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CONTRASTING RESULTS OF POTENTIAL TSUNAMI HAZARDS IN MUISNE, CENTRAL COAST OF ECUADOR

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ABSTRACT

After the 7.8 Mw Earthquake occurred in Ecuador on April 16 of 2016, the Ecuadorian Government declared the whole Island of Muisne into a risk hazard zone by a potential Tsunami impact and subsequent flooding. Based on the emitted resolution, human settlements in the affected area were prohibited, and a resettlement project in the village of Bunche is currently taking place. Nonetheless, our study demonstrates that the inundation chart used to release the mentioned resolution underestimate the flooding area in case of a real Tsunami impact. To support this conclusion, we present a new inundation chart for the three more probable scenarios, based on historical tsunami records and a seismic hazard assessment study in central coastal Ecuador.

Keywords: *Tsunami modeling, seismic hazard, worst case scenario, GIS, relocation*

1. INTRODUCTION

The evaluation of the extension of potential hazards of natural origin is sometimes a complicated and complex task. In case of tsunamis, a variety of parameters have to be taken into consideration in order to be able to calculate numerically, above and below the sea surface and through field evidences of past catastrophic events how far a newly generated tsunami will be able to reach shorelines and beyond (Tinti and Armigliato, 2003; Liu et al., 2007; Orfanogiannaki and Papadopoulos, 2007; Pignatelli et al., 2009; Ribeiro et al., 2011). An excellent example of negligence in such an issue has been the Japanese tsunami in March 2011, where due to known characteristics and due to contrasting economic interests, a lesser care took place in the construction of strategic infrastructure like the installation of the nuclear plant of Fukushima among other important industry (Holt et al., 2012; Acton and Hibbs, 2012; Synolakis and Kânoğlu, 2015; Kastenberg, 2015). The destruction and subsequent radioactive leaks of that nuclear plant, which threatens the public for the following thousands of years were in fact avoidable and leave a strong message for areas equally threatened by the same natural forces (Synolakis and Kânoğlu, 2015).

There should not be any significant margin for mistakes if it comes to the safety of life and also important infrastructure. Therefore, the main aim of this study is dedicated to evaluate the potential magnitude of future tsunamis in central Ecuador by the consideration of the seismic intensities of historic events in the same region and compare it with those results the governmental agencies have in mind for its public.

2. PAST TSUNAMI HAZARDS IN ECUADOR

Ecuador - situated in the northwestern side of South America - is part of an active continental platform, which has been in the historic past a frequent target of tsunamis. (Fig.1). This circumstances are given due to the subduction of the oceanic Nazca Plate with the continental South American and Caribbean Plates, both separated by the Guayaquil-Caracas Mega Shear (Kellogg and Vega, 1995; Gutscher et al., 1999; Gusiakov, 2005; Egbue and Kellog, 2010; Pararas-Carayannis, 2012). Additionally, the Ecuadorian coastline has suffered of tsunamis triggered by enormous mass failures of submarine landslides (Shepperd and Moberly, 1981; Pontoise and Monfret, 2004; Ratzov et al, 2007; 2010; Ioualalen et al., 2011; Toulkeridis, 2011; Pararas-Carayannis, 2012). Due to this geological setting and active geodynamics, the Ecuadorian coastline has witnessed a dozen times impacts of tsunamis generated in the vicinity of the subduction zone but also from regional as well as far-reaching tsunamis generated across the Pacific Ocean (Titov et al., 2005). Tsunamis of local origins during the last two centuries have reached intensities of up to 8.8 Mw (Rudolph and Szirtes, 1911; Kelleher, 1972; Beck and Ruff, 1984; Kanamori and McNally, 1982; Swenson and Beck, 1996; Pararas-Carayannis, 2012; Rodriguez et al., 2016; Toulkeridis et al., 2017a), while evidences of paleo-tsunami deposits are scarce (Chunga and Toulkeridis, 2014). The most prominent examples of tsunamis along the Ecuador–Colombia subduction zone include tsunamis in 1906 (Mw=8.8), 1942 (Mw=7.8), 1958 (Mw=7.7), 1979 (Mw=8.2) and 2016 (Mw=7.8) within the 600-km long rupture area of the great 1906 event (Collot et al., 2004; Toulkeridis et al., 2017b; b). While the 1906 event caused the death of up to 1500 persons in Ecuador and Colombia, the 1979 tsunami killed in Colombia at least 807 persons (Pararas-Carayannis, 1980). The evaluation of the last marine quakes, which generated tsunamis suggests that the probability of a major or great earthquake in this margin region is enormous, especially as there must be substantial strain accumulation in this region (Pararas-Carayannis, 2012). We have taken a detailed look upon Muisne and Bunche, which are locations in central coastal Ecuador and may suffer the same consequences like similar pacific ocean sites in the past.

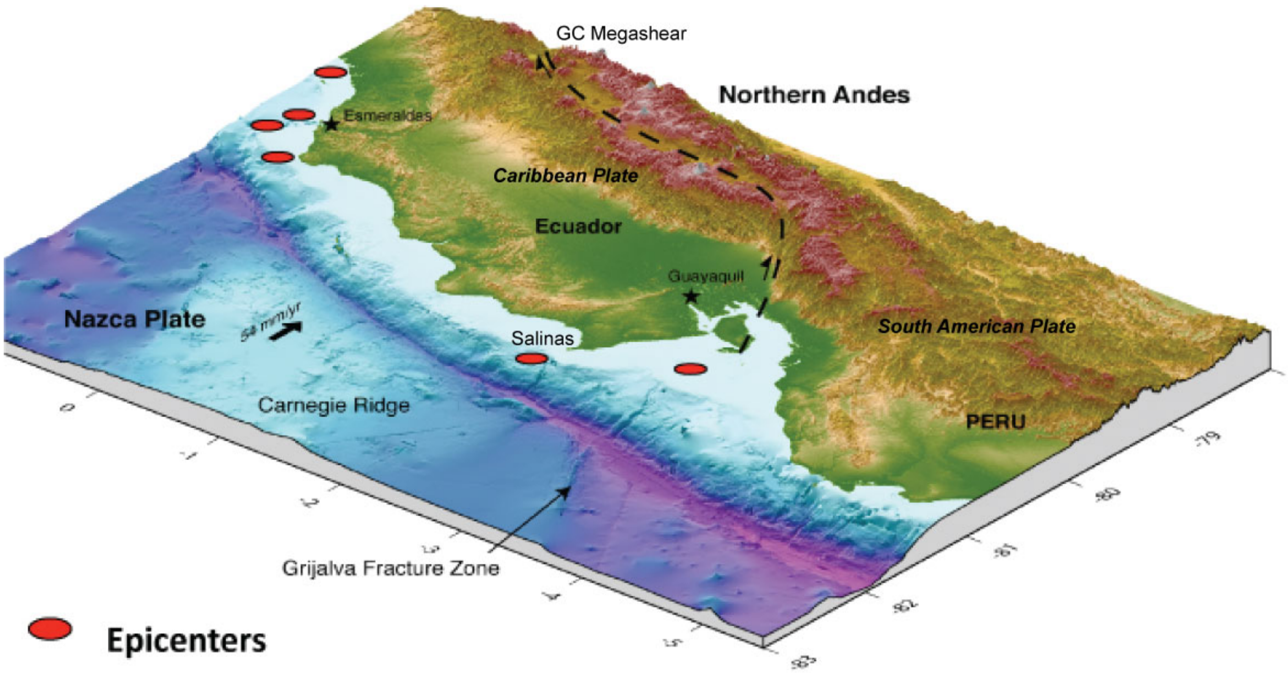

Fig. 1: Panoramic view of the morphology of western Ecuador and location of seismic epicenters, which generated tsunamis in the last 110 years. Adapted and modified from Collot et al., 2004.

3. GEOLOGIC SETTING OF MUISNE AND ITS SURROUNDING

Three types of geological formations appear in the close vicinity of Muisne (Fig. 2), which are the Miocene Onzole Formation, the Pliocene Borbón Formation Quaternary sediments. The up to 550 m thick Onzole Formation is mainly composed of blue siltstones, silty lutites, shales, tuffaceous clays and rarely sandstones and conglomerates and occasionally high contents of moluscs (Stainforth, 1948) (Fig. 3). The Borbon Formation is jusxtaposed discorcondantly upon the Onzole Formation and is composed of conglomerates followed by compact layers of coarse-grained sandstones having abundant occurrences of megafossils, mainly moluscs of marine facies (Stainforth, 1948). Both formations and their distinctive lithologies are divided by a ENE-WSW striking normal fault, which is followed by the Bunche river. In the Bunche river itself appear recent fluvial deposits such as sand, silt and clay materials. The Bunche river as well as the further to the north appearing San Francisco river are tectonically controlled. Around these geological faults appear a variety of landslides, but which are mainly generated by the intense deforestation in the area (Fig. 4), especially towards the

Northeastern side of Bunche in the mountain flanks with steep slopes near the river. A further, predominant NW-SE strinking transcurrent fault is appearing parallel to the coastline, above the swamp area and continental part of Muisne. Both fault systems appear to be active.

