Global Trends in Advancing Tsunami Science for Improved Hazard and Risk Understanding

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Abstract

This paper provides a timely review of progress and ongoing research needs in tsunami hazard and risk science since the most recent major event, the Tohoku tsunami in 2011. The tsunami community has made significant progress in understanding tsunami hazard from seismic sources. However, this is only part of the inputs needed to effectively manage tsunami risk, which should be understood more holistically, including non-seismic sources, vulnerability in different dimensions and the overall societal effects, in addition to its interaction with other hazards and cascading effects. Moreover, higher standards need to be achieved as far as the management of subjective choices and uncertainty quantification, which largely govern our basis for tsunami risk decision making.

Large tsunamis occur with relatively low frequency, if compared for instance with the ones of other perils such as hurricanes, floods and landslides, but have potentially high impacts including extreme numbers of casualties, and direct and indirect economic losses. In the last two decades this has been demonstrated, for instance, by the Indian Ocean (2004) and the Tohoku (2011) tsunamis. The scale of these disasters far exceeded the previously perceived risk in these areas. The relative rarity of tsunamis implies in fact a deficit of tsunami observations, which forces hazard and risk analysts to make subjective modelling choices. This in turn makes the uncertainties associated with tsunami risk analysis quite large. One likely reason for the underestimation of tsunami risk is the lack of rigorous, robust and standardized hazard and risk assessment methodologies, and the treatment of such large uncertainties.

Since 2004, methodologies such as probabilistic tsunami hazard analysis (PTHA) have emerged, which are increasingly used to address the above-mentioned issues. PTHA has focused thus far on tsunamis triggered by earthquakes. Further work is required to characterize events triggered by landslides, volcanoes, and meteorological loading, particularly in the frame of the current move towards the consideration of multiple hazards in disaster risk management, as shown by the multi-hazard context of the Global Risk Assessment Framework (GRAF). Additionally, the understanding of tsunami risk is not yet at the same level as the understanding of the hazard. To bring tsunamis up to speed in the context of the first priority of the Sendai Framework for Disaster Risk Reduction: "Understanding disaster risk", we must work to develop a sound Probabilistic Tsunami Risk assessment (PTRA) methodological framework. PTRA is intended to become a key component of effective tsunami risk management, applicable from urban to regional scales.

This background paper mostly reviews recent progress in tsunami hazard analysis and risk analysis. It also briefly sets out the future work required to improve tsunami risk understanding, management and coastal resilience. In

particular, we will seek to highlight current major gaps in tsunami risk understanding that need to be addressed, such as tsunami vulnerability (in several of its dimensions), the societal effects of tsunami risk, and tsunami in multi-hazard contexts and as a contributor to cascading risk.

Introduction

Several of the largest earthquakes of the 20th century created devastating tsunamis propagating oceanwide, mostly in the Pacific Ocean, which led to the formation of an international tsunami hazard community (Kong et al., 2015). Many of these events took place in the Pacific Ocean between 1946 and 1964, leading to fatal consequences at both near and far away locations from the source, eventually affecting several countries. Notable examples are the M_W8.6 1946 Aleutian, M_W9.5 1960 Chile, and M_W9.2 1964 Alaska earthquake tsunamis. The transoceanic propagation of these tsunamis partly took coastal communities off guard. Consequently, the international tsunami hazard community was formed as a direct result of society's need to understand, manage and mitigate risk from these types of events. To this end, early efforts were mostly focused towards the development of tsunami early warning systems in the Pacific Ocean, such as establishing the Pacific and the Japan Meteorological Agency Tsunami Warning Systems. Later, efforts towards hazard mapping and analysis were initiated in the 1970s through the introduction of the first numerical tsunami models (Houston and Garcia, 1974). However, prior to the next tsunami disaster, the Indian Ocean tsunami in 2004, tsunami warning systems outside the Pacific Ocean were absent. At that time, tsunami hazard analysis was primarily based on deterministic models, establishing inundation maps through credible worst-case scenarios.

The 2004 Indian Ocean tsunami hit a coastal population that was largely unprepared, resulting in more than 230,000 fatalities. Due to the enormous consequences, the need for more sophisticated and comprehensive methodologies to understand and manage tsunami risk in a wider range of locations became immediate. In the aftermath of this event, tsunami research and risk mitigation activities intensified and spread to many regions which previously had little focus on tsunami risk, particularly South and South East Asia (e.g. Birkmann and Fernando, 2008; Burbidge et al., 2008; Spahn et al., 2010; Strunz et al., 2011; Horspool et al., 2014). With better computational resources and models, tsunami simulations, hazard mapping and forecasting were improved (Kanoglu et al., 2015). To date, an important advance was the development and increased use of probabilistic tsunami hazard analysis (Geist and Parsons, 2006; Grezio et al., 2017).

Disaster loss data provided the first quantitative understanding of the vulnerability of buildings due to tsunamis. Such vulnerability analysis were initiated after the 2004 tsunami (Reese et al., 2007, Koshimura et al., 2009 and Suppasri et al., 2011). After the 2011 Japan tsunami, rich availability of damage data not only limited to buildings (e.g. Suppasri et al., 2013) but also small marine vessels (Suppasri et al., 2015 and Muhari et al., 2015), road bridges (Shoi and Nakamura, 2017) and aquaculture rafts and eelgrass (Suppasri et al., 2018) recently facilitated a wide range of new fragility models. Furthermore, societal awareness building and education received increasing focus (Mathbor, 2007; Løvholt et al., 2014), often in conjunction with new early warning systems with improved technology (e.g. Bernard and Titov, 2015).

However, failure to effectively warn and evacuate populations and the damage caused from tsunamis occurring in this time of expanding information after 2004, including the Mentawai 2010, Maule 2010, and Tohoku 2011 tsunamis, clearly demonstrated that further effort was needed to cope with tsunami-related risks (Synolakis, 2011). Although the evacuation failures in each of the previously mentioned events were different and involved social, religious, conflict and/or over-information reasons, the observed consequences from each of them provided valuable information in the set of activities involving different aspects of DRM and tsunami awareness building that should be further developed and improved at country level. In the Mediterranean Region, two tsunamis struck in 2017 in conjunction with strong earthquakes; the first occurred in Lesbos Island (Greece) and the second in the Gulf of Gökova (between Kos and Bodrum, Greece and Turkey, respectively). While both tsunamis were rather small, the second event created up 1-2 metres high inundation, which flooded coastal zones where part of the population failed to properly self-evacuated by running toward the coast following the ground shaking. These events thus clearly revealed that the population at both locations was largely unprepared. Moreover, the tsunami warnings sent to local authorities were not received in time by the population, despite the existence of the Tsunami Early Warning and Mitigation System in the North-eastern Atlantic, the Mediterranean and connected seas (NEAMTWS), since the "last-mile" of TWS (i.e. from characterizing the event to issuing the evacuation) is often still ineffective at many locations worldwide.

While the number of fatalities in the 2011 Tohoku tsunami was lower than after the Indian Ocean tsunami in 2004, direct economic losses (structural damage costs) were an order of magnitude higher than any past tsunami event. The Tohoku tsunami also showed the cascading nature of tsunamigenic hazard. The conjunction of earthquake loading and subsequent tsunami inundation and destruction is perhaps an obvious aspect. Most notably however, the 2011 Tohoku tsunami led to disastrous consequences due to the damage at the Fukushima Daishi reactor (Synolakis and Kanoglu, 2015). This also resulted in decommissioning of nuclear power plants in

Germany, with the associated economic consequences. Additional indirect effects on the car industry in countries far from Japan such as Thailand has been shown (UN-ISDR, 2013). In summary, the 2011 set of events showed up the society's lack of understanding and ability to deal with more complex systemic risks that have indirect, distant, and unforeseen consequences.

According to Okal (2015), there are indications that over time societies are coping better with tsunami hazards, gaining experience with each tsunami that has occurred since 2004. However, Okal also points out that there are also tendencies that unusual events such as *tsunami earthquakes* (earthquakes that cause unusually strong tsunamis compared to their earthquake magnitude) are less understood compared to tsunamis caused by conventional subduction zone events, and consequently, the way we manage their risk is less mature. The 2010 Mentawai event represents one such tsunami, but at least 4-5 disastrous tsunamis of similar nature have caused a high number of fatalities (i.e. >100) over the last 25 years or so. Because tsunamis are infrequent, rare events such as large landslide tsunamis, and tsunami earthquakes, may strike coastal populations in places where there is no previous record or societal memory of similar events. More generally, the low-frequency character of all types of tsunamis poses a particular challenge for understanding the hazard and managing the risk.

Evidently, our understanding of tsunami related hazards has improved greatly over the last 10 years. However, factors such as increasing coastal populations, large uncertainties due to the low frequency of events, poorly constrained and partly unknown vulnerability, combined with potential for technological and environmental damage, leave our understanding of tsunami risk obscure. In this paper, we review and discuss the state-of-the-art and gaps in understanding and managing tsunami hazards and risk. By reviewing recent studies, we show where development is presently taking place and point towards future development needs. Further, we discuss tsunami hazards in the context of a multi-hazard and multi-risk perspective.

State-of-the-art

Tsunami risk can be represented as a complex relationship between hazard, exposure and vulnerability. These components are reviewed in a separate manner below, although exposure and vulnerability are treated jointly with the risk as they are closely connected. In part, the separation reflects that knowledge on these different components has reached different levels of maturity within tsunami science. As indicated in the introduction section, previous efforts have largely concentrated on understanding tsunami hazard and intensity. To an extent, these efforts are related to the demand for evacuation maps and tsunami early warning systems (TEWS) as an action towards risk management, although in reality, tsunami evacuation maps have mostly been decoupled from rigorous hazard analyses. Finally, we review examples of recent tsunami risk assessments and mitigation studies across the world to be set into a more general context.

