ISSN 8755-6839

SCIENCE OF TSUNAMI HAZARDS

Journal of Tsunami Society International

Volume 39 Number 2 2020

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Noris Martinez[1] and Theofilos Toulkeridis[2]

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[2]Universidad de las Fuerzas Armadas ESPE, Sangolquí, **ECUADOR**

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1 National Institute of Aeronautics and Space (LAPAN), Bandung 40173, **INDONESIA**
2 Department of Geomatics Engineering, Institut Teknologi Sepuluh Nopember Kampus ITS Sukolilo ,Surabaya, 60111, **INDONESIA**
3 Mathematics Department, Master's Programme, Institut Teknologi Sepuluh Nopember, Surabaya 60111, **INDONESIA**

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[1]Ruhr-Universität, Bochum, **GERMANY**
[2]Universidad de las Fuerzas Armadas ESPE, Sangolquí, **ECUADOR**

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George Pararas-Carayannis
Tsunami Society International

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[1]Universidad Tecnológica de Panamá, Ciudad de Panamá, Panama
[2]Universidad de las Fuerzas Armadas ESPE, Sangolquí, Ecuador

*Corresponding author: ttoulkeridis@espe.edu.ec

ABSTRACT

In the last two decades, the vulnerability of coastal populations to the occurrence of natural phenomena such as tsunamis has increased, among other hazards that have existed throughout the development of civilizations and have constantly kept at risk the resources that a population needs for its development. The current study presents a representative sample of the perception of the population regarding the possibility of the occurrence of a natural phenomenon such as the tsunami on the Panamanian coasts. Although Panama is not at the top of the list of countries with high risk of current tsunamis, it does maintain an index that must be considered for the development of prevention strategies, so it is necessary to determine the perception of the population in order to execute contingency plans. The performed survey clearly demonstrates the poor preparation of the Panamanian population and the need for a drastic increase in the carrying out of all kinds of preventive activities towards tsunamis and their respective hazards.

Keywords: population vulnerability, survey, historic tsunamis, degree of exposure.

1. INTRODUCTION

Among any seismic movements, tsunamis are one of the most destructive and deadliest hazards of natural origin, especially in areas adjacent to oceanic environments (Pararas-Carayannis, 1969; Pararas-Carayannis, 2002; Adger et al., 2005; Pararas-Carayannis, 2006; Raschky, 2008; Alongi, 2008; Daniell et al., 2010; Seng, 2013; Esteban et al., 2018). Recently several studies documented with detailed evaluations the vulnerability of coastal areas with their corresponding strategic infrastructure as well as the degree of preparation of their habitants towards the impact of tsunamis and other associated natural occurring hazards of one or multiple origins (Latter, 1981; Scheffers, & Kelletat, 2003; Liu et al., 2007; Bryant, 2014; González-Riancho et al., 2015; Toulkeridis et al., 2017). In this respect, the 2004 tsunami with a magnitude of 9,3 struck in Indonesia and surrounding countries causing 350,000 deaths and 15 billion US$ of immediately economic lost (Athukorala and Resosudarmo, 2005; Jayatillekeand Naranpanawa, 2007), while in the case of Japans 9,0 magnitude tsunami of 2011, besides the 15,853 deaths, some 6,023 were injured and 3,282 remained missing, while approximately 300,000 building were destroyed, besides the 4,000 roads, 78 bridges and 29 railways, which were severely affected (National Police Agency of Japan, 2015). The economic damage reached approximately 210 billion US$ (Aon Benfiedl, 2015). Furthermore, the 8.8 magnitude tsunami of Chile in 2010, has led to some 500 deceased, while at least 1,5 million homes got damaged of which one third were completed destroyed, leaving an economic loss of approximately 30 billion US$ (Barcená et al., 2010).

On the other side the memory, education and awareness of occurred and potential tsunami disasters may be decisive in the preparation of the public (Frankenberg et al., 2013; Takeuchi, & Shaw, 2014; Benadusi, 2014). There has been statistical evidence of the degree of education and preparedness about natural disasters including tsunamis (Shaw et al., 2006; Muttarak, & Pothisiri, 2013; Esteban et al., 2013; Karanikola et al., 2015; Bronfman et al., 2016). Even worse, disaster education has not been included in public education in many areas even after the recent impact of tsunamis in a variety of countries in the surrounding of the Pacific (Gusiakov et al., 1997; Wood et al., 2002; Tang et al., 2008; Wood et al., 2010; Bisri and Sakurai, 2017).

However, in order to reduce such vulnerabilities and also in order to obtain a better knowledge of the degree of preparation of the general public, it should be considered fundamental to conduct studies with the goal to determine the level of vulnerability towards tsunami hazards for the corresponding population including their degree of knowledge, perception and preparation (Pararas-Carayannis, 1983; 1988; Taubenböck et al., 2009; Celorio-Saltos et al., 2018). Therefore, we have chosen to perform these aforementioned studies in a country in Central America, which is vulnerable of several tsunami sources such as Panama (Fernandez et al., 2000).

Central America has documented some fifty tsunamis in the last five centuries, which has led that Panama is threatened by tsunamis of the Pacific Ocean and the Caribbean Sea, which have been generated either by seismic movements or from volcanic activity

(Fernandez et al., 2000; NGDC/WDS, 2015; Intergovernmental Oceanographic Commission, 2018). In this sense, the main objective of the current study has been to contribute to the generation of knowledge about the factors that contribute to the increase or decrease of vulnerability towards tsunamis based on the degree of knowledge and preparedness of the academic population of Panama.

2. GEODYNAMIC SITUATION AND TSUNAMI HISTORY OF PANAMA

The country and the Isthmus of Panama, which are part of Central America, just adjacent to the northwestern corner of South America, are in between of some interesting plate tectonic constellation (Fig. 1). To the south there is the subduction of the northeastern trending oceanic Cocos as well as part of the oceanic Nazca plates, which subducts below the Caribbean plate along the Middle American Trench (Johnston, S. T., & Thorkelson, D. J. (1997; Johnston, S. T., & Thorkelson, D. J. (1997; Lonsdale, P. (2005).

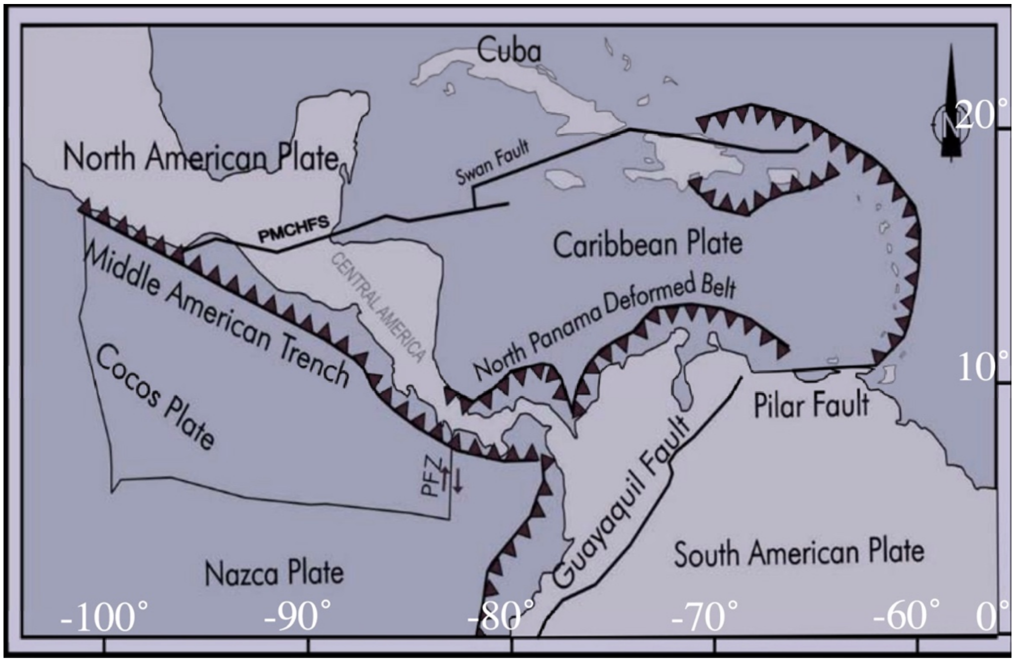

Fig. 1. Geodynamic setting of Central America including Panama situated west of the Caribbean plate (gray color), representing a volcanic islands arc, which has been formed by the subduction of the northeast moving Cocos plate under the Caribbean plate. Hereby, the PMCHFS is the Polochic-Motagua-Chamalecon Fault System and the PFZ represents the Panama Fracture Zone. Adapted from Fernández Arce and Alvarado Delgado, 2005.

Hereby, the division of the both oceanic plates is given by the presence of the Panama Fracture Zone (Lonsdale & Klitgord, 1978; Adamek et al., 1988). Furthermore, to the north of the country strikes a submarine fold and thrust belt known as the North Panama Deformed Belt (Camacho, & Víquez, 1993; Marshall et al., 2000; Camacho et al., 2010). Even further to the north there are the active island-arc tectonics of the Lesser Antilles as a product of the subduction of the oceanic parts of the North and South American plates (Mattson, P. H. (1984; Wadge, G., & Shepherd, J. B. (1984; Speed, R. C. (1985).

All aforementioned tectonic regimes characterize a seismically active region which has generated subduction related tsunamis, as well as tsunamis based on volcanic activity and by landslides (Fernandez et al., 2000; Lander et al., 2002; O'loughlin, K. F., & Lander, J. F. (2003; Pararas-Carayannis, G. (2004). However, tsunamigenic earthquakes are the most frequent origin of tsunamis in Central America (Fig. 2).

Hereby, there are some 54 registered tsunamis for Central America of the last 500 years (Fernandez et al., 2000; NGDC/WDS, 2015; Intergovernmental Oceanographic Commission, 2018). Of these, there are also a few reported and documented seismic events, that have generated tsunamis in Panama within the last 220 years (Fig. 3 and 4).

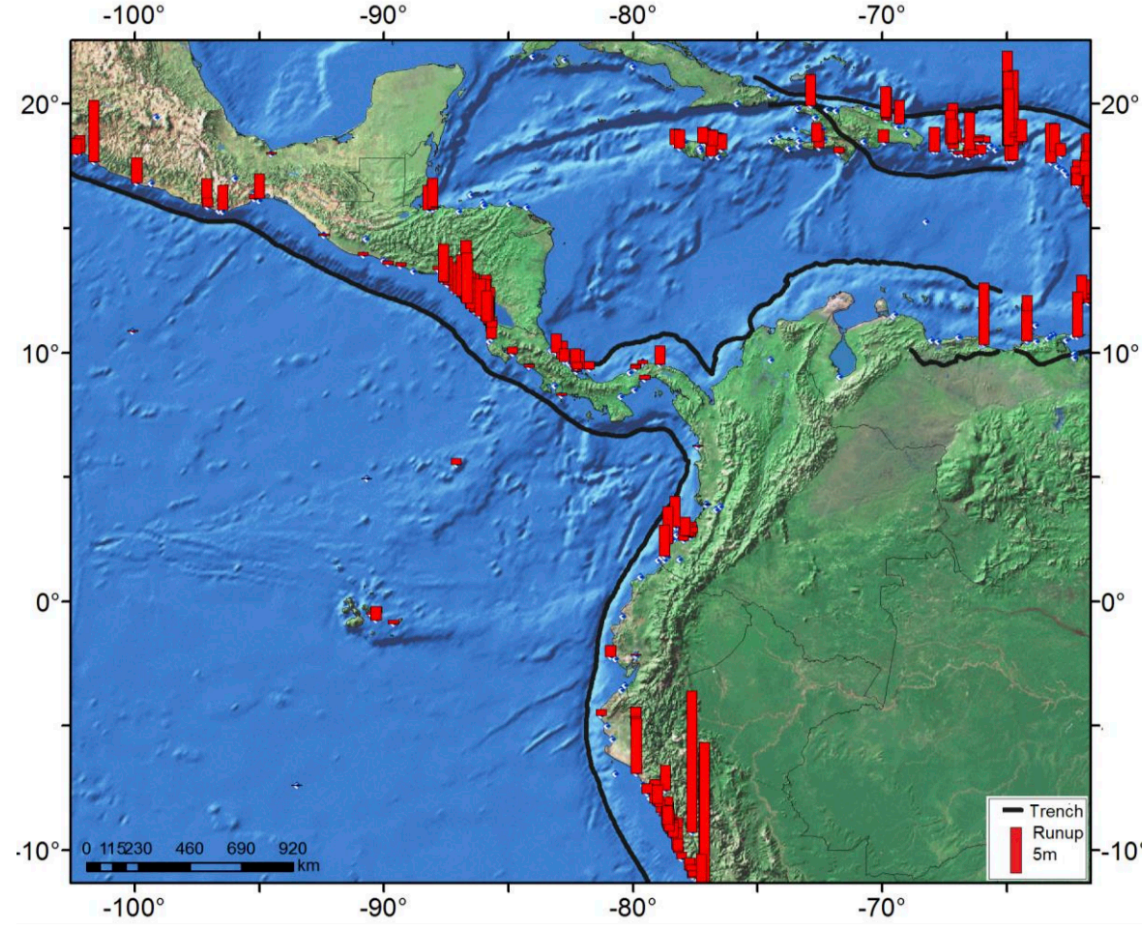

Fig. 2. Run-up and tsunamigenic earthquakes along Central America in 500 years. Source modified from Fernández et al. (2000) and NGDC/WDS (2015). Adapted from Intergovernmental Oceanographic Commission, 2018.

The first within the several events has been reported of February 22 in 1798 at Matina, near the Costa Rican border, where only some unusual noises have been eye-witnessed, which has been followed by another questionable tsunami at Panama City on the October

1873, where the city and Aspinwall shall have been affected by such seaquake (Molina, 1997; Lander et al., 2002). Shortly later, on the September 07 1882, the so far strongest documented earthquake and subsequent tsunami affected Panama, based on a 7.9 Ms earthquake, originating at the San Blas Archipelago, being observed also in Nicaragua, Colombia and Venezuela, leading to considerable damage and killing up to hundred people in San Blas in northern Panama (Milne, 1912; Sieberg, 1932; Ambraseys, 1995; Camacho & Víquez, 1993; Camacho, 1994).

This has been followed by another tsunami event of which validity is questionable at the November 5 1884 originated in the Panama Isthmus, having left destruction in Colombia as well as Panama (Grases, 1990). Just a little further to the south of the event of 1884, occurred on January 20 1904 another seismic event with a magnitude of 7 generating a questionable local tsunami with no significant reported damage (Oddone, 1907; Ambraseys, 1995; Ambraseys and Adams, 1996).

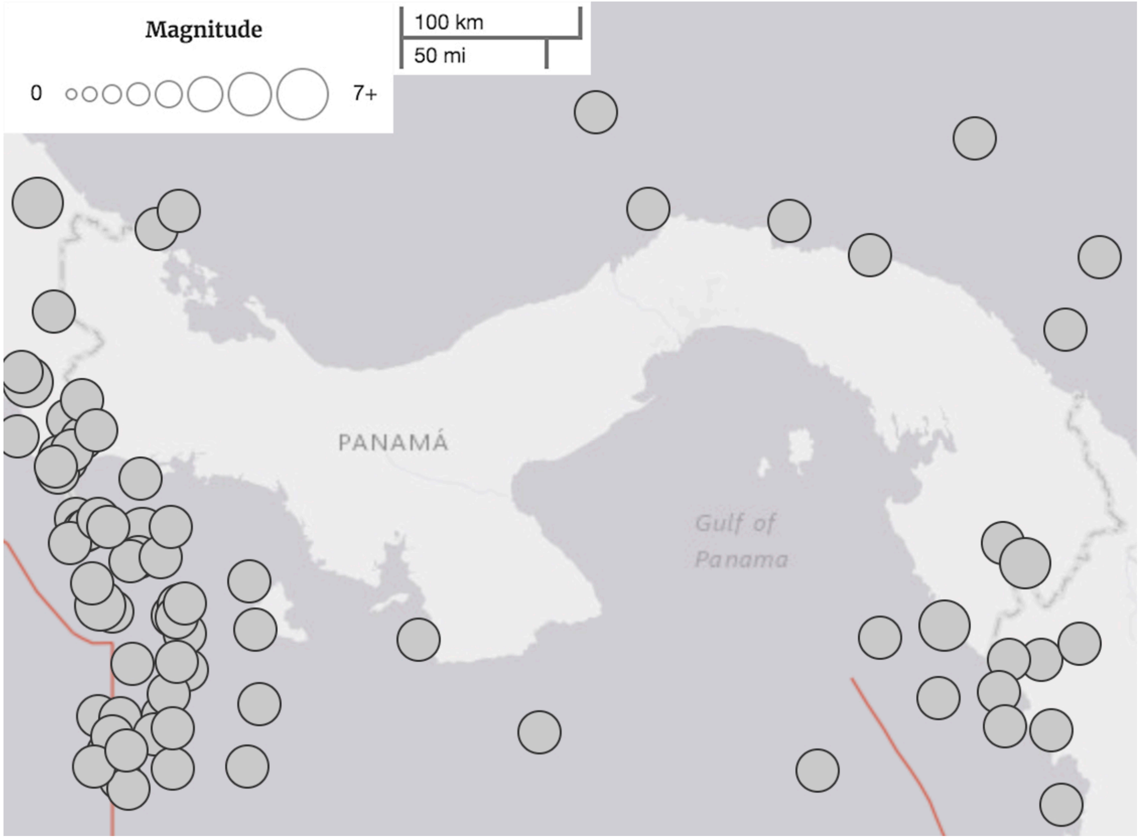

Fig. 3. Illustration of 79 seismic events with a magnitude of above 6.0 during the time period of 1924 and 2020 based on the earthquake catalogue of the United States Geological Survey (https://prod-earthquake.cr.usgs.gov/earthquakes/map), which are usually but not exclusively related to the given plate boundaries.

The October 2, 1913 seismic event in southern Panama has generated severe destruction, including effects of extensive cracking, liquefaction and landslides, leading to the disappearance of Pedasi village with its inhabitants and a sudden rise of the sea level probably misinterpreted as a tsunami (MacDonald and Johnston, 1913; Kirkpatrick, 1920; Ambraseys and Adams, 1996). Two further seismic events in 1934 and 1962 occurred on the Pacific side of the Costa Rican border, where marine quakes with magnitudes of 7 and 6.8 generated tsunamis with local inundation, even in the Galapagos Islands, but lacked of reported major destructions (Lander and Cloud, 1964; Iida et al., 1967; Soloviev and Go, 1984; Camacho, 1991; Fernandez et al., 2000). On July 11 1976 occurred the most recent seismic event with a magnitude of 6.7 along the southern Colombian border, which generated a minor local tsunami and some documented damages (Garwood et al., 1979; Grases, 1994).

Later, a regional tsunami on April 22 of 1991 originating from Costa Rica produced considerable inundation and damage in Panama, without human casualties (Plafker and Ward, 1992; Denyer *et al.*, 1992, Barquero and Rojas, 1994; Camacho, 1994; Ambraseys and Adams, 1996).

Fig. 4: Time of the known epicenters of tsunami events in the area of Panama, taken from (https://maps.ngdc.noaa.gov/viewers/hazards/?layers=0) as indicated by the National Oceanic and Atmospheric Administration´s (NOAA) National Centers for Environmental Information (NCEI). Explanation see text.

3. TSUNAMI RISK ASSESSMENT IN PANAMA

The institution in charge of preventive and reactive care in disasters in Panama is the National Civil Protection System (Sistema Nacional de Protección Civil), created by Law 22 of November 15, 1982 (Gaceta oficial No. 19695, 1982), and administratively regulated by Law 7 of February 11, 2005 (Gaceta oficial No. 25236, 2005). As the entity in charge of risk management and assessment in the Panamanian territory, its main objective is to execute specific mitigation and prevention measures to reduce hazards from any source, exposure and decrease the vulnerability of people to a catastrophe, in addition to carrying out response actions to any national emergency.

This institution has its own legal status and is under the directive of the Ministry of Government and Justice of Panama and being in charge of leading the Joint Task Force, created by Executive Decree No. 2 of January 7, 2015 (Gaceta oficial No. 27696, 2015). The Joint Security and Tourism Task Force (Fuerza de Tarea Conjunta de Seguridad y Turismo) is in charge of coordinating a timely and efficient response to a national emergency or disaster in a coordinated manner, and is made up of the National Civil Protection System (Sistema Nacional de Protección Civil - SINAPROC), the National Police, the National Naval Air Service (Servicio Nacional Aeronaval - SENAN), National Border Service (Servicio Nacional de Fronteras - SENAFRONT), Institutional Protection Service (Servicio de Protección Institucional - SPI), Benemérito Fire Department of the Republic of Panama (Benemérito Cuerpo de Bomberos de la República de Panamá - BCBRP), Panama Red Cross, Panama Maritime Authority (Autoridad Marítima de Panamá - AMP), National Environment Authority (Autoridad Nacional del Ambiente - ANAM), the Panama Tourism Authority (Autoridad de Turismo de Panamá - ATP), the Ministry of Health (MINSA), and the Single Emergency System (Sistema Único de Emergencias - SUME – 911).

