ISSN 8755-6839

SCIENCE OF TSUNAMI HAZARDS

Journal of Tsunami Society International

Volume 40 Number 1 2022

IMPACT AND RESPONSE IN CENTRAL AND SOUTH AMERICA DUE TO THE TSUNAMI GENERATED BY THE SUBMARINE ERUPTION OF HUNGA TONGA-HUNGA HA'APAI VOLCANO 1

Theofilos Toulkeridis[1]*, Noris Martinez[2], Gustavo Barrantes[3], Willington Rentería[4], Grey Barragan-Aroca[5], Débora Simón-Baile[1], Iván Palacios[1], Rodolfo Salazar[1], Elkin de Jesús Salcedo-Hurtado[6], and George Pararas-Carayannis[7]

[1]Universidad de las Fuerzas Armadas ESPE, Sangolquí, ***Ecuador***
[2]Universidad Tecnológica de Panamá, City of Panamá, **Panama**
[3]Universidad Nacional de Costa Rica, Heredia, ***Costa Rica***
[4] University of Southern California, Los Angeles, ***USA***
[5]Universidad Estatal de Bolivar, Guaranda, ***Ecuador***
[6]Universidad de Valle, Cali, ***Colombia***
[7]Tsunami Society International, ***USA***

EFFECTIVE TSUNAMI EARLY WARNING USING THE PRODUCT OF P-WAVE DOMINANT PERIOD AND SOURCE RUPTURE DURATION OF MORE THAN 50 SECONDS 39

Madlazim[1], Tjipto Prastowo[1], Muhammad Nurul Fahmi[1], Ella Melianda[2], Soerja Kusuma[3]

[1]Universitas Negeri Surabaya, Surabaya 60231, ***Indonesia.***
[2]Universitas Syiah Kuala, Aceh, ***Indonesia***
[3]Universitas Sebelas Maret, Surakarta, ***Indonesia***

TSUNAMI RISK COMMUNICATION: ASSESSING KNOWLEDGE GAPS AND SUITABLE SERIOUS GAMES 54

Steven Hawthorn[1], Rui Jesus[1,2], Maria Ana Baptista[3]

[1] NOVA LINCS, Faculdade de Ciências e Tecnologia, Univer, NOVA de Lisboa. ***Portugal***
[2]Instituto Superior de Engenharia de Lisboa, Instituto Politécnico de Lisboa, ***Portugal***
[3]Instituto Dom Luiz, Faculdade de Ciências da Universidade de Lisboa, ***Portugal***

WWW.TSUNAMISOCIETY.ORG

TSUNAMI SOCIETY INTERNATIONAL, 1325 South 33rd Avenue, Hollywood, Florida 33021, USA.

SCIENCE OF TSUNAMI HAZARDS is a CERTIFIED OPEN ACCESS Journal included in the prestigious international academic journal database DOAJ, maintained by the University of Lund in Sweden with the support of the European Union. SCIENCE OF TSUNAMI HAZARDS is also preserved, archived and disseminated by the National Library, The Hague, NETHERLANDS, the Library of Congress, Washington D.C., USA, the Electronic Library of Los Alamos, National Laboratory, New Mexico, USA, the EBSCO Publishing databases and ELSEVIER Publishing in Amsterdam. The vast dissemination gives the journal additional global exposure and readership in 90% of the academic institutions worldwide, including nation-wide access to databases in more than 70 countries.

OBJECTIVE: Tsunami Society International publishes this interdisciplinary journal to increase and disseminate knowledge about tsunamis and their hazards.

Submit manuscripts of research papers, notes or letters to the Editor. If a research paper is accepted for publication the author(s) must submit a scan-ready manuscript, a Doc, TeX or a PDF file in the journal format. Issues of the journal are published electronically in PDF format. There is a minimal publication fee for authors who are members of Tsunami Society International for three years and slightly higher for non-members. Tsunami Society International members are notified by e-mail when a new issue is available. Permission to use figures, tables and brief excerpts from this journal in scientific and educational works is granted provided that the source is acknowledged.

Recent and all past journal issues are available at: http://www.TsunamiSociety.org CD-ROMs of past volumes may be purchased by contacting Tsunami Society International at postmaster@tsunamisociety.org Issues of the journal from 1982 thru 2005 are also available in PDF format at the U.S. Los Alamos National Laboratory Library http://epubs.lanl.gov/tsunami/

ISSN 8755-6839

SCIENCE OF TSUNAMI HAZARDS

Journal of Tsunami Society International

Volume 41 Number 1 2022

IMPACT AND RESPONSE IN CENTRAL AND SOUTH AMERICA DUE TO THE TSUNAMI GENERATED BY THE SUBMARINE ERUPTION OF HUNGA TONGA-HUNGA HA'APAI VOLCANO

Theofilos Toulkeridis[1]*, Noris Martinez[2], Gustavo Barrantes[3], Willington Rentería[4], Grey Barragan-Aroca[5], Débora Simón-Baile[1], Iván Palacios[1], Rodolfo Salazar[1], Elkin de Jesús Salcedo-Hurtado[6], and George Pararas-Carayannis[7]

[1]Universidad de las Fuerzas Armadas ESPE, Sangolquí, Ecuador
[2]Universidad Tecnológica de Panamá, City of Panamá, Panama
[3]Universidad Nacional de Costa Rica, Heredia, Costa Rica
[4] University of Southern California, Los Angeles, USA
[5]Universidad Estatal de Bolivar, Guaranda, Ecuador
[6]Universidad de Valle, Cali, Colombia
[7]Tsunami Society International

*Corresponding author: ttoulkeridis@espe.edu.ec

ABSTRACT

The Hunga Tonga-Hunga Ha'apai submarine volcano erupted on Saturday 15, 2022 leading to a VEI 5 eruption at 17.27 local time, shaking the earth with a M5.8. As result of this explosion a tsunami was triggered. The reasons of the tsunami may have been by a complex magma-water interaction or by repeated submarine mass movements. However, this tsunami impacted most of the Pacific during the following couple of hours, reaching also Central and South America. There, local monitoring organizations handled differently this information provided by the PTWC, and so did authorities and local mass media in the transmission of information and consequences for the public. We report the events as occurred in the countries between Costa Rica, Panama, Colombia, Ecuador, Peru and Chile and the respective degree of reaction of the public.

Keywords: *Hunga Tonga-Hunga Ha'apai, volcanic tsunami, early alert, transmission of information, response, public preparedness*

1. INTRODUCTION

Historically, the Pacific side of Central and South America have been impacted by numerous tsunamis from local and distant earthquakes generated along subduction zones of active continental margins (Pararas-Carayannis, 1974; Lockridge, 1988; Gusiakov, 2005; Kowalik et al., 2005; Orfanogiannaki & Papadopoulos, 2007; Medina et al., 2021). The South American continent is subducted by the Nazca Oceanic Plate, while Central America is subducted also by the Cocos Oceanic Plate (Wadge & Burke, 1983; Protti et al., 1994; Trenkamp et al., 2002; Mann, 2007). Most of the tsunamis that impact the coasts of Central and South America are of such local tectonic origin earthquakes and strike shorelines within very short times after generation (Annaka et al., 2007; Løvholt et al., 2012; Carvajal et al., 2019). Nonetheless, there are also tsunamis generated from far-distant generating sources, like the 2011 Sanriku tsunami in Japan, which have impacted Central and South America some 20 hours or more after their generation (Pararas-Carayannis, 2011; Ide et al., 2011; Grilli et al., 2013; Kajitani et al., 2013; Murray et al., 2015; Chian et al., 2019). Once a tsunami is generated by a tectonic earthquake or some other source somewhere in the Pacific Ocean, the Pacific Tsunami Warning Center (PTWC) in Honolulu Hawaii, disseminates initial alerts and subsequent warnings about the arrival time of tsunami waves at various ports or other important sites along the coasts (Fukao, 1979; Bernard et al., 2006; Jiménez et al., 2018). Government institutions or centers receiving such information pass it on to Civil Defense authorities in each country, which in turn assess the potential risks and disseminate notifications to local authorities, followed by alerts or warnings by sirens to the public, so that evacuation to safer higher ground sites can be rapidly initiated (Park et al., 2005; Sahal & Morin, 2012; Itibita & Chen, 2017).

The procedures of evaluating earthquake events and tsunami generation in the Pacific Ocean Basin have been successfully implemented for various decades by PTWC (Bernard et al., 2006; Tkalich et al., 2007; Davis & Izadkhah, 2008; Lauterjung et al., 2010; Okal, 2015; Neußner, 2021). Countries receiving watch or warning information proceed with further transmission of evacuation plans, to ensure the safety of people living in coastal areas (Moe & Pathranarakul, 2006; Yahav & Salamon, 2022). However, if the earthquake source area is close, the arrival time of the tsunami waves may be too short, and authorities lack needed time to transmit information or warnings to the public (Anderson, 1969; Nakamura et al., 2011; Angove et al., 2019). Also, there are cases when authorities fail to adequately interpret or understand the risks of an incoming tsunami, thus taking a wrong decision which may lead to a disaster (Gregg et al., 2006; Igarashi et al., 2011; Farías, 2014). On the other hand, even when all procedures are handled correctly by the authorities and associated scientists, the public may react incorrectly and risk their lives (Allen & Melgar, 2019; Mileti & Sorensen, 1990). The success of any type of tsunami evacuation depends on the degree of preparedness, and of public education, repeated drilling exercises and corresponding signals, as well as on the infrastructure of tsunami-resistant buildings among others (Paton et al., 2008; Nandi & Havwina, 2018; Esteban et al., 2014; Johnston et al., 2005; Esteban et al., 2015; Edler et al., 2020; Suárez-Acosta et al., 2021; Del Pino et al., 2021; Toulkeridis et al., 2021).

For the above-stated timing, geographical, and disaster preparedness limitations, some of the tsunami warnings issued by PTWC and by National authorities - even for earthquake-generated events - fail occasionally to reach on time the public of threatened coastal areas. The problem of timely dissemination of warnings to the public becomes even more difficult to handle by national and international authorities, when a different and difficult to measure tsunami triggering mechanism is involved, which precludes rapid assessment of potential risk (Gardner-Stephen et al., 2019; Lane et al., 2020; Mikami et al., 2020; Selva et al., 2021; Rafliana et al., 2022).

Since tsunamis can be generated also by numerous other sources, such as flank failures of coastal or oceanic volcanoes, underwater slides, submarine Surtsean (phreatomagmatic) eruptions, sub air Plinian eruptions, Ultra-Plinian explosions, landslides, flank failures, subsidences and multiphase massive caldera collapses of a volcano, such events can generate destructive tsunamis – as for example that generated during the paroxysmal phase of the 1883 Krakatoa volcanic eruption (Pararas-Carayannis, 2004, 2006). Furthermore, tsunami-like waves can be generated by atmospheric air pressure pertrubations, and such was the case for the meteo-tsunami of 29 August 1916 at Santo Domingo, in the Dominican Republic (Pararas-Carayannis, 2019).

Large magnitude earthquakes involving significant vertical crustal dispacements such as those of the 1964 Alaskan earthquake, generated atmospheric pressure waves which propagated faster then tsunami waves and were recorded by micro-barographs. The use of such microbarographs was proposed subsequently to serve also as precursory method of forecasting tsunami generation (Pararas-Carayannis, 1967). Furthermore, tsunami waves can be also generated by a rapid, significant and progressive drop in atmospheric pressure which may be caused by a storm, in which case it would be localized and directional, as was the case with the meteo-tsunami of 29 August 1916 at Santo Domingo, in the Dominican Republic (Pararas-Carayannis, 2019).

However, violent eruptions and blast episodes such as that of 1883 Krakatau volcano, can also trigger rapidly moving atmospheric pressure pertrubations which, in turn, as they move over a shallow sea, can couple with the sea surface and generate tsunami-like waves affecting the surface of the sea – often with sizeable waves. Specifically, the atmospheric pressure shock waves from the 1883 explosions of Anak Krakatau volcano circled the earth and were recorded by barographs throughout the world (Pararas-Carayannis, 2004). Apparently, the Hunga Tonga-Hunga Ha'apai submarine volcano's violent explosive index VEI 5 eruption also generated strong atmospheric pressure waves and tsunami-like waves recorded at great distances. (See: http://www.drgeorgepc.com/Tsunami1883Krakatau.html)

In fact, similarly to the explosive 1883 volcanic eruption/explosion of Anak Krakatau reported above (Pararas-Carayannis, 2004), and according to a study pending final publication in EOS (Lin et al., Febr. 2022), the Hunga Tonga Hunga Ha'apai volcanic eruption of 15 January 2022, also created an impulsive giant Ionospheric Lamb Wave in the Northern Hemisphere which, traveling at the speed of sound (about 340 m/sec), reached Japan in six hours.

Also, using new technology, there were recordings of subsequent concentric wave shape traveling ionospheric disturbances (TIDs oscillations) from the Hunga-Tonga volcanic eruptions – which were observed simultaneously in both the northern and southern hemispheres. Thus, the main source mechanism for the 2022 tsunami generation and its observed far-field impacts, were not due to crustal movements related to the relatively shallow underwater eruption of the volcano in the Tonga archipelago, but to Lamb Wave atmospheric pressure turbulence and ionosphere/atmosphere interaction, which forced non-dispersive, horizontally traveling oscillations, similarly to those of Anak Krakatau volcano (Pararas-Carayannis, 2004).

Therefore, high amplitude tsunami waves can be generated not only by earthquakes, but also from less frequently-occurring events, such as impacts of falling asteroids, massive coastal and submarine landslides, and volcanic activity which may include flank and caldera collapses, or violent explosive eruptions that result in significant crustal and water displacements and atmospheric pressure shock waves (Latter, 1981; Bardet et al., 2003; Cita & Aloisi, 2000; Synolakis et al., 2002; Tappin, 2002; Pararas-Carayannis, 2002, 2004, 2011, 2014).

Although tsunami generation from falling space bodies is an extremely rare phenomenon, there is documentation that during the Cretaceous-Tertiary geological period, asteroids struck the earth and generated huge tsunami waves. For example, about 66 million years ago, a large asteroid of about 10 kilometers in diameter struck the earth and created the Chicxulub crater near the coastal area of Yukatan Peninsula of Mexico, and most probably generated a mega tsunami. In fact a study proposing a simulation of asteroid tsunami model validation – characterized as the P-C model - was used to calibrate, verify and validate theoretical modeling studies of asteroid tsunami generation, conducted at the Los Alamos National Laboratory (Pararas-Carayannis, 1999).

More frequent past events generating tsunamis resulted from crustal movements involving severe volcanic activity, as determined by studies of paleo-tsunami deposits (Pararas-Carayannis, 1973, 1974a, 1992; Watkins et al. 1978; Sharpton et al., 1992; Bourgeois, 1994; Dunbar & McCullough, 2012; Paris et al., 2020). Prominent examples may be the Coquimbo event in Chile in the Middle Pleistocene period, the Alika event in Hawaii some 120 thousand years ago, and the Storegga event of Norway some 7,000 years ago (Lipman et al., 1988; Paskoff, 1991; Bondevik et al., 1998; McMurtry et al., 2004; Goff et al., 2014).

Nonetheless, the oldest known tsunami in recent historical time scale was that generated by the 1638 B.C. explosion, caldera collapse, and flank failures of the volcano of Santorini in the Aegean Sea in Greece – which caused the destruction of the Minoan civilization on the Island of Crete, as well as destruction elsewhere in the Aegean Archipelago (Pararas-Carayannis, 1973, 1974a, 1992; Minoura et al., 2000: Manning et al., 2006; Nomikou et al., 2016; Driessen, 2019).

In more recent times, a very destructive tsunami was generated by the 1883 eruption of the Anak Krakatau (Krakatoa) volcano in the Sunda Straits, between the islands of Java and Sumatra in Indonesia (Latter, 1981; Paras-Carayannis, 1983; Tanguy et al., 1998; Choi et al., 2003). Within an hour after the fourth explosion/caldera collapse of the Anak Krakatau, waves reaching heights of up to 37 m (120 feet) destroyed 295 towns and villages and drowned a total of 36,417 people (Pararas-Carayannnis, 1983, 1999). As with the recent eruption/explosion of the Hunga Tonga-Hunga Ha'apai submarine volcano on 15 January 2022 near the Tonga Islands, the far field effects of the tsunami generated by the 1883 eruption of Anak Krakatau were noticeable around the world, but to a much greater extent.

Small sea level oscillations from the 1883 tsunami were recorded by tide gauges at Port

Blair in the Andaman Sea, at Port Elizabeth in South Africa, and as far away as Australia, New Zealand, Japan, Hawaii, Alaska, the North-American West Coast, South America, and even as far away as the English Channel (Pararas-Carayannnis, 1983, 1999). The unusual flooding, which occurred at the Bay of Cardiff, in the U.K. in 1883 was caused by atmospheric coupling of the pressure wave from the major Krakatau eruption.

A more recent eruption of the Anak Krakatau in 2018 caused a partial flank collapse of the volcano, and generated a local tsunami which killed some 437 people (Borrero et al., 2020; Zengaffinen et al., 2020; Heidarzadeh et al., 2020). While the 1883 eruption of the Anak Krakatau volcano occurred when no communication systems were in existence, the 2018 eruption occurred in contemporaneous times, and yet it was not possible to warn surrounding sites of its devastating potential (Sakurai & Murayama, 2019; Ye et al., 2020).

Finally, in the evening of 15 January 2022, the Hunga Tonga-Hunga Ha'apai submarine volcano near the Islands of Tonga, erupted violently and generated a destructive tsunami with local as well as far-field impacts in coastal areas of the Pacific Ocean. This was the strongest volcanic eruption/explosion in the 21st century.

The authors anticipate that further analysis of this event will be needed in order to evaluate the effectiveness of Civil Defense procedures for Latin-American countries between Costa Rica and Chile, in transmitting timely advisories and warnings for the protection of the public in coastal areas, from such volcanically-generated tsunamis.

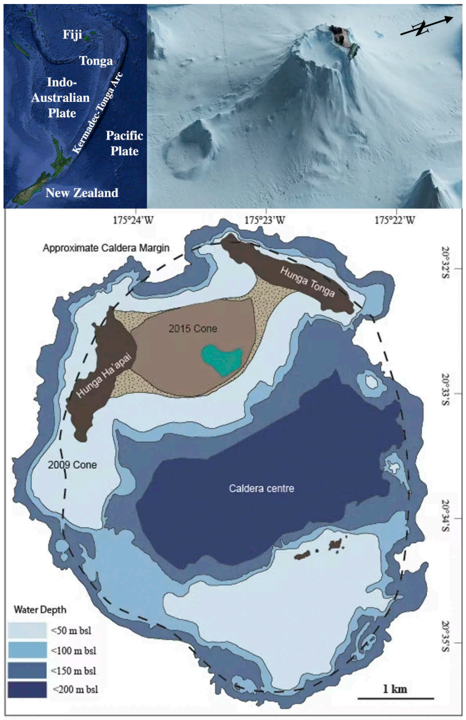


Figure 1. Upper left: Geodynamic setting of Tonga. Credit GoogleEarth^{TM} (2022). Upper right: A rendering of the volcano shows the part of the peak that is known as the two Tongan islands Hunga-Tonga and Hunga-Ha'apai. Credit Frederik Ruys; Below: Volcanic structure of Hunga Tonga-Hunga Ha'apai based on elevation and bathymetric map of this underwater volcano. Credit Shane Cronin / The Conversation, 2022.

2. GEODYNAMIC SETTING AND PRESENT TSUNAMI-TRIGGERING VOLCANIC ACTIVITY

The Hunga Tonga-Hunga Ha'apai volcano is located near to the islands of the Kingdom of Tonga, a group of 169 islands in the SW part of the Pacific Ocean, just north of New Zealand (Fig. 1). Volcanoes in this region developed by the interaction between the Indo-Australian and the Pacific Plate (Timm et al., 2014). Hereby, the descending oceanic Pacific Plate which subducts below the Tonga-Kermadec intra-oceanic arc, is the reason for the region's strong earthquakes and active volcanism (Fig. 1a; Hall & Spakman, 2002; Stern, 2004; Smith & Price, 2006).

2 A. Volcanic Evolution Along the Tonga-Kermadec Intra-Oceanic Arc

Along the central segment of the arc, rise some twenty volcanic edifices from the sea floor up to close or shortly above sea level (a.s.l.) (Worthington et al., 1999; Peate et al., 2001; De Ronde et al., 2007; Lupton et al., 2008). Two of these oceanic volcanic islands form the mainly submarine Hunga Tonga and Hunga Ha'apai volcanoes, which rise to some 114 meters above sea level (Fig. 1b; 1c; Colombier et al., 2018; Garvin et al., 2018; Brenna et al., 2022). These islands are remnants of a previously destroyed cone of the Hunga volcano, due to at least two caldera-forming processes some 840 to 980 years ago (Brenna et al., 2022). Historic and observed volcanic activity above and below the sea surface occurred in 1912, 1937, 1988, 2009 and 2014-15 (Global Volcanism Program, 2009; 2014; 2015; Brenna et al., 2022). The latter activity has been responsible for the creation of a single volcanic cone, when the two aforementioned islands got connected forming the 5 km long Hunga Tonga-Hunga Ha'apai and 1800 meters high submarine volcano (Brenna et al., 2022).

2 B. Recent Volcanic Activity Near the Islands of Tonga

The most recent volcanic activity initiated since the end of 2021, when the Hunga Tonga-Hunga Ha'apai underwater volcano erupted on December 20, 2021, continuing up to January 4 and later on to 13 January 2022 (Global Volcanism Program, 2021a; 2021b; 2021c; 2022). These eruptions are indicating smaller eruptions occurring at the edge of the caldera, while the subsequent stronger events were generated within the caldera when the upper part of the erupting magma collapsed inward, which resulted to a potentially massive deepening of the caldera (Brenna et al., 2022). The two precursor events produced slightly more land to the island, while the ash and gas clouds reached a height of up to 17 km (Fig. 2; Global Volcanism Program, 2021b; 2021c).

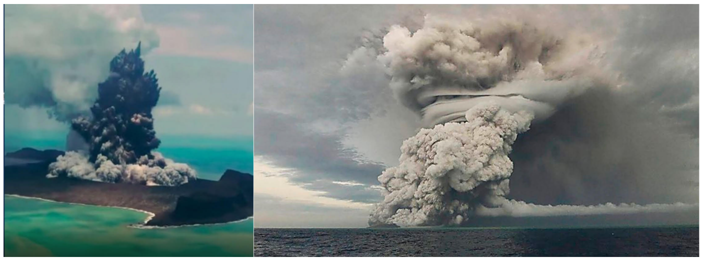


Figure 2. Images of the eruption of January 15, 2022. Credit Left: Digicel Tonga. Credit right: Tonga Geological Services / ZUMA Press / IMAGO

Following the new intense explosive phase on Thursday 13 January 2022 some 48 hours later. this volcanic activity continued until Saturday the 15th of January, leading to a VEI 5 eruption at 4.27 UTC (17:27 local time), and a magnitude M5.8 earthquake, as registered by the USGS (Fig. 3; 4; USGS, 2022). The blast of the shock wave from the major eruption travelling at the speed of 300 m /sec, was registered on many sites on the planet, including the other side of the Atlantic region (New York Times, 2022; Science.org, 2022). The eruption destroyed most of the island above sea level, generated an ash plume of some 19.2 km in height, and was followed by massive ashfall which reached the surrounding islands (BBC, 2022).

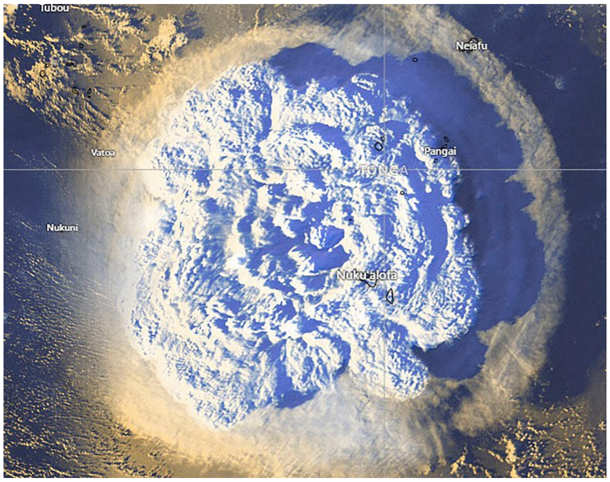


Figure 3. The enormous explosion as seen from the satellite. Credit US Geological Survey and Tonga Meteorological Services. Width of image is of about 600 km

Figure 4. Upper left: Hunga Tonga-Hunga Ha'apai prior eruption. Credit GoogleEarth™ in 2021; Upper right: The apparent volcanic activity as it appeared on January 7 2022. Credit: Planet Labs PBC/EYEPRESS/Shutterstock; Lower left: A Planet SkySat image shows Hunga Tonga-Hunga Ha'apai two hours before its eruption on January 15, 2022. Credit:Planet Labs PBC/via REUTERS; Lower right: Remains of the island as seen on January 17, 2022. Credit: Maxar Technologies

2 C. Tsunami Generated by the Paroxysmal Eruption of the Hunga Tonga-Hunga Ha'apai Volcano

This huge volcanic event triggered a tsunami, which impacted first the kingdom of Tonga affecting almost its entire population, and compromised many strategic infrastructures such as the submarine Internet cable, thus interrupting communication for weeks for many shorelines along the Pacific Ocean. The nearby islands of Tonga were impacted by the tsunami in less than one hour, New Zealand and Australia in four hours, Japan in eight hours, Russia and United States in more than ten hours, and finally South and Central America in more than twelve hours (Fig. 5).

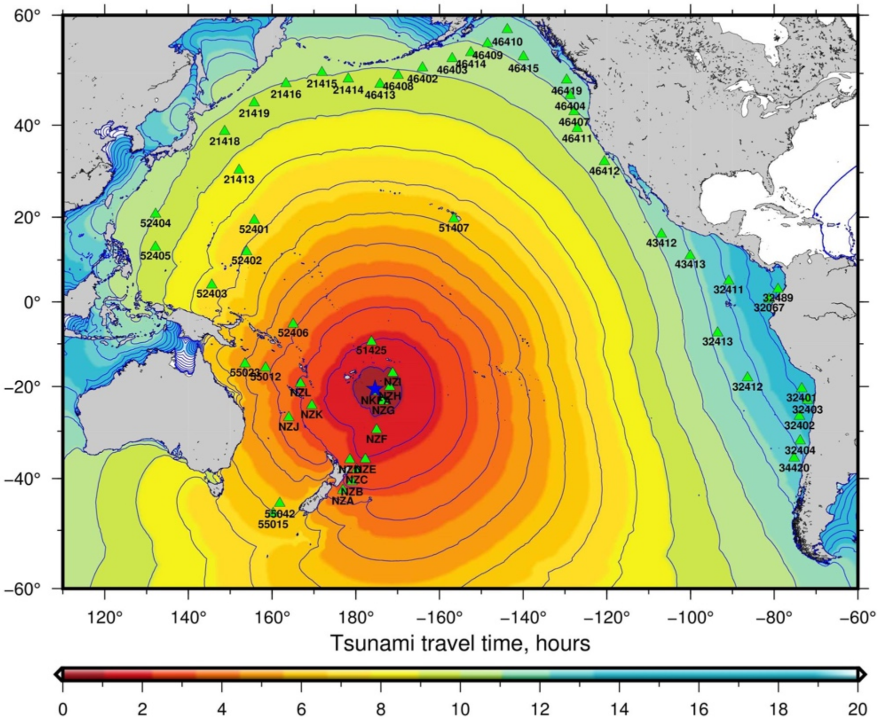


Figure 5. Tsunami travel time based on NOAA (NOAA, 2022a)

The origin of the tsunami generating area remained unclear initially, as the explosion of the Hunga Tonga-Hunga Ha'apai underwater volcano may have included three different possible mechanisms of tsunami generation. The first - and less possible - was that the tsunami was generated by the associated with the eruption magnitude M 5.8 earthquake, which however was too low to trigger a tsunami wave that could reach the shores of Asia and the Americas. The second mechanism for tsunami generation is based on the complex hydrothermal, high temperature molten magma-water interaction and the explosive blasting of both molten magma and gas reacting violently with the ocean´s water. If such interactive processes had occurred deeper in the sea, the hydrostatic pressure of the overlying sea water would have suppressed this process, but in the instant case the volcanic explosion occurred a little below the sea surface at a depth of about 150 to 200 meters below sea level (The Conversation, 2022).

A third possible mechanism of the tsunami source mechanism for this volcanic event is a massive and repeated submarine mass movement giving rise to marine landslides as well to flank or caldera collapses (The Conversation, 2022). Due to the enormous explosion only two smaller island fragments remained above sea level, which may favor the magma-water interaction or the flank collapse or even the combination of both triggering mechanisms (see Fig. 4).

3. EARLY ALERT AND RESPONSE BY THE AUTHORITIES AND THE PUBLIC

According to the USGS, the complex paroxysmal eruption of the Hunga Tonga-Hunga Ha'apai volcano occurred 68 km west of the island of Nuku'alofa of Tonga at 04:14:45 (UTC), on January 15, 2022 (USGS, 2022). This report takes this time as being the main tsunami initiation (PTWC, 2022). It is clear, in our understanding, that the source and development of this transoceanic tsunami is still unknown, and is out of the scope of this present report. Our subsequent analysis focuses on the tsunami recording by tide gauges in El Salvador, Costa Rica, Panama, Colombia, Peru, and Chile (Fig. 5, 6 and 7). Some of this information was available from the Flanders Marine Institute (Flanders Marine Institute, 2021). We have chosen the stations shown in Fig. 6 below, and the tide gauge records (Fig. 7), in order to have a panoramic picture of the tsunami impact on the Southeast Pacific coast of part of Central America and on the West of the South American continent.

Figure 6: Tide gauges station of the study area

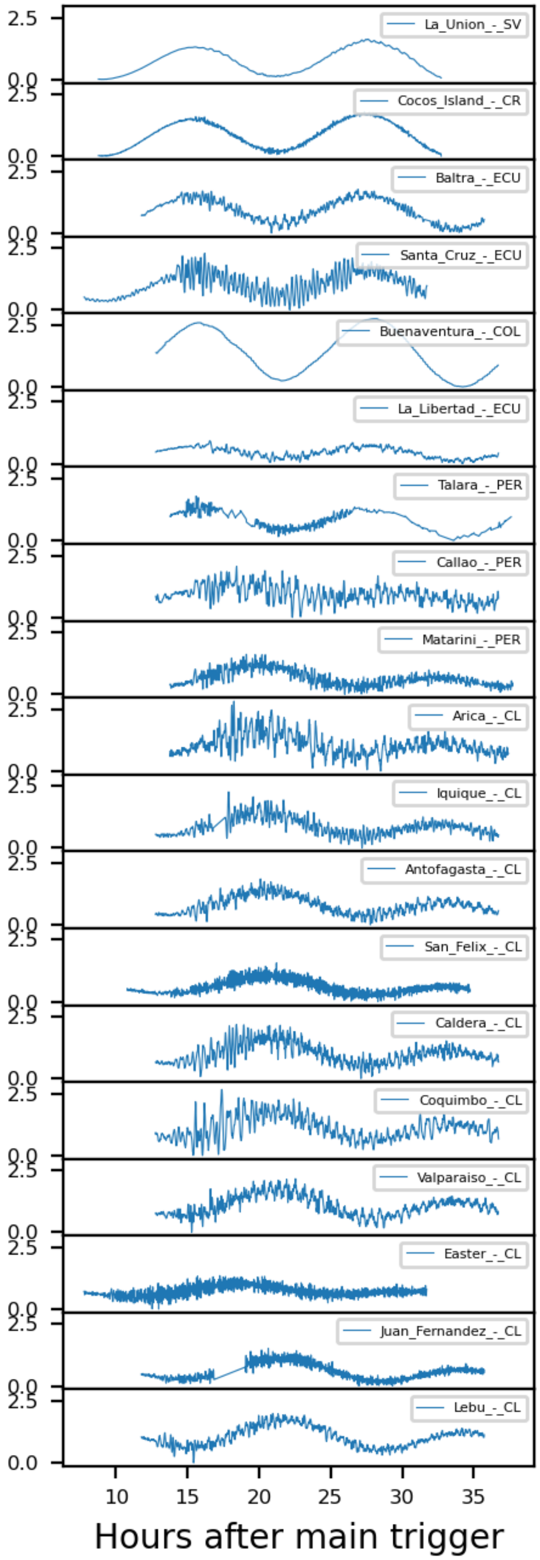


Figure 7. Tsunami wave amplitude registered at tide gauges stations

Analysis of tide gauge records (see Fig. 6 and 7 above) shows that the first tsunami wave arrival at the tide gauge station at Easter Island, Chile, was 9h 45min after the volcano's main eruption, and had a maximum wave amplitude of 0.5 meters. Most of the other stations recorded the tsunami's first arrival between 14-15 hours after the time of the volcano's paroxysmal eruption. The tide station at Eastern Island, located closer to the tsunami source, gives important information for the purpose of an early warning system for these kinds of events. The amplitude of the tsunami registered at the different tide gauges ranged from 0.1 - 1 meter. Maximum wave amplitude registered at the tide gauge in Arica, Chile, where the third tsunami wave reached a wave amplitude of ~ 1m. Regardless of the location, the stations in El Salvador, Costa Rica, Panama and Colombia, registered not important oscilllations. In the case of Buenaventura, Colombia, it is important to remark that this station is located in an estuary, where most of the energy of the tsunami dissipated by shoaling.

Another important issue about the tsunami's height is related to the stage of the tidal level at the time of arrival at each tidal station. In general, the tsunami's arrival occurred at or near high tide level in El Salvador, Costa Rica, Panama, Colombia, Ecuador, and northern Peru. Stations in southern Peru and all stations in Chile recorded the tsunami arrival close to low tide level. This is an important aspect of the tsunami impact since the tide gauges in Chile received the highest wave amplitudes of the tsunami (Fig. 7).

The very first tsunami message of the event in Tonga was issued at 0623 UTC, then at 0720 UTC, and later at 0852 UTC (NOAA, 2022b). In the first three messages, only local and some West Pacific sites were mentioned as potential tsunami impact sites (Vanuatu, New Zealand, Kiribati, Australia etc.), as well as the times of arrival and probable expected tsunami heights. The first advisory/warning of a tsunami impact in Central and South America was sent by the Pacific Tsunami Warning Center (PTWC) in Honolulu, Hawaii at 1246 UTC, on Saturday 15 January 2022 as "Tsunami Message Number 4", referring only to Chile and Mexico, excluding at that time Central and South American countries, which were further away from the tsunami generating source. However, a sixth message at 1645 UTC issued an advisory/warning to all other Central and South American countries (NOAA, 2022b). The last twelfth message was issued at 0246 UTC on Sunday 16 January 2022. Based on these advisories to country-members of the Pacific Tsunami Warning System (PTWS), we begun analyzing responses of authorities, of media and of the public for the countries in the region from Costa Rica and Chile.

3a. Costa Rica

According to historical tsunami catalogs and records, since 1746 Costa Rica has been impacted about 39 times by tsunamis (Fernandez et al., 2000; Chacón-Barrantes, & Protti, 2011; Chacón-Barrantes & Zamora, 2017; Chacon-Barrantes & Arozarena-Llopis, 2021). Most of the observed or recorded tsunamis were generated mainly from local tectonic sources. Even the tsunamis of 1950 and 1992 which had runups of up to 7.3 meters, there were no reported fatalities along the country's Pacific coast. Fortunately in Costa Rica there are regular educational and awareness programs, as well as occasional local drilling of evacuation exercises, for both of the country's Pacific and Caribbean coastal sides.

Following the PTWC advisory about the possible impact of a tsunami from the Hunga Tonga-Hunga Ha'apai volcanic event, the National Tsunami Monitoring System (SINAMOT) of Costa Rica in its Report # 1 at 9:54 local time, announced that the earthquake magnitude associated with the eruption in Tonga should be ignored, but that very strong currents would arrive, classifying them as of low threat (SINAMOT, 2022). Later SINAMOT reported that the impact times were cestimated to be at 12:20 in the Gulf of Nicoy, and at 12:53 in Quepos (Fig. 8).

Figure 8. Potential impact sites (in blue) of tsunami in Costa Rica with low threat (SINAMOT, 2022)

However, based on what was observed and reported elsewhere, it was recommended that all sea-related activities such as swimming, surfing, diving, snorkeling, artisanal fishing, water sports, should be terminated. Furthemore an order was issued to vacate the beaches, and in a general way abstain from such activities until further notice by the official media that there were no-longer existing threat conditions. At 10:16 local time, the national media issued such official notice, recommending evacuation of the Pacific coast for at least a period of one hour (12:30 pm to 1:30 pm). At 1:15 p.m. local time, abnormal behavior of the sea was reported at Potrero (Guanacaste), when the sea level rose and subsequently receded, twice. At 3:30 p.m., there was an announcement that monitoring was completed, and that there were no reports of losses or injured persons anywhere along Costa Rica's Pacific coast.

3b. Panama

Panama, like Costa Rica was impacted by tsunamis of both sides, at the Pacific Coast and on the Caribbean side. Tsunamis in Panama are subduction related, as well as based on volcanic activity and landslides (Fernandez et al., 2000; Lander et al., 2002; O'loughlin & Lander, 2003; Pararas-Carayannis, 2004). Unfortunately, there is a general lack of awareness of these oceanic hazards and there is a lack of implementation of concrete plans and actions at the local, regional and national levels, which leaves the population to be much more vulnerable to the possibility of a disaster caused by tsunamis and associated hazards (Martinez & Toulkeridis, 2020).

In Panama, the organization in charge of receiving, analyzing and disseminating technical-scientific information related to tsunami warnings is the Institute of Geosciences (IGC) of the University of Panama, which is part of the Tsunami Warning System for the Caribbean and the Pacific. It is the national and international organization which provides scientific information in the areas of earth sciences to the Panamanian authorities, the National Civil Protection System (SINAPROC), and the public in general. The IGC, upon receiving the tsunami alert for Panama on January 15, 2022, announced that this phenomenon did not represent a threat to the Panamanian coasts and notified the SINAPROC, which is responsible organization, foe management and communications of specific actions related to the prevention of risks in the country (Gaceta Oficial de Panamá, 2005)

SINAPROC, through its official Twitter account - citing the IGC Panama as an official source - ruled out the tsunami threat to the Panamanian coasts from the eruption of the Hunga-Tonga-Hunga-Ha'apai submarine volcano. But they stressed out that they would remain in constant monitoring and vigilance in the face of any adverse phenomenon presented in the region (Twitter.com/Sinaproc Panama, 2022).

The national press, citing the IGC and SINAPROC as official sources, issued different communiqués informing the general population of the situation in Panama in the face of this possible threat. Newspapers such as La Estrella de Panamá published headlines ruling out the tsunami warning for Panama due to the eruption of an underwater volcano near Tonga Island (La Estrella, 2022). For its part, ECOTV Panama confirmed the same news (ECOTV Panama, 2022). Other media, both written and television, maintained constant communications to the population in the afternoon of January 15, 2022, among which stand out the Sigo de Panamá (El Siglo de Panamá, 2022), TVN-2.com (TVN Canal 2, 2022), critica.com (La Crítica Panamá, 2022) and Telemetro.com (Telemetro Panamá, 2022).

Fortunately, no injuries, fatalities or any damages were reported by any media. However, in the aftermath we may report that most of the people living, working and or staying at the coast, did not realize that there has been any threat by a tsunami, indicating that the official and mass media notices did not reach them at all.

3c. Colombia

A very strong earthquake on January, 31, 1906 along the Colombian-Ecuadorian border generated a tsunami which killed about 1,500 people (Pararas-Carayannis, G. 2012; Yamanaka et al., 2017; Pulido et al., 2020; Yamanaka & Tanioka, 2021). Subsequent tsunamis, as one in 1979 also killed many, especially in the southern part of the country (Herd et al., 1981; Kanamori & McNally, 1982; Adriano et al., 2017). The preparation of the public for such disasters was inadequate because of prevailing structural, political, social and economic conditions and reasons (Harden, 2007; Mas et al., 2017).

Recognizing this insufficiency, the National Tsunami Detection and Warning System – SNDAT, was formed as a subsidiary of the National Disaster Risk Management System, with the responsibility of detecting and evaluating events having tsunamigenic potential, as well as defining and disseminating tsunami warnings for the coasts of Colombia. This system is currently made up of four national institutions, these being the General Maritime

Directorate (DIMAR), the Colombian Geological Service (SGC), the Institute of Hydrology, Meteorology and Environmental Studies of Colombia (IDEAM), the National Unit for Risk Management of Disasters (UNGRD), with the collaboration of the Seismological and Geophysical Observatory of the Colombian Southwest (OSSO) Corporation.