Dealing with tsunami risk requires a comprehensive and multidisciplinary approach. It is a topic that includes a wide range of areas, such as geophysics (e.g., seismology, geology and faulting), hydrodynamics and flow modelling (e.g., landslide dynamics, volcanology, coastal engineering, oceanography), vulnerability and risk assessment (e.g., geography, social sciences, economy, structural engineering, mathematical and statistical sciences), in addition to disaster risk management and mitigation. In this paper, emphasis is made on the state-of-knowledge mostly from a physical point of view, i.e. related to how we can address and quantify hazards and measureable losses, whereas the societal aspects are given less attention.

Hazard analysis and representation

Prior to the 2004 Indian Ocean event, tsunami hazard analyses were mainly performed on a worst-case scenario basis. Worst-case scenarios are used to delineate the possible impact of high consequence events with a relatively small or unknown likelihood. However, the design of the worst-case sources is intrinsically subjective and hazard levels could be arbitrarily defined. A usual criterion was, for instance, to use sources with similar potential as historical events to represent the hazard or to base the hazard on paleo-tsunami data where such information was available. However, the 2004 Indian Ocean tsunami clearly highlighted the limitation of this approach: the potential for events larger than the previously ones was not foreseen, because no events of similar magnitude were known to have occurred in this area. Moreover, it was believed that certain subduction zones could not produce great magnitude megathrust earthquakes. The research in the aftermath of the Indian Ocean tsunami have led to a revision of this understanding (e.g. Stein and Okal, 2007; Kagan and Jackson, 2013).

In the last decade or so, Probabilistic Tsunami Hazard Analysis - PTHA - has increasingly become the standard for quantifying this peril. In a nutshell, PTHA provides a framework for assessing the exceedance probability of tsunami intensities over a given time frame (e.g. the annual probability of exceeding a run-up height at a coastal location). Typically, PTHA integrates and weighs different types of information on tsunami source probabilities, uncertainty due to natural variability of source mechanisms and recurrence, uncertainty due to limited knowledge of the source characteristics and tsunami evolution, and how these uncertainties propagate to the target site. Consequently, PTHA opens opportunities for a more structured and transparent approach for quantifying tsunami risk, which is not achievable by applying scenario-based approaches. Additionally, well-designed probabilistic approaches cover all possible hazard levels better than worst-case scenarios, since small and mid-sized events are represented as well as the most extreme source scenarios.

The diffusion of a well-structured approach to probabilistic models for tsunami hazard analysis, quite long after some pioneering papers (Lin and Tung, 1982; Rikitake and Aida, 1988), was eased by the seminal study of Geist and Parsons (2006), and a range of applications followed spanning from local (e.g. Gonzalez et al., 2009; Lorito et al., 2015) to regional (e.g. Horspool et al., 2014) to global scales (e.g. Davies et al., 2018). An outcome of the above-mentioned studies, especially the most recent ones, is the recognition that large uncertainty is involved in tsunami hazard, especially in the end-tail (low probability region) of hazard curves, which is where the most extreme consequences are expected.

PTHA applications in fact span very different temporal and spatial scales. Traditionally, PTHA have covered intermediate to large regions, thus providing quantitative estimates of maximum tsunami elevation in deep coastal waters (e.g. Burbidge et al., 2008; Horspool et al., 2014). However, as tsunami damage is caused by the flow onshore and nearshore where coastal assets and population are located, additional effort is needed to characterise tsunami hazard intensities in those key areas too. Several tsunami intensity measures have been suggested; see for instance the Tsunami Pilot Study Working Group (2006):

- Tsunami flow depth, i.e. the maximum height the water reaches above land
- Wave current speed
- Wave current acceleration
- Wave current inertia (product of wave acceleration and flow depth)
- Wave current momentum flux (product of flow depth and square wave current speed)

A review of the numerical models commonly used for calculating these quantities can be found in Behrens and Dias (2015). While the Tsunami Pilot Study Working Group (2006) suggests that the wave current momentum flux is the best impact metric from a damage perspective, the flow depth is the quantity that is presently the most used tsunami hazard intensity measure. The reason for this is that the majority of building damage observations from the field (e.g. Suppasri et al., 2013) and probability of tsunami mortality risk (e.g. Reese et al., 2007) presents the vulnerability and fragility as functions of the flow depth as the sole damage indicator. The reason for this is that flow depth is the most readily observed intensity parameter (using water or debris marks) at multiple locations once tsunami water has receded to enable access for post-disaster reconnaissance. Hence, employing the flow depth for tsunami hazard metrics can straightforwardly be convolved with vulnerability information in a tsunami risk assessment. On the other hand, details in loading mechanisms involving more complex hazard metrics combining flow depth information, wave currents, and drag factors (see e.g. Foster et al., 2018, Petrone et al., 2017) might be lost when only the flow depth is used. Yet, the effects of such complex interactions are embedded intrinsically in the building fragility uncertainty derived from field studies.

Another key outcome of the work of the Tsunami Pilot Study Working Group (2006) and later by Gonzalez et al. (2009) was the recognition of use of geology to inform PTHA analysis. The example case was tsunami inundation probability for Seaside, Oregon. While no major tsunamis have struck Seaside in historical time, paleo-tsunami evidence shows clear potential for older destructive deposits. Consequently, it was necessary to assess whether tsunami hazard maps at the longest return periods complied with such paleo-tsunami evidence. The importance of paleo-tsunami information was particularly exposed following the impact of the 2011 Tohoku tsunami in Japan. Evidence for previous large tsunamis in the geological record such as the ~800 Jogan tsunami was partly neglected in Japanese legislation. Consequently, Japanese legislation was changed to link hazard to paleo-tsunami evidence and enhance knowledge of historical and geologic information (e.g. Sawai et al., 2011; Goto et al., 2014).

Modern PTHA methods have more recently been adapted to local applications for quantifying probability of tsunami inundation and related tsunami metrics. Because running local inundation models is time consuming, only a limited number of simulations can be performed. Such local PTHA methods then extract the subsets from a broader PTHA analysis, considering the scenarios that most contribute to the hazard to set up local inundation models (e.g. Lorito et al., 2015). As an alternative, statistical emulation on a well-designed set of simulations can make faster computations by producing thousands of runs almost instantaneously (e.g. Salmanidou et al., 2017, Guillas et al., 2018). The emulator would need to be trained based on a set of inundation simulations beforehand.

At present, local PTHA applications are primarily aligned towards analysing tsunami hazards onshore. However, evidence from recent tsunamis indicates that also tsunami currents pose a threat to near shore objects. Local PTHA methods should in principle be easily extendable to consider damage from currents, as the same inundation models can be used to characterise them. We are not aware of any PTHA studies encompassing hazards from nearshore currents. A review of the performance of inundation models for simulating currents is given in Lynett et al. (2017).

PTHA was used to quantify the tsunami hazard globally for the previous Global Assessment Report (GAR15). Because GAR15 was only oriented towards quantifying tsunami risk, official tsunami hazard maps following GAR15 were never issued. Yet, a set of upgraded global tsunami hazard maps, based on GAR15, including epistemic uncertainty (uncertainty due to our lack of knowledge) stemming from the probabilistic earthquake model and from approximated inundation modelling, was developed later (Davies et al., 2018). These global tsunami hazard maps presented Maximum tsunami Inundation Heights (MIH) at the shoreline due to earthquake sources for a large set of coastlines worldwide, using global tectonic information from the GEM faulted Earth model (Berryman et al., 2015) as input to constrain earthquake return periods. A specific challenge in the global tsunami hazard modelling was to estimate the MIH values without access to local detailed inundation modelling. For this purpose, amplification factors (see e.g. Løvholt et al., 2015) were used for MIH estimation. Because the amplification factors are less accurate than local inundation models, the related global hazard maps have larger uncertainty than local PTHA models. The difference in accuracy between local, regional, and global hazard models is typical for PTHA. As demonstrated, regional and global methods are to a degree capable of estimating MIH, to the expense of less accuracy and increased uncertainty.

All the studies cited above are based on earthquake sources, indicating that Seismic PTHA approaches (SPTHA) are much more developed than PTHA studies with other triggers (see e.g. the review of Grezio et al., 2017). In areas dominated by large earthquake sources originating from major plate boundaries, most often subduction zones, the main hazard contribution is clearly due to earthquake sources. However, at specific places in other areas such as Europe, the Caribbean, and eastern Indonesia, tsunamis generated by other sources are much more common. The recent tsunami from Anak Krakatoa in Indonesia is an important example of such an event. A peculiar example is the Hawaiian Islands where the Pacific Tsunami Warning Centre is lately dealing with earthquakes generated by the 2018 Kilauea volcano activity, which in at least one case generated a minor tsunami. In general, such sources could be either earthquake sources from non-subduction zone faults, or non-seismic sources (mainly landslides and volcanoes).

Another important source is ‘tsunami earthquakes’ (Kanamori, 1972), which generally occur in the very shallow part of subduction zones and account for one third of the events that have each caused more than 100 fatalities in the last 50 years (from the NCEI tsunami database, https://www.ngdc.noaa.gov/hazard/tsu_db.shtml). Polet and Kanamori (2016) define tsunami earthquakes as earthquakes that directly cause a regional or trans-oceanic tsunami that is greater in amplitude than it would be typically expected from its seismic moment magnitude. Unfortunately, the tsunami community is presently lacking a standard way to adequately model the generation of tsunami earthquakes. At present, two families of simplified tsunami-earthquake models exist: slumping-like displacement of the accretionary wedge region and activation of splay faults. The reality is probably more complex.

Landslide-generated tsunami models have traditionally employed worst-case scenarios (e.g. Okal et al., 2011; Harbitz et al., 2014), although a few probabilistic and semi-probabilistic studies have been conducted in recent years (e.g. ten Brink et al., 2006; Lane et al., 2016). However, landslide tsunamis inherit larger uncertainties due to a range of factors (Løvholt et al., 2015b), including their magnitude-frequency distribution, which at present is not captured in hazard models. The issue with source heterogeneity and probability in time is even more pronounced for simulating volcano-generated tsunamis.