A further initiative in risk management that Panama has been developing is the adoption of a National Policy for Comprehensive Disaster Risk Management (Política Nacional de Gestión Integral de Riesgo a Desastres - PNGIRD) through executive decree No. 1101 of December 30, 2010, which aims to "*provide to the Panamanian state and its institutions a regulatory framework to develop an integrated risk management associated with the impact of natural hazards and technological threats through a systemic and comprehensive approach to reducing vulnerability and promoting prevention, mitigation and effective response to disasters* "(Gaceta oficial No. 26699-B, 2011). This policy includes, in the context of disaster risk reduction, that Panama, due to its history, is exposed to risks associated with phenomena such as waterspouts, earthquakes, tsunamis, among others. It incorporates concrete actions that can be developed in the formal and non-formal educational infrastructure with a view to reducing the vulnerability of the population, working together with the civil society, local governments, universities, the Ministry of Education in the field of research, the academy and extensions.

One of the strategic allies of the National Civil Protection System, which receives and disseminates updated technical and scientific information regarding earth science, is the Geosciences Institute (IGC), which is part of the University of Panama. This was created by means of the Directive Council Resolution No. 6-77 of July 5, 1977. It is a research, teaching and higher extension entity with scientific and academic independence that have among its functions the continuous surveillance and monitoring of the country's seismic activities is in charge of alerting and guiding the National Civil Protection System and the community in general in the event of a disaster caused by seismic activity at the national level. It also maintains direct communication with the World and Regional Seismological Network and the Tsunami Warning System for the Caribbean and the Pacific.

Panama has been participating in a series of concrete actions on tsunami warnings, among which the European Commission Humanitarian Aid department's Disaster Preparedness Programme (DIPECHO) project for all Central America and Panama carried out by UNESCO, in conjunction with the Intergovernmental Oceanographic Commission-IOC, stands out (UNESCO-DIPECHO, 2019). It aims to strengthen early warning systems in the region, strengthening institutional capacities for tsunami warning and response. It includes a series of activities such as workshops, making flood maps and evacuating before Tsunamis, early warning drills in the coastal zone.

This DIPECHO project was developed from 2018 to 2019, with the participation of the National Civil Protection System-SINAPROC, Panama Maritime Authority -AMP, Geoscience Institute of the University of Panama-UP, Coordination Center for the Prevention of Natural Disasters in Central America - CEPREDENAC, Central American Integration System-SICA, Benemérito Panamanian Fire Department, National Tsunami Committee in Panama, Red Cross and the Tommy Guardia National Geographic Institute and leaves around 10,000 people trained in the event of a tsunami, from the communities of Puerto Armuelles, Baco, Limones, Rodolfo Aguilar and El Progreso, in the Barú district, Chiriquí Province.

4. METHODOLOGY

We have conducted a representative enquiry to the academic public in a variety of sites throughout Panama. Within the different sites where our survey has been applied, a coastal site has been included called Taboga Island, which is located south of the panama Channel inside the Gulf of Panama. This survey consisted of eleven basic questions and has been applied to 476 persons, of which 204 have been females, while the age range has been from 18 up to 70 years old, with a dominance of the age group between 18-28 (52,3%). The twenty different questions of the single sheet questionnaire should cover the perception, knowledge and awareness of the academic citizens and selected public about tsunami hazards versus the usual used term of a marine quake (maremoto) and its impacts (Scourse et al., 2018). Furthermore, the questions covered topics about the vulnerability of Panama towards tsunami hazards, risk awareness, historic knowledge of occurred tsunamis, which have impacted the country´s shorelines, evacuation plans, personal participation in tsunami drills, responsibilities of the corresponding authorities, types and forms of given tsunami alerts and source of information.

Based on the data that have been collected, a better idea may rise on social resilience and disaster risk reduction in Panama (Janes et al., 2010; Price and Narchi, 2018; Moreno et al., 2019). In the case of a tsunami, the ability to function and to act on the part of the citizens is crucial in order to behave appropriately and to be safe. The long-term objective of the study is therefore to derive measures for the optimization of disaster risk reduction, in particular through education, from the given results. This makes it possible to optimize the development of a risk-aware action competence and to increase the resilience to the natural hazard tsunami. This recent survey has also been conducted, as unfortunately, so far there is a lack of general and particular studies about tsunami awareness, science, preparation, perception and resilience such those in the nearby localities and the region (Pararas-Carayannis 2012; Matheus-Medina et al., 2018; Celorio-Saltos et al., 2018; San Martín et al., 2018), which may lead to an better improved coastal hazard assessment (Fernández-Arce and Alvarado-Delgado, 2005; Engel et al., 2016).

5. RESULTS AND DISCUSSION

The initial question of our survey, about the knowledge and awareness of a tsunamis has been responded positively with some 97,2%, while only 89,2% are aware of marine quakes (maremotos), for many a synonym for tsunamis in the region (Scourse et al., 2018). Surprisingly, only 61,1% of the surveyed are sure that Panama is vulnerable of tsunami hazards, while 30,9% are unsure if this is the case and some 7,7% discard any potential vulnerability. However, when specifically asked if there would be any memory of any tsunami which have impacted in past Panama, only some 11,1% have had that memory and of them the answer has been mainly about the 80´s of the last century. None of the recollected or knew of any historic tsunami impact in Panama. Besides, some 88,5% of the surveyed of the Island of Taboga answered that they are aware of potential impact of their habitat in case of a tsunami. While 20,3% have been informed about what to do in case of an incoming tsunami, some 34,2% answered to have knowledge form other sources about what to do if a tsunami would occur. Such other sources include mainly social media (66%). Nonetheless, only 10% of the interviewed have a knowledge of a given evacuation plan. However, when specifically asked what would be the potential source to be warned of an incoming tsunami, with the given options of a foghorn, radio, TV, seismic movement or none, inside the islands community of Taboga, the predominant answer (85,4%) has been that there is no form to be warned. However, 88,5% of the islanders would know where to evacuate to, in case of an incoming tsunami, while only 25% would know what alert warnings to recognize, although only 3,2% have ever participated in a tsunami evacuation drill. Only 17,6% are aware which organization is monitoring tsunamis in Panama, while in Taboga nobody knows these corresponding organizations. In the island of Taboga, there is an answer of 100% in the denial of ever received conferences or workshops about prevention of disasters including tsunamis, of any contingency plans of natural disasters including tsunamis or even about any realized studies by the local municipality in respect of the given vulnerability of people and their settlements towards tsunamis.

The low participation in tsunami drills is somehow not surprising. Panama participated with 31 other countries in a regional event called “Caribe Wave 2018” on March 15 2018, where it was supposed to simulate an 8.1 event on the Richter Scale with incoming waves of up to three meters. This event being promoted by the UNESCO and SINAPROC had the intention to understand the degree of the public’s preparation and being simultaneously also awareness raising (Fig. 5). It helped certainly as community training and capacity building, but unfortunately, the participation was very low. As long as there is a way to long time gap between the last (national) tsunami impact and recent days, the interest of participation and preparation will remain low.

Fig. 5: Tsunami drill of the March 15 2018 event in Panama. Credit Critica.com.pa

In this respect it is a challenge for the corresponding authorities to raise creatively and intelligently awareness of the existing tsunami hazards and especially in the known vulnerable coastal communities on both side of the country. Such communities need to be prepared to react correctly and respond timely when a tsunami alerts will be given. They will need also to know how to remain close to the affected areas prior the arrival of national and international aid agencies and institutions. The DIPECHO program teaches the local government and its organizations exactly the most effective life-saving efforts, which are usually conducted by the affected populations themselves, during and after a tsunami impact.

These activities may be accompanied by the installations of local but far reaching early warning systems and signs and corresponding emergency plans (Fig. 6). It is imperative to rethink the land use of vulnerable areas, to elaborate new coastal vulnerability maps based on a variety of potential scenarios, to apply potential relocations of entire villages and also where possible to apply a reinforcement of buildings and other strategic infrastructure, which is on reaching distance of tsunami hazards, as demonstrated in other countries of the region (Chunga and Toulkeridis, 2014; Matheus Medina et al., 2016; Toulkeridis, 2016; Rodríguez Espinosa et al., 2016; 2017; Chunga et al., 2017; Toulkeridis et al., 2017a; 2017b; 2018; Navas et al., 2018).

Once the local population may be prepared to a certain degree, than the regional authorities may use existing of how to prepare visitors and tourists towards tsunami hazards, as Tourism is especially vulnerable to disasters and, being fragmented, often its response is difficult to initiate and coordinate (Ritchie, B. W. (2004; Mistilis & Sheldon, 2006; Pforr & Hosie, 2008; Matheus-Medina et al., 2018).

Fig. 6: Installation of Tsunami evacuation signs in Panama. Credit Critica.com.pa

6. CONCLUSIONS

Panama has been historically impacted multiple times by a variety of tsunamis from the Atlantic as well as Pacific oceanic sides.

The Panamanian population, although they know what is a tsunami and its hazards, more than 35%, does not see or realize that Panama is a vulnerable country towards tsunamis or marine quakes. This is largely due to a lack of historical memory of events that occurred in the past.

Lack of awareness of this oceanic hazards and the lack of implementation of concrete plans and actions at the local, regional and national levels leave the population to be much more vulnerable to the possibility of a disaster caused by tsunamis and associated hazards.

It is necessary to include training and drill activities for the population in the topics of risk assessment within formal and non-formal education, as established by the national policy for comprehensive risk management for tsunami hazards and risks.

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ISSN 8755-6839

SCIENCE OF **TSUNAMI HAZARDS**

Journal of Tsunami Society International

Volume 39 **Number 2** **2020**

INDONESIAN TSUNAMI EARLY WARNING SYSTEM AUGMENTATION USING GNSS-TEC

Buldan Muslim1) , Mokhamad Nur Cahyadi2), and Charisma Juni Kumalasari3)

[1] *National Institute of Aeronautics and Space (LAPAN), Bandung 40173, Indonesia*

[2] *Department of Geomatics Engineering, Institut Teknologi Sepuluh Nopember Kampus ITS Sukolilo ,Surabaya, 60111, Indonesia*

[3] *Mathematics Department, Master's Programme, Institut Teknologi Sepuluh Nopember, Surabaya 60111, Indonesia*

Corresponding author: mbuldan@gmail.com

ABSTRACT

The Indonesian tsunami early warning system (INATEWS) has been developed and operated after the tsunami struck Aceh in December 2004. The INATEWS is based on a relationship model of earthquake parameters and tsunami potential. At the tsunami observation stage, INATEWS is still experiencing difficulties due to limited buoy stations. Alternative tsunami observations have been investigated using ionospheric TEC data from

GPS signal observations. This paper reviews the methods that have been studied and used for tsunami detection using ionospheric total electron content (TEC) from GNSS data. Status and development plans of real-time GNSS resource utilization for TEC measurement in Indonesia and its application for INATEWS augmentation are also discussed.

Keywords: INATEWS, Total Electron Content (TEC), GNSS

1. INTRODUCTION

The Tsunami Early Warning System is designed to detect the emergence of tsunami and provide warning to prevent casualties. New concepts and procedures for the fast and reliable determination of strong earthquakes, the modeling and simulation of tsunami, and the assessment of the situation have been implemented in the warning system. To anticipate the earthquake (EQ) and tsunami hazard, in November 2008 a tsunami early warning system in Indonesia was launched, known as InaTEWS (Indonesian Tsunami Early Warning System). Earthquake data that are integrated with various data of early warning devices such as GPS buoys, and tide gauges will confirm whether tsunami waves have already formed or not. This information will be forwarded to the public. The Early Warning System is operated by BMKG. Information from the different sensor systems are processed in the Tsunami Early cancellations respectively. The experiences from the capacity development program for local communities have been made available in the form of the Tsunami Kit that provides practical concepts that have been tested and validated, materials and tools for ongoing and future initiatives to strengthen local warning chains and tsunami preparedness throughout Indonesia. It is important to keep in mind that the effectiveness of InaTEWS greatly depends on the ongoing and future efforts to develop the required capacities in the downstream process (Hanka et al. 2010).

Recent developments in Real-time Precise Point Positioning (RTPPP) GPS processing (Ge et al., 2011) made it possible to use co-seismic displacement vectors registered by GPS more efficiently in the early warning process especially in the case of near-field tsunami. Babeyko and co-workers presented their recent results using a limited number of Japanese GPS stations for the direct inversion of co-seismic displacements into the slip distribution of the 2011 Tohoku Earthquake (Babeyko and Hoechner, 2012). They demonstrated how the slip distribution of an earthquake can be calculated with sufficient accuracy for early warning purposes within 2-3 minutes with a sufficient number of GPS stations. These findings have also been confirmed by other groups (Wei et al. 2011). Together with near-real time Tsunami modeling tools, this result will open a new perspective to switch the early warning process especially for near-field cases from the static and database oriented approach using pre-calculated Tsunami scenarios to a forecast approach based on directly measured sensor information from seismic and GPS networks in real-time.

Indirect tsunami observations by measurements of radio wave propagation through the ionosphere are based on ideas that have been anticipated in the past by Hines (Hines, 1972; 1974; Peltier and Hines,1976). Tsunami produces internal gravitational waves (IGWs) in an upward-spreading atmosphere. During upward propagation, IGWs are strongly amplified by atmospheric amplitudes due to the effect of decreasing atmospheric density to the extent of the atmospheric layer it passes. IGW interaction with plasma at ionosphere elevation in the results the variation velocity and density of plasma that can be observed by radio wave propagation in the ionosphere. Exciting research results on detection of the tsunamigenic peruvian earthquake on June 23, 2001 (M = 8.4 at 20:33 UT) to the total electron content (TEC) in ionosphere (Artru et al. 2005) which was measured by Japan's solid GPS network, GEONET opened up a modern debate on the feasibility of tsunami detection by radio wave propagation in the ionosphere. The gigantic tsunami of Sumatra-Andaman (Mw = 9.3, 0:58:50 UT, December 26, 2004 (Lay T et al. 2005) in which the magnitude larger than the Peruvian Tsunami, provides remote sensing observations worldwide in the ionosphere and an opportunity to explore ionosphere tsunami detection with large data sets. In addition to the seismic waves detected by global seismic networks (Park et al. 2005) co-seismic displacement is measured by GPS (Vigny et al., 2005); sea surface variations were measured by altimetry (Smith et al. 2005); detection of magnetic anomalies (Iyemori et al, 2005; Balasis and Mandea, 2007) and acoustic gravity waves (Le Pichon et al. 2005)~~;~~ a series of ionospheric disorders has been reported in recent literature using different techniques, such as Doppler sounding (Liu et al. 2006), over-the-horizon radar (Occhipinti et al. 2006), GPS (Liu et al. 2006; Lognonné et al., 2006; DasGupta et al. 2006) and altimeter (Occhipinti at al. 2006). Most observations show the relationship of Rayleigh waves in the ionosphere and tsunami. Numerical modeling by considering coupling between the lithosphere / atmospheric / ocean / atmospheric-neutral / ionosphere (Occhipinti et al, 2006; Occhipinti et al, 2008; Mai and Kiang, 2009; Hickey et al, 2009) produced several observations that proved the relationship between ionosphere impairment and displacement surfaces generated by Rayleigh waves and tsunami (Occhipinti et al. 2006).Through recent progress in tsunami detection using radio wave propagation in the ionosphere, we reviewed the results of detection methods of TEC disturbance caused by tsunami caused by 2004 Sumatra Earthquake until the 2011 tsunami in Tohoku. In addition we discussed a potential GNSS data network in Indonesia that could potentially be used to strengthen tsunami early warning in Indonesia.

2. REVIEWS OF DETECTION METHODOLOGY OF TSUNAMI EFFECT ON THE IONOSPHERE FROM GNSS DATA

2.1 High pass filter

Arthru used a high pass filter with a cut-off at 30 minutes to remove diurnal variation and receiver bias (Artru et al. 2005). Using single satellite observation to reduce mislocation of ionospheric pierce points (IPP), where the relative location of the different measurement points is still accurate. The traveling ionospheric disturbances (TID) are the common phenomenon of during day and night. In order to confirm that the tsunami, the preceding and following days are used as a reference. The criteria of wave-like perturbation of TID are more than 0.1 TECU. The daytime TID is more frequent than the nighttime TID.

2.2.2 Polynomial and band pass filtering

According to Galvan et al.(2011) used polynomial function to fit the TEC time series in order to fit the longer period variations such as diurnal variations and elevation angle dependence of the TEC ray path. After that they used a band pass filter of 0.5 - 5 mHz (corresponding to wave period of 33.3 to 3.3 minutes, a typical range of tsunami periods) to extract TID caused by tsunami.

2.3 Cut off TEC error: Three-sigma TEC error measurement (0.03 TECU)

The precision of GPS carrier phase measurement is less than 1 mm. According to the error propagation law, the measurement error of TEC is about 0.01 TECU. The detrended TEC in quiet condition is nearly the random noise, which is dominated by the measurement error. In quiet condition the detrended TEC value will usually fall into the three-sigma range of about 0.03–0.03 TECU. When the detrended TEC values are out of this range, the TEC anomalies could be detected. The high precision and high temporal-spatial resolution ionospheric TEC from GEONET provides the opportunity to discuss the detailed seismic ionospheric pattern and evolution (Jin et al. 2009).

2.4 Detrending STEC map with 10 minutes windows.

According to Tsugawa et al.(2011) used detrended TEC by subtracting TEC from 10 minutes windows moving average for detecting Tohoku tsunami effect on ionosphere using GEONET data.

2.5 Four-order zero phase shift Butterworth filter

According to Jin et al.(2014) corrected the times in GEONET by adding the difference between UTC and GPS time with 15 s on 11 March 2011 according to the International Earth Rotation and References Systems Service (IERS) Bulletins (http://hpiers.obspm.fr/eop-pc/). In order to degrade the multipath effects and the error of mapping function, measurements with low satellite elevation angles (less than 10° if not specified in following) are not used. In order to remove the TEC trend and high frequency fluctuations and other noises, the detrended TEC series are filtered with four-order zero phase shift Butterworth filter that is designed with a most flat frequency response in the pass band without phase shift. Here the TEC series obtained by GEONET dual frequencies GPS measurements are filtered with a 1–15 mHz window for detrending. The trend is mainly caused by SIP's motion and ionospheric background changes. They choose the 15 mHz as the high cut-off frequency in consideration of the 30 s interval of the GEONET ionospheric monitoring, avoiding the aliasing in signal processing and chose 1 mHz as a threshold to remove the background TEC variation. For Tohoku tsunami, TEC measurement near the epicenter could detected the acoustic wave and wave related to the Rayleigh wave (3–7 mHz) and tsunami-generated gravity wave (<3 mHz)

(Matsumura et al, 2014; Occhipinti et al, 2013) but also higher frequencies signal (7–15 mHz).

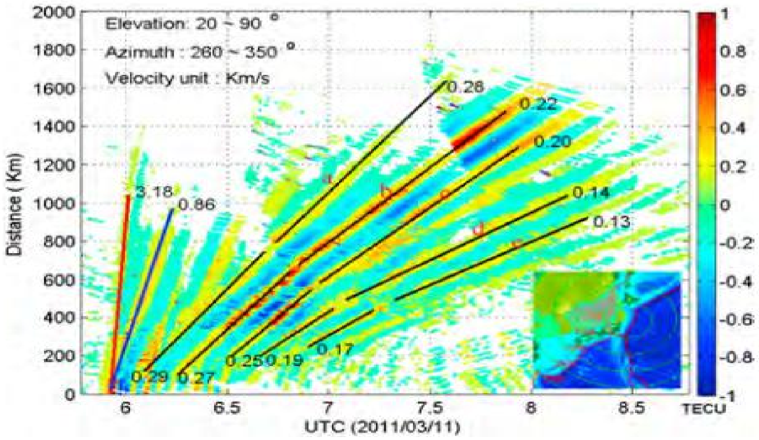


Figure 1. Travel time diagram of post-seismic TEC disturbances following the Tohoku earthquake on 11 March 2011. The SIP with azimuth angles of 260-350^0 and satellite elevation angles of 20-90^o are used. The disturbance amplitude is described by the scale color. The bottom right figure shows the SIP location area with a yellow sector patch. The red circles are equidistant lines to the epicenter corresponding to 500-2500 kms with a 500 kms interval (Jin S et al. 2014).