Furthermore, in July 2018, the General Maritime Directorate, through Decree 1338, was designated by the National Government to fulfill the functions of Tsunami Warning Focal Point - TWFP and of the National Tsunami Warning Center - CNAT, in order to monitor and evaluate the possibility of tsunami generation by seismic events, as well as to receive and transmit relevant technical data to the International Tsunami Warning Centers and to the National Unit for Disaster Risk Management. Since 2012, the General Maritime Directorate - Dimar implemented the Tsunami Warning Center in the city of Bogotá, to act as the main center, given that the location of the CAT in Tumaco would prevent its normal operation in the event of a tsunami event that affects the Pacific coast of Colombia. At the same time, in December 2016, the first version of the National Tsunami Detection and Warning Protocol was signed, which would allow coordinating the actions of the National Tsunami Detection and Warning System - SNDAT, and provide the National Risk Management System of Disasters of an instrument to unify information and issue alerts for events having the potential to generate tsunamis in Colombia. The Protocol was updated in 2018, and again in April 2020 by the SNDAT.

UNGRD🇨🇴
@UNGRD

Luego de la erupción presentada en el volcán 🌋 submarino de #Tonga, la @Dimarcolombia se encuentra haciendo monitoreo a la costa pacífica colombiana. Se recomienda estar atentos ante cualquier anomalía y tomar acciones preventivas.

Sistema Nacional de Gestión
del Riesgo de Desastres

UNGRD🇨🇴
@UNGRD

Luego de la erupción presentada en el volcán 🌋 submarino de #Tonga, la @Dimarcolombia se encuentra haciendo monitoreo a la costa pacífica colombiana. Se recomienda estar atentos ante cualquier anomalía y tomar acciones preventivas.

6:51 p. m. · 15 ene. 2022 · Twitter for iPhone

Figure 9. Official tweet issued by the UNGRD in Colombia on the occasion of the tsunami caused by the eruption of the submarine volcano Hunga-Tonga volcano in the Tonga Islands on January 15, 2022 (Source: https://twitter.com/UNGRD)

However, in the case of Colombia, no emergency was declared on January 15, 2022 for a possible tsunami from the Tonga archipelago that would affect the populations located on the western coast of the national territory. Despite of the existence of a National Tsunami Detection and Warning System and the established protocol, the first official communications by DIMAR regarding the tsunami threat to Colombia after the volcanic eruption near the island of Tonga, first appeared at 7:31 p.m. on January 15, 2022. At that time, DIMAR announced the state of observations in the Pacific basin, through several short posts and through its social media accounts, in addition to a press release. Therefore, the only official reaction was presented by the National Unit for Risk Management of Colombia (UNGRD), which on the day of the tsunami at 6:51 p.m. local time, published on Twitter that the General Maritime Directorate (DIMAR) was monitoring possible effects on the Pacific coast of Colombia (Fig. 9 above). In this sense, the newspaper El Colombiano, reported that the Colombian authorities are evaluating whether there is a risk of a tsunami, and that "the eruption of the submarine volcano near Tonga, in the South Pacific, has Latin American countries Chile and Ecuador on alert after generating a tsunami" (DIMAR, 2022).

Other national media outlets, such as Caracol Radio (AFP), in a news item broadcast on their website on January 16, 2022 at 8:07 p.m. local time, did not report any alert situation for Colombia either. This media mentioned the following: "The Darwin Volcanic Ash Advisory monitoring center, located in Australia, reported this Sunday about a new large volcanic eruption that was detected near the island of Tonga. This occurs three days after another eruption that generated an increase in waves in the Pacific and a moderate tsunami in countries such as the United States, Chile, Peru and Ecuador. The Pacific Tsunami Warning Center (PTWC) also added that it detected large waves in the area and that these could be from another explosion of the Hunga-Tonga volcano".

In general terms, it was established that after the tsunami had been generated in the Pacific Ocean by the eruption of the Hunga-Tonga volcano, there was no damage on the Colombian coast, and there is no report on the community's reaction to possible effects caused for this event. It should be noted that the local tsunami modeling for Colombia, considering seismic scenarios such as those of the 1906 and 1979 earthquakes, and of other seismogenic zones along the Colombian Pacific coast, with maximum recorded seismic events, show flood sheets that do not exceed 5.0 meters in towns such as Buenaventura, Tumaco, Juanchaco, Curay and Salahonda (Caballero y Ortiz, 2002; Cardona *et al*., 2007; Restrepo y Otero, 2007; Dirección General Marítima, 2013; Ministerio de Defensa Nacional *et al*., 2014; Cocuñame y Salcedo-Hurtado, 2017).

Nonetheless, the reactions of citizens on twitter to the DIMAR press release criticized the delay (18 hours) in issuing a communication, and the discrepancy with the measures taken by countries such as Chile and Ecuador that did issue tsunami warnings several hours earlier. The Redacción CV Noticias was the only Colombian national press outlet that made the report that reached the general population, by literally reproducing the DIMAR press release at 7:41 p.m. on January 15, 2022, just ten minutes after the publication of the same (Redacción CV Noticias, 2022).

Later, at 11:32 pm on January 15, 2022, DIMAR announced the tsunami risk reduction by posting the following two messages on its social networks: "According to the monitoring of the tsunami wave generated by the eruption of the volcano in waters near the island of Tonga, we report that no significant changes have been recorded in the sea level stations in Colombia during the last few hours" ….“Reducing the probability of tsunami risk for the Pacific Coast of our country”. These posts again received criticism from several citizens who noted the changes and rises in sea level reported in other countries of the Pacific, and demanded that a tsunami alert should have been declared in Colombia out of institutional responsibility and duty to the population.

The next day, on January 16, 2022, the national press, through the SEMANA medium, published an article reporting the cancellation of tsunami alerts in three countries: Ecuador, Peru and Chile. However, this article did not mention the official communications by the Colombian government agencies in charge of tsunami detection and warning (La Semana, 2022). It should be noted that the UNGRD did not issue any press release on January 15, 2022 regarding the tsunami threat due to the volcanic eruption in Tonga and this, despite the fact that it did issue two separate press releases with the title "There is no tsunami warning for the Colombian Pacific Coast", both on January 6, 2022 after the earthquake of magnitude 6.2 59 km from Corinto, Nicaragua, and on January 28, 2022 after the earthquake of magnitude 6.0, 30 km from Panama.

3d. Ecuador

Ecuador has suffered the impact of a variety of tsunamis during the last recorded two centuries, including the tsunami generated by the 8.8 Mw earthquake of 1906 (Pararas-Carayannis & Zoll, 2017; Ioualalen et al., 2011; 2014; Heidarzadeh et al., 2017; Chunga et al., 2017; 2019; Aviles-Campoverde et al., 2021). Several studies have documented vulnerabilities, damages, and also made proposals for improvements in awareness, education, early warning systems, as well as in the use of seismic and tsunami resistant temporal shelters (Celorio-Saltos et al., 2018; Chunga, K. & Toulkeridis, T. (2014; Del-Pino-de-la-Cruz et al., 2021; Edler et al., 2020; Matheus-Medina et al., 2016; 2018; Mato, F. & Toulkeridis, T. (2017; Rodríguez et al., 2016; 2017; Suárez-Acosta et al., 2021; Toulkeridis et al., 2017a; 2017b; 2018; 2019a; 2019b; Yepez et al., 2020). Since 1972, Ecuador has a monitoring organization named Oceanographic Institute of the Ecuadorian Navy (INOCAR) for oceanic processes and hazards. Also since 2019, the National Risk and Emergency Management Service (SNGRE) was created as an administrative unit at the ministry level to guarantee the protection of people and communities from the negative effects of natural or man-made disasters - which replaced the now extinct National Service of Civil Defense of 2007.

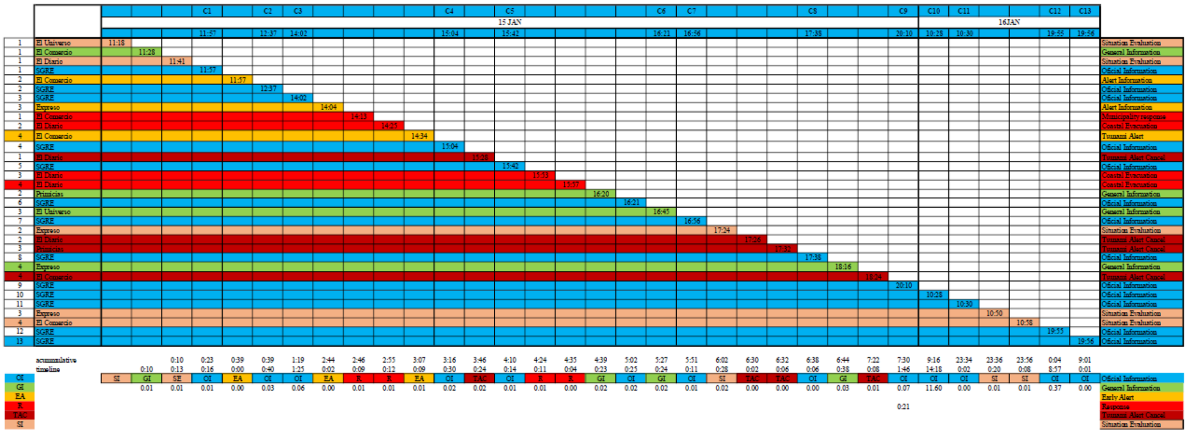
Immediately after the eruption/explosion of the Hunga Tonga-Hunga Ha'apai underwater volcano near Tonga, studies were initiated to review the situation in Ecuador, by studying and analyzing the information provided by the authorities, and anything else related that was published by different media reports or Internet sites. Also, the official information provided by INOCAR was communicated by the SGRE with thirteen consecutive statements beginning at 11:57 local time on the 15th of January 2022. The first statement informed the media (SNGRE, 2022a) that continuous monitoring of the Ecuadorian coast was being carried out.

Previously, there were three other media reports which provided general information regarding the activity of the underwater volcano. At that time there was no information about a possible tsunami. However, people residing or staying near Ecuadorian beaches reported receiving such information via Whatsapp^{TM} or other personal exchange of messages, starting long before midday (around 11.00) local time, prior to official notifications.

At 12:37 local time - 39 minutes later - a second statement was issued, reporting that authorities were still under continuous monitoring of the volcanically-generated tsunami, and recommended the suspension of maritime and recreational activities on the island coastal zone regions until 3:00 p.m., and until 5:00 p.m. on continental Ecuador. At 14:02, - after 1-hour 39 minutes - a third statement was issued suggesting suspension of maritime and recreational activities on the coasts of the island regions. After this early official warning, the media also begun warning and alerting the public. The first response was the evacuation of bathers from the beaches of Crucita, La Boca, Pueto Cayo and elsewhere.

A fourth official statement at 15:04, - after 3 hours and 16 minutes - activated sirens in tsunami warning mode for Puerto Ayora in the Galápagos islands. This statement was communicated by the media at 15:28. Then, a fifth statement at 15:42 informed that the monitoring continued, but the sixth statement at 16:21, after 5 hours and 2 minutes, the tsunami warning for Puerto Ayora was canceled.

A seventh statement at 16:56, 5 hours, 51 minutes later, was of a tsunami warning for the country's mainland coast. At 17:24, after 6 hour 02 minutes, the media issued statements that the tsunami warning was cancelled. Subsequently, at 17:38, after 6 hour 38 minutes, there was also an official announcement of the tsunami warning cancellation. Afterwards the media provided general information about the cancellation of the warning, and provided information that in La Libertad (Santa Elena), Manta (Manabí), Esmeraldas, and Bahía Academia (Galapagos) sea level disturbances of 50 centimeters were evident (SNGRE, 2022b).



							accumulative timeline				
	15 JAN		1	El Universo	11:18	Situation Evaluation			SI		
			1	El Comercio	11:28	General Information		0:10	GI	0.01	
			1	El Diario	11:41	Situation Evaluation	0:10	0:13	SE	0.01	
C1		11:57	1	SGRE	11:57	Oficial Information	0:23	0:16	OI	0.01	
			2	El Comercio	11:57	Alert Information	0:39	0:00	EA	0.00	
C2		12:37	2	SGRE	12:37	Oficial Information	0:39	0:40	OI	0.03	
C3		14:02	3	SGRE	14:02	Oficial Information	1:19	1:25	OI	0.06	
			3	Expreso	14:04	Alert Information	2:44	0:02	EA	0.00	
			1	El Comercio	14:13	Municipality response	2:46	0:09	R	0.01	
			2	El Diario	14:25	Coastal Evacuation	2:55	0:12	R	0.01	
			4	El Comercio	14:34	Tsunami Alert	3:07	0:09	EA	0.01	
C4		15:04	4	SGRE	15:04	Oficial Information	3:16	0:30	OI	0.02	
			1	El Diario	15:28	Tsunami Alert Cancel	3:46	0:24	TAC	0.02	
C5		15:42	5	SGRE	15:42	Oficial Information	4:10	0:14	OI	0.01	
			3	El Diario	15:53	Coastal Evacuation	4:24	0:11	R	0.01	
			4	El Diario	15:57	Coastal Evacuation	4:35	0:04	R	0.00	
			2	Primicias	16:20	General Information	4:39	0:23	GI	0.02	
			6	SGRE	16:21	Oficial Information	5:02	0:25	OI	0.02	
C6		16:21	3	El Universo	16:45	General Information	5:27	0:24	GI	0.02	
C7		16:56	7	SGRE	16:56	Oficial Information	5:51	0:11	OI	0.01	
			2	Expreso	17:24	Situation Evaluation	6:02	0:28	SI	0.02	
			2	El Diario	17:26	Tsunami Alert Cancel	6:30	0:02	TAC	0.00	
			3	Primicias	17:32	Tsunami Alert Cancel	6:32	0:06	TAC	0.00	
C8		17:38	8	SGRE	17:38	Oficial Information	6:38	0:06	OI	0.00	
			4	Expreso	18:16	General Information	6:44	0:38	GI	0.03	
			4	El Comercio	18:24	Tsunami Alert Cancel	7:22	0:08	TAC	0.01	
C9		20:10	9	SGRE	20:10	Oficial Information	7:30	1:46	OI	0.07	0:21
C10	16JAN	10:28	10	SGRE	10:28	Oficial Information	9:16	14:18	OI	11.60	
C11		10:30	11	SGRE	10:30	Oficial Information	23:34	0:02	OI	0.00	
			3	Expreso	10:50	Situation Evaluation	23:36	0:20	SI	0.01	
			4	El Comercio	10:58	Situation Evaluation	23:56	0:08	SI	0.01	
C12		19:55	12	SGRE	19:55	Oficial Information	0:04	8:57	OI	0.37	
C13		19:56	13	SGRE	19:56	Oficial Information	9:01	0:01	OI	0.00	

OI	Oficial Information
GI	General Information
EA	Early Alert
R	Response
TAC	Tsunami Alert Cancel
SI	Situation Evaluation

Figure 10. Timeline of transmission of information about the eruption in Tonga and consequences in Ecuador by the official institutions and national mass media.

The ninth official statement at 20:10 - after 7 hours 30 minutes - reported that the authorities were continuing to monitor the impact of the tsunami, while a tenth statement at 10:28, and an eleventh statement - after 9 hours 16 minutes and 23 hours 36 minutes -

recommended maintainance of caution in the execution of productive and recreational activities on the continental and insular coastal zones. Subsequently, the media followed with a commentary and evaluation of the situation.

A twelfth statement issued at 19:55 - after 1 day and 4 minutes - reported that authorities were still monitoring the event. However, a thirteenth statement at 19:56 - after 1 day 5 minutes – reported that the tsunami observation status was cancelled for the country's mainland and island coasts. In conclusion, the official information delivered with the 13 statements, combined with the information provided by the media, was provided every 21 minutes (Fig. 10 above).

In the Galapagos Islands, and as demonstrated by a variety of circulating videos, local fisherman and other boat-owners challenged or ignored the potential tsunami hazard of which they had been warned. Some of the smaller boats collided with each other while other boats tried to withstand with difficulty the power of the tsunami-generated sea currents. Locals in the area reported that there was unusual and repetitive tsunami wave activity that lasted for about two hours. Shown by many other circulating videos from a variety of touristic beaches in continental Ecuador, several vehicles of firefighters and policemen were patrolling along the coastlines warning people of the potential impact of a tsunami, at the expected time of the waves's arrival. However, tourists and locals alike ignored all warnings and stayed as close as possible to the beaches in order to film and photograph the incoming tsunami waves. Later, long after the arrival of the tsunami in many places in Ecuador, it appears that the sirens had scared the public and occasionally had let some to panicking. Such, but more severe reactions of the public in Ecuador, occurred with the earthquake and tsunami of 2016 (Mato and Toulkeridis, 2018; Toulkeridis et al., 2018).

3e. Peru

Peru is a country with a long shoreline, which has been struck frequently by tsunamis (Pelayo & Wiens, 1990; Bourgeois et l., 1999; Kulikov et al., 2005; Okal et al., 2006; Fritz et al., 2008; Omira et al., 2017). Awareness, preparedness, prevention and mitigation studies are advanced for this country, in order to reduce the vulnerability of tsunami impacts (Hébert et al., 2009; Yamazaki, et al., 2010; 2013; Mas et al., 2013; 2015).

The volcanic eruption of the Hunga Tonga-Hunga Ha'apai on 15 January 2022 near the island of Tonga in the Pacific Ocean, generated fear on the coast of Lima, where a false tsunami alarm was disseminated about abnormal waves on the coasts of the country. Initially the Peruvian Navy ruled out that a tsunami would strike, but later municipal officials intervened to evacuate people from coastal areas before the arrival of a possible tsunami. Soon thereafter, a local television station reported that dozens of tourists in the Lima district of Chorrillos evacuated, after receiving an alert from the Control Center of the Metropolitan Municipality of Lima (El Comercio, 2022). Also, the Directorate of Hydrography and Navigation of the Peruvian Navy indicated "a possible arrival of anomalous waves" to the Peruvian coast, generated by the eruption of the volcano near Tonga (El Pais, 2022).

At Pisco, in the southern region of Ica, the RPP News station reported unusual wave inundation, and that 38 stores located at the Chaco beach were affected by seawater entering restaurants and causing material damage (RPP Noticias, 2022). Other social media networks reported alterations in sea level at the Ancón resort north of Lima, and at Punta Negra, in the south of the Peruvian capital. The ASISMED - collectively made up of a team of specialists - indicated that a maximum wave height of 68 centimeters was recorded in the port of Callao, while in Marcona it reached 72 centimeters, and in Paita 65 centimeters. The National Institute of Civil Defense (INDECI) confirmed the presence of abnormal waves near the beaches (Prensa Libre, 2022).

The Navy, through the Directorate of Hydrography and Navigation, reported "constant monitoring" of sea levels after the volcanic eruption in Tonga, first on Twitter, stating that "the volcanic eruption in Nukualofa - Tonga, “DOES NOT GENERATE A TSUNAMI ON THE PERUVIAN COAST”, and for all to “remain calm” (Marina de Guerra, 2022). However, during the night of that same date, dozens of national police agents (PNP) and crews of municipal workers from Paracas, began the construction of sand dykes along the Paracas bay, to contain the advance of waves.

The contradictory communications raised questions for the Government of Peru to explain the reason for the delay in issuing a tsunami warning that left two dead, since the Navy's warning of "anomalous waves" as a result of the eruption of the volcano in Tonga came late, unlike the warnings and evacuations in Chile and Ecuador.

Subsequently, the Peruvian Prime Minister, Mirtha Vásquez, requested a report from the Navy on the technical criteria for the issuance of a tsunami alert, after they had notified late on Saturday of “anomalous waves” from the eruption of a volcano in Tonga and hours later, two women drowned inside a van that was swept away by the tsunami waves near the shore of Naylamp beach (El Pais, 2022).

The INDECI indicated that there were also alerts for strong waves in other areas of the country, such as the coast of the Department of Ica, the sout-central part of the nation, although without registering victims. INDECI itself also communicated through its account on the social network Twitter that "in the event of abnormal waves in different areas of the Peruvian coast, sports and recreational activities should be avoided during the wave period, as well as camps near beach areas”. They also reported that there was no damage in Paracas, Ica, due to the rise in sea level, however there was evidence of flooding and damage in 38 commercial premises, according to Mayor Juan Mendoza to the Radio Programas del Perú radio station (INDECI, 2022). Meanwhile, the PNP reported on Twitter that its troops "rescued 23 people after the first reports of abnormal waves on the Peruvian coast," without specifying under what circumstances or conditions (Swissinfo, 2022).

On the same day, the Peruvian Government announced that it had closed preventively 22 ports on the north and central Pacific coasts of the country because "anomalous waves" were expected from the eruption of the Hunga Tonga-Hunga Ha'apai volcano in Tonga. Also on the same day, there was a report that exceptional waves, mainly on the southern coast of the country, caused slight flooding in some coastal towns, and that more than 20 people had been rescued and that two women lost their lives at Naylamp beach of the Lambayeque region of the Peruvian north coast, where 2.5 meter high tsunami waves struck. The authorities added that the beach area was already declared "not suitable for bathers." (TelesurTV, 2022).

INDECI decreed on Monday the 17th the closure of 80 ports on the Peruvian coast, after registering disturbances higher than usual waves, as a consequence of the volcanic eruption of January 15, near Nukualofa, Tonga. Some of the temporarily closed port points were, in the ports of Pizarro, Zorritos, Paita, and Pimentel on the north coast; the ports of Chimbote, Casma, Huarmey, Chicoon along the central coast; and Puerto Viejo, Planchada, Quilca, and El Faro in the south (El Universo, 2022). The Peruvian Navy notified the suspension of fishing, sports and recreational activities near the sea.

The tsunami from Tonga caused an oil spill that affected two natural parks in Peru, for which the Government requested technical support from the United Nations to assess the impact and response measures spilled (NBCNEWS, 2022).

The Civil Defense indicated that the spill was controlled, and there was ongoing cleaning of the coast, in conjunction with the La Pampilla refinery off the Pacific coast of Peru, managed by Repsol, and by the ship “Mare Doricum”. Therefore, the authorities closed the recreational facilities near the spill to protect the tourists. The Environmental Prosecutor's Office indicated that a dense oil stain was observed on the beach of Ventanilla, located on the coast of the Peruvian capital (Voz de América, 2022).

3f. Chile

Chile has the longest shoreline of all Pacific countries and represents therefore the most frequented impacted coast by tsunamis in the recorded past (Lomnitz, 2004; Yamazaki & Cheung, 2011; An et al., 2014; Carvajal et al., 2017; DePaolis et al., 2021). The strongest ever-recorded earthquake with Moment magnitude Mw 9.5 occurred in Chile and generated a tsunami, which resulted in many deaths on both sides of the Pacific Ocean (Plafker & Savage, 1970; Liu et al., 1995; Cisternas et al., 2005). Nonetheless, Chile has a very advanced system of preparedness and mitigation (Atwater et al., 1999; Esteban et al., 2013; León & March, 2014; Catalan et al., 2020). Therefore, both the Hydrographic and Oceanographic Service of the Chilean Navy (SHOA) and the National Emergency Office of the Ministry of the Interior and Public Security (ONEMI), responded effectively to the tsunami advisory/warning issued by the Pacific Tsunami Warning Center (PTWC) at 01:27 (local time in Chile) on Saturday, on 15 January 2022 of a volcanic eruption of the Hunga Tonga-Hunga Ha'apai volcano 73 kilometers north of Nukuʻalofa, in Tonga

Given this information, and in accordance with the ONEMI – SHOA protocol, a State of Alert was declared in Chile for the regions of Coquimbo, Tarapacá, Atacama, Arica, Parinacota, Los Ríos and Los Lagos, and an Advisory of Precaution for the regions of Maule, Ñuble, Antofagasta, O'Higgins, Biobío Valparaíso and La Araucanía, adding also the Antarctic and the insular territory (ONEMI, 2022a). A forecasted tsunami height was that tsunami waves of one to two meters could be expectedto be above one and below two meters.

For its part, ONEMI declared a Red Alert for the coastal districts of the Arica and Parinacota, Tarapacá, Atacama, Coquimbo, Los Ríos and Los Lagos regions, and issued messages from the platform of the Emergency Alert System (SAE), addressing the communities of the coastline and island territories of the aforementioned regions (ONEMI, 2022a). Additionally, ONEMI quickly disseminated the information through social media networks (such as Twitter https://twitter.com/onemichile/with_replies), at 08:39 on January 15, 2022, reporting on a State of Precaution decreed by SHOA (Fig. 11).

onemichile
@onemichile

SHOA establece Estado de Precaución para Archipiélago Juan Fernández, Isla San Félix, Isla de Pascua y Antártica Chilena por erupción volcán en Toga. Más info. snamchile.cl

8:39 a. m. · 15 ene. 2022

Figure 11. Tweet sent by ONEMI on state of caution.

Figure 12. Recession of the sea on the coast of Coquimbo in Chile (La Cuarta, 2022b).

In turn, throughout the day, the main press media in Chile, reported on the decisions being taken about the event prior to its impact in Chile, and informed the public to evacuate the beaches of Easter Island due to a "minor tsunami" (El Mercurio, 2022a; La Cuarta, 2022a). Furthermore, in its official Twitter account the Geoscientific Network of Chile, indicated that the tsunami had reached Rapa Nui, that the island's tide gauge had registered up to 30 cm in height, and also estimated that waves would reach Easter Island at 10:43, at 08:43 a.m. the continental and insular-western Chile, respectively, the Juan Fernández at 2:12 p.m., the Antarctic Base Prat at 2:26 p.m., San Félix at 2:38 p.m., and the Antarctic Base O'Higgins at 2:56 p.m. (El Mercurio, 3:01 p.m.) (El Mercurio, 2022b). Later in the afternoon, the Chilean Geoscientific Network disseminated the first images of the recession of the sea on Chilean beaches (Fig. 12), and of what was happening in other coastal regions of the country (La Cuarta, 2022b). Finally, on the night of 15 January 2022, ONEMI summarized what was happening and indicated that there were minor flooding in several coastal areas - such as Iquique - and reiterated the advisory for the public to move to safe areas (La Cuarta, 2022c).

In the early hours of January 16, 2022 (00:07 local time), SHOA, through Bulletins No. 26 and 27, reported that the threat levels had decreased for the coastal communities of Arica, Parinacota and Atacama, canceling the tsunami red alert, although a State of Precaution was maintained for coastal regions of Arica, Parinacota, Tarapacá, Antofagasta, Atacama, Coquimbo, Valparaíso, O'Higgins, Maule, Ñuble, Biobío, La Araucanía, Los Ríos and Los Lagos, adding also the insular territory (Fig. 12; ONEMI, 2022b). Already on 17 January, SHOA asserted that this volcanic eruption was an unprecedented event, since it was the first time that such an event generated a tsunami alert in the entire territory of Chile (El Mercurio, 2022c). During the alert period (January 15 and 16, 2022), no victims were registered, since all inhabitants evacuated the threatened areas on time, according to local media reports (La Cuarta, 2022d), and unlike Peru where two people died, and the three f victims in the Tonga region.

4. CONCLUSIONS

Tsunamis generated by volcanic activity are not frequent as by earthquake related events. However, the same amount of attention must be given to volcanically-generated tsunamis in order to forecast potential impacts on shorelines in the Pacific and elsewhere.

The Hunga Tonga-Hunga Ha'apai submarine eruption triggered a tsunami, which had most likely a complex interaction of factors responsible for its development and propagation.

Authorities along the southeastern side of the Pacific Ocean, between Costa Rica and Chile, reacted differently to the announcement of a potential tsunami impact on their shorelines. It is unclear yet, why Colombia and Peru did not issue any warning to the public, although both countries have sophisticated institutional mechanisms and had sufficient time to react and warn.

Therefore, it is certain that alerts and early warning systems need to be re-evaluated and re-adjusted in different degrees per country along the Pacific and Latin America in particular, based on what occurred on 15 January 2022, following the eruption of the Hunga Tonga-Hunga Ha'apai submarine volcano.

REFERENCES

Adriano, B., Arcila, M., Sanchez, R., Mas, E., Koshimura, S., Arreaga, P., & Pulido, N. (2017). Estimation of the tsunami source of the 1979 Great Tumaco earthquake using tsunami numerical modeling. In *Proceedings of the 16th World Conference on Earthquake, 16WCEE* (Vol. 2017).

Allen, R. M., & Melgar, D. (2019). Earthquake early warning: Advances, scientific challenges, and societal needs. *Annual Review of Earth and Planetary Sciences*, *47*, 361-388.

An, C., Sepúlveda, I., & Liu, P. L. F. (2014). Tsunami source and its validation of the 2014 Iquique, Chile, earthquake. *Geophysical Research Letters*, *41*(11), 3988-3994.

Anderson, W. A. (1969). Disaster warning and communication processes in two communities. *Journal of Communication*, *19*(2), 92-104.

Angove, M., Arcas, D., Bailey, R., Carrasco, P., Coetzee, D., Fry, B., ... & Schindelé, F. (2019). Ocean observations required to minimize uncertainty in global tsunami forecasts, warnings, and emergency response. *Frontiers in Marine Science*, 350.

Annaka, T., Satake, K., Sakakiyama, T., Yanagisawa, K., & Shuto, N. (2007). Logic-tree approach for probabilistic tsunami hazard analysis and its applications to the Japanese coasts. In *Tsunami and its hazards in the Indian and Pacific Oceans* (pp. 577-592). Birkhäuser Basel.

Atwater, B. F., VEGA, M. A. C., Bourgeois, J., Dudley, W. C., Hendley, J. W., & Stauffer, P. H. (1999). Surviving a Tsunami-Lessons from Chile, Hawaii, and Japan. *US Geological Survey Circular*, (1187), 1-19.

Aviles-Campoverde, D., Chunga, K., Ortiz-Hernández, E., Vivas-Espinoza, E., Toulkeridis, T., Morales-Delgado, A., & Delgado-Toala, D. (2021). Seismically induced soil liquefaction and geological conditions in the city of Jama due to the Mw7.8 Pedernales earthquake in 2016, NW Ecuador. Geosciences, 11, 20

Bardet, J. P., Synolakis, C. E., Davies, H. L., Imamura, F., & Okal, E. A. (2003). Landslide tsunamis: Recent findings and research directions. *Landslide tsunamis: recent findings and research directions*, 1793-1809.

BBC (2022). Tonga eruption: How its impact spread so widely and violently. https://www.bbc.com/news/world-australia-60027360

Bernard, E. N., Mofjeld, H. O., Titov, V., Synolakis, C. E., & González, F. I. (2006). Tsunami: scientific frontiers, mitigation, forecasting and policy implications. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *364*(1845), 1989-2007.

Bondevik, S., Svendsen, J. I., & Mangerud, J. (1998). Distinction between the Storegga tsunami and the Holocene marine transgression in coastal basin deposits of western Norway. *Journal of Quaternary Science: Published for the Quaternary Research Association*, *13*(6), 529-537.

Borrero, J. C., Solihuddin, T., Fritz, H. M., Lynett, P. J., Prasetya, G. S., Skanavis, V., ... & Synolakis, C. E. (2020). Field survey and numerical modelling of the December 22, 2018 Anak Krakatau tsunami. *Pure and Applied Geophysics*, *177*(6), 2457-2475.

Bourgeois, J. (1994). Tsunami deposits and the KT boundary: A sedimentologist's perspective. In *New Developments Regarding the KT Event and Other Catastrophes in Earth History* (Vol. 825, p. 16).

Bourgeois, J., Petroff, C., Yeh, H., Titov, V., Synolakis, C. E., Benson, B., ... & Norabuena, E. (1999). Geologie setting, field survey and modeling of the Chimbote, Northern Peru, Tsunami of 21 February 1996. In *Seismogenic and tsunamigenic processes in shallow subduction zones* (pp. 513-540). Birkhäuser, Basel.

Brenna, M., Cronin, S., Smith, I., Pontesilli, A., Tost, M., Barker, S., & Tongaonevai, S. (2022). Post-caldera volcanism reveals shallow priming of an intra-ocean arc andesitic caldera: Hunga volcano, Tonga, SW Pacific. Lithos, in press

Carvajal, M., Araya‐Cornejo, C., Sepúlveda, I., Melnick, D., & Haase, J. S. (2019). Nearly instantaneous tsunamis following the Mw 7.5 2018 Palu earthquake. *Geophysical Research Letters*, *46*(10), 5117-5126.

Carvajal, M., Cisternas, M., & Catalán, P. A. (2017). Source of the 1730 Chilean earthquake from historical records: Implications for the future tsunami hazard on the coast of Metropolitan Chile. *Journal of Geophysical Research: Solid Earth*, *122*(5), 3648-3660.

Catalan, P. A., Gubler, A., Cañas, J., Zuñiga, C., Zelaya, C., Pizarro, L., ... & Cienfuegos, R. (2020). Design and operational implementation of the integrated tsunami forecast and warning system in Chile (SIPAT). *Coastal Engineering Journal*, *62*(3), 373-388.

Celorio-Saltos, J.C., García-Arias, J.M., Guerra-Luque, A.B., Barragan-Aroca, G., & Toulkeridis, T. (2018). Vulnerability analysis based on tsunami hazards in Crucita, central coastal of Ecuador. Science of Tsunami Hazards, 38(3): 225-263.

Chacón-Barrantes, S. E., & Protti, M. (2011). Modeling a tsunami from the Nicoya, Costa Rica, seismic gap and its potential impact in Puntarenas. Journal of South American Earth Sciences, 31(4), 372-382.

Chacon-Barrantes, S., & Arozarena-Llopis, I. (2021). A first estimation of tsunami hazard of the Pacific coast of Costa Rica from local and distant seismogenic sources. Ocean Dynamics, 71(8), 793-810.

Chacón-Barrantes, S., & Zamora, N. (2017). Numerical Simulations of the 1991 Limón Tsunami, Costa Rica Caribbean Coast. Pure and Applied Geophysics, 174(8), 2945-2959.

Chian, S. C., Wilkinson, S. M., Whittle, J. K., Mulyani, R., Alarcon, J. E., Pomonis, A., ... & Lopez, J. (2019). Lessons Learnt From the 2009 Padang Indonesia, 2011 Tōhoku Japan and 2016 Muisne Ecuador Earthquakes. *Frontiers in Built Environment*, *5*, 73.

Choi, B. H., Pelinovsky, E., Kim, K. O., & Lee, J. S. (2003). Simulation of the trans-oceanic tsunami propagation due to the 1883 Krakatau volcanic eruption. *Natural Hazards and Earth System Sciences*, *3*(5), 321-332.

Chunga, K. & Toulkeridis, T. (2014). First evidence of paleo-tsunami deposits of a major historic event in Ecuador. Science of tsunami hazards, 33: 55-69.

Chunga, K., Mulas, M., Alvarez, A., Galarza, J., & Toulkeridis, T. (2019a): Characterization of seismogenetic crustal faults in the Gulf of Guayaquil, Ecuador. Andean Geology, 46(1): 66-81.

Chunga, K., Toulkeridis, T., Vera-Grunauer, X., Gutierrez, M., Cahuana, N., & Alvarez, A. (2017). A review of earthquakes and tsunami records and characterization of capable faults on the northwestern coast of Ecuador. Science of tsunami hazards, 36: 100-127.

Cisternas, M., Atwater, B. F., Torrejón, F., Sawai, Y., Machuca, G., Lagos, M., ... & Husni, M. (2005). Predecessors of the giant 1960 Chile earthquake. *Nature*, *437*(7057), 404-407.

Cita, M. B., & Aloisi, G. (2000). Deep-sea tsunami deposits triggered by the explosion of Santorini (3500 y BP), eastern Mediterranean. *Sedimentary Geology*, *135*(1-4), 181-203.

Colombier, M., Scheu, B., Wadsworth, F. B., Cronin, S., Vasseur, J., Dobson, K. J., ... & Dingwell, D. B. (2018). Vesiculation and Quenching During Surtseyan Eruptions at Hunga Tonga‐Hunga Ha'apai Volcano, Tonga. *Journal of Geophysical Research: Solid Earth*, *123*(5), 3762-3779.

Davis, I., & Izadkhah, Y. O. (2008). Tsunami early warning system (EWS) and its integration within the chain of seismic safety. *Disaster Prevention and Management: An International Journal*.

De Ronde, C. E. J., Baker, E. T., Massoth, G. J., Lupton, J. E., Wright, I. C., Sparks, R. J., ... & Lebon, G. T. (2007). Submarine hydrothermal activity along the mid‐Kermadec Arc, New Zealand: Large‐scale effects on venting. *Geochemistry, Geophysics, Geosystems*, *8*(7).

Del-Pino-de-la-Cruz, C.E., Martinez-Molina, B.D., Haro-Baez, A.G., Toulkeridis, T. and Rentería, W. (2021). The proposed design of a smart parking area as a multiple use building for the eventual vertical evacuation in case of tsunami impacts in Salinas, Ecuador. Science of Tsunami Hazards, 40(3), 146-165

DePaolis, J. M., Dura, T., MacInnes, B., Ely, L. L., Cisternas, M., Carvajal, M., ... & Weiss, R. (2021). Stratigraphic evidence of two historical tsunamis on the semi-arid coast of north-central Chile. *Quaternary Science Reviews*, *266*, 107052.

DIMAR (2022). Comunicado de prensa. https://www.dimar.mil.co/comunicado-de-prensa-102

Driessen, J. (2019). The Santorini eruption. An archaeological investigation of its distal impacts on Minoan Crete. *Quat. Int*, *499*, 195-204.

Dunbar, P., & McCullough, H. (2012). Global tsunami deposits database. *Natural hazards*, *63*(1), 267-278.

ECOTV Panama (2022). Sinaproc confirma que no hay alertas de tsunami para Panamá. https://www.ecotvpanama.com/nacionales/sinaproc-confirma-que-no-hay-alertas-tsunami-panama-n5645770

Edler, D., Otto, K.H., & Toulkeridis, T. (2020). Tsunami hazards in Ecuador – Regional differences in the knowledge of Ecuadorian high-school students. Science of Tsunami Hazards, 39(2), 86-112.

El Comercio (2022). Oleajes anómalos en el litoral de Perú por erupción en Tonga. https://www.elcomercio.com/actualidad/mundo/oleajes-anomalos-peru-erupcion-tonga.html

El Mercurio (2022a). *"Características sin precedentes": El análisis del jefe del SHOA a la emergencia del fin de semana en las costas chilenas*. https://www.emol.com/noticias/Nacional/2022/01/17/1044186/analisis-jefe-del-shoa.html

El Mercurio (2022b). *Detallan que "tsunami que afecta a Rapa Nui llega hasta los 30 centímetros de altura" y SHOA informa horarios de arribo de olas*. https://www.emol.com/noticias/Nacional/2022/01/15/1044088/onemi-previene-tsunami-menor-chile.html

El Mercurio (2022c). *Onemi pide abandonar zona de playa en Isla de Pascua por "tsunami menor" tras erupción de volcán en Tonga*. https://www.emol.com/noticias/Nacional/2022/01/15/1044084/onemi-pide-abandonar-playa-pascua.html

El Pais (2022a). El Gobierno de Perú pide explicaciones por la alerta tardía de tsunami que dejó dos muertos. https://elpais.com/internacional/2022-01-17/el-gobierno-de-peru-pide-explicaciones-por-la-alerta-tardia-de-tsunami-que-dejo-dos-muertos.html

El Siglo de Panamá (2022). Erupción de volcán en Tonga no ha generado amenaza en costas panameñas. http://elsiglo.com.pa/panama/erupcion-volcan-tonga-generado-amenaza-costas-panamenas/24191822

El Universo (2022). Perú registró oleajes anómalos e inundaciones leves tras erupción volcánica en Tonga. https://www.eluniverso.com/noticias/internacional/peru-registro-oleajes-anomalos-e-inundaciones-leves-tras-erupcion-volcanica-en-tonga-nota/

Esteban, M., Thao, N. D., Takagi, H., Tsimopoulou, V., Mikami, T., Yun, N. Y., & Suppasri, A. (2015). The emergence of global tsunami awareness: Analysis of disaster preparedness in Chile, Indonesia, Japan, and Vietnam. In *Handbook of coastal disaster mitigation for engineers and planners* (pp. 205-233). Butterworth-Heinemann.

Esteban, M., Thao, N. D., Takagi, H., Valenzuela, P., Tam, T. T., Trang, D. D. T., & Anh, L. T. (2014). Storm surge and Tsunami awareness and preparedness in Central Vietnam. In *Coastal disasters and climate change in Vietnam* (pp. 321-336). Elsevier.

Esteban, M., Tsimopoulou, V., Mikami, T., Yun, N. Y., Suppasri, A., & Shibayama, T. (2013). Recent tsunamis events and preparedness: Development of tsunami awareness in Indonesia, Chile and Japan. *International Journal of Disaster Risk Reduction*, *5*, 84-97.

Farías, I. (2014). Misrecognizing tsunamis: ontological politics and cosmopolitical challenges in early warning systems. *The Sociological Review*, *62*, 61-87.

Fernandez, M., Molina, E., Havskov, J., & Atakan, K. (2000). Tsunamis and tsunami hazards in Central America. Natural Hazards, 22(2), 91-116.