Finally, destructive meteo-tsunamis (Geist et al., 2014) are relatively rare events, but due to the abundance of data on meteorological forcing conditions driving these events, their hazard analysis is likely to be at least somewhat less challenging. Therefore, the ability to use PTHA effectively is source-dependent, with non-seismic tsunami hazard analysis methods not yet at the level of SPTHA. Clearly, a roadmap is required for developing source-independent hazard analysis.

Risk and impact assessment

Risk and impact assessment requires the integration of *hazard* estimates with *exposure* data (describing, for example, the location and characteristics of structures, infrastructure, and population) and *vulnerability or fragility* functions (relationships describing the expected impact of several levels of hazard intensities on different types of exposure) to establish the likelihood and severity of impacts in terms of casualties, cost of direct damage, or number of damaged structures. Impact assessments estimate the consequences of one or a few scenarios, i.e., using deterministic assessment, which establish the potential impacts of tsunamis at one or more sites. Risk assessments include a frequency component, derived from the hazard frequency, to describe the expected severity of an event within a defined timeframe (e.g., the amount of loss expected to be exceeded once on average in, say, a 50-year period), or with a given annual probability of occurrence.

Since PTHAs are not always available, impact assessments are more common than risk assessments in tsunami science and are most commonly conducted for worst-case scenarios or recreation of key historical events to demonstrate potential impact on today's coastal exposure. These have been conducted for different tsunami triggers, including loss estimation due to a volcano-generated tsunami in the case of Santorini eruption (*Triantafyllou et al., 2018, Example Study 1),* which shows that the same data and model framework can be used to assess impact for seismic as well as volcanic tsunami sources (e.g. Paris et al., 2015). Scenario-based impact assessments have been used to inform evacuation planning (Fraser et al., 2014a, 2014b), assessment of evacuation maps (Dall'Osso and Dominey Howes, 2010), to perform building vulnerability assessments (Dall'Osso et al., 2009).

In an extension of approaches applying a single or few scenarios, Wegscheider et al. (2011) applied the probability of 137 different earthquake scenarios to assess risk reduction options in Bali, by representing the likelihood of inundation from different earthquake location and magnitudes. *Schaefer et al. (Example Study 2)* also conducted impact assessments to show the effect of seismic source characteristics (i.e. uncertainty in epicentral location and slip distribution) on loss estimates for several historical events; varying source characteristics resulted in a large variation in losses (factor of 10) between the average expected and worst-case loss scenarios. Over 3,000 tsunami scenarios, representing inundation from known seismic sources with varied uncertain source characteristics, were used to assess the relative tsunami risk along the coastline of El Salvador, in terms of population and buildings/infrastructure exposed to any tsunami scenarios (*Aguirre Ayerbe et al., Example Study 9)*.

PTRA is less developed than either tsunami impact assessment or PTHA, also due to the complex probabilistic description of the consequences and the computational expense of simulating interaction of tsunami flow with exposure onshore, particularly over large areas and for a large number of inundation estimates. However, PTRA is highly relevant for managing tsunami risk from urban to regional scales (e.g. Dominey Howes et al., 2010; Gonzalez-Riancho et al., 2014; Strunz et al. 2011; Løvholt et al., 2015; Jaimes et al., 2016). Its usefulness is well illustrated by the case of Japan where prior to 2011 tsunami hazard had been communicated based on expected scenarios only, in turn based on the largest historically known events, and risk management was designed accordingly. With the unexpected impacts of the Tohoku tsunami, the Japanese disaster prevention and risk management philosophy changed to integrate less frequent and extreme scenarios including those that had not already been experienced (*Mas et al., Example Study 6)*, for which PTRA is necessary.

Due to the complexity of simulating onshore inundation for the large numbers of events in a fully probabilistic event set, no PTRA studies have been carried out to date with a full range of probabilistic estimates of tsunami impact onshore, and only a few have done so for selected return periods (e.g., Dominey Howes, 2010; Løvholt et al., 2015a). Note however that while scenario-based risk assessment might be motivated by the need for very detailed simulations for engineering requirements, these should ideally happen though as a result of disaggregation from probabilistic estimates (e.g. Bazzurro and Cornell, 1999). Otherwise, tsunami risk assessments have often used more descriptive approaches (e.g. Dominey-Howes and Papathoma, 2007), which presently are not synchronized and integrated with PTHA.

Risk estimates are highly sensitive to the description of tsunami flow onshore and tsunami vulnerability relationships, which describe for instance the damage and/or loss level of buildings expected from a certain water depth. This is a key element in PTRA but any lack of data to inform these relationships amplifies uncertainty in risk estimates. While comprehensive building damage fragility data is available from field studies such as Suppasri et al. (2013), it is expected that additional improvements in such models can be obtained by incorporating building types, the fluid velocity field, as well as through refined statistical modelling (Charvet et al., 2014; 2017). In addition, lack of fragility data from locations covering the different regional building types is limiting the development and application of precise vulnerability models. It is encouraging that a variety of data has become available in recent years. For example, recent findings from the 2011 Japan tsunami reveals that road bridges are seemed to be able to withstand 10 m flow depth with only 10% probability of being washed away (Shoji and Nakamura, 2017). Besides, at flow velocity of 1 m/s and 5 m/s, small fishing boats will be washed away with 60% and 90% probability (Suppasri et al., 2014) and aquaculture rafts and eelgrass will be washed away with 90% probability when the flow velocity is 1.3 m/s and 3 m/s respectively.

Another consideration, particularly for near-source tsunamis, is how to account for the combined damage from both earthquake ground shaking (and other effects, e.g., liquefaction) and damage due to tsunami forces. There is currently progress in improving the uptake of both damage mechanisms; for example; Ordaz et al. *(Example Study 3) and Zamora (Example Study 4)* describe models that combine the damage estimate of both earthquake and tsunami using two vulnerability relationships, considering that the estimated damage occurs simultaneously. Improvements to be made include explicitly estimating the damage due to tsunami impact, on a building already damaged by earthquake ground shaking, particularly in the near field where both the tsunami and earthquake hazards are significant. This is an important component of risk analysis that needs to be improved to move tsunamis into the multi-hazard context and is a step closer with the development of methods to generate joint earthquake-tsunami hazard curves (e.g., De Risi and Goda, 2016).

In terms of global risk assessments, Løvholt et al. (2015a) employed a quantitative PTRA method to provide Probable Maximum Loss (PML) estimates for direct economic loss due to building damage for coastal nations worldwide. This is presently the most updated global model on tsunami risk. In terms of absolute PML, Japan by far exceeded other countries. However, normalizing the PML to the total exposed value of each country, it became clear that several small island states (SIDS) face similar relative tsunami risk in terms of economic loss compared to Japan. South and Southeast Asian countries as well as South American countries facing the Pacific otherwise dominated the tsunami risk hotspot. Perhaps more surprisingly, countries in the Eastern Mediterranean Basin also ranked high. It should be considered that the Global PTRA was one of the first PTRA applications in its kind, regardless of geographical scale. Consequently, there are large uncertainties in the different methods and data applied. For exposure estimation, there are also major shortcomings related to the availability of topographic datasets with sufficient resolution. Therefore, while this first global PTRA provides some clues about trends in global tsunami risk, we expect that with refined methods and better data, future global PTRA will provide largely improved and geographically refined estimates of future global tsunami risk.

Risk mitigation

A range of tsunami risk mitigation measures are practiced around the world. Increasingly common since 2004 is the implementation of tsunami warning systems, which can take many different forms with varying degrees of automation (rapid automatic triggering of the system in Japan to technician-based checking process and trigger of the system), warning dissemination methods (static voice/tone sirens, reliance on emergency services), and evacuation-related education and exercise programs, besides natural warnings of tsunami and what communities can learn from them (Gregg et al., 2006; 2007). Tsunami evacuation planning, including designation of evacuation routes and refuges, is applied in the U.S., Japan, and New Zealand, informed by government policy and technical guidance. Inclusion of tsunami risk in land-use planning and the design and construction of tsunami resistant structures are less widely applied. Construction of tsunami defences (breakwaters and coastal barriers) is most common in Japan, but the high associated economic costs (construction, maintenance and amenity costs) implies that they are not implemented more widely. Finally, coastal sedimentary systems and ecosystems, such as dunes, reefs, mangroves and other coastal forests, have received attention as natural protective barriers.

PTHA and PTRA can have an important role to play in assessing the effectiveness of mitigation strategies in different locations, and some applications of these methods have recently emerged. For example, PTRA can be used to investigate the effectiveness of, and inform investment in tsunami protection strategies, as demonstrated by *Suppasri et al. (Example Study 5)*, who tested the impact of seawalls, a greenbelt, an elevated road and a highway on tsunami inundation from a repeat of the 2011 tsunami. *Wood (Example Study 8)* demonstrates a range of valuable evacuation planning applications into which tsunami inundation estimates, and subsequent impact and risk estimates, are a relevant input. These include identifying the most vulnerable communities to different types of tsunami sources (e.g. near- or far-source), and planning routes given communities' demographics or topography and road network.

The American Society of Civil Engineers (ASCE) has included a chapter on tsunami loads in the recent update of the "Minimum Design Requirements for Buildings and Other Structures" (Chock et al., 2015), which forms the basis of the building code in the U.S. and influences building codes in numerous other countries. These requirements are based on probabilistic maps of tsunami hazard for the five states bordering the Pacific Ocean. They typically use the 2500-year average return period as a reference, roughly corresponding to an exceedance probability of 2% in 50 yr. Note that this implies longer return periods (i.e. smaller probability), if regarded as a probability, than the typical 475-year (10% in 50 years) used for civil seismic building codes. The Pacific Earthquake Engineering Research Center (PEER) has an active program to develop methodologies for Performance Based Tsunami Engineering. The Japanese government has guidelines for the design of tsunami resistant buildings, and the New Zealand government in the process developing similar technical guidance for the planning of tsunami resistant evacuation structures.

