A contribution to the selection of tsunami human vulnerability indicators: conclusions from tsunami impacts in Sri Lanka and Thailand (2004), Samoa (2009), Chile (2010) and Japan (2011)

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Abstract

After several tsunami events with disastrous consequences around the world, coastal countries have realized the need to be prepared to minimize human mortality and damage to coastal infrastructures, livelihoods and resources. The international scientific community is striving to develop and validate methodologies for tsunami hazard and vulnerability and risk assessments. The vulnerability of coastal communities is usually assessed through the definition of sets of indicators based on previous literature and/or post-tsunami reports, as well as on the available data for the study site. The aim of this work is to validate in light of past tsunami events the indicators currently proposed by the scientific community to measure human vulnerability, to improve their definition and selection as well as to analyse their validity for different country development profiles. The events analyzed are the 2011 Great Tohoku tsunami, the 2010 Chilean tsunami, the 2009 Samoan tsunami and the 2004 Indian Ocean tsunami. The results obtained highlight the need for considering both permanent and temporal human exposure, the former requiring some hazard numerical modelling while the latter is related to site-specific livelihoods, cultural traditions and gender roles. The most vulnerable age groups are the elderly adults and the children, the former having much higher mortality rates. Female mortality is not always higher than male and not always related to dependency issues. Higher numbers of disabled people do not always translate into higher numbers of victims. Besides, it is clear that mortality is not only related to the characteristics of the population but also the buildings. A high correlation has been found between the affected buildings and the number of victims, being very high for completely damaged buildings. Distance to the sea, building materials and expected water depths are highly determining factors regarding the type of damage in buildings.

1 Introduction

Natural disasters are triggered by extreme natural phenomena and become disasters because of the heightened vulnerability of the people and places where they occur (Mazurana et al., 2011). Vulnerability refers to the conditions determined by physical, social, economic and environmental factors or processes, which increase the susceptibility of the exposed elements to the impact of hazards (adapted from UN/ISDR, 2004).

With the aim of reducing the negative consequences of a potential tsunami event in a certain area, the scientific community is developing methodologies to better understand the tsunami hazard itself (Goseberg and Schlurmann, 2009; Harbitz et al., 2012; Álvarez-Gómez, 2013; Greiving et al., 2006, etc.) and the vulnerability conditions that may exacerbate the tsunami impacts (UNDP, 2011; UNU-EHS, 2009; Villagrán de León, 2008; González-Riancho, 2014; Sugimoto et al., 2003; Sato et al., 2003; Koshimura et al., 2006; Jonkman et al., 2008; Strunz et al., 2011; Post et al., 2009; Dwyer et al., 2004; Tinti et al., 2011; Dall'Osso et al., 2009; Cruz et al., 2009; Grezio et al., 2012; Koeri et al., 2009; Eckert et al., 2012, etc.).

As vulnerability is multi-dimensional, scale dependent and dynamic (Vogel and O'Brien, 2004), according to the scope of their work the various authors focus either on a specific dimension (i.e. human, ecological, socioeconomic, infrastructural, etc.) or on an integrated approach when dealing with coupled human and natural systems. Most of the vulnerability assessments are carried out by means of the definition of a set of indices and indicators which are normalized, weighted, aggregated and classified through a variety of methods to geographically represent the information (OECD, 2008; Alliance Development Works, 2012; Damm, 2010; Eckert et al., 2012; González-Riancho et al., 2014; etc.). The selected vulnerability indicators differ among authors and are based on previous literature, scientific knowledge and advances, lessons learned from tsunami disasters, the study scope and the availability of information. The ideas and concepts measured by all those indicators are, however, very similar.

The aim of this work is to understand whether the scientific community is proposing the right indicators to measure human vulnerability in light of past tsunami impacts. Accordingly, it focuses on the analysis of past tsunami events to understand and integrate the vulnerability conditions that worsened the tsunami human impacts. The specific objectives of this paper are to (i) compile some of the indicators currently applied to assess human vulnerability to the tsunami hazard and, based on them, propose a general scheme to homogenize tsunami human vulnerability concepts and indicators; (ii) validate the indicators as far as possible through available data from past tsunami events; and (iii) identify new indicators or approaches through the evidences detected in those past tsunami events.

2 Review of existing Tsunami Human Vulnerability indicators

A comprehensive review of the existing works on tsunami vulnerability assessment based on indicators has been carried out to identify those currently used to assess the human vulnerability. Although the various authors propose and apply different indicators according to the scope of their work and the available information, all of the applied exposure and vulnerability indicators follow specific thematic areas and can be grouped within four main categories and ten key issues. The 4 categories are: exposure, warning capacity, evacuation and emergency capacity, and recovery capacity. The 10 key issues are: (i) human exposure, (ii) reception of a warning message, (iii) understanding of a warning message, (iv) mobility and evacuation speed, (v) safety of buildings, (vi) difficulties in evacuation related to built environment, (vii) society's coping capacity, (viii) household economic resources, (ix) recovery external support, and (x) expected impacts affecting recovery. Table 1 summarizes the indicators compiled, which are organised within the proposed vulnerability categories/key issues/indicators scheme, detailing the sources that applied them in previous works.

3 Validation of existing indicators through past tsunami events

To validate the indicators presented in Table 1, the impacts generated in several countries (Japan, Chile, Samoa, Sri Lanka and Thailand) by different past tsunami events are evaluated. The events analyzed are the 2011 Great Tohoku tsunami, the 2010 Chilean tsunami, the 2009 Samoan tsunami and the 2004 Indian Ocean tsunami, their main characteristics being presented in Table 2. The validation is based on the comparison of the tsunami impacts on the population with the previous available census data of each country to understand if the tsunami mortality trends are related to the event itself or to pre-tsunami existing population patterns and vulnerability characteristics. To do that, the pre- and post-tsunami official censuses are analyzed for the various countries (Japan[1], Chile[2], Samoa[3], Sri Lanka[4], and Thailand[5]). Table 3 summarizes the indicators presented in Table 1 that can be validated in this work based on the information provided by these sources.

The following subsections present the validation of the indicators based on the available information. It is important to point out here some assumptions and/or limitations concerning the data and some sources of information. (1) Each indicator will be validated according to the information available, which means that not every indicator can be validated in every country. For example, the indicator age will be contrasted for four countries while some aspects related to the safety of buildings will be analysed only in Sri Lanka. (2) Although the tsunami censuses usually differentiate between fatalities (dead) and missing persons, this study will

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[1] **Japan post-tsunami census**: Damage Situation and Police Countermeasures associated with 2011 Tohoku District - off the Pacific Ocean Earthquake (National Police Agency of Japan, Emergency Disaster Countermeasures Headquarters, March 10, 2014), http://www.npa.go.jp/archive/keibi/biki/index_e.htm; **Japan pre-tsunami census**: Population Census of Japan (Statistics Bureau, Ministry of Internal Affairs and Communications), http://www.ipss.go.jp/p-info/e/psj2012/PSJ2012.asp

[2] **Chile post-tsunami census**: Nómina de fallecidos por el tsunami del 27.02.10 (Fiscalía Nacional de Chile, 31 de enero de 2011), http://www.fiscaliadechile.cl/Fiscalia/sala_prensa/noticias_det.do?id=125. **Chile pre-tsunami census**: Censo 2002 (Instituto Nacional de Estadísticas de Chile), www.ine.cl/cd2002/sintesiscensal.pdf.

[3] **Samoa post-tsunami census**: TSUNAMI, Samoa, 29 September 2009 (Government of Samoa, 2010), http://www.preventionweb.net/files/27077_tsunamipublication2wfblanks.pdf. **Samoa pre-tsunami census**: Samoa Population and Housing Census Report 2006 (Samoa Bureau of Statistics, July 2008), http://www.spc.int/prism/nada/index.php/catalog/10.

[4] **Sri Lanka post-tsunami census**: Census of Persons, Housing Units and Other Buildings affected by Tsunami, 26th December 2004 (Department of Census and Statistics of Sri Lanka), http://www.statistics.gov.lk/tsunami/. **Sri Lanka pre-tsunami census**: Census of Population and Housing 2001 (Department of Census and Statistics of Sri Lanka), http://www.statistics.gov.lk/PopHouSat/Pop_Chra.asp

[5] **Thailand post-tsunami census**: Thailand - Post Rapid Assessment Report: Dec 26th 2004 Tsunami (Asian Disaster Preparedness Center, ADPC, 2007), http://www.adpc.net/v2007/ikm/ONLINE%20DOCUMENTS/downloads/TsunamiRapidAssessmentReport_15Feb.pdf.

consider and analyse the sum of both categories as “total casualties”. (3) The different amount of victims in Japan or Sri Lanka (between 14000 and 19000 people) and Chile or Samoa (less than 200 people) makes necessary to accept some statistical limitations regarding the latter ones. (4) Regarding Sri Lanka, the age of tsunami victims over 30 years old is not available disaggregated in ranges of 10 yr. The 2001 census data do not cover the tamil areas (North and East), which were highly affected by the tsunami, due to the security situation of the country at that time. For this reason, it is not always possible to compare pre-and post-tsunami data about the Nothern Province Districts, namely, Jaffna, Killinochchi, Mullativu, Trincomalee and Baticaloe. (5) Regarding Japan, the unknown-gender-and-age victims have been excluded from the total number of death in Iwate, Miyagi and Fukushima Prefecture by the responsible Japanese authority. Therefore, 15331 from the total 15817 victims are analyzed in this work (97%).

Despite these limitations the quality of the databases applied in this work is good enough and allowed to generate well-founded, conclusive and useful information to validate the various indicators.

3.1. Human exposure

Different approaches are applied in literature to understand the potential human exposure to a tsunami hazard. Several authors base the hazard assessment on numerical modelling of the tsunamigenic sources to identify the potential flooded area and subsequent number of people located there (UNU-EHS, 2009; Eckert et al., 2012; González-Riancho et al., 2014). When no numerical modelling is available the human exposure assessment is usually based on the identification of a site-specific topographic contour line, the area below being assumed to be flooded (Sahal et al., 2014; Suharyanto et al., 2012). For both approaches is common to relate the human exposure to the number of people and population density by administrative unit (e.g. municipality, region, etc.).