Flanders Marine Institute (VLIZ), Belgium, and Intergovernmental Oceanographic Comission-UNESCO, France (2021). “Sea Level Station Monitoring Facility.” VLIZ. https://doi.org/10.14284/482.

Fritz, H. M., Kalligeris, N., Borrero, J. C., Broncano, P., & Ortega, E. (2008). The 15 August 2007 Peru tsunami runup observations and modeling. *Geophysical Research Letters*, *35*(10).

Fukao, Y. (1979). Tsunami earthquakes and subduction processes near deep‐sea trenches. *Journal of Geophysical Research: Solid Earth*, *84*(B5), 2303-2314.

Gaceta oficial No. 25236 (2005). QUE REORGANIZA EL SISTEMA NACIONAL DE PROTECCION CIVIL. LEGISLACIÓN DE LA REPÚBLICA DE PANAMÁ, 16pp

Gardner-Stephen, P., Wallace, A., Hawtin, K., Al-Nuaimi, G., Tran, A., Le Mozo, T., & Lloyd, M. (2019, October). Reducing cost while increasing the resilience & effectiveness of tsunami early warning systems. In *2019 IEEE Global Humanitarian Technology Conference (GHTC)* (pp. 1-8). IEEE.

Garvin, J. B., Slayback, D. A., Ferrini, V., Frawley, J., Giguere, C., Asrar, G. R., & Andersen, K. (2018). Monitoring and modeling the rapid evolution of earth's newest volcanic island: Hunga Tonga Hunga Ha'apai (Tonga) using high spatial resolution satellite observations. *Geophysical research letters*, *45*(8), 3445-3452.

Global Volcanism Program (2009). Report on Hunga Tonga-Hunga Ha´apai (Tonga). In: Sennert, S.K. (ed.), Weekly Volcanic Activity Report, 18 March-24 March 2009. Smithsonian Institution and US Geological Survey

Global Volcanism Program (2014). Report on Hunga Tonga-Hunga Ha´apai (Tonga). In: Sennert, S.K. (ed.), Weekly Volcanic Activity Report, 24 December-30 December 2014. Smithsonian Institution and US Geological Survey

Global Volcanism Program (2015). Report on Hunga Tonga-Hunga Ha´apai (Tonga). In: Sennert, S.K. (ed.), Weekly Volcanic Activity Report, 21 January-27 January 2015. Smithsonian Institution and US Geological Survey

Global Volcanism Program (2021a). Report on Hunga Tonga-Hunga Ha´apai (Tonga). In: Sennert, S.K. (ed.), Weekly Volcanic Activity Report, 15 December-21 December 2021. Smithsonian Institution and US Geological Survey

Global Volcanism Program (2021b). Report on Hunga Tonga-Hunga Ha´apai (Tonga). In: Sennert, S.K. (ed.), Weekly Volcanic Activity Report, 22 December-28 December 2021. Smithsonian Institution and US Geological Survey

Global Volcanism Program (2021c). Report on Hunga Tonga-Hunga Ha´apai (Tonga). In: Sennert, S.K. (ed.), Weekly Volcanic Activity Report, 29 December-4 January 2022. Smithsonian Institution and US Geological Survey

Global Volcanism Program (2022). Report on Hunga Tonga-Hunga Ha´apai (Tonga). In: Sennert, S.K. (ed.), Weekly Volcanic Activity Report, 12 January-18 January 2022. Smithsonian Institution and US Geological Survey

Goff, J., Terry, J. P., Chagué-Goff, C., & Goto, K. (2014). What is a mega-tsunami?. *Marine Geology*, *358*, 12-17.

Gregg, C. E., Houghton, B. F., Paton, D., Lachman, R., Lachman, J., Johnston, D. M., & Wongbusarakum, S. (2006). Natural warning signs of tsunamis: human sensory experience and response to the 2004 great Sumatra earthquake and tsunami in Thailand. *Earthquake Spectra*, *22*(3_suppl), 671-691.

Grilli, S. T., Harris, J. C., Tajalli Bakhsh, T. S., Masterlark, T. L., Kyriakopoulos, C., Kirby, J. T., & Shi, F. (2013). Numerical simulation of the 2011 Tohoku tsunami based on a new transient FEM co-seismic source: Comparison to far-and near-field observations. *Pure and Applied Geophysics*, *170*(6), 1333-1359.

Gusiakov, V. K. (2005). Tsunami generation potential of different tsunamigenic regions in the Pacific. *Marine Geology*, *215*(1-2), 3-9.

Hall, R., & Spakman, W. (2002). Subducted slabs beneath the eastern Indonesia–Tonga region: insights from tomography. *Earth and Planetary Science Letters*, *201*(2), 321-336.

Harden, C. (2007). Desastres de Origen Natural en Colombia 1979–2004. *Mountain Research and Development*, *27*(4), 380-381.

Hébert, H., Reymond, D., Krien, Y., Vergoz, J., Schindelé, F., Roger, J., & Loevenbruck, A. (2009). The 15 August 2007 Peru earthquake and tsunami: Influence of the source characteristics on the tsunami heights. In *Tsunami Science Four Years after the 2004 Indian Ocean Tsunami* (pp. 211-232). Birkhäuser Basel.

Heidarzadeh, M., Ishibe, T., Sandanbata, O., Muhari, A., & Wijanarto, A. B. (2020). Numerical modeling of the subaerial landslide source of the 22 December 2018 Anak Krakatoa volcanic tsunami, Indonesia. *Ocean Engineering*, *195*, 106733.

Heidarzadeh, M., Murotani, S., Satake, K., Takagawa, T., & Saito, T. (2017). Fault size and depth extent of the Ecuador earthquake (Mw 7.8) of 16 April 2016 from teleseismic and tsunami data. *Geophysical Research Letters*, *44*(5), 2211-2219.

Herd, D. G., Youd, T. L., Meyer, H., Arango C, J. L., Person, W. J., & Mendoza, C. (1981). The great tumaco, colombia earthquake of 12 december 1979. *Science*, *211*(4481), 441-445.

Ide, S., Baltay, A., & Beroza, G. C. (2011). Shallow dynamic overshoot and energetic deep rupture in the 2011 M w 9.0 Tohoku-Oki earthquake. *Science*, *332*(6036), 1426-1429.

Igarashi, Y., Kong, L., Yamamoto, M., & McCreery, C. S. (2011). Anatomy of historical tsunamis: lessons learned for tsunami warning. *Pure and applied geophysics*, *168*(11), 2043-2063.

INDECI (2022). Erupción volcánica de Tonga generó oleajes en Ica. https://www.gob.pe/institucion/indeci/noticias/576674-erupcion-volcanica-de-tonga-genero-oleajes-en-ica

Ioualalen, M., Monfret, T., Béthoux, N., Chlieh, M., Ponce Adams, G., Collot, J. Y., ... & Solis Gordillo, G. (2014). Tsunami mapping in the Gulf of Guayaquil, Ecuador, due to local seismicity. *Marine Geophysical Research*, *35*(4), 361-378.

Ioualalen, M., Ratzov, G., Collot, J. Y., & Sanclemente, E. (2011). The tsunami signature on a submerged promontory: the case study of the Atacames Promontory, Ecuador. *Geophysical Journal International*, *184*(2), 680-688.

Itibita, B., & Chen, S. (2017, December). Integrating an alert technology into PIC social context: An earthquake-induced tsunami alert for Pacific Island Communities. In *2017 4th Asia-Pacific World Congress on Computer Science and Engineering (APWC on CSE)* (pp. 149-153). IEEE.

Jiménez, C., Carbonel, C., & Rojas, J. (2018). Numerical procedure to forecast the tsunami parameters from a database of pre-simulated seismic unit sources. *Pure and Applied Geophysics*, *175*(4), 1473-1483.

Johnston, D., Paton, D., Crawford, G. L., Ronan, K., Houghton, B., & Bürgelt, P. (2005). Measuring tsunami preparedness in coastal Washington, United States. *Natural Hazards*, *35*(1), 173-184.

Kajitani, Y., Chang, S. E., & Tatano, H. (2013). Economic impacts of the 2011 Tohoku-Oki earthquake and tsunami. *Earthquake Spectra*, *29*(1_suppl), 457-478.

Kanamori, H., & McNally, K. C. (1982). Variable rupture mode of the subduction zone along the Ecuador-Colombia coast. *Bulletin of the Seismological Society of America*, *72*(4), 1241-1253.

Kowalik, Z., Knight, W., Logan, T., & Whitmore, P. (2005). Numerical modeling of the global tsunami: Indonesian tsunami of 26 December 2004. *Science of Tsunami Hazards*, *23*(1), 40-56.

Kulikov, E. A., Rabinovich, A. B., & Thomson, R. E. (2005). Estimation of tsunami risk for the coasts of Peru and northern Chile. *Natural Hazards*, *35*(2), 185-209.

La Crítica Panamá (2022). Sinaproc no hay amenaza de tsunami por erupción de volcán Tonga. https://www.critica.com.pa/nacional/sinaproc-no-hay-amenaza-de-tsunami-por-erupcion-de-volcan-tonga-620825

La Cuarta (2022a). *"No sabemos cuándo va a terminar esto, pero hay sectores estables": subdirector de la Onemi evalúa emergencia en zonas costeras*. https://www.lacuarta.com/cronica/noticia/no-sabemos-cuando-va-a-terminar-esto-pero-hay-sectores-estables-subdirector-de-la-onemi-evalua-emergencia-en-zonas-costeras/PUZLZB57V5AKDEONUC5THMN5GM/

La Cuarta (2022b). *Reportan imágenes de cómo ha retrocedido el mar en costas chilenas*. https://www.lacuarta.com/cronica/noticia/reportan-imagenes-de-como-ha-retrocedido-el-mar-en-costas-chilenas/UIZXNN4GM5ETXAUP2DBC7BXDXI/

La Cuarta (2022c). *Se mantiene Estado de Precaución en algunas regiones del país: Perú confirmó al menos 2 fallecidos por oleaje causado por el volcán de Tonga*. https://www.lacuarta.com/cronica/noticia/se-mantiene-estado-de-precaucion-en-algunas-regiones-del-pais-peru-confirmo-al-menos-2-fallecidos-por-oleaje-causado-por-el-volcan-de-tonga/KCBZDSTHHBAN5L3RC6XR6ZO3IQ/

La Cuarta (2022d). *Tsunami menor: Onemi pide abandonar playas de Isla de Pascua tras erupción de volcán submarino*. https://www.lacuarta.com/cronica/noticia/tsunami-menor-onemi-pide-abandonar-playas-de-isla-de-pascua-tras-erupcion-de-volcan-submarino/NE725X7PK5CANBRO3ZYOLLD6QU/

La Estrella (2022). Descartan alerta de tsunami en Panamá por erupción de volcán submarino cerca de isla Tonga. https://www.laestrella.com.pa/nacional/220115/descartan-alerta-tsunami-panama-erupcion-volcan-submarino-cerca-isla-tonga

La Semana (2022). Tres países cancelan alerta de tsunami tras erupción de un volcán submarino en Tonga. https://www.semana.com/mundo/articulo/tres-paises-cancelan-alerta-de-tsunami-tras-erupcion-de-un-volcan-submarino-en-tonga/202234/

Lander, J. and Cloud, W. (1964). U.S. Earthquakes 1962, U.S Department of Commerce, Coast and Geodetic Survey, Washington D.C., pp. 1–114.

Lane, E. M., Thomas, K. L., Schoenfeld, M. R., Wilson, T. M., & Hughes, M. W. (2020). The scientific response to the 14 November 2016 Kaikōura tsunami–Lessons learnt from a moderate event. *International journal of disaster risk reduction*, *47*, 101636.

Latter, J. H. (1981). Tsunamis of volcanic origin: summary of causes, with particular reference to Krakatoa, 1883. *Bulletin volcanologique*, *44*(3), 467-490.

Lauterjung, J., Koltermann, P., Wolf, U., & Sopaheluwakan, J. (2010). The UNESCO-IOC framework–establishing an international early warning infrastructure in the Indian Ocean region. *Natural Hazards and Earth System Sciences*, *10*(12), 2623-2629.

León, J., & March, A. (2014). Urban morphology as a tool for supporting tsunami rapid resilience: A case study of Talcahuano, Chile. *Habitat international*, *43*, 250-262.

Lin, J. T., Rajesh, P. K., Lin, C. C., Chou, M. Y., Liu, J. Y., Yue, J., ... & Kung, M. M. (2022). Rapid Conjugate Appearance of the Giant Ionospheric Lamb Wave in the Northern Hemisphere After Hunga-Tonga Volcano Eruptions. Preprint February 2022 DOI: 10.1002/essoar.10510440.1

Lipman, P. W., Normark, W. R., Moore, J. G., Wilson, J. B., & Gutmacher, C. E. (1988). The giant submarine alika debris slide, Mauna Loa, Hawaii. *Journal of Geophysical Research: Solid Earth*, *93*(B5), 4279-4299.

Liu, P. L. F., Cho, Y. S., Yoon, S. B., & Seo, S. N. (1995). Numerical simulations of the 1960 Chilean tsunami propagation and inundation at Hilo, Hawaii. In *Tsunami: Progress in prediction, disaster prevention and warning* (pp. 99-115). Springer, Dordrecht.

Lockridge, P. A. (1988). Historical tsunamis in the Pacific basin. In *Natural and man-made hazards* (pp. 171-181). Springer, Dordrecht.

Lomnitz, C. (2004). Major earthquakes of Chile: a historical survey, 1535-1960. *Seismological Research Letters*, *75*(3), 368-378.

Løvholt, F., Kühn, D., Bungum, H., Harbitz, C. B., & Glimsdal, S. (2012). Historical tsunamis and present tsunami hazard in eastern Indonesia and the southern Philippines. *Journal of Geophysical Research: Solid Earth*, *117*(B9).

Lupton, J., Lilley, M., Butterfield, D., Evans, L., Embley, R., Massoth, G., ... & Schmidt, M. (2008). Venting of a separate CO2‐rich gas phase from submarine arc volcanoes: Examples from the Mariana and Tonga‐Kermadec arcs. *Journal of Geophysical Research: Solid Earth*, *113*(B8).

Mann, P. (2007). Overview of the tectonic history of northern Central America. *Geological Society of America Special Papers*, *428*, 1-19.

Manning, S. W., Ramsey, C. B., Kutschera, W., Higham, T., Kromer, B., Steier, P., & Wild, E. M. (2006). Chronology for the aegean late bronze age 1700-1400 BC. *Science*, *312*(5773), 565-569.

Marina de Guerra (2022). Tweet - MGPI informa a la población que ante la erupción volcánica en Nukualofa - Tonga, este NO GENERA TSUNAMI EN EL LITORAL PERUANO. https://twitter.com/naval_peru/status/1482478877351890944

Martinez, N. & Toulkeridis, T. (2020). Tsunamis in Panama – History, Preparation and future consequences. Science of Tsunami Hazards, 39, (2): 53-68.

Mas, E., Adriano, B., & Koshimura, S. (2013). An integrated simulation of tsunami hazard and human evacuation in La Punta, Peru. *Journal of Disaster Research*, *8*(2), 285-295.

Mas, E., Adriano, B., Sanchez, R., Murao, O., & Koshimura, S. (2017). Tsunami Evacuation in the Pacific and Caribbean Coast of Colombia. In *Proceedings of the 16th World Conference on Earthquake, 16WCEE* (Vol. 2017).

Mas, E., Koshimura, S., Imamura, F., Suppasri, A., Muhari, A., & Adriano, B. (2015). Recent advances in agent-based tsunami evacuation simulations: case studies in Indonesia, Thailand, Japan and Peru. *Pure and Applied Geophysics*, *172*(12), 3409-3424.

Matheus Medina, A.S., Cruz D´Howitt, M., Padilla Almeida, O., Toulkeridis, T., & Haro, A.G. (2016). Enhanced vertical evacuation applications with geomatic tools for tsunamis in Salinas, Ecuador. Science of Tsunami Hazards, 35, (3): 189-213

Matheus-Medina, A.S., Toulkeridis, T., Padilla-Almeida, O., Cruz-D ́Howitt, M., & Chunga, K. (2018). Evaluation of the tsunami vulnerability in the coastal Ecuadorian tourist centers of the peninsulas of Bahia de Caráquez and Salinas. Science of Tsunami Hazards, 38(3): 175-209.

Mato, F. & Toulkeridis, T. (2017). The missing Link in El Niño's phenomenon generation. Science of tsunami hazards, 36: 128-144.

Mato, F. and Toulkeridis, T. (2018). An unsupervised K-means based clustering method for geophysical post-earthquake diagnosis. 2017 IEEE Symposium Series on Computational Intelligence (SSCI). 1-8

McMurtry, G. M., Fryer, G. J., Tappin, D. R., Wilkinson, I. P., Williams, M., Fietzke, J., ... & Watts, P. (2004). Megatsunami deposits on Kohala volcano, Hawaii, from flank collapse of Mauna Loa. *Geology*, *32*(9), 741-744.

Medina, M., Riquelme, S., Fuentes, M., & Campos, J. (2021). Tsunami modeling in the South American subduction zone inferred from seismic coupling and historical seismicity. *Pure and Applied Geophysics*, *178*(12), 4941-4965.

Mikami, T., Shibayama, T., Esteban, M., & Aránguiz, R. (2020). Comparative analysis of triggers for evacuation during recent tsunami events. *Natural Hazards Review*, *21*(3), 04020022.

Mileti, D. S., & Sorensen, J. H. (1990). *Communication of emergency public warnings: A social science perspective and state-of-the-art assessment* (No. ORNL-6609). Oak Ridge National Lab., TN (USA).

Minoura, K., Imamura, F., Kuran, U., Nakamura, T., Papadopoulos, G. A., Takahashi, T., & Yalciner, A. C. (2000). Discovery of Minoan tsunami deposits. *Geology*, *28*(1), 59-62.

Moe, T. L., & Pathranarakul, P. (2006). An integrated approach to natural disaster management: public project management and its critical success factors. *Disaster Prevention and Management: An International Journal*.

Murray, C. C., Bychkov, A., Therriault, T., Maki, H., & Wallace, N. (2015). The impact of Japanese tsunami debris on North America. *PICES Press*, *23*(1), 28-30.

Nakamura, Y., Saita, J., & Sato, T. (2011). On an earthquake early warning system (EEW) and its applications. *Soil Dynamics and Earthquake Engineering*, *31*(2), 127-136.

Nandi, N., & Havwina, T. (2018, April). The Preparedness Level of School Community in Handling the Earthquake and Tsunami Threats in Banda Aceh City. In *IOP Conference Series: Earth and Environmental Science* (Vol. 145, No. 1, p. 012097). IOP Publishing.

NBCNEWS (2022). Tonga volcano eruption blamed for huge oil spill in Peru. https://www.nbcnews.com/news/world/tonga-volcano-eruption-blamed-huge-oil-spill-peru-rcna13035

Neußner, O. (2021). Early warning alerts for extreme natural hazard events: A review of worldwide practices. *International Journal of Disaster Risk Reduction*, *60*, 102295.

New York Times (2022). *Here's What Scientists Know About the Tonga Volcano Eruption.* https://www.nytimes.com/2022/01/19/climate/scientists-tonga-volcano-eruption-effects.html

Nishenko, S., Camacho, E., Astorga, A., Morales, L. D., & Preuss, J. (2021). The 22 april 1991 Limón, Costa Rica tsunami field survey. Revista Geológica de América Central, (65), 1-16.

NOAA (2022a). Hunga Tonga 2022 tsunami travel time. https://ngdc.noaa.gov/hazard/img/tsunami-timeline/

NOAA (2022b). NOAA Pacific Tsunami Warning Center Messages – 15 January 2022. 12 messages, 50pp

Nomikou, P., Druitt, T. H., Hübscher, C., Mather, T. A., Paulatto, M., Kalnins, L. M., ... & Parks, M. M. (2016). Post-eruptive flooding of Santorini caldera and implications for tsunami generation. *Nature communications*, *7*(1), 1-10.

O'loughlin, K. F., & Lander, J. F. (2003). Caribbean tsunamis: a 500-year history from 1498-1998 (Vol. 20). Springer Science & Business Media, 265pp

Okal, E. A. (2015). The quest for wisdom: lessons from 17 tsunamis, 2004–2014. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *373*(2053), 20140370.

Okal, E. A., Borrero, J. C., & Synolakis, C. E. (2006). Evaluation of tsunami risk from regional earthquakes at Pisco, Peru. *Bulletin of the Seismological Society of America*, *96*(5), 1634-1648.

Omira, R., Baptista, M. A., & Lisboa, F. (2017). Tsunami characteristics along the Peru–Chile trench: Analysis of the 2015 Mw8. 3 Illapel, the 2014 Mw8. 2 Iquique and the 2010 Mw8. 8 Maule tsunamis in the near-field. In *The Chile-2015 (Illapel) Earthquake and Tsunami* (pp. 299-313). Birkhäuser, Cham.

ONEMI (2022a). *Monitoreo por Amenaza de Tsunami para el territorio nacional.* https://www.onemi.gov.cl/alerta/monitoreo-por-amenaza-de-tsunami-para-el-territorio-nacional/

ONEMI (2022b). *Se cancela Alerta Roja para las comunas del borde costero de las regiones de Arica y Parinacota y Atacama por tsunami.* https://www.onemi.gov.cl/alerta/se-cancela-alerta-roja-para-las-comunas-del-borde-costero-de-las-regiones-de-arica-y-parinacota-y-atacama-por-tsunam

Orfanogiannaki, K., & Papadopoulos, G. A. (2007). Conditional probability approach of the assessment of tsunami potential: application in three tsunamigenic regions of the Pacific Ocean. *Pure and Applied Geophysics*, *164*(2), 593-603.

Pararas-Carayannis, G. (1967) Source Mechanism Study of the Alaska Earthquake and Tsunami of 37 March 1964. Pacific Science, Vol. XXI, No. 3, July 1967.
See also: http://www.drgeorgepc.com/Earthquake1964Alaska.html

Pararas-Carayannis, G.: (1969), Chile Earthquake and Tsunami of 22 May 1960. Excerpts from archives compiled in preparation of a Catalog of Tsunamis in the Pacific Ocean and for the Catalog of Tsunamis in the Hawaiian Islands
http://www.drgeorgepc.com/Tsunami1960.html

Pararas-Carayannis, G.: (1973), The waves that destroyed the Minoan empire, Sea Frontiers 19(2), 94-106

Pararas-Carayannis, G.: (1974a). The waves that destroyed the Minoan empire, Revised for Grolier Encyclopedia, Science Supplement, Man and His World, pp. 314-321

Pararas-Carayannis, G. (1974b). An investigation of tsunami source mechanism off the coast of Central Peru. *Marine Geology*, *17*(4), 235-247.

Pararas-Carayannis, G, (1983). Tsunami Effects from the Krakatau Eruption. Unpublished review of the Smithsonian Institution's book Krakatau 1883: The volcanic eruption and its effects: by Simkin, T., and Fiske, R.S., published in 1983 by the Smithsonian Institution Press: Washington, D.C., 464 p.

Pararas-Carayannis, G. (1999). The Tsunami Generated by the August 26, 1883 Explosion of the Krakatau Volcano, The Tsunami Page of Dr. George PC. http://drgeorgepc.com/Tsunami1883Krakatoa.html

Pararas-Carayannis, G. (1992). The Tsunami Generated from the Eruption of the Volcano of Santorin in the Bronze Age. Natural Hazards 5: 115-123, 1992. 115 © 1992 Kluwer Academic Publishers. Printed in the Netherlands.

Pararas-Carayannis, G. (1999). Analysis of mechanism of tsunami generation in Lituya Bay. Science of Tsunami Hazards 17(3): 193-206.

Pararas-Carayannis, G., 2002a. Volcanically Generated Tsunamis, 2nd Symposium of the Tsunami Society, Honolulu, Hawaii, May 25-29

Pararas-Carayannis, G. (2002b). Evaluation of the threat of mega tsunami generation from postulated massive slope failures of island stratovolcanoes on La Palma, Canary Islands, and on the island of Hawaii. *Science of Tsunami Hazards*, *20*(5), 251-277.

Pararas-Carayannis, G., (2003). Near and far-field effects of tsunamis generated by the paroxysmal eruptions, explosions, and massive slope failures of the Krakatau volcano in Indonesia on August 26-27,1883. Science of Tsunami Hazards, January 2003, 21 (4). See also http://www.drgeorgepc.com/Tsunami1883Krakatau.html

Pararas-Carayannis, G. (2004). Volcanic tsunami generating source mechanisms in the Eastern Caribbean region. *Science of Tsunami Hazards*, *22*(2), 74-114.

Pararas-Carayannis, G. (2006). Risk Assessment of Tsunami Generation from Active Volcanic Sources in the Eastern Caribbean Region. Caribbean Tsunami Hazard, pp. 91-137. https://doi.org/10.1142/9789812774613_0005

Pararas-Carayannis, G. (2011a). The earthquake and tsunami of July 21, 365 AD in the Eastern Mediterranean Sea-Review of Impact on the Ancient World-Assessment of recurrence and future impact. *Science of Tsunami Hazards*, *30*(4).

Pararas-Carayannis, G. (2011b), Tsunamigenic Source Mechanism and Efficiency of the March 11, 2011 Sanriku Earthquake in Japan. *Science of Tsunami Hazards,* 30(2), pp 126- 152 http://tsunamisociety.org/302GPCc.pdf

Pararas-Carayannis, G.(2012). Potential of tsunami generation along the Colombia/Ecuador subduction margin and the Dolores-Guayaquil mega-thrust. *Science of Tsunami Hazards*, *31*(3).

Pararas-Carayannis, G. (2014). The Great Tohoku-Oki earthquake and tsunami of March 11, 2011 in Japan: A critical review and evaluation of the tsunami source mechanism. *Pure and applied geophysics*, *171*(12), 3257-3278.

Pararas-Carayannis, G., & Zoll, P. (2017). Incipient evaluation of temporal el Niño and other climatic anomalies in triggering earthquakes and tsunamis-Case Study: The Earthquake and Tsunami of 16 th April 2016 in Ecuador. *Science of Tsunami Hazards*, *36*(4).

Pararas-Carayannis, G. Meteotsunami of 29 August 1916 at Santo Domingo, Dominican Republic — Analysis of the destruction of the USS Memphis, Russian Academy of Sciences, Вычислительные технологии, Том 24, No 2, 2019, pp 16-36.

Paris, R., Goto, K., Goff, J., & Yanagisawa, H. (2020). Advances in the study of mega-tsunamis in the geological record. *Earth-Science Reviews*, *210*, 103381.

Park, J., Butler, R., Anderson, K., Berger, J., Benz, H., Davis, P., ... & Aster, R. (2005). Performance review of the global seismographic network for the Sumatra-Andaman megathrust earthquake. *Seismological Research Letters*, *76*(3), 331-343.

Paskoff, R. (1991). Likely occurrence of a mega-tsunami in the Middle Pleistocene, near Coquimbo, Chile. *Andean Geology*, *18*(1), 87-91.

Paton, D., Houghton, B. F., Gregg, C. E., Gill, D. A., Ritchie, L. A., McIvor, D., ... & Johnston, D. M. (2008). Managing tsunami risk in coastal communities: identifying predictors or preparedness. *Australian Journal of Emergency Management*, *23*(1), 4-9.

Peate, D. W., Kokfelt, T. F., Hawkesworth, C. J., Van Calsteren, P. W., Hergt, J. M., & Pearce, J. A. (2001). U-series isotope data on Lau Basin glasses: The role of subduction-related fluids during melt generation in back-arc basins. *Journal of Petrology*, *42*(8), 1449-1470.

Pelayo, A. M., & Wiens, D. A. (1990). The November 20, 1960 Peru tsunami earthquake: Source mechanism of a slow event. *Geophysical Research Letters*, *17*(6), 661-664.

Plafker, G., & Savage, J. C. (1970). Mechanism of the Chilean earthquakes of May 21 and 22, 1960. *Geological Society of America Bulletin*, *81*(4), 1001-1030.

Prensa Libre (2022). Así son los daños que dejó el tsunami en Tonga y Perú tras la erupción de volcán. https://www.prensalibre.com/internacional/efe/asi-son-los-danos-que-dejo-el-tsunami-en-tonga-y-peru-tras-la-erupcion-de-volcan/

Protti, M., Gu, F., & McNally, K. (1994). The geometry of the Wadati-Benioff zone under southern Central America and its tectonic significance: Results from a high-resolution local seismographic network. *Physics of the Earth and Planetary Interiors*, *84*(1-4), 271-287.

PTWC (2022). Message: American Samoa Warn/Adv./Watch #1 Issued Sat Jan 15 05:52:38 UTC 2022. https://tsunami.gov/?p=PHEB/2022/01/15/22015050/1/WEZS40

Pulido, N., Yoshimoto, M., & Sarabia, A. M. (2020). Broadband wavelength slip model of the 1906 Ecuador-Colombia megathrust-earthquake based on seismic intensity and tsunami data. *Tectonophysics*, *774*, 228226.

Rafliana, I., Jalayer, F., Cerase, A., Cugliari, L., Baiguera, M., Salmanidou, D., ... & Hancilar, U. (2022). Tsunami risk communication and management: Contemporary gaps and challenges. *International Journal of Disaster Risk Reduction*, 102771.

Redacción CV Noticias (2022). Dimar anuncia estado de observación en la cuenca del Pacífico tras erupción volcánica en aguas próximas a la isla Tonga https://cvnoticias.com.co/dimar-anuncia-estado-de-observacion-en-la-cuenca-del-pacifico-tras-erupcion-volcanica-en-aguas-proximas-a-la-isla-tonga/

Rodríguez Espinosa, F., Toulkeridis, T., Salazar Martinez, R., Cueva Girón, J., Taipe Quispe, A., Bernaza Quiñonez, L., Padilla Almeida, O., Mato, F., Cruz D´Howitt, M., Parra, H., Sandoval, W., & Rentería, W. (2017). Economic evaluation of recovering a natural protection with concurrent relocation of the threatened public of tsunami hazards in central coastal Ecuador. Science of tsunami hazards, 36: 293-306.

Rodriguez, F., Cruz D´Howitt, M., Toulkeridis, T., Salazar, R., Ramos Romero, G.E., Recalde Moya, V.A., & Padilla, O. (2016). The economic evaluation and significance of an early relocation versus complete destruction by a potential tsunami of a coastal city in Ecuador. Science of tsunami hazards, 35, 1: 18-35.

RPP Noticias (2022). Paracas: Varios locales afectados por oleajes anómalos tras erupción de volcán en Tonga. https://rpp.pe/peru/actualidad/paracas-varios-locales-afectados-por-oleajes-anomalos-tras-erupcion-de-volcan-en-tonga-noticia-1380925

Sahal, A., & Morin, J. (2012). Effects of the October 25, 2010, Mentawai tsunami in La Réunion Island (France): observations and crisis management. *Natural hazards*, *62*(3), 1125-1136.

Sakurai, M., & Murayama, Y. (2019). Information technologies and disaster management–Benefits and issues. *Progress in Disaster Science*, *2*, 100012.

Science.org (2022). Tonga shock wave created tsunamis in two different oceans https://www.science.org/content/article/tonga-shock-wave-created-tsunamis-two-different-oceans

Selva, J., Lorito, S., Volpe, M., Romano, F., Tonini, R., Perfetti, P., ... & Amato, A. (2021). Probabilistic tsunami forecasting for early warning. *Nature communications*, *12*(1), 1-14.

SNGRE (2022a). Comunicado 1 | Monitoreo permanente en las costas de Ecuador tras erupción volcánica en la isla de Tonga. https://www.gestionderiesgos.gob.ec/monitoreo-permanente-en-las-costas-de-ecuador-tras-erupcion-volcanica-en-la-isla-de-tonga/

SNGRE (2022b). Comunicado 7 | Se emite advertencia de tsunami para la costa continental del país. https://www.gestionderiesgos.gob.ec/comunicado-7-se-emite-advertencia-de-tsunami-para-la-costa-continental-del-pais/

Sharpton, V. L., Brent Dalrymple, G., Marín, L. E., Ryder, G., Schuraytz, B. C., & Urrutia-Fucugauchi, J. (1992). New links between the Chicxulub impact structure and the Cretaceous/Tertiary boundary. *Nature*, *359*(6398), 819-821.

SINAMOT (2022a). REPORTE DE TSUNAMI #1. https://unacostasegura.una.ac.cr/webServices/tsunamiViewer.php?pg=&sub=htmlViewer&idx=368

Smith, I. E., & Price, R. C. (2006). The Tonga–Kermadec arc and Havre–Lau back-arc system: their role in the development of tectonic and magmatic models for the western Pacific. *Journal of volcanology and geothermal research*, *156*(3-4), 315-331.

Stern, R. J. (2004). Subduction initiation: spontaneous and induced. *Earth and Planetary Science Letters*, *226*(3-4), 275-292.

Suárez-Acosta, P.E., Cañamar-Tipan, C.D., Ñato-Criollo, D.A., Vera-Zambrano, J.D., Galarza-Vega, K.L., Guevara-Álvarez, P.M., Fajardo-Cartuche, C.N., HerreraGarcés, K. K., Ochoa-Campoverde, C.V., Torres-Orellana, J.S., Rentería, W., Chunga, K., Padilla, O., Sinde-González, I., Simón-Baile, D. and Toulkeridis, T. (2021). Evaluation of seismic and tsunami resistance of potential shelters for vertical evacuation in case of a tsunami impact in Bahia de Caráquez, central coast of Ecuador. Science of Tsunami Hazards, 40(1), 1-37.

Swissinfo (2022). Daños importantes en Tonga tras erupción que causó dos muertos en Perú y alarma en el Pacífico. https://www.swissinfo.ch/spa/afp/daños-importantes-en-tonga-tras-erupció-que-causó-dos-muertos-en-perú-y-alarma-en-el-pacífico/47265090

Synolakis, C. E., Bardet, J. P., Borrero, J. C., Davies, H. L., Okal, E. A., Silver, E. A., ... & Tappin, D. R. (2002). The slump origin of the 1998 Papua New Guinea tsunami. *Proceedings of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences*, *458*(2020), 763-789.

Tanguy, J. C., Ribière, C., Scarth, A., & Tjetjep, W. S. (1998). Victims from volcanic eruptions: a revised database. *Bulletin of volcanology*, *60*(2), 137-144.

Telemetro Panamá (2022). No hay amenaza para costas panameñas tras erupción en Tonga, Sinaproc. https://www.telemetro.com/nacionales/no-hay-amenaza-costas-panamenas-erupcion-tonga-sinaproc-n5645745

TelesurTV (2022). Perú cierra 80 puertos tras erupción de volcán en Tonga. https://www.telesurtv.net/news/peru-cierra-puertos-erupcion--volcan-tonga-20220117-0025.html

The Conversation (2022). Why the volcanic eruption in Tonga was so violent, and what to expect next. https://theconversation.com/why-the-volcanic-eruption-in-tonga-was-so-violent-and-what-to-expect-next-175035

Timm, C., Davy, B., Haase, K., Hoernle, K. A., Graham, I. J., De Ronde, C. E., ... & Gamble, J. A. (2014). Subduction of the oceanic Hikurangi Plateau and its impact on the Kermadec arc. *Nature Communications*, *5*(1), 1-9.

Tkalich, P., Dao, M. H., & Chan, E. S. (2007). Tsunami propagation modeling and forecasting for early warning system. *Journal of Earthquake and Tsunami*, *1*(01), 87-98.

Toulkeridis, T., Chunga, K., Rentería, W., Rodriguez, F., Mato, F., Nikolaou, S., Cruz D´Howitt, M., Besenzon, D., Ruiz, H., Parra, H., & Vera-Grunauer, X. (2017b). The 7.8 Mw Earthquake and Tsunami of the 16th April 2016 in Ecuador - Seismic evaluation, geological field survey and economic implications. Science of tsunami hazards, 36: 197-242.

Toulkeridis, T., Jacome, A. and Mato, F. (2018). Ethics, Policy, and Risk Assessment of the Cotopaxi Volcanic Crisis in Ecuador—Vulnerable Society Versus Unprepared Volcanic Monitoring Staff and Authorities. In *Geoethics In Latin America* (pp. 153-170). Springer, Cham.

Toulkeridis, T., Parra, H., Mato, F., Cruz D´Howitt, M., Sandoval, W., Padilla Almeida, O., Rentería, W., Rodríguez Espinosa, F., Salazar martinez, R., Cueva Girón, J., Taipe Quispe, A., & Bernaza Quiñonez, L. (2017a). Contrasting results of potential tsunami hazards in Muisne, central coast of Ecuador. Science of tsunami hazards, 36: 13-40

Toulkeridis, T., Porras, L., Tierra, A., Toulkeridis-Estrella, K., Cisneros, D., Luna, M.,Carrión, J.L., Herrera, M., Murillo, A., Perez-Salinas, J.C., Tapia, S., Fuertes, W., & Salazar, R. (2019a). Two independent real-time precursors of the 7.8 Mw earthquake in Ecuador based on radioactive and geodetic processes—Powerful tools for an early warning system. Journal of Geodynamics, 126: 12-22

Toulkeridis, T., Barahona-Quelal, I. N., Pilco-Paguay, E. O., Cacuango-Casco, D. M., Guilcaso-Tipán, B. S., & Sailema-Hurtado, W. P. (2021). Evaluation of seismic and tsunami resistance of potential shelters for vertical evacuation in case of a tsunami impact in Manta and Salinas, central coast of Ecuador. Science of Tsunami Hazards, 40(4): 286-314

Toulkeridis, T., Mato, F., Toulkeridis-Estrella, K., Perez Salinas, J.C., Tapia, S., & Fuertes, W. (2018). Real-Time Radioactive Precursor of the April 16, 2016 Mw 7.8 Earthquake and Tsunami in Ecuador. Science of tsunami hazards, 37: 34-48.

Toulkeridis, T., Porras, L., Tierra, A., Toulkeridis-Estrella, K., Cisneros, D., Luna, M., Carrión, J.L., Herrera, M., Murillo, A., Perez-Salinas, J.C., Tapia, S., Fuertes, W. and Salazar, R. (2019b). A potential early warning system for earthquakes based on two independent real-time precursors – the case of Ecuador´s 7.8 Mw in 2016. Proceedings of the International Conference on Natural Hazards and Infrastructure 2019, 2nd International Conference on Natural Hazards and Infrastructure, ICONHIC 2019; Chania; Greece; 23 June 2019 through 26 June 2019; Code 257429

Trenkamp, R., Kellogg, J. N., Freymueller, J. T., & Mora, H. P. (2002). Wide plate margin deformation, southern Central America and northwestern South America, CASA GPS observations. *Journal of South American Earth Sciences*, *15*(2), 157-171.

TVN Canal 2 (2022). Sinaproc: No hay amenaza para las costas panameñas tras erupción de volcán en Tonga. https://www.tvn-2.com/nacionales/Sinaproc-amenaza-panamenas-erupcion-Tonga_0_6036896297.html

Twitter.com/Sinaproc Panama (2022). SINAPROC Panamá. https://twitter.com/Sinaproc_Panama/status/1482441232009908224?ref_src=twsrc%5Etfw

USGS (2022). M 5.8 Volcanic Eruption - 68 km NNW of Nuku‘alofa, Tonga. https://earthquake.usgs.gov/earthquakes/eventpage/us7000gc8r/region-info

Voz de América (2022). Perú: derrame de petróleo por oleaje tras erupción en Tonga. https://www.vozdeamerica.com/a/peru-derrame-petroleo-oleaje-erupcion-tonga-/6400554.html

Wadge, G., & Burke, K. (1983). Neogene Caribbean plate rotation and associated Central American tectonic evolution. *Tectonics*, *2*(6), 633-643.

Worthington, T. J., Gregory, M. R., & Bondarenko, V. (1999). The Denham caldera on Raoul Volcano: dacitic volcanism in the Tonga–Kermadec arc. *Journal of Volcanology and Geothermal Research*, *90*(1-2), 29-48.

Yahav, A., & Salamon, A. (2022). Tsunami Alert Efficiency. *Encyclopedia*, *2*(1), 383-399.

Yamanaka, Y., & Tanioka, Y. (2021). Study on the 1906 Colombia‐Ecuador Megathrust Earthquake Based on Tsunami Waveforms Observed at Tide Gauges: Release Variation of Accumulated Slip Deficits in the Source Area. *Journal of Geophysical Research: Solid Earth*, *126*(5), e2020JB021375.

Yamanaka, Y., Tanioka, Y., & Shiina, T. (2017). A long source area of the 1906 Colombia–Ecuador earthquake estimated from observed tsunami waveforms. *Earth, Planets and Space*, *69*(1), 1-11.

Yamazaki, F., Zavala, C., Nakai, S., Koshimura, S. I., Saito, T., & Midorikawa, S. (2010, March). Enhancement of earthquake and tsunami disaster mitigation technology in Peru: A SATREPS project. In *Proceedings of the 7th International Conference on Urban Earthquake Engineering* (pp. 1501-1506).