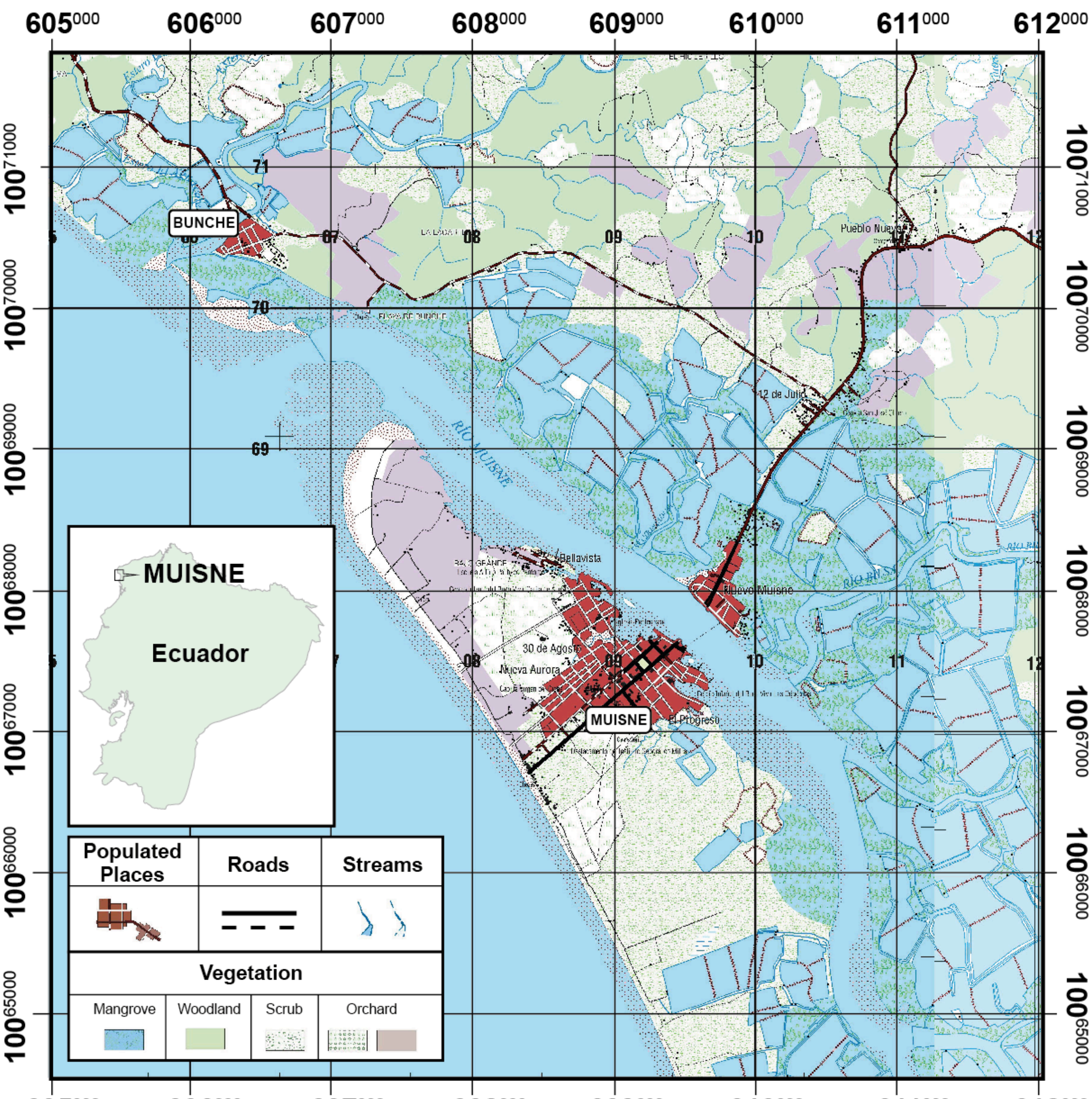

Fig. 2: Location of Muisne and Bunche within Ecuador and topographic area of the mentioned sites.

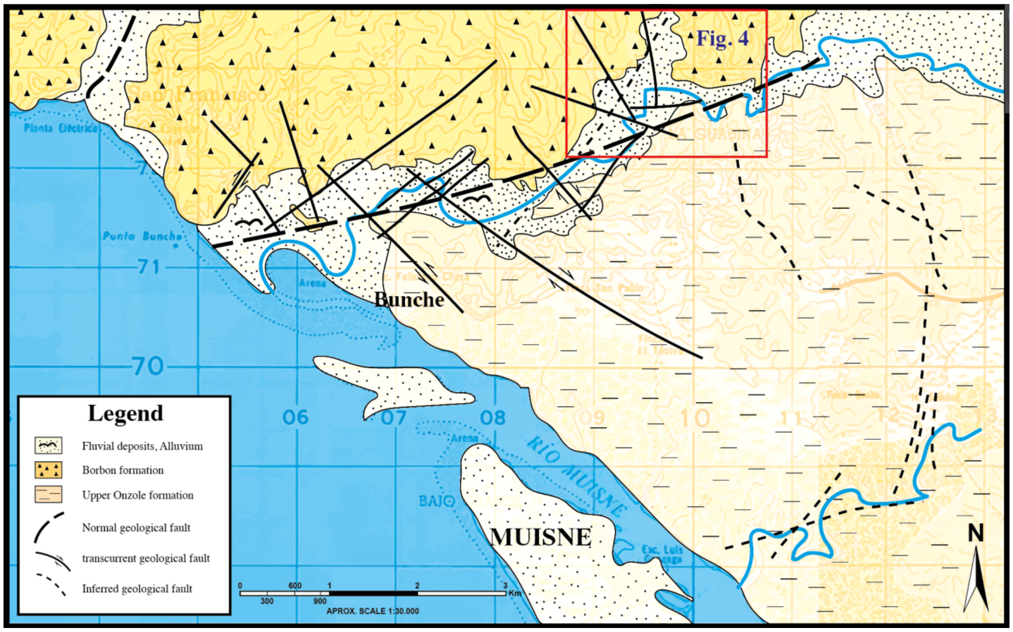

Fig. 3: Geological map of Muisne with the most dominant formations, units and fault structures.

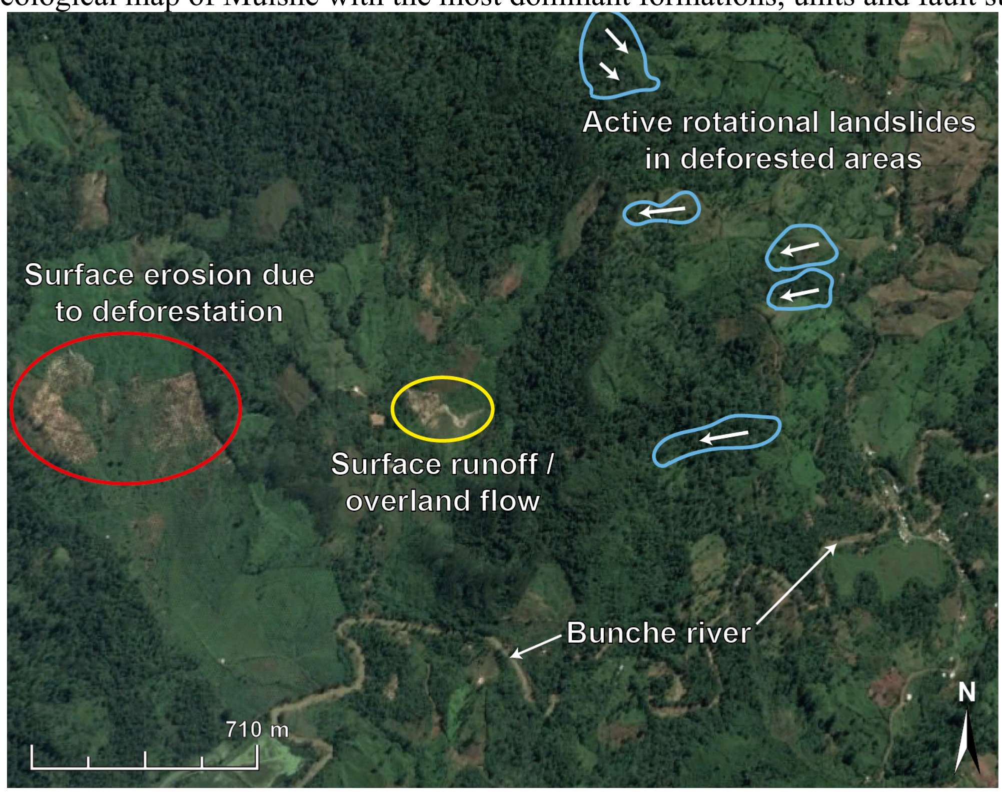

Fig. 4: A variety of mass-movements occurr in the study area close to Bunche, such as surface erosion by deforestation of African Palms corps (red circle), surface runoff / overland flow (yellow circle) as well as active rotational landslides in deforested areas (blue areas with arrows of fall directions). Based on Google Maps.