Figure 2 presented TEC disturbance time series and spectrograms around the epicenter from 05:00 UTC to 09:00 UTC. Here, the one-sided normalized power spectral density (PSD) is computed using the short-time Fourier transform. The length of the window is set as 30 min. In the upper left panel, the star is the location of the epicenter, and the circle is the location of the corresponding GEONET station. The black line is SIP's.

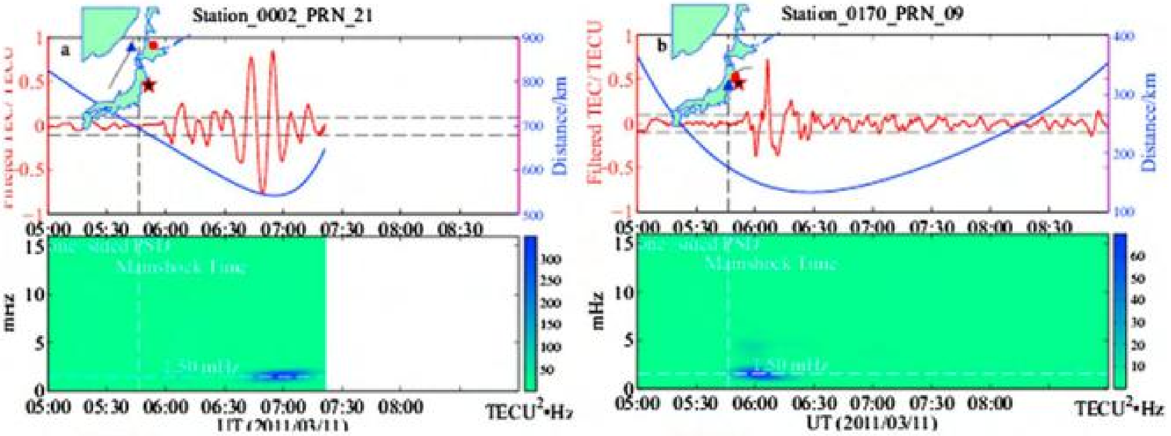


Figure 2. TEC disturbance time series and spectrograms around the epicenter from UTC 05:00 to UTC 09:00 (Jin S et al. 2014).

2.6 Adopted a simple ray-tracing technique commonly used in seismology

A simple ray-tracing technique (Aki and Richards, 2002) commonly used in seismology was employed here in to estimate the arrival times at the 12 monitoring stations for locating the earthquake source (or tsunami origin) as well as to find if the observed disturbances of the ionospheric GPS TEC is triggered by the tsunami. Firstly they try to guess a location of the tsunami source; calculate travel time of the tsunami propagating horizontally away from the trial source and triggering the acoustic gravity wave which in turn propagates vertically to reach each monitoring station; and compute a standard deviation of the differences between the calculated and the observed arrival times. They repeat this procedure through the whole set of grid points (trial source locations) and then contour the computed standard deviations to find the minimum, which is then considered to be a possible source.

Figure 3 shows that an average horizontal speed of 191 m/s (about 700 km/hr) and an average vertical speed of 730 m/s give an optimal induced time at 0106 UT±15 min and source location at – 1N, 93E which is about 580 km southwest of the earthquake epicenter.

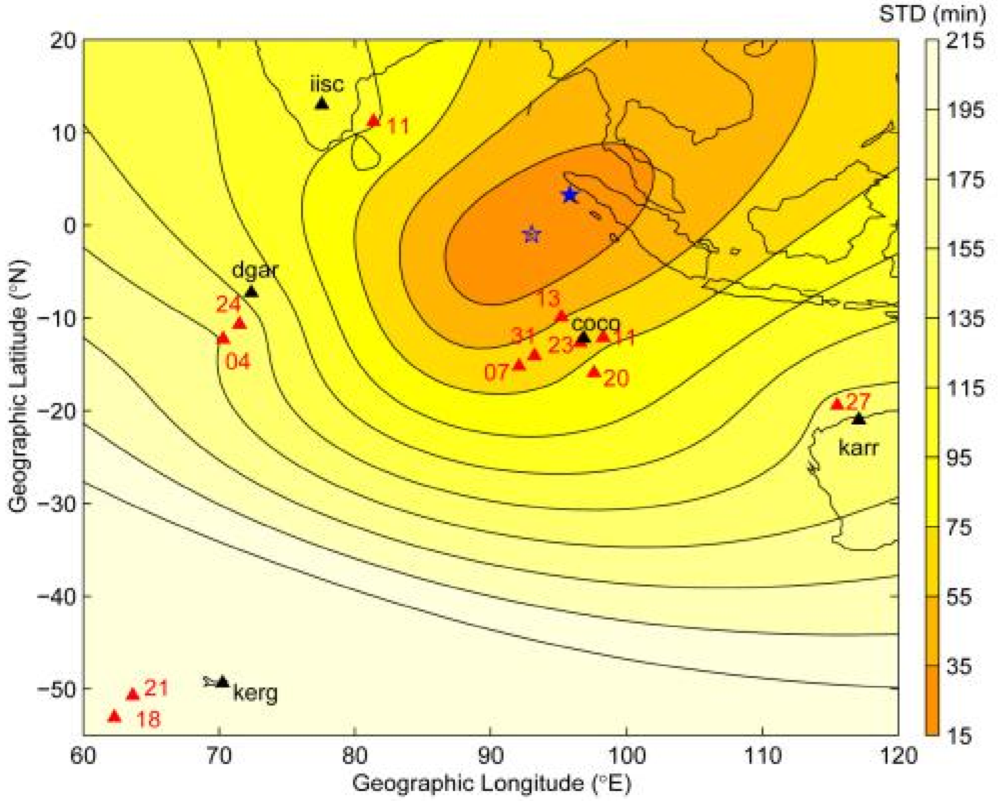


Figure 3. Contours of standard deviation of the differences between calculated and observed arrival times are shown. Locations of ground-based GPS receivers and associated monitoring stations are denoted by black triangles with station names and red triangles with GPS satellite numbers. Epicenter reported by U.S. Geological Survey and solid and open blue stars denote calculated source, respectively (Liu et al. 2006).

Note that the average horizontal and vertical speeds generally agree with those directly estimated from the time delay (Figure 4). Meanwhile, the estimated tsunami source location and the induced time are close to the epicenter and origin time of the earthquake given by the U.S. Geological Survey (http://earthquake.usgs.gov/eqcenter/eqinthenews/2004/usslav/).

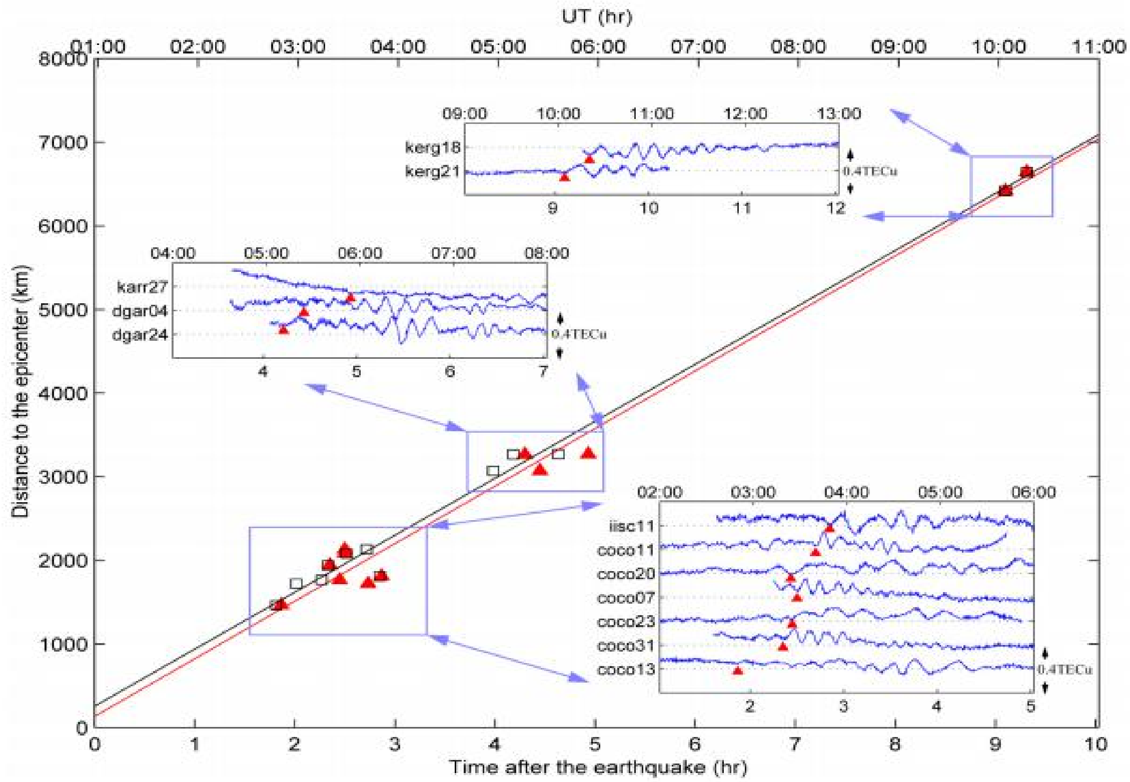


Figure 4. Average horizontal speeds of TIDs and tsunamis are shown. Arrival times (red triangles) vs. distance from epicenter to each monitoring station are employed to compute average horizontal speed of TIDs (red line). Arrival times of tsunami (black squares) at footprints (sub ionospheric points) of monitoring stations, which are extracted from published simulation results, are used to find average horizontal speed of tsunami (black line). Average vertical speed of acoustic gravity waves is estimated from time lag between the two lines (Liu et al. 2006).

2.7 Tsunami ionospheric hole (TIH)

A TEC depression with a radius of a few hundred kilometres, which remained stationary for approximately 1 hour was observed (Kakinami et al. 2012). This was termed as the tsunami ionospheric hole (TIH). A TIH was also visible after the Sumatra EQ and the 2010 M8.8 Chile EQ. Further investigations revealed that TIHs appeared after other megathrust and shallow global EQs with magnitudes greater than 7.215 (Astafyeva et al. 2013). A numerical simulation of the TIH elucidated the plasma dynamics. When the acoustic waves reached the ionosphere, the amplitude of the acoustic waves was intensified due to the very low density of neutral atmosphere. The acoustic waves forced the ionospheric plasma to considerably migrate only along the magnetic field line because of neutral-ion drag. Subsequently, in the decompression phase of the acoustic waves, the downward plasma caused dissociative recombination and suppressed ion production, creating a TEC depression, i.e. TIH. The immediate recombination and slow production caused the TIH to exist for a long time (Shinagawa et al. 2013), According to Astafyeva et al. (2013) reported a correlation not only between initial tsunami height and initial TEC enhancement amplitude, but also between initial tsunami height and TIH duration for 11 large global EQs.

Thus, the quantitative relationship between the initial tsunami height and amplitude of the TEC disturbance immediately above the tsunami source area is required to assess the possibility of using GPS-TEC ionospheric monitoring for a practical early warning system. According to Kamogawa et al.(2016) focus on the value of a TEC depression in a TIH to estimate initial tsunami height, because the TIH remains stationary. They discuss the possibility of constructing an early warning system using only the existing GPS network.

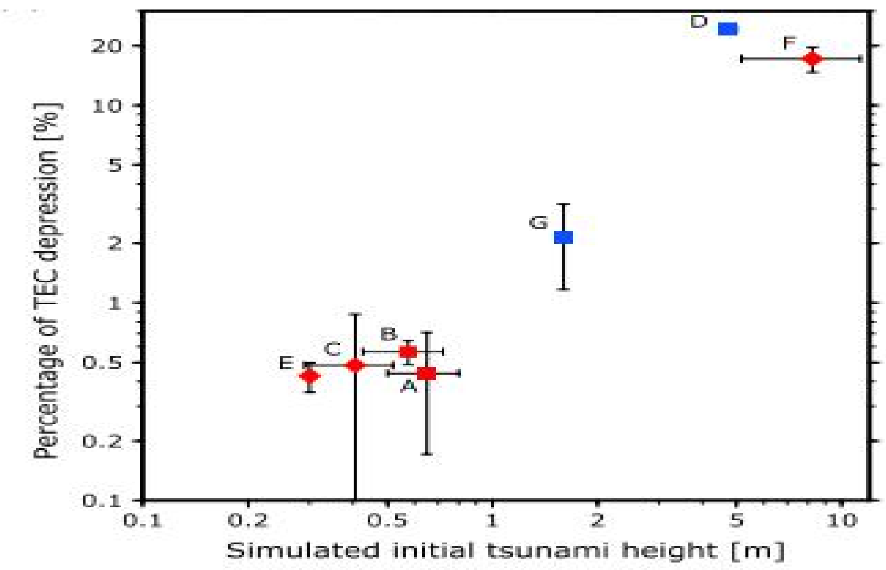
To derive the TEC disturbance caused by the TIH, According to Kamogawa et al.(2016) applied the following procedure. First, the least-squares quadratic curve of the slant TEC time-series in the period from 30 minutes prior to 40 minutes after the main shock was obtained, except for the Tohoku EQ and the Maule EQ. For the Tohoku and Maule EQs, only the period from 30 minutes prior to 7 minutes after the main shock was used because the TIH was too large to obtain appropriate approximation after the TIH. Peculiar bias components for each satellite and the receivers were reduced by the difference between this fitting curve and the raw data. Second, the difference in the vertical TEC (i.e. ΔvTEC) was derived by multiplying the cosine between the slant direction and the satellite earth direction by the difference between the fitting curve and the raw data. The period of the spectrum analysis was 4096 seconds, consisting of 1024-second data of ΔvTEC located in a constant part of a boxcar window function. The vertical axis indicates the distance between the SIP at the time of the main shock and the centre of the tsunami source area, and the horizontal axis indicates the period of the spectrum.

Several resonant modes of acoustic waves occurred; in particular, they were intense in the period from 150 to 210 seconds above the tsunami source area. According to Watada and Kanamori (Watada and Kanamori, 2010), the observed distinct patterns from 150 to 210 seconds are inferred to be resonant modes of the acoustic waves excited by the tsunami. To exclude the variations of resonance modes including the initial TEC pulse, i.e. the acoustic wave components, and extract the component of the TIH, the±150 sec running mean of ΔvTEC except the Niigataken Chuetsu-oki EQ was taken, i.e. low pass filter (LPF) ΔvTEC. For the Niigataken Chuetsu-oki EQ,± 90 sec running means is used because of a small TEC disturbance.

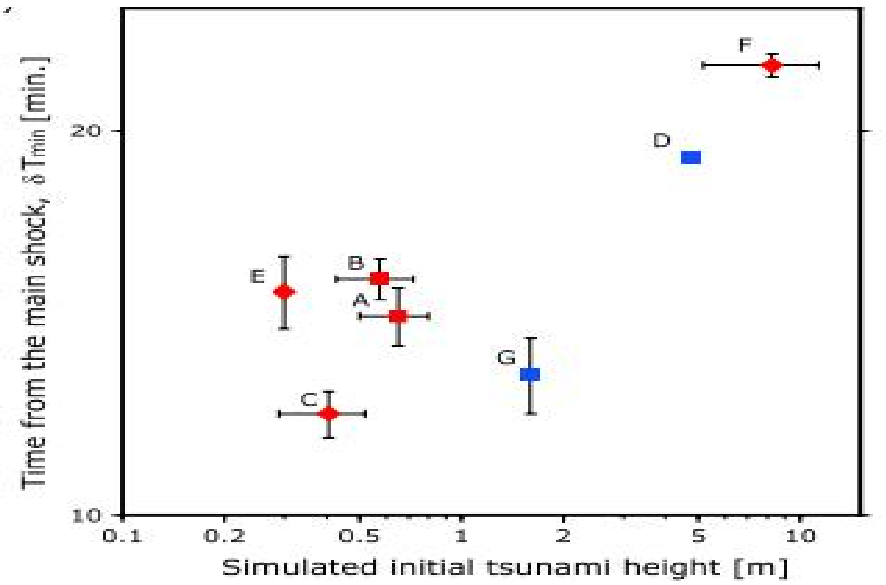
The following procedure was employed to estimate the value of the TEC depression of the TIH above the tsunami source area. First, the tsunami source area was defined to be the average location of the Tohoku EQ (N38.0, E143.4), the Maule EQ (S34.8, W72.9), and the Illapel EQ (S30.9, W72.3) reported by several articles 28–31,26,27,32, and equivalent to the epicentre of other small EQs. Time-series of LPF ΔTEC to estimate the TEC depression were selected such that the SIP at the time 7 min after the main shock was located within 100 kilometres from the tsunami source area of Mw≥ 8 EQs and 50 kilometres from the epicentre of the other EQs from 7 minutes to 24 (the Tohoku and Maule EQs) and 16 (the other EQs) minutes after the mainshock. They defined δ vTECTIH as the difference between the value of the LPF ΔvTEC 7 minutes after the main shock and the minimum value of LPF ΔvTEC, and δTmin as the interval between the main shock and the minimum time of LPF ΔvTEC.

Considering the simulation of Shinagawa et al.(2013), the TEC depression of TIH was assumed to be proportional to the electron density in the F2 region immediately before the TEC disturbance, because the depressed plasma migrates downward from the F2 region. In this study, the percentage TEC depression with respect to absolute vTEC, i.e. δvTECTIH/vTEC× 100, was discussed for comparison with different solar conditions such as during different seasons and at different local times. For derivation of absolute vTEC, data of Global Ionosphere Maps Total Electron Content (GIMTEC: ftp://ftp.unibe.ch/aiub/CODE/) was used. Finally, the average values and standard deviations of the percentage TEC depression (δvTECTIH/vTEC× 100) and δTmin for each EQ from the selected time-series of LPF ΔvTEC were obtained.

They focused on the percentage TEC depression caused by the TIH and the interval δTmin between the time of the main shock and the minimum value of LPF ΔvTEC (namely the largest TIH). The relationship between the percentage of the TEC depression, δTmin, initial tsunami height and EQ magnitude are illustrated in Fig. 5. As shown in Fig 5a, the percentage of TEC depression versus the initial tsunami height are correlated. In Fig. 5a, the Maule EQ (D) is slightly large, probably because the night-time small background TEC yielded relatively large error of the percentage of TEC depression, while δTmin of the Maule EQ shown in Fig. 5b seems appropriate. On other hand, in Fig. 5c, the four small EQs with small simulated initial tsunami height (A, B, C, and E) seems inappropriate, probably because of difficult identification for the small depression, while the percentage of TEC depression for them are relatively appropriate. Thus, the EQ with more than 1 m initial tsunami height during daytime might show a precise percentage of TEC depression and δTmin.



(a)



(b)

Figure 5. Relationship between percentage TEC depression and initial tsunami height and magnitude. A, B, C, D, E, F and G denote the 2003 M8.0 Tokachi-oki EQ and the 2004, M7.4 Off the Kii peninsula EQ, the 2007 M6.6 Niigataken Chuetsu-oki EQ, the 2010 M8.8 Maule EQ, the 2011 M7.0 Sanriku EQ, the 2011 M9.0 Tohoku EQ, and the 2015 M8.3 Illapel EQ. Red and blue means EQ in Japan and Chile, respectively. Rhombus and squares mean daytime (6–18 LT) and nighttime EQs in local time. (a) Initial tsunami height versus percentage TEC depression. (b) Initial tsunami height versus time after main shock (ΔTmin) (Kamogawa et al. 2016).