Discussion - progress and gaps

Hazard analysis

An issue that is particularly prominent for tsunamis is that they are a low probability hazard, but their consequences are potentially severe. Few large transoceanic tsunamis (for instance, tsunamis caused by earthquakes with magnitudes exceeding M_W9) are listed in our historical records, let alone multiple large tsunamis originating from the same location. Therefore, events such as the 2004 Indian Ocean tsunami were unexpected. The Indian Ocean tsunami led to a reassessment of the potential of major subduction zones to generate large earthquakes, showing that past models were partially flawed. In particular, Stein and Okal (2007) pointed out that great magnitude megathrust earthquakes could no longer be ruled out along any subduction zone. Yet, observations of megathrust earthquakes do not exist for many subduction zones. Still, as a consequence of the insight gained for instance by Stein and Okal (2007), the possibility of megathrust earthquakes to occur must be included in tsunami hazard and risk assessments.

More knowledge related to paleotsunami information can increase our knowledge related to potential large tsunami sources. In the areas with evidence for several paleotsunami deposits, geological information can ideally be used to constrain the low probability events for tsunami hazard maps and PTHA. Yet, as modelling is needed to link the tsunami propagation to the deposits (e.g. Jaffe and Gelfenbaum, 2007), transferring the deposit information to information about the tsunami and its source is far from trivial, and still under significant demand for development. At least at present, if available, paleotsunami information should be embedded into PTHA analysis, but some subjective expert judgement of uncertainty is probably still needed (see below). A possible pitfall with such geological evidence that should be avoided, is to use the geological data as upper limits of worst case events. Through the geological cycle, paleotsunamis will also exhibit variations, and one cannot rule out that stronger events (than those appearing in the geological record) can occur in the future. PTHA with uncertainty quantification is a necessary tool to assess the potential for such events. Note that the lack of completeness of tsunami observations catalogues in general was already clearly pointed out by Geist and Parsons (2006), which motivated the source probability and tsunami modelling approach to tsunami hazard analysis as opposed to the empirical approach based on observations for estimating tsunami probability directly from data.

However, when dealing with source probabilities, representation of large magnitude earthquake with limited or no observations implies also a high degree of uncertainty, and the treatment of this uncertainty in tsunami hazard analysis influences directly how we assess tsunami risk. This uncertainty is even larger for non-seismic sources such as landslides and volcanoes. Hence, PTHA is particularly sensitive to how we treat subjective choices where such data support is limited or absent. For instance, this can be related to where the knowledge of the tectonics or underlying physics is limited, but also where the high computational cost necessitates simplifying assumptions and approximations. Moreover, PTHA is highly sensitive to how different data and methods are weighted (e.g., Selva et al., 2016). On the other hand, the complex PTHA methodology available today requires expert input on the relevance and weighting a range of diverse components. This leads to the paradox that while a better general methodology is in place, no commonly accepted standard exists on how to conduct PTHA. For example, note that the Powell Center "Tsunami Source Standardization for Hazards Mitigation in the United States" is being organized by the USGS to develop tsunami source standardization for hazard mitigation in the U.S. Similar goals are in the scope of the Global Tsunami Model (GTM).

It should be noted that PTHA has adopted procedures from PSHA (Probabilistic Seismic Hazard Analysis). While many PSHA components can be based on empirical relations derived from large amounts of seismic data (e.g., magnitude recurrence relationships and ground-motion attenuation models), tsunami events need to be synthesized through numerical modelling for statistically significant event counts requiring large computational resources. In contrast from PSHA, PTHA applications concentrated mostly on large and well-known tsunami sources (e.g., subduction zones) neglecting the contribution of smaller sources. However, Selva et al. (2016) demonstrated that, at least in closed seas like the Mediterranean or the Caribbean, these smaller sources may significantly contribute to the tsunami hazard. Moreover, PSHA is less suited to describing tsunami hazards from non-seismic sources such as landslides, volcanoes and impulsive waves due to meteorological loading. In the absence of internationally recognized standards, how to address the above issues (decreasing uncertainty in PTHA and improving analysis of all tsunami sources) is still unclear.

When dealing with hazard assessments for critical infrastructures, the earthquake community has long had to deal with similar issues about managing subjective choices (e.g. SSHAC, 1997), particularly in the presence of high regulatory concerns. Alternative modelling descriptions of the reality do exist in fact for several, if not all, PSHA components, and the same holds for PTHA components. The degree of subjectivity when dealing with critical choices needs to be limited, or transparently managed and communicated, and epistemic uncertainty needs to be carefully addressed. Such a discussion, similarly to what already happened in the PSHA community, has started more recently within the PTHA community (see e.g. Grezio et al., 2017). Some research projects have put a significant effort to customize, update, and improve SSHAC standards for the specific purpose of SPTHA (see *Example Study 10*).

Risk assessment, vulnerability, management, and mitigation

The vulnerability of the built environment and population to tsunamis can be quantified as a function of various factors of the overland flow, or inundation (or hazard intensity measures), such as the flow depth, current velocity, and transport of flotsam (including the impact of debris). At present, the vulnerability of buildings due to tsunami loading is the quantity that is best constrained from field data, mostly owing to the collection of field data and ensuing statistical analysis following the 2011 Tohoku tsunami (Suppasri et al., 2013; see also *Example Study 2*). Ideally, the building vulnerability is represented by fragility functions relating the probability of a degree of damage to the flow depth of the tsunami. However, there are still large knowledge gaps relating the more complex tsunami flow processes mentioned above to the degree of damage, as well as large uncertainties in the damage inflicted by the hazard intensity measures in other types of buildings (Charvet et al., 2017). This partly owes to the lack of a sufficient number of field observations that can provide statistically founded empirical datasets. However, new experimental studies of tsunami loading on structures provide preliminary new insight and progress within this discipline (e.g., Foster et al., 2018; Petrone et al., 2017). On the other hand, resolving flow velocities will require more precision from tsunami inundation models. Today, applied models are designed to comply with maximum run-up heights using depth integrated models (see e.g. Pedersen, 2008), and measures such as flux limiters are often applied to ensure stability. Resolving the flow field and current velocities in the overland flow is expected to challenge such models. In the future, it is expected that interaction of experimental studies, numerical models of fluid loading and field observations will lead to a better understanding of tsunami dynamics, and in turn of structural fragility due to tsunami loading.

Tsunami vulnerability looking at risk of human injuries and mortality is less developed than that accounting for buildings. Reese et al. (2007) proposed a model for the probability of mortality based on the flow depth using field data from the 2006 Java tsunami. However, geographical and cultural differences have a significant influence on different societies' and societal groups' vulnerability to tsunami and capability to reduce that vulnerability (Birkmann and Fernando, 2008; Struntz et al., 2011; Løvholt et al., 2014). Engagement of tsunami social science research in informing such models is vital and must be increasingly conducted and incorporated. Tsunami risk mitigation measures such as early warning systems and physical protection measures can reduce casualties, likewise tsunami awareness building, training, and people's ability to evacuate with or without the presence of warning systems are likely to affect risk of tsunami mortality by significantly modifying the exposure to the risk (e.g., Selva 2013). On the other hand, the common practice in tsunami risk mitigation, such as tsunami early warning, do not have a link to hazard and risk analysis. In locations with a history of significant tsunamis, increased awareness of tsunami risk among the population is believed to have had a positive impact reducing on mortality rates in the hazard zone. For example, the huge death tolls seen after the 2004 Indian Ocean tsunami were not seen after the 2011 Tohoku event, despite inundation being equally extreme, and can, in part, be attributed to the preparedness of the coastal population in some parts of the Tohoku coastline. Similarly, the 2010 Chile tsunami caused by a strong M_W8.8 earthquake resulted in fewer casualties than would be expected from such a large event. On the other hand, Chilean authorities later failed to cancel tsunami evacuation orders following the 2015 Illapel tsunami (Aránguiz, 2016). However, the effect of education programmes on people's awareness of tsunami hazard, and their response actions in the event of a tsunami does not always result in positive action in an event, despite raised hazard awareness (e.g., Fraser et al., 2016). There are many diverse factors influencing vulnerability and evacuation responses, tsunami mortality rates, in different locations and scenarios of different severity, the location of population, and the local environment and topography, and demographics of the coastal population (see Example Study 8 and reference therein). The tsunami community requires more diverse sources of data and models to identify such variations in vulnerability between regions and communities and translate that knowledge into effective risk management.

Furthermore, societal implications of tsunamis, are less developed, and findings from such studies are seldom bridged with physical hazard and risk studies. Løvholt et al. (2014) concluded that the incorporation of the existing vulnerability information into disaster risk management is still low, and existing information is not translated systematically into action. To this end, the assessment of (societal, in particular) vulnerability has pointed out gaps in the ongoing tsunami risk reduction. Further work on the development of indicators and criteria to determine the use of vulnerability information in disaster risk management, also allowing assessing the effectiveness of key strategies and tools, like people-centered early warning systems, is needed. This will ensure the application of the most recent findings on disaster risk and assist in choosing the appropriate risk reduction strategies. In addition to this, the human behaviour component towards tsunamigenic risk has proven to be important (Johnston et al., 2016; Blake et al., 2018) and it has been seen that besides making risk data available at community level, training (e.g., drills) exercises that familiarize exposed population with these events with low occurrence frequency can contribute to timely evacuations that result in saved lives.

