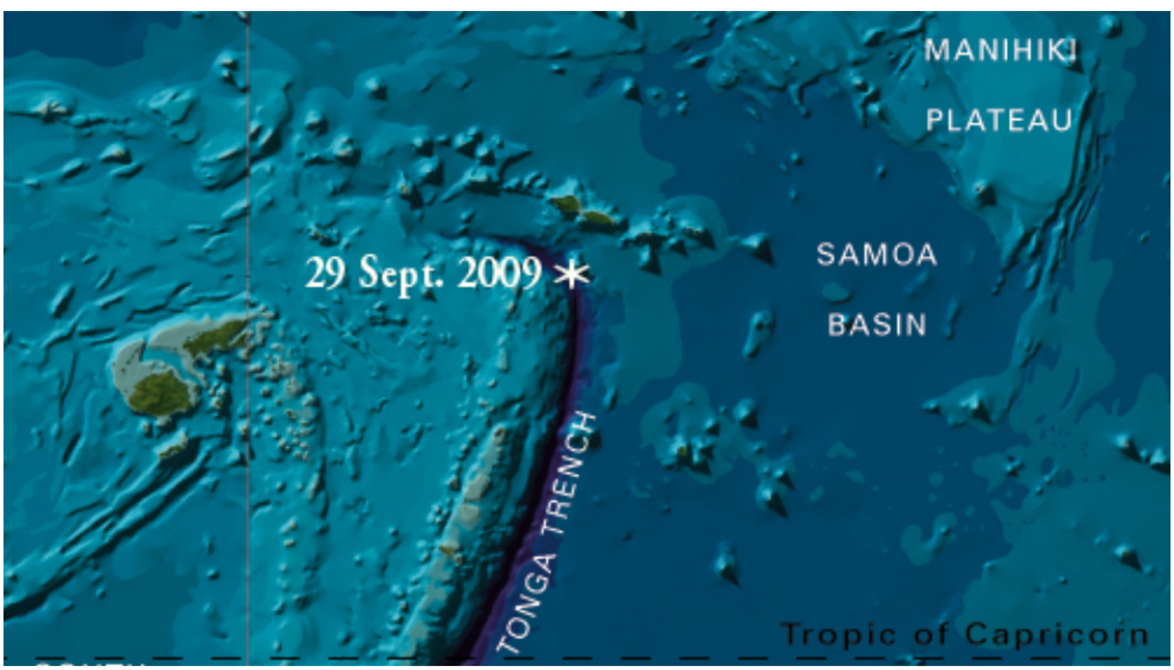

Fig. 4. Epicenter of the 29 September 2009 Earthquake on the Northern End of the Tonga Trench.

The 29 September 2009 earthquake occurred on the northern segment of the Tonga Subduction Zone where large earthquakes occur frequently. The tectonics in this northern region where the subduction zone changes direction are different than those of the central segment. The rates of crustal movements are different, and as expected, subduction becomes more oblique and shallower, thus resulting in more destructive and potentially tsunamigenic earthquakes. Fault mechanism solutions indicate that the earthquake of 29 September 2009 occurred along a normal fault rupture at the outer rise of the trench, as shown in Figure 4 above.

According to the USGS the distance of the epicenter of this earthquake was 120 miles (190 km) from American Samoa, 125 miles (200 kms) from Western Samoa, 406 km (252 miles) NNE from Neiafu, Tonga, 185 kms (115 miles) ENE of Hihifo, Tonga, 710 kms (440 miles) NNE of NUKU'ALOFA, Tonga, and 2700 kms (1680 miles) NNE of Auckland, New Zealand.

A 5.6-magnitude aftershock occurred 20 minutes later, followed by 14 aftershocks of magnitude 5.0 or higher. Fairly strong ground motions were felt throughout the islands of Samoa, American Samoa and northern Tonga. There were reports from Apia that the shaking lasted for at least two minutes. Such duration seems long even for an earthquake of high magnitude. Given the magnitude of 8 (USGS) or 8.3 (Pacific Tsunami Warning Center), the shallow focal depth and the length of rupture, the duration of ground motions could not have been greater than 50 to 60 seconds, with perhaps possible brief interruptions, unless there were sequential sub-events that extended the ground motions.

3.1.1 ***Rupture Length and Crustal Displacements*** - The distribution of aftershocks, the quake's magnitude and the focal mechanism analysis suggest that ruptures ranged by as much as 175 kms, along one or more normal faults on the outer-rise of the subducting Pacific plate. Maximum displacements of as much as 7 meters were reported but available centroid moment tensor solutions (USGS) indicated an average of 3.6meter vertical change.

3.1.2 Death Toll and Damages – On November 29, 2009, the reported death toll was about 160 but it may have been higher. Most of the deaths occurred in Western Samoa, in American Samoa and some in Niuatoputapu, in Tonga. Damaged telephone lines made it difficult to communicate and assess the casualties and the destruction from both earthquake and tsunami. There was extensive destruction of buildings in Apia and damage to plantations outside of the city. Many of the residents reported cracks to their homes. Several landslides occurred in the Solosolo region of the main Samoan island of Opolu of Western Samoa. About 3,000 people were rendered homeless.

3.2 The 29 September 2009 Tsunami

Based on the high magnitude of the earthquake, the Pacific Tsunami Warning Center issued a tsunami warning for numerous islands in the Pacific, including the Samoas, (both Western Samoa and American Samoa), the Cook Islands, Tonga, Fiji, New Zealand, French Polynesia and Palmyra Island. A tsunami watch was issued for Hawaii, Vanuatu, the Marshall Islands, Solomon Island, Johnston Island, New Caledonia, Papua New Guinea, Wake Island, Midway Island and Pitcairn. In New Zealand, a tsunami alert was issued by national Civil Defense, and the nation's national emergency center was activated.

3.2.1 Tsunami Effects - In American Samoa, the waves flattened coastal villages and killed many people. At the National Park Service facilities many people were reported missing. Cars and people were swept out to sea. A large boat was deposited ashore at the edge of the coastal highway (Fig. 5). More than 110 people were reported dead. The beach village of Sau Sau Beach Fale was leveled.

Fig. 5 Boat deposited ashore at the edge of the coastal highway

3.2 SOURCE MECHANISM OF THE EARTHQUAKE OF 29 SEPTEMBER 2009 ON THE NORTHERN END OF THE TONGA SUBDUCTION ZONE

As previously stated, the 29 September 2009 earthquake occurred near the seismically active northern end of the Tonga Trench and Arc where there is greater obliquity of collision and a sharp change in direction towards the west. This earthquake was particularly unusual in the sense that it did not occur on the inter-plate thrust fault within the subducting Pacific plate but further out on the outer-rise region – as discussed further in the following section.

3.2.1 The Outer Rise Earthquake of 29 September 2009 – This earthquake was an outer-rise event. The outer-rise is a geomorphologic feature on the subducting tectonic plate, which usually parallels the inter-plate, thrust fault of the subduction zone. It is formed further out by crustal stresses that force tensional flexing of the subducting plate, or by flexing due to transference of stresses from inter-plate earthquakes to the outer rise, which energize the existing, near failure, normal faults. Such outer-rise earthquakes are caused by extreme stresses that result in bending within the subducting oceanic plate itself before it enters the subduction zone. Fig. 6 shows both the epicenter of the 29 September 2009 earthquake and a schematic of the centroid moment tensor solution (USGS).

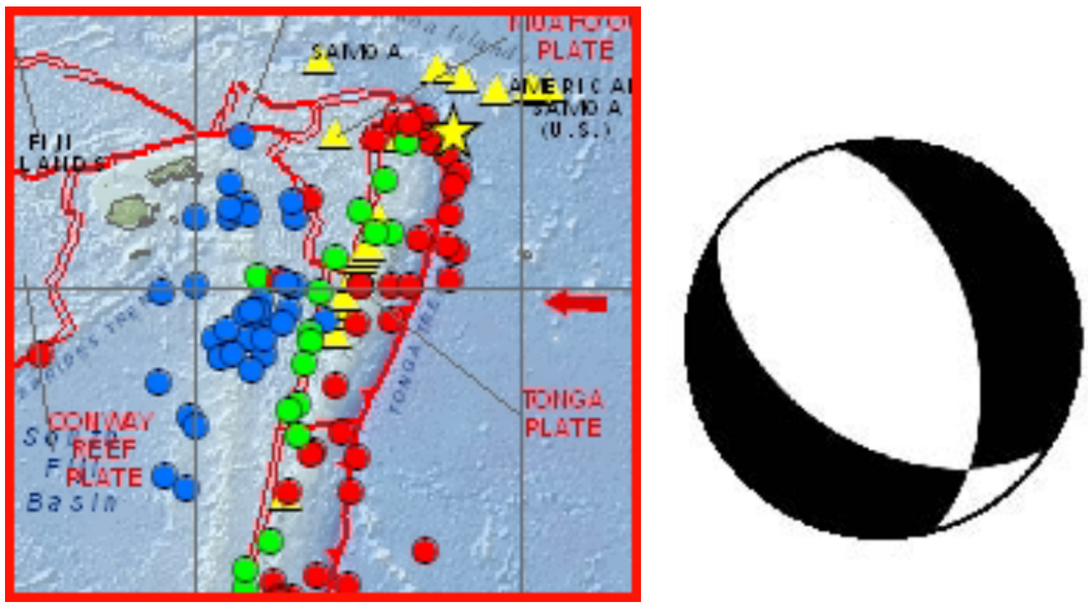

Fig. 6 Epicenter of the September 29 earthquake - Schematic of centroid moment tensor solution (USGS)

Outer-rise earthquakes are known to generate destructive tsunamis in this region of the Tonga trench and elsewhere. For example, the earthquake of 1917 - which occurred somewhat west of the September 29, 2009 event - was also an outer-rise event (Pararas-Carayannis, 1980). It had similar characteristics and generated an equally destructive tsunami.

The 8.4 magnitude, Sanriku earthquake of 2 March 1933 occurred also on the outer-rise of the subducting plate and generated a devastating tsunami in Japan that resulted in more than 3,000 deaths and considerable damage as far away as the island of Hawaii.

Similarly, the 19 August 1977 Lesser Sunda Islands (Nusa Tenggara islands - Sumba, Sumbawa) earthquake was also an outer-rise event, which generated a large tsunami that resulted in 189 deaths and was destructive along the coasts of Sumba, Sumbawa, and Lombok 4.and Bali. The effects of crustal displacements of the 1977 earthquake were not confined to the tectonic boundary region but extended to the subducted plate itself, resulting in more extensive faulting, uplift and subsidence, offshore and on offshore islands (Pararas-Carayannis, 1977).

4. THE TSUNAMI OF 29 SEPTEMBER 2009 IN THE SAMOAN ISLANDS REGION

The tsunami generated by the earthquake of September 29, 2009 was destructive along the coasts of Samoa, American Samoa and Tonga. It resulted in many deaths and left thousands of people homeless. Widespread damage was reported to the infrastructure at Pago Pago, American Samoa, in many parts of Samoa (Western) and on Niuatoputapu, in the Kingdom of Tonga. Fig. 7 below is the tsunami travel time chart of this event, showing also the location of DART buoys that recorded it (Source: NOAA Center for Tsunami Research).

4.1 The 29 September 2009 Tsunami in American Samoa, Western Samoa and Tonga

The first tsunami wave arrived at Pago Pago in American Samoa, (approximately 250 km from earthquake epicenter) at 18:08 UTC, about 20 minutes after the earthquake. A five-foot tsunami wave swept into Pago Pago and surged inland about 100 meters before receding, leaving some cars and debris stuck in mud. Electricity outages were reported and telephone lines were jammed. In Fagatogo, the tsunami inundation extended to the town's meeting field and covered portions of the main highway. Also, there were numerous rock slides in the area.

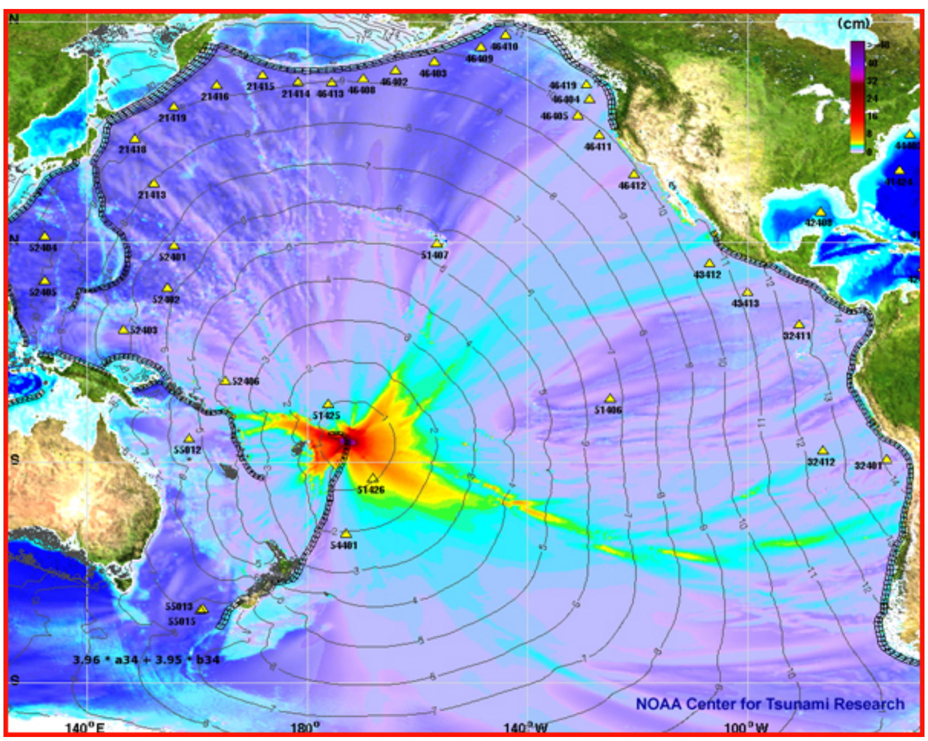

Fig. 7 The 29 September 2009 tsunami travel time chart. Location of DART buoys (Source: NOAA Center for Tsunami Research).

The following peak-to-through wave heights were recorded: 3.14m at Pago Pago (American Samoa); 1.40m at Apia (Samoa); 0.47m at Rarotonga and 8 cm at Penrhyn (Cook Islands); 14 cm at Nukualofa (Tonga) and 11 cm at Papeete (French Polynesia). However, wave heights on the open coasts were much higher. Only a 16-centimeter wave was recorded by the tide gauge in Honolulu, Hawaii. However, boaters at the Ala Wai Yacht harbor in Waikiki, observed a much greater sea level fluctuation.

The southern coasts of Savai and Upolu islands of Samoa (Western) were hardest hit by the waves. Yet, in spite of extensive damage to villages on the two main islands of Upolu and Savaii, subsequently the people in the stricken area wanted to rebuild on the same sites.

4.2 Dart Recordings of the 29 September 2009 Tsunami

In a little over one hour, the tsunami was recorded at DART® buoys 51425 and 51426. DART 51425 is located 370 Nautical Miles NW of Apia (Lat: 9.49 degrees S Lon: 176.25 degrees W). DART 51426 is located at 400 Nautical Miles SE of Tonga (Lat: 22.99 degrees S Lon: 168.10 degrees W). Based on tsunami source inferred from DART® data, forecast results were created in real time using the MOST model (Method of Splitting Tsunami) approximation. Subsequent numerical modeling based on additional centroid data, generated somewhat different results.

4.3 Evaluation of the Earthquake and Tsunami Source Mechanisms

As previously indicated, and as shown in Figures 1 and 4, at the northernmost segment of the Tonga subduction zone near the area where the September 29, 2009 earthquake occurred, the direction of convergence and subduction change in a westward direction. Earthquake distribution and source-mechanism determinations for 57 events along a narrow belt of high seismicity indicate a progressive down-warping and tearing of the Pacific plate as it enters the northern Tonga subduction zone, as well as shoaling of the subducted slab and dip-slip faulting along near-vertical planes oriented 285 degrees - coinciding with the observed direction of plate convergence. In fact, specific analysis of 21 events with focal depths of aftershocks ranging from 18-57 km, and of the 7 April 1995 (Ms =8) event and aftershocks, suggests that the Pacific plate is down-warped prior to the initiation of tearing - a process which may extend through the entire thickness of the oceanic lithosphere (Millen and Hamburger, 1998).

It has also been suggested that the northern Tonga ridge is the boundary of a rigid microplate (Bevis et al., 2002). The suggestion appears to hold true. Such microplate rigidity appears to be responsible for stresses that have resulted in crustal bending and have formed an extensive outer-rise on the Pacific plate before it enters the subduction zone at a rather steep angle. Oblique convergence may be also responsible for some rotation of the Tonga microplate.