4. PREVIOUS CONSIDERATIONS OF TSUNAMI HAZARDS IN MUISNE AND PROPOSED RELOCATION AREA

Through resolution No. SGR-073-2016 (SGR, 2016), the Risk Assessment Secretary in the range of a ministry of the Ecuadorian Government called Secretaría de Gestión de Riesgos (SGR) declared the whole Island of Muisne into a risk hazard zone by a potential Tsunami impact and subsequent flooding. The resolution has been supported in the Chart-SNGR-CITs-080350-Muisne (SGR, 2013; Fig. 5), previously elaborated in December 2012 by the same SGR. As a derived consequence, such resolution prohibited human settlements in the affected area, giving rise to a resettlement project in the village of Bunche. For the elaboration of such chart, the wave height has been estimated using the simplified Yamaguchi's empirical expression for tsunamigenic earthquakes originated at depths less than 100m (SGR, 2013). With the resulting wave height, the potential flood area has been estimated by the expression given by Synolakis for the calculation of the run-up at coastal profiles with steep slopes (Synolakis, 1991).

The equations used, however, underestimate the potential flood area. In this respect, the penetration distance will be much greater in reality due to physical variables that have not been taken into account in such chart, related to the generation, propagation and flood phases, commonly addressed in numerical simulation models (Imamura, Bernard, and Robinson, 2009; Kowalik, 2012): (1) At the generation phase, depending on the location of the seismic source and the magnitude generated, the displaced water mass can reach a larger volume function of the bathymetric profile (Titov et al., 2005). In order to estimate such volume, it is necessary to incorporate bathymetric information regarding the worst possible scenario considered (up 30-60 km off the coastline in our study). Unfortunately, such information is not available to date from the coastal limit of 30 km (50 Km in some cases); (2) The application of the Yamaguchi formula for the calculation of wave height presupposes an attenuation of energy by friction in shallow water, less than 100 m. Again, due to the lack of bathymetry data in the coastal profile, the possible amplification effect of the propagation zone remains unknown, as well as the possible change of direction and velocity of the generated tsunamigenic wave front, invalidating hereby its application. What is known is the presence of a slight sediment barrier off the coast of Esmeraldas, which, in the case of the propagation of a potential tsunami from lower latitudes, will contribute to a rise in sea level, underestimating thus the actual height of the tsunamigenic wave-front the results obtained by applying the Yamaguchi formula. This underestimation will be even greater considering the effects of refraction, diffraction, reflection and interference in the propagation phase (Barberopoulo, 2014; Kontar, Santiago-Fandiño and Takahashi, 2014), more noticeable in oblique propagation directions to the coast of Muisne and Bunche. The presence of these effects makes it necessary to estimate different wave heights corresponding to the different arrival wave fronts, whose maximum values also do not have to coincide with the first wave-front generated (Okal and Synolakis, 2016); (3) The application of the Synolakis formula (Synolakis, 1991) for the estimation of the flood area underestimates the actual result since the break zone of the wave can not be considered as steep slope. For the estimation of this area, in addition, it is necessary to provide information about the trajectories and speeds that will follow the water currents. These parameters depend not only on the terrain dimensions and characterization of watersheds, but also on the scenario of collapse of buildings and infrastructures and the characterization of the terrain on which the tsunami will impact. In this sense, the study area is located on a mangrove swamp, with severe flooding in the past due to the El Niño phenomenon (Vos, R., Velasco, M. and Labastida, E., 1999), making it more likely to have longer flood distances due to the impact of a potential tsunami (Synolakis and Bernard, 2006).

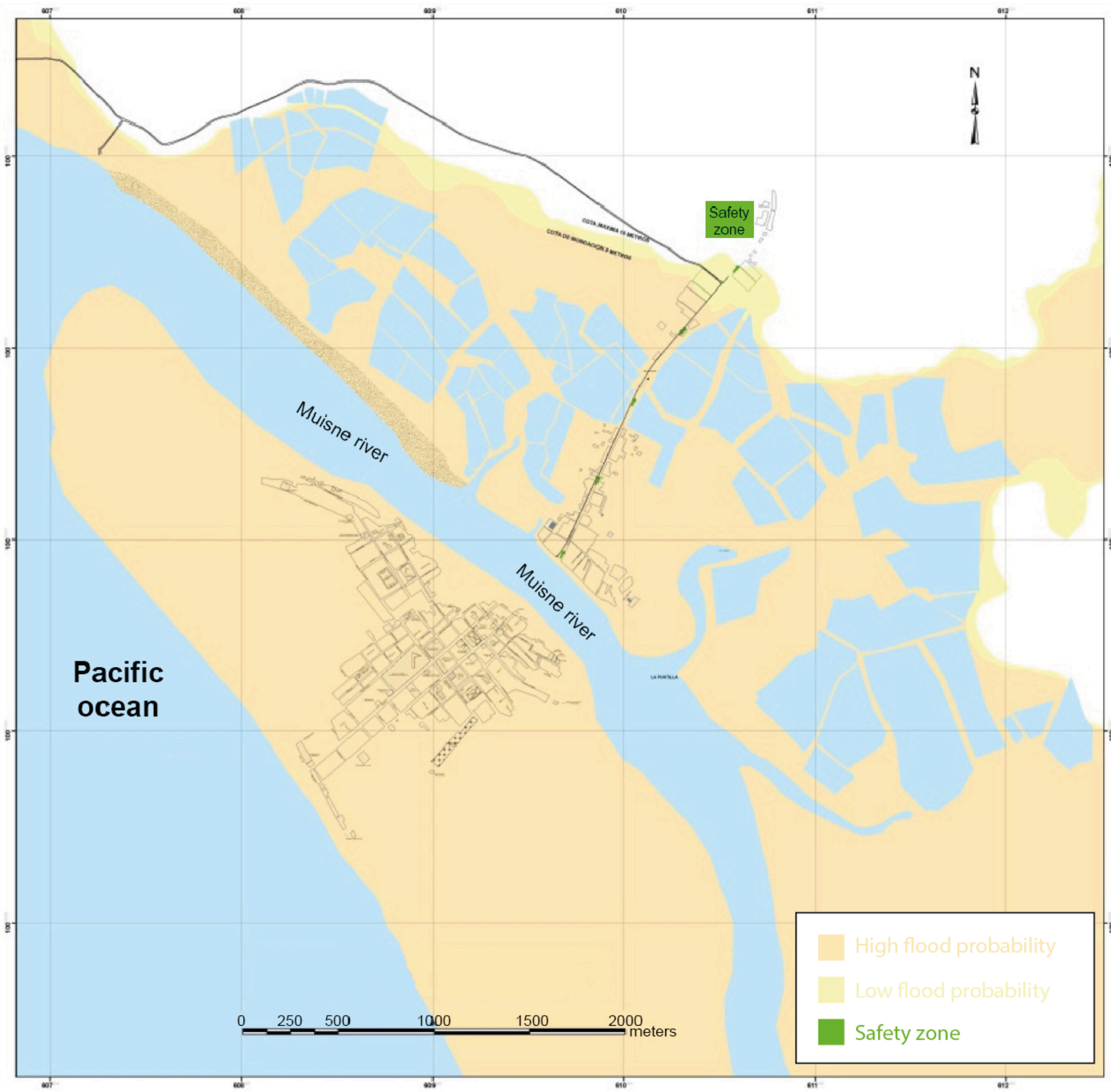

Fig. 5: Muisne's tsunami inundation chart with a simplified but not modified legend (Carta-SNGR-CITs-080350-Muisne). Chart elaborated in 2012 by the SGR.

REAL SEISMIC AND TSUNAMI HAZARDS POTENTIAL IN MUISNE AND SURROUNDING AREA

A recent seismic hazard study of continental Ecuador demonstrated the calculation of the potential seismic hazard or expected movement, due to the evaluation of past occurred earthquakes in the zone of influence (Parra et al. 2016). This has been based on the application of a zoned probabilistic model, where the risk is the sum of the contributions to the movement due to the seismicity of the different sources, what means in turn that the risk is not associated to a concrete earthquake, rather than by characterizing factors such as the frequency with which earthquakes occur of each seismic source, the energy that may be released at each source and the probability that an earthquake will be generated in a given distance range as well as the attenuation of the seismic movement in its path. Among the seismic hazard maps in generic rock-type soil conditions (Parra et al., 2016), it is observed that for a return period of 475 years in terms of peak acceleration of soil movement (PGA), it does correspond to the expected movement with the probability of exceedance of 10% in 50 years (Fig. 6). The highest values of peak acceleration are located in the province of Esmeraldas.

One of the inputs for the estimation of seismic hazard with a probabilistic approach is the delimitation of the area of interest in seismogenic zones, zones of uniform seismic potential or zones capable of generating earthquakes of similar characteristics, uniformly distributed. This implies to assume a temporal and spatial independence between earthquakes belonging to the same source. It requires also to identify each of them with a rate of seismic activity constant in time, so that earthquakes are independent and random events with equal probability of occurrence in the whole area and whose frequency and size is related by a logarithmic law. This will allow to estimate among other results the maximum potential earthquakes associated to each one of them.