Many of the sources for uncertainty associated with modelling tsunami hazard and vulnerability have been identified but so far there is no formal framework for their quantification and propagation during the risk assessment processes. Although the various examples of new tsunami risk quantification studies herein demonstrate progress (tsunami risk and loss quantification were rarely done until a few years ago), the diversity of approaches also identifies a gap on how to assess tsunami risk. Much more effort is needed in order to provide streamlined and standardized approaches to PTRA. At present, the tsunami community is on the brink of linking the various steps in a PTRA chain but is far from completing commonly accepted methods. The issue has been discussed within several recent research projects, such as the collaborative European tsunami research project ASTARTE (http://www.astarte-project.eu/, see e.g. Deliverable 8.39). To accomplish this task, a community effort is needed, utilizing the interdisciplinary competencies across a range of different scientific fields. Key aspects comprise standardization, improved understanding and quantification of tsunami vulnerability, including the societal effects. To this end, the global tsunami community effort, named the Global Tsunami Model (GTM, www.globaltsunamimodel.org) has identified standardization as one of its main objectives. We anticipate that when our understanding of tsunami risk and the related methodological aspects of tsunami risk assessment increases with time, GTM will formulate requirements for different components needed for tsunami risk assessment. At present, it is likely that this process will start with SPTHA because of its higher degree of development compared to tsunami hazard assessment for non-seismic sources, and also to tsunami vulnerability and risk assessment methods.

In the U.S. tsunami-specific design guidelines are being implemented for the first time from 2018 onwards in the building codes of the five Pacific coastal states. As in seismic resistant design, these are based on probabilistic analysis of the hazard. Similar developments are being considered in New Zealand and are anticipated in other countries. Moreover, in New Zealand, as well as in Italy (see *Example Study 10*), the tsunami warning evacuation zones are also based on PTHA, with a fixed average recurrence time, and a fixed level of epistemic uncertainty. The latter two choices are intrinsically political and tend to make the risk-reduction planning homogeneous, corresponding to a homogeneous level of residual risk. The implementation of such tsunami design guidelines is new and demonstrates progress within the tsunami risk management field. While examples of mitigation measures informed from probabilistic hazard and risk analysis have emerged as discussed above (*Example Studies 5, 8, and 10*), the majority of mitigation measures and evacuation maps worldwide are not linked to such analysis. Consequently, there might be a lack of scientific information in practical mitigation measures, which is a gap. It is expected that closing this gap can reduce tsunami risk and accordingly reduce damage and casualties in future events (e.g. Spahn et al., 2010). Furthermore, standardization and communication of best practices is timely to ensure appropriate design is employed in hazardous areas. At present, there is no overview of the different design practices, let alone standards related to risk informed design. To develop resilient communities and infrastructure, decision-makers from national to local levels also need to manage risk in a multi-hazard context. Standardization of tsunami hazard and risk metrics, and integration of these into multi-hazard risk analyses would contribute significantly to coastal resilience, building efforts through more robust multi-hazard quantification, cost-benefit analyses and resource allocation within risk management strategies.

Risk identification is only an initial step within a disaster risk management strategy. Understanding that risk is socially constructed, it is also relevant to integrate within tsunami risk assessments other dimensions of vulnerability, such as social, economic and environmental. Holistic risk assessment frameworks such as the ones proposed by Cardona (2001) and Carreño et al. (2007), allow integration of the physical risk results with a set of indicators that account for issues related to social fragility and lack of resilience. This allows at the end of the process to identify the sources that, overall, contribute the most to the total risk. Subsequently, this provides important information to policy-makers, disaster risk management officers and decision-makers that can serve as robust basis for the design of comprehensive risk mitigation. The growing number of tsunami risk studies such as those referred to in this paper and listed in the Appendix (although this by no means is not a comprehensive list of all available studies), shows promise that the tsunami community can accelerate the integration of tsunami risk science into more general risk problems and risk-solving approaches. However, due to the challenges and limited understanding of the various components involved in tsunami risk, accurate probabilistic tsunami risk studies are still difficult to achieve. Also, most tsunami risk assessment studies are presently conducted separately from other hazards, despite examples shown in this paper (see *Example Studies 3 and 4*). For instance, a gap in present practice is that earthquake and tsunami hazard are not produced with consistent earthquake source information. Another gap relates to consistency with respect to vulnerability and formulation of intensity measures for other coastal hazards such as storm surges. Through the establishment of the GTM, we feel confident that many of the critical challenges identified in this paper can be overcome allowing experts within complementary fields to interact in a structured way so that our understanding of tsunami risk is ultimately ameliorated. Through a better understanding of tsunami risk itself, development of standards and guidelines for tsunami risk assessment is likely to ease the integration of future tsunami risk analysis into multi-hazard risk assessments.

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Appendix 1 - Example studies

Example Study 1 - Tsunami loss estimation from earthquake scenarios

I. Triantafyllou, T. Novikova, M. Charalampakis, A. Fokaefs, G. A. Papadopoulos, Noa, Greece, National Observatory Athens, Greece (Pure and Applied Geophysics, in press)

Tsunami risk assessment is an important component of the long-term planning for risk reduction as well as for emergency actions during early warning. We quantitatively approached the concept of tsunami risk by considering it as a convolution of three main components, i.e. tsunami hazard, vulnerability of the assets at risk (e.g. buildings) and the economic value exposed. For testing the model a coastal segment at the **west of Heraklion, capital city of Crete Isl., Greece,** was selected in the frame of the FP7 European tsunami project ASTARTE. Heraklion was hit in the past by strong tectonic and volcanic tsunamis, generated along the Hellenic Arc which is the most active seismotectonic structure in the Mediterranean region. The **Minoan tsunami produced by pyroclastic flows during the LBA (17th century BC) great eruption of Thera (Santorini) volcano was selected as an extreme tsunami scenario for the hazard** (inundation) zone determination through numerical simulation based on Boussinesq equations for fully non-linear waves. It was found that the wave penetrates inland up to ~1.2 km, while the maximum water depth is ~14 m. **The building stock in the hazard zone area was obtained from the 2011 national census data and validated with the use of orthophotomaps, field inspection and Google Maps. Building vulnerability was determined with the use of the empirical GIS tool DAMASCHE developed within the European-FP6 tsunami project SCHEMA. The DAMASCHE tool was developed on the basis of 2004 Indian Ocean tsunami building damage data.** This tool produces damage levels by combining **tsunami water depth in the inundation zone and building construction types**. The damage level was translated to **economic loss on the basis of cost flat rates determined officially by the state for building replacement, i.e. either reparation or reconstruction, after the destructive earthquakes in Greece during 2014**. Testing the same method in a coastal segment of Rhodes Isl., Greece, for a tsunami produced by large earthquake of M~8 has been also proved successful. The method is applicable in other parts of the Mediterranean and beyond provided that appropriate data are available.

Example Study 2 - Tsunami loss estimating casting ancient events into present day situation

Andreas M. Schaefer, James E. Daniell, Friedemann Wenzel, Karlsruhe Institute of Technology

Almost any coast around the great oceans has been affected by tsunamis. But, the number of noteworthy events for specific locations is very limited and those generally occurred centuries ago. If a place that has been directly hit by a major tsunami in the past, it can be assumed that it will be affected by future events as well. Thus, it is necessary to reconstruct these historic events and the quantify their impact and implications under today's exposure conditions. Under this premise, several historic tsunamis have been reconstructed to quantify the socio-economic impact of potential future permutations of these events. Such historic tsunamis include the events of 365 in Crete, 1700 Cascadia, 1707 Nankai, 1746 Peru and 1787 offshore Mexico.

The risk assessment of each historic tsunami scenarios has been compiled considering multi-variate event permutations. Here, the earthquake rupture of the respective event is randomly modelled using stochastic slip distributions using the methodology of Goda et al. (2014). Beyond the rupture itself, earthquake epicenters have been varied in regards of the local tectonic setting to cover potential variations of a future event occurrence. This for example includes a major location uncertainty along the subduction front. The resulting sea floor deformation has been computed using Okada (1985). Tsunami wave propagation and inundation has been simulated using the Tsupy software of Schaefer and Wenzel (2017) with a resolution of up to 90m. For each scenario, several 100 permutations have been simulated from which the maximum inundation depth was used as the primary impact metrics. Exposure was resolved from spatial population density models translated into capital stock values after Daniell (2014). To assess the potential reconstruction costs and death tolls of each event, a harmonized vulnerability model on the basis empirical vulnerability data of e.g. Suppasri et al. (2012), Reese et al. (2011), Gokon et al. (2010) and Latcharote et al. (2017). It is noted, that the available empirical data implies a major bias towards Japanese exposure and vulnerability which introduces potential over- or underestimations with respect to the local conditions.

For the 365 Crete and the 1700 Cascadia tsunami, the epicenter was only mildly altered with a spatial uncertainty of about 100 km. In case of the 365 Crete tsunami with an average magnitude of 8.5, only the island of Crete itself was examined while the 1700 Cascadia tsunami with an average magnitude of 9.0 is limited to the coastal regions of Washington and Oregon in the United States. For these regions an average expected reconstruction cost of about $1.2 bn. for the United States and about half for the case of Crete has been estimated. Similarly, fatality rates of about 150 - 200 individuals can be expected on average. For Mexico 1787, Nankai 1707 and Peru 1746, both the magnitude ranges and the epicenter locations have been varied much stronger. In case of the Mexico scenario, magnitudes in the range of 8.4-8.8 along the coast of the province of Guerrero. Due to the limited amount of exposure along the coast, the average expected loss from inundation is expected to be in the 10s of millions, but with worst case scenarios reaching up to a tenfold. In case of the 1746 Peru tsunami, the metropolitan area of Lima was assessed in detail with earthquake magnitudes between 8.8-9.2 originating along the Peru Trench with a maximum distance from Lima of 400 km. It was found that the average expected tsunami of such a magnitude can cause losses of $1.4 bn. on average and more than 2000 fatalities. Here, worst case events can again reach a tenfold of those values. Similar results were found for the occurrence of tsunamis with earthquake magnitude of 8.4-8.8 along the Nankai trench, but due to the significant coastal exposure, can cause on average more than $10 bn. in direct losses and 1000s of fatalities.