Yamazaki, F., Zavala, C., Nakai, S., Koshimura, S., Saito, T., Midorikawa, S., ... & Bisbal, A. (2013). SATREPS project on enhancement of earthquake and tsunami disaster mitigation technology in Peru. *Journal of Disaster Research*, *8*(2), 224-234.

Yamazaki, Y., & Cheung, K. F. (2011). Shelf resonance and impact of near−field tsunami generated by the 2010 Chile earthquake. *Geophysical Research Letters*, *38*(12).

Ye, L., Kanamori, H., Rivera, L., Lay, T., Zhou, Y., Sianipar, D., & Satake, K. (2020). The 22 December 2018 tsunami from flank collapse of Anak Krakatau volcano during eruption. *Science advances*, *6*(3), eaaz1377.

Yépez, V., Toledo, J., & Toulkeridis, T. (2020). The Armed Forces as a State institution in immediate response and its participation as an articulator in the risk management in Ecuador. Smart Innovation, Systems and Technologies 181, 545-554.

Zengaffinen, T., Løvholt, F., Pedersen, G. K., & Muhari, A. (2020). Modelling 2018 Anak Krakatoa Flank Collapse and Tsunami: effect of landslide failure mechanism and dynamics on tsunami generation. *Pure and Applied Geophysics*, *177*(6), 2493-2516.

Watkins, N. D., Sparks, R. S. J., Sigurdsson, H., Huang, T. C., Federman, A., Carey, S., and Ninkovich, D.: 1978, Volume and extent of the Minoan tephra from Santorin volcano: New evidence from deep-sea sediment cores, Nature 271, 122-126.

ISSN 8755-6839

SCIENCE OF TSUNAMI HAZARDS

Journal of Tsunami Society International

Volume 41 Number 1 2022

EFFECTIVE TSUNAMI EARLY WARNING USING THE PRODUCT OF P-WAVE DOMINANT PERIOD AND SOURCE RUPTURE DURATION OF MORE THAN 50 SECONDS

Madlazim[1], **Tjipto Prastowo**[1], **Muhammad Nurul Fahmi**[1], **Ella Melianda**[2], **Soerja Kusuma**[3]

[1] *Universitas Negeri Surabaya, Surabaya 60231, Indonesia. E-mail: madlazim@unesa.ac.id*
[2] *Universitas Syiah Kuala, Aceh, Indonesia*
[3] *Universitas Sebelas Maret, Surakarta, Indonesia*

ABSTRACT

In this study, we used a tsunami-faulting model, where the discriminant for tsunami potential is the dominant period T_d of *P*-waves times the rupture duration of an earthquake T_{50ex} of more than 50 seconds. The product of T_dT_{50ex} was estimated in real time and validated with Tsunami Event Validity (TEV) from NOAA/WDC database. The T_dT_{50ex} discriminant was calculated using a direct procedure for the vertical component of *P*-wave seismograms velocity. The data were obtained from 51 earthquakes that occurred during 2011-2020 with magnitudes of $6.5 \leq M_w \leq 8.6$, containing 19 strike-slips fault, 11 normal-fault and 21 reverse-fault earthquakes. The results suggest that earthquakes are said to be potential to generate tsunamis when $T_dT_{50ex} \geq 10$ s is satisfied. In summary, T_dT_{50ex} is proved to be an efective tsunami discriminant to detect the presence of a tsunami wave after about 4 minutes an earthquake occurs, implying that this is (can be accessed at http://prediksi-tsunami.unesa.ac.id/www/index.html) a useful parameter for rapid and accurate tsunami early warning.

Keywords: *Tsunami early warning; P-wave dominant period; Source rupture duration more than 50 s; product of* T_dT_{50ex}*; efective tsunami discriminant.*

1. INTRODUCTION

There are currently two earthquake rupture models used for tsunami early warning. The first model is a seismic-faulting model and the second one is a tsunami-faulting model. The former is related to tsunami potential that depends on seafloor displacement. This displacement is related to the length L, width W, mean slip D, and depth z of earthquake rupture. The main discriminant used in this model for tsunami generation is the centroid-moment tensor magnitude $M_{\mathrm{w}}^{\mathrm{CMT}}$ reflecting the LWD product and is indirectly estimated using an inversion procedure (Polet & Kanamori, 2009). However, $M_{\mathrm{w}}^{\mathrm{CMT}}$ values depend on rupture depth, earth model, seismic instrument, and is only available 20-30 minutes or longer after an earthquake occurs (Lomax & Michelini, 2012). The tsunami model is particularly related to the length L and width W of the rupture. Two tsunami parameters for this model are rupture duration of more than 50 seconds $T_{50\mathrm{ex}}$, representing the length L of the rupture and P-wave dominant period T_{d}, representing the width W of the rupture. The values of T_{d} and $T_{50\mathrm{ex}}$ can be determined using direct procedures from P-wave seismograms on vertical velocity records. For near-field events, it only takes no more than 4 minutes to complete calculation (Madlazim et al., 2019).

Effective tsunami early warning is early warning that can communicate tsunami potential from an earthquake quickly and accurately so that people potentially affected by a tsunami have time to save their lives. Tsunamis are particularly most devastating in effects at distances less than 1000 km from the epicenter and may arrive within 20-30 minutes after the event origin time (OT). It follows that tsunami alert at these distances requires quick and accurate notification within 15 minutes or less after OT for effective early warning (Tsushima et al., 2011; Newman et al., 2011; Sutton et al., 2018). Currently, there have been many organizations that use the seismic model for rapid assessment of tsunami excitation, including the Indonesian Agency for Geophysics, Climatology, and Meteorology (BMKG), the Japan Meteorological Agency (JMA), the German-Indonesian Tsunami Early Warning System (GITEWS) and the Pacific Tsunami Warning Centre (PTWC). Lomax and Michelini (2011; 2012) argued that this model depends particularly on the initial estimates of earthquake epicenter, depth, seismic moment M_{o} and moment magnitude M_{w} or other equivalent magnitude scales.

Knowledge of seismic moment M_{o} is important for tsunami early warning because tsunami potential by a shallow, underwater earthquake depends on seabed displacement, which can be linked to the seismic potency represented by the LWD product. Since $M_{\mathrm{o}} = \mu LWD$, where μ is the shear at the source, then the seismic potency and hence tsunami potential must be scaled with $LWD = M_{\mathrm{o}}/\mu$ (Lomax and Michelini, 2011; 2012). On the other hand, M_{w} is a good discriminant for tsunami potential but it does not hold for all events having the potency for tsunami generation. In particular, the M_{w} discriminant does not work for slow 'tsunami earthquakes', which induce waves larger than would be expected from their sizes (Satake, 2002; Polet and Kanamori, 2009; Newman et al., 2011; Lomax and Michelini, 2012).

To avoid these problems, namely the lack of speed and accuracy in effective tsunami early warning, especially for near to regional distances, we recommend the use of the tsunami model, where the $T_{\mathrm{d}}T_{50\mathrm{ex}}$ discriminant is obtained quicker and more accurate for assessment of tsunami potential. A direct procedure for assessing possible tsunami generation caused by earthquakes was discussed by Lomax and Michelini (2009; 2011) and Madlazim et al. (2011; 2013; 2015; 2019). For large earthquakes, the $T_{\mathrm{d}}T_{50\mathrm{ex}}$ product increases as rupture depth decreases due to shear modulus effects and reduction in rupture velocity (Lomax and Michelini, 2012). This suggests that the $T_{\mathrm{d}}T_{50\mathrm{ex}}$ discriminant provides more information on tsunami impact than $M_{\mathrm{w}}^{\mathrm{CMT}}$ and other discriminants do for tsunami early warning (Lomax and Michelini, 2011; 2012; Madlazim et al., 2019). This implies that the potency for tsunami generation after an earthquake occurs is not directly related to the LWD product derived from the seismic model (Lomax and Michelini, 2011; 2012).

Tsunami potential is well constrained by information about the length and depth of rupture, where such information is provided by the product of $T_{\mathrm{d}}T_{50\mathrm{ex}}$. It follows that estimates of the rupture length and depth that are difficult and impossible to obtain quickly are not required. This reflects that the $T_{\mathrm{d}}T_{50\mathrm{ex}}$ value is found to represent a good tsunami discriminant derived from the tsunami model that corresponds to the observed tsunami waves (Satake, 1994; Lomax and Michelini, 2012; Lay et al., 2017). In this study, we show that using the vertical velocity records of the *P*-wave seismograms in our real-time application for tsunami assessment and its corresponding prediction, accessed at http://prediksi-tsunami.unesa.ac.id/www/index.html, the $T_{\mathrm{d}}T_{50\mathrm{ex}}$ calculation can then be completed in less than 4 minutes after the OT for short-range earthquakes.

METHODS

We used direct procedures of calculation for relatively quick assessment of tsunami generation using a tsunami discriminant, namely $T_{\mathrm{d}}T_{50\mathrm{ex}}$. This discriminant is the product of the *P*-wave dominant period T_{d} and the rupture duration $T_{50\mathrm{ex}}$ longer than 50 s from the vertical velocity records on the high-frequency, *P*-wave seismograms.

1. The measurement of *P*-wave dominant period T_{d}

We used definition of the dominant period T_{d} for an event as the median of the dominant period values for each station given by the peak of the τ_{c} algorithm (Nakamura, 1988; Wu and Kanamori, 2005; Lomax and Michelini, 2011) applied with a 5 s sliding time-window from 0 to 55 s after the *P*-wave arrival on velocity seismograms (Eq. 1). The T_{d} estimation was performed using a direct procedure with no inversion, making the calculation process relatively short. The first step of the T_{d} estimation was to determine time domain τ_{c} as follows:

$$\tau_{\mathrm{c}} = 2\pi \int_{T_2}^{T_1} v^2(t)dt / \int_{T_2}^{T_1} \acute{v}^2(t)dt \tag{1}$$

where $T_1 = 0$ (the onset time of *P*-waves) and $T_2 = 55$ s acquired from regional data. Detailed steps of the T_{d} estimation are as follows: (1) preparing raw earthquake velocity records from the vertical component of broadband seismograms in a miniseed format; (2) applying 4-poles and a corner frequency of 0.05 Hz Butterworth bandpass filter, the vertical component of velocity records for each station; (3) picking *P*-wave arrival times automatically for the vertical component of velocity seismograms; (4) integrating the seismograms and comparing them with the vertical acceleration of broadband seismograms times 2π of arrival times of *P*-waves automatically picked up from the vertical velocity records on the seismograms; and (5) taking the final results as values of the dominant period T_{d}, the maximum value in time domain (see Fig. 1, second panel).

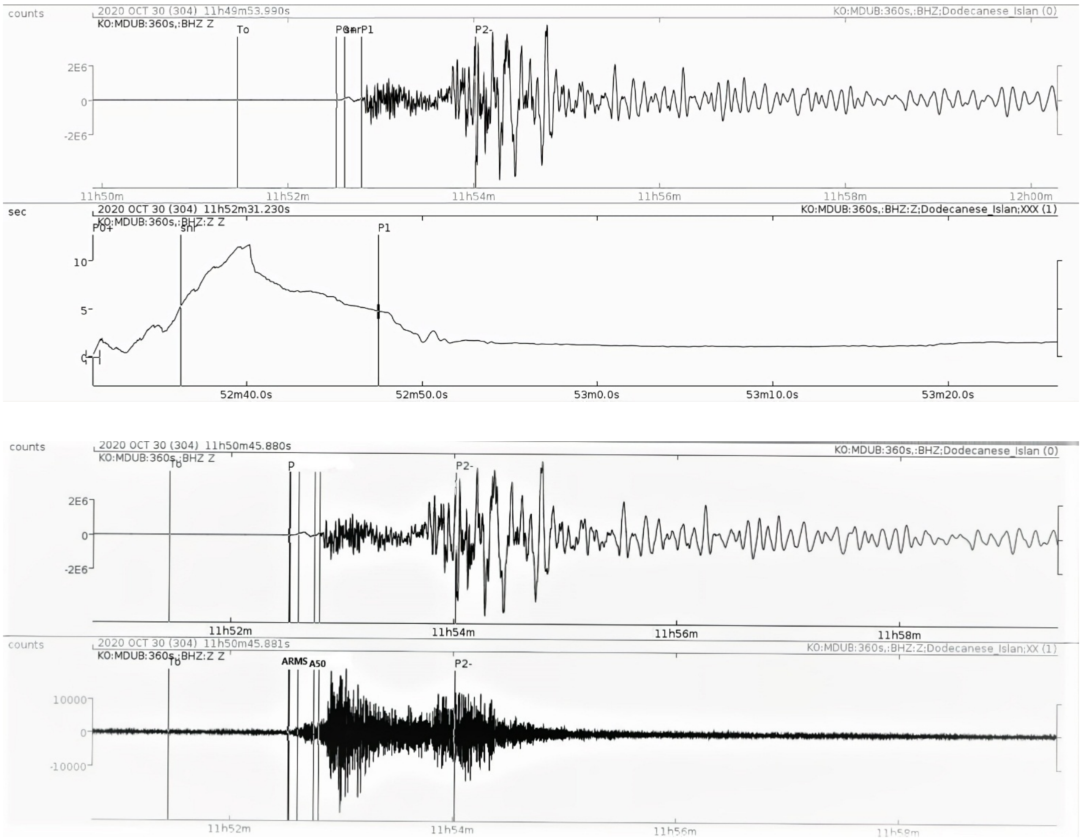


Figure 1. Schematic of a single-station, $T_d T_{50\mathrm{ex}}$ processing for the 2020.10.30, M_w 7.0, Dodecanese Island, Greece earthquake recorded by station KO.MDUP at 4.26° GCD. Top panel represents raw, broadband velocity and the second panel shows T_d estimate. The third panel is raw and bottom panel is HF seismogram, showing an estimate of $T_{50\mathrm{ex}} = A_{50}/A_{\mathrm{RMS}}$.

2. The measurement of rupture duration $T_{50\mathrm{ex}}$ longer than 50s

Earthquake rupture duration $T_{50\mathrm{ex}}$ longer than 50 s is a substitute for rupture duration (Lomax and Michelini, 2011). For estimates of the rupture duration longer than 50s, $T_{50\mathrm{ex}}$ were performed using a direct procedure with no inversion, making the calculation process relatively shortened. The first step of $T_{50\mathrm{ex}}$ estimates was determined according to Lomax and Michelini (2011) and Madlazim (2013) as follows:

$$T_{50\mathrm{ex}} = A_{50}/A_{\mathrm{RMS}} \qquad (2)$$

where A_{50} is the average amplitude for 50 until 60 seconds and A_{RMS} is the average amplitude for 0 until 25 seconds.

The followings are detailed steps of determining the $T_{50\mathrm{ex}}$ exceeding 50 s using a direct procedure: (1) preparing raw data from the vertical component of broadband seismograms in a miniseed format; (2) applying 4-poles and the 5-20 Hz Butterworth bandpass filter to obtain the high-frequency, vertical component of seismic velocity records for each station; (3) picking arrival times of *P*-waves automatically at the high-frequency, vertical velocity seismograms; (4) calculating the RMS amplitude and A_{50} values; and (5) estimating $T_{50\mathrm{ex}}$ using the ratio of A_{50} to the RMS amplitude values (see Fig. 1, bottom panel). Figure 1 describes Schematic of a single-station, $T_\mathrm{d}T_{50\mathrm{ex}}$ processing for the 2020.10.30, M_w 7.0, Dodecanese Island, Greece earthquake recorded by station KO.MDUP at 4.26° GCD. Top panel represents raw, broadband velocity and the second panel shows T_d estimate. The third panel is raw and bottom panel is HF seismogram, showing an estimate of $T_{50\mathrm{ex}} = A_{50}/A_\mathrm{RMS}$.

The product of $T_\mathrm{d}T_{50\mathrm{ex}}$ was chosen here as it was proved to bring more information about potential tsunami generation by underwater earthquakes than other discriminants do, for example, the moment magnitude M_w. As pointed out by Necmioglu and Özel (2014), determination of rupture duration had a relatively large uncertainty affecting accurate prediction of tsunami initiation hence being improper for tsunami hazard assessment. A similar situation to occur was found for earthquake magnitude, scaled with any measurement, as the earthquake magnitude was proved to be inaccurate for tsunami analysis and assessment (Madlazim and Prastowo, 2016).

The product of $T_\mathrm{d}T_{50\mathrm{ex}} \geq 10$ s is then found to be a good discriminant for tsunami generation. We modify the procedures described in Lomax and Michelini (2011), including the minimum distance reduced to 5° for all measurements by applying M-filter to select good seismograms for calculating T_d and $T_{50\mathrm{ex}}$ for local to regional events (Madlazim et al., 2018).

3. Application to recent large earthquakes

A total of 51 events, covering varying magnitudes from $6.5 \leq M_\mathrm{w} \leq 8.6$ during 2011-2020, and consisting of 19 strike-slips, 17 normal-faulting and 15 reverse-faulting mechanisms were examined in this study. These earthquakes were events with either continent-centered or ocean-centered epicenter (Table 1 see Appendix at end of this report). These events were analyzed using the tsunami discriminant in terms of $T_\mathrm{d}T_{50\mathrm{ex}}$ values for potential tsunami generation. The data were acquired from real-time network of seismic stations on the basis of regional and teleseismic real time data provided by the German Research Centre for Geosciences, known as GEOFON GFZ, and the Incorporated Research Institutions for Seismology-Data Management Center (IRIS-DMC).

RESULTS AND DISCUSSIONS

The earthquake data selected in this study (Table 1) is limited to earthquakes that have the smallest moment magnitude (M_w) 6.5, due to earthquakes with M_w below threshold signal to noise ratio is too bad and false automatic recognition of the P wave onset (Clément, J. and Reymond, D., 2014) which can causes false discriminant measurement results and becomes inefficient. A strong determination of the first motion of the P wave is key this method. We used the automatic picker Filter Picker - a Robust method, Broadband Picker for Real-Time Seismic Monitoring and Earthquake Early Warning for picking P wave data (Lomax, A. et al., 2012).

For all earthquakes examined in this study, we estimated $T_\mathrm{d}T_{50\mathrm{ex}}$ values and compared them with TEV. Estimates of T_d and $T_{50\mathrm{ex}}$ were performed using the direct procedures previously presented. Table 1, and Table 2 (see Appendix) explained that by using the $T_\mathrm{d}T_{50\mathrm{ex}}$ discriminant, the accuracy of tsunami early warning was obtained in about 4 minutes after the OT (True warning = TW) was 76%. Meanwhile, by using the discriminant moment magnitude (M_w), the accuracy of tsunami early warning was obtained in about 10 to 15 minutes after the OT (True warning = TW) was 71%. The rupture duration measurement by using direct procedure is faster than the M_w measurement because the discriminant measurement used the direct procedure method of earthquake seismogram data, without going through an inversion (Lomax, A. & A. Michelini, 2012). How good the M_w discriminant is in correspond to TEV values. Here, we used the threshold value of $M_w \geq 7.0$ given by an earthquake of land-centered or sea-centered origin, corresponding to TEV ≥ 3 for tsunami generation.

The results for all the events examined in this study that $T_d T_{50ex}$ values in the vertical axis for real-time application and evaluated at OT + 4 minutes, compared with TEV in the horizontal axis. The horizontal red solid-line and vertical red dashed line show the threshold value of $T_d T_{50ex}$ and TEV, respectively. Triangles indicate tsunami occurrences and circles indicate no tsunami threats. Quadrant one is a zone where $T_d T_{50ex}$ is equal to or greater than the threshold (10 seconds) and TEV is equal to or greater than 3. This means that in this zone an earthquake has the potential to cause a tsunami. Of the 37 tsunami events in zone three, the type of earthquake mechanism varies, not only revers, but there are also earthquakes with strike-slip and normal fault type mechanisms (Power et al., 2017; Ulrich et al., 2019). This shows that the strike-slip type earthquake and normal fault can generate tsunamis as long as the discriminant $T_d T_{50ex}$ is equal to or greater than the threshold. Meanwhile, quadrant 3 is a zone where $T_d T_{50ex}$ is less than the threshold (10 seconds) and TEV is less than 3. This means that in zone three an earthquake has no potential for a tsunami. Earthquakes that are in zones one and three in this article we call True Warning (TW). We call earthquakes in zones two and four in this article False Warning (FW) as shown in Fig.2.

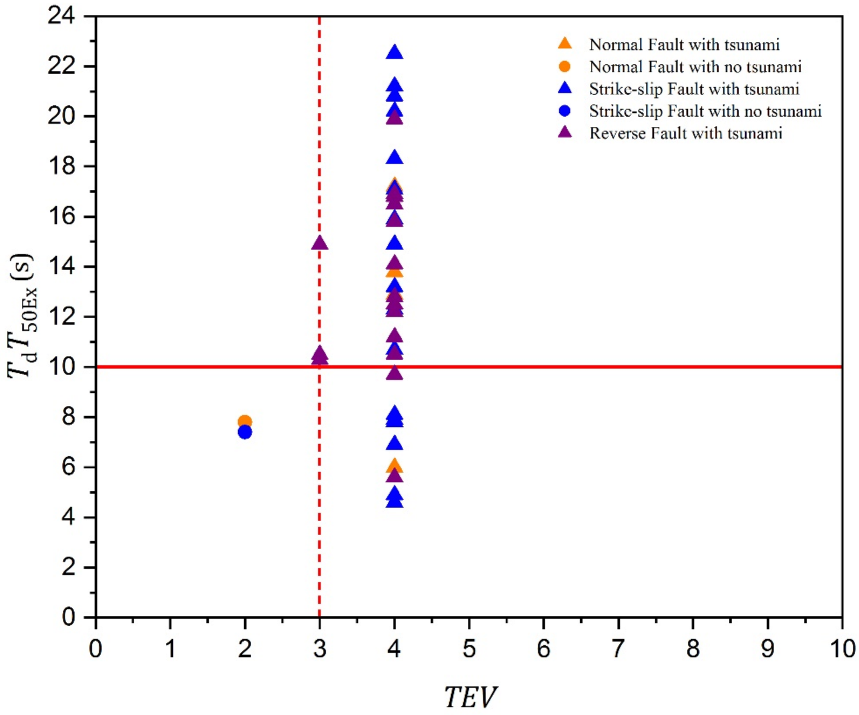


Figure 2. The results for all the events examined in this study. The $T_d T_{50ex}$ values in the vertical axis for real-time application and evaluated at OT+4 minutes, compared with tsunami importance TEV in the horizontal axis. The horizontal red solid-line and vertical red dashed-line shows the threshold value of $T_d T_{50ex}$ and TEV, resepectively. Triangles indicate tsunami occurrences and circles indicate no tsunami threats.

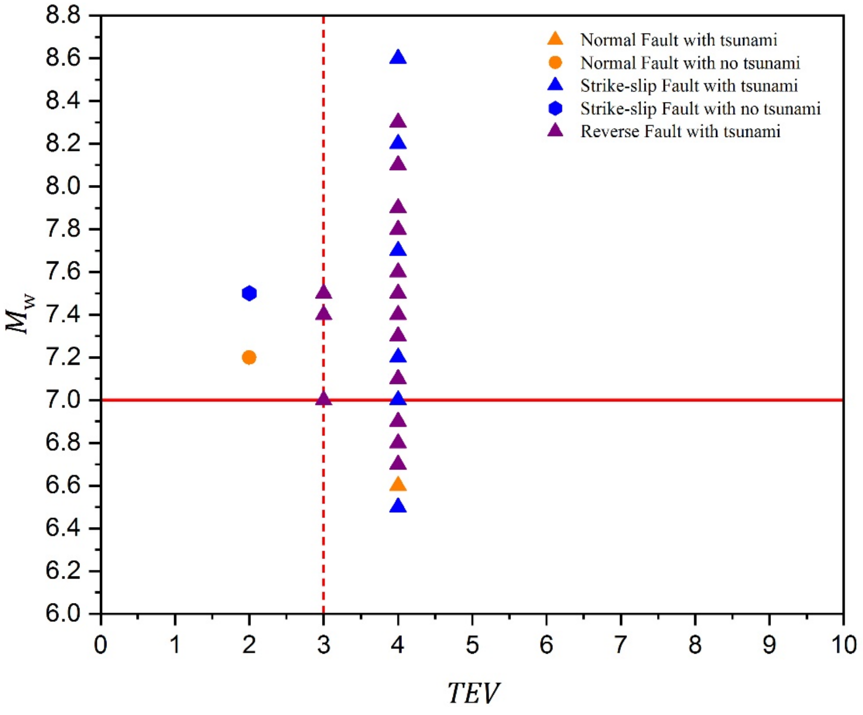


Figure 3. The results for all the events examined in this study. The $M_w$values in the vertical axis for real-time application and evaluated at OT + 15 minutes, compared with TEV in the horizontal axis.. The horizontal red solid-line and the vertical red dashed-line show the threshold value of M_w and TEV, respectively. Triangles indicate tsunami occurrences and circles indicate no tsunami threats.

The number of earthquakes occurring in the True Warning (TW) zone using the discriminant moment magnitude, M_w (Fig. 3) was less than that using the $T_d T_{50ex}$ discriminant (Fig. 2). Meanwhile, the number of earthquakes occurred in the False Warning (FW) zone using the discriminant moment magnitude (M_w) in Fig. 3 is mostly compared to those using the $T_d T_{50ex}$ discriminant (Fig. 2). This can be explained by the fact that M_w is a good discriminant for tsunami potential but it does not hold for all events having the potency for tsunami generation. In particular, the M_w discriminant does not work for slow'tsunami earthquakes, which induce waves larger than would be expected from their sizes (Satake, 2002; Polet and Kanamori, 2009; Newman et al., 2011; Lomax, A and Michelini, A., 2012).

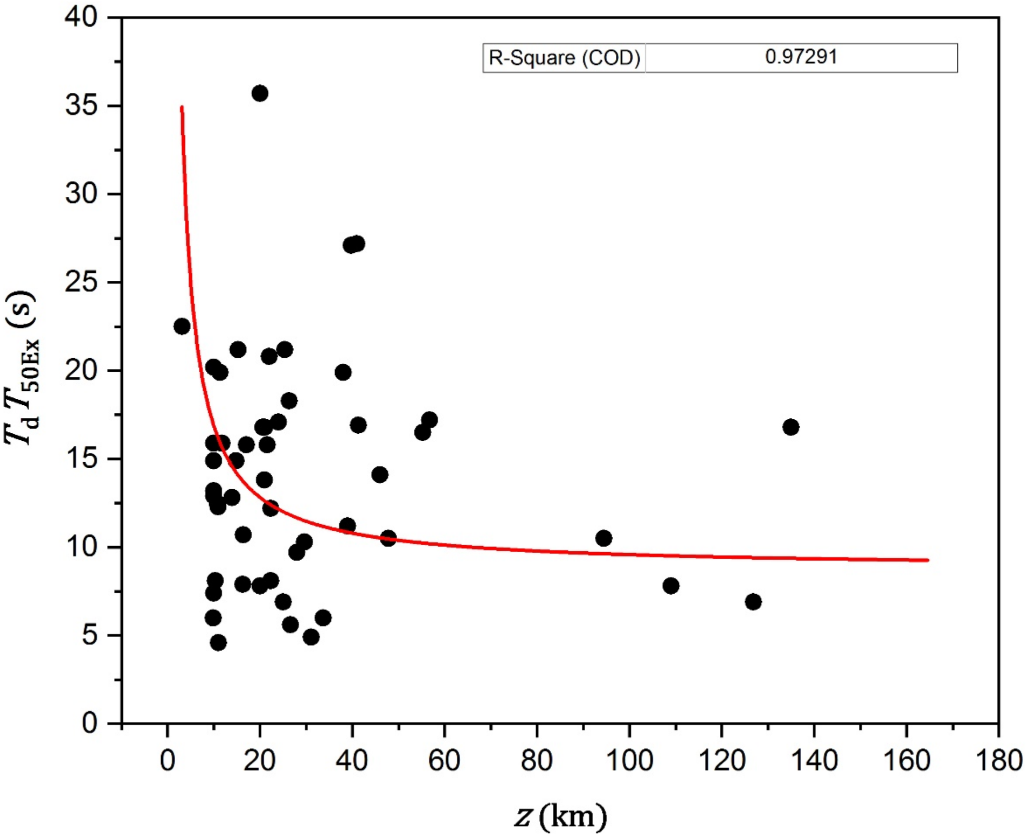


Figure 4. Relation between $T_d T_{50ex}$ values for all the events and source depths, where the red line is exponential curve-fitting for the data distribution with a determination coefficient of 0.97.

For a $T_d T_{50ex}$ value greater than or equal to 10 seconds, the depth of the earthquake source is less than or equal to 60 km. $T_d T_{50ex}$ discriminant not only provides information about the existence of vertical displacement of the earthquake, however, provides information about the depth of the earthquake source (Lomax, A. & Mechelini, A., 2009). In the tsunami faulting model, the rupture length, L is proportional to the rupture duration or T50Ex which can be expressed in terms of T50Ex is proportional to L / v_r, where v_r is the rupture speed of the earthquake. Since v_r corresponds to the S wave velocity and shear modulus, μ, which increases with depth, and because v_r is found to be very low at shallow depths for some earthquakes (Geist and Bilek 2001; Polet and Kanamori 2009), we can assume $v_r \propto z^q$, where z is the multiple mean rupture depths and q is positive. Then, rupture duration is proportional to L / z^q, indicating that rupture duration provides information about L and z, and most importantly, rupture duration grows with increasing L and decreasing z, two conditions for increasing tsunami potential.

The findings provide insight into a possibility that the tsunami potential is possibly induced by an earthquake either continent-centered or ocean-centered and is independent of source mechanisms. For example, a large tsunami wave was generated by a strike-slip event that hit Kaikoura region in New Zealand on 13 November 2016 (Power *et al*., 2017; Ulrich *et al*., 2019) although a large tsunami wave induced by this type of earthquake is rare. Strike-slip earthquakes commonly produce small tsunamis in size because vertical displacement of rupture is not strong enough to lift a huge amount of seawater (Ulrich *et al*., 2019). Meanwhile, for normal-faulting earthquakes, the rock layers from the hanging-wall drop down and the corresponding oscillatory force is relatively small to displace them back vertically. This mechanism is different from that induced by reverse-faulting earthquakes, where the rocks from the hanging-wall directly displace seawater upward.

CONCLUSIONS

Calculation of the T_dT_{50ex} discriminant is also completed almost four times quicker than that of the M_w scale, making it better for rapid assessment of tsunami hazard analysis. The results indicate that the potency for tsunami excitation weakly correlates to the LWD, derived from the seismic model (Lomax and Michelini, 2011; 2012), which reflects the earthquake size in terms of the M_w scale. These indicate that the T_dT_{50ex} discriminant, derived from tsunami tsunami faulting model, is quicker and more accurate than the M_w, obtained from seismic parameter, for effective tsunami early warning.

We have examined tsunami discriminant T_dT_{50ex} and validated them with TEV. We have also introduced a real-time, rapid assessment of tsunami potential using the T_dT_{50ex} discriminant, instead of M_w, which is filtered by the M-filter to select earthquake signals coming from the local and regional station to allow initial estimates of all tsunami parameters. We found that T_dT_{50ex}values provide more information on tsunami impact,source depth,, and size than M_w and other currently used discriminants do. The T_dT_{50ex} discriminant is sensitive to rupture length L and depth z, which control the vertical seafloor displacement and hence the potency for tsunami excitation. This discriminant can be obtained within 4 minutes after the origin time with real-time earthquake data available for most tsunami prone areas.

ACKNOWLEDGEMENTS

The authors would sincerely like to thank the Indonesian Agency for Geophysics, Climatology, and Meteorology (BMKG) for providing earthquake data used in this study. We also firmly acknowledge GEOFON GFZ and Incorporated Research Institutions for Seismology (IRIS) for which seismic data were freely available at http://eida.gfz-potsdam.de/webdc3/ and http://www.iris.edu/wilber3/find. This article has also benefited from constructive reviews from two anonymous reviewers. This work is funded by DRPM, The Ministry of Education and Culture, The Republic of Indonesia.

DATA AVAILABILITY STATEMENT (DAS)

We are happy to report the availability of data related to the results of our study as we write in this article. With this data accessibility information, we anticipate even more uses of this open data. The data analyzed in this study are available in the following urls: 1. T_dT_{50ex} data derived from public domain resources (our product). These data were derived from the following resources availablei n the public domain (our product) http://prediksi-tsunami.unesa.ac.id/www/history_event.html or http://prediksi-tsunami.unesa.ac.id/www/ 2).Tsunami Event Validity (TEV) data derived from public domain resources. These data were derived from the following resources available in the public domain: https://www.ngdc.noaa.gov/hazel/view/hazards/tsunami/event-search 3).Moment magnitude (M_w) and earthquake parameters data derived from public domain resources. These data were derived from the following resources available in the public domain: https://ds.iris.edu/wilber3/find_event and http://prediksi-tsunami.unesa.ac.id/www/

REFERENCES

Clément, J. and Reymond, D., 2014 New Tsunami Forecast Tools for the French Polynesia Tsunami Warning System. *Pure and Applied Geophysics* 172(3-4). DOI: 10.1007/s00024-014-0888-6

Geist, E. L. & Bilek, S. L., 2001. Effect of depth-dependent shear modulus on tsunami generation along subduction zones, *Geophys. Res. Lett.*, **28**(7), 1315-1318.

Lay, T., Ye, L., Bai, Y., Cheung, K. F., Kanamori, H., Freymueller, J., Steblov. G. M. & Kogan, M. G., 2017. Rupture along 400 km of the Bering fracture zone in the Komandorsky islands earthquake (M_w 7.8) of 17 July 2017, *Geophys. Res. Lett.*, **44**(12), 12161-12169.

Lomax, A. & Michelini, A., 2009. Tsunami early warning using earthquake rupture duration, *Geophys. Res. Lett.*, **36**, L09306.

Lomax, A. & Michelini, A., 2011. Tsunami early warning using earthquake rupture duration and *P*-wave dominant period: the importance of length and depth of faulting, *Geophys. J. Int.*, **185**(1), 283-291.

Lomax, A. & Michelini, A., 2012. Tsunami early warning within five minutes, *Pure Appl. Geophys.,* **170**, 1385-1395.

Lomax, A., Satriano, C, and Vassallo, M., 2012. Automatic Picker Developments and Optimization: FilterPicker a Robust, Broadband Picker for Real-Time Seismic Monitoring and Earthquake Early Warning. *Seismological Research Letters* 83:531-540.

Madlazim, 2011. Toward Indonesian tsunami early warning system by using rapid rupture durations calculation, *Sci. Tsu. Hazards*, **30**(4), 233-243.

Madlazim, 2013. Assessment of tsunami generation potential through rapid analysis of seismic parameters-case study: comparison of the Sumatra earthquakes of 6 April and 25 October 2010, *Sci. Tsu. Hazards*, **32**(1), 29-38.

Madlazim, 2015. Validation of Joko Tingkir software using tsunami importance, *Sci. Tsu. Hazards*, **34**(3), 289-198.

Madlazim & Prastowo, T., 2016. Evaluation of earthquake parameters used in the Indonesian Tsunami Early Warning System, *Earthq. Sci.*, **29**(1), 27-33.

Madlazim, Prastowo, T., Rohadi, S. & Hardy, T., 2018. Filter-M application for automatic computation of P-wave dominant periods for tsunami early warning, *Sci. Tsu. Hazards*, **37**(1), 26-33.

Madlazim, Rohadi, S., Koesoema, S. & Meilianda, E., 2019. Development of tsunami early warning application four minutes after an earthquake, *Sci. Tsu. Hazards*, **38**(3), 132-141.

Nakamura, Y., 1988. On the urgent earthquake detection and alarm system (UrEDAS), *Proc. of the 9th World Conference on Earthquake Engineering*, Tokyo-Kyoto, Japan.

Necmioglu, Ö. & Özel, N. M., 2014. An earthquake source sensitivity analysis for tsunami propagation in the eastern Mediterranean, *Oceanog.*, **27**(2), 76-85.

Newman, A.V., Hayes, G., Wei, Y. & Convers, J., 2011. The 25 October 2010 Mentawai tsunami earthquake, from real-time discriminants, finite-fault rupture, and tsunami excitation, *Geophys. Res. Lett.*, **38**, L05302.

Polet, J. & Kanamori, H., 2009. Tsunami Earthquakes, in Encyclopedia of Complexity and Systems Science, edited by A. Meyers, Springer, New York, pp. 10370.

Power, W., Clark, K., King, D. N., Borrero, J., Howarth, J. & Lane, E. M., 2017. Tsunami runup and tide-gauge observations from the 14 november 2016 M7.8 Kaikoura earthquake, New Zealand. *Pure Appl. Geophys*., **174**(7), 2457-2473.

Satake, K., 1994. Mechanism of the 1992 Nicaragua tsunami earthquake. *Geophys. Res. Lett*., **21**(23), 2519-2522.

Satake, K., 2002. *Tsunamis*, in International Handbook of Earthquake and Engineering Seismology, pp. 437–451, eds W.H.K. Lee, H. Kanamori, P.C. Jennings & C. Kisslinger, Academic Press, Amsterdam.

Sutton, J., Vos, S. C., Wood, M. M. & Turner, M., 2018. Designing effective tsunami messages: examining the role of short messages and fear in warning response, *Weath., Clim., and Soc.,* **10**(1), 75-78.

Tsushima, H., Hirata, K., Hayashi, Y., Tanioka, Y., Kimura, K., Sakai, S., Shinohara, M., Kanazawa, T., Hino, R. & Maeda, K., 2011. Near−field tsunami forecasting using offshore tsunami data from the 2011 off the Pacific coast of Tohoku Earthquake*, Earth, Plan. And Space.*, **63**, 821-826.

Ulrich, T., Vater, S., Madden, E. H., Behrens, J., van Dinther, Y., van Zelst, I., Fielding, E. J., Liang, C. & Gabriel, A. A., 2019. Coupled, physics-based modeling reveals earthquake displacements are critical to the 2018 Palu, Sulawesi Tsunami, *Pure Appl. Geophys*., **176**(32), 4069-4109.

Wu, Y. M. & Kanamori, H., 2005. Experiment on an onsite early warning method for the Taiwan early warning system, *Bull. Seismol. Soc. Am.*, **95**(1), 347-353.

APPENDIX (Tables 1 and 2)

Table 1. The results for tsunami parameter estimates from all the strike-slip and normal-faulting earthquakes within a time period of 2011-2020.