The comparison between victims ratio (victims by administrative unit / total victims), population ratio (population by administrative unit / total population) and population density in the affected administrative units in Japan, Chile and Sri Lanka, i.e. prefectures, regions, and districts, respectively, does not show a specific trend or relationship between these variables (Fig.1.). The correlation (Pearson coefficient, r) between the number of victims and the total population by analysis unit is 0.37, -0.06 and -0.39 for Japan, Chile and Sri Lanka, respectively, while the correlation between the victims and population density is 0.76, 0.48 and -0.40 respectively. Only Japan, where the tsunami travelled up to 10km inland in some areas, shows some correlation between these variables, being negative or very low for the other events.

More densely populated areas are supposed to have more people potentially affected if the area is exposed to the hazard; however, based on the post-tsunami census results it is not possible to connect for every event high density units with potential high number of victims. This would be only valid for events flooding huge coastal areas inland. Instead, population or population density in the exposed area might be a valid indicator. This statement is reinforced by some of the results provided along the article, such as those related to the distance to the sea. It can thus be asserted that for the identification of human exposure we need to perform some kind of numerical modelling to calculate the potential exposed area, which will vary from one place to another depending on physical characteristics of the coastal zone and the hazard itself.

3.2. Receiving and understanding a warning message

The population that is not able to understand a warning message (not being able to read, not speaking the language or having intellectual limitations, for example) is more sensitive to the threat, as will not be able to mobilize in a timely manner (UNU-EHS, 2009; Post et al., 2009; González-Riancho et al., 2014; etc.). Based on this idea, the indicators in Table 3 that could be validated in this section are age, education level, literacy/illiteracy, immigration, language skills and ethnicity. However, although all this information is available for Sri Lanka and the age of the victims also for the other tsunami events, the fact of not having issued the warning in most of the cases annul the possibility of validate the indicators. A summary of the tsunami warning in all the analysed tsunami events is presented next.

The 2011 Tohoku earthquake happened at 14:46 JST (local time). The Earthquake EWS sent out warnings 1 minute before the earthquake was felt in Tokyo, reaching the general public about 31 seconds after the earthquake occurred. The Japanese Meteorological Agency (JMA) issued a local tsunami warning 3 minutes after the quake struck. Residents of the hardest-hit areas only had around 15 minutes of warning, though Tokyo would have had at least 40 minutes of warning (MIT Technology review[6]). Just over an hour after the earthquake at 15:55 JST, a tsunami was observed flooding Sendai Airport.

The earthquake that triggered the 2010 Chilean tsunami happened at 3:34 (local time). An initial tsunami warning was issued for Chile by NOAA’s Pacific Tsunami Warning Center 11 minutes after the earthquake and Chile's Servicio Hidrográfico y Oceanográfico de la Armada (SHOA) issued a tsunami warning within the same timeframe. SHOA’s warning however was canceled shortly afterwards. Few coastal residents heard the warning or the cancelation due to widespread power outages, and the official warning had little impact on survival (Dengler et al., 2012). Also because the tsunami arrived within 30 min at many locations, and official evacuations and warnings by local authorities were often not in place prior to the arrival of the tsunami (Fritz et al., 2012).

The 2009 Samoan tsunamigenic earthquake happened at 6:48:11 (local time), the PTWC in Hawaii issuing its first alert 16 minutes after the quake, the Government of Samoa enacting then its own early warning protocols (UNESCO ITST Samoa, 2009). By that time the first tidal wave had crashed into villages and resorts in Samoa and American Samoa. Those who survived had already fled to higher land, rattled by powerful earth tremors lasting several minutes (UWI-CDEMA, 2010).

The earthquake that triggered the 2004 Indian Ocean tsunami happened at 6:28:53 and 8:28:53 in Sri Lanka and Thailand (local time) respectively. The first tsunami wave reached the coast at 08:30 - 08:45 in Sri Lanka and at 9:30 in Thailand (both local times). On December 26, 2004, there was no tsunami warning communication system in the Indian Ocean only for the Pacific where PTWC had the authority to issue the tsunami information. Unlike the Pacific, there was also very little real-time seismic data and no available sea level data from the Indian Ocean from which to confirm a tsunami and its size (Igarashi et al, 2011). It was then not possible to warn the population living at the coastal areas.

From the tsunami events analysed, Japan was the only country having a proper early warning system, which helped to warn the population about the approaching tsunami only 3 minutes after the earthquake happened. This fact, together with the society knowledge, awareness and preparedness against tsunami hazard helped to maximize the evacuees (Nakahara et al., 2013). Most of those who didn’t succeed to evacuate in time were living in the hardest-hit areas and had too less time (around 15 min) to reach safe areas. Besides, around the 66% of the victims were above 60 yr old, which indicates that when an early warning system properly works, special attention in vulnerability assessments must be paid to elderly adults due to the difficulties they face to evacuate immediately and quickly. Regarding this age group, the age indicator is also associated to the capacity of understanding a warning message; however, the death rate cannot be assumed to be directly

[6] MIT Technology review (http://www.technologyreview.com/news/423274/80-seconds-of-warning-for-tokyo/)

linked to this indicator. The difficulties found to validate the age in terms of understanding a warning message makes necessary to recommend its use only as a mobility and evacuation speed indicator.

3.3. Mobility and evacuation speed

The human susceptibility relates to the predisposition of human beings to be injured or killed and encompasses issues related to deficiencies in mobility and differential weaknesses associated with gender, age or disabilities (Villagrán de León, 2008). The population with any mobility handicap is more sensitive to a tsunami event in terms of evacuation, this being the case of people with health problems, disabilities, physical/intellectual limitations, elderly adults and children, for example. These persons with greater difficulties to escape will be probably supported by a family member, this fact being connected to the concepts of gender and dependency, since in many countries the woman is who normally deals with family members who have some type of limitation. This suggests that a slower small group of people composed of at least 2 or 3 persons will be generated around mobility handicapped people, the intrinsic sensitivity of the latter being transferred to his/her immediate surroundings. Therefore, the slow population is likely to endanger other people trying to help them, as all of them will have less time for evacuation. This should be considered when identifying the vulnerable population. According to this idea and to Table 3, age, gender, disability and dependency indicators are analyzed and validated in this section.

Age

Most of the authors highlight the age groups including the elderly adults and children as sensitive to possible tsunami events due to difficulties in both mobility and evacuation speed. The chosen age ranges in the diverse works vary according to the information available for each case study (i.e. census data). Most of the post-tsunami reports (Mazurana et al., 2011, Government of Japan, 2012; etc.) confirm the higher mortality associated to these groups. Rofi et al (2006) found that it was primarily people nine years and younger and 60 years and older who were killed in Indonesia's Aceh Barat and Nagan Raya districts during the tsunami in 2004. UNFPA (2005) stated that the majority of survivors in tsunami-affected villages in Nanggroe Aceh Darussalam province, both male and female, were in the teenage and adult range of 15-45 perhaps because they were physically and mentally strong enough to survive the tsunami and the post-tsunami period. Nakahara et al (2013) stated that whereas studies in Indonesia and Sri Lanka (Indian Ocean Tsunami 2004) reported higher mortality rates among children, elderly adults, and women, the 2011 tsunami in Japan is characterized by a lower mortality rates among children, increasing rates with age, and no sex differences maybe due to the existence of a better tsunami warning system. The higher mortality pattern among elderly adults in Aceh province, Indonesia, highlighted the difficulties to evacuate promptly or withstand the force of the tsunami (Doocy et al. 2007).

In order to better understand the real mortality patterns, Fig. 2 jointly analyzes the percentage of human losses by age groups for the four tsunami events (Fig. 2b), together with the age groups structure in the country before each event based on the immediately preceding census (Fig. 2a). The tsunami victims graph shows higher mortality percentages associated to older people and children. However, the mortality percentages vary substantially among countries. Focusing on the pre-tsunami census graph, three different country profiles can be distinguished according to their development level. Japan is a developed and aged country with the 43,4% of the population over 50 yr old and the 17,9% below 20 yr; Samoa is an undeveloped and young one with the 13,3% over 50 yr and the 49,2% below 20 yr; and both Chile and Sri Lanka, as developing and "medium-aged" countries, have an intermediate profile with around the 19% over 50 yr and around the 35% below 20 yr.

The higher or lesser percentages for the mentioned age groups are associated to these country development profiles and will explain some of the age-related tsunami human impacts. Thus, an aged country like Japan had much higher percentage of victims among people of 50 or more years old (78,1%); a young country like Samoa on the age groups 0-9yr (50,7%) and of 60 years or more (34%); Chile and Sri Lanka having intermediate values for both age groups. Compared to Chile, Sri Lanka had a higher death toll among children, maybe due to the timing of the tsunami. This age group analysis shows that even if higher mortality rates are found in older people and children, special attention should be paid to the profile of the country and the structure of the population before an event.

Figure 3c and Table 4 show the death rate ratios (DRR) by age groups and for the 4 tsunami events. The DRR is calculated dividing the percentage of tsunami victims (Fig. 3b) by the percentage of population for each age group (Fig. 3a). The result provided is the factor by which one must multiply the percentage of each population age group to estimate the expected percentage of victims in that group. The points located above the DRR with value 1 imply that the death related to these age groups is associated to a higher vulnerability to the tsunami event and not to the pre-event structure of the population. The most vulnerable age groups are those below 10yr and above 60yr old. Age groups above 60 yr old are always, for all the tsunami cases, amplifying their percentage in terms of victims, the DRR increasing with age. The DRR is between 0.96 and 1.60 for the age group 50-59, between 1.35 and 2.88 for the age group 60-69 yr old, and between 2.84 and 6.88 for people above 70 yr old. Children (0-9 yr old) DRR is lower than for elderly adults, being between 0.36 and 1.78. For the age groups between 10 and 49 the ratio varies between 0 and 1 for all countries and events, indicating that the percentage of expected victims in each of these age groups is less than the percentage given by the census, regardless of the development profile of the country.

The percentages in child victims for the four events show a range that goes from the 3% in Japan to the 47% in Samoa. Children, as a dependent group, are particularly sensitive to the timing of the tsunami as it determines their potential location and company, i.e. at school with teacher, at home with family, or playing with other children in the street, for example. According to Table 2 the approximate timing of each event was: Friday at 3pm (Japan), Saturday at 3:50am (Chile), Tuesday at 7:15am (Samoa), Sunday at 8:28am (Sri Lanka), and Sunday at 9:28am (Thailand). Only Japan received the tsunami on a weekday during working hours, this may be the reason for the low mortality in children. Nakahara et al. (2013) corroborates this idea suggesting that the timing of the tsunami might have influenced age–sex mortality patterns. While the 2004 Indian Ocean tsunami hit rural communities on Sunday morning, when children and women were at home but men were working away from home (e.g. engaged in offshore fishing), the 2011 Japan tsunami hit communities in the afternoon on a weekday, when children were attending school or kindergarten. The high tsunami preparedness and awareness of the Japanese society indicates that schools might have provided adequate protection and evacuation, justifying the low child mortality rate.