This outer rise is apparently traversed by several large, normal faults at different phases of potential failure. Significant tsunamigenic earthquakes may be triggered on this outer-rise region by the overall stresses of convergence as well as from stress transference from inter-plate thrust earthquakes occurring closer to the subduction boundary. Apparently, the

September 29, 2009 earthquake resulted from such a large-scale failure of not one but of several E-W trending normal faults on the outer-rise that parallel the trench. Failure of large normal faults on the outer rise can be very effective tsunami generators as they result usually in larger scale, crustal, vertical displacements and more extensive slip than earthquakes that occur closer to the convergence boundary. Also, the relatively shallow focal depths of such earthquakes on the outer rise, contribute to greater tsunamigenic efficiency. This is evident from both the 1917 (12 meter tsunami) and the 2009 earthquakes in this northern region of the Tonga microplate as well as in other regions in Japan, Indonesia and elsewhere (Pararas-Carayannis, 1977, 1980, 1994).

Also, at the outer-rise there may be transform faults at oblique angles to the overall tectonic trend and these may be asperities that may have limited the September 29, 2009 earthquake's rupture length and altered its source characteristics - thus resulting in differences in the centroid moment tensor solutions. The centroid solutions suggest two possible source geometries that differ mainly in orientation. However, it is possible that none of the centroid solutions depict all the source characteristics, particularly if there was rotation or a slight extrusion of crustal material along a transform fault at the southeastern end of the designated source. Such source mechanism could account for the abnormal tsunami wave recorded at the DART gauge to the south.

Therefore, any discrepancies in the results of numerical tsunami modeling studies can only be explained if we assume that the centroid solutions of source parameters may not reflect accurately the characteristics of an outer-rise event that involved a rather complex generating mechanism - which may have included rotation, several ruptures and crustal offsets. However, in spite of possible anomalies that cannot be properly justified, the overall modeling results give a fairly good picture of the tsunami's flux energy and directions of maximum propagation.

4.4 Dimensions of the Tsunami Source of the 29 September 2009 Event

Based on centroid solutions, the dimensions of the tsunami generating area can be approximated by an ellipsoid with major and minor axes. Thus the total tsunami generating area can be estimated:

A= π , r1 . r2 = 3.14 x 150 x 60 = 28, 260 km2

4.5 Modeling Studies

Based on centroid solutions for source characteristics, preliminary modeling studies were carried out by several researchers using three different numerical codes: the SWAN-JRC code, the HyFlux2 code which solves the equations with a different numerical method which is particularly relevant for inundation calculations; and the TUNAMI 2 code, of Prof. Imamura (Annunziato et al. 2009). These calculations were compared with the results obtained by the NOAA forecast MOST model (Method of Splitting Tsunami).

Subsequent numerical modeling studies of tsunami heights were carried out by other researchers (Thio & Somerville, Oct. 2009; Tohoku University, Oct. 2009) using the centroid and seismic moment information from Dr. Jascha Polet (Cal Poly, Pomona) (Magnitude 9, 15.321 South, 172.103 East; Strike -30.2, dip 50, slip -82) and from USGS, respectively.

Based on available centroid moment tensor solutions (USGS) that give different dimensions and orientations of tsunami sources, scientists at the Disaster Control Center of Tohoku University in Japan, used the Leap-frog Finite Difference Method (the TUNAMI-CODE they have developed) for their modeling study. The Leap-frog Finite Difference Method makes use of the non-linear shallow water equations, with a spatial grid size of 30 seconds and GEBCO bathymetry. Figures 8 and 9 illustrate the two different tsunami source regions that were used for these calculations which, as expected, generated somewhat different results.

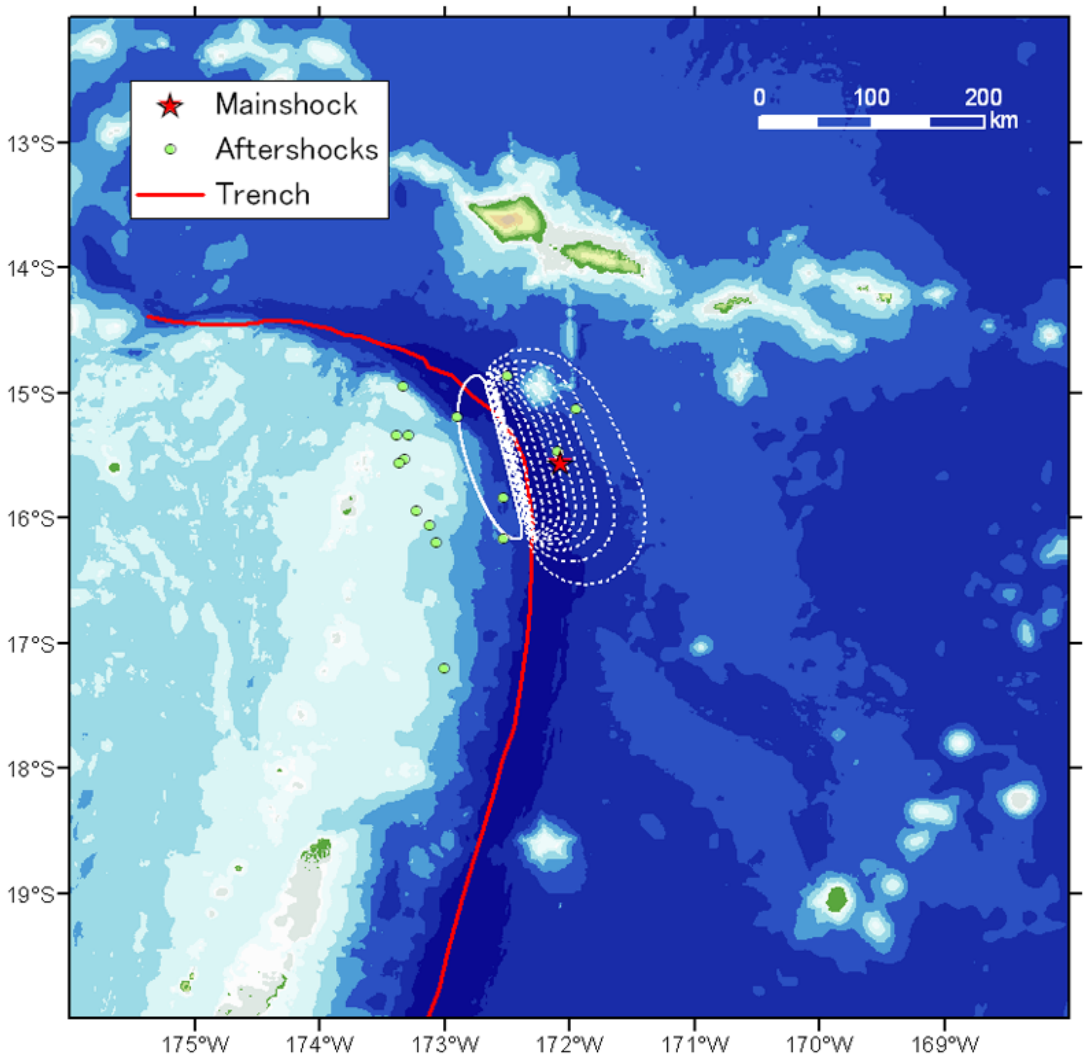

Fig. 8 Case 1. Tohoku University, (USGS data), Mo = 1.2 x 10**21 Nm
Fault Length / Width: 150 km / 75 km
Source Mechanism (Strike, Dip, Slip) = (345, 52, -61) Reference: USGS
Dislocation: 3.6 m.
http://www.tsunami.civil.tohoku.ac.jp/hokusai3/J/events/samoa_090930/source_case1.png

Both cases involved a different interpretation of source characteristics, orientation and displacements, which indicates uncertainties involving the tectonic interactions in this northern segment of the Tonga Trench and Arc. The USGS centroid moment tensor solutions are best double couple estimates based on data from 134 stations.

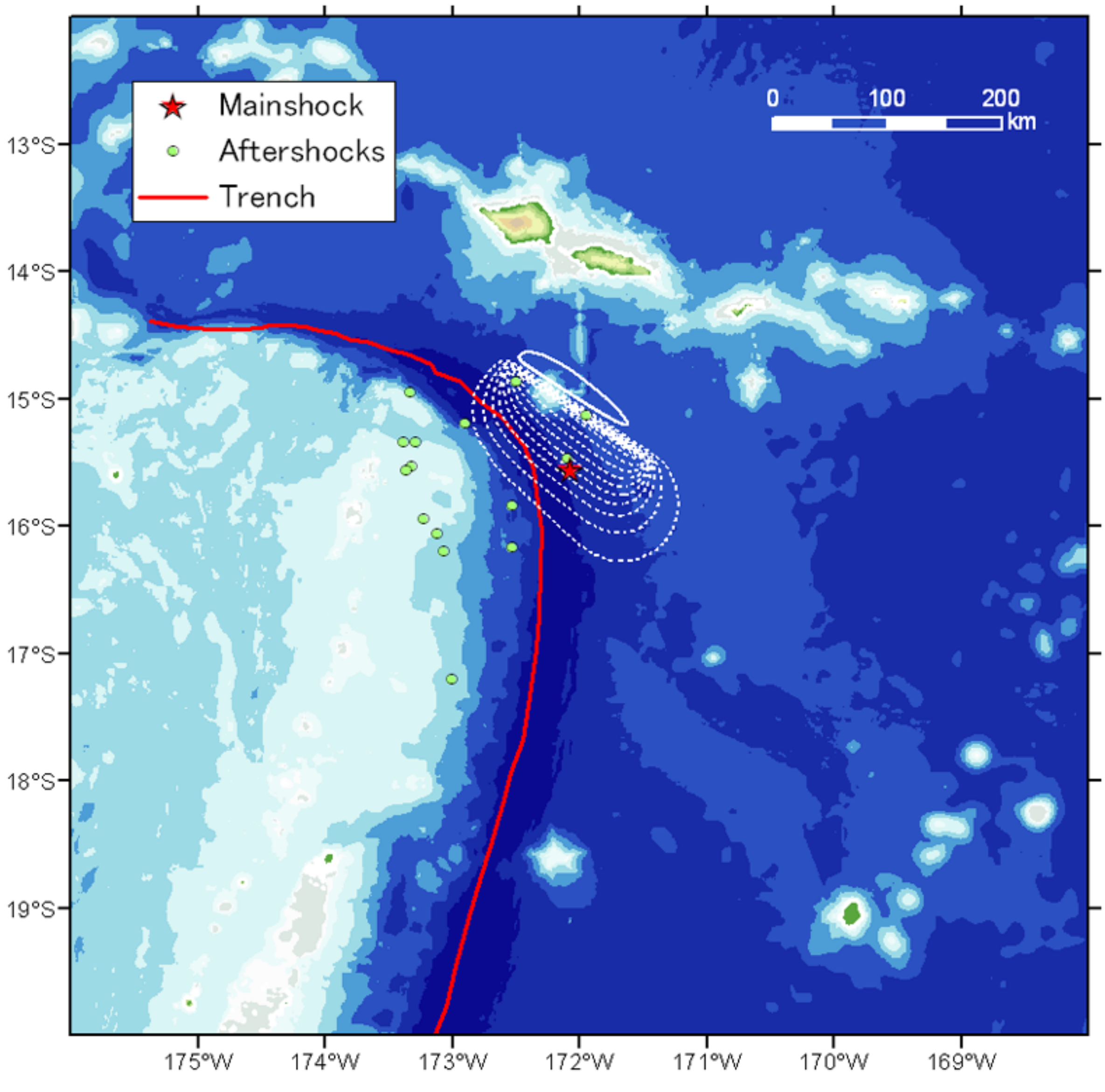

Fig. 9 Case 2 Tohoku University, (USGS DATA, Mo = 1.2 x 10**21 Nm
Fault Length / Width: 150 km / 75 km
Source Mechanism (Strike, Dip, Slip) = (124, 46, -120) Reference: USGS
Dislocation: 3.6 m

CONCLUSIONS

It must be obvious from the discussion above that there is still a great deal of uncertainty regarding the actual ocean floor displacements and the source mechanism of the outer-rise tsunami generated by the earthquake of 29 September 2009. A subsequent analysis will provide estimates of energy that went into tsunami generation and will attempt to reconcile results obtained by numerical modeling with the recording of the tsunami at DART buoy 51326.

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GLOBAL RESEARCH ON TSUNAMI EDUCATION AND TSUNAMI MITIGATION: A BIBLIOMETRIC ANALYSIS

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ABSTRACT

The present study analyzes research trends related to tsunami education and mitigation through bibliometric analyses, and explores the level of contributions of Indonesian researchers in the Scopus database. A total of 1293 documents were identified by this analysis, with 201 originating from Indonesia. The results showed that scientific publications related to tsunami education and mitigation have increased significantly, and that United States has published most of such papers. At the same time, the institution that won a lead role was Tohoku University, in Japan. Three institutions from Indonesia are ranked seventh, fourteenth, and fifteenth, namely the Bandung Institute of Technology, the University of Indonesia, and the University of Gadjah Mada. The most prolific author on this topic is N. Tanaka. Visualization of research trends on tsunami education and mitigation resulted in four clusters: (1) Tsunami waves; (2) Tsunami problems and monitoring; (3) Tsunami early warning systems; (4) Preparedness in dealing with tsunamis, and in the post-tsunami recovery process. The present research can help in the identification of trends related to tsunami education and tsunami impact mitigation, as well as in worldwide development in providing an overview for further study.

Keywords: *Tsunami, Education, Mitigation*

1. INTRODUCTION

Tsunami disasters pose increasingly complex challenges for modern society (Sellke & Renn, 2010). If preparedness is not handled properly, tsunamis can have substantial impacts of damage to critical infrastructure, on direct and indirect social losses, on the spread of infectious diseases, on necessary supply lines, on crime, on increased unemployment, and on mental health problems (UNDR, 2019; Aven. & Renn, 2010; Himaz, 2022). Fortunately, in recent years significant progress has been made in assessing the risks of tsunami hazards (Rafliana et al., 2022).

The historical records document that tsunamis have occurred frequently in various parts of the world. Examples of some extremely destructive historical tsunamis include the great Lisbon tsunami of 1755, the Indian Ocean tsunami of 2004, the Mentawai tsunami of 2010, the Tohoku tsunami of 2011, and many more (Rafliana et al., 2022). The impact of the December 26, 2004 tsunami was one of the greatest. It was generated by a powerful underwater earthquake off the coast of Sumatra Island, in Indonesia, and affected many countries in the Indian Ocean. The earthquake had a magnitude 9.1 on the Richter scale and the tsunami that was triggered initially hit the coastline of the city of Banda Aceh, killing more than 100,000 people, and left entire other coastal towns into piles of rubble (Idris et al., 2022). Some of the reasons that the tsunami was so devastating was because at that time the tsunami warning system in Indonesia was still inadequate and unable to issue advisories or warnings to communities, particularly in the rural areas. Also, at that time, evacuation plans had not been sufficiently prepared, and there was lack of community understanding and training about tsunami hazard mitigation and on how to deal with subsequent post-disaster impacts (Kim et al., 2022; Tanaka, 2009; Thuy et al., 2012).

Specifically, research on tsunamis in Indonesia was pioneered by Pararas-Carayannis (2004), who investigated the great Krakatau volcano eruption/collapse of 26-27 August 1883, and the devastating tsunami that was triggered. Moreover, for the Memoriam of 120 years of the Krakatau eruption and of the lessons learned from the giant tsunami, he presented a comprehensive paper on this event in Jakarta and in Anyer (Pararas-Carayannis, 1989a). Previously published was a comprehensive report of the earthquake and tsunami of 19 August 1977, (Pararas-Carayannis, 1977). Also, through the United Nations Development Program (UNDP) project and sponsorship of missions of Pararas-Carayannis, a five-year plan for developing a regional warning system in the Southwest Pacific was initiated (Pararas-Carayannis, 1989b). These preliminary studies became the starting point for tsunami mitigation efforts in Indonesia.

The 2004 Indian Ocean Tsunami triggered awareness from various countries about the tsunami risk, especially for Pacific countries with a high level of tsunami risk (Dhellemmes et al., 2001). In order to prevent a more significant impact, it is essential to work with vulnerable populations (i.e., people who live and work along the coast or visit the beach) to reduce risks. Since little can be done to reduce the causes of the tsunami hazard itself, attention should be focused on mitigating and increasing community knowledge and preparedness levels to reduce and manage risk (Goto et al., 2012; Imamura et al., 2012).