This study shows, how the potential future occurrence of tsunamis as they have been observed in human history can cause major damage. However, e.g. in case of a Cascadia megathrust earthquake or similar events offshore Mexico, due to limited coastal exposure, the expected losses due to tsunami inundation are potentially much smaller compared to the expected shaking damage. On the other hand, tsunamis near major coastal cities e.g. in case of Peru or Japan can be considered a primary threat in case of such an event. In addition, variations in epicenter and slip distribution lead to loss uncertainties by a factor of 10 between the average expected and worst-case scenarios.

Example Study 3 - Joint seismic and tsunami loss estimation in Mexico

Mario Ordaz, Eduardo Reinoso, Mario A. Salgado-Gálvez, Carlos Avelar, Benjamin Huerta, Evaluación de Riesgos Naturales (ERN)

The combination of geological and hydrodynamic coastal conditions makes many communities around the globe vulnerable to earthquakes and tsunamis. This means that significant life and economical losses can juxtapose in time and geographical location from two perils that usually, have been assumed and treated as independent. Catastrophe risk models that consider the likelihood of simultaneous effects at all spatial scales are important to produce more robust outputs, which are needed to increase risk awareness and help communities and civil protection agencies to develop realistic earthquakes and tsunami risk management policies and effective risk reduction actions. Few countries have developed tsunami risks analyses, most focusing only on the effects of water run-up and leaving aside damages and losses inflicted by the ground motion.

To address these issues, a peril-agnostic methodology, that allows the integration of interconnected and simultaneous hazards within a fully probabilistic loss assessment framework, is presented and applied to seismically triggered tsunami events that collectively represent the hazard.

In the proposed framework, risk is the product of convoluting hazard and vulnerability; for earthquake and tsunami the seismogenic area that can generate intensities at the domain under study are identified on the basis of geo-tectonic considerations and divided into seismic sources. The seismicity of each source is derived from historic records, tectonics and paleo-seismic evidence. The source seismicity is represented with a magnitude recurrence relationship that indicates the exceedance rate of a specific seismic magnitude; then for each source, stochastic earthquakes are generated such that in total represent all possible locations and magnitudes. This in summary is the classical probabilistic seismic hazard analysis approach.

For tsunami probabilistic hazard analysis, the process is as follows: to reduce computational burden, a subset of tsunami generating earthquakes is defined according to epicenter location (epicenter at sea and influence distance), minimum magnitude and hypocenter depth. Also, the source fault-dip is assumed from geo-tectonic data. Tsunami events share the stochastic earthquake subset annual occurrence frequency. For each earthquake event, the impulsive excitation for a tsunami propagation model is the seafloor maximum displacement obtained from fault-slip vertical component and rupture area. Fault-slip is estimated from empiric relationships of magnitude, rupture area and seismic moment. A nonlinear shallow water equation finite volume model in GeoClaw program considers the area bathymetry and topography with average depth cells. The chosen intensity variable, flood depth, is relevant to physical damage due to tsunami in agriculture, buildings and transportation infrastructure. Loss of life risk or analyses considering scour and foundation reduction may use flow velocity, inertia or moment flux as a complementary tsunami intensity measure (which can be incorporated also in this proposed approach).

The identification of the exposed assets to earthquake and tsunami hazard involves location, economic value (standard replacement cost per unit area), number of stories and structural type. Vulnerability functions are assigned for each building class and for each peril; in this case the hazard intensity measures chosen for earthquakes and tsunami are spectral accelerations and flood depth, respectively. Losses are assumed to be triggered simultaneously by the same triggering event and therefore, are combined within a fully probabilistic framework on which the losses associated to the individual hazard are conditionally independent random variables that can be later used to estimate the combined loss.. Risk is then expressed in terms of average annual losses (AAL) or pure premium for each exposed element, or in probabilistic terms, the expected annual loss (EAL) and loss exceedance curve (LEC). Within a portfolio of geographically dispersed sites, the losses are partially correlated and may be obtained as the expected value of the sum of the losses and the variance of the loss. Graphically, hazard and risk results for scenarios or for given return periods may be presented in maps or within GISs.

As an illustrative example, this approach is applied to the interconnected and simultaneous probabilistic risk assessment for earthquake and tsunami in the subduction zone of the Pacific Ocean in the Mexican coastline.

Example Study 4 - Joint seismic and tsunami loss estimation in Chile

Zamora, N, Poulos, A., Aranguiz, R., Catalán, P., Espinoza, S., CIGDEN, Chile

In recent years, disaster risk reduction measures and awareness have been increasing with the goal of developing a resilient society. However, there is no clear bridge between tsunami scientist, risk experts and stakeholders when addressing these challenges. Whereas disaster management deals with all possible factors that could affect communities at different levels, from protecting lives to mitigating economical losses, there are not many risk assessments tools available that can inform this process.

In this study, the seismic and tsunami hazard is jointly assess along the coast of northern Chile, and used to estimate their effect on infrastructure. The method is based on a Monte Carlo approach in order to account for the epistemic and stochasticity of earthquake and tsunami occurrences. Importance sampling is used to reduce the number of simulations, and hence increase the overall efficiency of the assessment. Synthetic seismic scenarios drawn from the seismic parameters of the Gutenberg-Richter relation are used to estimate the peak ground accelerations and the tsunami heights along the coastal areas. Selected scenarios are used to estimate inundation in Coquimbo where tsunami fragility curves were built after the 2014 M_W 8.2 earthquake. The fragility curves enabled to estimate the damage of some components of specific structures along the coast.

This work sets the basis to estimate the impact of earthquakes and tsunamis on the building stock, which could then be used to probabilistically assess the risk and resilience of houses and critical infrastructure, such as electric power, transportation, and healthcare. These results could inform risk reduction measures from the local to the national perspective in a bottom-up decision making process to build resilient systems that could cope with failures, mitigate economic losses, and reduce casualties. This is in line with the Chilean Strategic Plan for the Risk Management 2015-2018, that aims to provide the basis for a longer perspective toward risk reduction, and in accordance to the Sendai frame for the improvement of multi-risk preparedness programmes.

Finally, we point out that this type of studies are not common along Chile. Fragility curves are lacking limiting the rigorousness of probabilistic risk assessment. Nonetheless, as the first local study it is desirable to design strategies to systematically assess the exposure of infrastructure that could later be implemented in a national level. The latter will provide guidance regarding retrofit that could improve resilience of the most critical infrastructures for the sustainable activities of the country.

Example Study 5 - Tsunami mitigation measures in Japan

Anawat Suppasri, Kwanchai Pakoksung and Fumihiko Imamura, International Research Institute of Disaster Science (IRIDeS), Tohoku University

Sendai plain is different from Sanriku coast where often hit by large tsunamis with remarkable tsunami amplification property because of its narrow, V-shaped topography, rather than the plain coast. On the other hand, tsunami in Sendai plain is usually rather smaller than the Sanriku coast but its penetration distance is much longer (in order of few kilometers). After the 2011 disaster, both national and local governments came to advise multiple layers of protection, including elevation of roadways and railways and building canals parallel to the shoreline to reduce the tsunami energy and consequent damage. This study assesses the performances of multi-layered (different infrastructures) as structural tsunami countermeasures in Sendai City, based on the lessons from the 2011 Great East Japan Tsunami as an example of a worst-case scenario. Earthquake fault parameters proposed by Tohoku University what were determined based on the surveyed tsunami heights and the run-up heights were used to simulate initial condition of the 2011 tsunami. The TUNAMI-N2 model is used to simulate 24 cases of tsunami defense in Sendai City based on a combination of 5 scenarios of structural measures, namely, a seawall (existing and new seawall), a greenbelt, an elevated road and a highway (Fig. 1). The results of a 2D tsunami numerical analysis show a significant difference in the tsunami inundations in the areas protected by several combinations of structures. The elevated road provides the highest performance of the single schemes, whereas the highest performance of the 2-layer schemes is the combination of an existing seawall and an elevated road. For the 3-layer scenarios, the highest performance is achieved by the grouping of an existing seawall, a new seawall, and an elevated road. The combination of an existing seawall, a new seawall, a greenbelt and an elevated road is the highest performing 4-layer scenario. The Sendai City plan, with a 5-layer scenario, reduces the tsunami inundation area by 20 km2 with existing structural conditions. It is found that the combination of an existing seawall, a greenbelt, an elevated road and a highway (a 4-layer scheme) is the optimum case to protect the city against a tsunami similar to the 2011 Great East Japan Tsunami. The proposed approach can be a guideline for future tsunami protection and the evaluation of countermeasure schemes.