The literature on vulnerability assessments shows that the indicators to measure the sensitive age groups, and specifically children, vary a lot according to the available census information in each case study. Thus, several age groups have been proposed to be considered as sensitive, children below 5 yr (Dwyer et al., 2004; Grezio et al., 2012), below 6 yr (UNU-EHS, 2009), below 10 yr (González-Riancho et al., 2014), etc. However, the analysis of child-related age groups, i.e. 0-4 yr and 5-9 yr old, for the tsunami events studied in this work does not show a clear pattern when comparing pre- and post-tsunami censuses (Fig. 4). The pre-tsunami child population is pretty homogeneous, i.e. the 4 countries having around the 50% of both age groups. The tsunami victims shows a homogeneous distribution in Japan and Sri Lanka, this not being the case for Chile and Samoa. Nonetheless it should be acknowledged that the small size of both Chile and Samoa samples (28 and 68 child victims respectively) could affect the presented result, since Japan and Sri

Lanka (466 and 4368 child victims respectively) show similar percentages to the pre-tsunami census. Focusing on the latter, both age groups could be assumed to be similarly vulnerable in terms of number of victims and could be jointly assessed (i.e. 0-9 yr) in future vulnerability assessment studies.

Gender

As far as the gender indicator is concerned, the South Asian Disaster Knowledge Network (SADKN) defines the word "gender" as a cultural construct consisting of a set of distinguishable characteristics, roles and tasks associated with each biological sex[7]. This term is mainly associated to women in disaster risk management as women tend to be more at a disadvantageous position in society as compared to men. Several post-tsunami reports in different countries pointed out the higher death rate among women. For the Indian Ocean Tsunami (2004), surveys carried out by Oxfam in villages in Aceh Besar and North Aceh districts (Indonesia) confirmed higher mortality rates four times higher among females (Oxfam, 2005). Rofi et al (2006) found that two-thirds of those who died in Indonesia's Aceh Barat and Nagan Raya districts (Aceh province) were female. Oxfam (2005) mentions the massive and disproportionate toll cutting across ethnic lines that the tsunami took on the women of Sri Lanka. Regarding the East Japan Disaster (earthquake and tsunami), Saito (2012) stated that in the areas that were worst affected by the disaster, women made up 54 per cent of deaths. In Tohoku, gender roles remain very traditional and women are seen as responsible for taking care of other family members (Saito, 2012). Villagrán de León (2008) stated that, according to Guha-Sapir et.al. (2006) and Birkmann (2006), in the case of tsunamis women, children, and elder persons are more vulnerable than men. According to these results, most of the authors use gender as an indicator for tsunami vulnerability assessments (see Table 1).

Oxfam (2005) explained the gender results in various countries affected by the 2004 Indian Ocean tsunami stating that (1) while male were working either fishing far out at the sea or out in agricultural fields or markets, women and children stayed at home; (2) the sheer strength needed to stay alive in the torrent was also often decisive in determining who survived, many women and young children being unable to stay on their feet or afloat in the powerful waves and simply tired and drowned; (3) women clinging to one or more children would have tired even more quickly, (4) the skills that helped people survive the tsunami, especially swimming and tree climbing, are taught to male children in Sri Lanka to perform tasks that are done nearly exclusively by men. These 4 explanations respond to different aspects to be considered in future vulnerability assessments: probability and vulnerability. On one hand, the probability of being affected should be analyzed for each study area, and requires understanding the site-specific cultural traditions to correctly measure the temporal exposure (e.g. women and children at the beach on Sunday morning while men are working). On the other hand, it is essential to understand the vulnerability of specific sectors of society such as women and children due to their intrinsic characteristics (i.e. less physical strength) or to the gender-related roles (i.e. family care roles, dependency and specific skills like swimming).

The next analyses aim to confirm if the number of female victims is always higher and if the assumptions that assign higher vulnerability to women due to gender roles are acceptable for every tsunami cases. Figure 5 shows the human losses by sex for several tsunami events, together with the population structure in the country before the event, based on the immediately preceding census. Higher percentages of female victims are found in most of the events but in Chile, even when the population distribution in the country before the tsunami is male-predominant such as in Samoa. The percentage of female victims is higher when less developed is the country, and might be related to dependency and gender roles. However, to understand the reasons conditioning the higher female mortality, it is essential to analyze this information in an age-

[7] http://www.saarc-sadkn.org/theme_social_gender.aspx

disaggregated format. Figure 6 shows the population pyramids for the four countries and both pre- and post-tsunami censuses, illustrating the distribution of age groups by sex.

As far as the age analysis in Fig. 6 is concerned, the pre-tsunami graphs on the left confirm the previous classification of the countries according to development profiles: (i) Japan as an aged country with a contracting pyramid typical from developed countries with negative or no growth, population generally older on average, indicating long life expectancy and low death and birth rates; (ii) Chile/Sri Lanka with stationary pyramids typical from developing countries that tend to ageing and have finished their demographic transition; and (iii) Samoa as a young country, with an expanding population pyramid that is very wide at the base, indicating high birth and death rates, typical from undeveloped countries. The post-tsunami graphs on the risght show a coherent classification pattern: (i) Japan has the highest mortality among the age groups over 60 years; (ii) Chile and Sri Lanka show a quite homogeneous distribution among age groups with high mortality among elderly adults and children; and (iii) Samoa presents very high mortality among children and high among elderly adults. These results are summarized in Fig. 7 which presents population rates and tsunami mortality rates by type of population pyramid.

Back to Fig.6 and focusing now on the gender analysis, the high female mortality rate in Japan is mainly attributed to elder female of 70 years or more, this being an understandable distribution considering the superiority in numbers of women in Japan for that age range, shown in the Japan census 2010 graph. Therefore, the number of female victims in Japan is not a matter of gender, in terms of less resistance to tsunami for example, but a matter of probability due to female longevity in the country. The fact that Japan had a proper early warning maybe is shown by the low rate of young-adult victims, as they were able to evacuate fast. In Samoa, the high female mortality rate for age groups over 19 years has, however, a different explanation. It has probably more to do with gender roles related to the high birth rate and the care of the children. Regarding the higher male mortality in the 0-9 yr age group, it could be associated to a coincidence and the relative small amount of total child victims (68) compared to other events, as there are no relevant physical differences between boys and girls of that age. The higher male mortality in Chile is mainly related to children and elderly adults. The male to female mortality ratio (in number of victims) is 18:10, 17:14, and 19:14 for people below 10yr, above 60yr and above 70yr old respectively. The small amount of victims considered cannot statistically back up a conclusion on male mortality or male vulnerability. In Sri Lanka, the high female mortality rate for all the age groups may be related to 3 aspects, the first two being closely linked: the timing of the tsunami, the gender-related cultural issues and the disability of the population.

Disability

Disability, understood as any physical and/or mental limitation affecting the mobility of people and/or the ability to understand a warning message respectively, is referred by several authors (UNU-EHS, 2009; Dwyer et al., 2004; González-Riancho et al., 2014; Grezio et al., 2012; Post et al., 2009) to be a critical factor hindering the evacuation. This indicator is analyzed and validated here through the tsunami impacts in Sri Lanka in 2004, as no data is available for the other events.

As mentioned before, the 2004 Indian Ocean tsunami hit rural communities on Sunday morning, when children and women were at home or at the beach but men were working away from home (i.e. tsunami timing and gender issues). Besides, the analysis of the Sri Lankan disabled victims by sex and age (Fig. 8) shows a higher percentage of female disabled victims (65%) than male, while the census 2001 shows a male to female disability ratio of 1,3 : 1. Analysing the disabled victims by age groups the percentage of female disability for the *0-18*, *19-49* and *50 or more* age groups is 51%, 68% and 60% respectively. These disability conditions might have contributed to the higher mortality in women.

The 2001 census states that the 2% of the Sri Lankan population was disabled, the 3% of this percentage being affected by mental limitations while the 97% by different physical limitations: 18% in seeing, 19% in hearing/speaking, 24% in hands, 12% in legs, and 24% other physical disability. These percentages imply that disability in Sri Lanka is associated to understanding a warning message in a 22% (added mental hearing/speaking limitations) and to mobility and evacuation speed in an 88%. The 2004 post tsunami census provided a 7% of disabled victims (*another 7% of the victims had "not stated" disability*), from which the 30% corresponds to Mullaitivu, the 21% to Ampara, the 17% to Galle and the 13% to Jaffna, as shown in Fig. 9. The number and distribution of disabled victims is related to the number of victims, not to the disabled population in 2001. In other words, higher numbers of disabled people does not translate into higher numbers of victims.

Dependency

Gender-related roles are highly connected to the concept of dependency in the field of disasters, as women are in many cases and countries in charge of caring after the family members at home, such as children, elderly adults, ill and disabled people (Saito, 2012; Villagrán de León, 2008; Guha-Sapir et.al., 2006; Birkmann, 2006; Oxfam, 2005; etc). The dependency ratio has been calculated for the four countries as the added population below 10 and above 60 yr old (dependent population) multiplied by 100 and divided by the population between 10 and 59 years old (active population). The dependency ratio has been found very high for Japan (65.22) and Samoa (50.77) due to the amount of elderly adults and children respectively, and lower for both Chile (38.22) and Sri Lanka (38.09).