3. APPLICATION OF GNSS NETWORKS IN INDONESIA FOR TSUNAMI EARLY WARNING SYSTEM AUGMENTATION

3.1 Real Time GNSS Data In Indonesia

Positioning system in Indonesia which is carried out systematically and Continuity began in 1989. In that year activities began to take place Global Positioning System for Geodynamic Projects in Sumatra (GPS-GPS) to monitor active tectonic plate motion in Sumatra faults (C. Subarya, 2010). In 1991, The research project collaboration between BAKOSURTANAL and Scripps Institution of Oceanography and Rensselaer Polytechnique Institute, New York, United States of America was expanded to Eastern Indonesia to monitor active tectonic plate movements on "Triple Junction Plate". In 1992, along with the implementation of measurements GPS for the purposes of geodynamic research, GPS measurements are made for procurement Homogeneous and continuous National Horizontal Geodesy Control Network (JKHN) geometrically, and classified as Zero Order JKHN. Next year which is the same and the following year (up to 1994 status) a network expansion was made to lower order, and classified as Order One JKHN. In 1996 s.d 1998 The geodetic control net continues to be developed covering South Asia and Asia Southeast as part of the Geodynamic of South and Southeast Asia Project program (GEODYSSEA) which is a collaboration between BAKOSURTANAL and related agencies inside country and involve earth science researchers from the European Union (C. Subarya, 2010). Then since the early 2000s effectively began implemented continuous GPS (cGPS) observations (C. Subarya, 2010) which is the forerunner to InaCORS. The Aceh tsunami on December 26, 2004 contributed to the increase the number of cGPS stations in Indonesia. Counted several cGPS stations were built at the time in line with the German-Indonesia Tsunami Early Warning System (GITEWS) program. BAKOSURTANAL itself, in 2010 carried out massive cGPS development in tandem with the Indonesia Tsunami Early Warning System (InaTEWS) program. Counted number 40 cGPS stations were built on Java and began to be equipped with data communication systems in the form of a Virtual Private Network (VPN) so that cGPS stations can streaming data in the form of Radio Technical Commission for Maritime Services (RTCM) format to the GPS data center in the Cibinong BAKOSURTANAL office. In the BAKOSURTANAL GPS data center is installed the Networked Transport of software RTCM via Internet Protocol (NTRIP) Caster. The cGPS station besides functioning to monitor the movement of the related tectonic plates for the purposes of InaTEWS has also been able provide position correction services to RTK users. On the basis of the 2011 Geospatial Informaion Law, BAKOSURTANAL has changed its name to Geospatial Information Agency (BIG) which has full authority related to the administration of geospatial information in Indonesia. In 2013 the InaCORS network was utilized in the operation of the Indonesian Geospatial Referens System (SRGI 2013). Starting in 2013, InCORS is growing rapidly, so up to 2019 has been built 207 InaCORS stations spread across all regions of Indonesia as depicted in Figure 7.

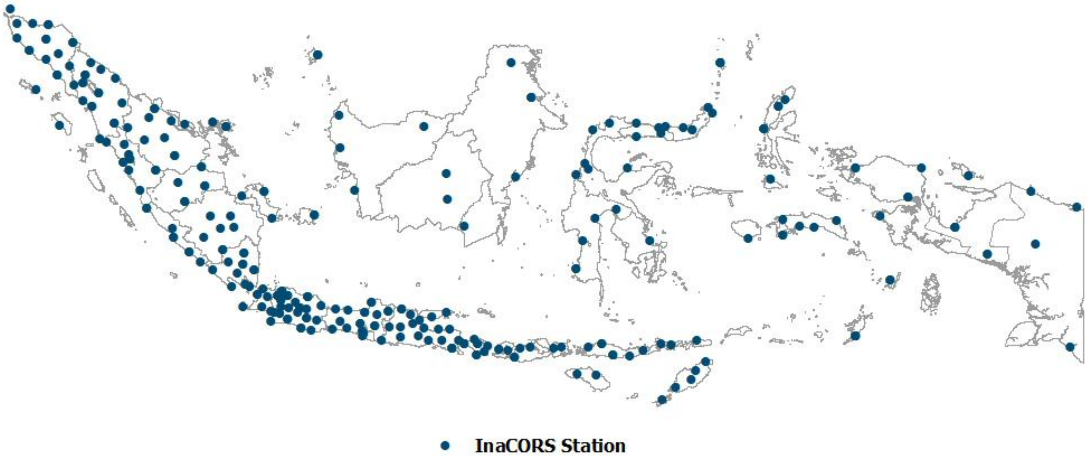


Figure 7. Distribution of InaCORS stations in Indonesia on April 2020

3.2 Methodology of INATEWS Augmentation using real time GNSS

Based on reviews of methodology for tsunami detection using ionospheric TEC, we plan to develop a methodology for INATEWS augmentation as shown in Figure 6. As illustrated in Figure 6, GNSS based INATEWS augmentation methodology are as follows. Firstly, the accessing and processing real-time RTCM GNSS data . Using the decoderrtcm.m function, GNSS data RTCM format is converted to ASCII data in PC memory. GNSS observation data was taken from RTCM data are pseudorange on L1 frequency (P1), pseudorange on L2 frequency (P2) , number of phases of carrier wave (number of cycles) on L1 frequency (L1), number of cycles on L2 frequency (L2), satellite number, epoch and position of GNSS station. Secondly the GNSS stastin position data and GPS satellite orbit data are used for calculation of ionospheric pierce point (IPP) coordinate and elevation. IPP elevation data can be used for the conversion of Slant TEC (STEC) to vertical TEC (VTEC). The VTEC data from the carrier phase data are still contain receiver bias, satellite bias, and unknown integer ambiguity cycles (N). Therefore all biases of VTEC are eliminated by using detrending method such as by subtracting VTEC at epoch t (VTEC(t)) with VTEC data on previous epoch (VTEC t-1) to obtain detrended VTEC (DVTEC). DVTEC needs to be filtered to identify the ionospheric accoustic - gravity wave caused by the tsunami by using a bandpass filter in the frequency range with a period of 3 - 33 minutes. DVTEC is filtered from the effects of acoustic-gravity waves to obtain LPF DVTEC to find the tsunami ionospheric hole (TIH) parameter, the decrease percentage in TEC due to the acoustic wave generated by the tsunami. Finally the tsunami parameters can be derived from ionosphere: the initial height of the tsunami from the TIH, the tsunami periode from the DVTECF data, and the tsunami velocity from the delay of ionosphere gravity-acoustic wave observed by single receiver from different GNSS satellites.

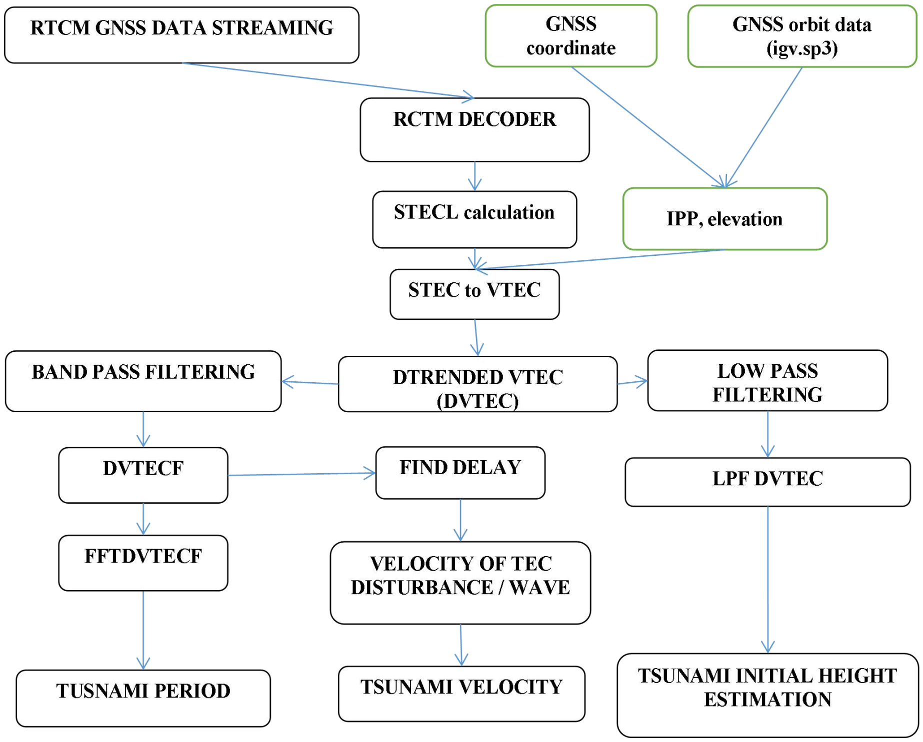


Fig. 6. Methodology for INATEWS augmentation

3.3 Real Time MSTID Monitoring Using Single GNSS Station

From one GNSS station, TEC spectrum analysis can be developed in real time by averaging detrended TEC every minute. After collecting the TEC detrended data every minute in 30 minutes, a spectrum analysis is updated every minute. Figure 8 showed the TEC spectrum from Tangerang station.

Figure 8 showed the DSTEC data for 30 minutes of observation derived from the average DSTEC every second. DSTEC spectral analysis for 30 minutes at a certain minute is illustrated by the DSTEC spectral contour of the middle panel of Figure 8. The abscissa of the middle panel of Figure 8 is GPS time, and it's ordinate is the DSTEC fluctuation period in minutes. The right panel of Figure 8 is the location of the ionospheric observation point (IPP) of the CTGR GNSS station in Tangerang on April 18, 2018.

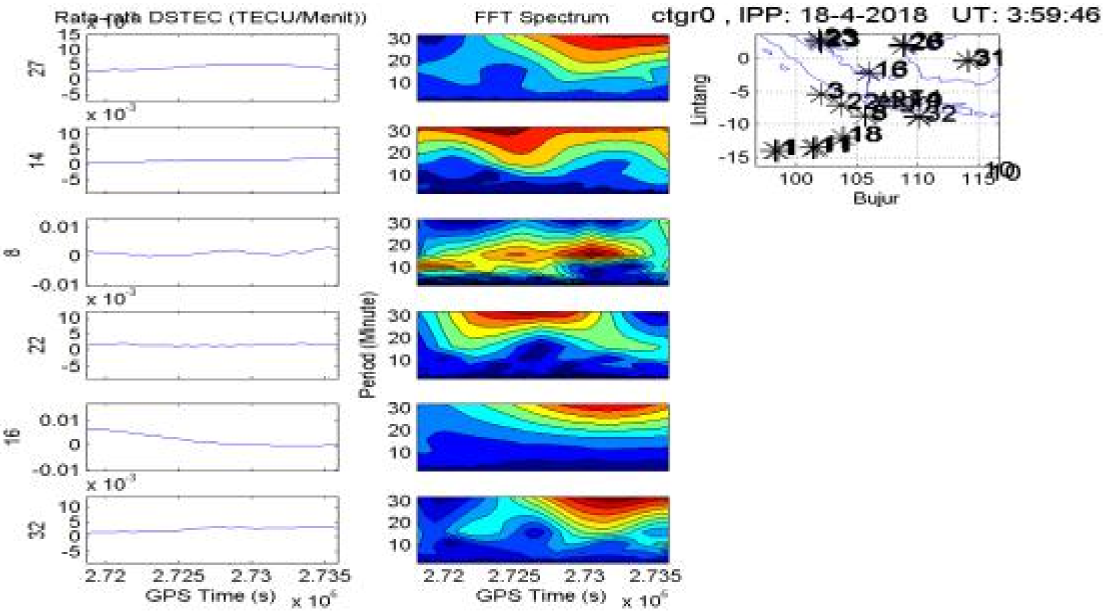


Figure 8. TEC spectrum from Tangerang station

4.CONCLUSIONS AND RECOMMENDATION

Since the Aceh Tsunami of December 26, 2004 and Tohoku tsunami of March 11, 2011, researchers have proven that TEC data from GNSS phase data can be utilized for the detection of tsunami effects on the ionosphere and can be used for estimating the tsunami epicenter, direction and speed, with the same method of epicenter determination from seismic data. Beside the ionospheric wave, tsunami ionospheric holes have been found and they have a relationship with the initial high of tsunami. Tsunami effect on the ionosphere can be detected by using filtering methods such as high pass filtering, band pass filtering, polynomial filtering, and TEC difference. The researchers believe that TEC GNSS can be used to strengthen existing tsunami early warning systems. But until now the detection of tsunami effects on the ionosphere is still in the research stage with off-line GNSS data. The implementation of tsunami detection using GNSS TEC requires real time GNSS data access in RTCM format.Tsunami effect detection methods with real time GNSS data that can be used for InaTEWS augmentation needs to be modified to estimate the tsunami effect on the ionosphere, determining the speed and direction of tsunami propagation in real time with a delay of several minutes. Unfortunately, the augmentation of TEWS with GNSS TEC data is only effective for large tsunamis and the epicenter is located 200 km farther from the coast. The InaTEWS augmentation by using real time GNSS TEC is under development and currently in the real time multi-station TEC estimation stage and TEC real time analysis spectrum from single GNSS station.

Acknowledgment

This research was funded through the INSINAS program of the Indonesian Ministry of research technology and higher education (No. 14/INS/PPK/E4/2020). And we gratefully thank the Indonesian Geospatial information agency for support in the preparation GNSS real time data. Also, Well deserved recognition is due to Joni Efendi for his consultations and suggestions for using GNSS RTCM data for real time TEC purposes.

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ISSN 8755-6839

SCIENCE OF TSUNAMI HAZARDS

Journal of Tsunami Society International

Volume 39 Number 2 2020

TSUNAMI HAZARDS IN ECUADOR – REGIONAL DIFFERENCES IN THE KNOWLEDGE OF ECUADORIAN HIGH-SCHOOL STUDENTS

Dennis Edler[1], Karl-Heinz Otto[1] and Theofilos Toulkeridis[2]*

[1]Ruhr-Universität, Bochum, Germany
[2]Universidad de las Fuerzas Armadas ESPE, Sangolquí, Ecuador

*Corresponding author: ttoulkeridis@espe.edu.ec

ABSTRACT

Ecuador is a highly vulnerable country in terms of natural hazards, such as volcanic eruptions and tsunami hazards. The education system has a key function to prepare children and adolescents for disaster scenarios. To achieve a nationwide standard of students' knowledge of tsunamis and tsunami hazards, academic research could provide assistance and analyze the current state of students' knowledge and identify possible regional differences. This article introduces to the geodynamic conditions of Ecuador and reports the results of a student questionnaire which was conducted at several Ecuadorian schools at the Pacific coast (Jama, Manta and Puerto Cayo) and in the capital Quito (control condition). It refers to five knowledge-based questions addressing five different topics of tsunami hazards: national regions at risk, locations of safety and danger, formation of a tsunami, risks caused by a tsunami, and protective measures. The statistical results point to significant knowledge differences between school locations at the coast. Comparisons between the coastal schools and Quito additionally indicate nationwide differences.

Keywords: Tsunami, Ecuador, disaster risk reduction, knowledge, education for sustainable development

1. INTRODUCTION

Many natural phenomena may suddenly become a ‘natural disaster’ or a ‘disaster of natural origin’ if they encounter a vulnerable and poorly prepared society (Cannon, 1994; Alexander, 1997; Van Aalst, 2006; McFarlane & Norris, 2006; Martinez & Toulkeridis, 2020). Besides the loss of many lives, the economic and ecological consequences are immense (Camerer & Kunreuther, 1989; Geis, 2000; Jonkman et al., 2003; Jonkman, 2005). Of the high variety of natural hazards, tsunamis are especially devastating to society and industry in coastal regions (Pararas-Carayannis G., 1983; Pararas-Carayannis, 1988; Rodriguez et al., 2006; Birkland et al., 2006; Krausmann & Cruz 2013; Pararas-Carayannis, 2013). The tsunamis of 2004 in Indonesia, 2011 in Japan, 2017 in Mexico and due to Krakatoa´s collapse in 2018 are examples of devastating ‘natural disasters’, highlighting the need for comprehensive disaster preparedness to reduce negative impact to a minimum (Delouis et al., 2010; Pararas-Carayannis, G., 2010; Simons et al., 2011; Pararas-Carayannis, G., 2014; Okuwaki and Yagi, 2017; Grilli et al., 2019). Above all, school education may be able to decisively contribute to the reduction of the vulnerability of a society through the mediation of risk-aware action (Nouri et al., 2011; Lange, 2012; Ronan et al., 2012; Muttarak & Lutz, 2014; Tatebe & Mutch, 2015). Ecuador is located on the Pacific Ring of Fire and is a country with one of the highest volcanic densities of the earth, which in addition to volcanic eruptions, may also be vulnerable to earthquakes and landslides, as well as tsunamis which pose a serious natural hazard to the population. Such hazards together with a variety of climatic processes most certainly will affect the country at any time, as shown during a variety of catastrophic events in the near past (Berninghausen, 1962; Schuster et al., 1996; Harden, 2001; Massonne and Toulkeridis, 2012; Chunga and Toulkeridis, 2014; Toulkeridis et al., 2015; Toulkeridis et al., 2017a; Mato and Toulkeridis, 2017; Toulkeridis and Zach, 2017; Pararas-Carayannis and Zoll, 2017; Jaramillo Castelo et al., 2018; Zafrir Vallejo et al., 2018).

However, tsunamis have impacted Ecuador relatively frequently, as documented in the history of the country and in several associated studies (Pararas-Carayannis, G. (1980; Herd et al., 1981; Kanamori & McNally, 1982; Mendoza & Dewey, 1984; Pararas-Carayannis, 2012; Ioualalen et al., 2011; 2014; Chunga & Toulkeridis, 2014; Heidarzadeh et al., 2017; Toulkeridis et al., 2017a; b; Pararas-Carayannis, 2018). Tsunamis with some devastating results, originated from the local, regional and far geodynamic environments prone to hit the Ecuadorian coastal areas and its relatively unprepared population as well as their settlements, which are situated in an active continental margin (López, 2013; Matheus Medina et al., 2016; Ye et al., 2016; Rodriguez et al., 2017; Chunga et al. 2017; Toulkeridis et al., 2018; Mato and Toulkeridis, 2018; Matheus-Medina et al., 2018; Chunga et al., 2019; Toulkeridis et al., 2019).

In order to evaluate the grade of preparation, we conducted the underlying empirical study by using a questionnaire. It was used to collect and analyze data on the everyday knowledge of students about tsunamis in selected coastal cities of Ecuador and in Quito. Furthermore, students' knowledge and risk awareness are examined. The study has the long-term goal of deriving measures for optimizing disaster risk reduction, in particular through education in schools. The role of the education system is therefore highlighted in the context of the current study. The results reported in this paper refer to five knowledge-based questions addressing five different topics of tsunami hazards: national regions at risk, locations of safety and danger, formation of a tsunami, risks caused by a tsunami, and protective measures.

2. SEARCH OF DEFINITIONS: NATURAL DISASTER, NATURAL HAZARD OR NATURAL PHENOMENON?

In everyday usage and the public media, the term "natural disaster" is the most common (Brown et al., 2009; Kaigo, 2012; Spence et al., 2015). However, there are other terms such as "natural hazard" or "natural event" that are not always used consistently. It is therefore intended to clarify the meaning of the terms mentioned here. Figure 1 illustrates "natural processes" as the starting point. They indicate the occurrence of natural processes such as earthquakes or volcanic eruptions. The impact on society now determines whether it is a "natural event" or a "natural hazard" (Kates, 1971; Cutter, 1996; Pelling, 2001; Alcántara-Ayala, 2002).

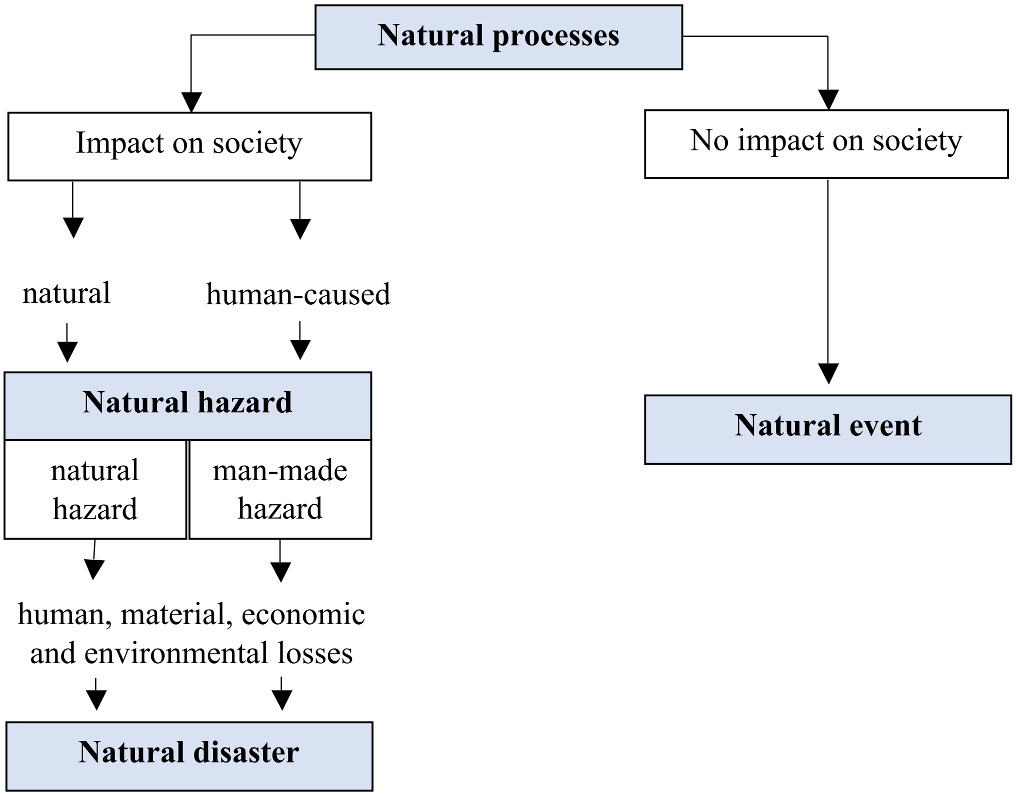

Fig. 1 Conceptual clarification of natural processes. (Adapted from Hoffmann, 2008)

The term "natural event" describes natural processes that have no influence on society (Hoffmann, 2008; Otto, 2009; Montz et al., 2017). By contrast, "natural hazard" refers to geological, climatological and other processes that may occur in the future and cause harm to a society (Otto, 2016). They are a threat to the life and property of humans and exceed by their extent a set tolerance limit (Otto, 2009). Humans may not be able to escape the "natural hazard" as such, but minimize (or even prevent) the (natural) risk in contrast to man-made hazard (Kates, 1976; Cannon, 1994; Cannon & Müller-Mahn, 2010).