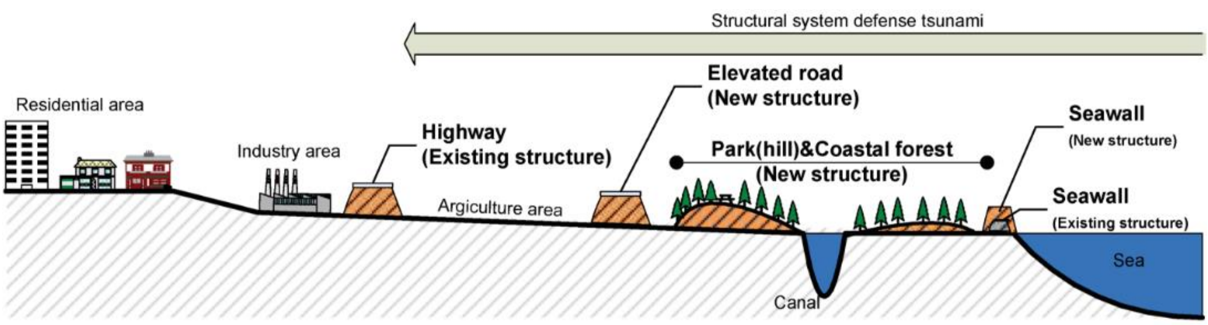

Fig. 1 Multi-layered tsunami countermeasures in Sendai City

Example Study 6 - New aspects related to tsunami evacuation planning triggered by the lessons of the Tohoku tsunami

Erick Mas and Shunichi Koshimura, International Research Institute of Disaster Science (IRIDeS), Tohoku University

Several changes have been made in the Japan disaster prevention philosophy, planning and activities after 3.11 (The Great East Japan Earthquake and Tsunami - GEJET). Some of those are reflected on the changes to the Basic Disaster Management Plan. The Central Disaster Management Council's technical committee recommended some changes based on the lessons of the 3.11 disaster. For instance, a new volume on tsunami disasters was suggested; hazard assessment philosophy shifted from the highest historical or most credible scenarios based on long-term evaluation of seismic activities, to considering all potential large earthquakes and tsunamis (Level 2) and relatively frequent events (Level 1). The assumption of two levels of tsunamis makes it possible to account for extreme events ensuring comprehensive measures for effective evacuations, and at the same time, to consider coastal protection infrastructures with a cost-benefit approach targeted to frequent events. It was suggested that evacuation planning in communities with fast tsunami arrival time should enable evacuation feasibility within five minutes. Thus, early warning and rapid evacuation decision, disaster knowledge, disaster education, hazard assessment and evacuation infrastructure are promoted to achieve such goal.

A particular amendment to the Disaster Countermeasures Basic Act is the establishment of a wide-area response for large scale disasters and the change of concept of evacuation, which was redefined as the various kinds of behaviors conducted to protect oneself instead of a definition related to simply going to an evacuation area. This means, that even remaining at home and ensuring one's safety is now also considered as an "evacuation behavior". Given this, a distinction between "designated emergency evacuation sites" and "designated evacuation shelters" was made for the type of phenomenon. Furthermore, during the reconstruction plan, public housing for disaster victims in low-lying areas were set to be equip with evacuation function from tsunami.

On the other hand, since some designated evacuation shelters were submerged by the tsunami during 3.11, an argument to the reliability of hazard maps made it necessary to reassess the way these are developed and how they are communicated to the public. Similarly, it was found that over relying on coastal protection, such as seawalls, did contribute to delay evacuation decision. These uncertainties on hazard assessment before and during the event are now stressed in disaster education and the limitations of various technologies must be understood by people in tsunami prone areas.

Another concept introduced after the 2011 disaster, which contributes towards effective evacuation and tsunami protection, is the multilayered tsunami countermeasure planning as a robust and resilient system to reduce the tsunami impact. Such concept combines multiple engineering efforts to mitigate the impact of a tsunami and the propagation of inundation inland.

Therefore, the lessons from the 3.11 had contributed to change paradigms in Japan on disaster prevention philosophy and laws, assessment methodologies, protective infrastructure and disaster education; all of these put together promote current efforts to develop disaster resilient communities.

Example Study 7 - Tsunami risk mitigation efforts in the Caribbean

Silvia Chacon, Departamento de Física, Universidad Nacional, Costa Rica

Over the past 10 years the ICG/CARIBE-EWS significantly broadened its detection network, including seismic and sea level stations and focused on increasing tsunami awareness and preparedness within the region. The 2017 hurricane season as well as the January 10 Honduras earthquake tested the system.

Hurricanes Irma and Maria caused unprecedented damages to Caribbean countries, including seismic and sea level stations and communication infrastructure, while also increasing the sensibility of the population to catastrophic events. In the Northeastern Caribbean at one point 82% of the seismic stations were offline (Sardina et al, 2018). These events highlighted the need to be prepared also for the infrequent, but high impact events, like tsunamis.

In January 2018, when many countries were still recovering from the hurricanes and most stations were still down, a M_W7.6 earthquake stroke the Caribbean coast of Honduras triggering the first tsunami threat message for neighboring states. This event was the first requiring distribution of the PTWC enhanced products, which were implemented in 2016.

On a post event questionnaire administered by the Caribbean Tsunami Information Center (CTIC), while all Member States acknowledged receiving the alert from the PTWC in a timely matter, the national and local dissemination was pointed by most as a major weakness. About 23% of Member States reported communications problems on distributing the alert or cancellation information during the event. This event occurred during night time, making particularly difficult the decision making and communication procedures.

The high level of participation in the annual regional tsunami exercise CARIBE WAVE 18 with over 680,000 participants hailing from 46 of the 48 countries and territories, is an indicator that the countries, from authorities to coastal communities, are committed to improving their warning systems.

Example Study 8 - Applications of vulnerability assessments to improve tsunami evacuation planning in the United States

Nathan Wood, Western Geographic Science Center, U.S. Geological Survey

Successful evacuations are critical to saving lives from future tsunamis. Effective evacuation planning requires a comprehensive understanding of the number and type of people who may be in tsunami-hazard zones, their ability to evacuate in a timely manner before wave arrival, and possible interventions that could improve their likelihood of success. Over the past decade, there has been considerable progress in the United States to characterize these aspects of community vulnerability to tsunami threats and to use this information to improve evacuation planning.

To provide insight of the magnitude of possible tsunami evacuations in U.S. coastal communities, the number of people in tsunami-hazard zones has been estimated for several states and territories, including Washington[1], Oregon[2], California[3], Hawaii[4], American Samoa[5] and select coastal communities in Alaska[6]. Community-level variations in population exposure to tsunamis include estimates of residents and employees in tsunami-hazard zones, as well as the number of schools, adult residential care facilities, medical facilities, businesses with a high customer presence, and public venues that cater to tourists. These exposure assessments also include inventories of demographic attributes (e.g., age and socioeconomic status) for residents, because certain attributes may influence an individual's ability to prepare for and respond to a tsunami. Methodologies also have been developed to identify hot-spots of demographic sensitivity to tsunamis using statistical methods that address the multivariate nature of at-risk populations[7]. Information on the number and type of at-risk individuals provides emergency managers with the means to depart from one-size-fits-all evacuation strategies and, instead, to develop strategies tailored to local conditions and needs.

There has been considerable progress in understanding whether or not at-risk individuals would be able to reach safety before wave arrival. This is particularly important in several parts of the U.S. coastline where local tsunamis could inundate coastal communities in a matter of minutes and kill thousands of people. A geospatial modeling approach[8] and tool[9] for estimating pedestrian travel times out of tsunami-hazard zones has been developed and is now being used by several U.S. states and Puerto Rico in their evacuation mapping programs. The U.S. Federal Emergency Management Agency has incorporated this methodology into the tsunami module of their HAZUS loss-estimation software. Regional assessments of evacuation potential have been completed[10] to identify the number of individuals that may not have sufficient time to evacuate before wave arrival. This information helps emergency managers to determine if at-risk individuals need training to move faster and more efficiently, or if vertical-evacuation infrastructure is needed.

Other applications of evacuation modeling to support local planning have included studies that have developed pedestrian travel-speed maps[11], estimated population demand at assembly areas[12], and determined whether earthquake-related landslides may block evacuation corridors[12]. Studies have provided insight on the evacuation implications of post-disaster recovery decisions[13], scenario-based evacuations versus those based on composite zones[14,15], and landslide versus tectonically generated tsunami scenarios[6]. Pedestrian evacuation modeling, population exposure assessments, and statistical analysis have been integrated to identify regional community clusters based on similar vulnerability profiles, which help state and federal emergency managers to determine where to invest in education, evacuation training, or vertical-evacuation infrastructure[16]. For U.S. communities threatened by local tsunamis but lacking nearby high ground, evacuation modeling has been integrated into a multi-criteria decision analysis framework to support vertical-evacuation siting[17]. Future population exposure to local tsunamis has also been projected to inform potential capacity needs of vertical-evacuation structures[18]. Insights gleaned from these various evacuation studies have contributed to the development of a tsunami vertical-evacuation structure in one U.S. coastal community and to discussions of similar structures in other communities.

Evacuation modeling has also been applied to distant tsunami scenarios in U.S. coastal communities. Regional evacuation modeling[19] is helping emergency managers and transportation planners on O‘ahu Island (Hawai’i) to identify areas where pedestrian evacuations for distant tsunamis are realistic and therefore vehicle use could be discouraged. Vehicular evacuation modeling was done for a densely populated island in southern California to determine if and how individuals could successfully evacuate before waves arrived hours after a distant earthquake[20].

Prior to these vulnerability studies, emergency managers could install hazard zone signs, run outreach programs, and hope for the best if a tsunami was generated. They lacked information and tools on how to best invest their limited risk-reduction resources. Results of these various studies now help managers to develop tsunami evacuation strategies that are tailored to local conditions, such as outreach efforts that recognize demographic differences, evacuation training to minimize travel times, and vertical-evacuation refuges in places where natural high ground is too far.

Example Study 9 - Integrated tsunami risk assessments to support disaster risk reduction planning

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IHCantabria-Universidad de Cantabria

Integrated tsunami risk assessments are essential to include all risk components, i.e., hazard, exposure and vulnerability; different dimensions pertaining to the coastal system i.e., human, socioeconomic, infrastructures, environmental; and different spatiotemporal scales. The integrated method, applied to different sites, include the **participation** of tsunami-exposed **communities** by means of workshops, field surveys, specification of local requirements, validation of methodological proposals, and dissemination activities. In addition, public **disaster management decision-makers** are involved and participate during the entire process of the works, from the very beginning of the projects (definition of scope, context and methodology) to the final dissemination activities.