Communicating on how the decision-making process at the individual and community levels must be developed in order to build a better understanding elements of risks, impacts, and consequences, is very important prerequisite in establishing actions that must be taken to deal with tsunami disaster mitigation (Nakano et al., 2020; Bird & Dominey, 2008; Frase et al., 2016). Therefore, it is necessary to carry out effectively risk communications. According to Rafiana et al. (2022), risk communication is one of the things that most influence the size of the impact of natural disaster events. Risk communication can refer to public or private communications that inform individuals about the existence, nature, form, severity, or acceptance of risk (Wachinger et al., 2013). Therefore, communication about the risk is an essential prerequisite for effective management of such hazard, and improves preparedness and resilience (Chen et al., 2001; Klinke & Renn, 2010; Eisner, 2005; Cruce & Hilman, 2011). One of the efforts that can be made to improve risk communication is to implement and introduce tsunami education and tsunami mitigation procedures to the community (Pararas-Carayannis, 1989b).

In brief, public education has been found to be effective in increasing the public's perceptions of tsunami risks and their acceptance of needed safety measures. Research conducted in Acapulco, Mexico, found that high school students are more interested in learning information rather than learning appropriate needed actions that must be taken to protect their lives, which also implies a missing link between risk perception and proactive action (Nakano, 2018). Communicating disaster-related knowledge is widely considered to increase people's risk perceptions, directing them to proactively take preparedness actions, and respond appropriately during natural disasters (Sakurai et al., 2020; Dengler, 2005; Bernard et al., 2006). Despite the importance of implementing tsunami education and tsunami mitigation, little research has been done to collect data and analyze the evaluation of the contributions of papers in terms of improving the implementation of tsunami education and tsunami mitigation.

Undertaking a bibliometric analysis provides an appropriate method for evaluating the contribution of an article to the advancement of knowledge (Chen & Ho, 2015). Bibliometric indicators, including the area of research, source documents, publication output, source language, distribution of countries and institutions, top authors, number of citations, and keywords, have been frequently used to analyze research trends (Yang et al., 2017). Thus the aim of the present study is to analyze research trends related to tsunami education and tsunami mitigation through bibliometric analyses, and also explore Indonesian researchers' level of contributions to the Scopus database. Therefore this study focused on the research trend of tsunami education and tsunami mitigation with the following six questions:

a) What was the extent of publication output of tsunami education and tsunami mitigation profile for the time period of 1978-2021?
b) What was the extent and distribution of tsunami education and tsunami mitigation publications across countries and institutes in the world?
c) Who were the top authors involved in tsunami education and mitigation globally?
d) How effective were the publication patterns of tsunami education and tsunami mitigation?
e) How did the visualization results of tsunami education and tsunami mitigation research trend?
f) What was the research extent and contributions of Indonesian authors on tsunami education and tsunami mitigation?

2. RESEARCH METHOD

To respond to the above listed questions, the present study used a bibliometric analysis as recommended in publipreviously hsed papers (Kulakli & Osmanaj, 2020; Masitoh et al., 2021, Suprapto, 2021). Data regarding research on tsunami education and tsunami mitigation were obtained from the Scopus database. By entering keywords in the metadata search "**TITLE-ABS (tsunami AND education OR tsunami AND mitigation) AND (EXCLUDE (PUBYEAR , 2022))**", a total of 1.293 documents related to tsunami education and tsunami mitigation were found.

The metadata search results were stored in .csv and .ris formats for further analysis. Then VOSviewer and Microsoft Excel software were used to visualize the data into graphs, tables, and maps. Additionally the study used the VoSViewer to determine research trends on tsunami education and tsunami mitigation (Van Eck & Waltman, 2020). Furthermore, an analysis of research trends was undertaken, which included a profile of publications, publication distribution across countries and institutes, top authors researching tsunami education and tsunami mitigation in the world, publication patterns, visualization results, and contributions of Indonesian authors involved in researching tsunami education and mitigation.

3. RESULTS AND DISCUSSION

3.1 Profile of Publication Output

As previously stated and as shown in Figure 1 below, a total of 1293 documents were found in the Scopus database relating to tsunami education and tsunami mitigation for the period of 1978 to 2021. However the number of papers and documents increased significantly over the years. Before 2005, there were only less than ten documents found. After 2005 there were more than ten documents per year and up to 2021, there were hundreds per year. Although the number of papers and documents decreased several times, Fig.1 indicates that the research trend has increased significantly in the last four decades. Thus, if the present trend continues, it can be expected that there will be even a more drastic increase in the number of articles in the 2021 to 2025 time period.

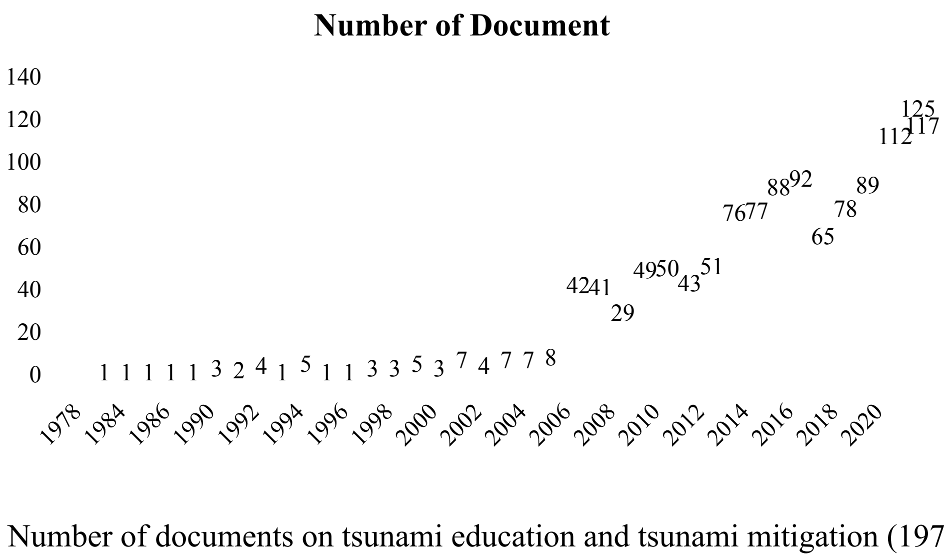

Figure 1. Number of documents on tsunami education and tsunami mitigation (1978-2021)

There are 6 document sources related to tsunami education and tsunami mitigation, namely journals, conference proceedings, books, book series, trade journals, and reports. Based on Figure 2 below, it can be seen that journals dominate the number of documents based on sources of as many as 707 publications. These numbers were followed by conference proceedings, as many as 395 documents, and books as many as 108 documents. Book series, trade journals, and reports were the fewer document sources.

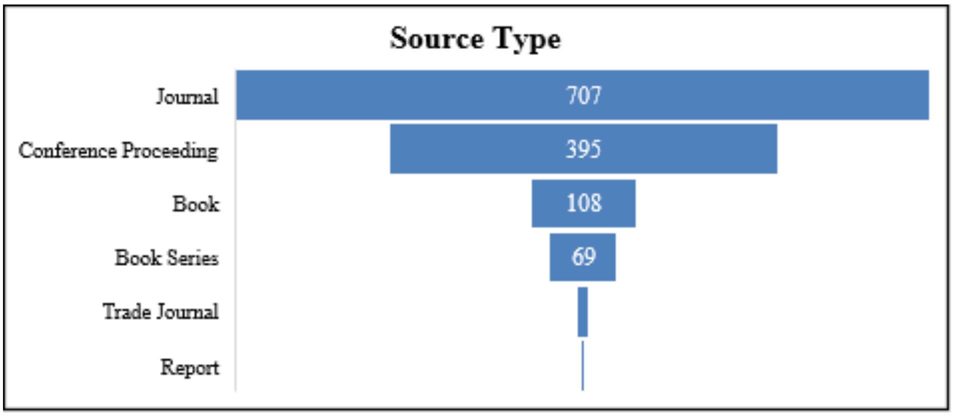

Figure 2. Number of documents by source type

Furthermore, and as shown in Figure 3, there are several types of documents. As shown, the types of documents relating to tsunami education and tsunami mitigation were a majority of 644 articles, followed by 412 conference papers and 104 book chapters.

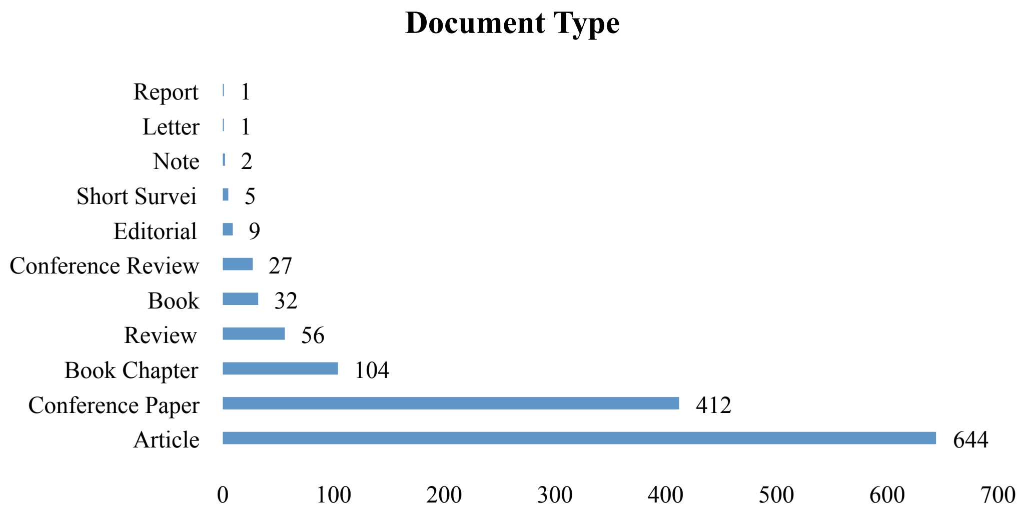

Figure 3. Number of documents by document type

From the total of 1293 documents, most were written in English (1261 documents). Other documents were in Chinese (16 documents), in Spanish (7 documents), and in Japanese (5 documents). The other documents used Croatian, French, German, Italian, Malay, Persian, Polish, and undefined language documents with 1 document each, as shown in Figure 4 below.

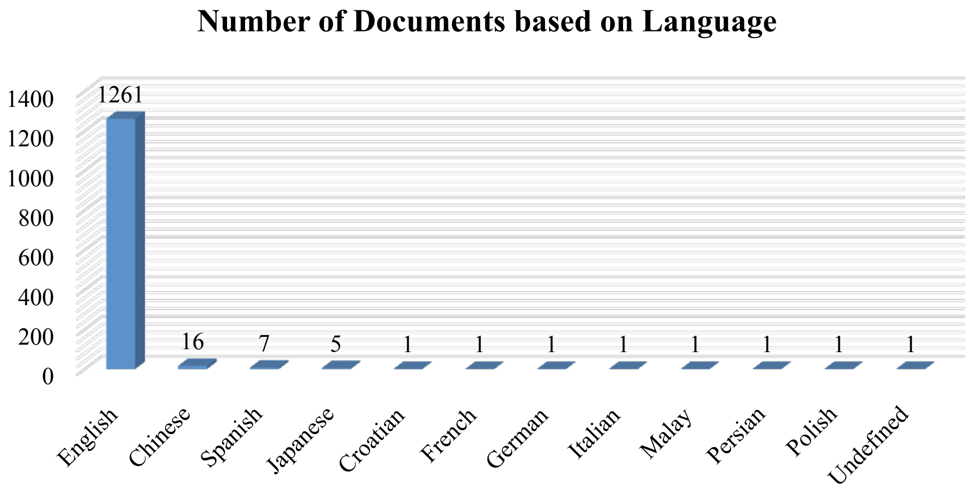

Figure 4. Number of document based on language

There are several keywords to search for in this topic of tsunami education and tsunami mitigation. Tsunami and Tsunamis are the most dominating keywords in this topic, followed by designations such as “Disaster”, “Earthquakes”, “Hazards:, “Risk Assessment”, “Disaster Mitigation”, “Disaster Management”, “Floods”, and “Disaster Prevention” (Figure 5).

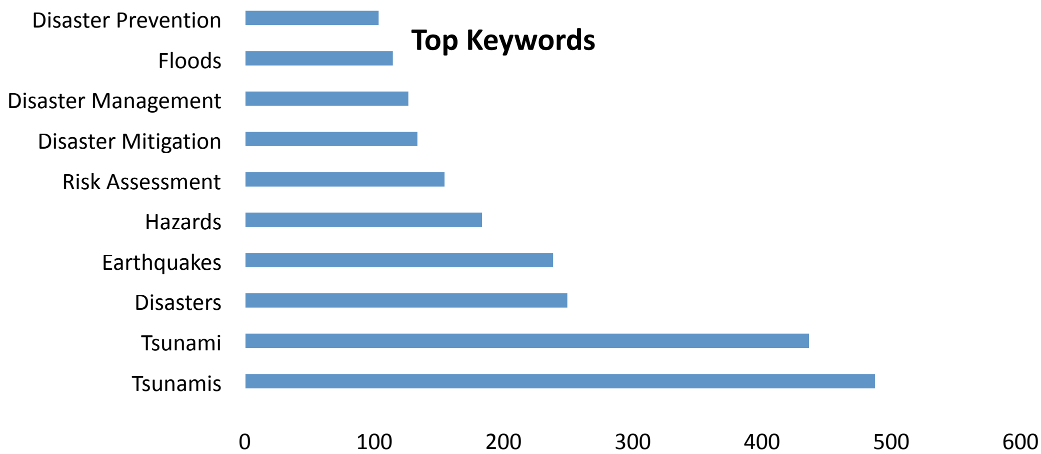

Figure 5. Top Keywords to search for tsunami education and tsunami mitigation

There are several dominant subject areas in studies relating to tsunami education and mitigation (see Table 1). The most dominant subject area is “Earth and Planetary Sciences”, with 660 documents, then Engineering and Environmental Science” with 431 and 369 papers, respectively.

Table 1. Subject Area in studies related to tsunami education and tsunami mitigation

No	Subject Area	Number of Documents
1	Earth and Planetary Sciences	660
2	Engineering	431
3	Environmental Science	369
4	Social Sciences	179
5	Computer Science	112
6	Physics and Astronomy	83
7	Agricultural and Biological Sciences	65
8	Energy	59
9	Mathematics	53
10	Medicine	32

3.2 Publication Distribution Across Countries and Institutes

Based on the number of documents between countries (Figure 6), it can be seen that the most documents came from the United States with 306 papers, followed by Japan with 294 papers and Indonesia with 201 papers. At the same time, the other seven countries that contributed the most were India and the UK, with 75 and 69 documents.

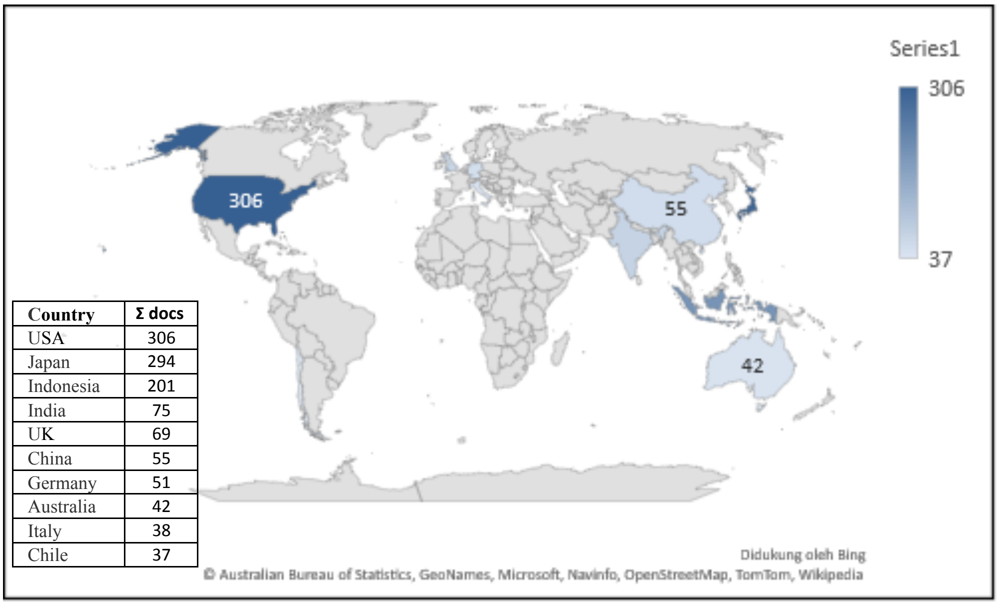

Figure 6. Number of documents by countries

Classification of the number of documents relating to tsunami education and mitigation by institutions can be seen in Table 2. Tohoku University with 66 papers is the highest-ranking institute, followed by The University of Tokyo and the National Oceanic and Atmospheric Administration with 45 and 30 documents, respectively. Three institutions from Indonesia ranked as 7th, 14th, and 15th. The Institut Teknologi Bandung (ITB) is ranked seventh with 22 papers, the Universitas Indonesia (UI) is ranked 14th with 15 documents, and Universitas Gadjah Mada (UGM) is ranked 15th with 14 papers.