Based on a seismic catalog that covers a period from 1584 to 2014 (Fig. 6), a differentiated seismic zoning has been elaborated by tectonic regimes observed in Ecuador (Fig. 7). This allows the knowledge about the occurrence of earthquakes in the past to establish a seismicity pattern and to extrapolate it to the future. These seismic events are homogenized in their parameter from size to momentum (Mw) obtaining a range of magnitudes Mw of 4.0 to 8.8 and are mostly associated with the sources of subduction (Fig. 8).

Once the seismogenic zones and the seismicity have been defined and delimited, the frequency of occurrence of the earthquakes according to their magnitude or seismic potential in each zone is estimated using a Gutenberg-Richter model of recurrence (Gutenberg and Richter, 1944), truncated to a minimum magnitude of 4.0 (Mw) and to the maximum magnitude estimated for each zone (Cosentino et al., 1977), using the maximum likelihood method proposed by Weichter (1980) for the Gutenberg-Richter line.

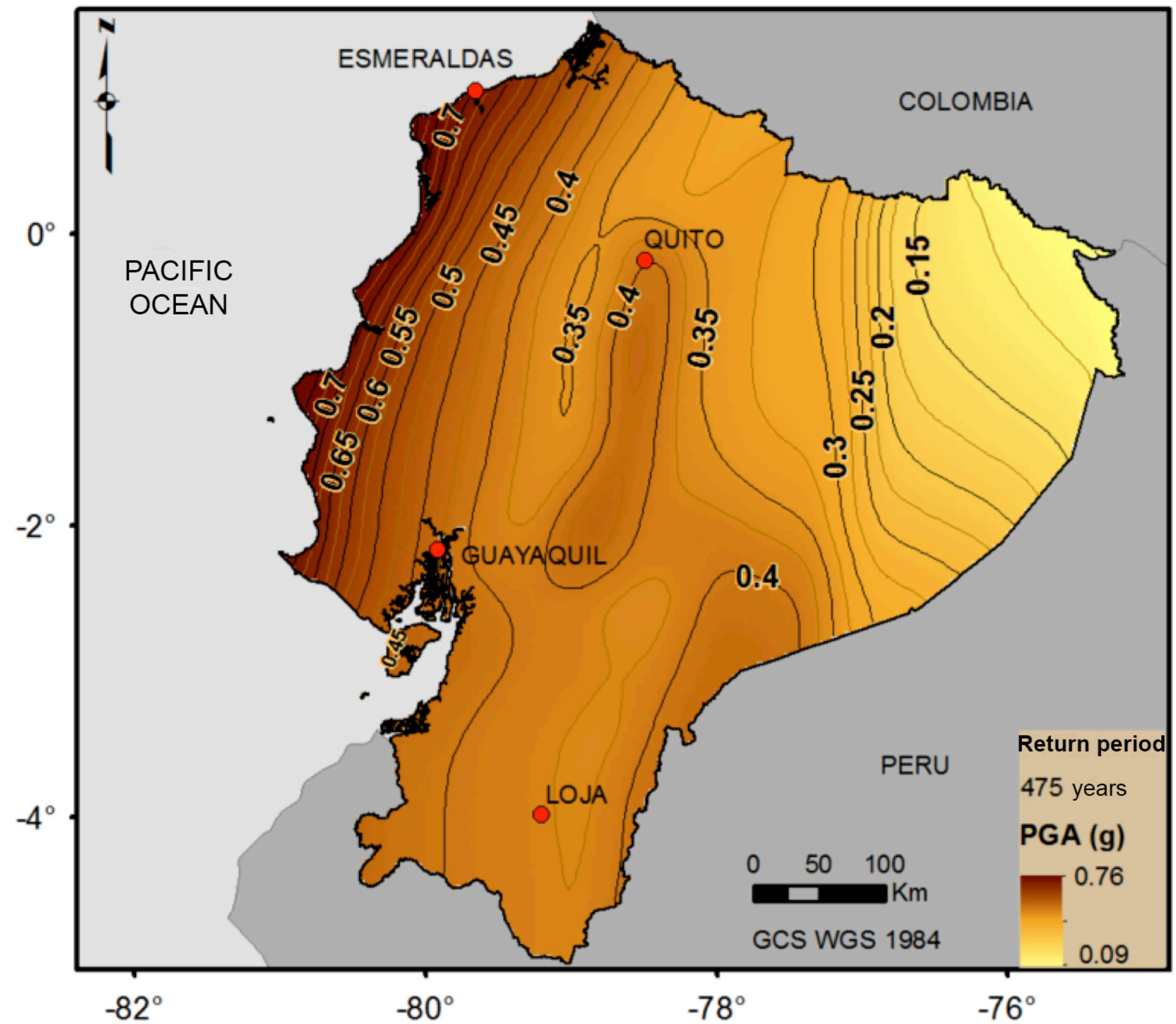

Fig. 6: Seismic hazard map of Continental Ecuador in terms of PGA (g) for a return period of 475 years (Parra et al., 2016). The seismic catalog contains records from 1587 to June 2014, includes historical and instrumental information published in specific studies and by different agencies of seismic monitoring, such as the Instituto Geofísico de la Politécnica Nacional del Ecuador, the Intenational Seismological Center (ISC), and the National Earthquake Information Center-Preliminary Determination of Epicenters (NEIC-PDE, 2016), as well as information of historic earthquakes obtained by Rivadeneira et al. (2007), Beauval et al (2010; 2013) and Alvarado (2012).

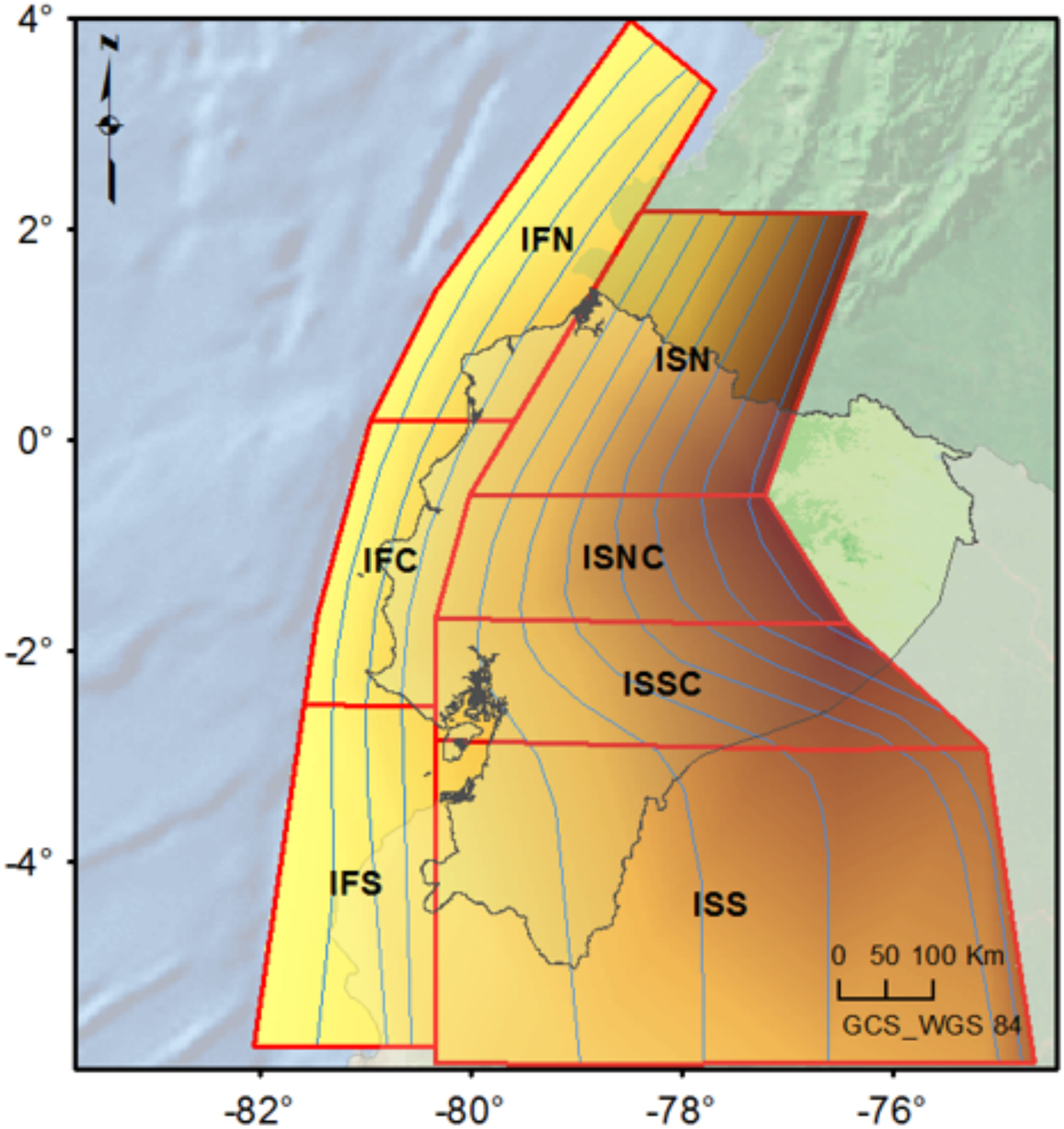

Fig. 7: Seismogenic Zoning for Ecuador related to subduction (Parra, 2016). Zones are defined as: IFN: Interface North; IFC: Interface Center; IFS: Interface South; ISN: In-slab North; ISNC: In-slab North Center; ISSC: In-slab South Center; ISS: In-slab South.