No.	Origin Time (UTC)	Location	Latitude	Longitude	Depth (km)	M_w	T_d (s)	T_{50ex}	T_dT_{50ex} (s)	*TEV*	*TCC*	Event	Type	Status
1.	2011-07-06 19:03:18	Kermadec Island	29.3° S	176.2° W	25.4	7.6	10.2	2.1	21.2	4	1	Yes	ONF	TW
2.	2012-03-09 07:09:53	Vanuatu Island	19.2° S	169.8° E	33.7	6.6	6.7	0.9	6.0	4	1	Yes	ONF	FW
3.	2012-04-11 08:38:37	Off West Coast of North Sumatra	2.2° N	93.0° E	26.3	8.6	9.4	2.0	18.3	4	1	Yes	OSSF	TW
4.	2012-04-11 10:43:10	Off West Coast of North Sumatra	0.8° N	92.4° E	21.6	8.2	7.8	2.0	15.8	4	1	Yes	OSSF	TW
5.	2013-01-05 08:58:19	Southeastern Alaska	55.2 ° N	134.8 ° W	3.1	7.5	14.1	1.6	22.5	4	1	Yes	OSSF	TW
6.	2013-02-28 15-26-38	Santa Cruz Island	10.9° S	166.2° E	22.4	7.0	4.9	1.7	8.1	4	1	Yes	OSSF	FW
7.	2013-07-21 05:09:32	Cook Strait	41.7° S	174.4° E	16.3	6.5	8.2	0.9	7.9	4	1	Yes	OSSF	FW
8.	2013-04-19 03:05:52	Kuril Island	46.1° N	150.9° E	109.0	7.2	2.9	2.8	7.8	2	1	No	ONF	TW
9.	2014-04-01 23:46:47	Near Coast Of Northern Chile	19.6° S	70.9° W	17.1	8.1	7.1	2.2	15.8	4	1	Yes	ORF	TW
10.	2014-04-12 20:14:38	Solomon Islands	11.2° S	162.1° W	15.3	7.6	11.7	1.8	21.2	4	1	Yes	OSSF	TW
11.	2014-04-19 13:28:00	Solomon Island	6.7 ° S	154.9° E	39.8	7.5	12.5	2.1	27.1	4	1	Yes	ORF	TW
12.	2014-11-15 02:31:42	Northern Molucca Sea	1.8° N	126.5° E	47.8	7.0	4.5	2.3	10.5	3	1	Yes	ORF	TW
13.	2015-02-16 23:06:28	Off East Coast Of Honshu	39.9 ° N	143.1 ° E	10.8	6.7	5.4	2.3	12.5	4	1	Yes	ORF	TW
14.	2015-03-29 23:48:31	New Britain Region	4.8° S	152.6° E	41.3	7.5	10.2	1.7	16.9	4	1	Yes	ORF	TW

No.	Origin Time (UTC)	Location	Latitude	Longitude	Depth (km)	M_w	T_d (s)	T_{50ex}	T_dT_{50ex} (s)	*TEV*	*TCC*	Event	Type	Status
15.	2015-05-05 01:44:04	New Britain Region	5.5° S	151.9° E	29.6	7.5	5.2	2.0	10.3	3	1	Yes	CRF	TW
16.	2015-07-10 04:12:42	Solomon Island	9.4° S	158.3° E	20.0	6.7	7.2	1.1	7.8	4	1	Yes	OSSF	FW
17.	2015-07-18 02:27:32	Santa Cruz Island	10.5° S	165.1° E	11.8	6.9	9.3	1.7	15.9	4	1	Yes	ONF	TW
18.	2015-09-16 22:54:32	Near Coast Of Central Chile	31.6° S	71.7° W	22.4	8.3	5.1	2.4	12.2	4	1	Yes	ORF	TW
19.	2015-11-17 07:10:07	Greece	38.7° N	20.6° E	11.0	6.5	2.5	1.0	4.6	4	3	Yes	CSSF	FW
20.	2016-03-02 12:49:48	Southwest of Sumatra	4.9° S	94.3° E	24.0	7.8	8.4	2.05	17.1	4	1	Yes	OSSF	TW
21..	2016-04-16 23:58:36	Near Coast Of Ecuador	0.4° N	79.9° W	20.6	7.8	9.4	1.8	16.8	4	1	Yes	CRF	TW
22.	2016-08-12 01:26:36	Southeast of Loyalty Island	22.5° S	173.1° E	16.4	7.2	9.4	1.1	10.7	4	1	Yes	OSSF	TW
23.	2016-08-1 07:32:22	South Georgia Island Region	55.3° S	31.9° W	10.0	7.4	10.0	1.5	14.9	3	1	Yes	ORF	TW
24.	2016-11-1 11:02:59	Kaikoura New Zealand	42.7° S	173.1° E	22.0	7.8	11.0	1.9	20.8	4	1	Yes	CSSF	TW
25.	2016-11-21 20:59:49	Near East Coast of Honsu	37.4° N	141.4° E	11.4	6.9	8.8	2.3	19.9	4	1	Yes	ONF	TW
26.	2016-11-24 18:43:48	Off Coast Of Central America	11.9° N	88.8° W	10.3	6.9	7.4	1.0	8.1	4	1	Yes	ONF	FW
27.	2016-12-08 17:38:46	Solomon Island	10.7° S	161.3° W	41.0	7.8	12.5	2.2	27.2	4	1	Yes	ORF	TW
28.	2016-12-09 19:10:07	Solomon Island	10.7° S	161.1° W	21.1	6.9	12.5	1.4	16.8	4	1	Yes	ORF	TW
29.	2016-12-17 10:51:10	New Ireland Region	4.5° S	153.5° E	94.5	7.9	5.6	1.9	10.5	4	1	Yes	ORF	TW
30.	2016-12-25 14:22:27	Southern Chile	43.4° S	73.9° W	38.0	7.6	9.0	2.2	19.9	4	1	Yes	ORF	TW

No.	Origin Time (UTC)	Location	Latitude	Longitude	Depth (km)	M_w	T_d (s)	T_{50ex}	T_dT_{50ex} (s)	TEV	TCC	Event	Type	Status
31.	2017-01-03 21:52:30	South of Fiji Island	19.4° S	176.1° E	126.9	6.9	9.5	0.7	6.9	4	1	Yes	ONF	FW
32.	2017-01-2 04:30:22	Solomon Islands	6.2° S	155.1° E	135.0	7.9	9.5	1.8	16.8	4	1	Yes	ORF	TW
33.	2017-07-17 23:34:13	Komandorskiye Ostrova	54.5° N	168.8° E	10.9	7.7	7.6	1.6	12.3	4	1	Yes	OSSF	TW
34.	2017-09-08 04:49:20	Near Coast of Chiapas Mexico	15.0° N	93.9° W	56.7	8.1	7.2	2.4	17.2	4	1	Yes	ONF	TW
35.	2017-11-01 02:23:55	Loyalty Islands	21.7° S	168.9° E	9.9	6.6	6.3	0.9	6.0	4	1	Yes	ONF	FW
36.	2018-01-10 02:51:31	North of Honduras	17.5° N	83.5° W	10.0	7.5	11.1	1.8	20.2	4	1	Yes	OSSF	TW
37.	2018-01-14 09:18:45	Near Coast Of Peru	15.8° S	74.7° W	39.0	7.1	7.5	1.5	11.2	4	1	Yes	ORF	TW
38.	2018-01-23 09:31:42	Gulf of Alaska	56.0° N	149.0° W	25.0	7.9	2.7	2.6	6.9	4	1	Yes	OSSF	FW
39.	2018-09-28 10:02:43	Palu Indonesia	0.2° S	119.8° E	10.0	7.5	8.4	1.9	15.9	4	3	Yes	CSSF	TW
40.	2018-08-29 03:51:56	Southeast Of Loyalty Islands	22.1° S	170.0° E	26.6	7.1	6.3	0.9	5.6	4	1	Yes	ORF	FW
41.	2018-10-25 22:54:52	Ionian Sea	37.5° N	20.6° E	14.0	6.8	5.3	2.4	12.8	4	1	Yes	ORF	TW
42.	2018-12-05 04:18:08	Southeast of Loyalty Island	21.9° S	169.4° E	10.0	7.5	8.6	1.5	12.9	4	1	Yes	ONF	TW
43.	2019-05-14 12:58:26	New Britain Region	4.1° S	152.6° E	10.0	7.5	8.6	0.8	7.4	2	1	No	OSSF	TW
44.	2019-06-15 22:55:04	Karmades Island	30.6° S	178.1° W	46.0	7.3	12.4	1.1	14.1	4	1	Yes	ORF	TW
45.	2020-01-28 19:10:24	Cuba Region	19.4° N	78.8° W	14.8	7.7	8.8	1.7	14.9	4	1	Yes	OSSF	TW

46.	2020-03-25 02:49:20	East Of Kuril Islands	48.9° N	157.7° E	55.3	7.5	8.3	2.0	16.5	4	1	Yes	ORF	TW
47.	2020-06-18 15:29:04	South Of Kermadec Islands	33.3° S	117.8° W	10.0	7.4	6.8	1.9	13.2	1	1	Yes	OSSF	TW
48.	2020-06-23 12:49:53	Near Coast Of Oaxaca, Mexico	15.9° N	96.0° W	20.0	7.4	18.9	1.9	35.7	4	1	Yes	CRF	TW
49.	2020-07-22 06:12:44	Alaska Peninsula	55.0° N	158.5° W	28.0	7.8	4.2	2.3	9.7	4	1	Yes	ORF	FW
50.	2020-10-19 20:54:39	South Of Alaska	54.6° N	159.6° W	31.1	7.6	2.3	2.2	4.9	4	1	Yes	OSSF	FW
51.	2020-10-30 11:51:27	Dodecanese Islands, Greece	37.1° N	26.8° E	21.0	7.0	8.6	1.6	13.8	4	1	Yes	ONF	TW

Notes: CSSF (Continental Strike-Slip Fault), OSSF (Oceanic Strike-Slip Fault), CNF (Continental Normal Fault), ONF (Oceanic Normal Fault), CRF (Continental Reverse Fault), ORF (Oceanic Reverse Fault), FW (False Warning), TW (True Warning), TEV (Tsunami Event Validity), TCC (Tsunami Cause Code)

Table 2. The results for assessment of tsunami potential using M_w and T_dT_{50ex} discriminants.

Discriminant	Available (minutes after OT)	Threshold Value	True Warning (TW)			False warning (FW)		
			$TEV \geq 3$	$TEV < 3$	%**	$TEV \geq 3$	$TEV < 3$	%**
M_w	15	7.0	36	0	71%	13	2	29%
T_dT_{50ex}	4	10.0 s	39	2	76%	12	0	24%

*51 events classified; 39 occurrences have $TEV \geq 3$

** percentage of True Warning or False Warning

ISSN 8755-6839

SCIENCE OF TSUNAMI HAZARDS

Journal of Tsunami Society International

Volume 41 Number 1 2022

TSUNAMI RISK COMMUNICATION: ASSESSING KNOWLEDGE GAPS AND SUITABLE SERIOUS GAMES

Steven Hawthorn[1], Rui Jesus[1,2], Maria Ana Baptista[3]

[1] *NOVA LINCS, Faculdade de Ciências e Tecnologia, Universidade NOVA de Lisboa*
[2]*Instituto Superior de Engenharia de Lisboa, Instituto Politécnico de Lisboa*
[3]*Instituto Dom Luiz, Faculdade de Ciências da Universidade de Lisboa*
Contact email: shawthorn@googlemail.com

ABSTRACT

The study developed a survey instrument to identify tsunami risk perception and knowledge gaps in school children, and undertook a review of existing classroom deployable tsunami serious games for risk communication, along with evidence for their effectiveness. Analysis of responses suggests more action-oriented content would provide a more comprehensive understanding of the tsunami risk. It found that while children show a general awareness of the tsunami concept, recognition of natural warning signs of tsunami could be improved. A lack of evidence for the effectiveness of serious games represents a significant research gap. While serious games show promise in the communication of the tsunami risk, the coverage of action oriented key messages from disaster risk reduction organisations could be significantly improved. It is believed that this, combined with an improved understanding and coverage of curricular objectives will improve the effectiveness of future games.

Keywords: *Tsunami, risk communication, serious games, children*

1. INTRODUCTION

A central notion in the disaster risk reduction (DRR) process is the idea that appropriately prepared individuals make better decisions and reduce their exposure to risk. Part of this preparedness stage involves communication of information about the risk from one party to another, broadly referred to as risk communication (RC). While a number of methods of RC are available, this paper is focused on the potential for using serious games (SGs) as an innovative way to communicate natural hazard risk (specifically related to tsunami) to children.

This research aimed to assess whether innovative technologies in the form of SGs improve tsunami risk communication and identify the current availability and evidence for effectiveness for such games to communicate tsunami risk.

In particular, the research aimed to; 1) identify how children perceive tsunami risk in Morocco, in order to identify existing knowledge gaps; 2) review and investigate the existing provision of classroom deployable serious games for tsunami risk communication, and; 3) assess peer reviewed evidence for the effectiveness of existing SGs to communicate tsunami risk.

Morocco is seismically active and has endured significant earthquakes in the past (Cherkaoui, 2012) (Omira et al., 2012) with coastal impacts by tsunamis (Kaabouben et al., 2009). Subsequently, it was chosen as a suitable location for the distribution of a survey investigating tsunami risk perception. While alerting systems offer a technological solution to notifying people of an incoming tsunami, earthquakes can occur sufficiently close to the coast that timely alerts are not effective (Pincock, 2007) (Andres et al., 2010) (Papadopoulos et al., 2020). Recognition of natural warning signs (NWS) such as ground shaking, allows individualas to make immediate evacuation decisions. However, tsunami can also travel long distances over which NWS would not be evident. Education including natural warning signs combined with operational sensor-based warning systems would provide complementary approaches to warn the authorities and inform evacuation decisions.

The purpose of this paper is twofold and is organized as follows. First, it presents the results of a survey conducted with school children to understand their perception of tsunami risk and identify knowledge gaps (which will inform the development a digital SG for tsunami risk communication). Second, it summarises a review of existing classroom deployable tsunami SGs, assesses peer reviewed evidence for their effectiveness and finally brings part 1 and part 2 together by mapping the identified knowledge gaps with coverage of key messages in the selected tsunami games.

2. TSUNAMI RISK PERCEPTION SURVEY

2A. Communicating Risk

Risk communication is not new (Petal, 2008) and a variety of definitions of risk communication exist (Barry et al., 2013), but passage of information between parties is central to the concept. In the context of natural hazards, risk communication is a key element in the mitigation stage of the disaster management cycle, usually as general education, but also specific training in the preparedness stage. Central to the effectiveness of the communication is the harmonisation of the risk message that will enable individuals to make appropriate decisions and take action. The International Federation of Red Cross and Red Crescent Societies (IFRC) refers to these as action-oriented key messages (AOKM) (International Federation of the Red Cross and Red Crescent Societies; Save the Children International, 2018a) (UNESCO International Tsunami Information Center, n.d.).

2A 1. Action Oriented Risk Communication

In this study, risk communication focuses on education to equip individuals to recognise imminent hazard and inform appropriate decisions to reduce risk, primarily by evacuating prior to the arrival of the first wave. However, effective risk communication does not simply mean providing information in the form of a probability of hazard occurrence.

Initial risk communication approaches focused on the transmission of a risk message to address a presumed knowledge deficit between scientific experts and lay public (Demeritt, 2014) (Wardman, 2008) (Simis et al., 2016). This ‘deficit model’ of risk communication assumed that once the knowledge deficit had been filled, the information recipients would be able to respond appropriately. Discussion and debate has criticised this approach and suggested that a more interactive approach is preferable (Bodmer, 1985). Although logically comprehensible, disaster information provided in isolation can be considered meaningless (Simis et al., 2016).

Poorly conceived risk communications can have a negative effect, if provided without information to enable to develop coping appraisals (Rogers, 1975). Interactive activities, combined with debriefing activities, support the development of action plans and provide learners with coping appraisals. AOKM, as part of an interactive exchange-based process from credible DRR organisations rather than delivery of an information product, can improve risk communication and decision appropriateness (Rollason et al., 2018).

Interactive activities (such as SGs) are supported by constructivist pedagogic approaches where knowledge development is considered an emergent property of a construction, analysis and review process. This approach considers simple fact transfer as insufficient, as students need to actively process information to develop knowledge (Bodner, 1986) (Bada, 2015) (Gampell et al., 2019). The knowledge development process is aided by participatory, interactive and discursive activities. Such activities have the advantage of putting learners in virtual situations that are impossible to re-create, but allow decision-making in stressful and uncertain conditions.

A review of earthquake preparedness from an information type perspective (passive, interactive and experiential) suggested experiential information significantly impacted preparedness process in a positive way (J. Becker et al., 2012). This suggests risk communication should combine passive ‘fact’ information with interactive and experiential information in a social ‘real world’ context to improve effectiveness of the risk message. SGs can go some way to providing this context and can harness learner engagement as an inherent property of play, suggesting that more effective learning if players are enjoying the experience (Prensky, 2002). Learner motivation is an important consideration in risk communication as traditional “fact transfer” exercises tend to challenge learner motivation (Anastasiadis et al., 2018) but research suggests that engagement of learner curiosity through their own experience reduces the dilution effect of observational learning of someone else’s experience (Duerden & Witt, 2010). Innovative interactive approaches using new technologies can generate greater engagement and provide support for additional discursive activities and debriefing sessions. It is believed that this will improve the effectiveness of risk communication (Crookall, 2010) (Bellotti et al., 2013) and that SGs provide a vehicle where increased engagement and therefore more effective learning can take place.

2A 2. Children in Disasters

This work is aimed at secondary school children, for the following reasons. Children are exceptionally vulnerable in emergencies as the receivers of potentially misinformed advice and incompetent emergency management (Ronan et al., 2015) (Hasegawa, 2013). They can be significantly impacted by, and tend to suffer disproportionately from natural hazard events (Mitchell et al., 2009) (Kousky, 2016) (Amri et al., 2018) and arguably should be enabled to make apprroriate decisions if necessary (Ogie et al., 2019). Children have a lot to contribute to disaster preparedness activities (Pfefferbaum et al., 2018), may be better informed than adults, and can affect decision making of family members to positively affect disaster outcomes. An example is the case of a well informed 10-year-old girl who raised the alarm before the 2004 Indonesian Tsunami (Rajib et al., 2011).

The idea of adults attuned to the needs of family, and children as passive recievers of risk information has been challenged (Mitchell et al., 2009) concluding that children have a significant role to play in DRR. Specifically, they noted that children can act as conduits for risk communication, but need DRR institutions willing to include the perspective of children. A further reason for focussing on children is the lack of research on the effects of disaster information on children (Midtbust et al., 2018) which suggests that schools are appropriate places for programmes outlining potential risks as part of a formal education process. School children are a ‘captive audience’ who can be guided through activities that are curriculum focused. This process would inform teachers of actionable advice from specialist disaster agencies through ongoing practice (Ball & Mcdiarmid, 1989), however the deployment challenges of using SGs in school environments should not be underestimated given the limited techical training that some educators have (Marklund & Taylor, 2016).

Students were working from home due to COVID 19, a simple online survey was used to assess the perception of tsunami risk in a group of school children in Morocco.

3. SURVEY METHODOLOGY

3A 1. Previous Tsunami Risk Surveys

A number of previously conducted surveys were reviewed as related work for this study. In Indonesia a study of 169 children found that a curriculum focused program for disaster education was effective, (Adiyoso, W., & Kanegae, 2012). The 77 question European Union ASTARTE survey was directed at adults and included a single question focused on ‘precursor signs’ as an indication of imminent tsunami. In southern Portugal an earthquake risk survey undertaken with adults briefly addressed tsunami risk. The majority of respondents (94%) felt that Portugal was not prepared to deal with an earthquake emergency situation although tsunami was not explicitly mentioned (Vicente et al., 2014). In Italy, 1600 individuals were surveyed to assess their perception of tsunami risk. Results showed that tsunami risk perception was generally low, affected by media accounts of large tsunami in Indonesia (2004) and Japan (2011) and the risk of minor events is neglected or underrated (Crescimbene et al., 2020). A survey of 314 Ecuadorian senior high school pupils concentrated on differences in tsunami knowledge between coastal dwellers and city inhabitants of Quito and indicated significant regional differences between the two groups (Edler & Toulkeridis, 2020).

This brief review of surveys demonstrates very little research focus on inputs from children in understanding their perception of tsunami risk in the Mediterranean region.

3A 2. Survey Approach

In the initial part of this work, an inductive approach using an attitudinal survey (Likert, 1932) was used to obtain a representative perspective of children’s attitude to tsunami risk in Morocco. This work is an extension of the results (Hawthorn et al., 2021b). Respondents were invited to agree or disagree, to (17) statements relating to tsunami hazard, risk of tsunami and habits related to coastal visits. The items used simple language, and offered five levels of response; strongly disagree; disagree; neither agree or disagree; agree; and strongly agree. The online survey was kept short to respect classroom time constraints and learner attention spans. It was distributed to language teachers and geography teachers at AEFE (The Agency for French Education Abroad) administered schools in Fes, Casablanca, Rabat and Tangier as a cross curricular English and geography activity, as both subjects are relevant disciplines to the risk communication problem.

The research focussed on children in Morocco, because it is seismically active with a both a Mediterranean and Atlantic Ocean coastline, where most population centres are located.

3A 3. Survey Results

Frequency distributions are shown as rounded percentages and summed as agreement and disagreement catergories (Fig. 1) to summarise the responses, 170 participants started the survey: 46% female, 48% male, 6% preferred not to say; 15 respondents provided partial responses, resulting in 155 complete responses. Response frequencies were calculated as percentages using available responses to the item.

The majority (88%) of respondents lived more than 50km away from the coast, but visit the coastal cities (79%) or spend holidays close to the beach (78%). Most respondents were under 15 years old (80%), and all respondents (except 1) lived in Morocco.

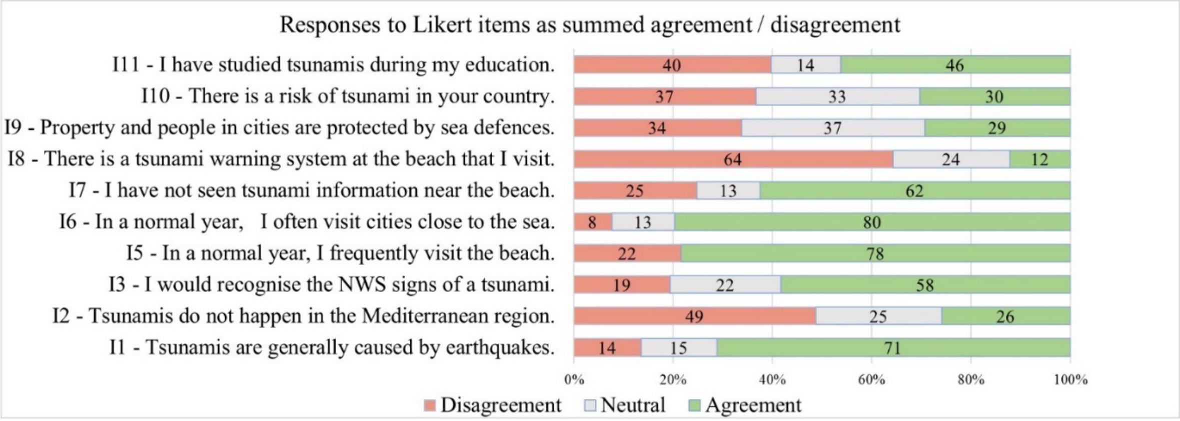


Figure 1. *Responses to main Likert items as summed agreement / disagreement.*

Respondents were asked if they would recognize the NWS of tsunami. Over half, (58%) asserted they would, 22% neither agreed or disagreed and almost 20% indicated that they wouldn't. Item 4 presented four valid NWS, and two spurious NWS. Respondents were asked to indicate if the NWS were valid or invalid. The four correct NWS elicited the following responses; ground shaking 34% yes, 66% no; a loud noise from the sea 21% yes, 79% no; bubbles in the water, 41% yes, 59% no; water going out to sea 34% yes, 66% no.

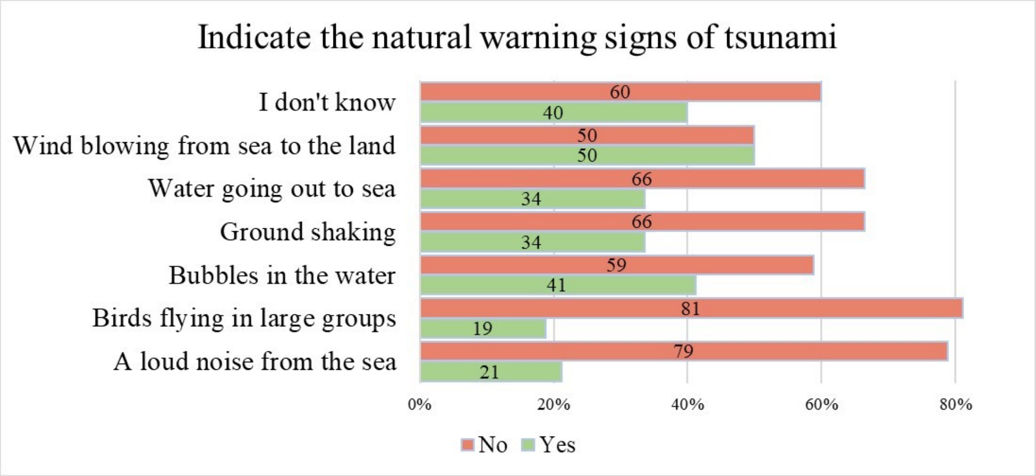


Figure 2. *Responses to item 4 - indicate the natural warning signs of tsunami.*

The results of this survey suggest that respondents understood the relationship between earthquakes and tsunami, but were unable to recognize tsunami NWS and that there was significant uncertainty related to tsunami risk in Morocco.

3A 4. Measures of Association

The research investigated measures of association for selected variables. Values express a greater than relationship with an unknown degree of difference and are considered ordinal data (Wu & Leung, 2017). Non-parametric, bivariate analysis for Likert items computed Kendall's tau correlation coefficient for selected variables (Boone & Boone, 2012). To assess respondents' knowledge of tsunami NWS a derived variable was created as a summed score of correct responses to item 4 – (Indicate the natural warning signs of tsunami). This provided a tsunami NWS knowledge score for each respondent. Strength of correlation was determined in accordance with (Asuero et al., 2006), where 0 - 0.29 is little if any correlation, 0.3 - 0.49 is a low, 0.5 - 0.69 is moderate, 0.7 - 0.89 is high and 0.9 - 1 is very high. The correlation results are summarised below. The number of respondents varies as some respondents only partially completed the survey. Pairwise deletion was used to deal with missing values.

Correlation 1 examined the relationship between the responses to item 1, (Tsunamis are generally caused by earthquakes) and a derived variable, made up of summed answers to item 4, (Knowledge of tsunami NWS). There was a very weak, positive correlation between the two variables, $r_\tau = .0185$, $N = 170$; however, the relationship was not statistically significant ($p = .781$). This suggests that the learning activity which communicated the causality between earthquakes and tsunami, did not address tsunami NWS.

Correlation 2 examined the relationship between the responses to item 3, (I would recognise the natural warning signs of a tsunami) and a derived variable, made up of summed answers to item 4 – (as above). There was a weak, positive correlation between the two variables, $r_\tau = .151$, $N = 170$; the relationship was statistically significant at the 0.05 level ($p = .019$). This suggests that the respondent's level of certainty about recognising tsunami was not related to their knowledge of tsunami NWS.

Correlation 3 examined the relationship between the responses to item 1, (as above) and item 10 – (There is a risk of tsunami in your country). There was a very weak, positive correlation between the two variables, $r_\tau = .024$, $N = 155$; however, the relationship was not statistically significant ($p = .719$). This suggests that the learning activity which communicated the causality between earthquakes and tsunami, did not address tsunami risk related to the respondent's country of residence.

Correlation 4 examined the relationship between item 2, (Tsunamis do not happen anywhere in the Mediterranean region) and item 10, (as above). There was a weak, positive correlation between the two variables, $r_\tau = .192$, $N = 155$; the relationship was statistically significant the 0.05 level ($p = .004$). The result suggests that respondents understanding of tsunami risk in the Mediterranean region and their understanding of tsunami risk in their country of residence are not related.

Correlation 5 was computed to assess the relationship between item 10, (as above) and item 16, (I live close to the sea). There was a very weak, positive correlation between the two variables, $r_\tau = .052$, N = 155; however, the relationship was not statistically significant ($p = .462$). The respondent's perception of tsunami risk in their country did not appear to be associated with their residential proximity to the sea. This result concurs with the finding of (Lujala et al., 2015), suggesting that living in close proximity to a hazard is not enough to affect understanding of tsunami risk.

The results of the correlation analysis suggest greater coverage and coordination between general tsunami awareness and AOKM would improve respondents' ability to respond to NWS in a timely and appropriate way.

4. TSUNAMI SERIOUS GAMES

The following section summarises the availability of classroom deployable SGs for communicating tsunami risk.

4A 1. Serious Games for Risk Communication

The oxymoronic nature of the term 'serious game'(Bente & Breuer, 2010) contributes to the complexity of defining the term. Comprehensive discussions are available in (Sawyer, 2002) (Michaud & Alvarez, 2008) (Michael & Chen, 2006) but are beyond the scope of this paper. A serious game can be considered an activity with game elements which is designed to be enjoyable and educational. However, the SG industry covers occupations including health, defence and advertising, therefore definitions can be affected to territorial focus (Djaouti et al., 2011). The focus of this research is on the feasibility of combining innovative computer technologies with interactive approaches in the form of SGs. The definition of SGs for this article is a piece of software that combines a video game structure with a non-entertaining educational purpose.

The study reviewed SG and simulations in escalating situations, then focused on SG for natural hazards and tsunami scenarios which contain evacuation decisions. Applications of SGs include combat training, (Hunt et al., 1987), (Yildirim, 2014), (Angelevski & Bogatinov, 2014), (Samčović, 2018) healthcare training, (Khorram-Manesh et al., 2016), (Zhang et al., 2018), industrial emergency management training, (Metello et al., 2008), and civil defence emergencies (Ra et al., 2016), (Mossel et al., 2017). However, a distinction must be made between military or medical professionals who understand the likelihood of applying their learning in an emergency situation and school learners who perceive the risk of an emergency scenario to be low. In such cases so called 'stealth learning' is appropriate (Sharp, 2012).

Evacuation scenarios have tended to focus on crowd events (Garcia-Garcia et al., 2012) and building examples (Ribeiro et al., 2012). A review of SGs in evacuation scenarios (Feng et al., 2018) showed a significant emphasis on fire rather than earthquake scenarios, use university students as participants, and it recommended a focus on earthquake safety training but did not explicitly mention tsunami evacuation. Most studies utilized university students, with a single study using a virtual environment and children as research subjects (Smith & Ericson, 2009).

A review of SGs in disaster risk scenarios identified 45 non-commercial SGs for disaster risk management, 5 of which were specific to tsunami hazard, 3 were computer-based, Disaster Master, Stop Disasters and Earth Girl (Solinska-nowak et al., 2018). Significant work has been undertaken on analog games played in groups for risk professionals and policy makers (Suarez & Patt, 2004), (Suarez, 2013), (Parker et al., 2016). While engaging, fun and informative, (Suarez, 2015) they need a trained facilitator, and reach relatively small number of professional players, as such they were not considered in this study.

4A 2. TSGs Review Method

The review adopted a systematic approach and used Google Scholar due to its comprehensive coverage simple and general reliability of the research results retrieved (Martín-Martín et al., 2018). The results were sorted using the Publish or Perish software (Harzing, 2016). A multifaceted search included references in journals and a manual search of the ISCRAM Digital Library. The review focused on digital SGs designed to communicate tsunami hazard risk and to school aged children (9-16). The specific review criteria are summarised as follows; a) it focused on digital SGs aimed at children (aged 9-16) and used articles in peer reviewed journals, but included relevant government and disaster agency reports; b) it concentrated on classroom deployable games, which are preferably online, require minimal installation, and supported with educational materials.

4A 3. TSGs Evidence for Effectiveness

Five SGs were found that met the review criteria. An additional number were found that would be challenging to deploy in a classroom environment. These included commercially developed games (Whaley, 2019) which require PlayStation consoles unavailable in schools. A number of university developed simulations (Hatayama et al., 2019), (Jacoby et al., 2019), (Kawai & Kaizu, 2019) provide interesting insights but were developed with analysis in mind, are not easily accessible and would prove challenging to deploy in the classroom. Tsunami Fighters is an SG which appears to offer a useful addition, however, at the time of writing it was not accessible for evaluation, (Alifia et al., 2020).

4A 4. Summary of Classroom Deployable Games

The review found 5 digital serious games for tsunami risk communication which were summarised in (Hawthorn et al., 2021a). “Stop Disasters” is included even though it does not involve an evacuation scenario.

4A 5. Evidence for effectiveness of the selected tsunami games

Part of the second objective of this study was to assess evidence for the effectiveness of the specific SGs identified during the review. This section provides a brief summary of research evidence specifically related to the effectiveness of the four games, Disaster Master, Earth Girl 2, Stop Disasters and Tanah – Tsunami and Earthquake Fighter.

A full debate on measuring the effectiveness of SGs is beyond the scope of this paper, however it is central to the idea that SGs could be a more effective way to teach natural hazard risk. It is also important to reflect on what 'we' as educators are trying to communicate specifically in terms of evacuation, in particular the question of increasing risk to oneself to assist others, versus focussing on self-reliance. This is referred to as evacuation philosophy and is relevant as it affects the game design and effectiveness criteria against which a game can be evaluated.

The "Tendenko" philosophy (born out of generations of experience living in the Tohoku region of Japan) (Yamori, 2020) recommends active self-determined evacuation without delay for any reason, including to help others. In some cases where arrival time of the first wave is short, inhabitants must recognise ground shaking as a warning sign and begin immediate evacuation using their own initiative (Harnantyari et al., 2020).

Altruistic approaches focus on helping others as a priority, even if this increases one's own risk. The differences in these two evacuation philosophies are reflected in the reward mechanisms of different games and could influence how learners make future decisions during a potential tsunami event, and therefore warrant careful consideration by game developers because what games 'teach' will affect how learners react to a natural hazard event and could result in negative outcomes.

Evaluation of the effectiveness of SGs appears to be infrequent (Gampell et al., 2017) and as such there is a significant research gap related to assessing effectiveness of using SGs to communicate risk. A meta-analysis reviewed SGs in the educational context where games tend to be used to teach traditional school subjects, concluded that evidence for serious games as effective learning materials is quite strong (Backlund & Hendrix, 2013). Of 40 studies, 29 produced positive results, 7 were neutral, 2 negative and 2 unclear. While academic achievement was not significantly different between the experimental and the control groups, learners in the experimental group improved learning motivation was reported.

An example using an experiential approach in the form of a game-based approach for flood risk management produced improved outcomes for learner motivation, and more effective results in when compared with a textbook-based learning approach (Meera et al., 2016). This section summarizes peer reviewed evidence of effectiveness for the use of the selected tsunami games outlined in this paper. From an educator's perspective, **Disaster Master** is perhaps the easiest game to deploy in a classroom as it requires very little setup or instruction for learners to use. The application covers 4 out of 7 of the AOKM related to decision-making and evacuation. Although no evidence of effectiveness testing was found in the literature, Findlay (Findlay, 2017) summarized learning points in a knowledge matrix. Disaster master provides a general overview of a natural hazards and could be useful as the basis for discursive activities.

Stop Disasters does not include evacuation decision making, instead, focusing on community resilience planning. A Brazilian study using 10–13-year-old high school children used pre-test post-test assessment of game experience, to investigate potential areas of improvement and understanding of natural disasters. The study compared a game approach with a traditional approach and concluded that subjects in the game player group significantly changed their perception of risks and improved their risk awareness (Felicio et al., 2014). The results suggest it was effective in this case.

In the case of **Earth Girl or Earth Girl 2,** no research evidence was found related to the effectiveness of the game.

Tanah – Tsunami and Earthquake Fighter specifically addresses the preparation and evacuation issue in an earthquake / tsunami scenario. There is very limited research related to the effectiveness of this game. However, one study (translated from Indonesian using software) using a pre-experimental design and a one group pretest-posttest design used a simple random sampling technique to assess the effectiveness of the game. The subjects were 10-year-old school children.

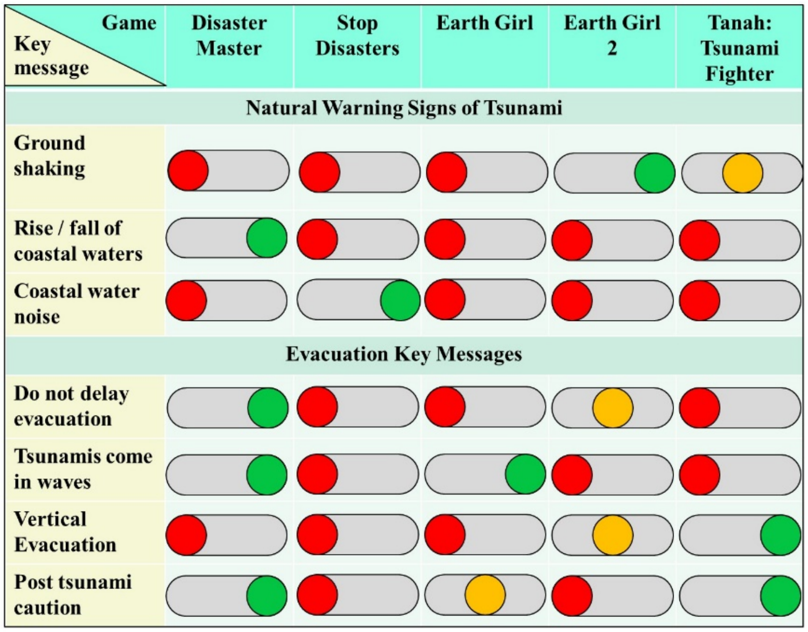
The statistical analysis used a Wilcoxon test, where p = 0.000 <0.05. The work concluded that there was a significant effect and concluded that using a game based approach prepared students to face disasters (Ariandini, 2019). As such, there is some evidence that the Tanah – Tsunami and Earthquake Fighter game is effective in communicating tsunami risk to children.

Another study concluded a significant difference existed between experiment group and control group for use of an (unspecified) android-based earthquake game (Winarni et al., 2021).

5. DISCUSSION

5A 1. Mapping Tsunami SGs to AOKM

This section of the paper brings together the knowledge gaps identified in part 1 and the classroom deployable TSGs in part 2. This was done by using a simple matrix to map the extent of coverage of AOKM in the selected tsunami games (Hawthorn et al., 2021a).



Game / Key message	Disaster Master	Stop Disasters	Earth Girl	Earth Girl 2	Tanah: Tsunami Fighter
Natural Warning Signs of Tsunami					
Ground shaking	🔴	🔴	🔴	🟢	🟡
Rise / fall of coastal waters	🟢	🔴	🔴	🔴	🔴
Coastal water noise	🔴	🟢	🔴	🔴	🔴
Evacuation Key Messages					
Do not delay evacuation	🟢	🔴	🔴	🟡	🔴
Tsunamis come in waves	🟢	🔴	🟢	🔴	🔴
Vertical Evacuation	🔴	🔴	🔴	🟡	🟢
Post tsunami caution	🟢	🔴	🟡	🔴	🟢

Figure 3. *Mapping key messages to coverage in the selected games.*

The table presented above (Fig. 3) shows a mapping between the key messages from (International Federation of the Red Cross and Red Crescent Societies; Save the Children International, 2018a) and their coverage in the selected games. A green indicator represents comprehensive coverage in the game, amber represents partial coverage and red represents very limited or zero coverage. The mapping shows that none of the selected games address all 7 of the key messages.

A key finding of the work suggests that existing games do not comprehensively address actionable risk messages. Subsequently, it is suggested that coverage of all 7 AOKM is likely to increase the effectiveness of the tsunami SGs from the educational perspective.

Reflection on the limited coverage of AOKM remains speculative without a thorough knowledge of the game development process. Inclusion of tsunami NWS may have been considered unnecessary as most game scenarios involved an operational warning system. It is also feasible that the game requirements elicitation process disregarded some AOKM or that they were 'traded out' as part of a requirements prioritisation process during the game development. The 'Drop, Cover, Hold' key message related to earthquake actions (International Federation of the Red Cross and Red Crescent Societies; Save the Children International, 2018b) was included in the 'Tanah' game. Only two of the five games reviewed 'Disaster Master' and 'Tanah-Earthquake and Tsunami Fighter' addressed the issue of self-evacuation decision making.

5A 2. Development Considerations to Improve Effectiveness

Children naturally explore their environment and make sense of their world through play and are increasingly exposed to high levels of technology. Digital games facilitate contextualisation of players learning experiences, support situated cognition and can provide a more engaging experience than traditional education methods and evidence suggests that SGs can be effective learning tools if well implemented (Bellotti et al., 2013), (De Gloria et al., 2014), (Clark et al., 2016). However, due to the essentially multidisciplinary approach required in developing SGs and lack of formal methods, the infusion of pedagogy in a deep and effective way represents a complex challenge (De Gloria et al., 2014).

Although a number of approaches are available (Braad et al., 2016), it is widely accepted that game characteristics and specifically game mechanics can significantly affect learning outcomes (De Gloria et al., 2014), (Clark et al., 2016), (Alexiou, 2018). However, this study suggests the need for thorough consideration of desired learning outcomes and their alignment with specialist (in this case DRR) organisation recommendations. Decisions made at the project initiation stage, in terms of stakeholder inclusion, are likely to influence effectiveness outcomes as well as design pre-occupations. A critical consideration is the classroom deployment model for a SG.

While game developers tend to focus on game mechanics and narrative elements for increasing game effectiveness, (Becker & Gopin, 2016) add to the discussion in the context of using commercial off the shelf (COTS) games for learning. They outline a number of characteristics that affect the effectiveness of the game which can also be applied to the design and development of serious games and are likely to impact their effectiveness. The key points are that games should be a) linked to teaching objectives; b) technologically accessible and useable by educators; c) supported by education materials such as discursive activities, worksheets and quizzes. The 4 pillars of educational games (4PEG) template they propose may serve as a useful guide to the educational perspective for game designers. They note that one key challenge of using game technology is the need for teachers to justify their use, by demonstrating curricular ties, justifying student assessment and informing lesson plans. Without these resources it will not matter how good the gameplay aspects of the game are.

However, this approach assumes that the curriculum has been updated with relevant information, in this case AOKM. It is possible that the AOKM for tsunami are not currently incorporated into the educational curriculum and therefore were overlooked during game development. Intrestingly the earthquake AOKM “drop, cover hold” is found in curriculum materials (Taylor & Moeed, 2013) but potentially tsunami AOKM were given lower prioriry than more general awareness raising information.

Engagement characterisitics of a game should also consider the educator’s perpective, as teachers who remain uncommitted to an SG for any reason will simply opt for an alternative activity. Stakeholder contributions to the SG requrements development process have been suggested and the equitable involvement of all stakeholder groups is likely to significantly affect the effectiveness of the futute games (Hawthorn et al., 2921a).