Table 2. Number of documents by institutions

No	Institution	Number of Documents
1	Tohoku University	66
2	The University of Tokyo	45
3	National Oceanic and Atmospheric Administration	30
4	Universitas Syiah Kuala	26
5	Kyoto University	24
6	Saitama University	24
7	Institut Teknologi Bandung	22
8	Japan Agency for Marine-Earth Science and Technology	17
9	University of Hawaiʻi at Mānoa	17
10	Middle East Technical University METU	16
11	University of Washington	16
12	United States Geological Survey	15
13	University of Southern California	15
14	Universitas Indonesia	15
15	Universitas Gadjah Mada	14
16	Istituto Nazionale Di Geofisica E Vulcanologia, Rome	13
17	Universiti Sains Malaysia	13
18	GNS Science	13
19	Waseda University	13

3.3 Ranking of Authors in Researching Tsunami Education and Mitigation

Figure 7 shows a list of research authors on tsunami education and mitigation. The most prolific writers for that period of time are Tanaka, Imamura, Koshimura, Suppasri, Bernard, Muhari, Syamsidik, Mas, Nistor, Tinti, and Yalciner.

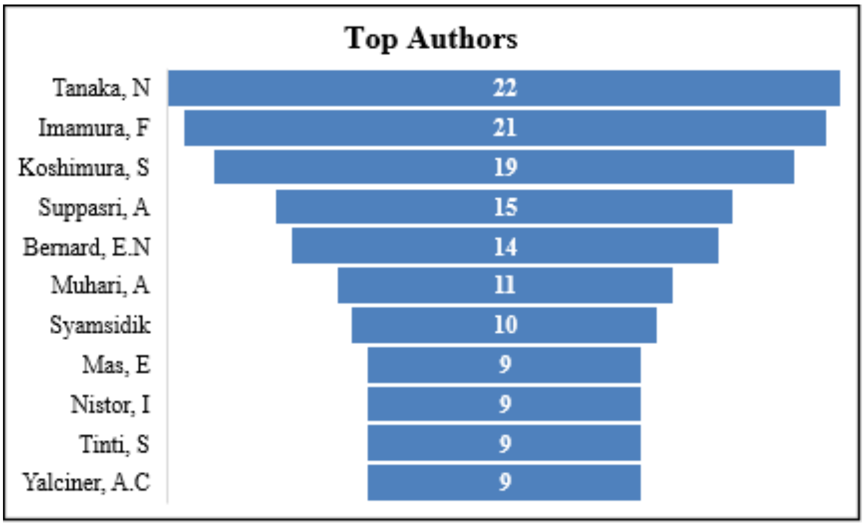

Figure 7. Top authors in researching tsunami education and mitigation

Table 3 lists the top citations on tsunami education and mitigation. Based on this classification, most of the article citations were those by Masson (2006) with 577 authorities, then followed by Synolakis (2002), Synolakis (2006), Moe (2006), and Synolakis (2008), who were the top 5 authors publishing on the topic of tsunami education and mitigation.

Table 3. Top citations on tsunami education and tsunami mitigation

Author (s)	Journal / Proceeding	Number of Citations
Masson et al. (2006)	Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 364(1845), pp. 2009-2039	577
Synolakis et al. (2002)	Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences 458(2020), pp. 763-789	271
Synolakis et al. (2006)	Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 364(1845), pp. 2231-2265	234
Moe et al. (2006)	Disaster Prevention and Management: An International Journal 15(3), pp. 396-413	211
Synolakis et al. (2008)	Pure and Applied Geophysics 165(11-12), pp. 2197-2228	204

3.4 Publication Patterns

Table 4 presents 18 journals or proceedings that contributed the most to tsunami education and mitigation research. At the top of the ranking, the journal Natural Hazards published most documents on tsunami education and mitigation (60 papers), followed by the IOP Conference Series: Earth and Environmental Science, and Pure and Applied Geophysics with 59 and 40 documents, respectively.

Table 4. Number of Document by Source title

No	Source Title	Number of Documents
1	Natural Hazards	60
2	IOP Conference Series: Earth And Environmental Science	59
3	Pure and Applied Geophysics	40
4	International Journal of Disaster Risk Reduction	25
5	Journal of Disaster Research	22
6	Journal of Physics Conference Series	20
7	Journal of Earthquake And Tsunami	18
8	Natural Hazards and Earth System Sciences	17
9	AIP Conference Proceedings	16
10	Science of Tsunami Hazards	16
11	Proceedings of The International Offshore And Polar Engineering Conference	15
12	Ocean Engineering	12
13	Advances In Natural and Technological Hazards Research	11
14	8th US National Conference on Earthquake Engineering 2006	10
15	Geosciences Switzerland	10
16	Developing Tsunami Resilient Communities The National Tsunami Hazard Mitigation Program	9
17	Journal of Coastal Research	9
18	Proceedings of The Coastal Engineering Conference	9

3.5 Visualization Results of Research Trend on Tsunami Education and Mitigation

Using the VoSViewer software, the present study visualized research trends for the 1293 documents relating to tsunami education and mitigation in the Scopus database. The following are the visualization results relating to tsunami education and mitigation (Figure 7), and from 2011 to 2020 (Figure 8). Worldwide visualization produced four green, yellow, blue, and red clusters. The first cluster (green) corresponds to tsunami waves. The second cluster (yellow) relates to tsunami problems and monitoring. The third cluster (blue color) relates to the tsunami warning. The last cluster (red) refers to preparedness for tsunamis and the post-tsunami recovery process.

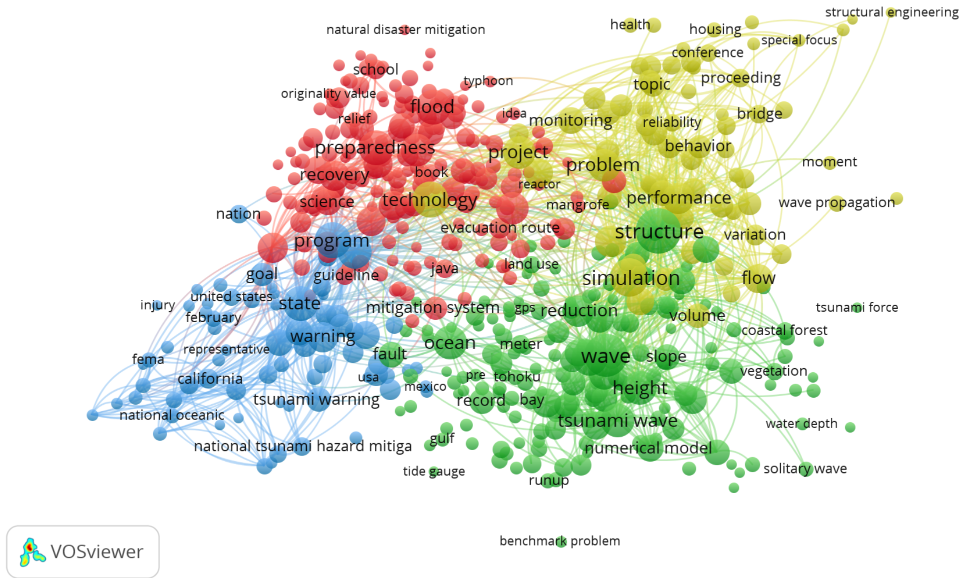

Figure 8. Network visualization (all years)

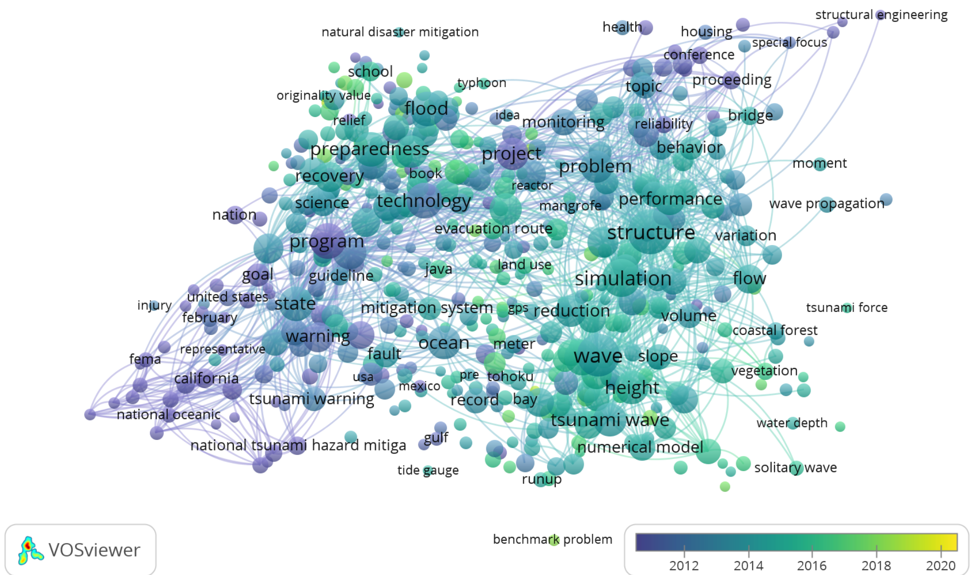

Figure 9. Overlay visualization (for 2011-2020)

Figure 10a below presents a visualization of the main authors, co-authors, and the most influential writers of publications relating to tsunami education and mitigation. The visualization distinguishes six main groups of authors, namely Tanaka et al., Imamura et al., Synolakis et al., Li et al., Nistor et al., and Castro et al. Among these researchers, there is one researcher from Indonesia, namely F. Imamura. Furthermore, in Figure 10b, a visualization of co-occurrence across all keywords is presented, which shows that Tsunami and Tsunamis are the most dominant keywords, followed by disasters and hazards.

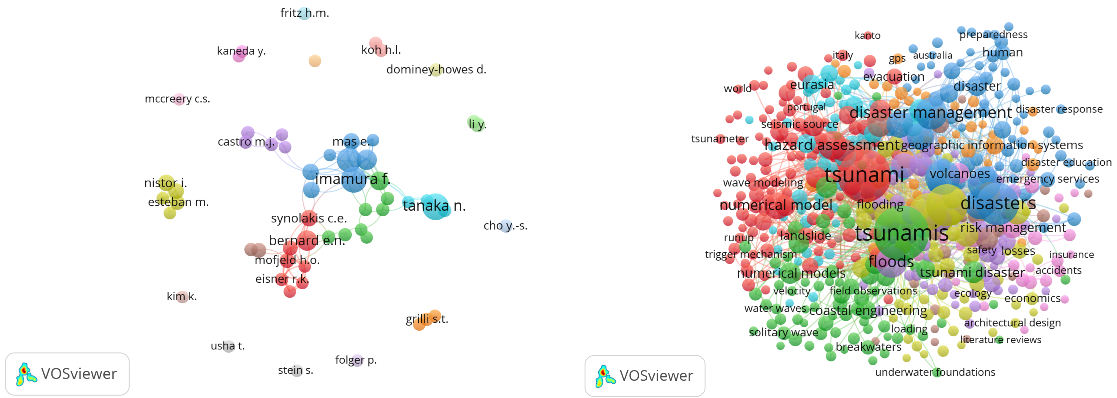

Figure 10 (a) A network visualization of co-authorship, (b) A network visualization of co-occurrence across all keywords

Scientists from different countries are involved in research of tsunami education and mitigation, since tsunamis are natural disasters that occur in numerous parts of the world. Therefore, it is necessary to indicate the countries of scientists who are involved in tsunami research, education and mitigation - intended to minimize the impact of the disaster. Figure 11 presents a visualization of co-authorship across countries. On the other hand, Figure 12 below shows a visualization of co-citation across authors (Figure 12a), and a visualization of citations across countries (Figure 12b).

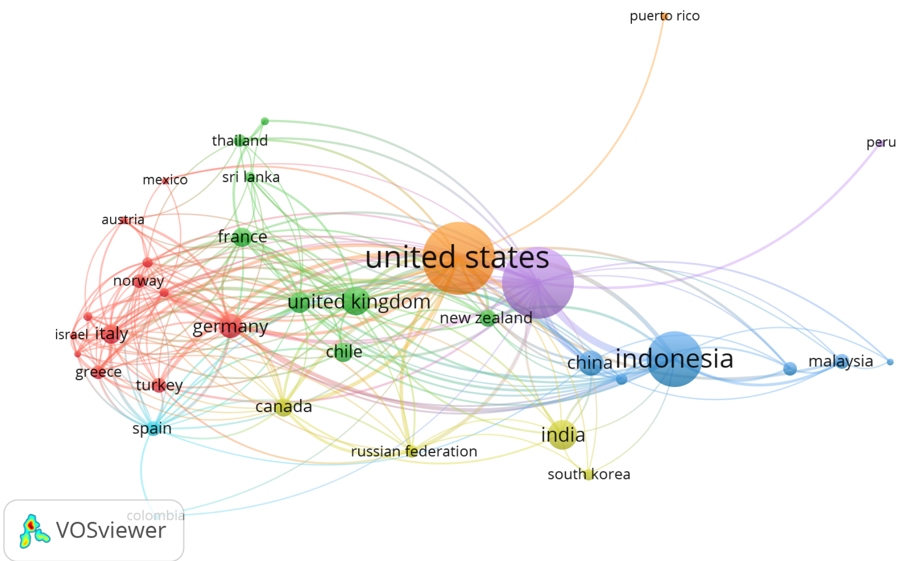

Figure 11. A network visualization of co-authorship across countries

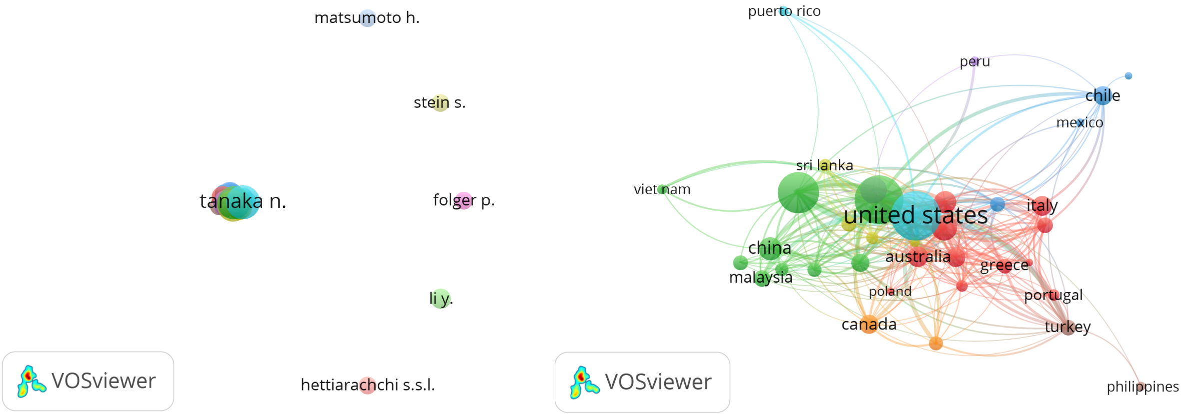

Figure 12. (a) A network visualization of co citation across authors (b) A network visualization of citation across countries

3.6 The Contribution of Indonesian Authors on Researching Tsunami Education and Mitigation

Indonesia contributed 201 documents discussing tsunami education and tsunami mitigation, of which 187 were published in the last ten years. Based on Figure 13, it can be seen that there has been a significant increase in the number of documents in the previous five years from 2016 to 2021.

Figure 13. Annual number of research documents on tsunami education and tsunami mitigation in Indonesia

As international researchers produced four clusters related to research trends on tsunami education and tsunami mitigation, Indonesian researchers also had four clusters (red, green, yellow, and blue) of similar work as portayed by Figure 14. The first cluster (red) relates to tsunami mitigation and tsunami simulation. The second cluster (green) refers to tsunamis as a disaster and how awareness and preparedness deal with tsunamis. The third cluster (yellow) relates to the tsunami as a natural disaster. The last cluster (blue color) relates to evacuation routes and their capacity to deal with tsunamis.