Considering these dependency ratios, to understand the number of victims strictly related to dependency issues Fig. 10 presents the female mortality considering first all age groups (Fig. 10a) and then only the active female population that might be in charge of taking care of family members (Fig. 10b). The pre-tsunami censuses (in light red colour) show in both graphs a homogeneous male/female distribution of around 50% for all the countries and both analyzed age groups. When analyzing the female victims (in dark red colour) for all age groups, higher mortality rates are found for Japan, Samoa and Sri Lanka. However, focusing on the female active population graph (Fig 10b), only Samoa's and Sri Lanka's female mortality have been proved to be related to dependency issues, the higher mortality in Japan (53%) shown in Fig. 10a being then only associated to elderly female adults due to a larger female longevity. Dependency and gender-related roles seem to be associated to a greater extent to undeveloped and developing countries. According to Ting and Woo (2009), traditionally, elderly care has been the responsibility of family members and was provided within the extended family home. Increasingly in modern societies, elderly care is now being provided by state or charitable institutions. The reasons for this change include decreasing family size, the greater life expectancy of elderly people, the geographical dispersion of families, and the tendency for women to be educated and work outside the home. The population in Japan has the highest life expectancy in the world and is aging faster than any other industrialized country. Thus despite the laws designed to help ensure family support, traditional support that once was guaranteed is no longer assured today (Rickles-Jordan, 2007).

The "Survey on Tsunami Evacuation", targeted to people affected by the earthquake and tsunami in the Iwate, Miyagi and Fukushima Japanese prefectures (n=521 women, 336 men) and jointly conducted by The Cabinet Office, Fire and Disaster Management Agency and the Japan Meteorological Agency in July 2011, concluded that almost the 30% of male evacuated alone, women having a stronger connection with their local community than men, as the 82% evacuated in small groups.

3.4. Safety of buildings

The safety of buildings, in terms of their capacity for providing shelter in case of a tsunami event, is analyzed here as a human vulnerability indicator through the relationship between the number of victims and the type of damage in buildings for the different tsunami events, this information being available in the various tsunami censuses analyzed. According to this relationship, several indicators affecting the type of damage (see Table 3) are analyzed and validated in this section: type of building, shoreline distance and building materials.

The existing connection between the total number of victims and the number of buildings affected is shown in Fig. 11 for the tsunami events of Japan 2011, Sri Lanka and Thailand 2004. The Pearson correlation coefficient (r) between number of victims and total number of buildings affected is medium-high for the three events analyzed, i.e. r=0.53 (Japan), r=0.79 (Sri Lanka), r= 0.99 (Thailand). Besides, the analysis of the type of damage in the affected buildings shows a very high correlation between the number of completely damaged buildings (total collapse category for Japan) and the number of victims: 0.88, 0.86, and 0.99 for Japan, Sri Lanka and Thailand, respectively. In the cases of Iwate prefecture in Japan, or Mullaitivu and Hambatota districts in Sri Lanka, a higher proportion of victims than affected buildings is identified, maybe due to the fact that a very high percentage of the affected buildings were completely damaged (64% in Iwate, 91% Mullaitivu, 60% in Hambatota) so the population had almost no place for evacuation or sheltering. Considering the *completely damaged* and *partially damaged (unusable)* houses as those that did not provide shelter during the tsunami event and that forced the population to escape and search for other shelters, there is a high correlation between these group of buildings and mortality results.

The following analyses try to understand the possible correlation patterns between the building's type of damage and other variables such as distance to the sea, topography, type of building, water depth, building materials, or number of storeys. Most of the data used comes from the post-tsunami census of Sri Lanka 2004, together with some conclusions from previous authors regarding relevant aspects about the safety of buildings.

Distance to the sea

Figure 12 shows the analysis of the type of damage in buildings for the tsunami event of Sri Lanka in 2004 based on their distance to the sea. No data is available to analyze other events. There is a high correlation between distance to the sea and type of damage of buildings (Fig. 12b): the 72% of the housing units within or on the 200m boundary line from the shoreline were inoperative both as flooding shelter during the event and as housing unit after the event, since they were completely damaged (62%) or partially damaged-unusable (10%). The percentage of usable housing units after the event increases from the 28% within or on the boundary line (Fig. 12b) to the 57% outside the boundary line (Fig. 12c). The distance to the sea is proved to be a highly determining factor regarding the type of damage in buildings and consequently the number of victims. This factor should be considered in future human vulnerability analyses.

Coastal topography

As far as coastal topography is concerned, Nakahara et al (2013) suggested for Japan that the lower overall mortality rates in Fukushima may be due to the greater expanse of flatlands and the larger number of people living inland, and thus the smaller proportion of people inundated, in contrast to the situation in Iwate and Miyagi, where most of the population live in narrow coastal strips. Suppasri et al. (2013) proved that the damage probabilities for buildings located in the ria coast (2011 Tohoku tsunami, Ishinomaki city results) generally increase more and are higher than those in the plain coast, possibly due to higher velocities associated to the coastal topography. The probability of having buildings (mixed structural material) washed away for different inundation depths and for the plain coast and ria coast respectively is as follows: <0.05 and

0.4 (2m), 0.1 and 0.6 (3m), 0.5 and 0.8 (5m), 1 and 0.9 (9m). Regarding the impacts of the 2004 Indian Ocean Tsunami in Sri Lanka, Wijetunge (2013) stated that shore-connected waterways such as rivers, canals and other water bodies like lakes and lagoons provided a low-resistant path for the tsunami-induced surge to travel upstream into areas further interior in the study zone (southwest coast). Besides, he compared the impacts on 3 adjacent coastal stretches (in Hikkaduwa Divisional Secretariat) to understand how different factors besides the oncoming tsunami amplitude explain the differences in the extent of inundation. Relatively low-lying onshore terrain, negative landward slopes and, probably to a lesser extent, the type and density of land cover are the main factors that have converged unfavourably to cause greater tsunami impact on one stretch (average inundation distance 1.2km inland, 81 victims) compared to neighbouring stretches (average inundation distance 150m and 350m inland, 12 and 19 victims respectively).

The direct exposure of the Sri Lankan Northern and Eastern provinces (Jaffna - Ampara) to the tsunami trajectory, the location of the coastal communities on a flat coastal plain indented every few kilometers by coastal lagoons and local topography-related tsunami effects contributed to the huge death tolls in the area (72% of the victims).

Type of building

Fig.13a compares the number and percentage of buildings affected by the tsunami in Sri Lanka 2004 by type of building (housing and non-housing units) and type of damage together with the number of victims. Housing units (HU) are defined by the Sri Lankan Department of Census and Statistics (DCS) as those buildings which are place of dwelling of human beings, are separated from other places of dwelling and have separate entrance, whether permanent or temporary structures such as huts, shanties, sheds, etc. Non-housing units (NHU) are those buildings or part of a building which are not used as a place of dwelling, such as offices, petrol filling stations, shops, etc. Very similar percentages of type of damage have been obtained for the two types of buildings; nonetheless the total numbers are very different. From the total number of buildings affected (99546 buildings), the 89% are HU (88544 buildings) while the 11% NHU (11002 buildings). The tsunami census carried our by the Sri Lankan government, focuses on HU, therefore, the next analyses in Fig.13 do so as well.

Building materials and water depths

Fig.13b shows the damage in Sri Lankan HU by type of material. The affected buildings in the area from Jaffna to Ampara show higher percentages of temporary materials and have associated higher numbers of victims. Mullaitivu had 5700 HU affected (ninth position among the 13 districts) with 2652 victims representing the 19% of the total victims (second district most affected). This huge human impact can be partly explained by the building materials, as 72% of the damaged HU had temporary roof, the 68% temporary walls and the 65% temporary floors, being the highest percentages among the 13 districts. This result highlights the relevance of materials in the response of buildings to the impacts of the tsunami. This is coherent with the result obtained in Fig. 11, where Mullaitivu appears with the 77% of affected buildings as completely damaged.

Fig. 13c shows the correlation between type of damage in HU and water depths. Almost the 73% of the affected HU by water heights between 2,1 and 3 m in Sri Lanka were critically damaged (completely and partially –unusable- damaged), the percentage increasing up to 92% and 94% for water heights above 3,1 m and 6.1m, respectively Fig.13d shows the correlation between the number of affected HU with the submerged water heights and the number of victims by region. Based on the affected HU, Jaffna, Ampara and Galle received the highest tsunami waves, with between 101 and 350 HU having faced waves of more than 9m.

According to the fragility functions developed for Samoa 2009 by Reese et al. (2011), the severe and collapse damage are clearly a function of building type, with residential timber structures the most fragile, followed by masonry residential and reinforced concrete residential structures. Based on residential masonry building data, it was clearly shown that shielding reduces while entrained debris increases the fragility of structures (i.e. reduce the damage state exceedance probability for a given water depth). These results roughly confirm the observations made in the aftermath of the Java tsunami where exposed buildings have sustained damage levels 2 to 5 times higher than the shielded ones (Reese et al., 2007). The tsunami fragility curves provided by Suppasri et al. (2013) for Japan 2011, shown that reinforced concrete (RC) is the strongest structure against water depth, followed by steel, masonry and wood. All wood buildings and most lightweight buildings were washed away when inundation depth was >10m while only 50% or less for steel and RC, these latter materials playing therefore very important role in preventing a building to be collapsed or washed away. The tsunami fragility curves provided by Tinti et al (2011) for Banda Aceh (Indonesia) 2004 also prove that the damage increases with flow depth for all building materials. Total collapse of buildings occurs to light constructions and reinforced concrete buildings with flow depths of about 4m and more than 15m respectively.

Number of storeys

According to Suppasri et al (2013) for the 2011 Tohoku tsunami, buildings of three or more storeys confirmed to be much stronger than the buildings of one or two storeys under the same inundation depth (results provided for reinforced concrete and wood buildings). The differences in damage probability between one-storey and two-storey buildings were not very large. However, the damage probability is significantly reduced for the case of multi-storey buildings over three floors, the probability of having a RC building washed away being 0.2 for a 10m inundation depth. According to the UNESCO ITST Samoa (2009), buildings are more likely to survive with less damage if they have elevated floor levels, reinforced concrete or core-filled concrete block walls, sound foundations, are shielded, and are well constructed.

To sum up the results on safety of buildings results, the number of victims is directly related to the number and type of damage of affected buildings and more specifically to the completely damaged ones. The type of damage depends on the location of the building and the building fragility. The location of the building implies higher or lesser flow depths conditioned by the distance to the sea and the topography, while the building fragility relate to the resistance of the building to the hazard and depends on the building materials and the number of storeys. Therefore, it is proposed here to include these two building-related aspects (location and fragility) in future human vulnerability assessments.

3.5. Economic resources

Population groups with lower incomes are more sensitive to the threat due to various reasons related to living in precarious areas, having homes built with non-resistant materials, most likely not having their property insured, having less money to recover from the impact (e.g. rebuilding your home, surviving for a while unemployed, economically supporting the family, migrating, etc.).