6. CONCLUSIONS AND RECOMMENDATIONS

The following section summarises the conclusions of this work and presents the corresponding recommendations for future studies. It is divided into three parts, the risk perception survey, the existing tsunami games and the effectiveness of SGs for tsunami risk communication.

A review of previous **surveys** of children’s tsunami risk perception showed a very limited number. The survey undertaken as part of this work showed significant uncertainty around tsunami risk in Morocco. While limited in scope it suggests that future tsunami projects should aim to assess and clarify tsunami risk perception in vulnerable groups, such as children. Specifically, the survey indicated a lack of knowledge of AOKM and uncertainty in recognising NWS. It is recommended that NWS and DRR AOKM be included in the curriculum in the same way that the earthquake AOKM ‘drop, cover, hold’ is mentioned in curriculum materials.

Classroom deployable **tsunami games** are rare. Of those available, the coverage of NWS is insufficient (max 57%). It is recommended that future game developments 1) refer to AOKM available from DRR organisations, and 2) consider the implications a particular evacuation philosophy from both an educator and learner perspective.

The review of evidence for **effectiveness** of tsunami SGs is extremely limited, although general material related to SGs show improved learner motivation and engagement. A key conclusion from this work suggests that effectiveness from an educational perspective could be significantly improved. It is recommended that AOKM and specifically tsunami NWS are comprehensively included in future games. This study agrees with (Gampell et al., 2020) in that the pedagogical implications of using SGs in the classroom require additional study. In conclusion, while no single method of risk communication will address all communication scenarios (Demeritt, 2014), it is reasonable to suggest that SGs have can play an important role in an increasingly digital learning experience.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the financial support by FCT through project UIDB/50019/2020 – IDL and the grant given to S. Hawthorn by NOVA LINCS.

REFERENCES

Adiyoso, W., & Kanegae, H. (2012). The effect of different disaster education programs on tsunami preparedness among schoolchildren in Aceh, Indonesia. Disaster Mitigation of Cultural Heritage and Historic Cities. 6(1), 165–172. https://core.ac.uk/download/pdf/60537577.pdf

Alexiou, A. (2018). Digital game elements, user experience and learning: A conceptual framework. Educ Inf Technol, 23, 2545–2567. https://doi.org/10.1007/s10639-018-9730-6

Alifia, R. R., Rahma, F., Hamida, U., Koesoema, A. P., S.irawan, Y., & Egawa, S. (2020). Tsunami Fighters: Collaborative Multilingual Mobile Game for Earthquake and Tsunami Disaster Preparedness Education. IEEE Region 10 Humanitarian Technology Conference, R10-HTC, December. https://doi.org/10.1109/R10-HTC49770.2020.9357038

Amri, A., Haynes, K., Bird, D. K., & Ronan, K. (2018). Children's Geographies Bridging the divide between studies on disaster risk reduction education and child-centred disaster risk reduction: a critical review. Children's Geographies, 16(3), 239–251. https://doi.org/10.1080/14733285.2017.1358448

Anastasiadis, T., Lampropoulos, G., & Siakas, K. (2018). Digital Game-based Learning and Serious Games in Education. International Journal of Advances in Scientific Research and Engineering, 4(12), 139–144. https://doi.org/10.31695/ijasre.2018.33016

Andres, M., Gelcich, S., Araya, G., Olea, G., Castilla, J. C., & Espı, M. (2010). The 2010 tsunami in Chile : Devastation and survival of coastal small-scale fishing communities. Marine Policy, 34, 1381–1384. https://doi.org/10.1016/j.marpol.2010.06.010

Angelevski, S., & Bogatinov, D. (2014). Computer gaming technology for military training–serious games. INTERNATIONAL SCIENTIFIC DEFENCE, SECURITY AND PEACE JOURNAL, 14(26), 73–85. http://eprints.ugd.edu.mk/12694/

Ariandini, K. A. N. L. (2019). The Effect on Education Based on Android Games of Conversion of Tsunami and Earthquakes [Denpasar Health Polytechnic]. http://repository.poltekkes-denpasar.ac.id/id/eprint/2435

Asuero, A. G., Sayago, A., & Gonz, A. G. (2006). The Correlation Coefficient : An Overview. Critical Reviews in Analytical Chemistry, 36(10), 41–59. https://doi.org/10.1080/10408340500526766

Backlund, P., & Hendrix, M. (2013). Educational games - Are they worth the Effort?: A literature survey of the effectiveness of serious games. 2013 5th International Conference on Games and Virtual Worlds for Serious Applications, VS-GAMES 2013, December. https://doi.org/10.1109/VS-GAMES.2013.6624226

Bada, S. O. (2015). Constructivism Learning Theory: A Paradigm for Teaching and Learning. Journal of Research & Method in Education (IOSR-JRME), 5(6), 66–70. https://doi.org/10.9790/7388-05616670

Ball, D., & Mcdiarmid, G. (1989). The Subject Matter Preparation of Teachers. In W. R. Houston (Ed.), Handbook for Research on Teacher Education. New York: Macmillan. https://www.researchgate.net/publication/234587984_The_Subject_Matter_Preparation_of_Teachers_Issue_Paper_89-4

Barry, M. M., Oroviogoicoechea, C., & Guillen-grima, F. (2013). A literature review on effective risk communication for the prevention and control of communicable diseases in Europe Insights into health communication. January. https://doi.org/10.2900/64747

Becker, J., Paton, D., Johnston, D., & Ronan, K. (2012). A model of household preparedness for earthquakes: How individuals make meaning of earthquake information and how this influences preparedness. *Natural Hazards*, *64*(1), 107-137. https://doi.org/10.1007/s11069-012-0238-x

Becker, K., & Gopin, E. (2016). Selection Criteria for Using Commercial Off the Shelf Games (COTS) for Learning. In K. Schrier (Ed.), Learning, Education & Games: Volume Two: Bringing Games into Educational Contexts (Issue January, pp. 43–60). ETC Press. https://www.researchgate.net/publication/308402340_Selection_Criteria_for_Using_Commercial_Off_the_Shelf_Games_COTS_for_Learning

Bellotti, F., Kapralos, B., Lee, K., Moreno-Ger, P., & Berta, R. (2013). Assessment in and of serious games: An overview. Advances in Human-Computer Interaction, 2013. https://doi.org/10.1155/2013/136864

Bente, G., & Breuer, J. (2010). Why so serious? On the Relation of Serious Games and Learning. Eludamos - Journal for Computer Game Culture, 4(1), 7–24. http://www.eludamos.org/index.php/eludamos/article/viewArticle/vol4no1-2

Bodmer, W. F. (1985). The Public Understanding of Science. Report of a Royal Society Ad Hoc Group Endorsed by the Council of the Royal Society. https://royalsociety.org/~/media/royal_society_content/policy/publications/1985/10700.pdf

Bodner, G. M. (1986). Constructivism: A Theory of Knowledge. Journal of Chemical Education, 63, 873–878. https://doi.org/http://dx.doi.org/10.1021/ed063p873

Boone, H. N., & Boone, D. A. (2012). Analyzing Likert Data. Journal of Extension, 50(2), 1–5. https://archives.joe.org/joe/2012april/pdf/JOE_v50_2tt2.pdf

Braad, E., Žavcer, G., & Sandovar, A. (2016). Processes and models for serious game design and development. Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), 9970 LNCS(October), 92–118. https://doi.org/10.1007/978-3-319-46152-6_5

Cherkaoui, T.-E. (2012). Seismicity and Seismic Hazard in Morocco 1901-2010. Bulletin de l'Institut Scientifique ·, 34(January), 45–55. https://www.researchgate.net/publication/264545014%0ASeismicity

Clark, D. B., Tanner-smith, E. E., & Killingsworth, S. S. (2016). Digital Games, Design, and Learning: A Systematic Review and Meta-Analysis. Review of Educational Research, 86(1), 79–122. https://doi.org/10.3102/0034654315582065

Crescimbene, M., Cerase, A., Amato, A., Cerbara, L., & Longa, F. La. (2020). Tsunami risk perception in southern Italy (EGU General Assembly 2020; EGU2020-22528). https://doi.org/https://doi.org/10.5194/egusphere-egu2020-22528

Crookall, D. (2010). Serious games, debriefing, and simulation/gaming as a discipline. Simulation & Gaming, 41(6), 898–920. https://doi.org/10.1177/1046878110390784

De Gloria, A., Bellotti, F., & Berta, R. (2014). Serious Games for education and training. International Journal of Serious Games, 1(1). https://doi.org/10.17083/ijsg.v1i1.11

Demeritt, D. (2014). Models of best practice in flood risk communication and management. December. https://doi.org/10.1080/17477891.2014.924897

Djaouti, D., Alvarez, J., & Jessel, J.-P. (2011). Classifying Serious Games. In Patrick Felicia (Ed.), Handbook of Research on Improving Learning and Motivation through Educational Games: Multidisciplinary Approaches (Issue January, pp. 118–136). https://doi.org/10.4018/978-1-60960-495-0.ch006

Duerden, M. D., & Witt, P. A. (2010). The impact of direct and indirect experiences on the development of environmental knowledge, attitudes, and behavior. Journal of Environmental Psychology, 30(4), 379–392. https://doi.org/10.1016/j.jenvp.2010.03.007

Edler, D., Otto, K., & Toulkeridis, T. (2020). Tsunami hazards in Ecuador – regional differences in the knowledge of Ecuadorian high-school students, Sci. Tsunami Hazards. 39, (2). 86–112. http://tsunamisociety.org/392EdlerEtAl.pdf

Felicio, S. P. A. S., Silva, V. S. R., Dargains, A. R., Souza, P. R. A., Sampaio, F., Carvalho, P. V. R., Gomes, J. O., & Borges, M. R. S. (2014). Stop disasters game experiment with elementary school students in Rio de Janeiro: Building safety culture. ISCRAM 2014 Conference Proceedings - 11th International Conference on Information Systems for Crisis Response and Management, May, 585–591. https://www.researchgate.net/publication/298069702_Stop_Disasters_Game_Experiment_with_Elementary_School_Students_in_Rio_de_Janeiro_Building_Safety_Culture

Feng, Z., González, V. A., Amor, R., Lovreglio, R., & Cabrera-Guerrero, G. (2018). Immersive virtual reality serious games for evacuation training and research: A systematic literature review. ArXiv, July. https://www.researchgate.net/publication/325332898_Immersive_Virtual_Reality_Serious_Games_for_Evacuation_Training_and_Research_A_Systematic_Literature_Review

Findlay, B. (2017). Digital Games in Disaster Preparedness Education (Issue July 2017) [University of Auckland]. https://doi.org/10.13140/RG.2.2.24698.03527

Gampell, A., Gaillard, J. C., Parsons, M., & Le Dé, L. (2020). 'Serious' Disaster Video Games: An Innovative Approach to Teaching and Learning about Disasters and Disaster Risk Reduction. Journal of Geography, 119(5), 159–170. https://doi.org/10.1080/00221341.2020.1795225

Gampell, A. V., Gaillard, J. C., Parsons, M., & Fisher, K. (2017). Beyond Stop Disasters 2.0: an agenda for exploring the contribution of video games to learning about disasters. Environmental Hazards, 16(2), 180–191. https://doi.org/10.1080/17477891.2016.1275502

Gampell, A. V., Gaillard, J., & Parsons, M. (2019). On the use of participatory methodologies for video game research: Exploring disaster risk reduction in video games. Methodological Innovations, 12(3), 205979911988427. https://doi.org/10.1177/2059799119884277

Garcia-Garcia, C., Luis Fernández-Robles, J., Larios-Rosillo, V., & Luga, H. (2012). ALFIL: A crowd simulation serious game for massive evacuation training and awareness. International Journal of Game-Based Learning, 2(3), 71–86. https://doi.org/10.4018/ijgbl.2012070105

Harnantyari, A. S., Takabatake, T., Esteban, M., Valenzuela, P., Nishida, Y., Shibayama, T., Achiari, H., Rusli, Marzuki, A. G., Marzuki, M. F. H., Aránguiz, R., & Kyaw, T. O. (2020). Tsunami awareness and evacuation behaviour during the 2018 Sulawesi Earthquake tsunami. International Journal of Disaster Risk Reduction, 43(November 2019). https://doi.org/10.1016/j.ijdrr.2019.101389

Harzing, A.-W. (2016). Publish or Perish. Research in International Management. https://harzing.com/resources/publish-or-perish

Hasegawa, R. (2013). Disaster Evacuation from Japan's 2011 Tsunami Disaster and the Fukushima Nuclear Accident. IDDRI, May, 1–54.
https://orbi.uliege.be/bitstream/2268/195804/1/STUDY0513_RH_DEVAST report-1.pdf

Hatayama, M., Kosaka, T., & Hernandeze, A. H. (2019). Analysis on Tsunami Evacuation Options with Agent-based Simulation in Tourist Area. 2018 5th International Conference on Information and Communication Technologies for Disaster Management, ICT-DM 2018. https://doi.org/10.1109/ICT-DM.2018.8636385

Hawthorn, S., Jesus, R., & Baptista, M. A. (2021a). A Review of Digital Serious Games for Tsunami Risk Communication. International Journal of Serious Games, 8(2), 21–47. https://doi.org/https://doi.org/10.17083/ijsg.v8i2.411

Hawthorn, S., Jesus, R., & Baptista, M. A. (2021b). Identification of Knowledge Gaps to Inform a Serious Game for Tsunami Risk Communication. 14th Conference on Human Systems Interaction. https://doi.org/10.1109/HSI52170.2021.9538748

Hunt, J., Broom, J. M., Greene, W. H., Crawford, J. W., Martere, R. F., & Parish, J. R. (1987). Multipurpose Arcade Combat Simulator (MACS). In U.S. Army Research Institute for the Behavioral and Social Sciences.
https://www.researchgate.net/publication/235167850_Multipurpose_Arcade_Combat_Simulator_MACS

International Federation of the Red Cross and Red Crescent Societies; Save the Children International. (2018a). Public awareness and public education for disaster risk reduction: Action-oriented key messages for households and schools - Second edition - Updated and revised. https://media.ifrc.org/ifrc/wp-content/uploads/sites/5/2018/11/PAPE-AW-WEB-min.pdf

International Federation of the Red Cross and Red Crescent Societies; Save the Children International. (2018b). Public Awareness and Public Education for Disaster Risk Reduction. https://media.ifrc.org/ifrc/messages-disaster-prevention/#3

Jacoby, D., Coady, Y., Dahl, E., Wynden, A., & Richardson, M. (2019). VR Tsunami! ACM SIGGRAPH 2019 Appy Hour, 1–2. https://doi.org/10.1145/3305365.3329728

Kaabouben, F., Baptista, M. A., Brahim, A. I., Mouraouah, A. El, & Toto, A. (2009). On the Moroccan tsunami catalogue. Natural Hazards and Earth System Science, 9, 1227–1236.

Kawai, Y., & Kaizu, Y. (2019). Tsunami evacuation simulation system for disaster prevention plan. Proceedings - 2019 International Conference on Cyberworlds, CW 2019, 362–365. https://doi.org/10.1109/CW.2019.00067

Khorram-Manesh, A., Berlin, J., & Carlström, E. (2016). Two Validated Ways of Improving the Ability of Decision-Making in Emergencies; Results from a Literature Review. Bull Emerg Trauma, 4(4), 186–196. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5118570/pdf/bet-4-186.pdf

Kousky, C. (2016). Impacts of Natural Disasters on Children. Future of Children, 26(1), p73-92. https://doi.org/http://dx.doi.org/10.1353/foc.2016.0004

Likert, R. (1932). A technique for the measurement of attitudes. ARCHIVES OF PSYCHOLOGY, 22(No. 140), 5–55. https://legacy.voteview.com/pdf/Likert_1932.pdf

Lujala, P., Lein, H., & Rød, J. K. (2015). Climate change, natural hazards, and risk perception: the role of proximity and personal experience. Local Environment, 20(4), 489–509. https://doi.org/10.1080/13549839.2014.887666

Marklund, B. B., & Taylor, A. A. (2016). Educational Games in Practice : The challenges involved in conducting a game-based curriculum. The Electronic Journal of E-Learning, 14(2), 122–135. https://academic-publishing.org/index.php/ejel/article/view/1749/1712

Martín-Martín, A., Orduna-Malea, E., Thelwall, M., & Delgado López-Cózar, E. (2018). Google Scholar, Web of Science, and Scopus: A systematic comparison of citations in 252 subject categories. Journal of Informetrics, 12(4), 1160–1177. https://doi.org/10.1016/j.joi.2018.09.002

Meera, P., McLain, M. L., Bijlani, K., Jayakrishnan, R., & Rao, B. (2016). Serious Game on Flood Risk Management (pp. 197–206). https://doi.org/10.1007/978-81-322-2553-9_19

Metello, M. G., Casanova, M. A., & Carvalho, M. T. M. (2008). Using serious game techniques to simulate emergency situations. Proceedings of the Brazilian Symposium on GeoInformatics, April 2014, 171–181. https://www.researchgate.net/publication/220913332_Using_Serious_Game_Techniques_to_Simulate_Emergency_Situations

Michael, D., & Chen, S. (2006). Serious Games: Games That Educate, Train, and Inform. Course Technology PTR. https://www.researchgate.net/publication/234812017_Serious_Games_Games_That_Educate_Train_and_Inform

Michaud, L., & Alvarez, J. (2008). Serious Games: Advergaming, edugaming, training... IDATE. https://www.researchgate.net/publication/286354308_Serious_Games_Advergaming_edugaming_training

Midtbust, L. G. H., Dyregrov, A., & Djup, H. W. (2018). Communicating with children and adolescents about the risk of natural disasters. European Journal of Psychotraumatology, 9(sup2). https://doi.org/10.1080/20008198.2018.1429771

Mitchell, T., Tanner, T., & Haynes, K. (2009). Children as agents of change for Disaster Risk Reduction: Lessons from El Salvador and the Philippines. (No. 1; Issue 1). https://www.researchgate.net/publication/228376320_Children_as_Agents_of_Change_for_Disaster_Risk_Reduction_Lessons_from_El_Salvador_and_the_Philippines

Mossel, A., Vienna, A.-, Peer, A., & Göllner, J. (2017). Requirements Analysis on a Virtual Reality Training System for CBRN Crisis Preparedness. ISSS-2015, 1–20. https://journals.isss.org/index.php/proceedings59th/article/view/2486

Ogie, R. I., Rho, J. C., & Clarke, R. J. (2019). Artificial Intelligence in Disaster Risk Communication: A Systematic Literature Review. 2018 5th International Conference on Information and Communication Technologies for Disaster Management, ICT-DM 2018, 1–8. https://doi.org/10.1109/ICT-DM.2018.8636380

Omira, R., Baptista, M. A., & Mellas, S. (2012). The November 1st , 1755 Tsunami in Morocco : Can Numerical The November , 1 st , 1755 Tsunami in Morocco : Can Numerical Modeling Clarify the Uncertainties of Historical Reports ? May 2017. https://doi.org/10.5772/51864

Pablo Suarez. (2015). Games4sustainability:Climate Risk Management game - MASHLM. https://games4sustainability.org/2015/12/15/pablo-suarez-games/

Papadopoulos, G. A., Lekkas, E., & Katsetsiadou, K. (2020). GeoHazards Tsunami Alert Efficiency in the Eastern Mediterranean. GeoHazards, May, 44–60. https://doi.org/https://doi.org/10.3390/geohazards1010005

Parker, H. R., Cornforth, R. J., Suarez, P., Allen, M. R., Boyd, E., James, R., Jones, R. G., Otto, F. E. L., Walton, P., & Parker, H. R. (2016). Using a Game to Engage Stakeholders in Extreme Event Attribution Science. 353–365. https://doi.org/10.1007/s13753-016-0105-6

Petal, M. (2008). Disaster Risk Reduction Education: Material Development, Organization, and Evaluation. Regional Development Dialogue Journal, 28(2), 1–25. https://www.researchgate.net/publication/277821824_Disaster_Risk_Reduction_Education_Material_Development_Organization_Evaluation

Pfefferbaum, B., Pfefferbaum, R. L., & Van Horn, R. L. (2018). Involving children in disaster risk reduction: the importance of participation. European Journal of Psychotraumatology, 9(sup2). https://doi.org/10.1080/20008198.2018.1425577

Pincock, S. (2007). Gaps exist in tsunami preparedness plans. The Lancet, 369(9579), 2065. https://doi.org/10.1016/S0140-6736(07)60960-X

Prensky, M. (2002). The Motivation of Gameplay or, the REAL 21st century learning revolution. On The Horizon, 10(No. 1), 5–11. https://doi.org/10.1108/10748120210431349

Ra, G., Sung, J., Yu, H., & Min, H. (2016). Analysis of Serious Games Based on Pedagogical Features and Proposal of Civil Defence Training Game. Int. J. Comput. Vision Robot., 6(3), 235–243. https://doi.org/10.1504/IJCVR.2016.077354

Rajib, S., Yukiko, T., Qi, R. G., & Koichi, S. (2011). Chapter 1 Disaster Education: An Introduction. In R. Shaw, K. Shiwaku, & Y. Takeuchi (Eds.), Disaster Education (Vol. 7, pp. 1–22). Emerald Group Publishing Limited. https://doi.org/10.1108/S2040-7262(2011)0000007007

Ribeiro, J., Almeida, J. E., Rossetti, R. J. F., Coelho, A., & Coelho, A. L. (2012). Using serious games to train evacuation behaviour. Iberian Conference on Information Systems and Technologies, CISTI. https://www.researchgate.net/publication/261280150_Using_serious_games_to_train_evacuation_behaviour

Rogers, R. W. (1975). A Protection Motivation Theory of Fear Appeals and Attitude Change1. The Journal of Psychology, 91(1), 93–114. https://doi.org/10.1080/00223980.1975.9915803

Rollason, E., Bracken, L. J., Hardy, R. J., & Large, A. R. G. (2018). Rethinking flood risk communication. Natural Hazards, 92(3), 1665–1686. https://doi.org/10.1007/s11069-018-3273-4

Ronan, K. R., Alisic, E., Towers, B., Johnson, V. A., & Johnston, D. M. (2015). Disaster Preparedness for Children and Families: a Critical Review. Current Psychiatry Reports, 17(7), 1–9. https://doi.org/10.1007/s11920-015-0589-6

Samčović, A. B. (2018). Serious Games in Military Applications. Military Technical Courier, 66(3), 597–613. https://doi.org/10.5937/vojtehg66-16367

Sawyer, B. (2002). Serious games: Improving public policy through game-based learning and simulation. https://www.researchgate.net/publication/243771574_Serious_games_Improving_public_policy_through_game-based_learning_and_simulation

Sharp, L. (2012). Stealth Learning: Unexpected Learning Opportunities Through Games. Journal of Instructional Research, 1, 42–48. https://doi.org/10.9743/jir.2013.6

Simis, M. J., Madden, H., Cacciatore, M. A., & Yeo, S. K. (2016). The lure of rationality: Why does the deficit model persist in science communication? Public Understanding of Science, 25(4), 400–414. https://doi.org/10.1177/0963662516629749

Smith, S., & Ericson, E. (2009). Using immersive game-based virtual reality to teach fire-safety skills to children. Virtual Reality, 13(2), 87–99. https://doi.org/10.1007/s10055-009-0113-6

Solinska-nowak, A., Magnuszewski, P., Curl, M., French, A., Keating, A., Mochizuki, J., Liu, W., Mechler, R., & Kulakowska, M. (2018). An overview of serious games for disaster risk management – Prospects and limitations for informing actions to arrest increasing risk. International Journal of Disaster Risk Reduction, 31(August), 1013–1029. https://doi.org/10.1016/j.ijdrr.2018.09.001

Suarez, P. (2013). Using games to experience climate risk: Empowering Africa’s decision-makers. http://www.climatecentre.org/downloads/files/Games/CDKNGamesReport.pdf

Suarez, P., & Patt, A. (2004). Cognition, caution, and credibility: the risks of climate forecast application. Risk, Decision and Policy, 9(1), 75–89. https://doi.org/10.1080/14664530490429968

Taylor, M., & Moeed, A. (2013). Curriculum shockwaves ? Geography , science , and the Canterbury earthquakes. Curriculum Matters, 9, 8–28. https://www.nzcer.org.nz/system/files/CM2013_9_008_1.pdf

UNESCO International Tsunami Information Center. (n.d.). International Tsunami Information Center Home Page. Retrieved September 15, 2020, from http://itic.ioc-unesco.org/index.php

Vicente, R., Miguel, T., Maio, R., & Koch, H. (2014). Awareness, perception and communication of earthquake risk in Portugal : Public survey. Procedia Economics and Finance, 18(September), 271–278. https://doi.org/10.1016/S2212-5671(14)00940-X

Wardman, J. K. (2008). The Constitution of Risk Communication in Advanced Liberal Societies. Risk Analysis, 28(6), 1619–1637. https://doi.org/10.1111/j.1539-6924.2008.01108.x

Whaley, B. (2019). Virtual Earthquakes and Real-World Survival in Japan’s Disaster Report Video Game. Journal of Asian Studies, 78(1), 95–114. https://doi.org/10.1017/S0021911818002620

Winarni, E. W., Purwandari, E. P., & Wachidi, W. (2021). The effect of android-based earthquake game toward Bengkulu City elementary school student’s knowledge about earthquake disaster preparedness. Journal of Physics: Conference Series, 1731(1). https://doi.org/10.1088/1742-6596/1731/1/012090

Wu, H., & Leung, S. (2017). Can Likert Scales be Treated as Interval Scales ?— A Simulation Study. Journal of Social Service Research, 43(4), 527–532. https://doi.org/10.1080/01488376.2017.1329775

Yamori, K. (2020). Disaster Risk Communication (K. Yamori (ed.)). Springer Singapore. https://doi.org/10.1007/978-981-13-2318-8

Yildirim, S. (2014). Serious Game Design for Military Training. Games: Design and Research Conference, January 2010, 1–10. https://www.researchgate.net/publication/265707723_serious_game_design_for_military_training

Zhang, C., Grandits, T., Härenstam, K. P., Hauge, J. B., & Meijer, S. (2018). A systematic literature review of simulation models for non-technical skill training in healthcare logistics. Advances in Simulation, 3(15), 1–16. https://doi.org/doi.org/10.1186/s41077-018-0072-7

ISSN 8755-6839

SCIENCE OF **TSUNAMI HAZARDS**

Journal of Tsunami Society International

Volume 41 **Number 1** **2022**

ANALYSIS OF THE TOP 100 CITED PUBLICATIONS IN EARTHQUAKE RESEARCH DURING 1991 TO 2021

Binar Kurnia Prahani[*1], Khoirun Nisa[1], Mohd Zaidi Bin Amiruddin[1], Nadi Suprapto[1], Madlazim[1], and Saiyidah Mahtari[2]

[1] *Universitas Negeri Surabaya, Surabaya 60231, INDONESIA*
[1] *Universitas Lambung Mangkurat, Banjarmasin 70123, INDONESIA*
Email: binarprahani@unesa.ac.id

ABSTRACT

Earthquake research has expanded over the past few decades. Also, over the past 30 years, earthquakes have become a major study because earthquakes occur every year in each region. The aims of this research is to analyze the top 100 cited articles in the earthquake field from 1991 to 2021. Research give an idea of citation, author, year, journal and country characteristics of these articles using literature review, bibliometric analysis and VOSViewer which the data from Scopus database. The research found that articles is most document type of top 100 cited papers which 2005 was the most published year for the article. The average number of citations per article was calculated as 727 citations per paper. The journal Nature is the primary source of the Nature Publishing Group, which governs the publication of the most influential earthquake studies. Kanamori is recognized as the most productive author who received the highest number of quotes and the most incredible link strength. The United States dominates the production of highly cited articles. The research areas in these papers are mainly emphasized on earthquake, states, geological, sciences, earth, and japan. Further research related to earthquakes can also be directed to the relevance of the tsunami. The results of the Scopus database show 2,098 document results [January 17, 2022] with the title "earthquake tsunami."

Keywords: *Bibliometric, Earthquakes, Top 100 cited, Tsunami,* VOSViewer.

1. INTRODUCTION

Indonesia has volcanic paths from Sumatera to Papua so probability to occur earthquake and tsunami disasters is very high (Deta et al, 2020). This can be seen from the large number of earthquakes and tsunamis that occurred in Indonesia. In addition, research about earthquake has grown over in the past few decades. Besides, earthquake become a top study in the last thirty years because every year, in each region in the world was current earthquake (Pakiser and Shedlock, 2014). Several studies have been conducted on the characteristics of prevention and mitigation such as tsunamis and their impacts, displacement of most vulnerable areas, vertical evacuation, seismic hazard and coastal resilience to tsunamis (Toulkeridis et al, 2018; Mato and Toulkeridis, 2018; Toulkeridis et al, 2019). Research could help scientists better track dangerous earthquakes for future (Rusydy et al, 2020). For example, the Earthquake Engineering and Structural Dynamics Journal have publication of papers on several aspects about engineering related to earthquakes since 1970 until now. The other example, Geoenvironmental Disasters have publications from 2014 to 2022. The number of papers in this both journal has steadily growing since its inception.

During the pandemic, the use of secondary data in research is helpful for researchers. Currently, there are studies of bibliometric analysis in various disciplines. One way to conduct a bibliometric analysis study is to use the VOSViewer software, making it easier to interpret the data visually. In addition, the advantage of this analysis is that it analyzes many scientific publications written on any subject. In bibliometric research, researchers can use citation analysis to consideration a systematic metric degree and use to discover the maxim impactful studies in a field (Suprapto et al, 2021). Papers that receive more citations are expected to have good research quality and to influence specializations in a particular field (Suprapto et al, 2021).

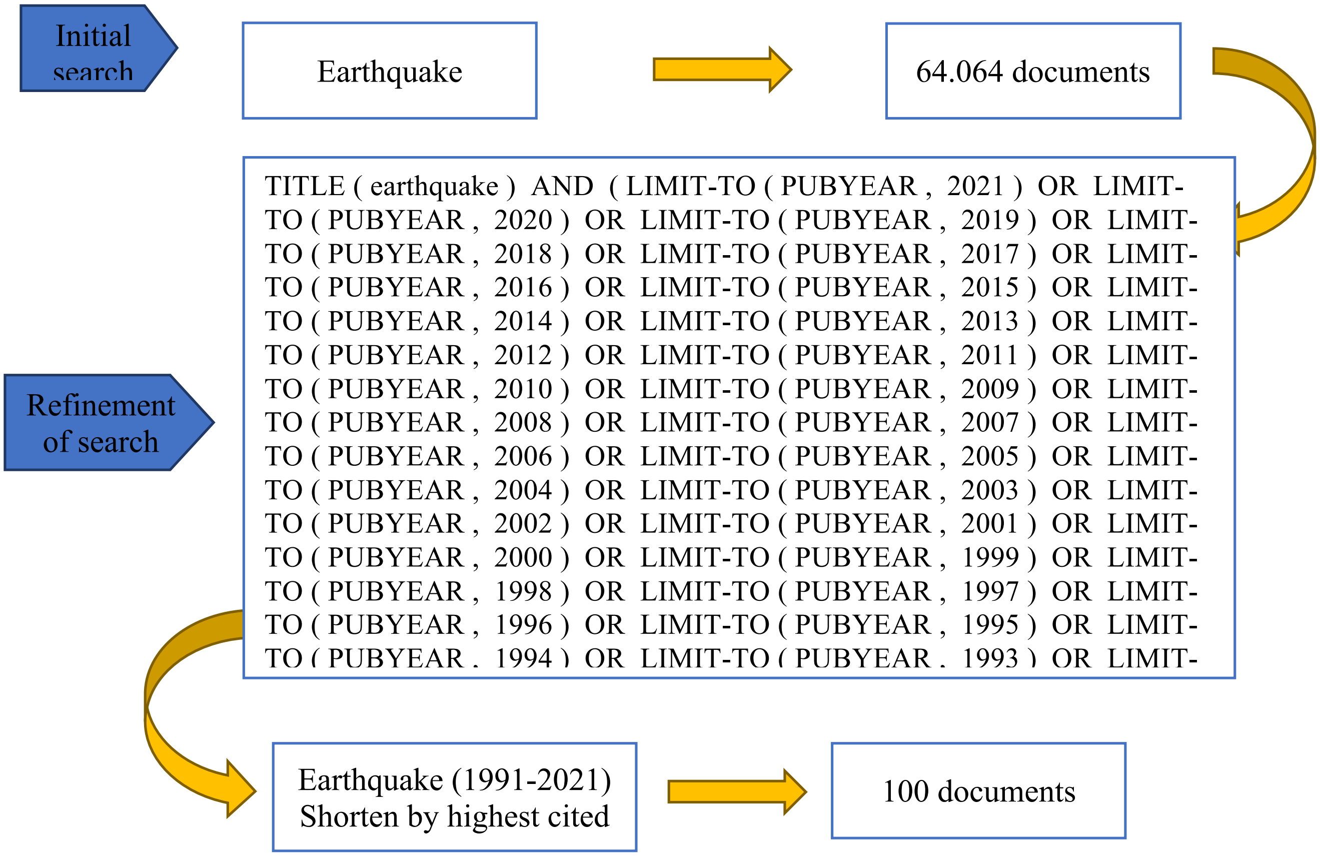
Research Objective

This research reviewed the trends of earthquake research in terms of top one hundred cited papers to identify the status of earthquake research and help researchers in future studies. The research's main objective is to explore the top one hundred cited papers on earthquake from 1991 to 2021. The specific objectives that will be discussed in this research because they are essential as a reference for future research on earthquake:

1) To know the types of publications of the top one hundred cited papers in earthquake.
2) To study the year-wise distribution of the top one hundred cited papers in earthquake.
3) To identify the sources publishing of the top one hundred cited papers in earthquake.
4) To study the authorship pattern and prolific author of the top one hundred cited papers in earthquake.
5) To know the country of origin of the papers and collaboration among them
6) To study the period of references of the top one hundred cited papers in earthquake.

2. METHODS

Research use qualitative descriptive using bibliometric analysis (Suprapto et al., 2021; Kulakki and Osmanaj, 2020, Yang et al, 2017). The database sources are from Scopus and searched for the subject category "earthquake" using the string given below. There are five steps in conducting bibliometric analysis such as keyword determination, initial search results, search refinement, initial data statistics and data analysis creation (Schmeisser, 2013; Setyaningsih, 2018).



```
TITLE ( earthquake )  AND  ( LIMIT-TO ( PUBYEAR ,  2021 )  OR  LIMIT-TO ( PUBYEAR ,  2020 )  OR  LIMIT-TO ( PUBYEAR ,  2019 )  OR  LIMIT-TO ( PUBYEAR ,  2018 )  OR  LIMIT-TO ( PUBYEAR ,  2017 )  OR  LIMIT-TO ( PUBYEAR ,  2016 )  OR  LIMIT-TO ( PUBYEAR ,  2015 )  OR  LIMIT-TO ( PUBYEAR ,  2014 )  OR  LIMIT-TO ( PUBYEAR ,  2013 )  OR  LIMIT-TO ( PUBYEAR ,  2012 )  OR  LIMIT-TO ( PUBYEAR ,  2011 )  OR  LIMIT-TO ( PUBYEAR ,  2010 )  OR  LIMIT-TO ( PUBYEAR ,  2009 )  OR  LIMIT-TO ( PUBYEAR ,  2008 )  OR  LIMIT-TO ( PUBYEAR ,  2007 )  OR  LIMIT-TO ( PUBYEAR ,  2006 )  OR  LIMIT-TO ( PUBYEAR ,  2005 )  OR  LIMIT-TO ( PUBYEAR ,  2004 )  OR  LIMIT-TO ( PUBYEAR ,  2003 )  OR  LIMIT-TO ( PUBYEAR ,  2002 )  OR  LIMIT-TO ( PUBYEAR ,  2001 )  OR  LIMIT-TO ( PUBYEAR ,  2000 )  OR  LIMIT-TO ( PUBYEAR ,  1999 )  OR  LIMIT-TO ( PUBYEAR ,  1998 )  OR  LIMIT-TO ( PUBYEAR ,  1997 )  OR  LIMIT-TO ( PUBYEAR ,  1996 )  OR  LIMIT-TO ( PUBYEAR ,  1995 )  OR  LIMIT-TO ( PUBYEAR ,  1994 )  OR  LIMIT-TO ( PUBYEAR ,  1993 )  OR  LIMIT-
```

Figure 1. Flowchart research

The data were collected on January 10, 2022. The obtained result does not limit to type of language and publication type then sorted according to "times cited" from highest cited to lowest cited. Then the data of top one hundred cited papers downloaded in *.ris* or *.csv* file format which will then be uploaded to the VOSViewer software. In this study, two analytical techniques were used to perform bibliometric analysis. The first analysis technique uses VOSViewer to reveal the network visualization of the keywords used obtained from the *.ris* file metadata. The second analytical technique, descriptive analysis, analyzes the year of publication, country, affiliation, language, and others obtained from the analyzed *.csv* metadata using *Microsoft Excel* and word cloud generator for visualization (Suprapto et al., 2021).

3. RESULTS AND DISCUSSION

3A. Publication Type

Table 1. Document Type of Top Cited Papers

Document Type	**Frequency**	**Total Cited**	**Mean**	**Median**	**S.D.**
Article	82	56275	686,28	533,5	435,50
Book	2	1035	517,50	517,5	55,86
Conference paper	3	3929	1309,66	627	1254,98
Review	12	8856	738,00	524	388,28
Short Survey	1	511	511,00	511	-
Total	**100**	**70606**	**752,49**	-	-

Table 1 shows the document types of the top one hundred cited papers about earthquake from 1991 to 2021. Of these 100 papers, 82 papers were in the form of articles, 2 were in the form of a book, 3 papers were in conferences, 12 were review papers, and 1 were in the form of a short survey. The average number of citations per paper in each category varied on average 752. However, the standard deviations of conference papers were high is 1254,98. At the same time, the average citations rate of the conference papers was the highest at 1309,66. In contrast, book and short surveys were secondary with an average of citations. The majority of the language used in the top one hundred cited papers related to the earthquake in 1991-2021 was English.

3B. Year-wise distribution of top 100 cited papers

The top one hundred cited papers of earthquake research have been published during 1991 to 2021, which 2021 is the year with the highest number of papers (3,953). Thus, 2005 with ten papers was the largest published year, followed by 2011 (8 papers), 1997 and 1998 (7 articles each). These top 100 papers received an average of 727,68 citations for a total of 70606 citations. The mean citations per paper was the highest at 1666 in 1991 and the mean citations per paper per year was the highest at 105 for 2013.

Table 2. Year wise distribution of papers

Year	Papers	Citations	ACPP	ACPPY	Citable Years
1991	3	5000	**1666,66***	53,76	31
1992	5	3062	612,40	20,41	30
1993	5	4462	892,40	30,77	29
1994	5	4779	955,80	34,14	28
1995	2	1065	532,50	19,72	27
1996	4	2007	501,75	19,29	26
1997	7	4619	659,86	26,39	25
1998	7	**5702***	814,57	33,94	24
1999	3	2309	769,66	33,46	23
2000	4	4398	1099,50	49,97	22
2001	2	953	476,50	22,69	21
2002	3	1533	511,00	25,55	20
2003	3	1281	427,00	22,47	19
2004	3	1538	512,67	28,48	18
2005	**10***	5672	567,20	33,36	17
2006	4	2430	607,50	37,96	16
2007	3	1706	568,67	37,91	15
2008	5	2414	482,80	34,48	14
2009	5	2707	541,40	41,65	13
2010	3	3734	1244,66	103,72	12
2011	8	4189	523,62	47,60	11
2012	3	2395	798,33	79,83	10
2013	2	1906	953,00	**105,88***	9
2014	1	745	745,00	93,12	8
Total	**100**	**70606**	**727,68**	**1036,63**	
*ACPP=Average Citation per Paper, ACPPY=Average Citation Per Paper Per Year, *the highest number*					

3C. Sources of Publication

The lists of sources of top 100 cited papers shown in Table 3. 41 sources either journal or conference proceedings have published the top 100 papers. The journal “Nature” is the main source publishing thirteen papers, followed by “Bulletin of the Seismological Society of America” publishing ten papers, and “Science” publishing eleven papers. The top three sources that have published the top cited papers are “Nature” were 11711 citations, “Bulletin of the Seismological Society of America” were 9439 citations, and “Science” were 7132 citations. The largest publisher is the Seismological Society of America with 16 papers and total of citations is 13,274, followed by Nature Publishing Group with 13 papers and total of citations is 17111.