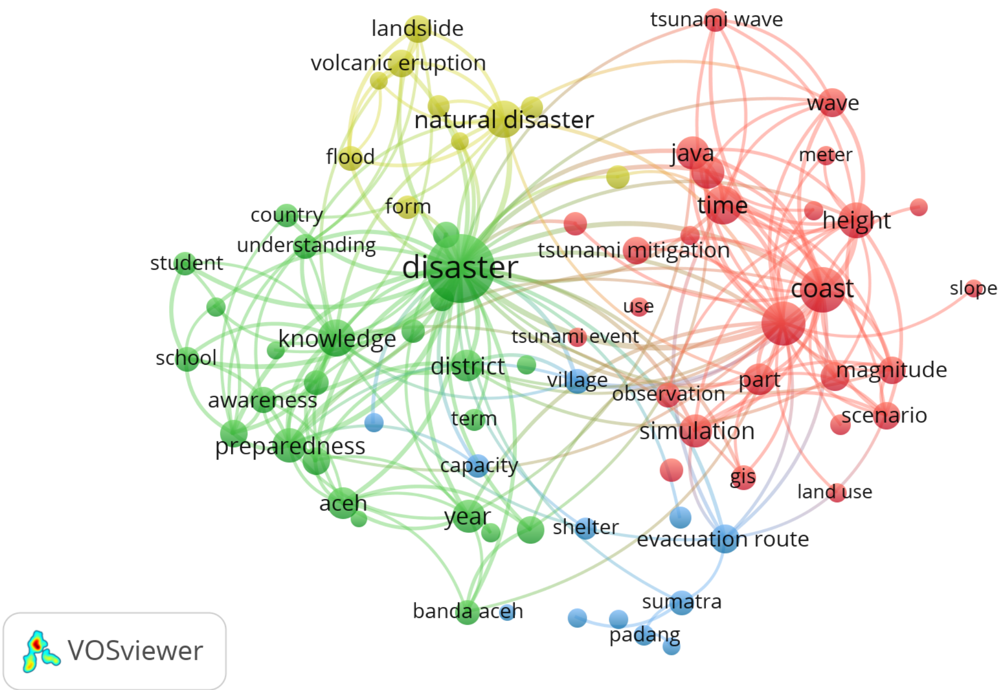

Figure 14. A network visualization of metadata (data from Indonesia only)

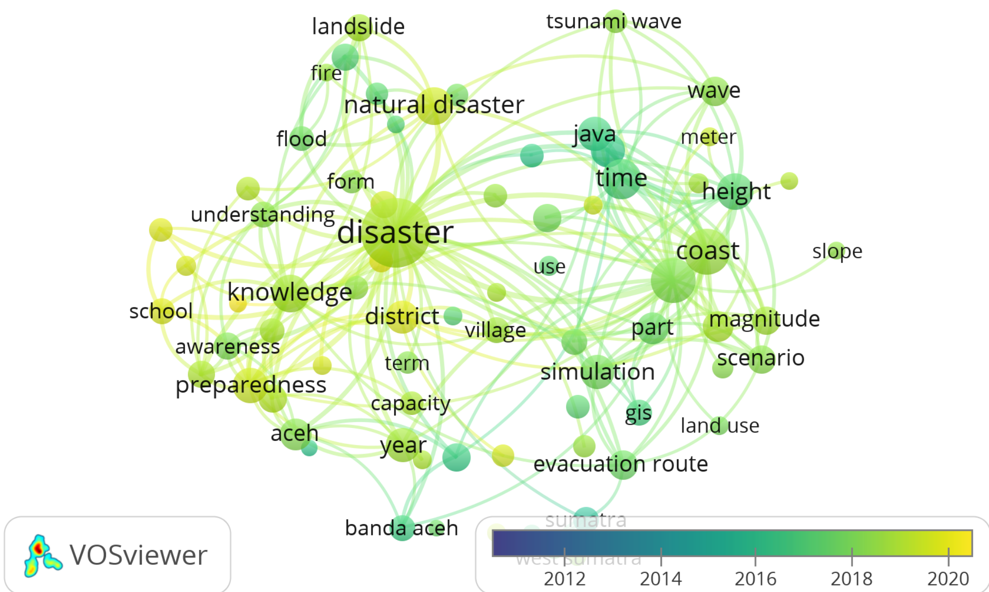

Figure 15. An overlay visualization 2011- 2020 (data from Indonesia only)

Table 5 presents the top 10 rankings of journals or proceedings that have contributed the most to Indonesia's tsunami education and tsunami mitigation research. First of these was the IOP Conference Series Earth And Environmental Science with 53 documents, followed by the Journal Of Physics Conference Series, and AIP Conference Proceedings with 20 and 13 papers, respectively. At the same time, other journals or proceedings published less than ten documents.

Table 5. Number of document by source title (data from Indonesia only)

No	Source Title	Number of Documents
1	IOP Conference Series Earth and Environmental Science	53
2	Journal of Physics Conference Series	20
3	AIP Conference Proceedings	13
4	International Journal Of Geomate	6
5	IOP Conference Series Materials Science and Engineering	6
6	Natural Hazards	6
7	Science of Tsunami Hazards	6
8	International Journal of Disaster Risk Reduction	5
9	Journal of Disaster Research	4
10	Disaster Advances	3

Figures 16a and 16b present graphs and visualizations of the names of leading Indonesian researchers, and their colleagues who have actively contributed to research trends on tsunami education and mitigation. Based on the data, it can be seen that Syamsidik (Syamsidik et al., 2015) is the most prolific writer on this topic in Indonesia, followed by Muhari (Muhari et al., 2019) and Suppasri (Suppasri et al., 2012).

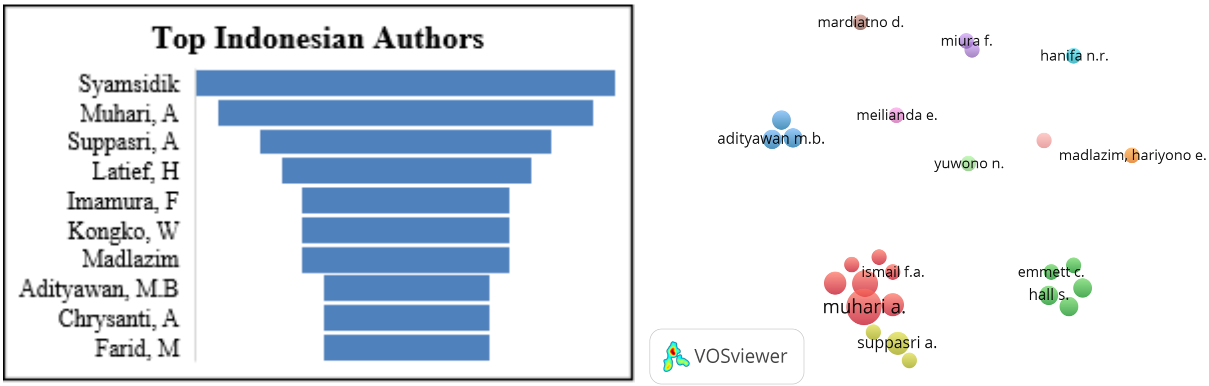

Figure 16. (a) Indonesia's leading authors on tsunami education and tsunami mitigation. (b) A network visualization of Indonesian co-authorships

Not much different from keywords regarding research trends on tsunami education and tsunami mitigation in the world, in Indonesia, the keywords are dominated by tsunami, tsunamis, and disaster mitigation (see following Figure 17).

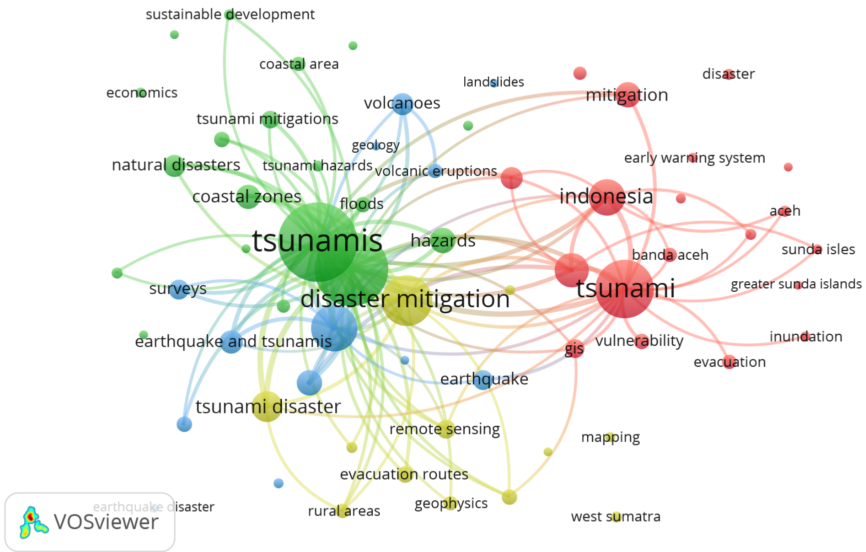

Figure 17. A network visualization of Co-occurrence among all keywords

As previously indicated tsunamis are natural disasters that occur frequently in various parts of the world (Rafliana et al., 2022). Often, the disastrous impact of such disasters can be extremely deleterious to the economy, security, technology, and public health. The occurrence of destructive tsunamis, which often result in great losses of lives, create also fears in stricken communities, so that frequently survivors feel depressed, and their mental health is affected (Aven & Renn, 2010; Himaz, 2022). Various countries widely research tsunami education and tsunami mitigation to also educate the public on how to minimize the impact of a tsunami not only physically but also in coping with mental health problems.

As stated, the number of documents related to tsunami education and mitigation programs have increased significantly throughout the years. Until now, hundreds of papers on these important issues have been completed every year. Although the number of such documents has decreased several times, this research trend has increased significantly in the last four decades. Thus, it is expected that there will be a drastic increase in the number of articles in 2021-2025, and related education and mitigation programs.

Based on the number of documents published by different countries, it can be seen that the most documents came from the United States which amounted to 306 papers, followed by Japan with 294 papers and Indonesia with 201 papers. Tohoku University had the top ranking with 66 documents, followed by the University of Tokyo and the National Oceanic and Atmospheric Administration with 45 and 30 papers, respectively. Three institutions from Indonesia are ranked 7th, 14th, and 15th, namely the Institut Teknologi Bandung, the Universitas Indonesia, and the Universitas Gadjah Mada.

The most prolific writers on tsunami education and mitigation were Tanaka, Imamura, Koshimura, Suppasri, Bernard, Muhari, Syamsidik, Mas, Nistor, Tinti, and Yalciner. The top article citations were achieved by Masson (2006) with 577 authorities, then followed by Synolakis (2002), Synolakis (2006), Moe (2006), and Synolakis (2008), with the top 5 prolific citation in the topic of tsunami education and mitigation.

The top ranking journals or proceedings that contributed the most to research on tsunami education and mitigation for the period of the present study were Natural Hazards (60 documents), followed by the IOP Conference Series Earth And Environmental Science and by Pure And Applied Geophysics with 59 and 40 papers, respectively.

Researchers worldwide produced four green, yellow, blue, and red clusters. The first cluster (green) corresponds to the impacts of tsunamis. The second cluster (yellow) relates to tsunami problems and monitoring, and the third cluster (blue color) relates to the tsunami warning. Finally, the last cluster (red) refers to preparedness for tsunamis and the post-tsunami recovery process.

Indonesia contributed a total of 201 documents discussing tsunami education and tsunami mitigation, of which 187 were published in the last ten years. There has been a significant increase in the number of documents in the previous five years. Syamsidik is the most prolific writer on this topic in Indonesia for the period of the study, followed by Muhari and Suppasri.

4. CONCLUSIONS

Several essential points regarding research on tsunami education and mitigation, especially during the period 2011 to 2021, are that the number of documents related to these subjects increased significantly throughout the years, dominated mainly by articles in journals. Based on the number of documents published by countries, most papers were those by the United States. The institution that produced the greater number of documents relating to tsunami education and mitigation was Tohoku University in Japan. Three institutions from Indonesia ranked seventh, fourteenth, and fifteenth in the number of documents that were published, namely the Institut Teknologi Bandung, the Universitas Indonesia, and the Universitas Gadjah Mada.

The most prolific writer on tsunami education and mitigation for the period of the present study is Tanaka, in Japan. Meanwhile, the journals or proceedings that contributed the most to tsunami education and mitigation research for the period of the study was the Natural Hazards journal. Visualization of research trends on tsunami education and mitigation resulted in four clusters: (1) On the tsunami disaster; (2) On related tsunami problems and monitoring; (3) On the effectiveness of tsunami warnings; (4) On preparedness in dealing with tsunamis and the post-tsunami recovery process.

Indonesia contributed 201 documents discussing tsunami education and mitigation, of which 187 were published in the last ten years. Syamsidik is the most prolific writer on this topic in Indonesia, followed by Muhari and Suppasri. This research can help readers identify trends related to tsunami education and tsunami mitigation globally and provide an overview for future research.

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MITIGATION OF THE ADVERSE IMPACT OF TSUNAMI HAZARDS ASSISTED BY GEOGRAPHIC INFORMATION SYSTEM: STUDY IN MUNJUNGAN COASTAL-TRENGGALEK - INDONESIA

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ABSTRACT

Coastal areas of Indonesia that are close to tectonic plates are vulnerable to earthquakes and generated tsunamis. The Munjungan Coast South of East Java-Indonesia is such a vulnerable tsunami area. This coastal area, besides being close to tectonic plate boundaries, has the shape of an open bay which makes it particularly vulnerable to tsunami impacts and, therefore, in need of strict disaster mitigation measures. Assisted Geographic Information System (GIS) applications with map overlay techniques and by the Arc View 3.3 software program can help in the taking of measures that can reduce the impact of tsunami hazards. The processed product of the GIS methodology in the form of a tsunami hazard zoning map, as well as designated evacuation route maps, can be helpful tools in tsunami impact mitigation, when a significant and potentially tsunamigenic earthquake occurs. The present study used a survey method and area sampling to obtain a better understanding of the public's perceptions and attitudes in responding more effectively to the potential of tsunami disasters. Based on the interpretation of the zoning map for the classification of disaster-prone areas and route maps for evacuation, four villages were identified as being more prone to tsunami disasters. The condition of the population in these four disaster-prone villages, despite their higher level of knowledge about tsunamis, was not followed by their perceptions and proper attitudes towards mitigating the potential danger. People on the coast of Munjungan did not appear to be particularly concerned about the tsunami hazard.

Keywords: *mitigation, tsunami hazard, geographic information system*

1. INTRODUCTION

Many kinds of natural disasters occur in Indonesia, so this condition causes some to the country to be named a "supermarket" for natural disasters. Among the natural disasters are earthquakes, tsunamis, volcanic eruptions, floods, and other hydro-meteorological events. Specifically, because of the country's geographical position. extensive coastlines of many of its islands and high tectonic activity earthquake-generated tsunamis in Indonesia have claimed many victims

Geographically, Indonesia is an earthquake-prone area because it has crossed by the meeting point of 3 tectonic plates, the Indo-Australian Plate, the Eurasian plate, and the pacific plate. The path of the meeting of these plates is at sea, so if an earthquake occurs on a large scale and with a shallow depth, it will potentially cause a tsunami. With Indonesia's geographical conditions, coastal areas and islands can experience natural disasters, such as earthquakes, tsunamis, hurricanes, and storms (Rumondor et al., 2019).

Earthquakes due to the movement of tectonic plates can be the source of a tsunami, which cannot have predicted when it will occur (unpredictable), but the location or location where the potential for an earthquake occurs can be known. For coastal areas close to tectonic plate paths, an earthquake will have the potential to cause a tsunami disaster. If the people living in the disaster-prone areas are not aware of the tsunami threat, the risks generated will be severe.

Tsunamis experienced by coastal areas in Indonesia generally occur less than 30 minutes after an earthquake. This happens because the distance between the subduction zone and the adjacent coastal area is relatively close, while the speed of tsunami waves can reach 600–900 km/hour. Based on the results of a disaster risk study compiled by the Indonesian national disaster management agency in 2015, it can have seen that the most significant number of people exposed to earthquake risk is on java island, with the asset value exposed on java island exceeding rupiah 140 trillion. Then according to BNPB records, the Aceh tsunami disaster was a disaster that claimed many victims. The Aceh tsunami caused the death toll in the entire world region to reach 283,100 people. Meanwhile, the death toll in Indonesia reached 108,100 people, and 127,700 people have lost (Marwanta, 2005)

Noting that coastal areas are prone to tsunami disasters, but on the other hand, coastal areas are areas that are very densely populated, and the world population living in coastal areas ranges from 50-70% of the world population. In Indonesia, 60% of the population lives in coastal areas. Therefore, it is interesting to examine humans' knowledge, perceptions, and attitudes who still survive and live in tsunami-prone areas. Theoretically, if residents know the conditions of their environment correctly, then their perceptions and attitudes are also correct. Likewise, if residents are well aware that their environment has the potential for an earthquake and tsunami disaster to occur, then they will behave and act to be alert and at the same time be able to avoid themselves if the earthquake and tsunami disaster strike their surrounding environment.