The method relies on a **comprehensive tsunami hazard modelling** (Álvarez-Gómez et al., 2013, Álvarez-Gómez et al., 2014; Aniel-Quiroga et al., 2015) and on an **indicator-based approach** (Aguirre-Ayerbe, 2011; González-Riancho et al., 2014; Aguirre-Ayerbe et al., 2018b) to analyse the exposure, vulnerability and risk of the coastal dimensions and the resilience of the society and communities at risk.

One of the main concerns of these works was to establish a clear **link between integrated tsunami risk results and risk reduction measures** considering site-specific characteristics and thus obtaining useful outcomes for risk management. This was approached by means of a specific methodology developed for the selection of tsunami countermeasures, schematized in fig. 1 right, and through a causal relationships system.

Evacuation planning and modelling, is one of the major tsunami risk reduction measures when focusing at saving lives. A method has been developed and applied in two case studies: El Salvador (González-Riancho et al., 2013) and Colónia de Sant Jordi (Aguirre-Ayerbe et al., 2018a; ASTARTE project deliverable 9.36, p21-28, 2017).

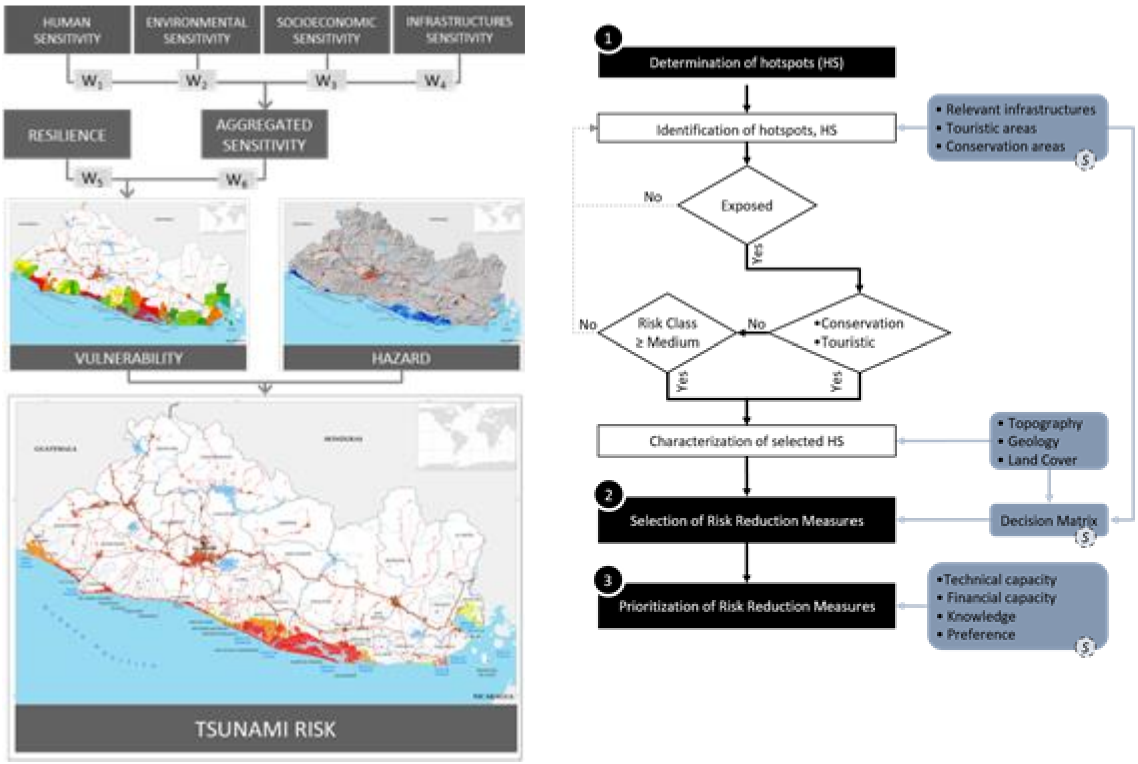

Figure 1. Left: Tsunami risk assessment simplified workflow developed in El Salvador case study. Right: Scheme of the methodology for the selection and prioritization of recommended tsunami risk reduction measures.

Example Study 10 - TSUMAPS-NEAM SPTHA, epistemic uncertainty and the management of subjective choices, SPTHA-based evacuation maps.

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D'Angelo L., Dolce M., Pagliara P., Panunzi E., Scalzo A., Santini M., Di Bucci D., Italian Civil Protection Department (ICPD), Italy

Di Manna P., Vittori E., Lalli F., National Institute for Environmental Protection and Research

The Seismic-PTHA (SPTHA) for the NEAM Region.

Probabilistic Tsunami Hazard Assessment (PTHA) is an indispensable step toward long-term coastal planning and for effectively designing and using Tsunami Warning Systems. The TSUMAPS-NEAM project (http://www.tsumaps-neam.eu/), co-funded by the European Union Civil Protection Mechanism, was devoted at producing the first region-wide long-term homogenous PTHA map from earthquake sources for the coastlines of the North-East Atlantic, the Mediterranean, and connected Seas (NEAM) region. The hazard assessment was built upon state-of-the-art procedures and standards, enriched by some rather innovative/experimental approaches such as: (1) the statistical treatment of potential seismic sources, combining all the available information (seismicity, moment tensors, tectonics), and considering earthquakes occurring on major crustal faults and subduction interfaces; (2) an intensive computational approach to tsunami generation and linear propagation across the sea up to an offshore fixed depth; (3) the use of approximations for shoaling and inundation, with amplification factors based on local bathymetry; and (4) the exploration of several alternatives for the basic input data and their parameters which produces a number of models that are treated through an ensemble uncertainty quantification.

Managing subjectivity & elicitations in the TSUMAPS-NEAM project.

The ensemble uncertainty quantification performed in the latter point involves weighting of alternative models. In turn, this requires the management of potential technical controversies within a multiple-expert environment, which is critical for any hazard/risk assessment project. The procedure for the management of subjective choices and uncertainty quantification of TSUMAPS-NEAM is rooted in a formalized Multiple-Expert Integration protocol, developed in the framework of the European project STREST (2013-2016), dealing with stress test methodology for non nuclear critical infrastructures in Europe (http://www.strest-eu.org). In a nutshell, the purpose of the multiple-expert uncertainty management protocol is: i) to establish roles and responsibilities, in order to guarantee transparency, independency, accountability and achievement of procedural consensus; ii) to achieve homogeneous, documented and traceable decision making; iii) to establish homogeneous principles for the management of alternative and scientifically acceptable models. The workflow of TSUMAPS-NEAM is composed of three main phases: Pre-assessment, Assessment, and Outreach. In these phases, different groups of experts interact to shape the project's development, within a predefined protocol. This protocol is based on a clear definition of roles and interaction among the different experts. This occurs in two ways: through structured information elicitations (literally meaning to draw out information), based on mathematical aggregation of opinions made by a pool of experts); and through a participatory independent review. The roles of the different groups of experts are defined as follows: the Project Manager (PM), the Technical Integrator (TI), the Evaluation Team (ET), the Pool of Experts (PoE), and the Internal Reviewers (IR). All these actors should interact along the project to assure transparency and accountability of the different actors, while PM, TI, and IR should be independent to guarantee fairness of the results. Different roles and responsibilities are assigned to different actors, as represented in Figure 1.

Evacuation Maps for the Italian Tsunami Warning System.

Improvement of preparedness and risk management by appropriate national and local actions is fundamental to reduce to an acceptable level the tsunami risk faced by the coastal communities. The major actions regard on one hand the acquisition of a sound scientific knowledge and its communication to establish a solid people awareness of the hazard and, on the other hand, the development of an early warning system and corresponding clear evacuation procedures. Based on this strategy (according to the Sendai Framework Target E), in the last 5 years the Italian Civil Protection Department (ICPD), the National Institute for Geophysics and Volcanology (INGV) and the Italian National Institute for Environmental Protection and Research (ISPRA), have been working to set-up the national tsunami early warning system. From the TSUMAPS-NEAM SPTHA the tsunami intensity with a return period of 2500 yr, and corresponding the 84% percentile of the epistemic uncertainty have been used as a basis for evacuation maps. These levels were established by ICPD based on the definition of the acceptable risk level, taking into account international experiences for the tsunami risk - for example New Zealand adopted similar levels - as well as national experiences for the management of other types of hazard/risk. A simplified GIS-based methodology has been adopted to define the inundation areas and derive two reference evacuation zones (for the two reference levels of alert) for each Italian municipality. Finally, ICPD had drafted the national guidelines for the local administrations on how to update/plan for the emergency management in case of tsunami event.

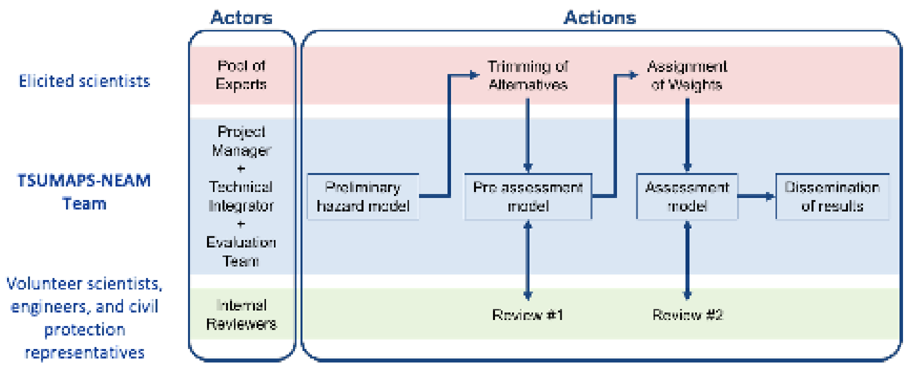

FIGURE 1: Simplified flowchart of the different roles and actions of the different groups of experts involved in TSUMAPS-NEAM.

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