Table 3. Sources of top cited papers

Sources	**Publisher**	**Papers**	**Citations**	**ACPP**
Nature	Nature Publishing Group	**13***	**11711***	**900,85***
Bulletin of the Seismological Society of America	Seismological Society of America	10	9439	943,9
Science	American Association for the Advancement of Science	11	7132	648,36
Journal of Geophysical Research: Solid Earth	Blackwell Publishing Ltd	9	4977	553
Geophysical Journal International	Oxford University Press	3	3965	1321,66
Seismological Research Letters	Seismological Society of America	6	3835	639,16
Journal of Geophysical Research	Wiley-Blackwell	6	3819	636,5
Journal of Personality and Social Psychology	APA	2	3676	1838
Geology	Geological Society of America	2	1201	600,5
Nature Geoscience	Springer Nature	2	993	496,5
Physical Review Letters	American Institute of Physics Inc. American Physical Society	3	1756	585,33
Proceedings of the 19th International Conference on World Wide Web, WWW '10	The Association for Computing Machinery	1	2758	2758
Physics of the Earth and Planetary Interiors	Elsevier	1	1471	1471
Geotechnique	ICE Publishing Ltd.	1	1280	1280
GSA Today	Geological Society of America	1	670	670
Annals of the Institute of Statistical Mathematics	Springer Netherlands	1	642	642
New England Journal of Medicine	Massachusetts Medical Society	1	634	634
International Journal of Information Management	Elsevier Ltd	1	627	627
Tectonophysics	Elsevier	1	580	580
Ionospheric Precursors of Earthquakes	Springer Berlin Heidelberg	1	557	557
Safety Science	Elsevier Sci Ltd, Exeter, United Kingdom	1	544	544

Sources	Publisher	Papers	Citations	ACPP
Annual Review of Earth and Planetary Sciences	Annual Reviews Inc.	1	533	533
Journal of Structural Engineering	ASCE	1	524	524
Earthquake protection	Willey	1	518	518
Landslides	Springer Verlag	1	517	517
Proceedings of the National Academy of Sciences of the United States of America	National Academy of Sciences	1	503	503
Earthquake and Volcano Deformation	Princeton University Press	1	478	478
Reports on Progress in Physics	Institute of Physics Publishing	1	463	463
Engineering Geology	Elsevier	1	461	461
Dizhen Dizhi	Guojia Dizhen-ju	1	460	460
Surveys in Geophysics	Springer Nature	1	454	454
Reviews of Geophysics	Blackwell Publishing Ltd	1	449	449
Geophysical Research Letters	Blackwell Publishing Ltd	1	445	445
Tunneling and Underground Space Technology	Elsevier	1	442	442
Environment and Behavior	SAGE	1	427	427
Journal of Asian Earth Sciences	Elsevier	1	424	424
British Journal of Psychiatry	Royal College of Psychiatrists	1	423	423
Science in China, Series D: Earth Sciences	Zhongguo Kexue Zazhishe/Science in China Press	1	418	418
Journal of Earthquake Engineering	Taylor & Francis	1	417	417
Acta Geophysica Sinica	Science Press	1	410	410
Total		**100**	**73452**	**28297,53**
*ACPP=Average Citation per Paper, *the highest number*				

3D. Top 10 Authors of Top 100 Cited Papers and Top Papers

328 authors have actively pony up to the top one hundred cited papers on the keyword "earthquake". Table 4 describes the top 10 authors, the number of most cited papers, and the best papers authored. There are top ten authors who have published two or more of the top cited papers. Kanamori as the most author that has published many papers, received the most number of paper citations and the highest link strength (11). But, Kanamori’s papers do not include the top three cited papers.

Table 4. Top 10 Authors

Top 100 Cited Papers			Top Papers	
Authors	**Total Papers**	**Total Link Strength**	**Authors**	**Total Papers**
Kanamori	**5***	**11***	Kanamori	**185***
Stein, r. s.	7	9	Hayakawa	170
Ammon, c. j.	2	8	Satake, K.	147
Lay, t.	2	8	Liu, J.	136
Beroza, g.c.	4	7	Burgman, R.	133
Ide, s.	4	7	Lay, T.	132
Shelly, d.r.	3	6	Wu, Y. M.	117
Ekstroom, g.	2	5	Xu, C.	116
Ji, c.	2	5	Yamazaki, F.	112
Nettles, m.	2	5	Rundle, J. B.	101
**the highest number*				

Top authors clusters and number of authors over time are shown in Figure 2. Thus, in the earthquake paper, there are 16 author clusters such as Wen, Beroza, Okai, Wiemer, Zhang, Abrahamson, Kanamori, Shearer, Cornell, Stein, Segall, Bilham, Ellsworth, Hubbard, Boore, Christensen. Kanamori and Stein clusters are the biggest author clusters that have top cited papers.

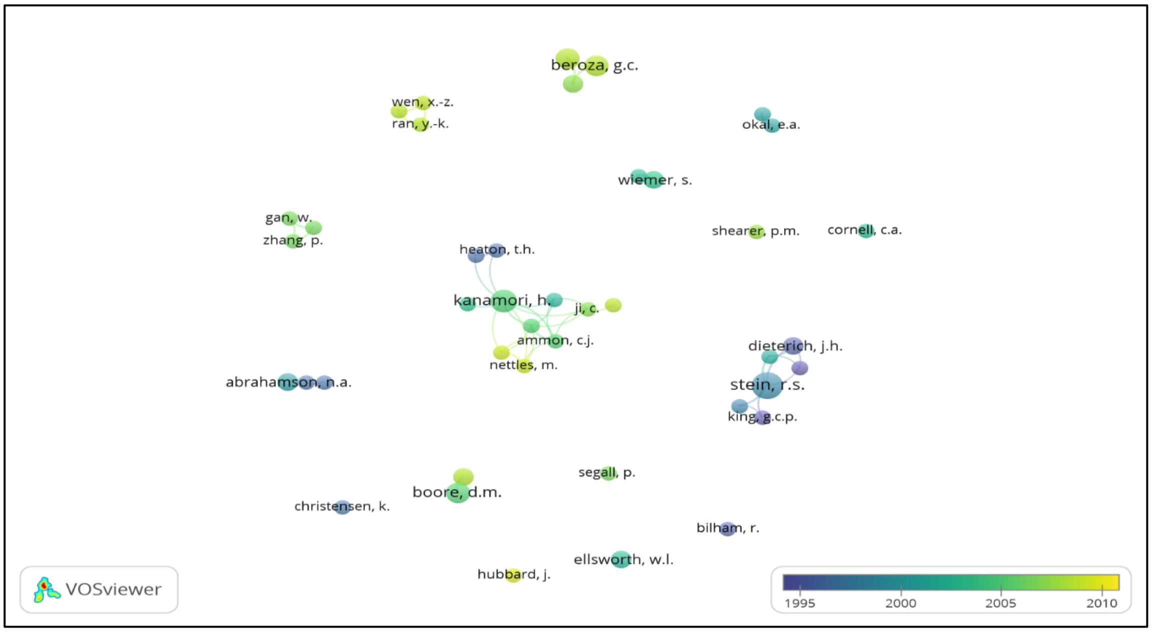


Figure 2. Top authors over time.

3E. Publication Countries in Top 100 Cited Papers and Top Papers

The data obtained from Scopus were then sorted by author affiliation and country. Only the first author was considered when calculating the country of publications. Based on graph and table 5, most of the countries in the earthquake research were dominated by the United States that have published 56 papers and total citations were 38915, followed by Japan that have published 16 papers and total citations were 9366. Despites, China dominates with 15.825 papers, followed by United States (12.875 papers), Japan (9.621 papers).

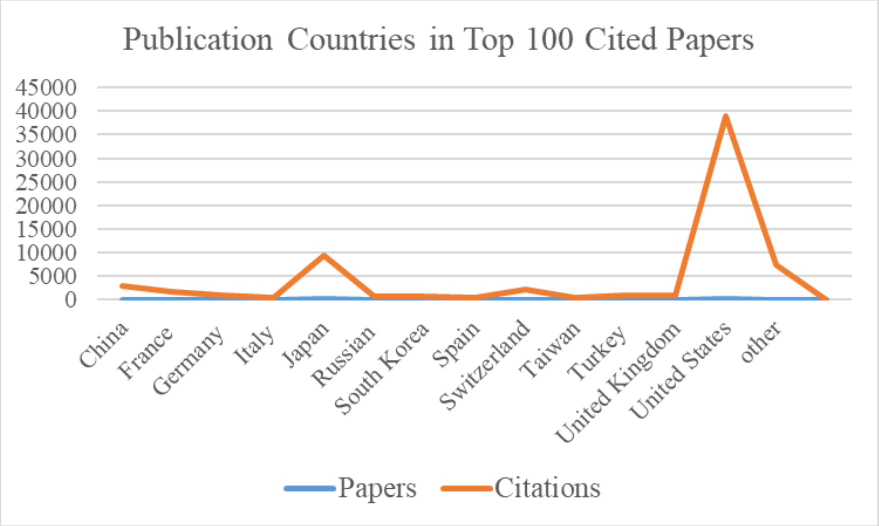


Figure 3. Publication Countries in Top 100 Cited Papers

Table 5. Top 5 of Country of Publications

Top 100 Cited Papers			**Top Papers**	
Country	**Papers**	**Citations**	**Country**	**Papers**
United States	**56***	**38.915***	China	**15.825***
Japan	12	9.366	United States	12.875
China	6	2.932	Japan	9.621
Switzerland	3	2.196	Italy	4.356
Australia	2	2986	India	2.474
**the highest number*				

3F. Keywords of Papers

The most commonly used keywords are graphically shown in Figure 4. The font size of the text in figure represents the frequency of the words used in the papers. Words that were used more commonly are earthquake, earthquakes, states, geological, sciences, earth, japan, etc.

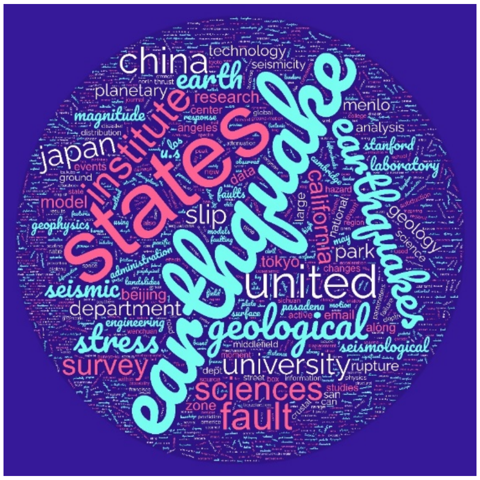


Figure 4. The most relevant keywords

Thus, findings are obtained from research about earthquake. The number of repetitions of a keyword is set to a minimum of 4. From the observations on the map using the VOSViewer*,* 4 different clusters such as 71 keywords were obtained as presented in figure 5.

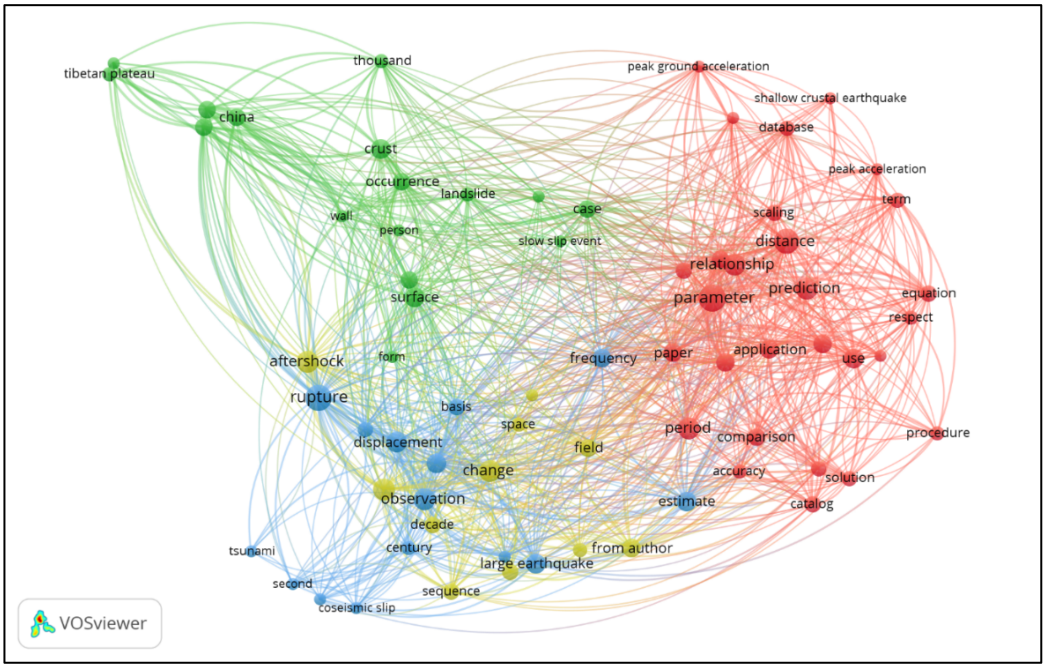


Figure 5. Visualization of the earthquake research from 1991 to 2021

The first red clusters contain 28 items such as accuracy, application, catalog, comparison, database, difference, distance, equation, factor, function, order, paper, parameter, peak acceleration, peak ground acceleration, period, prediction, procedure, relationship, respect, response, scaling, shallow crustal earthquake, shallow earthquake, solution, term, uncertainly, and use. The second green clusters contain 17 items such as case, china, crust, faulting, form, landslide, longmen shan, may, occurrence, person, slow slip event, strong earthquake, surface, thousand, tibetan plateau, wall, wenchuan earthquake. The third blue clusters contain 15 items such as basis, century, coseismic slip, displacement, estimate, frequency, large earthquake, map, moment magnitude, observation, rupture, second, seismic wave, tohoku oki earthquake, and tsunami. While the fourth cluster consists of 11 items such as aftershock, bar, change, decade, earthquake occurrence, field, from author, landers earthquake, sequence, space, and stress change represents by yellow.

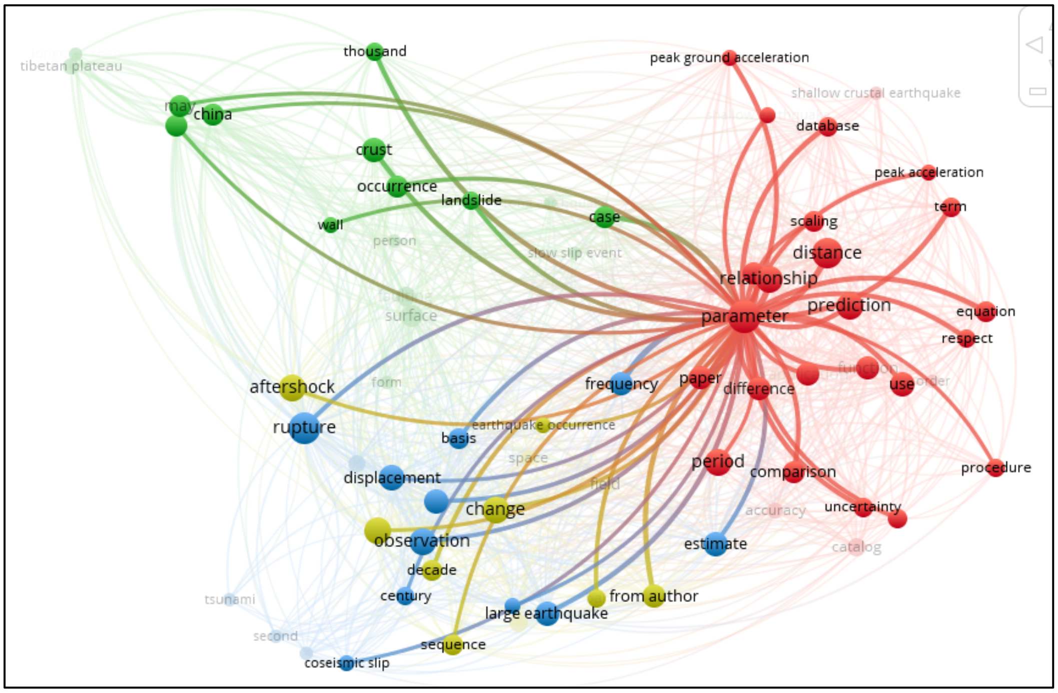


Figure 6. Visualization red clusters

Figure 6 explains that the earthquake is related to parameter and relationship. According to Madlazim (2021), when measuring the resulting amplification, a relationship between the number of tsunamis and the destruction rate of earthquakes can be found as the failure rate parameter plays an important role in run-up amplification. In addition, to calculate acceleration, researchers measure the distance and magnitude of earthquake sources from the point location (Sari et al., 2021).

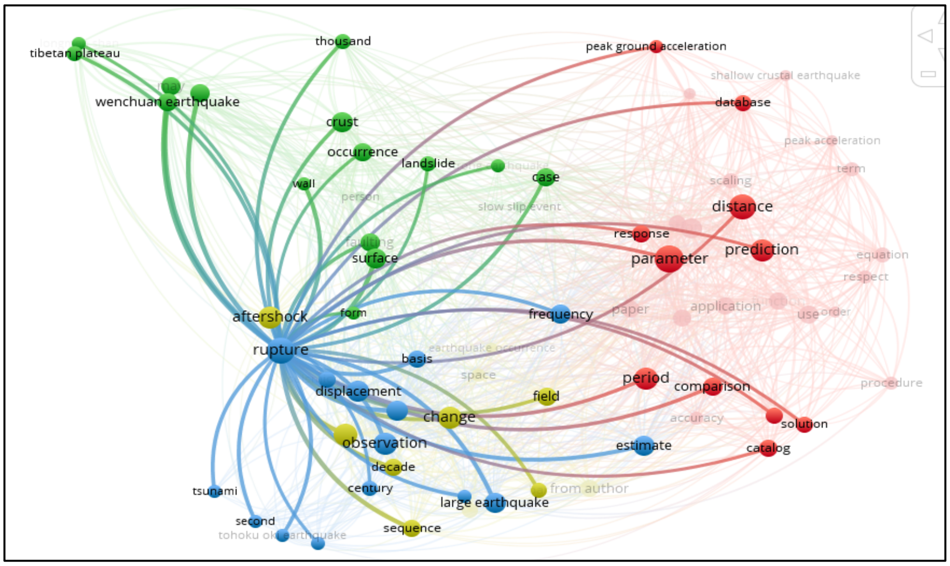


Figure 7. Visualization blue clusters

Figure 7 explains the relationship between earthquake and other keywords especially displacement, and tsunami. Zaytsev et al (2021) explain that earthquake or slip-strike where the fault axis and another fault have regular displacement along it. Then, energy is transferred to the surface of the water, so a tsunami can occur after the earthquake. The different types of earthquakes have been identified and classified by the time and frequency of their energy release by seismologists (Madlazim et al, 2021). High-frequency ocean earthquakes can cause tsunamis due to the interaction of geodynamic constellations and various tectonic plates (Sladen et al, 2010; Hagen and Azevedo, 2018; Parwanto and Oyama, 2014; de La Cruz et al, 2021).

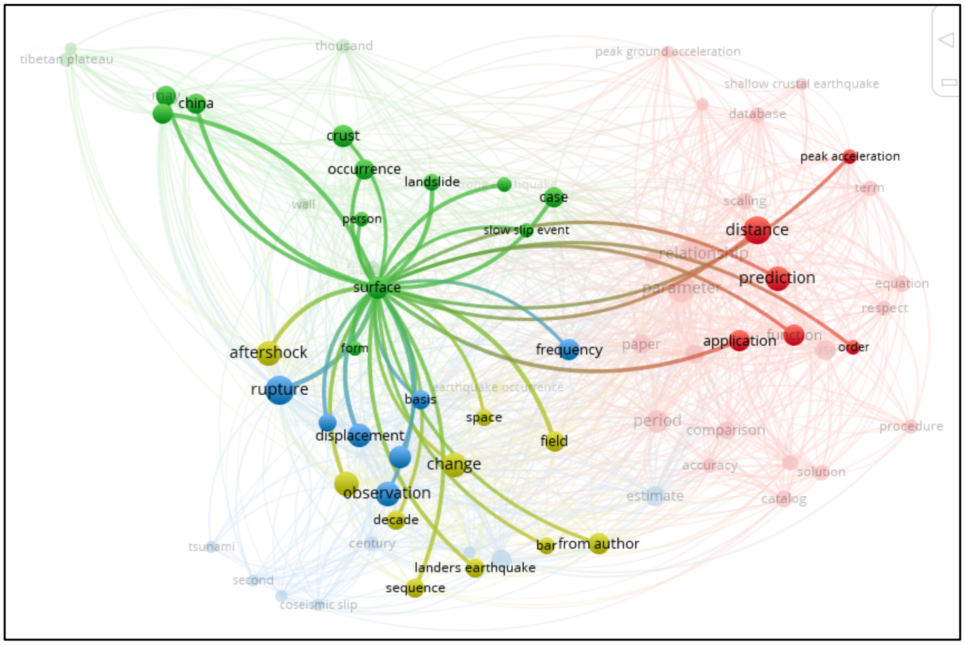


Figure 8. Visualization green clusters

Figure 8 explains that the keywords “surface” and “landslides” have a relationship with earthquake. Landslides is one of areas is at risk of an earthquake or the seismic hazard zone and its generally close to the seismic zone location (Sari et al, 2021). One of the methods to predict the seismic hazard on the earth surface is the wave propagation method. Spectral velocity in earth surface gives information for earthquake resistant design as application in infrastructure engineering (Mikhail et al, 2019).

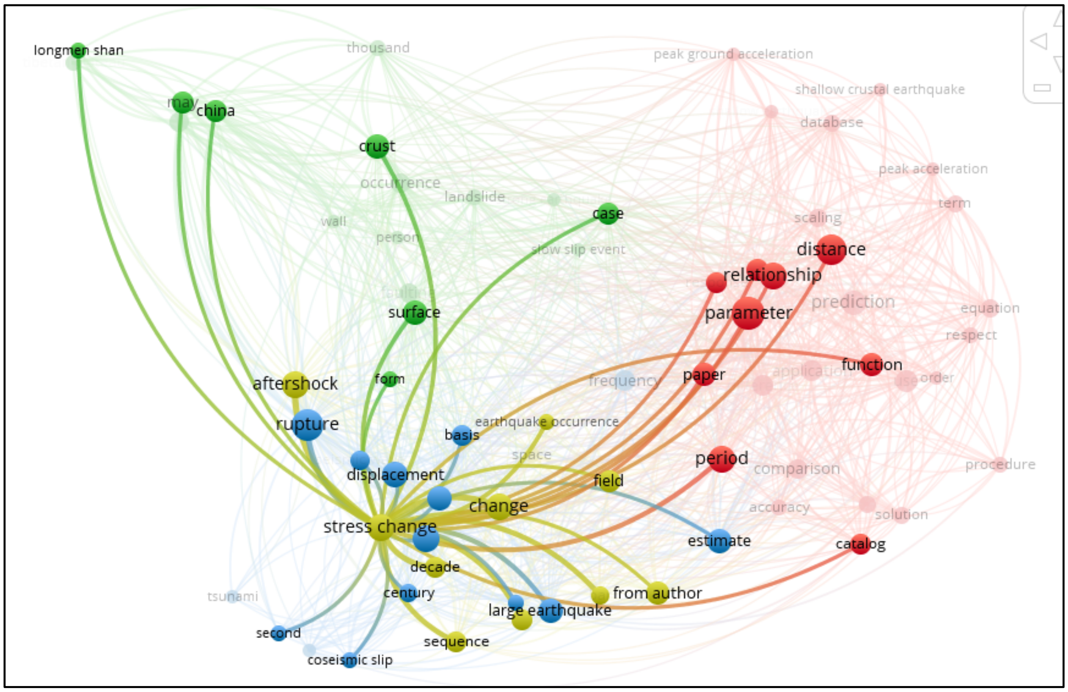


Figure 9. Visualization yellow clusters

Figure 9 describes keywords “stress change” in an earthquake that has a relationship with other clusters such as displacement in blue cluster, parameter in red cluster, and surface in green cluster. According research by Hardebeck and Okada (2018), earthquakes can extrade the stress field withinside the lithosphere as they relieve and redistribute strain. Earthquake-precipitated strain modifications were located as temporal rotations of the predominant strain axes following fundamental earthquakes in plenty of tectonic settings. In earthquake, there are term aftershocks, common effects of earthquakes of normal hypocentral depths that occur in the fragile crust (Ammon et al, 2020).

3G. Study Literature Top Cited Paper

Table 6. Top Cited Paper about Earthquake During 1991-2021

Title	Authors	Source	Cited by	Finding	Recommendation/ Limitations
Earthquake Shakes Twitter Users: Real Time Event Detection by Social Sensors	Sakaki, T., Okazakim M., and Matsuo, Y. (2010)	Proceedings of the 19th International Conference on World Wide Web'10	2758	The authors specifically explored the real-time nature of Twitter for event detection. Each Twitter user acts as a sensor and sets up actions to detect events based on sensory observations.	This study provides insights into semantic analysis and future integration of microblogging data.
Traveltimes for Global Earthquake Location and Phase Identification	Kennett, B. L. N., and Engdahl, E. R. (1991)	Geophysical Journal International	2554	Although the computational cost is not higher than that of a traditional lookup table, the accuracy of constructing the travel time for the source at any depth is improved. Thus, for a given epicenter depth, it is possible to very quickly compile the complete list of transit times and associated derivatives for the major seismic phases observable at a given epicenter distance.	-
A Double-Difference Earthquake Location Algorithm: Method and Application to the Northern Hayward Fault California	Waldhauser, F., and Ellsworth, W. L. (2000)	Bulletin of the Seismological Society of America	2472	An effective method of finding the hypocenter with high resolution over long distances is a positioning method that includes traditional absolute transit time measurements and/or cross-correlation measurements of P and S wave differential transit times.	It is recommended that in the future researchers can use this method to finding the hypocenter
A	Nolen-	Journal of	2014	Students uncovered to	This research

Title	Authors	Source	Cited by	Finding	Recommendation/ Limitations
Prospective Study of Depression and Posttraumatic Stress Symptoms After a Natural Disaster: The 1989 Loma Prieta Earthquake	Hoeksema S., and Morrow J. (1991)	Personality and Social Psychology		greater risky or hard conditions because of the earthquake additionally had accelerated symptom ranges 10 days after the earthquake.	cannot explain the causal relationship between variables
Static stress changes and the triggering of earthquakes	King, G. C. P., Stein, R. S., and Jian Lin (1994)	Bulletin-Seismological Society of America	1799	Movement during an earthquake causes a change in stress. An increase in voltage causes additional earthquakes. Raising the voltage to less than half a bar is enough to cause an earthquake and lowering the voltage by a similar amount is enough to subdue	This research can be a reference to development the earthquake's research

3I. Research Implication

Visualization of each cluster can be used as an alternative for future researchers to obtain ideas and initial explanations in studies related to earthquake topics. This research provides new insights to librarians, researchers, and policy makers around the world to advance earthquake research and build a full Scopus document. The study also provides librarians, researchers, and policy makers insight and information into research trend profiles in Scopus documents. Librarians and researchers can conduct more in depth research development and collaboration between other universities as an effort to increase publications and more references/information for continuous research about earthquake. Besides, the policy makers can pre-plan for earthquake disaster, policy makers can implement disaster mitigation policies that include design and manufacture, urban planning, financial planning, policy direction and public reaction (Heidari et al, 2020). Further research related to earthquakes can also be directed to the relevance of the tsunami. The results of the Scopus database show 2,098 document results [January 17, 2022] with the keyword earthquake tsunami.

3. CONCLUSIONS

This paper is the first bibliographic study of its kind among 100 cited papers in the field of "earthquakes". Research data covering the top 100 earthquake publications from 1991 to 2021 were obtained from the Scopus database. It is found that the top one hundred papers and article is most publication document type, followed by reviews and a few as lectures and books. The majority of these top-cited papers were published in 2005. The average number of citations per article was calculated as 727 citations per paper. The journal Nature is the primary source of the Nature Publishing Group, which governs the publication of the most influential earthquake studies. Most research articles have multiple authors. Kanamori is recognized as the most productive author. At the same time, Kanamori received the highest number of quotes and the most incredible link strength. The United States dominates the production of highly cited articles, followed by Japan and China. The research areas in these papers are mainly emphasized on earthquake, states, geological, sciences, earth, japan. In this study, we only used the Scopus database to search for relevant publications using the keyword "earthquake". Bibliometric data, such as index or citation times, indicate the scope and impact of the work, respectively. However, due to the way research is conducted and how scientific publications work, it is not necessarily accurate and exhaustive. Future research should focus on other disasters, use one or more keywords, and collaborate with Google Scholar, the Web of Science data, for in-depth analysis.

ACKNOWLEDGEMENTS

Thanks to Unesa for providing support for conducting this research project.

REFERENCES

de La Cruz, C. E. D. P., Molina, B. D. M., Baez, A. G. H., Renteria, W., Espinosa, F. R., and Toulkeridis, T. 2021. The Proposed Design of A Smart Parking Area as A Multiple Use Building for The Eventual Vertical Evacuation in Case of Tsunami Impacts in Salinas, Ecuador. *Science of Tsunami Hazards.* 40(3): 1-20.

Deta, U. A., Fadilah, R. N., Agustina, P. Z. R., Prakoso, I., Nurlailiyah, A., Saregar, A., Misbah, and Lestari, N. A. 2020. The Scientific Argumentation Profile of Earthquake Mitigation of Non-Science Undergraduate Student in Universitas Negeri Surabaya. *J. Phys: Conf, Ser*. 1467. 1-5

Hagen, M., & Azevedo, A. (2018). Deep and ultra-deep earthquakes worldwide, possible anomalies in South America. *Natural Science*, 10(06), 199.

Hardebeck, J. L., and Okada, T. 2018. Temporal Stress Changes Caused by Earthquakes: A Review. *Journal of Geophysical Research: Solid Earth.* 123(2): 1350-1365.

Heidari, S., Vatankhah, S., Tourani, S., and Heidari, M. 2020. The Perceptions of Policymakers on Earthquake Mitigation: A Qualitative Study in an Iranian Context. *International Journal of Disaster Resilience in the Built Environment.* 11(3): 403-414.

Kennett, B. L. N., and Engdahl, E. R. 1991. Traveltimes for Global Earthquake Location and Phase Identification. *Geophysical Journal International*. 105(2): 429-465

King, G. C. P., Stein, R. S., and Jian Lin. 1994. Static stress changes and the triggering of earthquakes. Bulletin- Seismological Society of America. 84(3): 722-743. Ammon, C. J., Velasco, A. A., Lay, T., and Wallace, T. C. 2020. *Foundations of Modern Global Seismology Second Edition.* United States: Academic Press.

Kulakli, A., & Osmanaj, V. (2020). Global research on big data in relation with Artificial Intelligence (A Bibliometric Study: 2008-2019). *International Journal of Online and Biomedical Engineering*, 16(2), 31-46

Madlazim, Fahmi, M. N., Realita, A., and Sari, D. P. 2021. Rupture Imaging For The 30 October Tsunamigenic Earthquake in the Eastern Aegean Sea. *Science of Tsunami Hazards.* 40(4): 228-237.

Mato, F. and Toulkeridis, T. (2018). An unsupervised K-means Based Clustering Method for Geophysical Postearthquake Diagnosis. 2017 *IEEE Symposium Series on Computational Intelligence (SSCI)*. 1-8.

Mikhail, R., Irsyam, M., Nazir, R., Asrurifak, M., Hutapea, B. M., Rustiani, S., Munirwansyah, M., and Harninto, D. S. 2019. Development of Nationwide Surface Spectral Acceleration Maps for Earthquake Resistant Design of Bridges Based on National Hazard Maps of Indonesia 2017. *Journal of Engineering and Technological Sciences.* 51(4): 501-515.

Nolen-Hoeksema S., and Morrow J. 1991. A Prospective Study of Depression and Posttraumatic Stress Symptoms After a Natural Disaster: The 1989 Loma Prieta Earthquake. *Journal of Personality and Social Psychology*. 61(1): 115-121.

Pakiser, Louis, and Shedlock, Kaye, M. 2014. *Earthquakes.* United States: Government Printing Office Superintendent.

Parwanto, N. B., & Oyama, T. (2014). A statistical analysis and comparison of historical earthquake and tsunami disasters in Japan and Indonesia. *International Journal of Disaster Risk Reduction*, 7, 122-141.

Rusydy, I., Ikhlas, Setiawan, B., Zainal, M., Idris, S., Basyar, K., and Putra, Y. A. 2020. Integration of borehole and vertical electrical sounding data to characterise the sedimentation process and groundwater in Krueng Aceh basin, Indonesia. *Groundwater for Sustainable Development.* 10: 1-11.

Sakaki, T., Okazakim M., and Matsuo, Y. 2010. Earthquake Shakes Twitter Users: Real Time Event Detection by Social Sensors. *Proceedings of the 19th International Conference on World Wide Web'10*. 851-860.

Sari, A. M., Fakhrurrozi, A., Syahbana, A., J., Sarah, D., Daryono, M. R., Setiadi, B., Bakar, R. A., and Lee, J. C. 2021. Seismic Wave Propagation in Bandung Wasin, West Java. *Science of Tsunami Hazards.* 40(4): 238-254.

Schmeisser, B. (2013). A systematic review of literature on offshoring of value chain activities. *Journal of International Management*, 19(4), 390–406.

Setyaningsih, I., Indarti, N., & Jie, F. (2018). Bibliometric analysis of the term 'green manufacturing'. *International Journal of Management Concepts and Philosophy*, 11(3), 315–339.

Sladen, A., Tavera, H., Simons, M., Avouac, J. P., Konca, A. O., Perfettini, H., and Cavagnoud, R. 2010. Source model of the 2007 Mw 8.0 Pisco, Peru earthquake: Implications for seismogenic behavior of subduction megathrusts. *Journal of Geophysical Research: Solid Earth*, 115(B2).

Suprapto, N., Kusnanik, N. W., Iriani, S. S., Wibawa, S. C., Sujarwanto, S., Yulianto, B., Suprapto, S., Hariyanto, A., & Nurhasan, N. 2021d. The comparison of Scimago Institutions Rankings (SIR), Scopus, and SINTA profile: A case of the top Indonesian Institutions. *Library Philosophy and Practice (e-journal)*, 5788, 1-11.

Suprapto, N., Prahani, B. K., & Deta, U. A. 2021. Top 100 cited publications in physics education in the last thirty years: A bibliometric analysis. *Library Philosophy and Practice (e-journal), 5928*, 1-13.

Toulkeridis, T., Mato, F., Toulkeridis-Estrella, K., Perez Salinas, J.C., Tapia, S. and Fuertes, W. 2018. RealTime Radioactive Precursor of the April 16, 2016 Mw 7.8 Earthquake and Tsunami in Ecuador. *Science of Tsunami Hazards*, 37: 34-48.

Toulkeridis, T., Porras, L., Tierra, A., Toulkeridis-Estrella, K., Cisneros, D., Luna, M.,Carrión, J.L., Herrera, M., Murillo, A., Perez-Salinas, J.C., Tapia, S., Fuertes, W. and Salazar, R. 2019. Two independent realtime precursors of the 7.8 Mw earthquake in Ecuador based on radioactive and geodetic processes—Powerful tools for an early warning system. *Journal of Geodynamics*, 126: 12-22.

Waldhauser, F., and Ellsworth, W. L. 2000. A Double-Difference Earthquake Location Algorithm: Method and Application to the Northern Hayward Fault California. *Bulletin of the Seismological Society of America*. 90(6): 1353-1368.

Yang, L., Sun, T., & Liu, Y. (2017). A bibliometric investigation of flipped classroom research during 2000-2015. *International Journal of Emerging Technologies in Learning*, 12(6), 178-186.

Zaytsev, A., Pronin, P., Giniyatullin, A., Pelinovsky, E., and Zaytseva, M. 2021. Impact Analysis of the 2018 Tsunami on Sulawesi Island Using Satellite Imagery. *Science of Tsunami Hazards*. 40(4): 218-227.

ISSN 8755-6839

SCIENCE OF TSUNAMI HAZARDS

Journal of Tsunami Society International

Volume 41 Number 1 2022

SPATIAL MODELING OF TSUNAMIS AND TSUNAMI INUNDATION ANALYSIS OF “PANJANG” BEACH IN BENGKULU CITY, INDONESIA

Yulian Fauzi [1*], Hardiansyah[2], Zulfia Memi Mayasari[1], and Agus Susanto [3]

[1] *Faculty of Mathematics and Natural Sciences, Univ. of Bengkulu, Bengkulu, INDONESIA*
[2] *Faculty of Engineering, University of Bengkulu, Bengkulu, INDONESIA*
[3] *Student Mathematics Department, University of Bengkulu, Bengkulu, INDONESIA*
Corresponding author: yulianfauzi@unib.ac.id

ABSTRACT

Modeling the potential for tsunami inundation at tourist sites is required as a disaster mitigation effort. Spatial modeling through the application of Geographical Information System (GIS) is a method that can be used to assess the potential for inundation and the impact of a tsunami. This study aims to obtain a spatial description of the potential distribution of tsunami inundation in the tourist area of Panjang beach, Bengkulu City. Appropriate input parameters were derived from Digital Elevation Model (DEM) data, and satellite remote sensing and field data were analyzed through GIS. The slope parameter is derived from DEMNAS data belonging to the Geospatial Information Agency (BIG), land use is generated from open street map (OSM), and coastline distance created from vector map of the study area. The simulation of the tsunami height on the coastline using a scenario of 10 meters causes the land in the Panjang beach area to be inundated with an area of 1.4 – 3.5 km2 with a range of 415 – 765 meters from the coastline. The map of potential tsunami inundation resulting from spatial modeling provides the same inundation pattern as the tsunami inundation map issued by BNPB. The extent and range of the tsunami inundation are directly proportional to the height of the tsunami on the coastline, the higher the tsunami on the coastline, the wider the tsunami inundation, and the farther the tsunami range on the land. The results of this study can be used as initial information for the management of coastal areas as tourist sites related to disaster mitigation.

Keywords: *Spatial Modeling, Tsunami Inundation, DEMNAS, Panjang Beach, Bengkulu*

1. INTRODUCTION

Modeling the potential for tsunami inundation requires parameters and variables that are accurate and have similarities with the real in the field, because inundation modeling is a representation of the real conditions that exist in the research location (Hafeez & Zone, 2008). The parameters for modeling the potential for tsunami inundation are the topography and land use of the coastal area which are manifested in the form of DEM data and surface roughness value. The maximum reach and extent of tsunami inundation in coastal areas are strongly influenced by these two parameters. Another important parameter for the spatial model is the tsunami height at the coastline. The data of tsunami height on the coastline is used as a starting point to determine the maximum range and extent of tsunami inundation that can be generated. The tsunami height used in this study is the result of a study of the potential for high tsunamis on the coast of Bengkulu City.

This study aims to spatially model the potential distribution of tsunami inundation on the land and to assess its impact through mapping the maximum range and area of tsunami inundation using GIS. Tsunami modeling in coastal tourism areas is very important to do as an effort to minimize the potential risk of a tsunami disaster in the area (Sambah & Miura, 2014). The number of activities of residents and tourists in the Panjang beach tourist area of Bengkulu City needs to be anticipated and planned for the level of safety in the event of a tsunami disaster.

Inundation maps or tsunami hazard maps can be made by tracing historical tsunami data or modeling tsunamis. A method for estimating a tsunami disaster and the level of tsunami hazard and vulnerability can be done through spatial modeling (Fauzi, et al, 2020). The tsunami inundation model is a spatial model that is used to simulate the characteristics of the tsunami inundation through the calculation of the decrease in the height of the tsunami inundation on the mainland. The parameters used in this model consist of slope, surface roughness (land cover/land use), and tsunami height at the coastline (Berryman, 2006; and Smart et al., 2016). The tsunami spatial model is widely used by researchers in the geospatial field because it is easier to apply, but without considering the tsunami source and tsunami propagation factors (Mardiatno, 2008).

Spatial modeling of tsunami inundation potential is used to simulate the characteristics of tsunami inundation from the coastline to the mainland. Berryman (2006), in his research developed the Hill and Mader (1997) tsunami inundation model by adding the slope of the land. The development of this model succeeded in obtaining the average tsunami inundation from an area by finding the maximum and minimum inundation. The model developed by Berryman (2006) succeeded in attracting the attention of researchers in Indonesia to apply it in Indonesia. Several studies that use this model include research conducted by Putra (2008), Purbani (2012), Fauzi et al (2014), Zahro (2017), and Wahyuni (2020). Research conducted by Putra (2008) used the Berryman model to model the tsunami inundation in Banda Aceh City. This study succeeded in developing the coefficient of surface roughness values derived from several land uses. Purbani (2012) used the Berryman model to model the tsunami on Pulau We Banda Aceh with the help of the Builder model. The use of the Berryman model to model tsunami inundation in coastal areas was carried out by Fauzi et al (2014) on the coast of Bengkulu City, Zahro (2017) on the coast of Serang Regency, Banten, and Wahyuni (2020) on the coast of Kulonprogo DIY. These three studies use scenarios of tsunami height at the coastline through historical assumptions and approaches and the characteristics of tsunamis that can occur in coastal areas.