Based on the results of Fauzi's research in Wonogiri, it is known that the low level of public knowledge about the meaning of disaster, events that can cause disasters, causes of earthquakes, aftershocks of earthquake disasters, and actions taken in case of earthquake disasters, because people are still ordinary. There is a lack of socialization about earthquake disasters (Rachman, 2018).

The southern coastal environment of Munjungan District, Trenggalek Regency, is one of the coastal areas in Indonesia that is prone to earthquakes and tsunamis. Because this coastal environment is located in the southern part of the island of Java and is directly opposite the Indian Ocean and not too far from the path of subduction of tectonic plates at the bottom of the Indian Ocean, another potential of the Munjungan Coastal area for its vulnerability to tsunamis besides being close to the tectonic plate path is the shape of the coast in the coastal area as an open bay beach and a relatively flat topography. Thus, the giant waves without barriers can directly hit the coastal area if a tsunami occurs.

In addition to the physical condition that shows a high level of hazard vulnerability to the Tsunami disaster in the Munjungan Coast, another thing that is no less important and requires attention is the large number of people who live in the Munjungan coastal area. According to the population records of the Central Statistics Agency, it has known that from 11 villages in Munjungan District, there are seven villages located in the Coastal area and inhabited by a population of 53,521 people (BPS, Munjungan Dalam Angka, 2016). With the condition of the Munjungan coastal environment vulnerable to tsunami disasters and other hands, many people live in the area; therefore, it is necessary to take early mitigation steps to make a zoning map of disaster-prone areas. Besides that, it is also necessary to prepare instructions or guidelines for the direction of the evacuation route.

Geographic Information systems can be applied to assist in making maps and, at the same time, spatial analysis. (Tomaszewski, Judex, Szarzynski, Radestock, & Wirkus, 2015) Therefore, having a GIS device at the Department of Geography Education, State University of Surabaya, can help to create a disaster zoning map and at the same time make a map of evacuation routes to secure a tsunami disaster in the research area. Making a Zoning Map for the level of disaster vulnerability and an Alternative Route Map for Evacuation roads is expected to help identify the spatial and environmental aspects of areas prone to disasters. Because based on the zoning map of disaster vulnerability, it is possible to identify vulnerable areas and areas that are safe from tsunami disasters. Then, based on the Alternative Evacuation Route Map, it is hoped that it can have as a source of information for the Munjungan residents about the route to save themselves if a tsunami disaster occurs in their area.

Making a Map on Zoning of Areas Vulnerable to Tsunami Disasters and Maps of Alternative Evacuation Routes in the form of digital maps that are processed using a Geographical information system, with the background that making maps in digital form can be easily used for inventory, monitoring, and evaluation. By digital map product, if they want to call back or repair/revise data, it can be quickly done at any time. The nature of the product resulting from data processing with a dynamic Geographic Information system is the background behind the application of this information system, which has chosen to assist in analyzing the mitigation of the adverse impact of tsunami hazards. The existence of the tool depends on the person who uses it. Likewise, a disaster mitigation map instrument will function if they pay attention to the people behind the tool. Alternatively, the existence of a tool depends on the human who uses it.

Regarding the target of disaster mitigation, humans or residents who live in disaster-prone areas, the research conducted will also reveal residents' level of knowledge, perceptions, and attitudes towards disasters that constantly threaten their living environment. Because revealing and knowing the level of knowledge, perceptions, and attitudes of the population towards disasters that constantly threaten their environment can sharpen the analysis of research results. Thus, it has hoped that the research results can provide more operational input in avoiding or saving the population or community in the research area from the danger of a tsunami hazard.

2. METHODS

The method used in this research is a survey with quantitative descriptive. The object and location of this research are residents in Munjungan district, Trenggalek Regency, east java province, Indonesia. The reason for choosing this area to be researched is because this area has a high vulnerability to earthquake and tsunami disasters, but the population in this area is relatively large.

2.1. Collection Techniques, and Data Sources

In this study, the collected data have been into two groups. The first group is the data used for making maps and the second group is the data to find out the knowledge-perception and attitude of the population towards the existence of the tsunami disaster. Data for making maps related to the physical condition of the area (height, beach shape, coastal slope, coastal roughness, and land use) has to collect through observation and documentation. The altitude data have sourced from a Topography Map scale of 1: 50,000 with an interval of 12.5 meters, while data related to the knowledge-perception and attitude of the population towards the tsunami were collected through interviews and Focus Discussion Groups (FGD) with respondents.

2.2. Population and Sample

The research population is the head of the family who lives in a tsunami-prone area. Data related to the physical condition of the research area as a whole becomes the object of research, while to obtain data related to the knowledge-perception and attitude of the population about the tsunami, the data acquisition have based on the sample.

The sampling method has chosen promotional area random sampling. Based on the mapping done, there are four villages prone to tsunami disasters, namely Craken, Masaran, Munjungan, and Tawing villages. The four villages became the area sample frame. The random sampling area has based on the Tsunami Hazard Level map made with the GIS Program. The number of households living in these four villages in 6260 households. Referring determination of the number of samples from Isaac and Michael with a significance level of 90%, from a population of 6260 households, the minimum sample in the study was 163 households. In this study, a sample of 254 households has taken. Sampling was carried out randomly, according to the number of households in each village.

2.3. Data analysis technique

Data related to the level of vulnerability to tsunamis will be analyzed using a Geographic Information System (GIS), namely the map overlay technique using the Arc View 3.3 software program. The overlay technique is carried out and followed by a query. The overlaid maps are land use maps, coastal shape maps, coastal slope maps, coastal roughness maps, and elevation maps. The level of vulnerability to the tsunami to described with the query process. The next step is that the tsunami-prone zoning map overlaid with administrative maps and land use maps. Based on the results of this overlay, the level of vulnerability of each village in Munjungan District to the tsunami disaster can have mapped. Then, the data related to the knowledge perceptions and attitudes of the population regarding the earthquake and tsunami were analyzed descriptively, namely with percentages equipped with qualitative explanations. Data related to the level of vulnerability to tsunamis will be analyzed using a Geographic Information System (GIS), namely the map overlay technique using the Arc View 3.3 software program. The compile a zoning map of the level of vulnerability to tsunami disasters, the overlay technique is carried out and followed by a query. The overlaid maps are land use maps, coastal shape maps, coastal slope maps, coastal roughness maps, and elevation maps. The level of vulnerability to the tsunami disaster to describe with the query process. The next step is that the tsunami-prone zoning map overlaps with administrative and land use maps. The results of this overlay, the level of vulnerability of each village in Munjungan District to the tsunami disaster mapped. Then, the data related to the knowledge perceptions and attitudes of the population regarding the earthquake and tsunami were analyzed descriptively quantitatively, namely with percentages equipped with quantitative explanations.

3. RESULTS

3.1 Mapping of Tsunami Hazard Areas

Based on observations, it has known that several variables that are estimated to affect the level of tsunami susceptibility, namely the shape of the coast, the roughness of the coast, and the level of the slope of the coast associated with the residences of the population (villages) are relatively the same. The beach is U-shaped, sloping, and the beach is smooth (sand), and between the coastline and the settlements, the separation is mainly sand, rice fields, and gardens; this shows that the coastal area of Munjungan District has a high level of vulnerability to tsunami disasters (Fig. 1).

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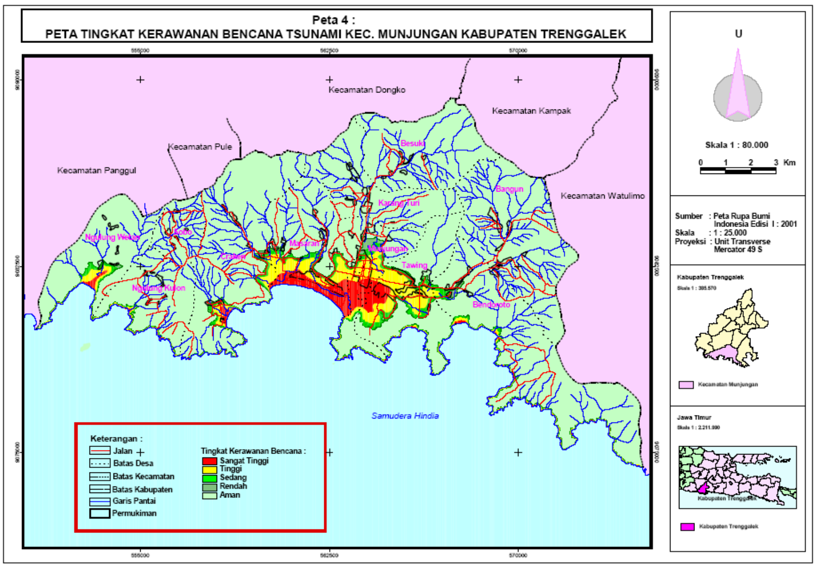

Fig. 1. Tsunami Hazard Level

Therefore, the variables vary from one place to another are the height and distance between the coast and the mainland. Referring to the zoning of tsunami-prone areas from Bakosurtanal, namely that up to a height of 20 meters above sea level, it is still a tsunami-prone area and taking into account the distance between the coastline to the mainland, a map of the level of vulnerability to tsunami disasters can be made. In measurements, the furthest distance from the shoreline to the mainland with an altitude below 20 meters is less than 4 km.

Theoretically, with conditions like those in Munjungan, with a run-up level as high as 10 meters, tsunami waves can reach the mainland with a distance of more than 4 km. Therefore, based on this distance variable, all areas with a height of fewer than 20 meters are still reachable if a tsunami occurs. Map of the level of vulnerability to a tsunami can be made based on altitude with the criteria mentioned above.

This study has successfully mapped; namely, there are four villages included in the tsunami-prone area, but there is no early warning tool for tsunami disasters in these areas so far. In the four villages, most residents do not understand the tsunami. The public's lack of understanding about the tsunami resulted in the community has been easily deceived by not sourced information. After the Jogya earthquake in 2006, rumors circulated in this area that there would be two tsunamis, and the police even participated in warning the public that a tsunami would occur, even though previously there had been no earthquake or signs of a tsunami distance of more than 4 km. The mapping of the zoning of disaster-prone areas has presented as follows in figure 1 above.

3.2 Mapping Of Alternative Evacuation Routes

In the research conducted to create a map of alternative evacuation routes that are safe against tsunamis, the method used has based on a map of the tsunami hazard level by tracing the route selection with the considerations mentioned above. Choosing route alternative for evacuating based on factors: reached distances, avoid the cross river, near the street, and the route is good. The results of alternative mapping routes in a Tsunami has presented in the following figure 2.

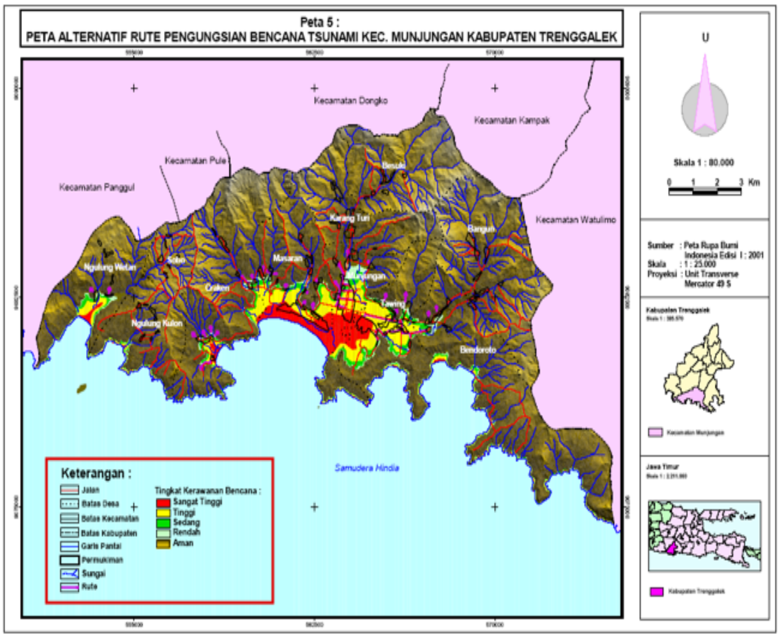

Figure 2. Mapping Mapping Of Alternative Evacuation Routes

3.2.1 Disaster Knowledge of People in Munjungan

All respondents (100%) stated that earthquakes often occur but have never been accompanied by a tsunami in the area where they live. The earthquakes in their area have not been strong enough to cause significant damage. According to most respondents (78.35%), the impact caused by the earthquake was the collapse of houses, while respondents who stated that the earthquake caused the tsunami took the second-largest number, namely 14.57%. Regarding knowledge about tsunamis, most of the respondents (93.39%) have heard of the term. Only a few respondents stated that they had never heard of the term tsunami, namely 6.61%. As a source of knowledge about the tsunami, most respondents came from TV media (71.79%). In more detail, the sources of information regarding the tsunami have to see in the Table.1.

Table : 1. Information Sources of Tsunami

Information Sources	Number of respondents	**(%)**
Apparatus	18	6,43
Televission	101	71,79
News Paper	6	2,14
Other person	37	13,12
Radio	8	2,85
Scholl	6	2,14
Police	2	0,71
Internet	1	0,36
Book	1	0,36
Total	280	100

Sources : Primer data

This study has successfully mapped this area. Namely, there are four villages included in the tsunami-prone area, but there is no early warning tool for tsunami disasters in these areas so far. In the four villages, most residents do not understand the tsunami. The public's lack of understanding about the tsunami resulted in the community has easily deceived by not sourced information. After the Jogya earthquake in 2006, rumors circulated in this area that there would be a tsunami twice, even the police took part in warning the public of a tsunami, even though previously there was no earthquake or signs of a tsunami coming.

3.2.2 Tsunami Disaster Perception of People Munjungan

Although all of the respondents in this study live in disaster-prone areas, most of the respondents (88.58%) have the perception that their place of residence is safe from the threat of disasters. Respondents who stated that their area was prone to earthquakes and tsunamis were 18.51%, while those who said they did not know were 1.57%. Account 82.76% of respondents perceive that their area is safe. The reason is that there has never been a tsunami in their area. In detail, the reasons for respondents who perceive their homes to be safe from tsunamis have seen in the following table 2.

Table: 2. People's Perception Is Safe for Tsunami

People's Perception	%
There has never been a tsunami in the village	88.58
The village environment is protected by the hills	1.97
The village environment is quite high	6.40
Guarded by “Nyi Roro Kidul (Fiction Figur)	0.99
There is a key to the antidote to disaster	0.49
No response	1.57
Total	100.00

Sources : Primer Data

Respondents who perceive that their place of residence is safe from the threat of a tsunami disaster do not/do not know what actions they will have in the event of a tsunami disaster. To is natural because they believe that a tsunami disaster will not occur in their area. Although the percentage is small, it is interesting that the community still has a strong perception of a disaster due to religious and supernatural factors surrounding the population's beliefs in the research area

3.2.3 Attitude to Disaster from Munjungan People

For respondents who perceive that their area is prone to tsunami disaster (15.51%), most of them already have an attitude in anticipating the possibility of a disaster and tsunami in their area. Most of the respondents (44.68%) stated that if there were a relatively strong earthquake, they would immediately run to find a high place. In detail, the respondent's attitude to anticipate the possibility of an earthquake resulting in a tsunami disaster has seen in Table 3.

The attitude of the community in the event of a disaster has known that most of the population (44.68%) will run to find a safe place, then some of the community (36.19) will save themselves if there are signs/warnings, and there are some people (19,15). %) who stay at home. The Munjungan people, the potential tsunami disaster in their neighborhood, do not pay much attention to the safety of their lives.

4. DISCUSSION

4.1 Results of Mapping of Tsunami Vulnerability Zoning and Tsunami Disaster Evacuation Routes for Early Mitigation

Geographical Information System applications for various mapping purposes have been carried out extensively. The following is an example of the application of GIS to map the Tsunami disaster zoning in Pariaman-West Sumatra. (Hadi & Astrid, 2017). Thus, the results of this study have strengthened the concepts and theories in the use of Geographic Information Systems for the creation of Zoning Hazard Level Maps and, at the same time, mapping evacuation routes. Referring to the Geospatial Information Agency classification, the use of a scale of 1:50,000 to 1:100,000 is said to be more of a division at the landscape level, which only reflects the influence of endogenous processes. On a 1:50,000 scale map, spatial information presented at a macro level can be recognized (Brahmantyo & Salim, 2018). Thus, related to the source of the base map used in this study is a topographic map with a scale of 1: 50,000, the resulting map derivatives have not been able to describe in detail the actual morphology of the earth's surface. However, as a material or tool or initial mitigation medium in a relatively broad environmental coverage such as the research area, the map produced from the research conducted is sufficient to be used as a source of macro-spatial information.