According to this idea, the indicators from Table 3 that could be validated in this section are income/savings/poverty and employment/type of occupation. However, unlike the other events only the Sri Lanka 2004 post-tsunami census characterizes the victims based on such criteria. These socioeconomic indicators are usually proposed and applied in tsunami vulnerability assessments as an insight on the potential recovery capacity of the exposed communities, based on the household economic resources or the expected impacts affecting recovery (key issues VIII and X, respectively. See Table 1). Nevertheless, when working with the actual fatalities associated to different monthly income or to each type of occupation or livelihood, the information obtained is much different. This difference relates to whether to count 'actual' or 'potential' losses in the assessment. The acquired knowledge based on post-tsunami data focuses on the understanding of (i) the poverty-related human vulnerability, (ii) which the most vulnerable livelihoods are in terms of activity location, cultural traditions, the different gender roles by activity, etc.; (iii) which livelihoods struggle after the event due to lack of workers; and (iv) which livelihoods will suffer economic losses with the subsequent impact to households' and country's economies.

Figure 14 shows the number of victims and affected buildings and the percentage distribution of completely damaged housing units by reported monthly income of the housing unit. Very high percentages of low-income-profile HU are found for this type of damage, especially in the Northern and Eastern provinces (Jaffna-Batticaloe), where the 73-95% of the completely damaged HU had a monthly income of less than 5,000 Rs (27.71€, on 2014/07/10). The percentage of HU within this income category is around 50-60% in the other districts.

Figure 15a shows that the 32% of the victims in Sri Lanka were related to the primary sector of the economy (3% agriculture/farming, 29% fishing), the 12% to the secondary sector (4% coir industry, 1% lime stone industry, and 7% other manufacturing industries), the 27% to the tertiary sector (15% trade, 1% tourism, and 11% other related services), the 9% to the government sector, and the 20% to an unidentified category ("other"). The victims from the Northern and Eastern provinces (Jaffna-Batticaloe) are mainly related to fishing, while from Ampara to Galle (Southern province) the victims are more related to the government sector, tourism, trade and services, coir and other manufacturing industries.

Figure 15b shows the distribution of victims by employment and sex. The 65% of the victims with identified employment (n=1998) were men, this higher percentage being related to the higher female unemployment rate (13.0) than for male (7.9), according to the 2001 Sri Lankan Census. This figure allows for the understanding of cultural gender roles related to livelihoods. Fisheries activity for example is mainly male (90-97% male victims) while the coir industry instead is a female activity (96% female victims). To assess the vulnerability of the socioeconomic activities of a study site it is important to acknowledge the location where each activity takes place in terms of tsunami exposure, its social and economic contribution to the community, region or country, as well as gender-related aspects. This will facilitate the promotion of adequate awareness and training campaigns on the various risk reduction measures.

4 Discussion

Table 4 summarizes the main results obtained from the analyses presented in this work.

5 Conclusions

After several tsunami events with disastrous consequences around the world, coastal countries have realized the need to be prepared, which is conditioned by the existence of early warning systems, the development of tsunami risk assessments to identify critical spots, and various awareness and training campaigns, among others. Consequently, the international scientific community is striving to develop and validate methodologies for tsunami hazard, vulnerability and risk assessments.

A comprehensive review of the existing works on tsunami vulnerability assessment based on indicators has been carried out to identify those currently used to assess the human vulnerability. Most authors agree on some indicators such as age, sex, illiteracy, disability, critical buildings, number of floors, etc., and some of them add some more creativity trying to capture all aspects affecting in some way the preparedness and response to such event, e.g. coordination networks, social awareness, and so on. Although the various authors propose and apply different indicators according to the scope of their work and the available information, all of the applied exposure and vulnerability indicators follow specific thematic areas and have been organized within four main categories and ten key issues.

To validate the compiled indicators, the impacts generated in several countries (Japan, Chile, Samoa, Sri Lanka and Thailand) by the 2011 Great Tohoku tsunami, the 2010 Chilean tsunami, the 2009 Samoan tsunami and the 2004 Indian Ocean tsunami are evaluated. The validation is based on the comparison of the pre- and post-tsunami official censuses to understand if the tsunami mortality trends are related to the event itself or to pre-tsunami existing population patterns and vulnerability characteristics. This section resumes the most relevant results.

Permanent human exposure, understood as the number of communities/people normally located in the hazard area, is proved to be not only related to population density of the administrative unit (which is the most commonly applied indicator) but of the exposed area. Tsunami hazard modelling is essential to identify the communities at risk. Temporal human exposure is related to site-specific livelihoods, cultural traditions and gender roles, has daily/weekly/monthly variability, and requires studying the temporal patterns of the community before proposing vulnerability indicators. This is the case for example of the tsunami impacts in Sri Lanka on Sunday morning, where women and children were at the beach while men were fishing.

Focusing on the population-based indicators, age has proved to be important in a vulnerability assessment. Death rate ratios (DRR) by age groups are provided in this work to understand whether the death related to each age group is associated to a higher vulnerability to the tsunami event or to the pre-event structure of the population. The DRR are conditioned by the country's development profile (population pyramids). The results confirm that the most vulnerable age groups are the elderly adults and the children; however the former have much higher mortality rates than the children, being especially high for age groups above 60 yr old and increasing with age. Mortality of other age groups is just related to the population structure before an event. Child age groups (0-4 and 5-9 yr) are equally vulnerable in high death toll events. Regarding sex/gender issues, it has been found that female mortality is not always higher than male. Consequently further considerations are needed regarding the development profile of the country and associated population pyramid, potential women longevity, gender roles, dependency, cultural traditions, etc. Besides, female mortality is not always related to dependency issues (only Samoa and Sri Lanka in this work). Dependency and gender-related roles seem to be associated to a greater extent to undeveloped and developing countries. Regarding disability, higher numbers of disabled people did not translate into higher numbers of victims in the affected districts of Sri Lanka.

Besides, based on the overall results obtained it is clear that mortality is not only related to the characteristics of the population but also the buildings. In this sense, a high correlation has been found between the affected buildings and the number of victims, being very high for completely damaged buildings. The factors determining the type of damage in buildings have been analyzed and can be grouped in two categories: building location and building fragility. Regarding the building location, the distance to the sea has proved to be a highly determining factor being consequently correlated to the number of victims. Regarding the building fragility, building materials and expected water depths have confirmed to be high correlated to the type of damage, which agrees and reinforces previous works on the topic in different countries (Tinti et al., 2011; Supasri et al., 2013). The calculation of tsunami water depths requires the numerical modeling of the hazard.

As highlighted in this section, tsunami hazard modelling is essential to identify the exposed area and communities, as well as the expected wave depths, both indicators conditioning the expected number of victims.

The results and conclusions presented in this paper validate in light of past tsunami events some of the indicators currently proposed by the scientific community to measure human vulnerability and help defining site-specific indicators in future tsunami vulnerability assessments.

Finally, we would like to highlight the excellent work done by the government of Sri Lanka to characterize the impacts suffered as a result of the Indian Ocean tsunami of 2004 and the great usefulness that means to science the fact of making it available and easily accessible to the public.

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Table 1. Existing indicators review and new framework for tsunami human vulnerability. (*) Sources: [1] UNU-EHS (2009); [1b] UNU-EHS (2009) *desired indicators finally not applied;* [2] Dwyer et al. (2004); [3] González-Riancho et al. (2014); [4] Grezio et al. (2012); [5] Scawthorn et al. (2006a,b): HAZUS-MH model; [6] Eckert et al. (2012); [7] Post et al (2009); [8] Koeri (2009) ; [9] Wijetunge (2013); [10] Ruangrassamee et al. (2006).

Categ.	Key Issues	Review of currently applied tsunami human vulnerability indicators	Sources*
Expo-sure	I. Human exposure	Number of people exposed	[1, 3, 4, 8]
		Population density	[1b, 9]
		Housing density	[9]
Warning capacity	II. Reception of a warning message	Isolated communities	[3]
		Early warning system (EWS)	[3]
		Access to specific means of communication	[7]
	III. Understanding of a warning message	Age	[1, 3, 7]
		Education level	[1, 1b, 7]
		Illiteracy	[1, 3]
		Immigration	[1, 1b]
		Language skills	[2, 7]
		Ethnicity	[5]
		Social and institutional awareness	[3, 7]
Evacuation and emergency capacity	IV. Mobility and evacuation speed	Age	[1, 1b, 2, 3, 4, 7]
		Gender	[2, 5, 7]
		Disability	[1b, 2, 3, 4, 7]
		Health	[7]
		Dependency	[7]
	V. Safety of Buildings	Type of building	[2, 6, 8]
		Building materials	[3, 4, 5]
		Building conditions	[4]
		Number of floors	[3, 4, 6]
		Isolate buildings	[4]
		Elevation	[6]
		Shoreline distance	[6]
	VI. Difficulties in evacuation related to built environment	Distance to safe places: evacuation, isolated communities, access to main roads	[3, 7]
		Critical buildings: schools, hospitals, hotels, malls, etc.	[1b, 3, 4]
		Number of people in critical buildings	[3]
		Critical infrastructure: road network	[3, 7]
		Critical infrastructure: hazardous/dangerous infrastructures	[3]
		Vertical evacuation: number of floors	[1, 1b, 3, 7]
	VII. Society's coping capacity	Emergency and health infrastructures	[1b, 3]
		Health capacity: number of hospital beds, density of medics	[1b]
		Social and institutional awareness	[3, 7]
		EWS, hazard maps, evacuation routes/drills	[3]
		Local civil protection commissions, contingency plans, coordination networks, emergency human resources	[3]
Recovery capacity	VIII. Household economic resources	Income, savings, poverty	[1b, 2, 3, 7, 9]
		Economic dependency ratio: male dependency	[1, 1b]
		Ownership, tenure: land, housing, car	[2, 7]
		Employment, type of occupation	[1b, 2, 7]
		Insurance: health, house	[2, 7]
	IX. Recovery External Support	Basic services availability: water/electricity supply, emergency/health infrastructures	[1b, 3]
		Access to social networks of mutual help: neighbourhood, family, formal and informal institutions	[1b, 2, 7]
		Temporary shelters, public funds, catastrophe insurance, medical/public health human resources, development human resources	[3]
	X. Expected impacts affecting recovery	Human: injuries, degree of damage experienced	[2, 7]
		Socioeconomic: loss of jobs/livelihoods, loss of contribution to GDP/foreign trade, affected local income source, job diversity	[1b, 3, 7]
		Environmental: loss of sensitive ecosystems and ecosystem services	[3]

	Infrastructures: residence/building damage, cascading impacts related to dangerous / hazardous infrastructures	[2, 3, 5]
	Cultural: cultural heritage	[1b]

Table 2. Description of the past tsunami events used to validate the human vulnerability indicators. Data from USGS Earthquake Hazards Program (http://earthquake.usgs.gov); UWI-CDEMA, 2010; UNESCO ITST Samoa, 2009; countries' official reports on tsunami victims (EQ= earthquake, TS= tsunami, EWS= early warning system, N/A= not available; JST= Japan System Time; CLT= Chile Standard Time; WST= West Samoa Time; IST= India System Time; ICT= Indochina Time).