Ultimately, the term "natural disaster" signifies a grave disruption of the functioning of a social system through the advent of an extreme natural process that usually results in enormous human, material, economic and environmental losses (Otto, 2009). The problem or cause of a disaster is often attributed to nature itself (Felgentreff, 2012;, Otto, 2016). However, the term "natural disaster" refers less to the event itself, but much more to the economic and social consequences. Whether a natural event is assessed as a disaster is defined by the significance of the consequences on the living conditions of those affected and depends on precaution and people's ability to react (Schmidt-Wulffen, 1982; Merz, 2008). It has been emphasized that all disasters are always humanitarian disasters in which human concern is central (Felgentreff et al., 2012).

Thus, especially humanities and social scientists represent the position that the occurrence of a disaster depends on various factors such as land use, occupation, construction, infrastructure, preparation and warning systems and the term "natural disaster" is inappropriate (Otto, 2009). Alternatively, it is also possible to speak of a "social disaster" from this perspective. In the context of this work, in terms of tsunamis, the term "natural hazard" is used because humans always pose a threat to them.

3. GEODYNAMIC SETTING OF ECUADOR´S COAST AND BRIEF HISTORY OF ITS TSUNAMIS

Ecuador is situated along the Pacific Rim, where its coastal continental platform is a regularly target of earthquake activity and the subsequent generation of tsunamis (Gusiakov, 2005; Pararas-Carayannis, 2012; Rodriguez et al., 2016). The active continental margin and associated subduction zone between the oceanic Nazca Plate with the continental South American and Caribbean Plates, which are both separated by the Guayaquil-Caracas Mega Shear (Kellogg and Vega, 1995; Gutscher et al., 1999; Egbue and Kellog, 2010) give rise to tsunamis of tectonic as well submarine landslide origin (Shepperd and Moberly, 1981; Pontoise and Monfret, 2004; Ratzov et al, 2007; 2010; Ioualalen et al., 2011; Pararas-Carayannis, 2012).

A further origin of earthquakes and tsunamis has been credited to the Galápagos volcanism, where massive sector collapses may give rise to the so-called iminamis (Kates, 1976; Cannon, 1994; Keating & McGuire, 2000; Pararas-Carayannis, 2002; Whelan & Kelletat, 2003; McGuire, 2006; Pinter & Ishman, 2008; Cannon & Müller-Mahn, 2010; Toulkeridis, 2011; Montz et al., 2017)). Such sector collapses are visible in the western flank of Ecuador volcano at the northwestern side of Isabela Island and may be due for the active Roca Redonda volcano, at the northern end of the same island (Rowland et al., 1994; Standish et al., 1998; Glass et al., 2007). These rarely occurring tsunamis of partial collapses of volcano flanks have a great impact in close and far situated settlements, as recently demonstrated with Anak Krakatau volcano (Babu & Kumar, 2019; Grilli et al., 2019).

However, the volcanoes of the Galapagos are drifted with the oceanic Nazca Plate towards the continent forming the aseismic Carnegie Ridge (Johnson & Lowrie, 1972). With time, this volcanic ridge may become an obstacle in the oblique subduction process and may generate within the subduction zone a potential valve of marine quakes, earthquakes and occasionally tsunamis along the Ecuadorian coast (Pilger, 1983; Pararas-Carayannis, 2012; Toulkeridis et al., 2018).

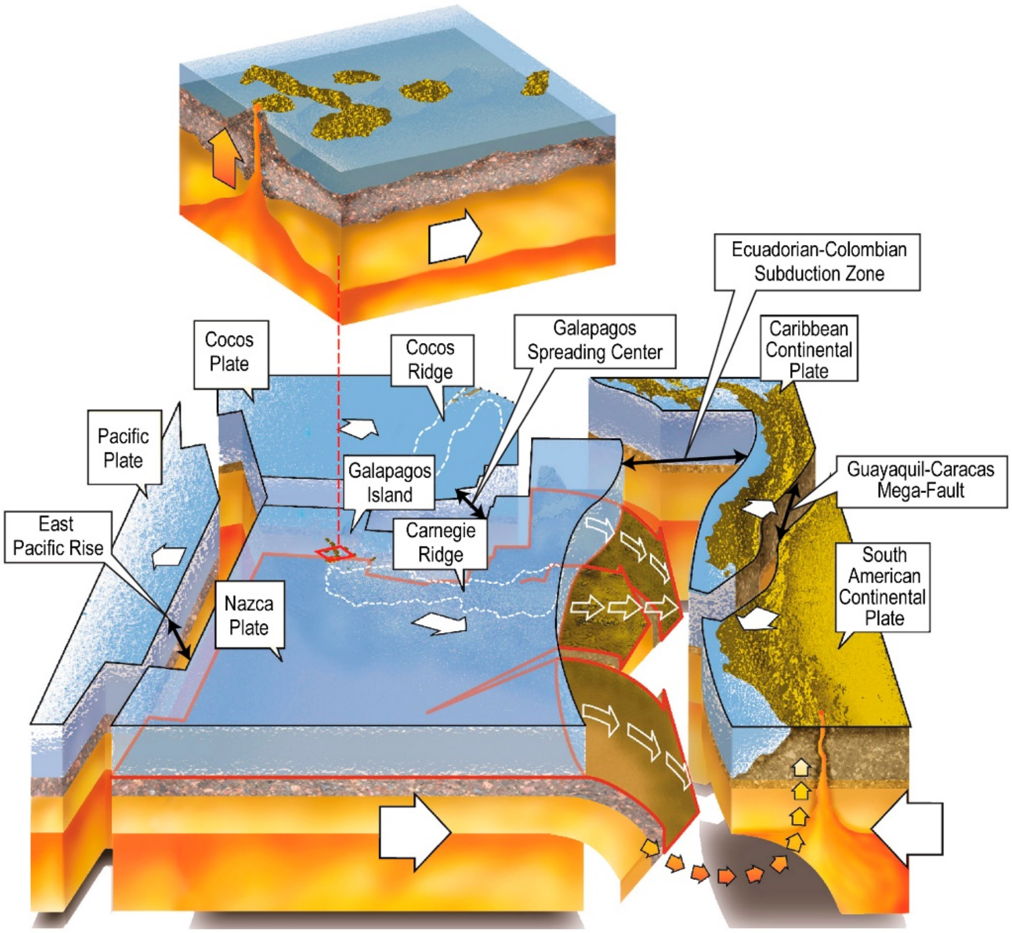

Fig. 2: Geodynamic setting of Ecuador with associated oceanic and continental plates and a variety of plate boundaries, such as the divergent plate boundaries named East Pacific Rise and Galapagos Spreading Center, the convergent plate boundary represented by the Ecuadorian-Colombian Subduction zone, as well as the transcurrent plate boundary represented by the Guayaquil-Caracas Maga-Fault. Also shown the Galapagos Islands and the Carnegie Ridge. Adapted from Toulkeridis, 2013, modified of Toulkeridis et al., 2017.

Due to the given geodynamic circumstances, Ecuador has been exposed repetitively to tsunami hazards, as it has been documented several times after the occurrence of local earthquakes, such as January 31, 1906 (8.8 Mw), October 2, 1933 (6.9 Mw), of December 12, 1953 (7.3 Mw) of January 19, 1958 (7.8 Mw), December 12, 1979 (8.2 Mw) and April 16, 2016 (7.8 Mw), besides other less documented impacts (Berninghausen, 1962; Kanamori and McNally, 1982; Pararas-Carayannis, 2012; Chunga and Toulkeridis, 2014; Toulkeridis et al., 2017a; 2017b; 2018). However, the earthquake with a distant origin tsunami, which occurred on March 11, 2011 in Japan with a magnitude of 8.9 on the Richter scale (Simons et al., 2011; Norio et al., 2011), have generated a considerable run-up in the Galápagos and the Ecuadorian mainland (Rentería et al., 2012; Lynett et al., 2013). Therefore, such high vulnerability together with a potential of high losses and damage is given by the fact that the infrastructure of the fishing, tourism and other industries and the movement to live along the beaches, have been highly developed within the last decades along the Ecuadorian coasts (Rodriguez et al., 2016; Navas et al., 2018).

4. TSUNAMI DISASTER RISK MANAGEMENT IN ECUADOR

4.1 Damage forecast

The World Risk Index indicates the disaster risk of a country through extreme natural processes and enables an international comparison of 172 countries (Bündnis Entwicklung Hilft, 2018). A total of 27 indicators are included in this index, which is divided into two dimensions, being exposure and vulnerability. Exposure describes the threat of a protected property (population, infrastructure) by extreme natural processes, the vulnerability consists here of the components susceptibility, coping and adaptation. Susceptibility includes indicators such as infrastructure, housing, nutrition, poverty, economic power and income distribution. Coping with this is the stability of the government, disaster preparedness, early warning systems, medical care, social networks and material security. Finally, adaptation involves adaptation strategies, citizen participation, education, environmental status and relevant investments. According to the World Risk Report of 2018, Ecuador has a high disaster risk of 8.10%, ranking 55th in the World Risk Index and 3rd in South America. The vulnerability of Ecuador is 45.94%, the exposure is 17.63%. These values apply throughout Ecuador and include any natural hazards (Bündnis Entwicklung Hilft, 2018).

In the context of the current study, however, especially the vulnerability to the natural hazard tsunami is of interest. The province of Esmeraldas in northern Ecuador is declared an area of very high vulnerability (UNESCO, 2012; Chunga et al., 2017). This counts also for the cities of Manta, Puerto Cayo and Jama in the province of Manabí, where we collected data for the underlying study (Cruz D'Howitt et al., 2005; Celorio-Saltos et al., 2018). This is especially true for flat urban areas, while higher elevations are excluded. Decisive factors include the natural conditions that exist in a wide and shallow beach, as well as the exposed development and infrastructure, as well as the lack of evacuation plans and low knowledge of the population about tsunamis (Celorio-Saltos et al., 2018).

Therefore, we may conclude that due to high seismic activity and various historical tsunami events in Ecuador and neighboring countries there is a high likelihood of a tsunami occurring in Ecuador. Furthermore, many coastal cities and their populations are characterized by high vulnerability. This underlines the need for proper preparation in case of emergency.

4.2 Disaster preparedness

In order to be protected of natural hazards such as a tsunami, some measures are taken to prepare the population, to warn early and to minimize human and material losses. For example, there are institutions worldwide that are monitoring seismic activity and its impact on the oceans and warn in the event of an imminent tsunami. The largest warning system in the Pacific Ocean is the Deep-ocean Assessment and Reporting of Tsunami (DART). In addition, evacuation exercises will be conducted to increase social resilience and optimize evacuation plans. In the sense of education for sustainable development, schools are an important institution for sensitizing students to natural hazards and for promoting risk-aware behavior. In the following all mentioned aspects are taken up and presented in detail.

Ecuador, like most of the other countries along the ring of fire counts with the provision of valid and real-time information about tsunamis by the Intergovernmental Coordination Group for the Pacific Tsunami Warning and Mitigation System (ICG / PTWS), which is coordinated by the Intergovernmental Oceanographic Commission (IOC). The IOC manages the International Tsunami Information Center (ITIC) and the Pacific Tsunami Warning Center (PTWC) in Hawaii, which in turn work with other international institutions. The ITIC oversees all activities regarding tsunami warnings and works to improve communication structures, data management and forecasting methods. The PTWC manages the PTWS Tsunami Early Warning System. In Ecuador, the Oceanographic Institute of the Navy (Insituto Oceanográfico de la Armada, INOCAR) is the most important national institution. Since 1976, the INOCAR is part of the PTWC and is dedicated, in addition to the regular tasks, to tsunami research. The main tasks of INOCAR are the implementation, coordination and control of oceanographic surveillance and exploration, as well as shipping. In addition, in 2009 the Insular Hydrographic and Oceanographic Service (Servicio Hidrográfico y Oceanographic Insular, SHOIAR) and in 2016 the Northern Hydrographic and Oceanographic Service (Servicio Hidrográfico y Oceanografico Norte, SHONOR) were established in Esmeraldas, which serve as the information center and alarm center for tsunamis in the region. Disaster risk management and management in general is the responsibility of the National Risk and Emergency Management Service (Servicio Nacional de Gestión de Riesgos y Emergencias). This institution is responsible for the identification, prevention and prevention of natural hazards risks.

A further issue is the tsunami early warning system DART, which measures occurring earthquakes and seaquakes, wave movements, as well as changes in sea level and water pressure in the Pacific Ocean (Meinig, 2005). The Pacific Marine Environmental Laboratory (PMEL) develops and installs the first generation of the DART system in 2000. Since a few modifications improved the system, counting also with a satellite, which serves as the communication bridge between the measuring station and the Tsunami Warning Center. Nonetheless, since Ecuador has a short proximity to the subduction zone, it should be taken into consideration that an early warning is hardly possible due to the small distance between a potential epicenter and the coast. Therefore, a suitable local early warning system need to be installed in Ecuador, which will allow immediate alerting of coastal areas. In order to be able to use early warnings effectively for disaster preparedness appropriate strategies and technical systems must be integrated into the social context and , linked to issues of vulnerability and risk awareness (Birkmann, 2008). Only if early warnings reach the population in short time and if they may be managed in a risk-conscious and appropriate manner may enable an effective disaster risk reduction. Educational work by responsible institutions such as schools and evacuation exercises will certainly promote the risk-conscious behavior of the population (Lauterjung, 2008). In this respect, evacuation exercises are often carried out to prepare the population for emergencies and thereby increase social resilience. In Ecuador, the so-called tsunami drills are being carried out (Ministerio de Telecomunicaciones y de la sociedad de la Información, 2019). The evacuation plans are executed and tested. Finally, it evaluates how well the alarm systems work and how much time is needed for the population to go to safety.

4.3 Disaster risk management through Education

It is generally known, that the goal of disaster risk reduction must be to reduce vulnerability and increase resilience (Godschalk, 2003; Johnston et al. 2005; Vink & Takeuchi, 2013; Briceño, 2015; Otto, 2016). Above all, school education can make a decisive contribution here, since in schools behavioral rules for emergencies and risk-conscious behavior can be communicated at an early stage (Dikau, 2016; Hufschmidt & Dikau, 2013). The students also share their acquired knowledge with their social environment, which also strengthens the resilience of the community (Bündnis Entwicklung Hilft, 2018). Schools are thus at the center of municipal disaster risk management (UNESCO, 2012). As a result of the strong earthquake in 2016, Ecuador participated in the project "More education, less risk: strong disaster risk reduction and resilience through education", which was carried out by UNESCO until 2017 (Bündnis Entwicklung Hilft, 2018). The goals of the project are to reduce vulnerability and strengthen the resilience of communities and their educational institutions. A basic understanding of hazards, risks and potential harm should be encouraged to develop deeper risk awareness. An anchoring of natural hazards and risk issues in different subjects is indispensable. For this reason, Ecuador's core curricula are considered in more detail below to evaluate the extent to which natural hazards and disasters are embedded there. Subsequently, an exemplary lesson sequence on the topic tsunami and disaster preparedness will be presented, which serves as orientation for the didactic implementation in the school context.

The subject of geography is particularly suitable for the development of competencies that enable the students to act responsibly and sustainably, due to the strong interlinking of scientific and social science aspects (Otto, 2016). This raises the question as to what extent preventive content and topics of civil protection are or should be part of school education (Hufschmidt & Dikau, 2013). In Ecuador, science is taught as a collective subject called natural sciences, in which the subjects of biology, physics, chemistry and geography are anchored. A closer look at the core syllabus of such matter (Ministerio de Educación, 2016a) reveals that keywords like natural hazards, earthquakes or tsunami are completely missing (Fig. 3). Thematic block 4, the Earth and the Universe, merely discusses the dangers of Ecuador's position on the Pacific Ring of Fire. The students should be aware of and be prepared for possible dangers (Ministerio de Educación, 2016a) “In this context, students will understand that Earth's transformations can generate risks, to which we must be prepared, especially, for finding our country in the Pacific Ring of Fire". Furthermore, the subject of plate tectonics in connection with volcanism may be found, but not in relation to other natural hazards such as earthquakes or tsunamis (Ministerio de Educación, 2016a). Social sciences are also taught in Ecuador as a collective subject and include the subjects of history, social studies and philosophy.

Natural hazards as well as safety and prevention measures are addressed at all grade levels (Ministerio de Educación, 2016b). The El Niño phenomenon, the Cotopaxi and the Tungurahua volcanoes as well as forest fires are mentioned as current natural hazards in Ecuador, the terms earthquake or tsunami lacks here or elsewhere (Ministerio de Educación, 2016b). Thus, while core curricula incorporate natural hazards and disaster preparedness, earthquakes and tsunamis are not explicitly listed, although these are among the largest natural hazards in Ecuador, along with volcanism. The core curricula therefore do not allow any precise conclusions to be drawn regarding the natural hazards actually treated in the classroom.

ELEMENTAL SCHOOL	MIDDLE SCHOOL	HIGH SCHOOL
O.CS. 2.3 Identify, differentiate and describe the geographical, political, administrative, economic and social characteristics of the province using cartographic tools, to strengthen their local identity and function in the natural environment and social; considering possible natural hazards and measures of security, prevention and control.	O.CS. 3.3 Locate Ecuador in the Andean space and study its relief, climate, and territorial division, with emphasis on the provinces, to build a national identity rooted in the values and needs of local territories, especially those related to possible natural hazards and security measures, prevention and control.	O.CS. 4.3 Establish the characteristics of planet Earth, its formation, the location of continents, oceans and seas, through the use of cartographic tools to determine its importance in resource management and natural disaster prevention.

Figure 3: Extract of the core curriculum with underlined keywords. Adapted from Ministerio de Educación, 2016a.

In order to ensure effective disaster preparedness through school education, the didactic preparation of scientific content is indispensable. In the framework of the UNESCO project "Adaptive Learning of Tsunami Preparedness Mechanisms in coastal communities of Colombia, Ecuador, Peru and Chile", initiated in 2010, a didactical collection on natural hazards for teachers and students has been prepared (UNESCO, 2012). This consists of three books for different grade levels, as well as three other books for the teachers. Contents are the origin and effects of tsunamis, tsunami early warning, evacuations and security concepts of the schools. The aim is to strengthen a "risk culture", with a first regional focus on the province of Esmeraldas in Ecuador, which is considered to be particularly vulnerable. However, the Servicio Nacional de Gestión de Riesgos y Emergencias is planning a duplication of teaching materials for the entire coast of Ecuador. Whether this has been implemented so far is unclear. The materials will at least be made available on the ITIC website.

5. METHODOLOGY AND DATA COLLECTION

5.1 Concept of used methodology

The data has been collected using a questionnaire in Ecuadorian schools in the coastal towns of Manta, Puerto Cayo and Jama. In addition, students in Quito who live far from the coast were also interviewed (control group). Additionally to the knowledge, attitudes and ideas of students on the natural hazard tsunami, risk awareness should also be investigated. Based on this, the collected data should provide information on social resilience and disaster risk reduction in Ecuador. In the case of a tsunami, the ability to function and to act on the part of the students is crucial in order to behave appropriately and to be safe. The long-term objective of the study is to derive measures for the optimization of disaster risk reduction, in particular through education, from such results. In order to be able to implement the planned overall study, a special research design was developed, which is shown in detail in Figure 4.