Based in reference to Dwi Jokowinarno's opinion, at least six steps are needed to mitigate the tsunami disaster. The first policy protects life, infrastructure, and the coastal environment. The development of an early warning system and the construction of protective buildings are examples of protection measures developed. (Jokowinarno, 2011). The first step proposed by Dwi Jokowinarno was based on the results of research conducted in a hazard zoning map and an evacuation route map. Utilization of data processing and data analysis with GIS has the following advantages: input processed data can be sourced from various spatial and non-spatial data, and are easy to update, to store, and to retrieve. This GIS's characteristics can also be used as a tool for inventory, monitoring, evaluation, and planning to be carried out for overall disaster mitigation starting from the pre-disaster stage, during the disaster, and post-disaster stage

Regarding the dynamics of changes in physical data, it is slower than socio-economic data. Therefore, considering the input data processed by GIS in this study in the form of physical data, the existence of the data in the form of a spatial map of the zoning of the tsunami hazard level and the Tsunami route map is relatively longer used in the research area.

4.2 Knowledge-Perception and Attitude of Tsunami Hazard for Early Mitigation

The knowledge of the Munjungan community as a research location about the earthquake and tsunami disaster in its environment is sufficient. However, perceptions and attitudes towards constantly threatened disasters have been adequately owned by the research area's people. The knowledge of the Munjungan Community about the Tsunami Earthquake has expected to be their essential capital to avoid the victims of the earthquake and tsunami disaster. The experience of an earthquake that hit West Sumatra in September 2009 killed 1,195 people, allegedly due to a lack of knowledge and community preparedness in anticipating disasters in East Java-Indonesia(Simandalahi, Apriyeni, & Pardede, 2019). Because the people of Munjungan have a higher knowledge of the tsunami danger, this higher level of knowledge will become their capital to save themselves if a tsunami hits the environment they lived in.

Their high knowledge of disasters in their environment seems to have still interference with local wisdom about "superstitious" beliefs. Another strength to avoid disasters seems to be an integral part of the coastal communities of South-Java Island, including in the research area. (Handoko, Hariyono, & Pujimahanani, 2018). Communities around the southern coast of Java Island, including Munjungan, have confidence in the coastal authorities in their environment. Apart from all that, almost every country has its own legend stories that will enrich the country's cultural treasures. Whether it is true or not, please hold fast to each other's beliefs and respect them (Yuri Rahayu, 2016). Myths or local wisdom like this affect people's knowledge, perceptions, and attitudes in some research areas.

The experience of the Palu Tsunami disaster psychologically seems to have traumatized the local population. Those whom a Tsunami has never hit in their lives, but the tsunami in 2020 can change the local community's perception regarding the existence of their place of residence where the disaster has occurred (Margaretha, 2021). This condition may need to be owned by the people of the Munjungan area always to be ready for disasters that continue to threaten their environment. The study results showed that the community's perception in the coastal area of Munjungan said that their place of residence was safe from the threat of a tsunami disaster, so this situation was concerning. Because even though they know about the danger of a tsunami that constantly threatens their environment, they have never experienced a tsunami disaster, this condition causes their perception that the area is safe from tsunamis, and they choose to stay in the risk area. The theory of environmental adaptation stated that the population could overcome the stressor in the threat of a tsunami disaster. (Eka B. Z. Pamekas.et al, 2019). According to Bell, in the theory of environmental psychology, the Munjungan population is already in a home-statistical condition. The tsunami stressor that threatens the environment has been reduced by the knowledge, perception, and behavior of the people of Munjungan that they have never experienced a tsunami.

Based on the community's attitude if there will be an earthquake and tsunami, it seems that it is also in line with their perception. The community's attitude that some will run to protect themselves (44.68%) in the event of a disaster, then the condition of the community like this is encouraging. However, if we look at when the population flees from the disaster, the condition is very worrying. Because people who behave will run away to save from disaster if they have received information (36.19%), it is even more tragic if we know the attitude of 19.15% of the people in the research area will still choose to stay at home even though there has been a disaster in their environment.

Thus, in the coastal area of Munjungan, where this research concetrated, it can be seen that people's knowledge about their environment that is vulnerable to earthquake and tsunami disasters, but this knowledge does not reflect their perceptions and attitudes to avoid themselves or save themselves from the threat of the earthquake and tsunami.

Homeostatic conditions in the Munjungan coastal community at the research location are based on the perception of safety from earthquake and tsunami disasters because the people in the area have never experienced such a disaster. This perception is suspected of having more victims if a disaster and tsunami occurs in this area of research. Based on the still strong opinion of the people of Munjungan that their area is safe from tsunami disasters, it is necessary to take more intensive steps to prevent future losses of lives and property.

5. CONCLUSIONS

The Geographic Information System produces a zoning map for tsunami-prone areas and a map of alternative evacuation routes. Based on the Tsunami Hazard Zoning Map, it has been concluded that four villages have been included in the tsunami-prone zone. Based on the results of a survey of four tsunami-prone villages, it is concluded that the residents in these villages have never experienced a tsunami disaster, so they have an erroneous perception of safety from tsunamis, and have the attitude of continuing to live in their present potentially dangerous coastal areas.

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PUBLIC HEALTH AND WATER QUALITY ISSUES IN SOUTH-WESTERN THAILAND AFTER THE DECEMBER 2004 TSUNAMI: LESSONS LEARNED AND ACCTED UPON

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ABSTRACT

In December 2004, a major earthquake in the Andaman Sea generated a tsunami radiating across the Andaman Sea and Indian Ocean, including coastal resort communities of Thailand among affected areas. When the tsunami struck, the Thai coast local resort communities were filled with seasonal holiday travellers from Europe and elsewhere combined with the local populations. Devastation in low lying coastal plain was indiscriminate and extensive, resulting in over 5,000 dead and 500,000 displaced.

Water supplies, sewage disposal, and solid waste management facilities were almost uniformly destroyed. Local water supplies and surface waters were immediately contaminated and subject to continuing contamination by human wastes in the absence of functioning collection and treatment systems. Public health efforts were prioritized to avoid epidemic waterborne illness. Water quality monitoring including analysis for waterborne *Cryptosporidium* and *Giardia* along with enteric disease surveillance are described to illustrate this feature of managing of natural disaster.

Keywords: *Tsunami; health effects; water quality; risk management; Cryptosporidium and Guardia; social support*

Graphical Abstract

1. INTRODUCTION

On Sunday, 26th of December 2004, at about 08:00 local time (ICT, UTC + 7), a magnitude 9.0 earthquake occurred off the northwest coast of Sumatra, Indonesia. The epicentre was under the Andaman Sea at 3.32 N 95.85 E, (Figure 1). Worldwide, this was the fourth largest earthquake in the last century. The earthquake generated tsunamis that radiated out across the Indian Ocean striking first Sumatra and the nearby Andaman Sea islands, southwestern Thailand, Sri Lanka, India, and eventually the northeastern coast of Africa. Over 220000 people were killed and a half million were injured. More than 100000 were missing and over 500000 displaced in northwest Indonesia alone. [1]

Areas near the epicentre in Indonesia, e.g., Meulaboh, and Banda Aceh on the northwestern end of Sumatra, were devastated by the earthquake and tsunamis (Figure 2). In Thailand, Phuket and adjacent coastal tourist districts were heavily affected.

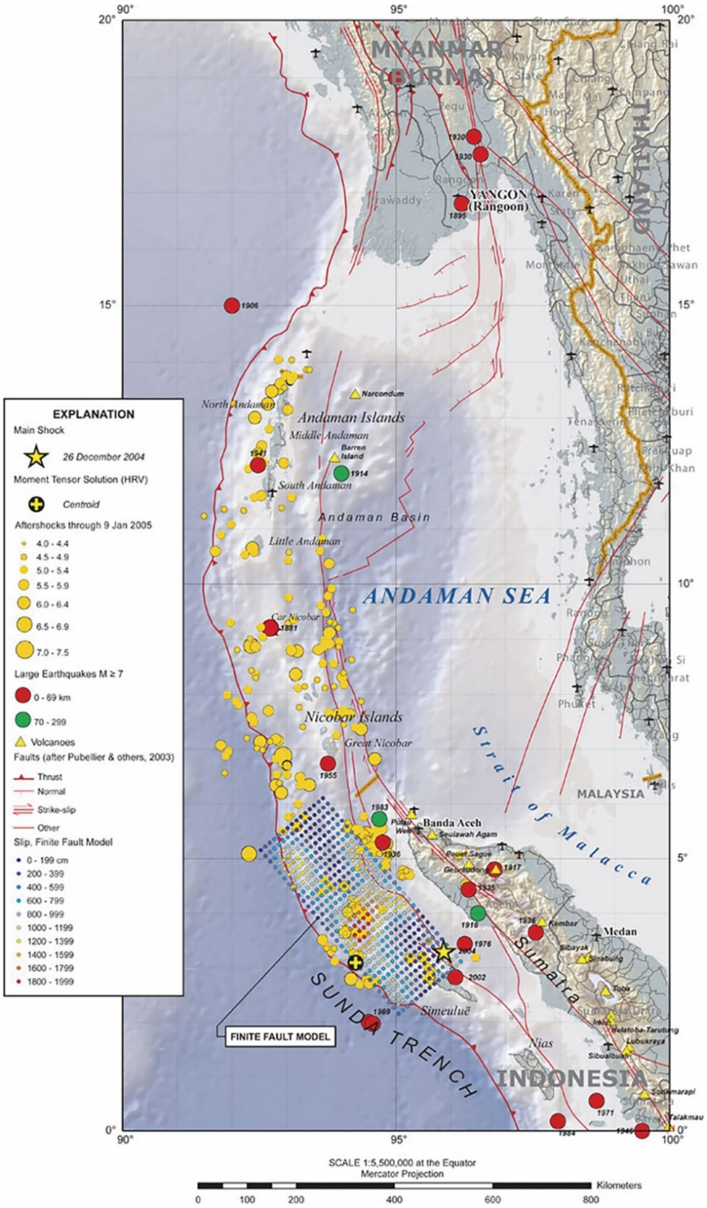

Figure 1 Andaman earthquake epicentre and after shock of > 4.0 Richter, 26 December 2004 [17].

The primary focus of this paper is the impact of the tsunami on public water supply and related public health effects in the southwest coastal tourist areas of Thailand. However, we provide an introductory description of local geography and conditions along with overriding physical effects of the earthquake and tsunami necessary to provide some perspective to those who find themselves responsible for sanitation and health issues under the most strenuous conditions in the aftermath of such a disaster.

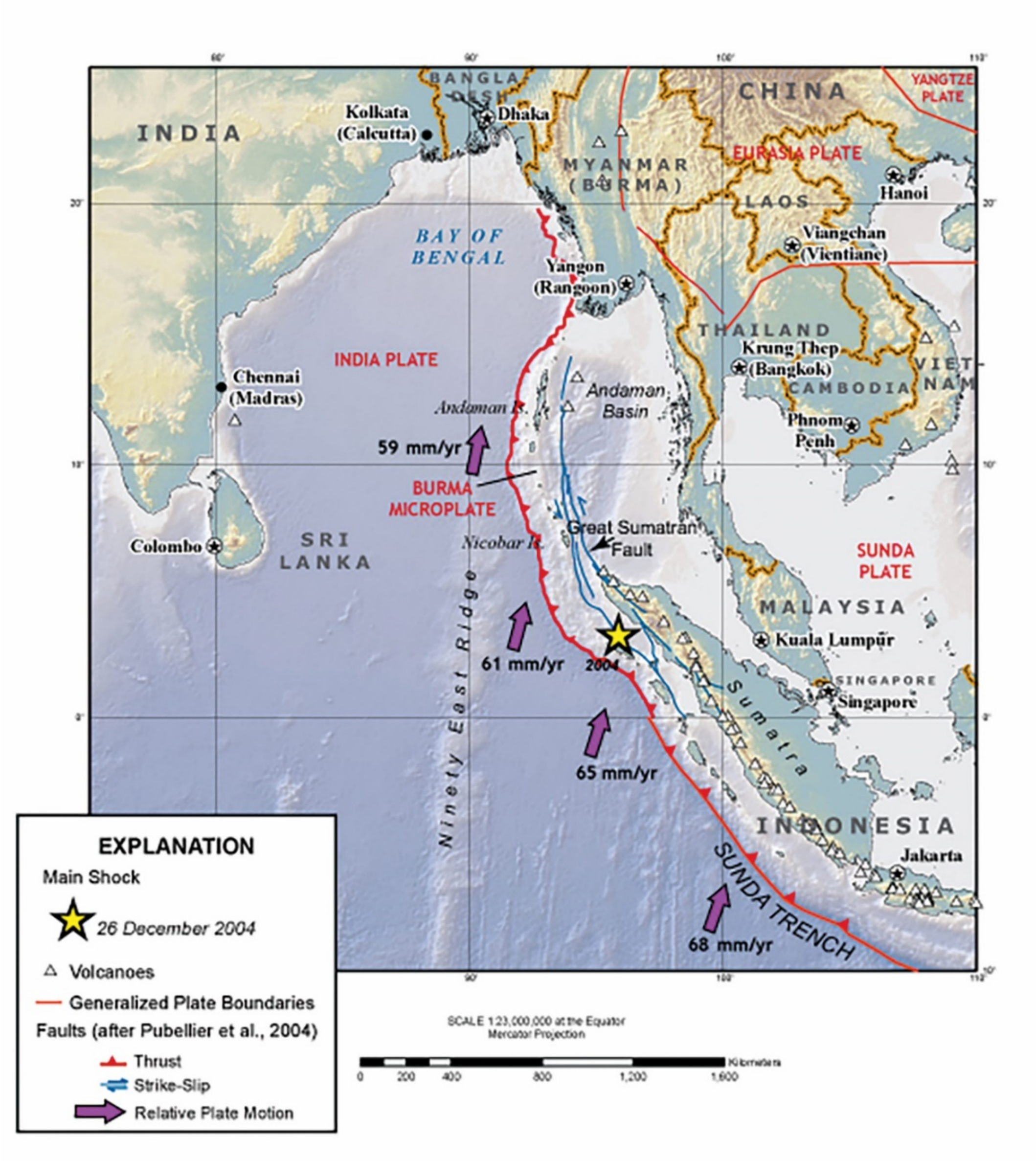

Figure 2. Indian Ocean earthquake and tsunami, 26 December 2004 [17].

Nearly a year after the occurrence of these events, the World Health Organization (WHO) reported on environmental health relief efforts in the regions affected by the earthquake and tsunamis [2]. An estimated five million people were affected by the disaster either directly or indirectly. Physical damage included indiscriminate destruction of structures leaving the population homeless, without access to food, basic sanitation, healthcare facilities, and with means of transportation and communication severely impaired. In the three weeks following the primary earthquake and tsunami more than 200 aftershocks of magnitude greater than four were recorded (Figure 3) contributing to continuing psychological effects on the traumatized local populations.

Figure 3. IKONOS satellite image, Area 2, Khao Lak, Phang Nga, Thailand before (left) and after (right) the tsunami on 29 December 2004 [18].

In Thailand, specifically, effects were spread throughout the six south-west coastal provinces including Phang Nga, Phuket, and Krabi where coastal towns, villages, and resorts were virtually flattened. The WHO estimated that over 650,000 of the local population and tourists were affected (Table 1). Totals compiled more than six months after the occurrence indicated 5300 dead, 3000 missing, and 17000 injured for Thailand alone. Foreign tourists, particularly from Europe enjoying warm holidays away from the European winter comprised over a third of the casualties.

2. PUBLIC HEALTH EFFECTS OF THE TSUNAMI

In assessing conditions and associated relief requirements, WHO listed major public health effects including immediate loss of life and the need to deal with the dead and injured. Bodies had to be located, collected, identified, and final disposition had to be arranged, all tasks for which neither facilities nor precedent existed and had to be created from scratch. Injured had to be cared for. Nearly 1000 children were orphaned and required care. Throughout the affected areas health care facilities were damaged or destroyed. Temporary facilities required independent supply of all equipment and materials including water supply sewage disposal, and management of solid wastes containing significant hazardous and infectious components. In the months following the tsunami the WHO reported on local conditions indicating that as many as 50000 rescue workers including 200 disease surveillance specialists had been deployed in affected areas to monitor and control potential disease outbreaks. In that period, WHO public health protection priorities were focused on supplying safe drinking water to displaced populations, strengthening sanitary and hygiene conditions in relocation camps, and heightening disease surveillance to detect and limit potential disease outbreaks [1].