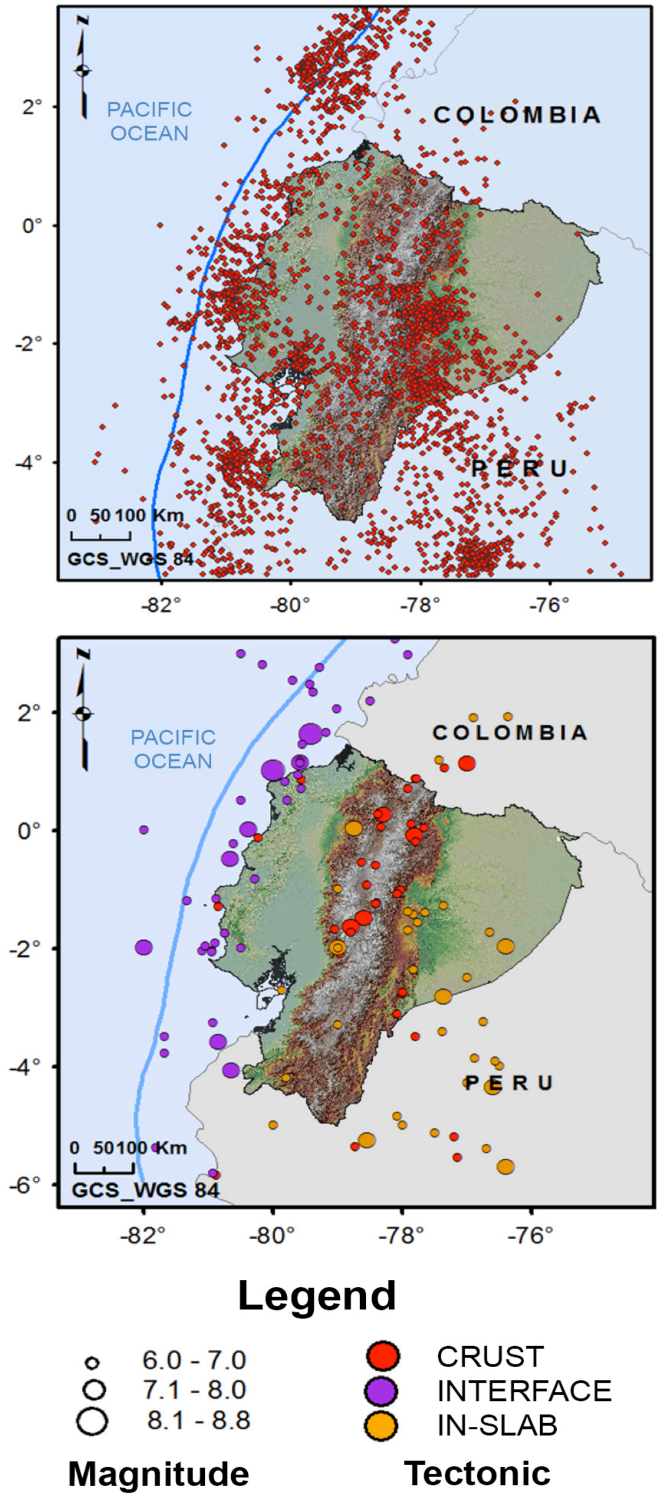

Fig. 8: Representation of seismic events in a period from 1584 to 2014, based on data mentioned in Fig. 6.

For the studied region, the seismic hazard is dominated by the process of the subduction interface (Parra, 2016). This seismic source is located at the beginning of the subduction, where part of the movement of the Nazca plate is blocked, which causes deformation of the denser subducted plate, accretion of the continental margin and accumulation of tension (Egbue and Kellog, 2010). From the Esmeraldas peninsula to the north, the direction of the subduction trench has an N38ºE orientation, reaching a depth of 3900 m in front of the province of Esmeraldas (Goyes, 2009; Collot et al., 2009). Chunga et al. (2009) suggest that the immersion of the Benioff plane shows an angle of 4º to 5º, while Manchuel et al. (2009) propose an inclination of the slab with an angle of 10º in front of the province of Esmeraldas. Hayes et al. (2012) estimates an angle of inclination of the ceiling of the oceanic plate of 16º to a depth of 40km, while Parra et al. (2016) calculated an inclination angle of between 7° and 11°. From the forementioned, we conclude that in front of the Ecuadorian coastline in the study region, there is a beginning of a low-slope subduction, which would be the main cause of accumulation of tension and generation of seismicity up to a depth of 40 to 50 km (Chunga et al., 2009; Marcaillou et al., 2009).

In a recent study a seismogenic zone has been located in the vicinity of the Esmeraldas Peninsula called the North Interphase (IFN; Fig. 7), which extends from the trench to a distance of approximately 120 km east of the pit (Parra et al., 2016). Although most of the earthquakes are located in this zone of interface, its distribution is heterogeneous, having a high concentration from the center towards its northern end. There, great seismic events are located such as the Mw 8.8 and 8.1 registered in 1906 and 1979, respectively. The Foci are there located between the coastline and the subduction trench (Fig. 8). According to the method of the calculation of the hazard, it is assumed that in the IFN zone seismicity is equivalent throughout its area, which implies that the seismic events within the zone are independent random events whose sizes are associated with their frequencies by a logarithmic law, bounded to a minimum magnitude and a maximum magnitude, and with a rate of seismic activity constant over time.

The seismicity of this zone has been adjusted to a Gutenberg-Richter model, according to the expression Ln N = α-β (m), truncated to a minimum magnitude m_0 of 4.0 (M_W), while the line-adjustment of Gutenberg-Richter to obtain its seismicity parameters has been made by the method of maximum likelihood, using the proposal of Weichert (1980). This allows taking into account different periods of completeness depending on the magnitude, obtaining an approximation of the parameter β, its uncertainty and the rate of events of a magnitude $\geq$ m0, having the particularity of this zone where a lower slope for large earthquakes, so it represents in fact a double adjustment (Table 1; Fig. 9).

Table 1: Seismicity parameters of the IFN seismogenic zone (Parra et al., 2016)

Adjustment (4.0-5.9)		**Adjustment (≥ 6.0)**	
ALFA	14.059	ALFA	8.739
BETA	-1.87	BETA	-1.000
SIGMA BETA	0.099	SIGMA BETA	0.370
RATE 4.0	6.609	RATE 6.0	0.142

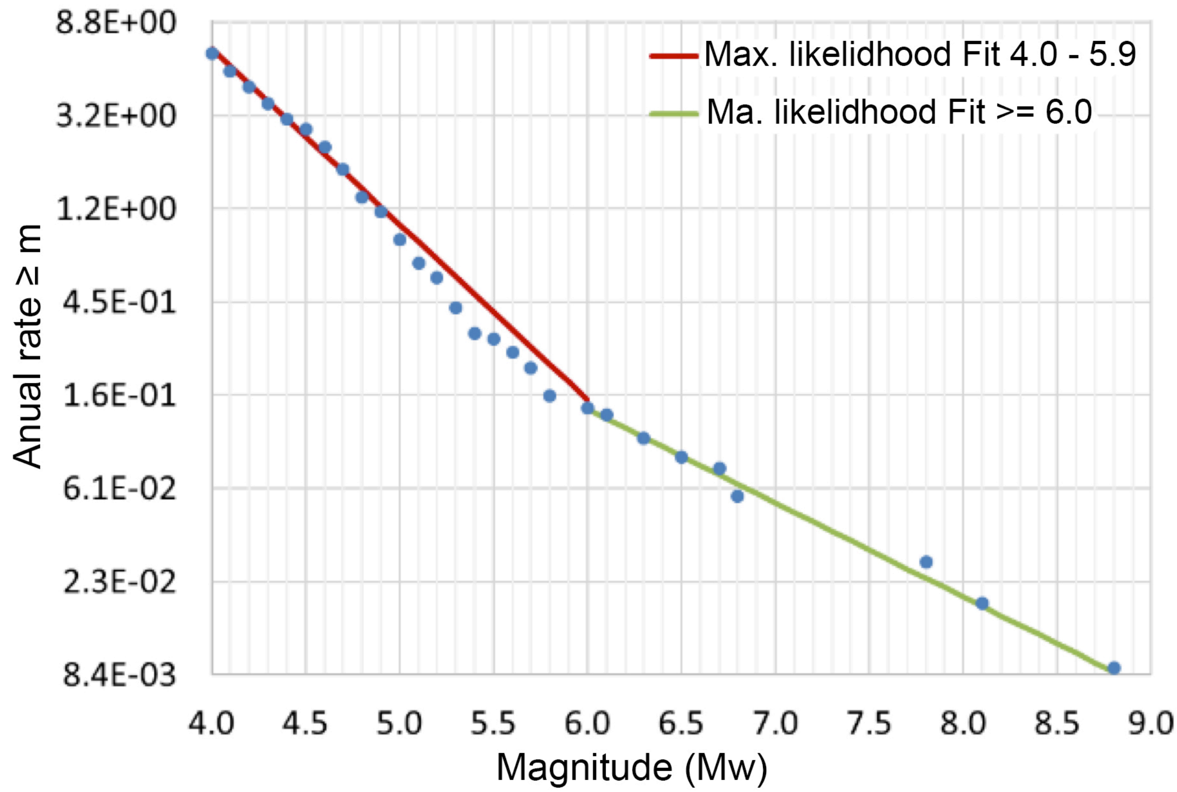

Fig. 9: Adjustment to the seismicity of the IFN seismogenic zone (Parra et al., 2016)