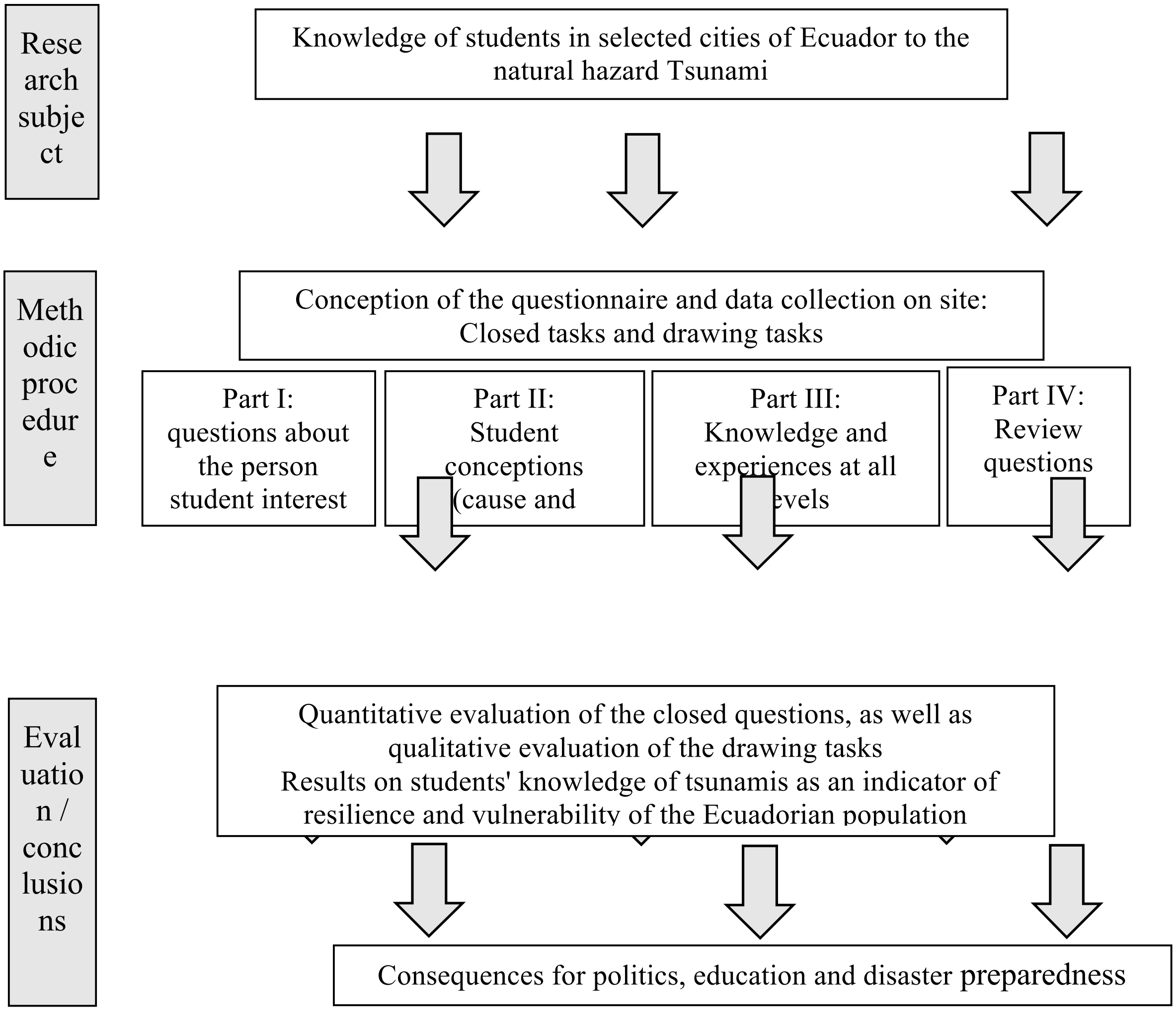

Figure 4: Concept of used methodology

For a better classification, the actual state of research on student conceptions in general as well as on the topic tsunami is sketched below. It must be emphasized, however, that not only students' ideas in the didactic context, but above all the explicit (action) knowledge of students on the natural hazard tsunami, as well as the resulting social resilience, are the focus of this work. In recent decades, student stereoscopic images have increasingly become the focus of academic research and are considered didactically valuable (Reinfried, 2010). In accordance with the concept change approach, the everyday ideas of the students should be taken into account in the classroom. Based on this, possible misconceptions should be converted into scientifically correct knowledge through subject-specific learning (Otto, 2016). Thus, there are already some studies in the area of geography for students on natural hazards. For example, they address the topics of flood, volcanism and earthquakes, and the associated plate tectonics. A study on students' knowledge of active volcanoes and protective measures in Ecuador was carried out in 2014 and main results were already published (Otto et al., 2019; Otto et al 2020). Studies addressing students' conceptions on tsunami hazards have only hardly been conducted so far (Etterich, 2013). This underlines the lack of appropriate research, which is quite surprising, as the student interest in the topic of "natural disasters", especially in tsunamis, is very high (Etterich, 2013). For the vulnerability of the coast of Ecuador to tsunamis, several scientific papers have been published (Cruz D'Howitt et al., 2005, Toulkeridis 2005, Pararas-Carayannis 2012, Sebastian Matheus-Medina et al., 2018, Cesar Celorio-Saltos et al., 2018, San Martín et al., 2018).

5.2 Context of data collection

In total, 314 students participated in this study. The questionnaire focused on the coastal cities of Manta, Puerto Cayo and Jama. For a comparative study, data was also collected in the capital Quito. All students are in their last year of study, the third year of their Bachelor, having an average age of about 17 years (∅ = 16.97; SD = 1.292).

City	School	Gender		Total
		male	female	
Puerto Cayo	Unidad Educativa Fiscal	41	43	84
Jama	Unidad Educativa Fisical Rambuche	20	11	31
Manta	Unidad Educativa Naval Jambelí	21	10	31
Quito	Unidad Educativa 24 de Mayo & Colegio Ing. Juan Suárez Chacón	45	123	168
Total		127	187	314

Figure 5: Number of students interviewed

5.3 Measuring instrument

The overall study method referred to a questionnaire with closed questions. Closed answer items were chosen in this study for better standardization and quantitative comparability. For quality assurance and linguistic error correction, the Spanish version of the questionnaire was additionally proofread by two native speakers.

The analyses conducted for this article are based on a selection of questions. These questions address five different topics of tsunami hazards: Ecuadorian regions at risk, locations of safety and danger, formation of a tsunami, risks caused by a tsunami, and protective measures. The first topic based on a (severely generalized) map of a Ecuador where settlements at risk could be selected (by ticking boxes). The second topic was built on a sketch including typical locations, from the coastline to a city center. The other three topics were based on written statements which were either right or wrong. Students were encouraged to mark one of these options. The data sets of the individual students were only considered if they gave an answer to all questions.

The collected data were first digitized and coded in Microsoft Excel, starting from the collected printed sheets, before they were imported and evaluated in the statistical evaluation software SPSS. The digitization was double-checked to avoid mistakes. Based on the individual answers, the rates of correctly answered question items (percentages) were calculated in SPSS, for each of the five questions and for all study participants. These five rates were used as dependent variables in pair wise comparisons (t-tests for independent samples). The grouping variable was the school location (Manta vs. Jama vs. Puerto Cayo vs. Quito). The homogeneity of variances was evaluated based on Levene's test.

6. RESULTS

The presentation of the statistical analyses is subdivided into five sub-sections. Each of these section refers to one of the five knowledge-based topics addressed in the questionnaire, i.e. Ecuadorian regions at risk, locations of safety and danger, formation of a tsunami, risks caused by a tsunami, and protective measures. The statistics presented in each section are further subdivided into two parts, i.e. 1) pairwise comparisons between the three coastal cities (Manta, Jama, Puerto Cayo) and 2) pairwise comparisons of all three coastal cities with Quito (control condition).

6.1 Knowledge of Ecuadorian regions at risk

Coastal Cities

The independent-measures t-test on the rate of correctly answered question showed a significant difference in the means for MANTA (M = 85.81, SD = 16.2) and JAMA (M = 72.52, SD = 14.9); t(59.559) = -3.360, $p < 0.001$.

The independent-measures t-test on the rate of correctly answered question showed no significant difference in the means for PUERTO CAYO (M = 83.33, SD = 14.6) and MANTA (M = 85.81, SD = 16.2); t(113) = -0.783, p = 0.436.

The independent-measures t-test on the rate of correctly answered question showed a significant difference in the means for PUERTO CAYO (M = 83.33, SD = 14.6) and JAMA (M = 72.52, SD = 14.9); t(113) = -3.510, $p < 0.001$.

Coastal Cities vs. Quito

The independent-measures t-test on the rate of correctly answered question showed no significant difference in the means for MANTA (M = 85.81, SD = 16.2) and QUITO (M = 80.54, SD = 16.9); t(197) = 1.603, p = 0.111.

The independent-measures t-test on the rate of correctly answered question showed a significant difference in the means for JAMA (M = 72.52, SD = 14.9) and QUITO (M = 80.54, SD = 16.9); t(197) = -2.476, p = 0.014.

The independent-measures t-test on the rate of correctly answered question showed no significant difference in the means for PUERTO CAYO (M = 83.33, SD = 14.6) and QUITO (M = 80.54, SD = 16.9); t(250) = 1.290, p = 0.198. The reported results are graphically compiled in Figure 6.

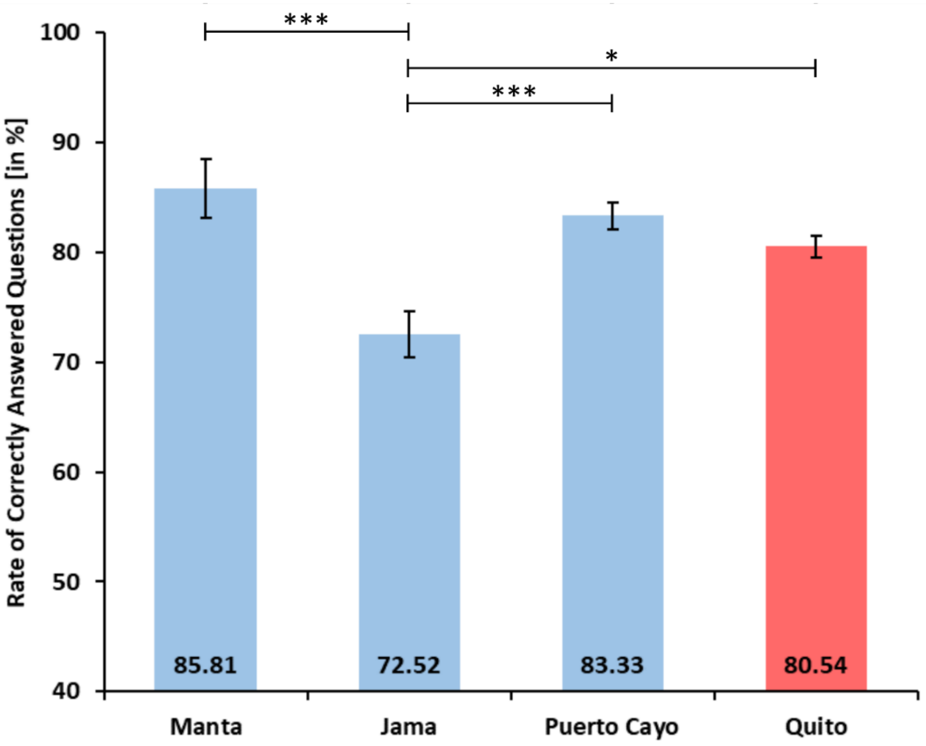

Figure 6: Pairwise comparisons – Ecuadorian regions at risk

** = p < 0.05; *** = p < 0.001; error bars represent standard errors of the means*

6.2 Knowledge of locations of safety and danger

Coastal Cities

The independent-measures t-test on the rate of correctly answered question showed a significant difference in the means for MANTA (M = 77.42, SD = 10.1) and JAMA (M = 70.25, SD = 15.6); t(51.592) = 2.150, p = 0.036.

The independent-measures t-test on the rate of correctly answered question showed a significant difference in the means for PUERTO CAYO (M = 73.02, SD = 8.5) and MANTA (M = 77.42, SD = 10.1); t(113) = 2.338, p = 0.021.

The independent-measures t-test on the rate of correctly answered question showed no significant difference in the means for PUERTO CAYO (M = 73.02, SD = 8.5) and JAMA (M = 70.25, SD = 15.6); t(36.817) = -0.939, p = 0.354.

Coastal Cities vs. Quito

The independent-measures t-test on the rate of correctly answered question showed a significant difference in the means for MANTA (M = 77.42, SD = 10.1) and QUITO (M = 72.69, SD = 14.5); t(55.443) = 2.216, p = 0.031.

The independent-measures t-test on the rate of correctly answered question showed no significant difference in the means for JAMA (M = 70.25, SD = 15.6) and QUITO (M = 72.69, SD = 14.5); t(197) = -0.850, p = 0.396.

The independent-measures t-test on the rate of correctly answered question showed no significant difference in the means for PUERTO CAYO (M = 73.02, SD = 8.5) and QUITO (M = 72.69, SD = 14.5); t(243.669) = 0.228 p = 0.820. The reported results are graphically compiled in Figure 7.

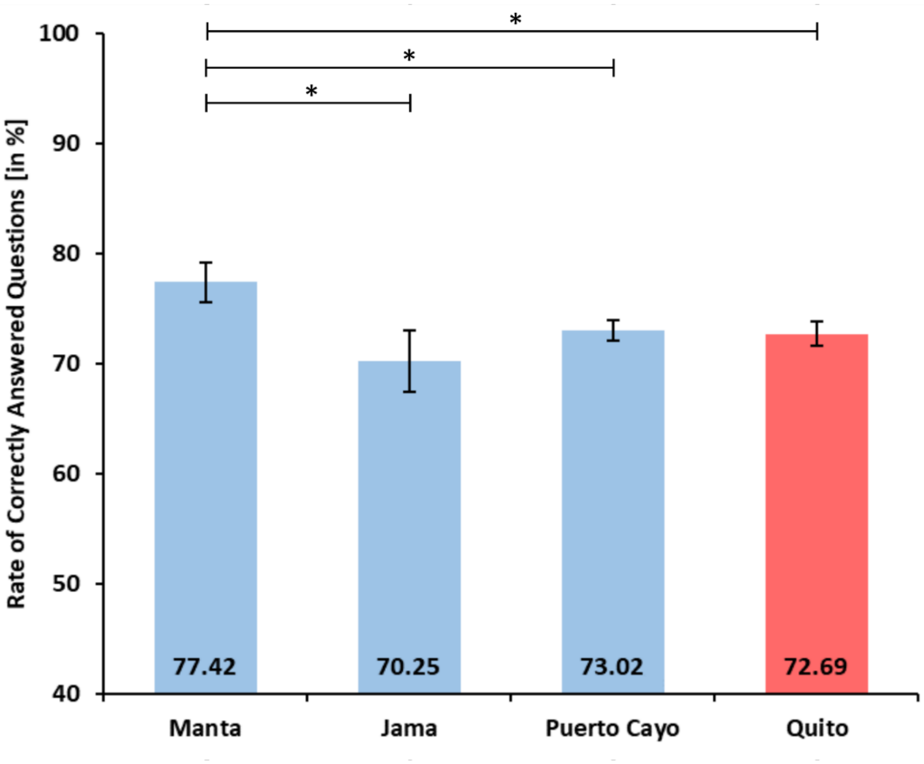

Figure 7: Pairwise comparisons – locations of safety and danger
** = $p < 0.05$; error bars represent standard errors of the means*

6.3 Knowledge of the formation of a tsunami

Coastal Cities

The independent-measures t-test on the rate of correctly answered question showed no significant difference in the means for MANTA (M = 66.12, SD = 16.5) and JAMA (M = 60.22, SD = 20.0); t(60) = -1.268, p = 0.210.

The independent-measures t-test on the rate of correctly answered question showed no significant difference in the means for PUERTO CAYO (M = 67.12, SD = 14.6) and MANTA (M = 66.12, SD = 16.5); t(113) = 0.324, p = 0.746.

The independent-measures t-test on the rate of correctly answered question showed no significant difference in the means for PUERTO CAYO (M = 67.12, SD = 14.6) and JAMA (M = 60.22, SD = 20.0); t(42.419) = 1.764, p = 0.085.

Coastal Cities vs. Quito

The independent-measures t-test on the rate of correctly answered question showed a significant difference in the means for MANTA (M = 66.12, SD = 16.5) and QUITO (M = 54.41, SD = 15.5); t(197) = 3.832, p < .001.

The independent-measures t-test on the rate of correctly answered question showed no significant difference in the means for JAMA (M = 60.22, SD = 20.0) and QUITO (M = 54.41, SD = 15.5); t(36.887) = 1.530, p = 0.135.

The independent-measures t-test on the rate of correctly answered question showed a significant difference in the means for PUERTO CAYO (M = 67.12, SD = 14.6) and QUITO (M = 54.41, SD = 15.5); t(250) = 6.273, p < 0.001. The reported results are graphically compiled in Figure 8.

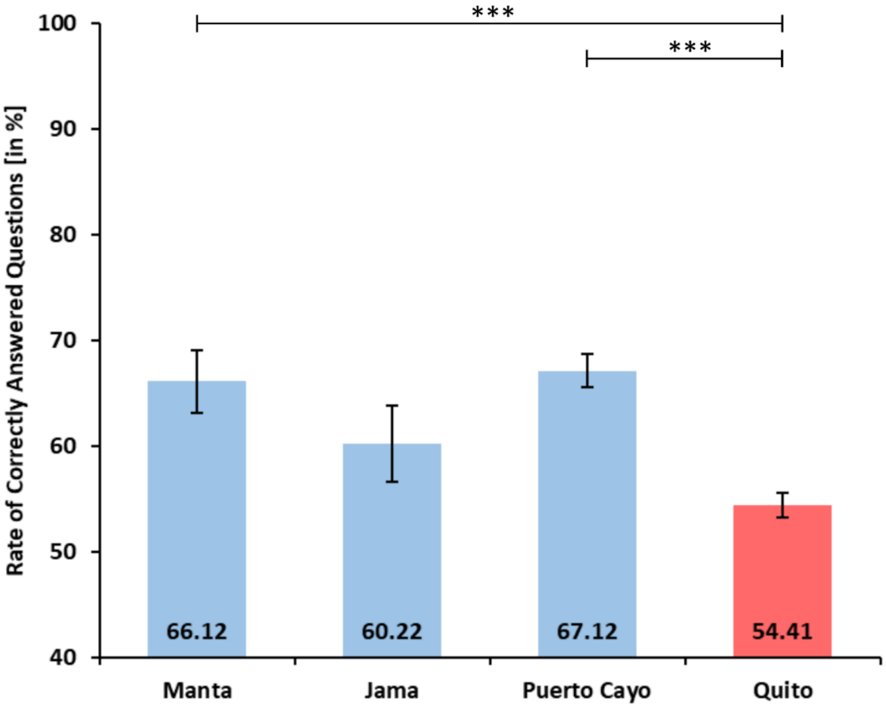

Figure 8: Pairwise comparisons – formation of a tsunami

**** = p < 0.001; error bars represent standard errors of the means*

6.4 Knowledge of risks caused by a tsunami

Coastal Cities

The independent-measures t-test on the rate of correctly answered question showed no significant difference in the means for MANTA (M = 82.26, SD = 13.6) and JAMA (M = 77.42, SD = 20.8); t(60) = 1.086, p = 0.282.

The independent-measures t-test on the rate of correctly answered question showed no significant difference in the means for PUERTO CAYO (M = 83.73, SD = 17.1) and MANTA (M = 82.26, SD = 13.6); t(113) = -0.431, p = 0.667.

The independent-measures t-test on the rate of correctly answered question showed no significant difference in the means for PUERTO CAYO (M = 83.73, SD = 17.1) and JAMA (M = 77.42, SD = 20.8); t(113) = -1.654, p = 0.101.

Coastal Cities vs. Quito

The independent-measures t-test on the rate of correctly answered question showed no significant difference in the means for MANTA (M = 82.26, SD = 13.6) and QUITO (M = 79.37, SD = 17.1); t(197) = 0.892, p = 0.374.

The independent-measures t-test on the rate of correctly answered question showed no significant difference in the means for JAMA (M = 77.42, SD = 20.8) and QUITO (M = 79.37, SD = 17.1); t(197) = -0.563, p = 0.574.

The independent-measures t-test on the rate of correctly answered question showed no significant difference in the means for PUERTO CAYO (M = 83.73, SD = 17.1) and QUITO (M = 79.37, SD = 17.1); t(250) = 1.911, p = 0.057. The reported results are graphically compiled in Figure 9.