Table 1. Total and affected areas by the tsunami classified by province [16].

Province	Village			Household			Population		
	Total	Tsunami Affected	Percent Affected	Total	Tsunami Affected	Percent Affected	Total	Tsunami Affected	Percent Affected
Ranong	178	45	0.2528	56471	1126	0.0199	178664	3770	0.0211
Phang Nga	318	68	0.2138	72737	4615	0.0634	236274	19509	0.0826
Phuket	103	61	0.5922	109686	952	0.0087	278480	13065	0.0469
Krabi	383	112	0.2924	79148	2759	0.0349	380367	15812	0.0416
Trang	720	51	0.0708	162177	660	0.0041	611436	12118	0.0198
Satun	276	59	0.2138	67626	81	0.0012	273702	2376	0.0087
Total	**1978**	**396**	**0.2002**	**547845**	**10193**	**0.0186**	**1958923**	**66650**	**0.0340**

Source: *Department of Disease Control, Ministry of Public Health, Nonthaburi, Thailand. Data as of 31 March 2005.*

Threats of infectious disease principally through environmental media including water and food were presumed to be present and broadcast as traveller advisories by foreign tourist agencies (e.g., UK) [3].

Advisories cautioned against potentially water or food borne typhoid, infection potential from injury including tetanus, hepatitis B, and *Vibrio vulnificans* in salt water coastal and inundated areas; leptospirosis characteristic of flood contamination; and increased vector borne (mosquito) endemic diseases; malaria, dengue haemorrhagic fever (dengue or DHF) and Japanese Encephalitis (JE).

Public health response was coordinated by the Thai Government including assessment of water supplies, sewerage systems, and solid waste management facilities to determine the extent of damage and contamination, and to assess the needs for immediate action and eventually, restoration services to local populations. Response activities can be divided into three phases: immediate, the initial 48 hours; interim, 2–10 days; and recovery 10 days to present. Key public health-related activities in these periods, Table 2, began with the process of locating, collecting, and processing the dead, and relocating the surviving population into temporary "migration centres". A critical need for the relocated population was to provide for food, shelter, and sanitation.

Table 2. Key public health and sanitation activities in post-tsunami periods.

Post Tsunami Period	Essential Public Health-Related Activities
Immediate: **0 to 48 Hours**	Locate, collect, and process dead; locate and treat injured; relocate dispossessed; provide for basic needs: water, food, shelter, sanitation. Assess magnitude of needs, locate, and acquire needed personnel, equipment, supplies.
Interim: **2 to 14 Days**	Continue processing dead; provide for continuing basic needs, sanitation, and health care of relocated population; Establish reliable water sources and provide for interim sanitation; Establish controls and routine for maintaining sanitary conditions in relocation centres including food preparation; personal sanitation practices; and waste disposal; Establish disease surveillance system; Begin clean-up of debris concentrating on dead animals, decaying materials, and physical hazards.
Recovery: **After First Two Weeks**	Complete removal of debris. Re-establish essential utilities; electric power; secure water supply, initially to relocation centres then to communities, rebuild water supply and wastewater disposal systems. Begin transfer of population from relocation centres to permanent dwellings. Reassign temporary external resource personnel.

Outside of the migration centres the debris including all manner of contamination from the devastating waves, accompanying flooding, and indiscriminate distribution of crushed and broken building materials, household goods, rubbish, dead animals, and waste materials of every description presented a chaotic blanket of dangerous contamination to the local population and relief workers. Through the first ten days, public health work focused on water supply and sanitation needs of the relocated population, and on assessing the condition of water supply, sewerage, and solid waste management facilities. A survey of water supply facilities in the affected areas showed that very few systems were able to function without significant repair (Table 3).

In devastated areas facilities were heavily damaged. Inundation filled ponds and tanks with sand, seawater, and general debris. Sewerage facilities generally closer to the shoreline were typically more heavily damaged. Normally buried water distribution and sewer pipe systems were also heavily damaged by the force of the tsunami, resulting erosion, and transported debris, in which such tsunami damages were detected with remote sensing [4].

Table 3. Water supplies in tsunami affected areas, 5000 households in six provinces.

Province	Village			Household			Population		
	Total	Tsunami Affected	Percent Affected	Total	Tsunami Affected	Percent Affected	Total	Tsunami Affected	Percent Affected
Ranong	178	45	0.2528	56471	1126	0.0199	178664	3770	0.0211
Phang Nga	318	68	0.2138	72737	4615	0.0634	236274	19509	0.0826
Phuket	103	61	0.5922	109686	952	0.0087	278480	13065	0.0469
Krabi	383	112	0.2924	79148	2759	0.0349	380367	15812	0.0416
Trang	720	51	0.0708	162177	660	0.0041	611436	12118	0.0198
Satun	276	59	0.2138	67626	81	0.0012	273702	2376	0.0087
Total	**1978**	**396**	**0.2002**	**547845**	**10193**	**0.0186**	**1958923**	**66650**	**0.0340**

Source: Department of Water Resources, Ministry of Natural Resources and Environment, Bangkok, Thailand. Data from 27 December 2004 to 1 March 2005.

Water quality testing was a very difficult task. The water quality team arrived after an eight-hour drive from Bangkok with the sampling equipment. The goal was in a few days to sample key ground water wells, the reservoir, the tap water as well as key impacted pond areas where wastewater was accumulating, and the beach. The team was able to collect 10 samples. Onsite pH, EC, were measured and the bacterial, other chemical and protozoan tests were measured in samples transported back to the lab. As expected, ponds and a ditch used for shower water were contaminated with fecal bacteria, as was the reservoir that has been used as a water supply. Protozoan pathogens were only detected in the shower water and the reservoir. This demonstrated the need for filtration of any surface water for use as potable water. In addition, the contamination of the ditch suggested infection in the population. Wells in low-lying areas were assumed contaminated due to flooding and inundation. However, testing was needed to assess actual conditions (e.g., elevated salinity, conductivity, total dissolved solids (TDS)) and potential contamination (e.g., coliforms, faecal coliforms, enterococci). Surprisingly, some shallow wells in affected areas were not contaminated (Table 4).

Dealing with contaminated water supplies and potential for further contamination due to disrupted sanitation systems was a critical problem in the recovery period. To deal with this a team was formed of local health personnel, external personnel from the National Health Department, and other available trained personnel. Problems were identified and prioritized, then pursued as resources permitted. Tasks included selection and development of temporary water sources with appropriate disinfection and bacteriological confirmation; arrangement for mobile water supply systems; control of flies and other vectors; provision of health education to victims and the temporarily relocated population on topics of personal hygiene, general sanitation, and food sanitation. Other services provided in support of local authorities included: provision for water and food quality surveillance including monitoring conditions and sampling food and water; construction and maintenance of temporary sewage treatment facilities (initially privies and leach pits); provision for routine storage and collection of solid waste; and installation of a treatment system (anaerobic filter onsite treatment system) to serve the body collection area at Phuket and Krabi province. Recognizing the extent of damage and duration of need requiring many months of maintenance for significant populations in major relocation centres, new permanent water systems were developed.

Table 4 Analysis results of physical, chemical, and water-borne pathogen of tested water.

Collected Date	Water Type	Enterococci (cfu/100 ml)	*E. coli* (cfu/100 ml)	Protozoa *Cryptosporidium & Giardia*	pH	EC (s/cm)	TOC (mg C/l)	Turbidity (NTU)	Salinity (g/l)
21 January 2005	Shallow Well, Chlorinated	0	0	Negative	-	-	-	-	-
21 January 2005	Shallow Well, Chlorinated	<0.5	<0.5	Negative	-	-	-	-	-
22 January 2005	Pond	2419	1986	Negative	8.4	27.7	30.5	15.6	18.6
22 January 2005	Pond	2419	2419	Negative	8.0	25.5	34.6	31.5	16.9
22 January 2005	Tap Water	0	0	Negative	-	-	-	-	-
22 January 2005	Beach Area	<0.5	<0.5	Negative	-	-	-	-	-
22 January 2005	Pond	2419	387	Negative	8.1	6.67	33.6	23.3	4
22 January 2005	Ditch, with shower from temporary relocation camp	2419	207480	Positive	-	-	-	-	-
22 January 2005	Pond	1413	>2500	Negative	7.9	8.35	30.8	6.39	5
22 January 2005	Water Reservoir	>2500	456	Positive	7.7		30.5	3.37	8.2
23 January 2005	Pond	>2	>1000	Positive	8.3	28.4	30.2	32.6	6.2

Infectious disease surveillance during the first month from 26 December 2004 to 25 January 2005 found significant occurrence of GI upset (diarrhoea and vomiting), initially as many as 126 cases/day decreasing to 100 cases/day, an incidence rate of 2950/100000 population. This was nearly double the normal rate for the same period of the previous year (IR = 1758/100000). This emphasized the need for improvement of food sanitation, control of water supply, health education, and disease control to avoid serious disease outbreaks. Surveillance for other diseases showed few cases of malaria and DHF cases. However, numbers were not significantly different from normal and did not appear related to the disaster and aftermath.

The support of clinical and environmental laboratories for performing chemical and microbiological tests in the affected areas was essential to meeting public health needs. Testing confirmed the obvious contamination resulting from inundation with heavily contaminated sources and the general distribution of contamination from inundation and the receding water. Testing was essential to assess the condition of groundwater sources and to verify the condition of water from upland sources not affected by flooding, and of water in beach bathing areas. While no previous information was available for the affected area cursory qualitative testing for protozoan parasites *Cryptosporidium* and *Giardia* confirmed their presence as general environmental contaminants, Table 4. This underscored the potential for waterborne transmission as an additional post-tsunami hazard [5, 6]. In comparison to the magnitude of post-tsunami GI upset occurrence in relocation centres, a routine occurrence of cryptosporidiosis at 2–5 per 100000 or giardiasis at 15–20 per 100000 would be undetectable. Previous investigations, largely of selected and impaired populations have demonstrated that cryptosporidiosis and giardiasis occurrence in Thailand is comparable to other similar regions of the world [7-11]. However, since both organisms have been demonstrated to cause both water and food-borne outbreaks vigilance for adherence to sound and effective water and food sanitation practices as well as attention to personal hygiene needs remain important elements of public health protection particularly under crowded and difficult conditions.

3. LESSONS LEARNED AND FUTURE RECOMMENDATIONS FOR DISASTER MANAGEMENT

Coastal zones and small islands are often densely populated areas that increase people's risk and vulnerability. Nearly three billion people or almost half the world’s population live in coastal zones, which are prone to hazards including tropical cyclones, floods, and tsunamis. Governments and local authorities need to consider human habitats in long-term development planning, ensuring that risks are minimized. The most important – and costly – prevention system is a tsunami early warning system monitoring seismic events and corresponding wave patterns, determining the earthquake’s magnitude and epicentre and subsequently detects the tsunami waves.

Such system can detect the propagation of a tsunami wave before it collides with the shoreline, however, efficient means of communication between relevant authorities and local communities are required to ensure a rapid response. Information exchange between scientists, politicians and local authorities is therefore of high importance. Numerous activities should be considered to improve disaster prevention and, if necessary, recovery and rescue actions. Those include safe construction of buildings, escape routes, storage of food, drinking water and medical supplies, robust transportation options (helicopters are almost indispensable for these purposes) and digital communication devices. In addition, regular drills for rescue forces should be carried out at time intervals. Finally, international, regional, and national organizations should improve their coordination and exchange of information to establish pre-emptive instruments of disaster prevention.

Recent studies provided evidence that wastewater represents a potential source of health risks due to the presence of severe acute respiratory syndrome coronavirus (SARS Cov-2) [12-14]. The disease caused by SARS-CoV-2 is now referred to as coronavirus disease 2019 (COVID-19 and was subsequently declared a global pandemic. The presence of SARS-CoV-2 RNA in human feces was reported in studies.[15] In light of these findings, it became clear that knowledge on occurrence, persistence and possible routes of transmission of water-borne pathogens and in particular viral agents is currently essentially limited. It is therefore urgently required to strengthen research efforts such as wastewater-based-epidemiology aimed at the surveillance of wastewater to understand the public health risks created by these organisms. The ultimate goal of these efforts would be to gather information on prevalence, genetic diversity and possible ways for the eradication of viral threats such as COVID-19.

4. SUMMARY AND CONCLUSIONS

The effects of unprecedented earthquake and tsunami destruction on coastal populations can barely be imagined. The figures of 5300 dead, 3000 missing and 17000 injured within 150 km of coastline in a heavily patronized tourist area of south-west Thailand underscore the magnitude and extent of devastation. Immediate and continuing 3333needs for public health protection in affected areas must rely on basic principles and ability to find, organize, and apply available personnel and resources.

Organisation and application of public health protection resources in response to natural disasters whether a typhoon in Myanmar, earthquake in China, or earthquake and tsunami in South Asia or the pacific islands requires both immediate action and application of essential services for extended periods of time. Recognition of the nature of specific local effects and their potential public health consequences is essential to minimising secondary and hopefully preventable health impact on the affected populations. Water quality effects through overt contamination and disruption of normal water supply and wastewater disposal services must be assessed quickly with appropriate response as resources permit.

Experienced professionals can make effective initial assessment of water quality conditions qualitatively. Confirmation of conditions by selective chemical and biological testing should be applied as soon as resources permit. An understanding of expected levels of environmental pathogen levels as well as enteric disease occurrence rates in the local or comparable populations can be an important asset to public health personnel in monitoring the status of affected populations.

While prevention of natural disasters is out of the question, skilful, well organized, and dispassionate application of public health fundamentals can minimise the degree of human suffering following the event. Thoughtful re-examination of recent experiences such as described here in Thailand's southwestern provinces can assist in facilitating actions needed in future occurrences.

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ANNOUNCEMENT

DR. AGGELIKI BARBEROPOYLOY OF TUFTS UNIVERSITY IN MEDFORD MASSACHUSETTS USA, JOINTS THE EDITORIAL BOARD OF SCIENCE OF TSUNAMI HAZARDS

Introduction: Our journal "SCIENCE OF TSUNAMI HAZARDS" is dedicated to the publication of new scientific ideas, focusing on presenting the results of theoretical-methodological and applied research on a broad global context. The consistency of our journal, published four times a year since 1981, allows researchers to present the results of their work in a dynamic way, as well as to compare scientific conceptualization in the context of research conducted internationally. To achieve this goal of involving a wide range of scientific disciplines, "Science of Tsunami Hazards" needs the help of an editorial board with broad expertise. For this reason we recently invited Professor Aggeliki Barberopoulou of Tufts University, to join the Editorial Board of our journal, and I am pleased to announce that she has accepted.

Following is a brief bio-summary of Dr. Barberopoulou's impressive background, on a variety of research projects she has undertaken in the past, and most recently in teaching GIS classes, Remote Sensing and Python programming for geospatial applications, and in advising students at Tufts University.

George Pararas-Carayannis,PhD
Editor-in-Chief,
SCIENCE OF TSUNAMI HAZARDS

Brief Bio-Summary of Dr. Aggeliki Barberopoulou

Prof. Barberopoulou's research is broadly centered on natural hazards and risk, with the goal of understanding the response of the environment to natural disasters in order to better prepare for, respond to and recover from them. She has provided technical assistance and support to experts' panels, emergency management (for planning/preparedness) and has participated in community preparedness, training, exercises, evaluations/assessments, and post-disaster field surveys.

For more than ten years she worked extensively with emergency management officials and represented California as the numerical modeler of the Golden State at the National Tsunami Hazard Mitigation Program and the Tsunami Steering Committee of California. In New Zealand she also served in the Tsunami Experts Panel (TEP) that provides support and advice to the Ministry of Civil Defense and Emergency Management (MCDEM) during a tsunami.

Barberopoulou holds a Master of Science in Applied Mathematics from the University of Washington in Seattle, W.A., and a PhD in Geophysics, also from the University of Washington.

Prior to joining Urban, Environmental Policy and Planning at Tufts University she worked at the Viterbi School of Engineering at the University of Southern California (USC) as a postdoctoral research associate and later as a Research Assistant Professor prior to accepting a position as permanent tsunami scientist across the Pacific at GNS Science, New Zealand. She has also held positions as a research scientist at the National Observatory in Athens, Greece, and more recently as a senior scientist at AIR in Boston. She has been teaching GIS classes since 2019 and has designed her own class in GIS & Hazards. At Tufts University she is teaching GIS classes, Remote Sensing and Python programming for geospatial applications while advising students.

When she is not doing research or teaching, she may be found doing public outreach, as she is a big advocate on teaching science beyond the walls of a classroom.

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