For the estimation of the maximum magnitude (M_{max}) in this zone, we started with the Gutenberg-Richter model and analyzed the tendency of seismicity to its maximum values. In our case, this results in the fact that at the point of cut of the line with the X axis (Ln (N) = 0), where N represents the accumulated theoretical number of earthquakes in their completeness period, the maximum observed magnitude of 8.8 recorded in 1906 coincides with the estimated trend of seismicity when the line intersects the X-axis (M_{GR} in Fig. 10).

In order to estimate the random uncertainty (Δ) inherent to the M_{max}, we performed a modeling using a uniform probability distribution, considering all the values that this parameter is able to take between two limit values (Mw, Mmax), being then the value of $\Delta = Mmax - M_W$, when $M_W$being the size of the immediate seismic event lower than the maximum observed in the study area. In our case it would be the random uncertainty inherent to the M_{max} of 8.8 and the value of the lower limit being 8.1 Mw of the uniform probability distribution, with a Δ of 0.7.

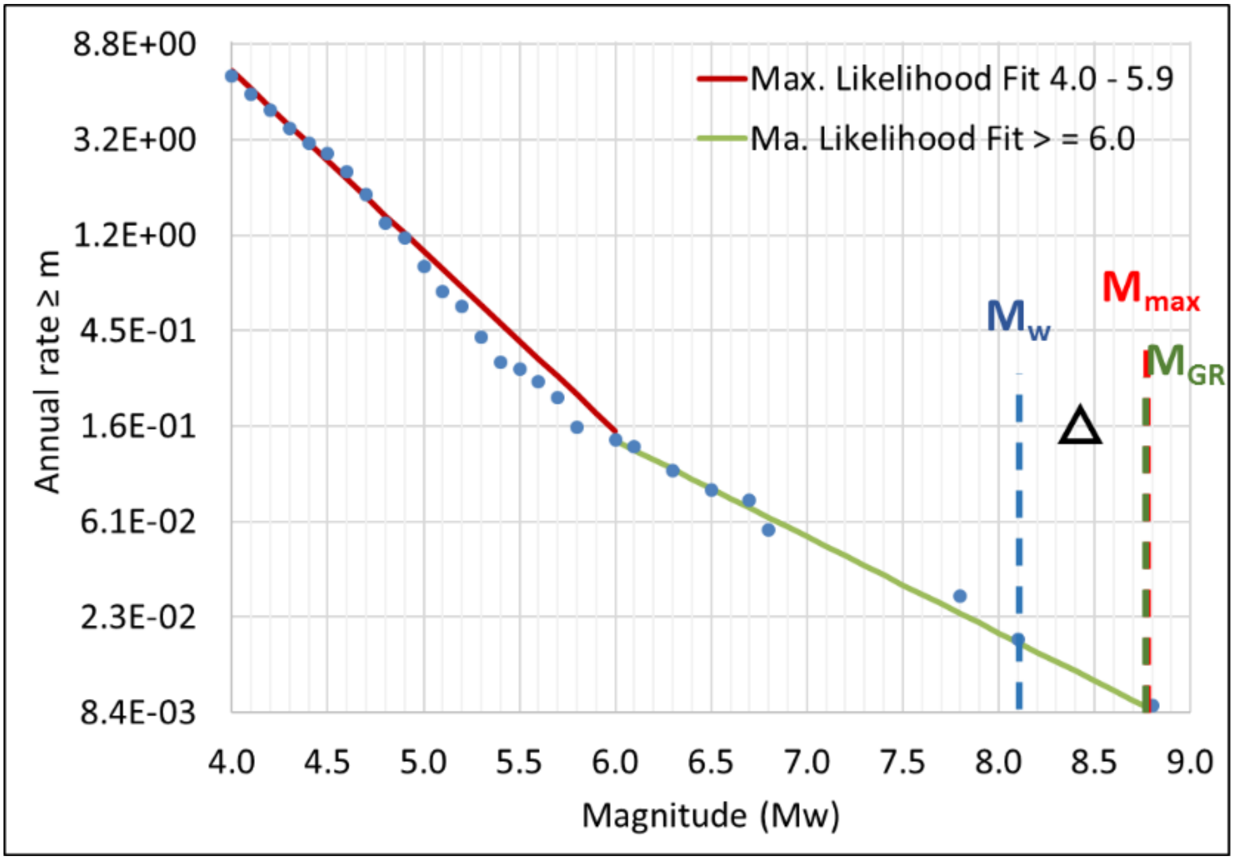

Fig. 10: Estimation of M_{max} and its uncertainty in the IFN zone. Symbols: M_{max}: maximum magnitude estimated for the zone; M_{GR}: magnitude estimated by seismicity trend; M_w: minimum magnitude constituting the lower limit of the uniform probability distribution (Parra et al., 2016).

Furthermore, specific results are obtained for the point of calculation located in Esmeraldas (Latitude 0.9871, Longitude -79.6558) representing hazard curves for 6 parameters representative of the strong movement: PGA, SA (0.1s), SA (0.2s), SA (0.5s), SA (1s) y SA (2s) (Fig. 11).

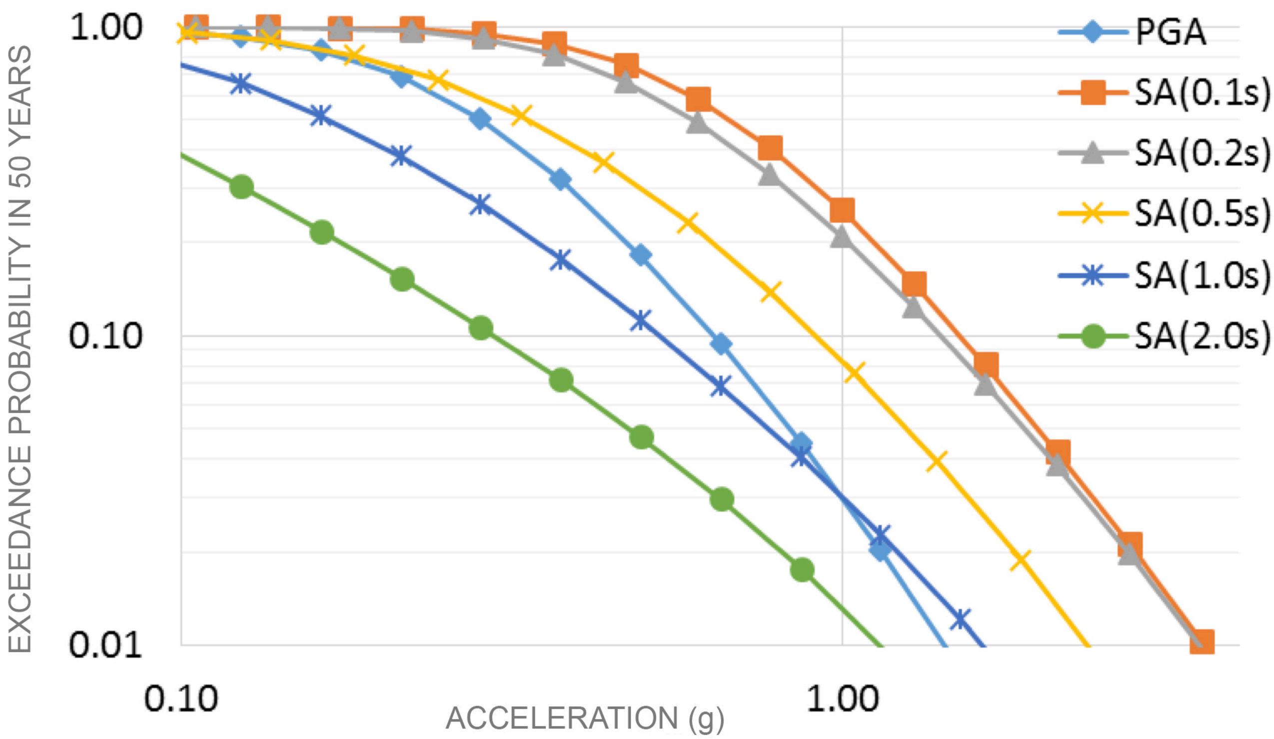

Fig. 11: Seismic hazard results for Esmeraldas (Parra et al., 2016)

From the results extracted for PGA in a return period of 475 years, we obtain results of the disaggregation of the hazards for Esmeraldas. This is a technique that consists of a decomposition of total hazard into partial contributions, and whose purpose is to define the characteristics of the earthquake that contributes most to the exceedance of movement in the site, obtaining pairs (Mw, Range of distance) that contribute the most to its hazard. Hereby, the danger that would be expected in the city of Esmeraldas, would be the consequence of the process of subduction interface, whose greater contribution corresponds to a control earthquake characterized by the pair (M_W 7.5 and a distance range between 30-60km; Fig. 12).