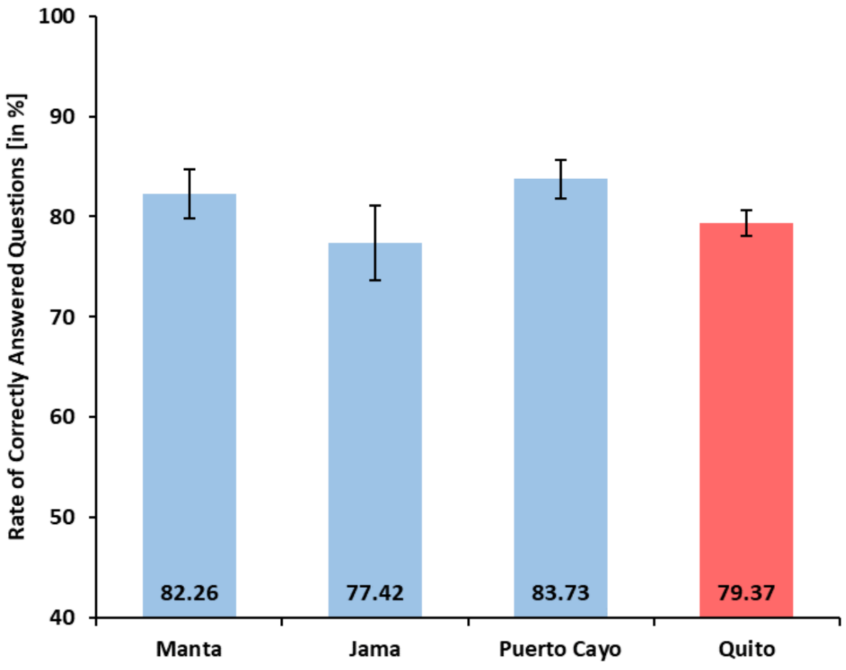

Figure 9: Pairwise comparisons – risks caused by a tsunami
error bars represent standard errors of the means

6.5 Knowledge of protective measures

Coastal Cities

The independent-measures t-test on the rate of correctly answered question showed no significant difference in the means for MANTA (M = 54.69, SD = 14.7) and JAMA (M = 58.68, SD = 11.6); t(60) = -1.189, p = 0.239.

The independent-measures t-test on the rate of correctly answered question showed a significant difference in the means for PUERTO CAYO (M = 60.49, SD = 11.0) and MANTA (M = 54.69, SD = 14.7); t(113) = -2.289, p = 0.024.

The independent-measures t-test on the rate of correctly answered question showed no significant difference in the means for PUERTO CAYO (M = 60.49, SD = 11.0) and JAMA (M = 58.68, SD = 11.6); t(113) = -0.774, p = 0.441.

Coastal Cities vs. Quito

The independent-measures t-test on the rate of correctly answered question showed no significant difference in the means for MANTA (M = 54.69, SD = 14.7) and QUITO (M = 53.80, SD = 12.6); t(197) = 0.352, p = 0.726.

The independent-measures t-test on the rate of correctly answered question showed a significant difference in the means for JAMA (M = 58.68, SD = 11.6) and QUITO (M = 53.80, SD = 12.6); t(197) = 2.012, p = 0.046.

The independent-measures t-test on the rate of correctly answered question showed a significant difference in the means for PUERTO CAYO (M = 60.49, SD = 11.0) and QUITO (M = 53.80, SD = 12.6); t(250) = 4.154, p < 0.001. The reported results are graphically compiled in Figure 10.

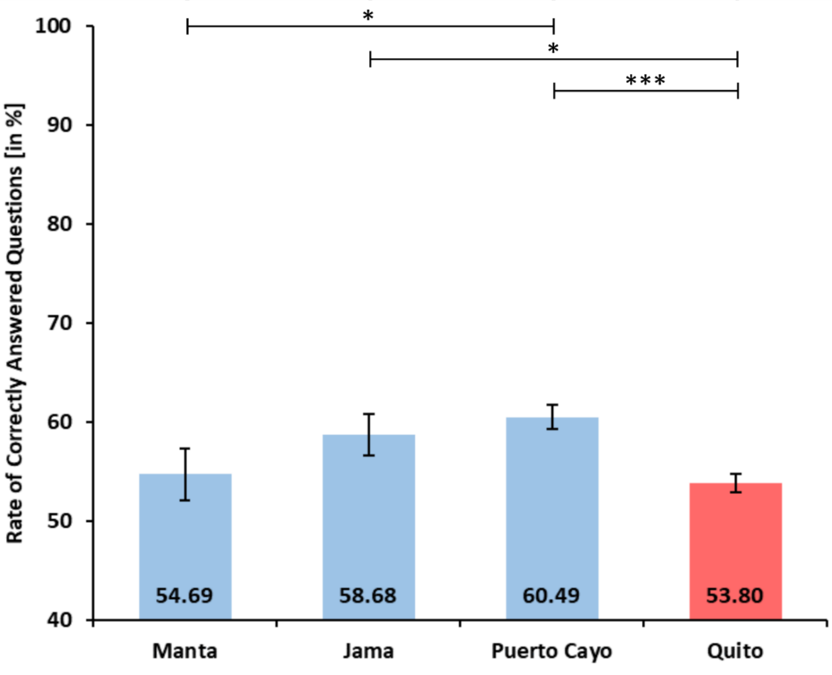

Figure 10: Pairwise comparisons – protective measures

- *= p < 0.05; *** = p < 0.001; error bars represent standard errors of the means*

7. DISCUSSION

The aim of this empirical study was to analyze regional differences in the knowledge of high school students concerning tsunamis and behavior in hazard situations. The analyses should provide statistically valid insights into the current situation of the student's knowledge on tsunamis. These insights could serve as a component for future discussions on extending or adapting school curricula in order to optimize the preparation of students for tsunami hazards in Ecuador. Similar analyses were made with regard to volcanic risks (Otto et al. 2020, 2019). Although this questionnaire cannot be compared to a nationwide study, it identifies regional weaknesses in the current state of students' knowledge on tsunamis – based on a selection of representative knowledge-based questions and based on available schools along the Ecuadorian coastline and the capital city.

The statistical results point to the fact that Ecuador does not seem to have a common standard in students' knowledge on tsunamis. Significant differences between the coastal cities occur in three of the five topics investigated, i.e. regions at risk (Figure 6), locations of safety and danger (Figure 7), and protective measures (Figure 10). While the students in Manta appear to have an outstanding knowledge on the two spatial topics (regions at risk, locations of safety and danger), the Manta students show weaker performances than the Puerto Cayo students in terms of protective behavior in a tsunami hazard scenario. Equal knowledge levels between the coastal cities appear in questions on tsunami formation and risks.

Regional differences in student's knowledge on tsunamis become more obvious when comparing the coastal cities with the control group in Quito. The capital city Quito is located in the interior of the country and its urban centre and outskirt is not shaped by peculiarities of a coastal region. According to our analyses, knowledge on the vulnerable regions in the country (Figure 6) and tsunami risks (Figure 9) lies on an equal level, when comparing the Quito students with the students in the coastal cities. An advantage over the Jama students can be observed in the question of Ecuadorian regions at risks.

Obvious differences occur in the other investigated topics of tsunami knowledge. In terms of locations of safety and danger (Figure 7), tsunami formation (Figure 8) and protective measures (Figure 10), the Quito students show weaknesses in the performance over students in the coastal regions. This especially applies for the topics of tsunami formation and protective measures, where knowledge gaps are clearly displayed. It seems that Quito students, who live far away from a vulnerable tsunami region, have a certain basic knowledge on tsunamis, but lack important aspects which can be of high importance in a disaster situation.

Reasons for the reported effects could lie in the strength and weaknesses of individual school classes. It could also occur that individual performances of teachers, field trips (an event which was not undertaken by the entire study sample) or specific educational media influence the students' knowledge (c.f. Krakowka 2012, Metzler & Woessmann 2012, Münzer et al. 2009). Moreover, the individual impacts of parents and other educators (family and friends) was not measured and considered as a factor in the analyses. These possible influencing factors point to the methodological limitations of this study.

The regional differences shown in the statistics correspond to previous empirical findings reported in studies on students' knowledge on natural disasters in Ecuador. Otto et al. 2020 and 2019 also found that the presence of volcanoes in the surrounding of school locations has a significant impact on students' knowledge in Ecuador. Students in Quito showed better performances than students in Guayaquil. These results already pointed to imbalances in (nationwide) education standards.

The differences reported in the present study cannot be explained by referencing to other and similar empirical investigations, as an obvious lack of literature still exists. Distantly related, the results are in line with empirical findings on knowledge deficits of students in natural science processes, such as volcanological processes (e.g. Carlino et al. 2008, Hemmerich and Wiley 2002, Parham et al. 2010). Overall, the present study should be seen as an exploratory empirical study, with an approach to acquiring a first and robust empirical data set.

8. SUMMARY AND OUTLOOK

This empirical investigation is part of a long-term project in Ecuador focused on educational measures that increase knowledge of natural hazards. The reported findings indicate regional differences in the knowledge on important aspects of tsunamis, i.e. regions at risk, locations of safety and danger, formation of a tsunami, risks caused by a tsunami, and protective measures . These regional differences occur between school locations along the Ecuadorian coastline. Moreover, a weaker knowledge was observed in the capital Quito. The occurrence of regional differences backs up findings which were identified in terms of students' knowledge of volcanic risks. We would like to offer the observed effects to optimize nationwide educational standards in future debates on school curricula.

Future studies should not only extend the study sample to repeat effects on a larger scale and show the robustness of these effects, they should also focus on modern digital educational media which could help to transfer spatial knowledge in a more effective, efficient and motivating way. Such media could base on modern 3D visualization techniques in real-time, such as audio-visually animated (cartographic) media in Virtual Reality (VR) and Augmented Reality (AR). In current debates of Geo-information Sciences, media based on VR and AR techniques were already suggested as suitable educational media (e.g. Büyüksalih et al. 2020, Edler et al. 2019, Klippel et al. 2019, Lindner et al. 2019) . They were also proposed as tools to support training simulations and disaster management (c.f. Kersten and Edler 2020).

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ISSN 8755-6839

SCIENCE OF **TSUNAMI HAZARDS**

Journal of Tsunami Society International

Volume 39 **Number 2** **2020**

SEISMOTECTONICS AND MECHANISMS OF TSUNAMI GENERATION ALONG ACTIVE BOUNDARIES OF YOUNG, MARGINAL SEA BASINS AND SPREADING RIDGES OF THE SOLOMON ISLANDS REGION – Case Study: The Earthquake and Tsunami of 1 April 2007 in the Solomon Islands

George Pararas-Carayannis

Tsunami Society International

ABSTRACT

The Solomon Islands region is characterized by high seismic activity. During the last 100 years there have been numerous strong earthquakes with periodic variation of recurrence. Some of them on either side of the Solomon Island Volcanic Arc have generated destructive tsunamis not only in the Solomons but also in neighboring Papua New Guinea. Most of the larger magnitude earthquakes occur on the northeast side of the Solomon Island Arc and Trench along a 350 km segment, close to the Islands of Guadalcanal and San Christobal. On the northeast side of the Solomon Island Arc larger ruptures of adjacent slabs are possible which could involve the New Ireland segment or the North Solomon Trench. However, significant earthquake activity occurs also along the southeast side of the Solomon Island Arc, but not as frequently. A great magnitude 8.1 earthquake on 1 April 2007 in the southeast region generated a tsunami that was particularly destructive in the Islands of the New Georgia Group of the Northwest Solomon Islands. The present study examines the impact of this earthquake and of the tsunami it generated, and reviews the seismotectonic setting of the Solomon Islands region for the purpose of understanding the regional mechanisms of tsunami generation along the active boundaries of young, marginal sea basins and spreading ridges.

Keywords: *Solomon Island Volcanic Arc and Trench; San Cristobal Trench; Woodlark Basin; Seismotectonics; Marginal Sea Basins; Spreading Ridges.*

1. INTRODUCTION

A great magnitude 8.1 earthquake on April 1, 2007 struck the New Georgia Group of the Northwest Solomon Islands and generated a destructive tsunami (Fig. 1). There were numerous fatalities in the Solomons and in Southeast Papua New Guinea. A few minutes later a second earthquakeof 6.7 magnitude, occurred 75 miles west-southwest of Chirovanga, Choiseul, Solomon Islands, and 1,410 miles north of Brisbane, Australia.

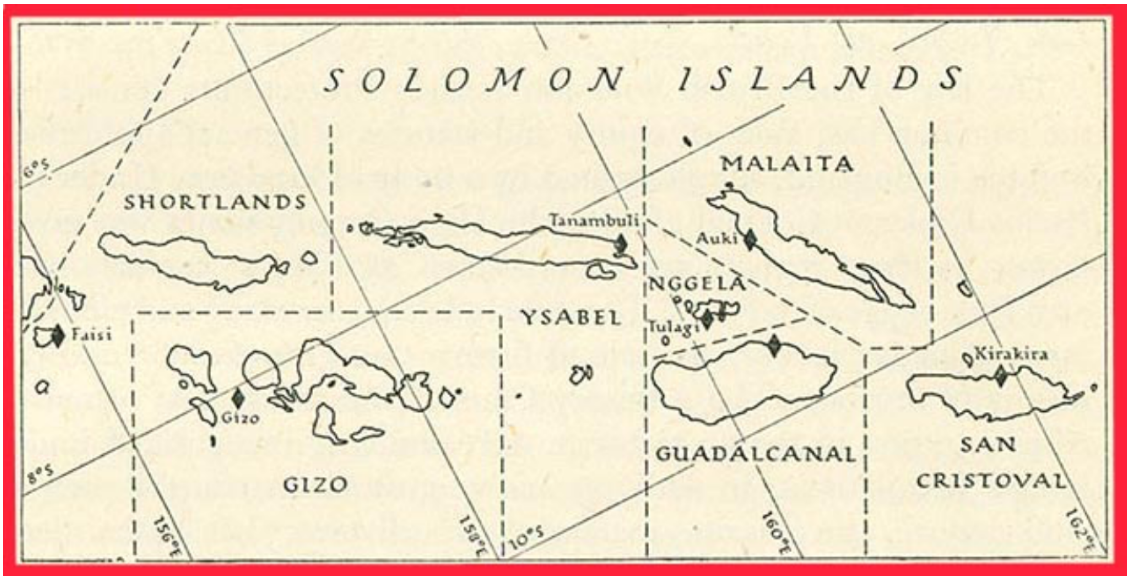

Fig. 1. The Solomon group of Islands

Tsunami waves of up to five meters in height struck mainly parts of the western province of the Solomon Islands. The waves were particularly destructive on Gizo, Noro and Taro Islands inundating as much as 50-70 meters (164-230 feet) inland. The waves were particularly destructive to buildings and homes. Large boats were washed ashore and communication links were wiped out. There was significant damage a Nusa Tupe island where the airport is located and the Provincial capital Gizo's main airport, hospital, and to coastal roads.

The Pacific Tsunami Warning Center (PTWC) in Honolulu issued a regional tsunami warning for the immediate area of the Solomon Islands, but because of the short time of the tsunami's travel time to the impacted areas, it did not help with timely evacuations. However a tsunami warning was expanded to include Papua New Guinea, Vanuatu, Nauru, New Caledonia, Northeastern Australia, Fiji, Chuuk, Pohnpei, Kosrae, Indonesia, Tuvalu, Kiribati, Kermadec Islands, Marshall Islands and New Zealand. An advisory was issued for Hawaii, but not a watch or warning. The warnings and advisory were cancelled nine hours later.

The following sections of this report examine the impact of this earthquake and of the tsunami, and a cursory review the seismotectonic setting of the Solomon Islands region for the purpose of understanding the regional mechanisms of tsunami generation along active boundaries of young, marginal sea basins and spreading ridges.

2. THE EARTHQUAKE OF 1 APRIL 2007 IN THE SOLOMON ISLANDS

On April 1, 2007, at 20:40 UTC, 7:40 a.m. local time (April 2, local date) a Richter magnitude 8.1, earthquake struck the New Georgia Group of the Northwest Solomon Islands and generated a destructive tsunami. Its epicenter was at 8.6° S., 157.2° E., or about 45km (25 miles) south-southeast of Gizo, a small fishing town on Gizo Island in the New Georgia Islands and 345km (215 miles) north-west of Honiara, (Fig. 2). Its focal depth was 10 km (6.1 miles). Based on the U.S.G.S. Centroid solution, the following values were estimated: Fault plane: strike=331 dip=38 slip=120; Fault plane: strike=115 dip=58 slip=69. A second quake of 6.7 magnitude a few minutes later, occurred 75 miles west-southwest of Chirovanga, Choiseul, Solomon Islands, and 1,410 miles north of Brisbane, Australia. According to residents at Gizo, the strong ground motions of the earthquake lasted for almost two minutes. The quake's motions were felt as far as Honiara, the capital of the Solomon Islands.

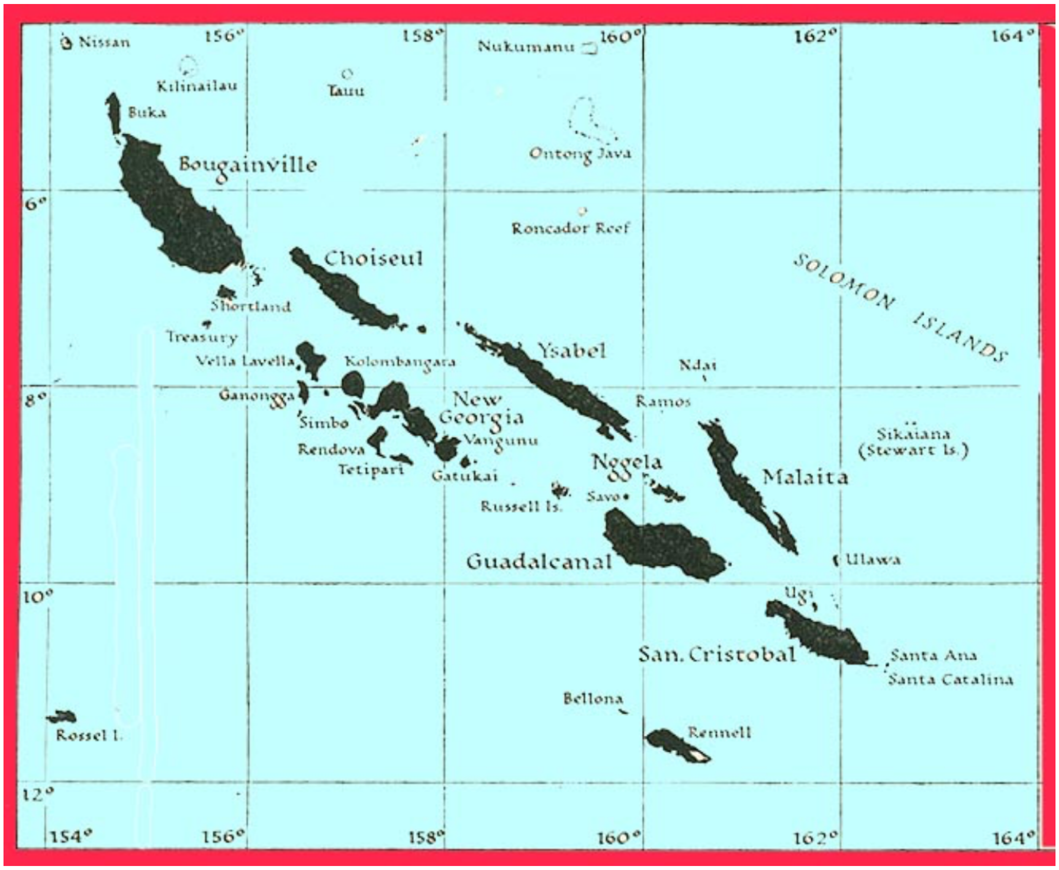

Fig. 2 Map of the New Georgia Group of the Northwest Solomon Islands.

There were several strong aftershocks following the main earthquake. The largest of these aftershocks, with a magnitude 6.4 struck at_11:45 hrs on _3 April 2007 near Gatokae and the surrounding areas of Marovo Lagoon in this Western province of the Solomon Islands.

3. THE TSUNAMI OF APRIL 2, 2007 IN THE SOLOMON ISLANDS

Destructive tsunami waves of up to five meters in height struck parts of Choiseul, Vella La Vella, Kolombangara, New Georgia, Gizo, Simbo and Ranoggah, in the western province of the Solomon Islands. The tsunami was particularly destructive at Gizo, Noro and Taro islands. The first tsunami wave reached the Gizo Township about five minutes after the earthquake. Fortunately the earthquake occurred during the day and most people seeing the sea receding moved to higher ground - thus many lives were saved. Ranunga Island was also struck by the tsunami.

There was substantial damage to the Western Provincial capital of Gizo and along the Entire Township and villages on the island. Gizo, the main town of about 1,000 people was hit by waves several meters high, destroying buildings, homes and washing people out to sea. Witnesses described the waves as inundating 50-70 meters (164-230 feet) inland. Communication links were wiped out. Large boats washed ashore and were deposited in the middle of the town. There was damage at Nusa Tupe Island, power failure and damage to telephone and extensive damage to Gizo's main airport and coastal roads. The Gizo hospital was inundated and was damaged extensively - making it inoperative.