	2011 Great Tōhoku Tsunami	2010 Chilean Tsunami	2009 Samoan Tsunami	2004 Indian Ocean Tsunami
Date	11/03/2011 (Friday)	27/02/2010 (Sat.)	29/09/2009 (Tuesday)	26/12/2004 (Sunday)
EQ magnitude	9.0 Mw	8.8 Mw	8.1 Mw	9.1Mw
EQ epicentre	38.32N 142.37E *(70 km E of Oshika Peninsula, Tōhoku)*	35.91°S, 72.73°W (*12.5 km from Chilean coast)*	15.51°S 172.03°W (190 km S of Apia, Samoa)	3.32N 95.85E (250 km SSE of Banda Aceh, Sumatra, Indonesia)
EQ hypocentre	30 km	35 km	18 km	30 km
EQ time	05:46:24 UTC	06:34:14 UTC	17:48:10 UTC	00:58:53 UTC
Mainly affected countries	Japan, Pacific Rim	Chile	Samoa, American Samoa, Tonga, French Polynesia, Cook Islands, Fiji, New Zealand	Indonesia, Sri Lanka, India, Thailand, Maldives, Somalia, Malaysia, Myanmar, Tanzania, Seychelles, Bangladesh, Kenya
Country analyzed	Japan	Chile	Samoa	Sri Lanka (SL), Thailand (TH)
Mainly affected regions in the country	Tohoku Region (T): Iwate, Miyagi and Fukushima Prefectures	Valparaíso, O'Higgins, Maule, Biobío	Lalomanu, Saleapaga, Satitoa, Maleala, Poutasi	SL: Jaffna, Mullaitivu, Trincomalee, Batticaloe, Ampara, Hambatota, Matara, Galle; TH: Phang Nga, Krabi, Phuket, Ranong, Trang
EQ local time	14:46:24 JST	03:34:14 CLT	06:48:10 WST	06:28:53 IST (SL); 08:28:53 ICT (TH)
TS arrival time	After 14-18 min.	After 30 min.	After less than 16 min.	After 2h (SL), after 1h (TH)
EWS (local warning issued)	Yes	No	Yes (not enough time)	No
TS maximum wave height	Up to 40.5 m (Miyako, Iwate)	3.02m (Pichilemu, O'Higgins)	8 m (Vaigalu and Vaovau beach, South)	SL: 3-10m; TH: N/A
TS Max distance travelled inland	Up to 10 km (Sendai area, Miyagi).	200 metros (Coi Coi)	N/A	SL: N/A; TH: N/A
Fatalities	15884 (T: 15817)	156	140	SL: 13391; TH: 5395
Missing	2633 (T: 2629)	25	4	SL: 799; TH: N/A
Total casualties	**18517 (T: 18446)**	**181**	**144**	**SL: 14190; TH: 5395**

Table 3. Indicators validated in this paper based on available information. Shaded cells: indicators not validated, albeit the information is available, since the countries didn't issue a tsunami warning before the first wave reached the coastline.

Tsunami human vulnerability key issues	Indicators	Japan 2011	Chile 2010	Samoa 2009	Sri Lanka 2004	Thailand 2004
I. Human exposure	Number of people exposed	X	X		X	
	Population density	X	X		X	
II. Reception of a warning message	Early Warning System	YES	NO	YES	NO	NO
III. Understanding of a warning message	Age	X	X	X	X	
	Education level				X	
	Illiteracy				X	
	Immigration				X	
	Language skills				X	
	Ethnicity				X	
IV. Mobility and evacuation speed	Age	X	X	X	X	
	Gender	X	X	X	X	
	Disability				X	
	Dependency	X	X	X	X	
V. Safety of Buildings	Type of building				X	
	Materials				X	
	Shoreline distance				X	
VIII. Economic resources	Income, savings, poverty				X	
	Employment, type of occupation				X	
X. Expected Impacts affecting recovery	Socioeconomic: loss of jobs /livelihoods/GDP				X	
	Infrastructures (residence /building) damage	X			X	X

Table 4. Tsunami death rate ratios (Japan 2011, Chile 2010, Samoa 2009 and Sri Lanka 2004). The age of tsunami victims over 30 years old in Sri Lanka is not available (N/A) disaggregated in ranges of 10 yr, the mean value for this age range being calculated considering only the other 3 tsunami events.

	Tsunami death rate ratios				
Age groups	2011 Japan	2010 Chile	2009 Samoa	2004 Sri Lanka	Mean
0-9	0,36	0,95	1,77	1,78	1,21
10-19	0,29	0,43	0,15	0,83	0,43
20-29	0,31	0,66	0,24	0,65	0,46
30-39	0,39	0,58	0,54	N/A	0,51
40-49	0,56	0,53	0,49	N/A	0,53
50-59	0,96	1,60	0,98	N/A	1,18
60-69	1,35	2,88	1,77	N/A	2,00
70 or more	2,84	3,37	6,88	N/A	4,36

Table 4. Summary of the conclusions obtained on tsunami vulnerability indicators (DRR=death rate ratios, HU=housing units, NHU=non-housing units).

	Conclusions on vulnerability indicators	Validated in
	HUMAN EXPOSURE	
	Exposure. Human exposure is not only related to population density. Important to consider indicators related to buildings as well as temporal exposure patterns related to livelihoods, cultural traditions and gender roles. Hazard modelling essential to identify exposed area and wave depths.	Japan, Chile, Sri Lanka
	MOBILITY AND EVACUATION SPEED	
	Age. Vulnerable age groups: elderly adults and children, the former having higher mortality rates. Mortality of other age groups just related to the population structure before an event. Child age groups (0-4 and 5-9 yr) equally vulnerable in high death toll events. DRR conditioned by country's development profile (population pyramids), being especially high for age groups above 60 yr old and increasing with age.	Japan, Chile, Samoa, Sri Lanka
	Sex/ gender. Female mortality is not always higher. Further considerations needed (population pyramids, development profile of the country, longevity, gender roles, dependency, cultural traditions, etc.).	Japan, Chile, Samoa, Sri Lanka
	Disability. The number and distribution of disabled victims is related to the number of victims, not to the disabled population in the pre-tsunami census. Higher numbers of disabled people does not translate into higher numbers of victims.	Sri Lanka
	Dependency. Female mortality is not always related to dependency issues (only Samoa and Sri Lanka in this work). Dependency and gender-related roles seem to be associated to a greater extent to undeveloped and developing countries.	Japan, Chile, Samoa, Sri Lanka
	SAFETY OF BUILDINGS	
	Type of damage. High correlation between affected buildings and number of victims, very high for completely damaged buildings.	Japan, Samoa, Sri Lanka
Building location	**Distance to the sea.** Distance to the sea is proved to be a highly determining factor regarding the type of damage in buildings and consequently the number of victims. 72% of the housing units within the 200m boundary line from the shoreline were completely damaged.	Sri Lanka
	Coastal topography. Higher mortality rates in narrow coastal strips compared to flatlands. Higher probability of buildings damage in ria coast compared to plain coast. Greater tsunami impacts on shore-connected waterways, low-lying onshore terrain, and negative landward slopes.	Japan (Nakahara et al., 2013; Supasri et al., 2013) Sri Lanka (Wijetunge, 2013)
	Shielding. Shielding reduces the fragility of structures.	Samoa (Reese et al., 2007, 2011)
Building fragility	**Type of building.** Not relevant. HU and NHU had similar percentages of type of damage.	Sri Lanka
	Building materials. High correlation between building materials, type of damage and number of victims. Affected buildings present higher percentages of temporary materials and have associated higher numbers of victims.	Sri Lanka
	Water depths. High correlation between water depths, building materials and type of damage. Almost the 73% of the affected HU by water heights between 2,1 and 3 m in Sri Lanka were critically damaged. Higher percentages of lightweight buildings washed away compared to reinforced buildings under the same inundation depth in Indonesia and Japan.	Sri Lanka; Indonesia (Tinti et al., 2011), Japan (Supasri et al., 2013)
	Debris. Entrained debris increases the fragility of structures.	Samoa (Reese et al., 2011)
	Storeys. Buildings of three or more storeys confirmed to be much stronger than buildings of one or two storeys under the same inundation depth.	Japan (Supasri et al., 2013)
	ECONOMIC RESOURCES	
	Income / poverty. Very high percentages of low-income-profile related to completely damaged housing units. Vulnerable groups and impacts affecting recovery.	Sri Lanka
	Type of occupation. The activity location (tsunami exposure), its social and economic contribution, as well as gender-related aspects are important to identify vulnerable livelihoods and potential socioeconomic impacts affecting recovery.	Sri Lanka

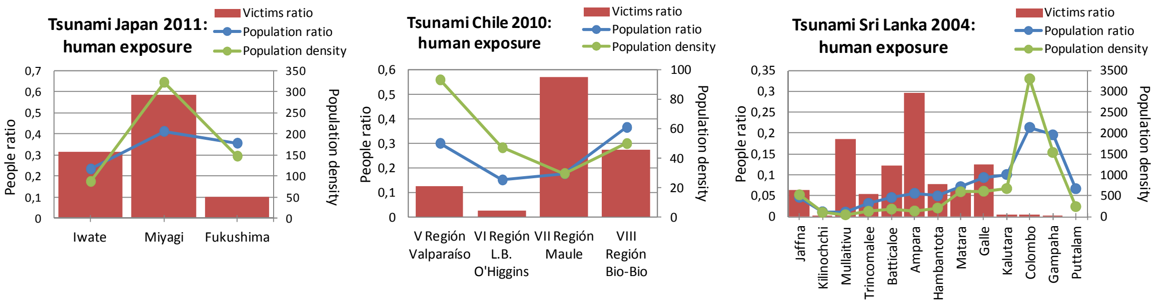

Fig. 1. Correlation between tsunami victims ratio, population ratio and population density (Japan 2011, Chile 2010 and Sri Lanka 2004).