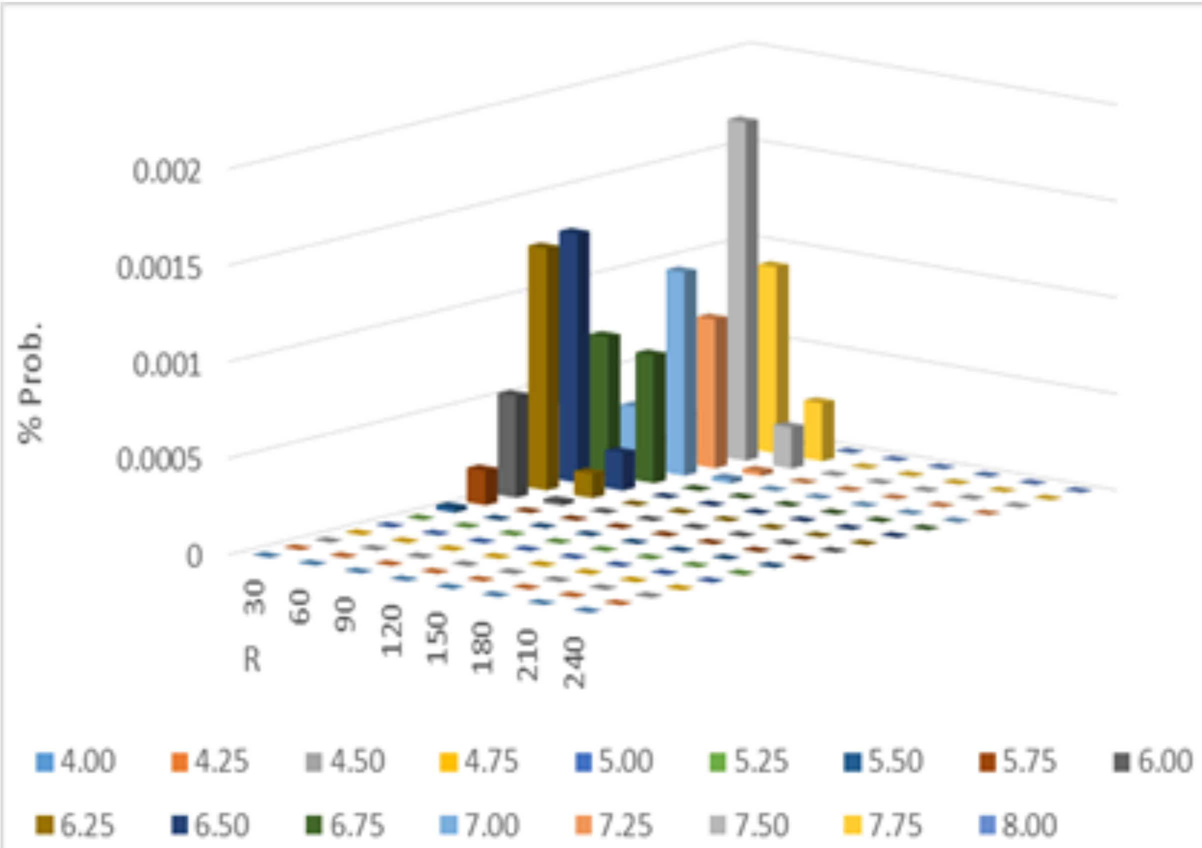

Fig. 12: Results of the disaggregation of the hazard for Esmeraldas (Parra et al., 2016)

For the determination of the seismic hazard scenario, a hybrid approach will be used: probabilistic-deterministic, which will be the input for the estimation of a potential future tsunami. For this purpose, three seismic events have been considered:

- One of magnitude Mw 8.8, concordant with the Mmax obtained by analysis of the trend of seismicity at its maximum value in the IFN zone, as explained previously (Fig. 9).
- One of magnitude Mw 8.1, which constitutes the lower limit of the uniform probability distribution obtained from the estimation of the random uncertainty inherent to the maximum magnitude M_{max} for the IFN zone.
- Another with a magnitude of Mw 7.5 to a distance range of 30-60 km from the calculation point (Latitude 0.9871, Longitude -79.6558), concordant with the Earthquake Control obtained from the seismic hazard breakdown for Esmeraldas

For the location of the three events, we assume that the more distant the focus of the earthquake of the shoreline of our study sector, the bigger the tsunami waves will be, for which a model will be used that will be described below, as this model is already applied with a deterministic character.

5. NUMERICAL CALCULATIONS OF THE TSUNAMI IMPACTS IN MUISNE AND SURROUNDING

Based on the fore-mentioned we determined the potential impact of the three tsunami scenarios would have in the surrounding area of Muisne. Tsunamis, which have an enormous impact on land, may reach like in the case of Japan's Tsunami in 2011 an inundation effect that may reach up to 4 km in distance, covering 90 percent of such inundations in distances of less than 2.5 km (Abe et al., 2012). These data have been determined by using transects to measure debris and other tsunami deposits and once transects were settled, they added topography (elevation) using RTK GPS instruments. They were able to measure the extent of tsunami deposits and inundation distance on the field (Abe et al., 2012).

We, in order hand, used a mathematical model to predict extend of tsunami deposits and inundation distance. We start with potential earthquake/tsunami magnitude in Richter scale that could affect in Muisne coast based on historical data (Earthquake Track, 2016). We have used a magnitude of 5 or higher in our model because of these values represent the most extreme and dangerous from record.
Using the magnitude value as the only probabilistic value and establishing a frequency curve, we obtained a logarithmic equation to determine each return period as follows:

$$M=5+0.65\ln T \qquad (1)$$

Where,
"M" is the Richter scale magnitude and "T" is the return period measured in years. In addition and because of the area is a tourism alternative as well as it has a potential high population rise, we considered three different return periods, being 75, 100 and 220 years as return as the best suited for our model. Based on these considerations and applying Eq. 1, these would correspond to earthquakes with magnitudes of 7.5, 8.0 and 8.5 M. Supported by historical earthquakes analysis, for example Japan's earthquake of 2011 generated a 40.5 m height wave (Mori et al., 2011; Saito et al., 2011; USGS, 2016), and taken in account the data of wave heights and run-up´s presented by Kryukov and Butenko (2013) on studies carried out by Vorobev et al. (2006) of all tsunamis generated by earthquakes since July 21, 365 b.c. up to December 26, 2004, these authors present a list of the heights of tsunami waves generated since the year of 1991 in the Pacific Ocean. These data and those presented up today allowed us to obtain an empirical equation to determine the height of the wave as a function of any earthquake's magnitude.

$$h_0=3{,}75*10^{-6}*e^{1{,}8M} \qquad (2)$$

Where,
h_0 – is the wave height expressed in m.
Thus, for a potential 8.5 M earthquake, wave height would be h_0 = 16.54 m. However, technically and historically it is more likely that a 7.5 M earthquake in this area would occur and for that type of earthquake applying Eq. 2, a wave height would be h_0 = 2.74 m. This would be the wave-height that would be generated in the sea and the dissipation may be negligible when the depth exceeds 10 meters

(Levin and Nosov, 2009). According to Kryukov and Butenko (2013) when the wave meets the continental platform, the wave breaks with a height equal to:

$$h_r = 1{,}5 h_o$$

Therefore, the breaking heights of the waves for magnitudes 7.5, 8.0 and 8.8, respectively, are 4.14, 14.96 and 43 meters (Fig. 13 and 14). Based on the determined considerations of the coverage area of future potential tsunamis, we have evaluated this and other natural collateral hazards in the surrounding area of Muisne. This evaluation may serve to choose responsibly the most adequate resettlement area in case of a political decision towards a relocation of the public living in Muisne.

1. CONCLUSIONS

For the elaboration of flood charts by tsunamis, the use of numerical models is common. Such models are developed on complex mathematical support for the simulation of the generation, propagation and flood phases. Its application, however, necessarily requires high-resolution bathymetric data, not available up today for the Ecuadorian coast from the limit of 30 km (50 km in some cases). Its capability, on the other hand, about a realistic estimate of the flood phase for big tsunamis is still under discussion. Nonetheless, based on historical records and the study of seismic hazard in the central coast of Ecuador, we can conclude that the impact of a potential tsunami on the coast of Muisne will be much higher than estimated. In this respect, the underestimation of the flood area reflected by the Chart-SNGR-CITs-080350-Muisne (SGR, 2012; Fig. 5), as we have demonstrated for the more conservative flood estimate within the three more probable tsunami scenarios, invalidates Bunche's designation as resettlement location.