On South Choiseul Island, waves of up to 10 meters in height swept through the village of Sasamunga. The waves penetrated up to 500 meters inland and destroyed at least 300 houses. Sasamunga lost its hospital and health centers. Also, the villages of Nukiki, Zepa and Luta sustained considerable damage. At Simbo Island the tsunami waves penetrated 200 meters inland. At Mono Island four people were reported missing.

In Southeast Papua New-Guinea, there were numerous fatalities. According to reports at least 50 people were killed (mainly by the tsunami) in the region. However, the death toll was probably greater since communications with remote islands were affected. According to the initial government damage assessment, about 916 houses were damaged or destroyed and about 50,000 people were affected.

Most of the damage occurred to the islands within the Woodlark Spreading Basin, where the tsunami energy was contained by the surrounding islands. However, a small tsunami was recorded by distant tide gauge stations. At Port Kembala (Australia) a 0.2 ft wave was registered with a 14 minute period. At Vanuatu, the recorded wave was 0.15 ft and the period ranged from 22 to 28 minutes. At Cape Ferguson (Australia) the tide gauge recorded 0.11 meter (0.4 ft) and a period of 12 minutes. At Manus (Papua-New Guinea) the tide gauge recorded 0.3ft maximum wave height and a period of 40 minutes. At Honiara (Solomons) the tide gauge recorded 0.6 ft and a period of 62 minutes.

4. PAST GREAT EARTHQUAKES AND TSUNAMIS IN THE SOLOMON ISLANDS REGION

Most of the earthquake activity on the northeast side of the Solomon Island Arc occurs along a 350 km segment of the North Solomon Trench close to Guadalcanal and San Christobal Islands. The region has produced about 10 major earthquakes in the last fifty years including the Ms 7.7 on June 15, 1966 and the Ms 7.7 on February 7, 1984 events (Richter magnitudes). The two great earthquakes of 14 and 26 July 1971 (about 12 days apart) had rather high moment magnitudes of Mw=9 and Mw=8.1. The earthquake of July

14, 1971 had its epicenter at 5.50 South 153.90 East in the New Ireland, Bismark Sea Region. The July 26, 1971 earthquake had its epicenter at 4.94 South, 153.17 East in the same region. Earthquakes in this region appear to occur as doublets, often within a few days of each other. Also, a great deal of strong earthquake activity occurs along the southeast side of the Solomon Island Arc.

As the April 2, 2007 event demonstrated, the region is capable of triggering great earthquakes and destructive tsunamis. On July 21, 1975, a magnitude 7.9 earthquake (epicenter at 6.60 South, 154.90 East), further north along the San Cristobal Trench, generated a large tsunami which hit Bougainville Island and killed an estimated 200 people. It is believed that the same tsunami was destructive also in the same western province of the Solomon Islands, but no details are available.

Major and great earthquakes can occur on either side of the Solomon Island Volcanic Arc. On the northeast side of the Solomon Island Arc larger rupture of adjacent slabs are possible which could involve the New Ireland segment or the North Solomon Trench. The most significant earthquake that would occur in the area that could approach an M9 magnitude earthquake would be expected near the Solomon Sea-Bismarck Sea triple junction, or one closer to the 1971 events. Any large earthquake in the region could generate a destructive local tsunami.

5. SEISMOTECTONIC SETTING OF THE SOLOMON ISLANDS REGION - UNDERSTANDING REGIONAL MECHANISMS OF TSUNAMI GENERATION ALONG ACTIVE BOUNDARIES OF YOUNG, MARGINAL SEA BASINS AND SPREADING RIDGES

In view of the high seismic activity of the Solomon Islands region, and in order to understand regional mechanisms of tsunami generation, the folowing is a cursory review of the prevailing tectonic interactions.

The Solomon Islands - an archipelago of 492 islands - is a volcanic arc along an extensive tectonic zone situated at an active margin boundary of two converging plates, where earthquakes occur frequently. The seismotectonic dynamics, geometry and direction of subduction in this volcanic arc region are complicated. Fig. 3 is a simplified diagram illustrating the type of oceanic/oceanic crust convergence occurring near the Solomon Islands Arc.

The spatial distribution of earthquakes on both sides of the Solomon Island Arc supports the existence of several subduction zones. Along the entire plate margin, there is not one simple plate boundary but a cluster of small plate boundaries which accommodate the mechanisms of the total interaction in the region (Brooks, 1965; Denham, 1969). The geometries of subduction differ for segments along the entire Papua-New Guinea and Solomon Islands region. One has to look at the geologic history of the entire Southwest Pacific to understand the complex evolutional dynamics that control present seismicity (and tsunami generation mechanisms) on both sides of the Solomon Island Arc.

Ontong-Java Plateau begun to collide with the Solomon Islands section of the Outer Melanesian Arc, but several major events that followed resulted in the break-up and segmentation of the Arc. At the outset, the direction of subduction beneath the Solomon Islands and Vanuatu arcs was reversed. The subduction of the Pacific Plate stopped, and eastward subduction of the back-arc basins beneath the Solomon and Vanuatu Arc segments, begun.

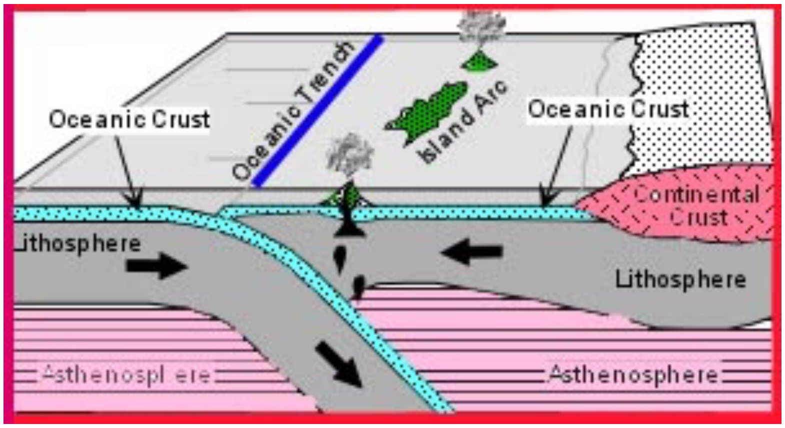

Fig. 3 Illustration of Oceanic/Oceanic Crust Convergence along certain regions of the Solomon Island Arc

In brief, the Solomon Island Arc is migratory arc system which developed from the early Eocene to Late Miocene as part of a continuous Outer Melanesian Arc (Rodd, 1993). The Arc extended from Papua New Guinea through the Solomon Islands, Vanuatu, Fiji and Tonga/Lau, to New Zealand. According to Rodd (1993), in the Late Miocene, the oceanic Ontong-Java Plateau collided with the Solomon Islands section of the Outer Melanesian Arc. Fig. 4 (modified after Goodliffe et al. 1999), shows the GrapBathymetry, Spreading Center, the Woodlark Ridge, and the Woodlark Spreading Basin in relation to the San Cristobal Trench in the vicinity of the New Georgia islands Group of the Solomon islands. The tsunami generating source area of the April 1, 2007 is pointed by the arrow and is near southwest subduction zone of the New Georgia Group of islands.

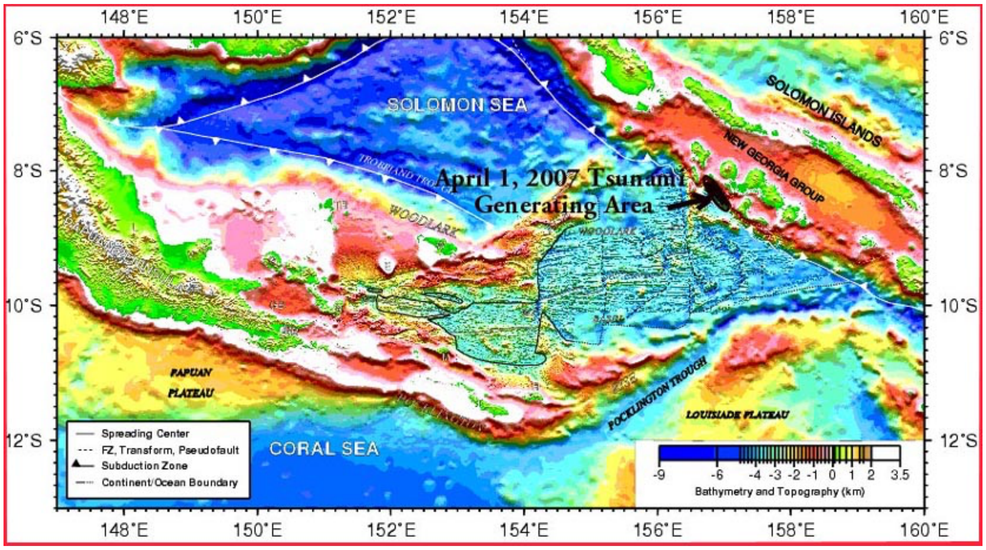

Fig. 4 Graphic showing Bathymetry, Spreading Center, the Woodlark Ridge, and the Woodlark Spreading Basin in relation to the San Cristobal Trench in the vicinity of the New Georgia islands Group of the Solomon islands. The tsunami source area is that pointed by the arrow. (Modified after Goodliffe et al. 1999)

In recent years, several research investigations have been undertaken in the region to help understand present processes of subduction, accretion and fragmentation of oceanic plateaus at subduction zones and their deformational effects on the overriding Solomon island arc (Mann, 1997; Mann et al. 1997, 2004; Mann & Taira, 2004; Goodliffe et al. 1997, 1999; Phinney et al. 1999, 2004; Martinez et al. 1999; Miura et al. 2005; Taira et al. 2004; Taylor et al. 1995, 1999, 2005; Cowely et al. 2004).

The researchers are looking at different models of tectonic interactions. For example, one of the models postulates wedging of the Solomon Island Arc beneath the Ontong Java plateau - the largest oceanic plateau in the world - Northeast of the Solomon Islands. The other model postulates an oceanic accretionary wedge geometry with northeastward component towards the Ontong Java plateau (Fig. 5).

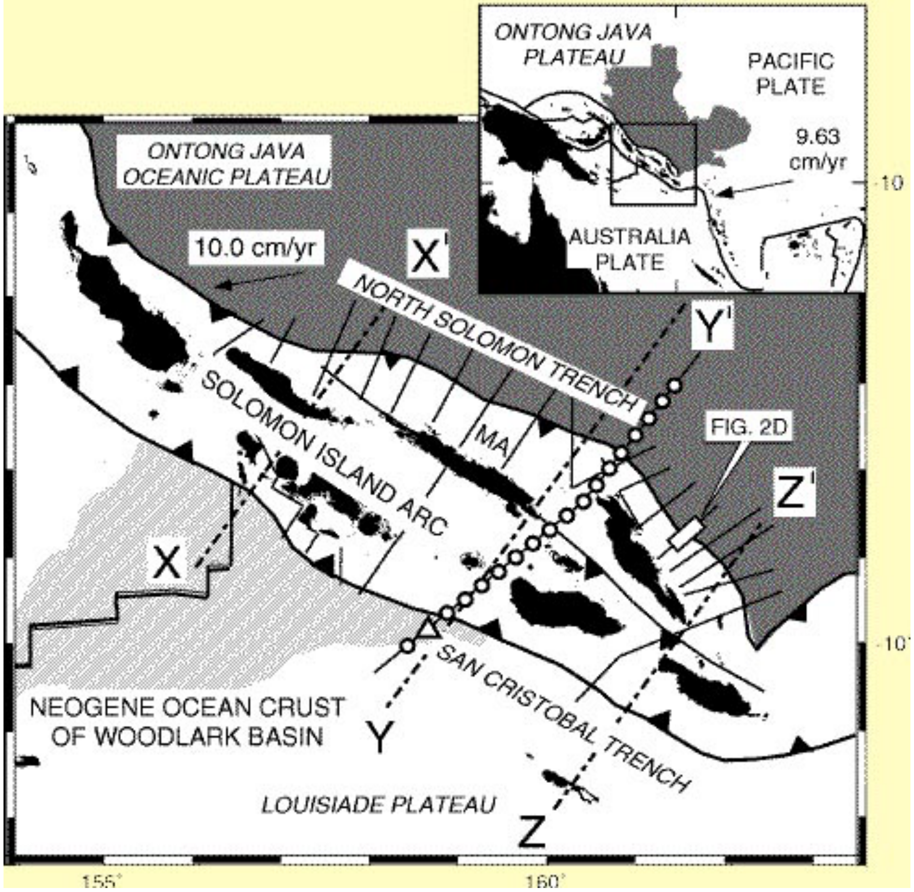

Fig. 5. Map of the University of Texas (Institute of Geophysics from studies conducted in the Solomons) showing the Ontong Java Institute of Geophysics Oceanic Plateau, and the North Solomon Trench on the Northeast of the Solomon Island Arc and the San Cristobal Trench in relation to the Woodlark Ridge and Spreading Woodlark Basin on the Southwest.

On the Southwest side of the Solomon Island Arc near the New Georgia Islands where the April 1, 2007 earthquake occurred, the tectonics are also very complicated - as also illustrated by Figure 6 (Yu-Ting Kuo, et al, 2017), and additionally supported by GPS observations.

The April 1, 2007 earthquake occurred near the suduction zone in close proximity to the San Cristobal Trench, on the east end of the Woodlark Basin and very near the triple junction formed by the subduction of the Woodlark Spreading Ridge.

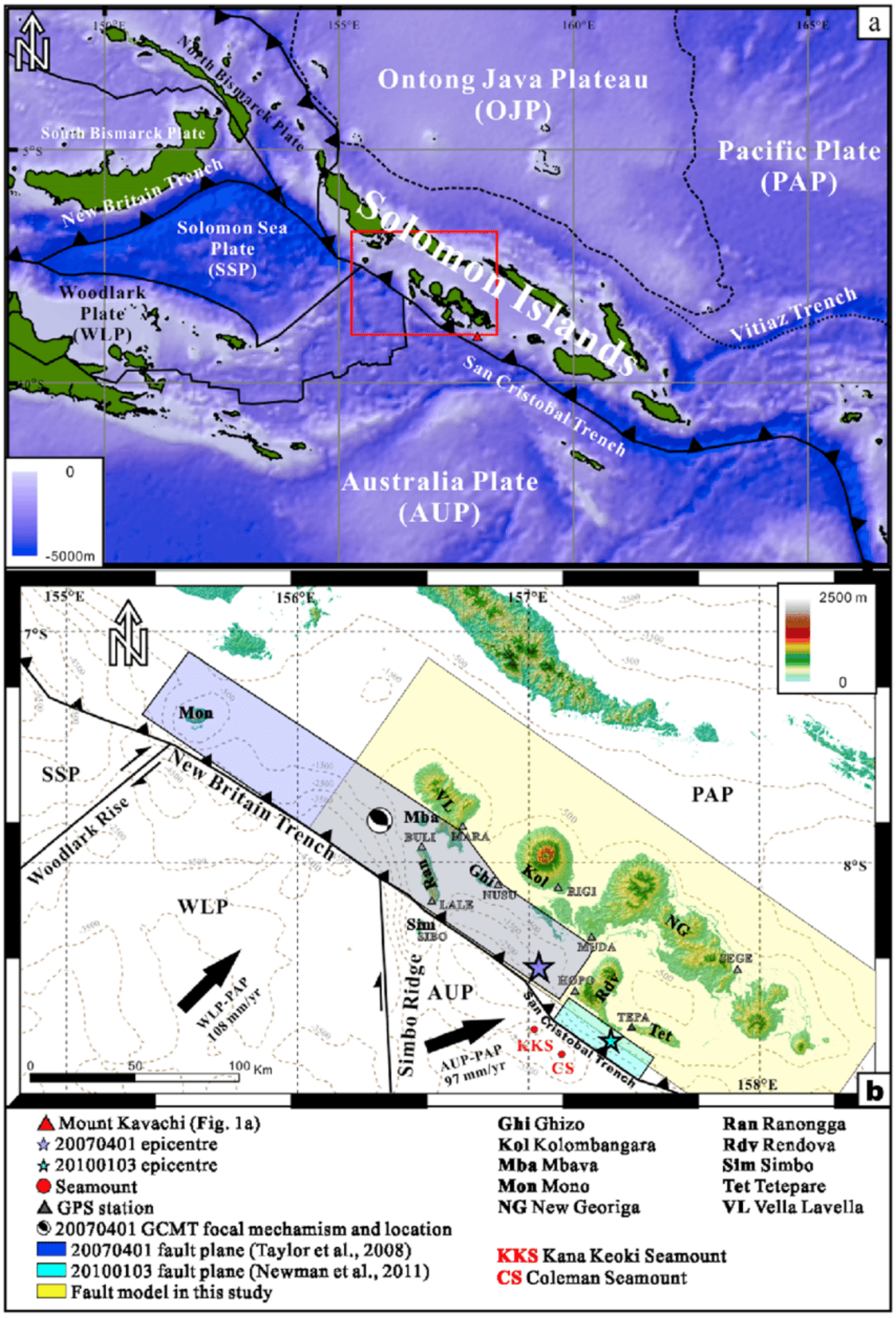

Fig. 6. Bathymetry and plate tectonic features around the Solomon Islands (red box represents region shown in Figure 1b). (b) Plate tectonic setting for the Western Solomon Islands and the inferred rupture zones of the 2007 and 2010 earthquakes (After Kuo et al, *2017)*

The April 1, 2007 earthquake's estimated rupture, with an orientation of about 331 degrees, parallels the orientation of the direction of the axis of the San Cristobal trench Fig. 6). As stated, the Woodlark Basin is a young marginal basin which is both propagating westward (from a spreading center) into the Papuan Peninsula while - at the same time - spreading and being subducted eastward beneath the Solomon Islands (Taylor et al. 1995, 1999, quoting Weissel et al., 1982) - in this case beneath the New Georgia Island Group.

It is difficult to comment further on the dynamics of the region and its potential for future tsunami generation as there is no known historical tsunami data. As pointed out (Shinohara et al. 2003), without detailed and accurate seismicity studies, it is difficult to accurately describe the plate subduction processes of this complex zone. The region does not represent a typical subduction zone as other tsunamigenic areas of the world - since there is spatial progression from continental rifting to seafloor spreading and to shallow subduction at the eastern margin of the Woodlark Basin. Such mechanism of shallow subduction beneath a volcanic island arc can account for large earthquakes and destructive tsunami generation. However - and although earthquakes in this region that can occur may be large in magnitude - the rupture lengths may be limited, the tsunami generating areas may be relatively small, and the tsunami impact may be confined by the physical barriers and the local bathymetry of the Woodlark basin and of surrounding island groups trapping tsunami energy. Thus, no tsunami with far reaching impact can be expected from this region.

6. CONCLUSIONS

The great magnitude 8.1 earthquake of 1 April 2007 that struck the New Georgia Group of the Northwest Solomon Islands, generated a tsunami particularly destructive on Gizo, Noro and Taro islands. The rupture length of this earthquake was limited, the tsunami generating areas was relatively small and the tsunami impact was confined by the physical barriers and the local bathymetry of the Woodlark basin and by the surrounding island groups, which trapped and contained most of the tsunami's energy. No significant waves were recorded by distant tide stations. This indicates that no tsunami with far reaching Pacific Ocean impact can be expected from the Woodlark basin region.

In general the present study confirmed and concluded that the seismotectonic dynamics of the Solomon Islands region and the mechanisms of tsunami generation along active boundaries of young, marginal sea basins and spreading ridges are complex. Destructive local tsunamis can be generated on either side of the North Solomon Islands trench and volcanic Island arc - which are bounded by zones of opposing subduction where strong earthquakes occur frequently.

It is difficult to accurately describe the plate subduction processes of this complex zone. The region does not represent a typical subduction zone as other tsunamigenic areas of the world. In this region there is spatial progression from continental rifting to seafloor spreading and to shallow subduction at the eastern margin of the Woodlark Basin.

Several research investigations of the region have been taken to help understand present processes of subduction, accretion and fragmentation of oceanic plateaus at subduction zones and their deformational effects on the overriding Solomon island arc. Such mechanisms of shallow subduction beneath a volcanic island arc can account for large earthquakes and destructive tsunami generation. However, in spite of the fact that earthquakes in this region may be large in magnitude - the generated tsunamis are locally destructive but historically do not have far reaching Pacific-wide destructive impact.

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ISSN 8755-6839

SCIENCE OF TSUNAMI HAZARDS

Journal of Tsunami Society International

Volume 39 Number 2 2020

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