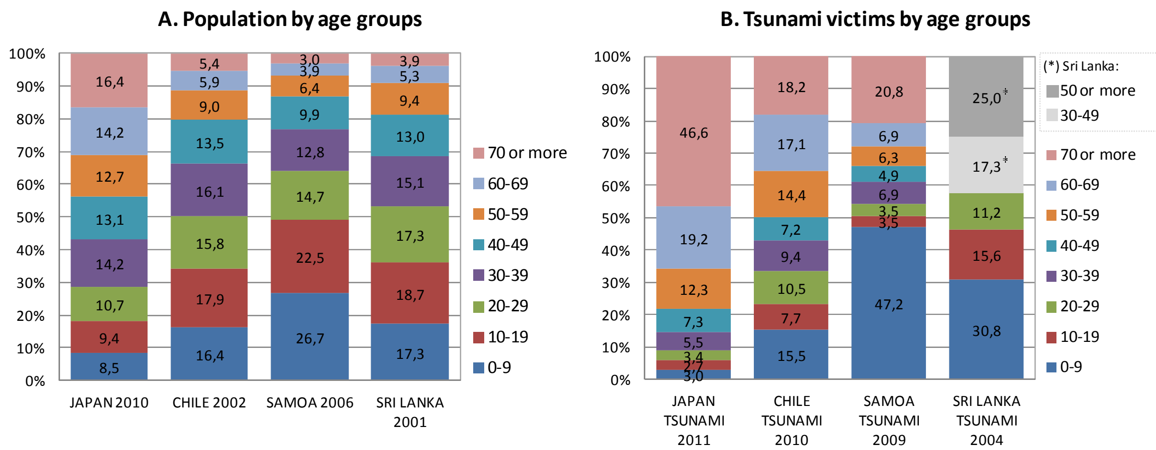

Fig. 2. Age groups analysis for several past tsunami events (Japan 2011, Chile 2010, Samoa 2009 and Sri Lanka 2004). A: pre-tsunami census, B: tsunami victims. The age of tsunami victims over 30 years old in Sri Lanka is not available disaggregated in ranges of 10 yr.

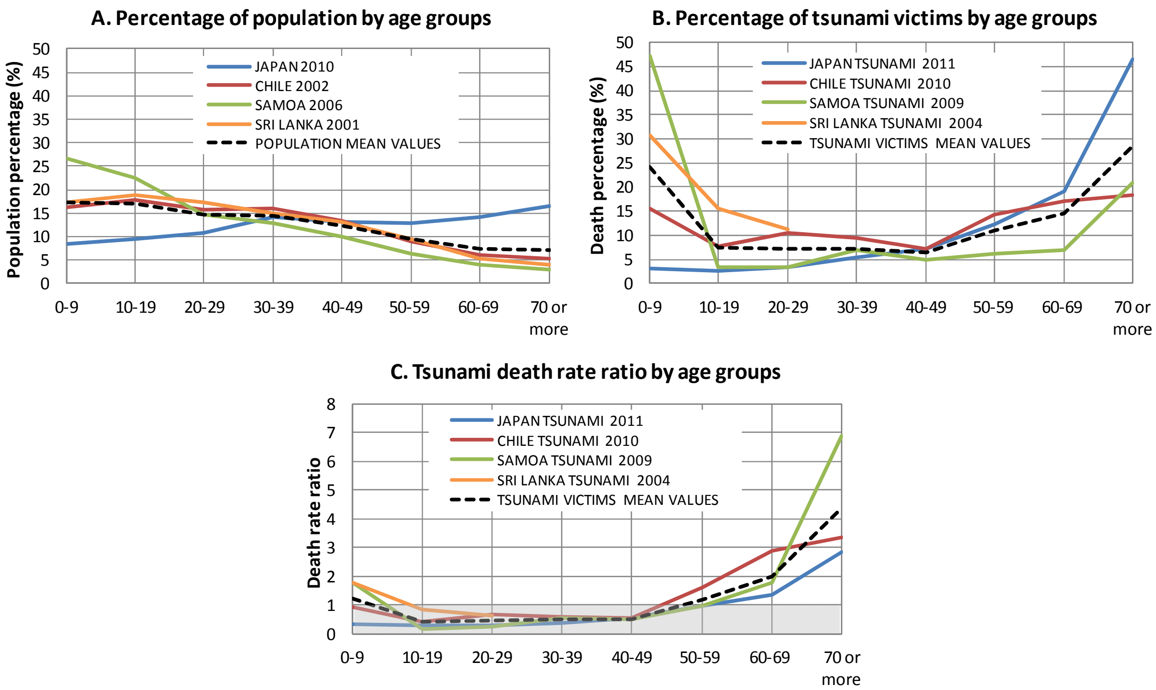

Fig. 3. Analysis of mortality by age groups (Japan 2011, Chile 2010, Samoa 2009 and Sri Lanka 2004). A: pre-tsunami census; B: tsunami victims; C: tsunami death rate ratio (C=B/A). The age of tsunami victims over 30 years old in Sri Lanka is not available disaggregated in ranges of 10 yr, consequently this age range not being represented in the graph. The mean values for this age range are calculated considering only the other 3 tsunami events.

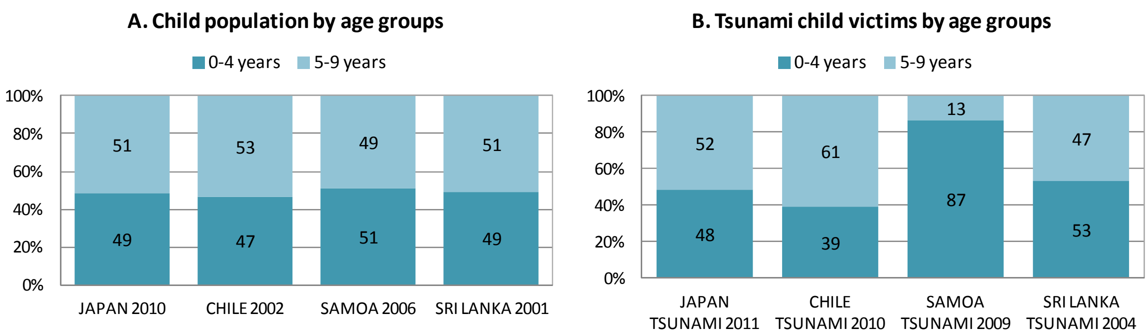

Fig. 4 Analysis of child age groups (Japan 2011, Chile 2010, Samoa 2009 and Sri Lanka 2004). A: pre-tsunami census, B: tsunami victims.

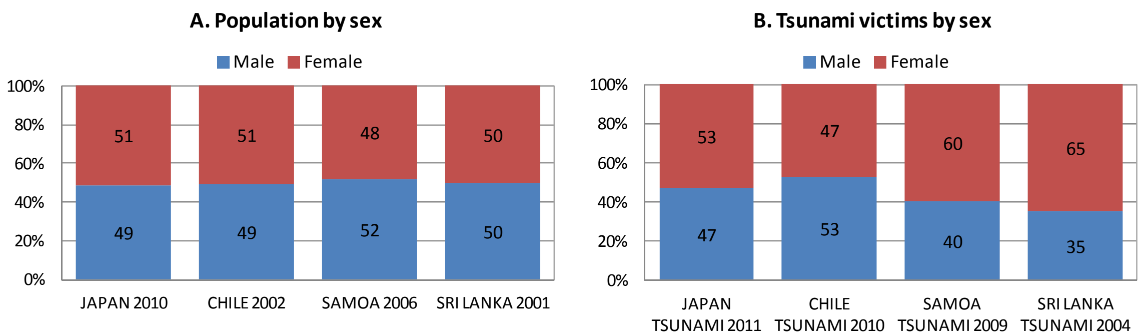

Fig. 5. Gender analysis (Japan 2011, Chile 2010, Samoa 2009 and Sri Lanka 2004). A: pre-tsunami census, B: tsunami victims.