2. MATERIAL AND METHODS

2.1 DATA

The elevation data used in this study was obtained from the National Digital Elevation Model (DEMNAS). DEMNAS is built from several data sources including IFSAR data (5m resolution), TERRASAR-X (5m resolution) and ALOS PALSAR (11.25m resolution), by adding the stereo-plotting mass point data. The spatial resolution of DEMNAS is 0.27-arcsecond. The datum or vertical reference used is the Earth Gravitational Model 2008 (EGM 2008). The integrated data is added with mass points through the assimilation process. Mass points are points that contain three-dimensional coordinate information, namely x, y and z on the earth's surface. The assimilation process in DEMNAS data uses GMT-surface with a tension of 0.32.

Land use data uses Open Street Map (OSM) data and field surveys. Land use data converted to surface roughness values refers to the conversion carried out by Berryman (2016) and BNPB (2012). This study uses information on tsunami heights at the coastline based on data on Indonesia's maximum tsunami inundation potential issued by the National Disaster Management Authority (BNPB).

2.2 STUDY AREA

This research was conducted in Bengkulu City (Figure 1). Bengkulu City is an earthquake and tsunami prone area, because this area is directly opposite the Indian Ocean which is the meeting point of the Eurasian and Indo-Australian plates. In general, Bengkulu City is located at an altitude between 0-100 m/dpl, with sporadic distribution in every area of the city, causing a bumpy city morphology. The location with the highest point (up to 100 m/dpl) is in the southeast (Selebar sub district). While the lowest point (between 0 m/dpl – 10 m/dpl) is in the South, North and East, while the Bengkulu City Center itself is at an altitude between 10-25 m/dpl.

In 2020, the city has an estimated population of 371,828 with a total area of 151.70 square kilometers. Bengkulu City is located on the West Coast of Sumatra and faces the Indian Ocean. In this city, the local government through the Regional Disaster Management Agency (BPBD) has compiled a tsunami hazard mapping and tsunami evacuation route. The government works with community groups to develop evacuation maps and identify the best evacuation places (vertical and horizontal).

2.3 TSUNAMI MODEL

The potential for tsunami inundation modeling is made by developing the concept of water loss (Hloss) developed by Berryman (2006) and simple hydraulics principles developed by Smart et al., (2016). Both of these tsunami inundation models work in the spatial domain so that the model developed is a spatial model. The activity carried out in this stage is to examine the tsunami inundation model through a mathematical approach, so that the model variables and parameters can be well defined.

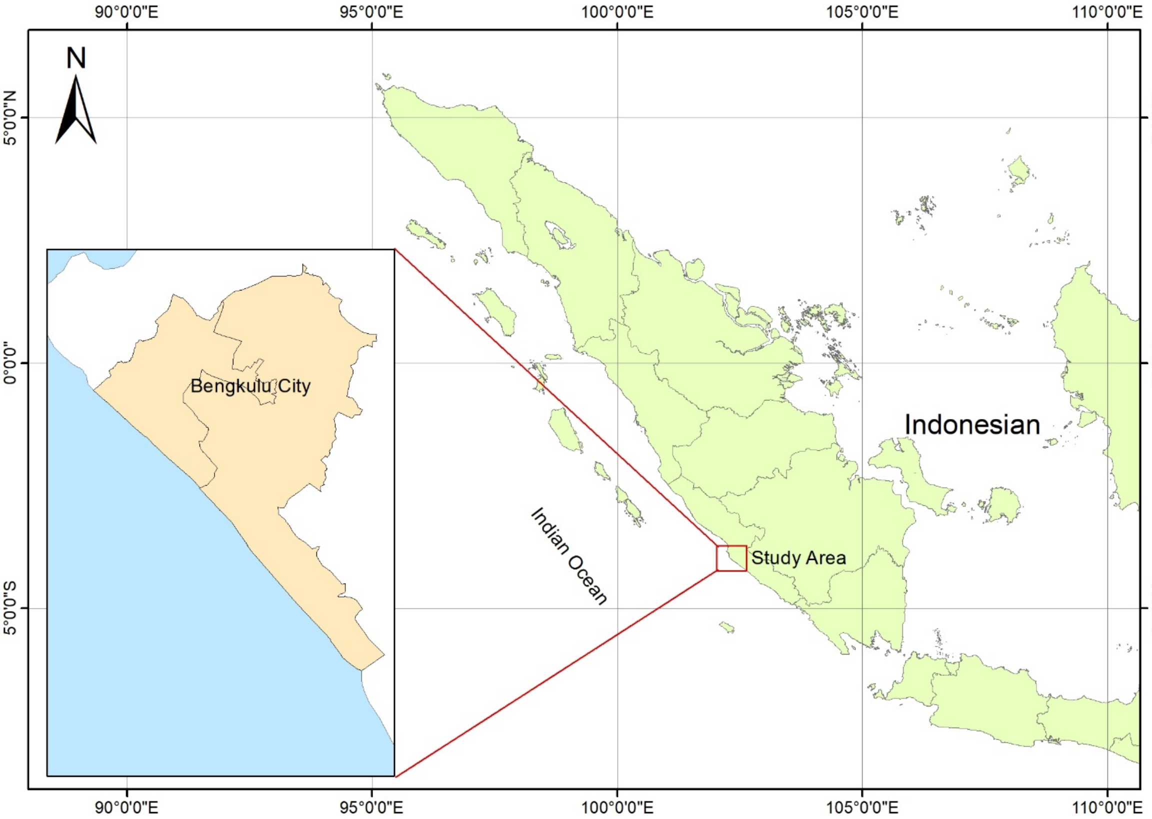


Figure 1. Map of study area

The Hloss method is a tsunami inundation model based on the height of the waves from the shoreline. This model is implemented using a cost-distance function which calculates g distance to the nearest source for each pixel, by minimizing the distance specified in a cost surface. The source for the function is the pixel value representing the ocean wave/ tsunami, and the cost surface is the pixel representing the tsunami wave height loss (Hloss). The Hloss equation is presented in equation 1.

$$H_{loss} = \left({167n^2} \middle/ {H_0^{1/3}} \right) + 5\sin S \qquad (1)$$

Information:

H_{loss} : Decrease in water level per meter from inundation distance
n : Roughness surface coefficient
H_0 : The height of the tsunami waves at the coastline
S : Slope

The development of a tsunami inundation model by considering simple hydraulics was carried out by Smart et al., (2016). The tsunami inundation was studied from a one-dimensional perspective with the slope measured parallel to the direction of the tsunami. The equation for the distance of the tsunami inundation on land is given in equation 2.

$$L = \frac{3a}{2} ln\left(\frac{Y_s}{aS_0} + 1 \right) \qquad (2)$$

Information:

L : Tsunami inundation distance
Y_s : Run up height at the coastline
S_0 : Slope
a : Surface roughness

The tsunami inundation modeling follows the equation for decreasing the height of the tsunami inundation and the distance of the tsunami inundation on the mainland. The model parameters consist of the tsunami height at the shoreline, the surface roughness index value and the slope/elevation of the slope. The model building algorithm developed in this study is described as follows:

Input: Surface roughness value (n^2 or a)

Tsunami height at the coastline (Ho or Y_s)

Elevation (S)

Process: Count $H_{loss} = \left(\frac{167\,n^2}{H_o^{\ 1/3}}\right) + 5\sin S$

$$\text{Count } L = \frac{3a}{2} ln\left(\frac{Y_s}{a\,S_0} + 1\right)$$

Output: *Cost Raster* H_{loss} (tsunami height)

L (tsunami inundation distance)

The next step is build a potential tsunami inundation model based on the Berryman Model through the creation of a Builder model algorithm. The results of the Builder model in the ArcGIS software are calculated and analyzed the distance of the tsunami inundation horizontally from the coastline to the mainland using the Cost Distance method. The results of the calculation of the cost distance will get the potential range of a tsunami in coastal areas. The calculation of the tsunami range using the Smart Model is carried out using the help of ArcGIS and Excel. The surface roughness data was developed from the research results of Smart et al., (2016).

3. RESULTS AND DISCUSSION

3.1 TSUNAMI SPATIAL MODEL FORMULATION

The tsunami inundation modeling using the Berryman equation using altitude data in the form of DEM data. DEM data is converted into radian data by utilizing the tool facilities contained in ArcGIS. Tsunami inundation modeling is used to estimate tsunami inundation from the coastline to the mainland and generally this model is developed through empirical methods. This model was developed through mathematical calculations based on the calculation of the loss of tsunami height per meter of inundation distance. The slope (*Sin S*) represents the straight line of the sloping side of a triangle, corresponding to the mean slope taken from the sloping soil profile (topography) of the coastline. In this way, *Sin S* compensates for the flat topography of the Hills and Mader equation (Pignatelli et al., 2009). The onshore tsunami inundation diagram resulting from the Berryman model is modified from the tsunami wave diagram developed by Pignatelli et al., (2009) as shown in Figure 2.

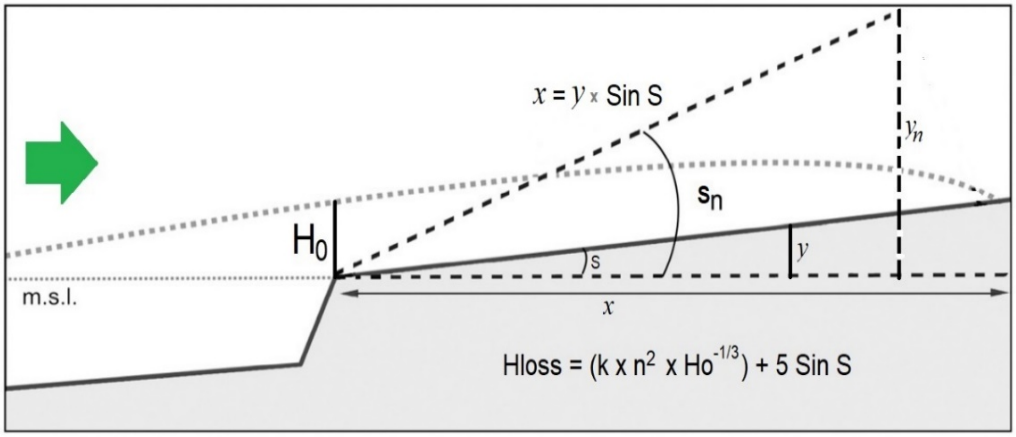


Figure 2. Tsunami wave diagram

3.2 MAPPING OF THE HEIGHT LOCATION/ELEVATION AND LAND USE

Research on tsunami inundation modeling begins with mapping the location/elevation and land use. The height of the research area is manifested in DEM data taken from DEMNAS. In addition to DEM data, the main data in tsunami inundation modeling is land use data sourced from open street map (OSM) data. Open Street Map or OSM is a web-based project for creating a free and open world map. OSM was built entirely by volunteers by conducting surveys using GPS, digitizing satellite images, and collecting and releasing publicly available geographic data. The research area for tsunami inundation modeling in this study is limited to two sub-districts, namely Ratu Samban and Ratu Agung sub-districts. The selection of these two sub-districts was used as research locations based on the fact that the coastal areas of these two sub-districts are favorite tourist sites in Bengkulu City. The number of tourists who visit the research site is very crowded, especially on weekend and holidays. The image map of the research area is presented in Figure 3.

3.3 DETERMINATION OF ELEVATION AND SURFACE ROUGHNESS INDEX

The altitude data used in this study is DEM data, namely altitude data taken from the ground surface which reflects the height of the ground surface. DEM data sourced from DEMNAS processed into altitude data in the form of slope radian format so that it can be included in the tsunami inundation model. From the DEM height data in the study area, it can be concluded that the elevation of the coastal surface of Ratu Samban and Ratu Agung sub-districts is a fairly gentle elevation (Figure 3). This condition causes the research area to be an area prone to tsunami disasters. Several public facilities are located in this area such as Bencolen Mall, Sport Center, Hotel and Cafe/restaurant.

Land use is using the land that is carried out optimally by utilizing all available resources in an effort to develop the using land in an area. The composition of built and undeveloped land in Bengkulu City is almost the same. The result of the interpretation of land use is converted into a surface roughness index value. The coefficient of surface roughness is distinguished by the type of detailed land use/land cover according to Berryman (2006) and BNPB (2012). The results of the interpretation and classification of land use are converted into surface roughness index values and presented in a table listing the surface roughness coefficient values (Table 1).

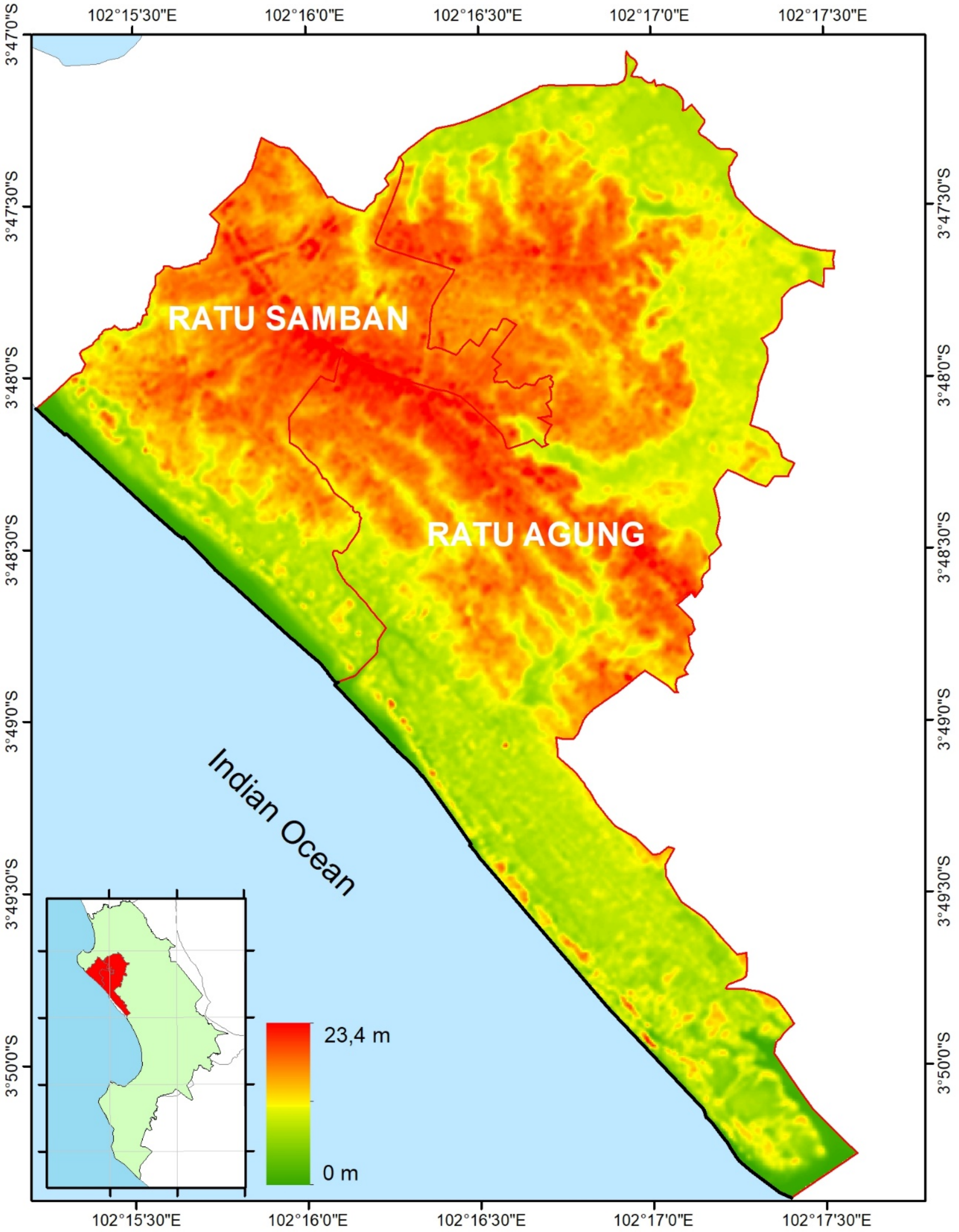


Figure 3. DEM map of ratu samban and ratu agung sub-districts

Table 1. List of surface roughness coefficient value

No	Type of land use	Surface Roughness Coefficient
1	Pond	0,010
2	River	0,007
3	Sand	0,018
4	Open field	0,015
5	Meadow	0,020
6	Ricefield	0,020
7	Empty land	0,015
8	Moor	0,025
9	Field	0,025
10	Plantation/coastal forest	0,035
11	Shrubs	0,040
12	Settlements/build-up land	0,045
13	Mangrove forest	0,025

Source: Berryman (2006); BNPB (2012);

3.4 TSUNAMI INUNDATION MODELING SIMULATION

The tsunami inundation potential model was designed by developing the concept of water level loss developed by Berryman (2006). In this concept, a mathematical calculation is carried out based on the calculation of the loss of tsunami height per 1 m of inundation distance (inundation height) calculated by considering the distance to the slope and surface roughness. The main data used for modeling tsunami inundation are elevation and surface roughness. The elevation data was extracted from the DEM map, while the surface roughness data was converted from the land use map.

The modeling input data in this study uses a resolution of 10 meters, this refers to the results of the research by Handayani (2014) and Marfai et al., (2018) that the tsunami inundation model is more accurate at medium data resolution. The greater the resolution of the input data, the wider the tsunami inundation area generated in the modeling. After obtaining the surface roughness index map and the DTM map, the modeling process was carried out following the equation given by Berryman (2006). To calculate the distribution of tsunami inundation on land, a cost distance analysis is used with the maximum distance value being the height of the tsunami on the coastline. The calculation of the cost distance results in the distribution of the tsunami inundation from the coastline to the mainland. The model used to model the tsunami inundation is Builder, this model is often referred to as a 'visual programming language' or often referred to as a tool used to create a script. Model Builder can be used to map out a repetitive workflow that involves many other jobs, making it easier for users to perform their tasks. The tsunami inundation model was designed using the Model Builder which was processed with ArcGIS software. The results of the calculation of the cost distance to the Hloss value produce the distribution of tsunami inundation on the mainland of the Ratu Samban and Ratu Agung sub-districts starting from the coastline. The inundated area is analyzed to find the area of inundation and the maximum range of tsunami inundation. The simulation results of tsunami inundation modeling for the three worst scenarios, namely Ho = 10 meters, using the Berryman equation are presented in Figure 4.

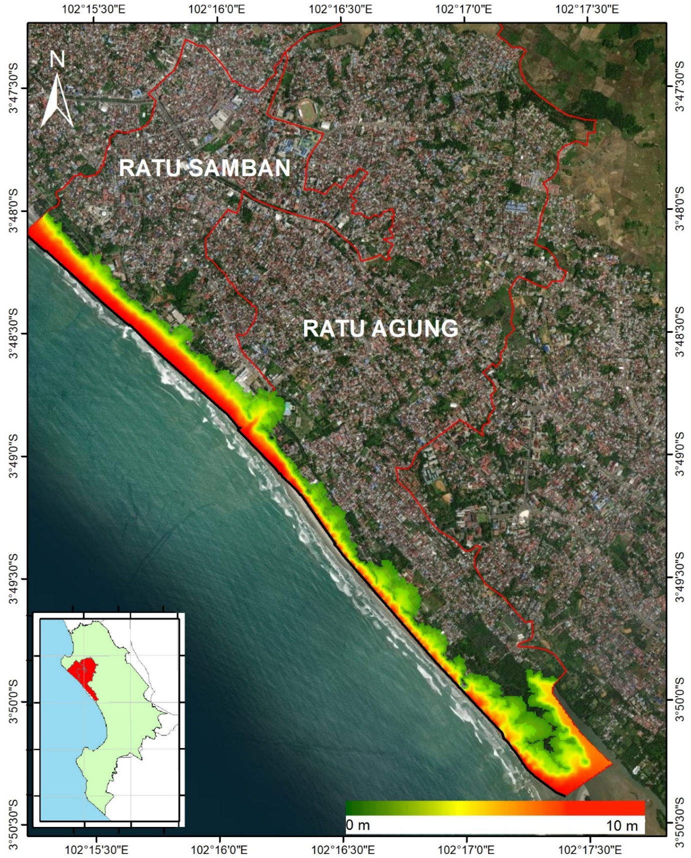


Figure 4. Simulation results of tsunami inundation modeling with the height of 10 meters

The development of a tsunami inundation model by considering simple hydraulic principles was carried out by Smart et al. (2016). The tsunami inundation was studied from a one-dimensional perspective with the slope of the coastline measured parallel to the direction of the tsunami and the difference in land topography was not taken into account. Both tsunami inundation models (Berryman and Smart) use the same input model, namely the tsunami height at the coastline. The results of measuring the reach of the tsunami inundation with a tsunami height of 10 meters on the coastline resulted in a maximum range of 621.89 meters for the Berryman model, 537.5 meters for the Smart model. While the minimum reach reaches 186.54 meters for the Berryman model and 312.3 meters for the Smart model (Figure 5). The difference in the maximum range of the two models, can be due to the two equations using different elevation and surface roughness classifications in the modeling. The Smart model uses 3 elevation classes, namely mild slope (0.01), moderate slope (0.5) and steep slope (0.2). The surface roughness coefficient values in the Smart model are divided into 4 classes of land cover types as shown in Table 2.

Table 2. List of surface roughness coefficient values

No	Onshore roughness condition	Aperture value a (m)
1	Smooth open ground, beach	200
2	Undulating open ground	100
3	Light buildings, coconut plantations	80
4	Dense vegetation, jungle	10

Source: Smart et al., (2016)

The analysis of the modeling results shows that the maximum range of tsunami inundation from the Smart model produces almost the same results as the Berryman model. The maximum range generated by the Berryman and Smart Models is presented in Figure 5.

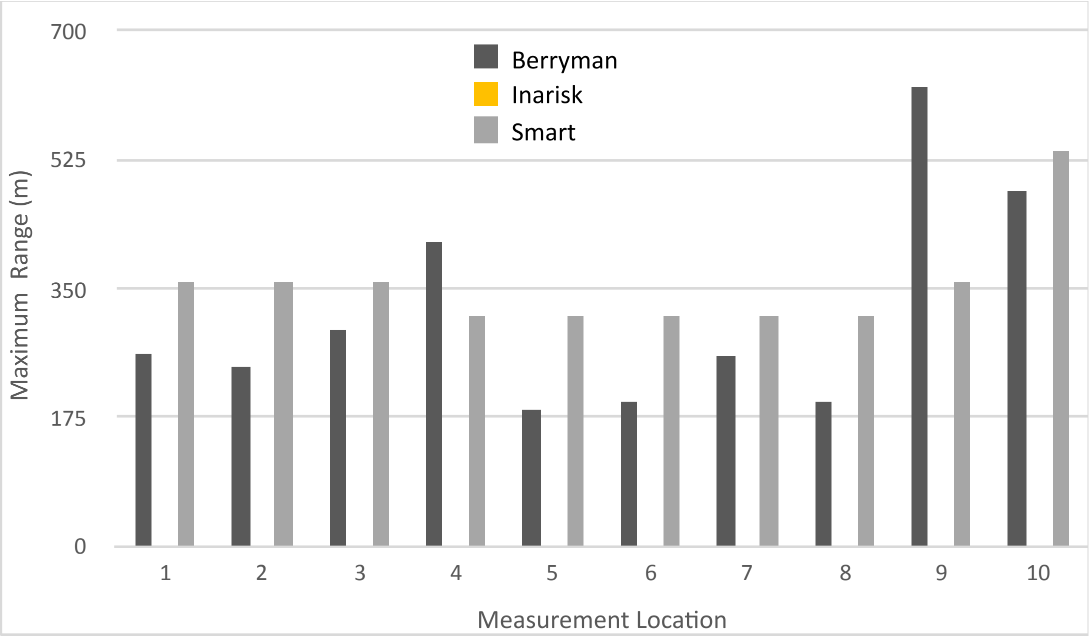


Figure 5. Maximum range of Berryman and Smart models

1. CONCLUSIONS

The use of GIS-based spatial models for modeling the potential for tsunami inundation provides an overview of the impact of tsunami inundation on land. In this study, three parameters are applied to create a tsunami inundation potential map. DEMNAS data can be used for modeling potential tsunami inundation for areas that do not yet have high-resolution DEM data. The tsunami inundation map shows that most tourist sites in Panjang beach Bengkulu are vulnerable to tsunamis. Most of the tourism infrastructure along the coast has a high vulnerability to tsunamis. The tsunami inundation pattern generated from the Berryman and Smart models shows the same thing as the inundation potential issued by BNPB. For a better modeling of the potential for tsunami inundation, it can be done by detailing the variation of the surface roughness value.

ACKNOWLEDGMENTS

Thanks are due to the University of Bengkulu which funded this research through the Penelitian Unggulan Universitas scheme with contract number 1775/UN30.15/PG/2021.

REFERENCES

Berryman, K., 2006. *Review of Tsunami Hazard and Risk in New Zealand*. Lower Hutt, Institute of Geological and Nuclear Science.

BNPB, 2012. Lampiran Perka BNPB No. 2 Tahun 2012 tentang Pedoman Umum Pengkajian Bencana, *Panduan Nasional Pengkajian Risiko Bencana Tsunami*. Jakarta, BNPB.

Fauzi, Y., Suwarsono, S. & Mayasari, Z. M., 2014. The Run up Tsunami Modeling in Bengkulu using the Spatial Interpolation of Kriging Technique. *Forum Geografi*, 28 (2), 103–112. https://doi.org/10.23917/forgeo.v28i2.427

Fauzi, Y., Hartono, H. & Kongko, W., 2020. Numerical Modeling of Tsunami and Tsunami Vulnerability Analysis of Temon Coastal Region in Yogyakarta, Indonesia. *Disaster Advances*, 13 (5), 33- 41.

Hafeez, H. & Zone, S., 2008. Inundation of Tsunami Waves and Its Relation to the Tsunami Run Up. *Fakistan Journal of Meteorology*, 5 (9), 5–10.

Handayani, W., 2014. Pemanfaatan Foto Udara Format Kecil untuk Ekstraksi Digital Elevation Model (DEM), Pemodelan Genangan dan Perkiraan Kerugian Akibat Tsunami di Wilayah Pesisir Parangtritis. *Tesis*. Universitas Gadjah Mada.

Hills, J.G. & Mader, C.L., 1997. Tsunami Produced by the Impacts of the Small Asteroids, *Ann. N.Y. Acad. Sci*. **822**, 381-394.

Jaffe, B. E. & Gelfenbuam, G., 2007. A Simple Model for Calculating Tsunami Flow Speed from Tsunami Deposits. *Sedimentary Geology*, 200 (3–4), 347–361. http://doi.org/10.1016/j.sedgeo.2007.01.013.

Mardiatno, D., 2008. Tsunami Risk Assessment using Scenario-Based Approach Geomorphological Analysis and Geographic Information System, A Case Study in South Coastal Areas of Java Island-Indonesia. *Dissertation*. University of Innsbruck.

Marfai, M.A. & Rosaji. F.S.C., 2018. *Gis Exersice Book, Coastal Monitoring and Hazard Modeling*. Yogyakarta, Badan Penerbit Fakultas Geografi UGM.

Pignateli, C., Sanso, P. & Mastronuzzi. G., 2009. Evaluation of Tsunami Flooding Using Geomorphologic Evidence. *Marine Geogology,* 260, 6-18. https://doi:10.1016/j.margeo.2009.01.002.

Putra, R., 2008. Kajian Risiko Tsunami Tehadap Bangunan Gedung Non-Hunian dengan Skenario Variasi Ketinggian Run-up pada Garis Pantai; Studi Kasus Kota Banda Aceh Indonesia. *Tesis*. Universitas Gadjah Mada.

Purbani. D., Boer. M., Marimin., Nurjaya.I.W, & Yulianda. F., 2012. Aplikasi Penginderaan Jauh dan Sistem Informasi Geografi untuk Mengetahui Pola Sebaran Genangan Tsunami dan Tingkat Kerentanan, Studi Kasus: Pulau Weh. *J. Segara*, 8 (1), 35-44.

Sambah. A., & Miura. F., 2014. Integration of Spatial Analysis for Tsunami Inundation and Impact Assessment, *Journal of Geographic Information System*, 6, 11-22. http://dx.doi.org/10.4236/jgis.2014.61002

Smart, G.M., Crowley, K.H.M. & Lane, E.M., 2016. Estimating Tsunami Run Up. *Natural Hazard, 80,* 1933-1947. Springer. http://doi:10.1007/s11069-015-20528

Wahyuni, 2020. Analisis Risiko Bencana Tsunami untuk Mendukung Tata Ruang Pesisir di Kabupaten Kulonprogo. *Disertasi.* Universitas Gadjah Mada.

Zahro, Q., 2017. Spatial Study of Tsunami Risk in Serang, Banten, *Jurnal Sains dan Teknologi Bencana*, 12 (1), 44-52. https://doi.org/10.29122/jstmb.v12i1.3699

ISSN 8755-6839

SCIENCE OF TSUNAMI HAZARDS

Journal of Tsunami Society International

Volume 41 Number 1 2022

NUMERICAL MODELING OF TSUNAMI WAVES

Book Written by:

Juan Horrillo, William Knight and Zygmunt Kowalik

REVIEW

by
George Pararas-Carayannis
President, Tsunami Society International
Editor, Science of Tsunami Hazards

The book entitled "Numerical Modeling of Tsunami Waves" by Professor Juan Horrillo, (Texas A&M University), William Knight ((National Tsunami Warning Center (retired), USA) and Professor-Emeritus Zygmunt Kowalik (University of Alaska, Fairbanks, USA), is a well-written, comprehensive treatise of the evolving science of computer modeling of tsunami waves. Their book presents an all-encompassing treatment of the subject based on research collaboration that began about 20 years ago on numerical methods to the dynamics of long-period waves, and particularly to tsunami waves. With a detailed, analytical, well-organized, orderly, and constructive approach, the authors review the basic techniques, the evolution of numerical schemes, then introduce the application of finite-methods to the study of tsunami waves, and subsequently go into the solving of more elaborate problems arising from investigations of recent tsunamis.

The 397-page monograph represents a good summation of the state of the art of numerical modeling and refinements, which encompasses all aspects and acting synergies that help understand the realities of the tsunami disaster, regardless of the source mechanism from different causes - whether by earthquakes, landslides, or massive slumps, and which can be verified by actual observations and instrumental recordings. With skillful and methodical presentation and examples - ensuring that every aspect of modeling receives appropriate consideration - the authors not only explain how the basic theory is applied, but also introduce several new important ideas, procedures and concepts in tsunami science that can be used as the fundamental basis for the simulations of long period waves.

The first chapter of the monograph provides a general introduction to the system of coordinates used in computing large-scale phenomena on the rotating Earth such as tsunami, tides, or storm surges. Specifically examined are the equations of motion and continuity, the conservation of energy, and the flow dynamics in both Cartesian and spherical coordinate systems. Subsequently described are the possible motions and the hydrostatic approximations in both vertical and horizontal directions - thus constructing energy equations, and vertically integrating them on a sphere. Furthermore, since the surface dynamics of such impulsively generated long period surface waves are affected by the ocean/sea bathymetry, consideration is given to the source mechanisms - whether involving ocean floor displacements by earthquakes, underwater landslides, or slumps. Thus, the dynamics of the two-layer fluid system involving a layer of higher density such as that of a slump, are carefully included in the solution of the equations of motion and continuity. Finally discussed carefully is the behavior of the small amplitude waves and the velocity of propagation in a channel-like sea environment, neglecting Coriolis, dissipation, and non-linear terms, However, attention is given by the authors in describing in simple terms the dispersion processes – described more analytically in Chapter 6 of the monograph.

In the second chapter of the monograph, and in a very skillful and methodical manner, the authors explain in great detail the finite difference methods of long wave propagation in one dimension, and demonstrate how the physical properties of the waves - and particularly how the phase velocity is associated with a chosen numerical algorithm. Further discussed are the computational errors of the numerical modeling methodology, the approximations of the differential equations being used for a tsunami's propagation phase, and finally describe terminal tsunami run-up.

In Chapter Three, the authors use a step-by-step approach to describe the processes of tsunami generation by both earthquakes and landslides. Subsequently introduced are the basics of Seismology, simple rheological models, a discussion of the numerical procedures, and of the general long-wave algorithms.

Chapter Four extends the description to real ocean applications to two major historical tsunamis, namely the Indian Ocean tsunami of December 2004 and the Kuril Island tsunami of November 2006. Subsequently introduced in the spherical coordinate system are: a) the construction of finite difference equations, b) the boundary conditions, and c) the source mechanisms of these two tsunami events. Verification, calibration, and refinement of the modeling methodology is obtained by comparisons between recorded observations and the numerical results, giving particular attention to the effects of scattering, diffraction, and reflection. Based on all these considerations, the energy flux is subsequently analyzed as a way for further refinement in order to determine the impact that bathymetric features may have on refraction, diffraction, scattering, pathways and terminal tsunami run-up amplification on distant shores located thousands of miles from a tsunami's source region.

Chapter Five describes the thorough transformation that tsunami waves undergo upon arriving at near-shore regions, where their amplitudes and particle velocities are greatly magnified. Explained in this chapter are the roles of the different mathematical terms in the equations of motion and continuity that contribute to such shallow water amplification. Additionally discussed are the effects of amplification due to resonance, when the already enhanced tsunami waves enter the shallower bathymetry of bays and ports, such as the ports of Skagway in Alaska and of Crescent City in California.

Chapter Six presents the influence dispersion has on transoceanic long wave propagation, energy flux, pathways, time of travel, and probable synergistic impact on tsunami run-up at a distant shoreline, in contrast to previously-considered tsunami models which are based on the shallow water approximation which ignores the effects of wave dispersion. In describing in greater detail dispersion in this chapter, a term is included in the equation of motion, which represents the sum of both hydrostatic and non-hydrostatic components, and uses as descriptive examples the transoceanic propagation of recent events, namely the Japan (Tohoku) Tsunami of 2011, and the Indian Ocean Tsunami of 2004 – both demonstrated by previous studies as generating long period waves that were particularly dispersive (Kulikov 2005; Horrillo et al., 2006; Saito et al., 2011). Based on these considerations, the equation for the energy flux is developed.

Chapter Seven of the monograph addresses and details the three-dimensional (3D) methods that are being used for applications of numerical modeling, particularly because the initial tsunami generation phase where the prevailing domain is compact, or when high initial speeds are triggered. Additionally explained in this chapter is the numerical methodology of connecting the 3D generation domain to 2D depth averaged equations which are being used for the tsunami's transoceanic propagation, with the numerical method applied to the Gulf of Mexico.

Chapter Eight of the monograph emphasizes and describes the guidelines used by developers of tsunami hazard mitigation maps, formulated by the National Tsunami Hazards Mitigation Program (NTHMP). Such mapping work has been carried out for the Gulf of Mexico but expected to be similarly applied to other vulnerable regions threatened by comparable tsunamigenic sources and regional climatology and geomorphological features.

A final discussion in the monograph includes several of the computational programs related with the individual chapters, and additionally provides the Internet link to the Texas A&M University at Galveston Tsunami Research Group (TRG) Internet page where the Fortran Codes can be found (https://www.tamug.edu/tsunami/Tsunami-Codes.html).

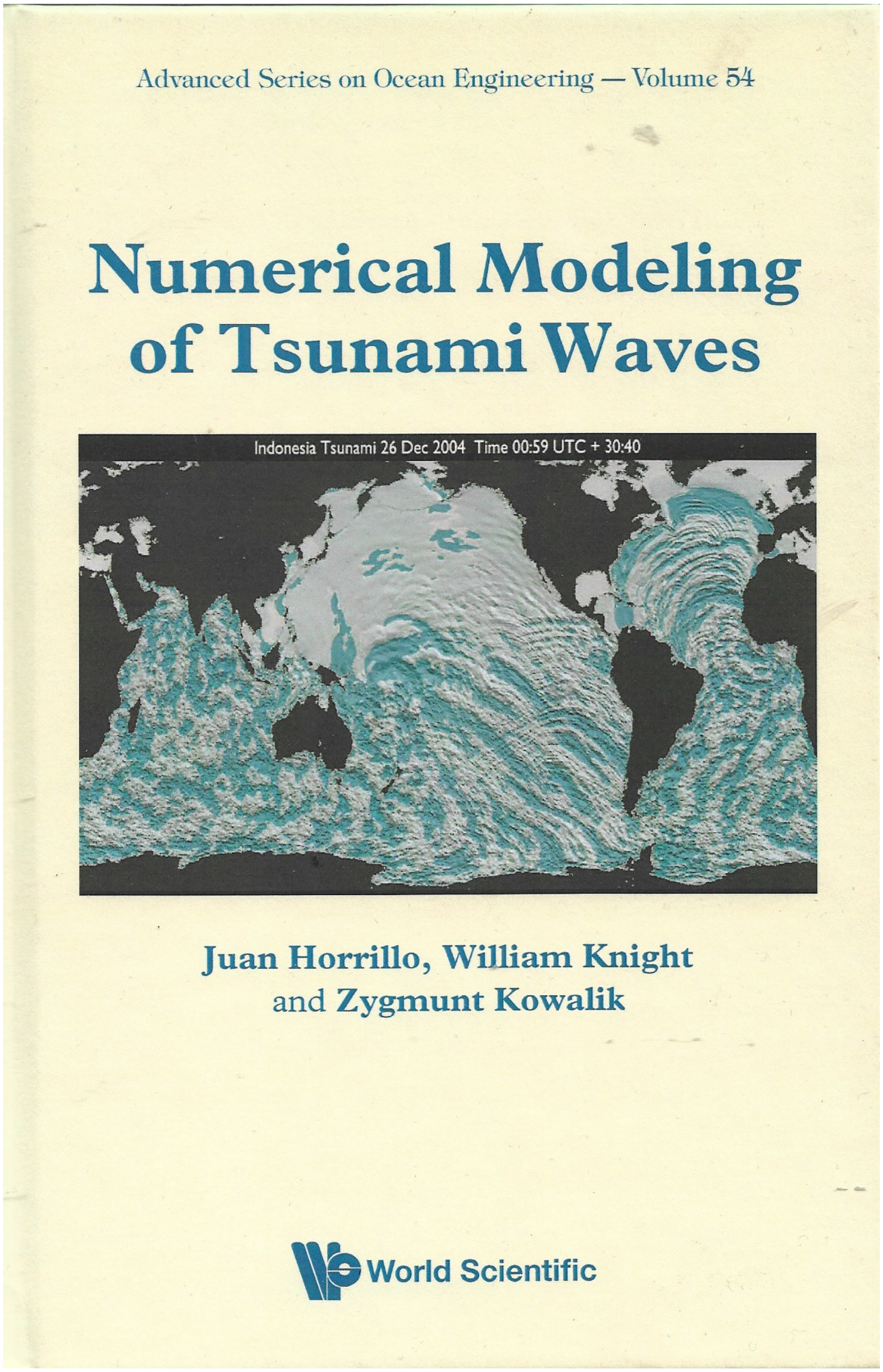
CONCLUSION

In a very skillful and methodical manner - the authors provide in the reviewed monograph, new insights on the subject of numerical modeling, its gradual upgrading, and updates with what is being done presently with state-of-the-art, high-performance computers, which allow for even more accurate simulations of tsunami waves generated from a variety of source mechanisms - whether from earthquakes, landslides, or other sources.

The eight chapters of the monograph, include thorough reviews of theoretical principles and of the development of codes for specific applications to computer modeling of real and theoretical data sets, as well of examples from the literature specific to the methodology used. These new codes allow the rapid solution of highly complex equations that describe tsunami wave generation, tsunami wave energy propagation, dispersion, and allow the prediction of near and far field wave characteristics. These characteristics relate to the unique mechanisms of wave generation from different sources and the effects on the distribution of wave energy and its attenuation across a body of water. The modeling is based on finite discretization in space and time, using structured rectangular meshes with codes and using finite difference schemes. However, the codes that are used for the calculations have been modified or extended to allow for mesh refinements.

Finally, and in addition to validating the results with historical data, the monograph provides several conclusions concerning the effects of various source characteristics on wave generation, propagation and termination – all of great importance in both understanding these processes, but also of being of significance to Tsunami Warning Systems in issuing more accurate predictions, and thus enabling Civil Defense Authorities to evaluate the tsunami risks and take measures that will protect human lives, properties and important infrastructure.

In summary, the monograph entitled "Numerical Modeling of Water Waves" by Juan Horrillo, William Knight and Zygmunt Kowalik represents an outstanding work of scholarship and a valuable reference for any researcher involved in numerical modeling.



Advanced Series on Ocean Engineering — Volume 54

Numerical Modeling of Tsunami Waves

Indonesia Tsunami 26 Dec 2004 Time 00:59 UTC + 30:40

Juan Horrillo, William Knight
and **Zygmunt Kowalik**

World Scientific

ISSN 8755-6839

SCIENCE OF **TSUNAMI HAZARDS**

Journal of Tsunami Society International

Volume 41 **Number 1** **2022**

WWW.TSUNAMISOCIETY.ORG

TSUNAMI SOCIETY INTERNATIONAL, 1325 South 33rd Avenue,Hollywood, Florida 33021, USA.

WWW.TSUNAMISOCIETY.ORG