Apart from the inappropriate relocation suggested by the SGR, for the resettlement project that is currently running, two additional issues has not be taken into account: (1) any seismic-resistant construction solution as it has been projected for Bunche is totally ineffective if the settlement zone is highly unstable, as is the case of the mangrove which extends over the whole affected area, so that a project of conditioning of the ground prior to the construction of the resettlement is required; (2) according to the international guidelines (Bernard 2005; UNISDR, 2015), the resettlement project should contemplate the following design sections: (i) natural and / or artificial mitigation barriers; (ii) safe evacuation infrastructures; (iii) safe resettlement of the productive matrix; (iv) early warning system; (v) effective evacuation plans; and (vi) training plans for the population.

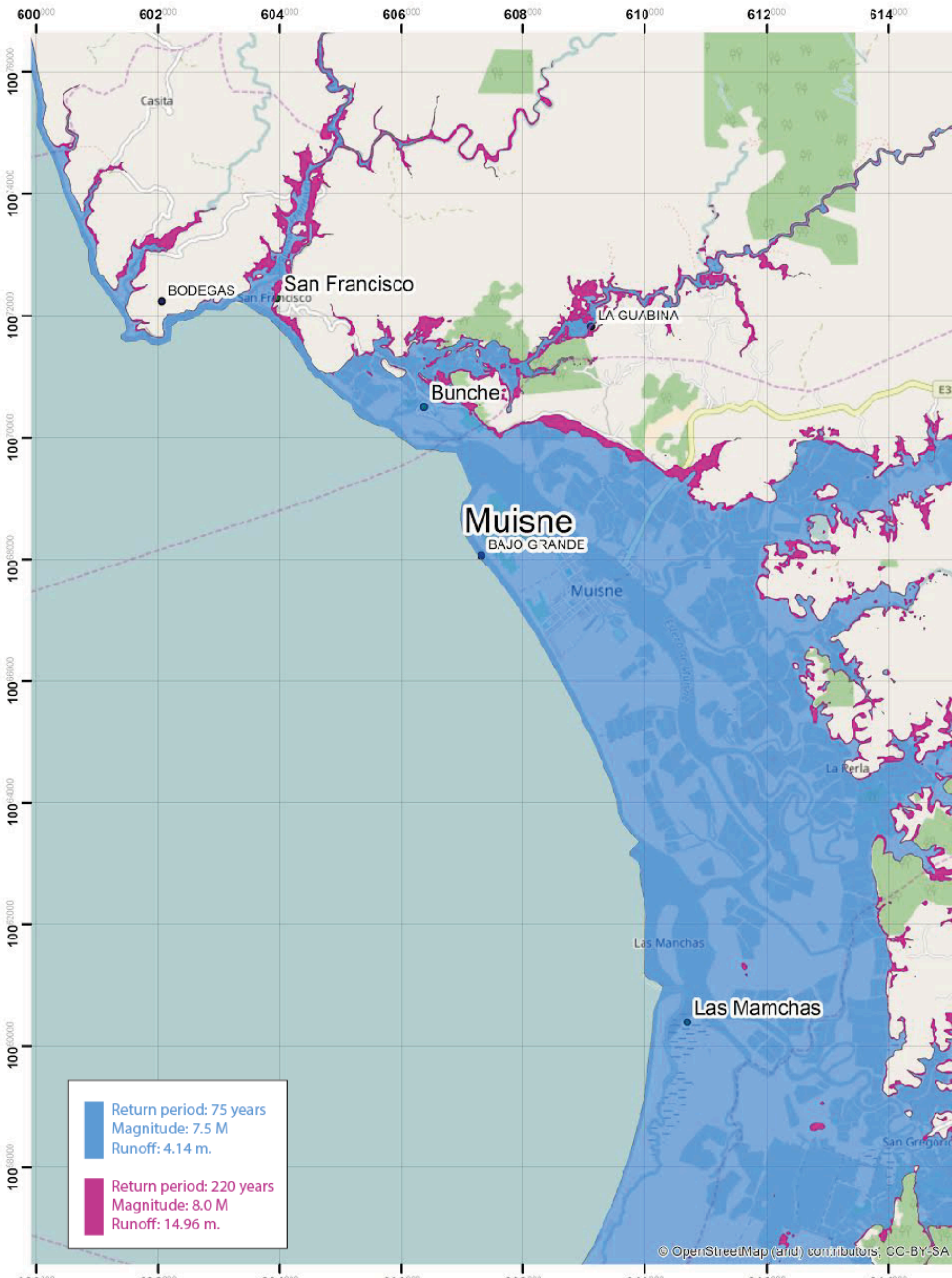

Fig. 13: Tsunami and subsequent flooding hazard map for the potential events of Mw 7.5 and Mw 8.1. For explanations see text.

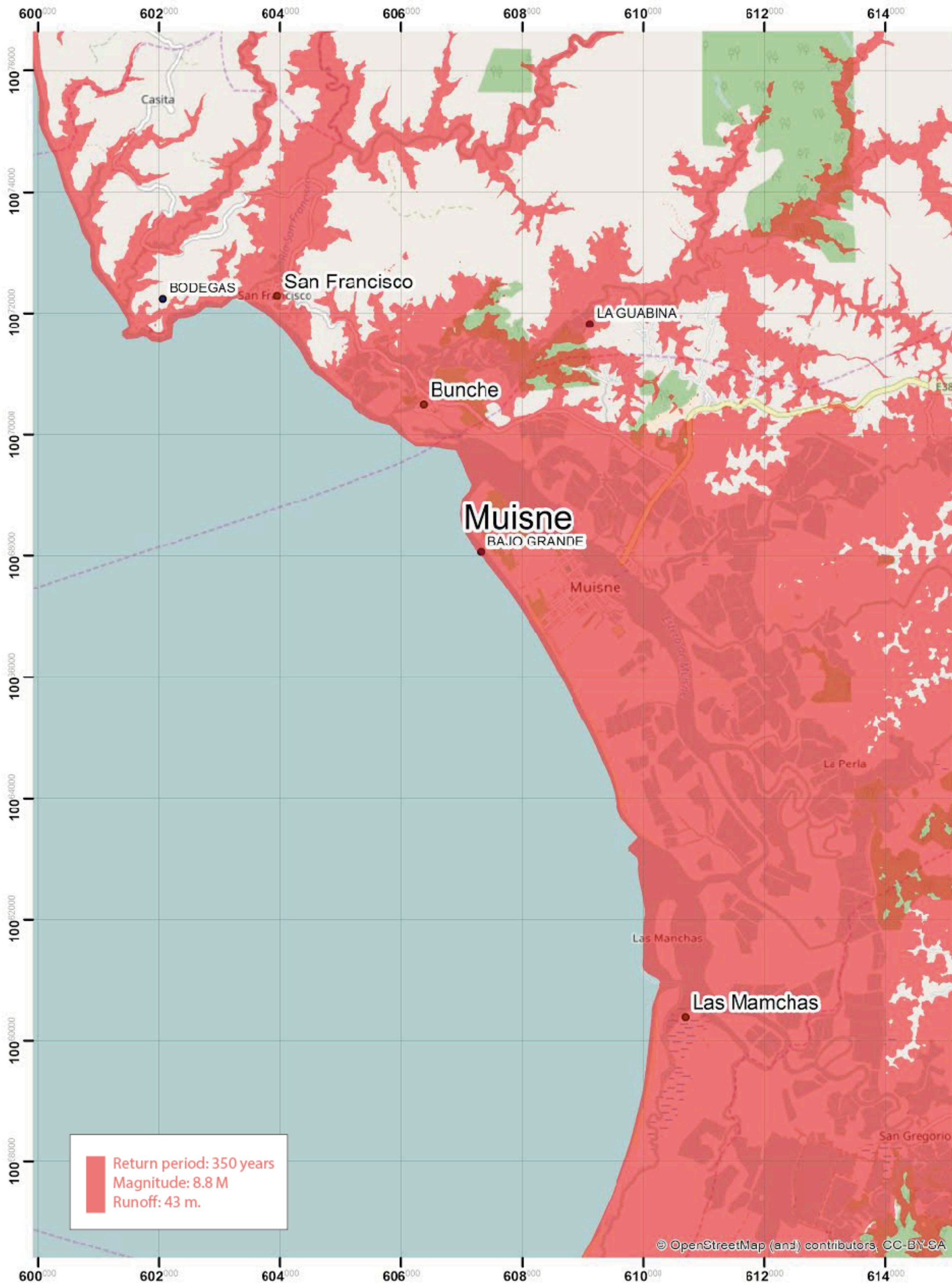

Fig. 14: Tsunami and subsequent flooding hazard map for the event of a potential Mw 8.8. For explanations see text.

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