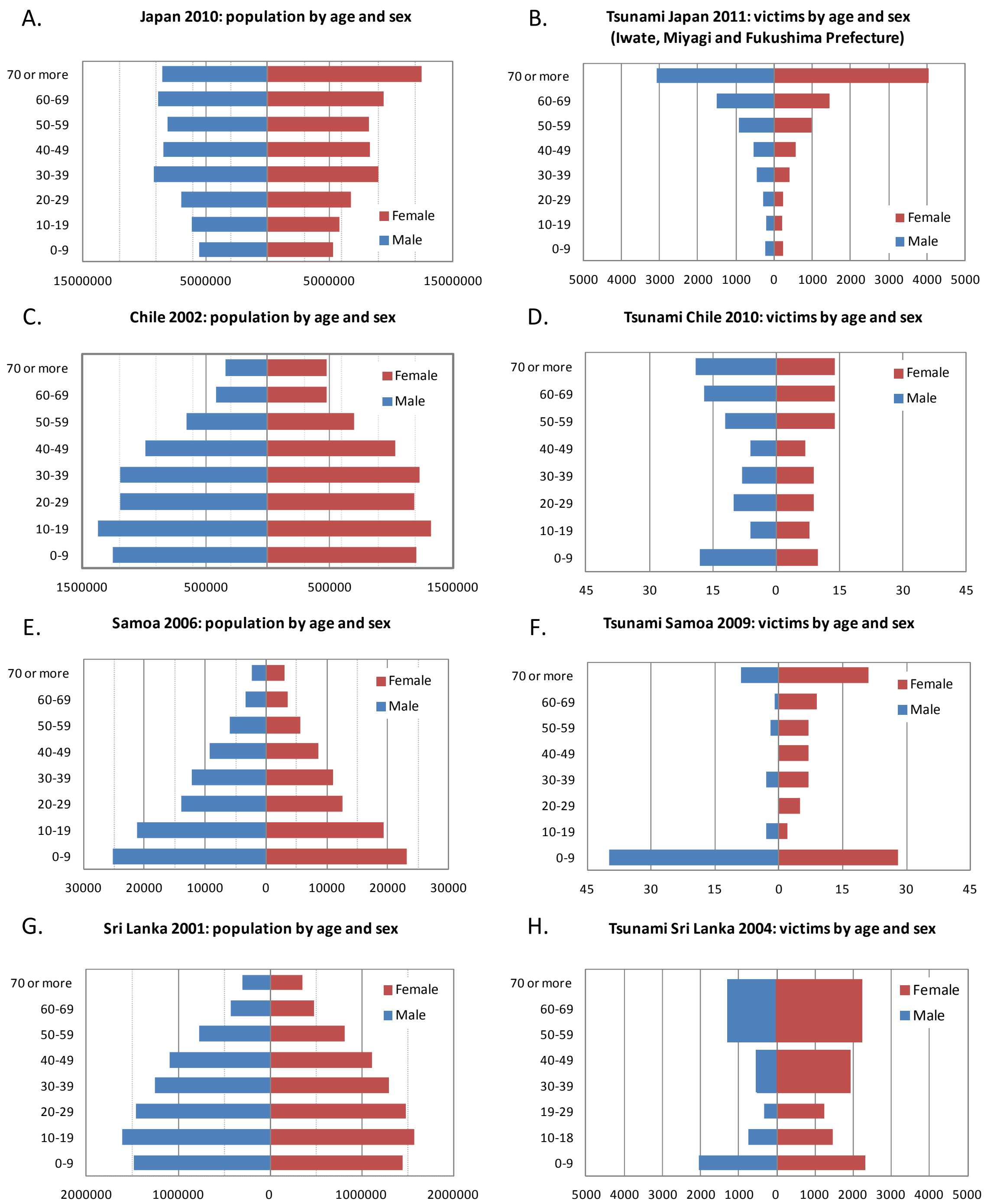

Fig. 6. Population pyramids (left: pre-tsunami census, right: tsunami victims). The age of tsunami victims over 30 years old in Sri Lanka is not available disaggregated in ranges of 10 yr (Fig. 6H)

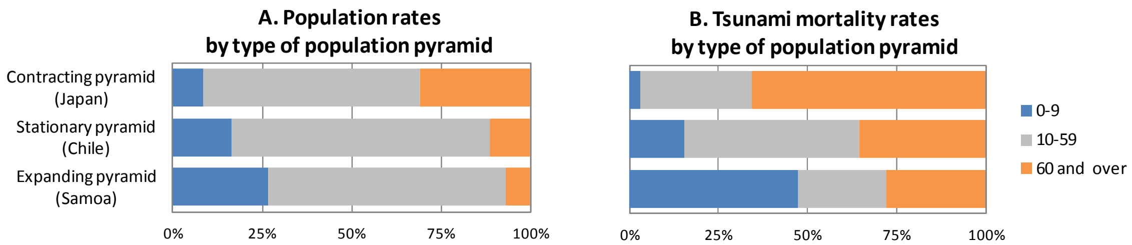

Fig. 7. Comparison between population rates (A) and tsunami mortality rates (B) by type of population pyramid.

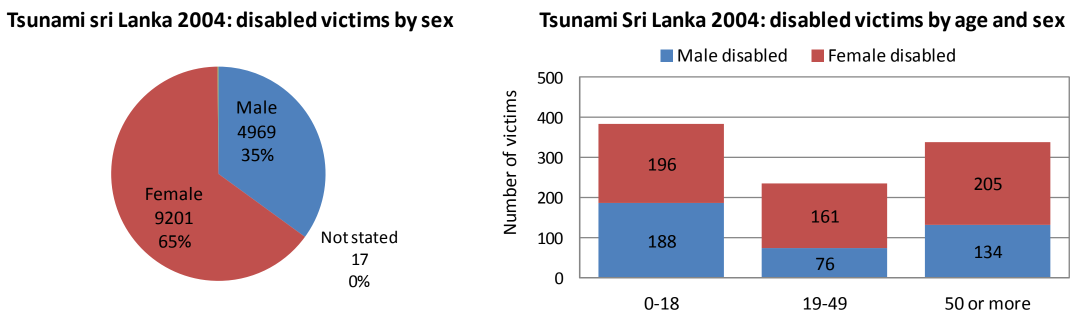

Fig. 8. Tsunami disabled victims by age and sex (Sri Lanka 2004).

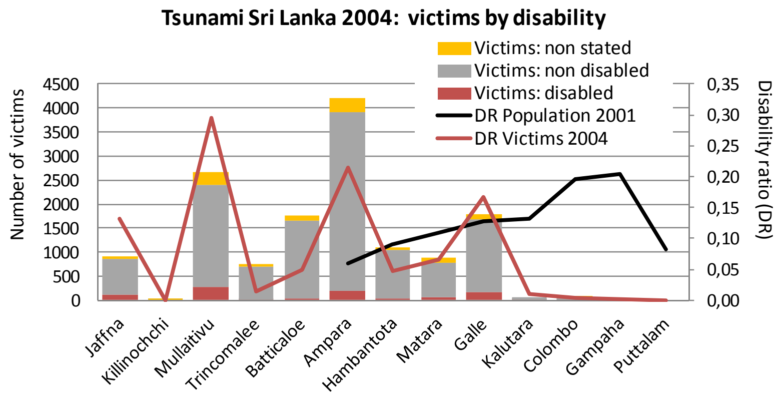

Fig. 9. Tsunami victims in the different affected coastal divisions in Sri Lanka (2004) by disability and pre-/post-disability ratios (disability ratio = disabled by district/total disabled). No data about disabled population in the tamil districts (Jaffna-Batticaloe) is available in the census 2001.

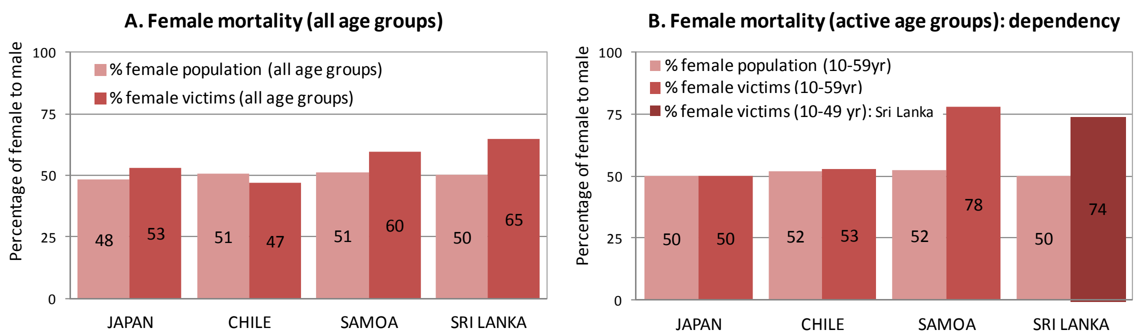

Fig. 10. Female mortality for different tsunami events and its relationship with the concept of dependency (Japan 2011, Chile 2012, Samoa 2009 and Sri Lanka 2004). Pre-tsunami censuses appear in light red and tsunami victims in dark red. A: female mortality considering all age groups, B: female mortality considering only the "active" age groups (10-59yr for Japan, Chile and Samoa, while 10-49 yr for Sri Lanka due to data availability), assuming that women in this age range may have been in charge of family members as children and elderly adults. Higher percentages of female victims in the active age group compared to the pre-tsunami percentages provide the female mortality associated to dependency issues.

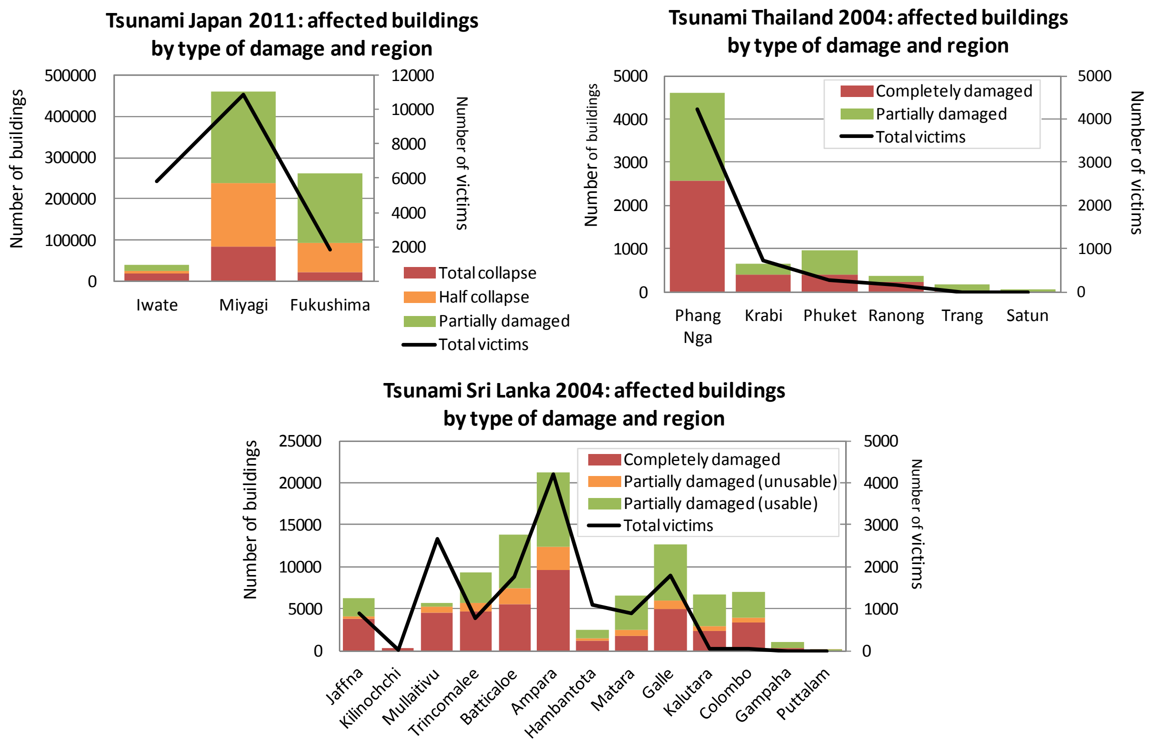

Fig. 11. Correlation between total tsunami victims and affected buildings by type of damage and region (Japan 2011, Thailand 2004 and Sri Lanka 2004).

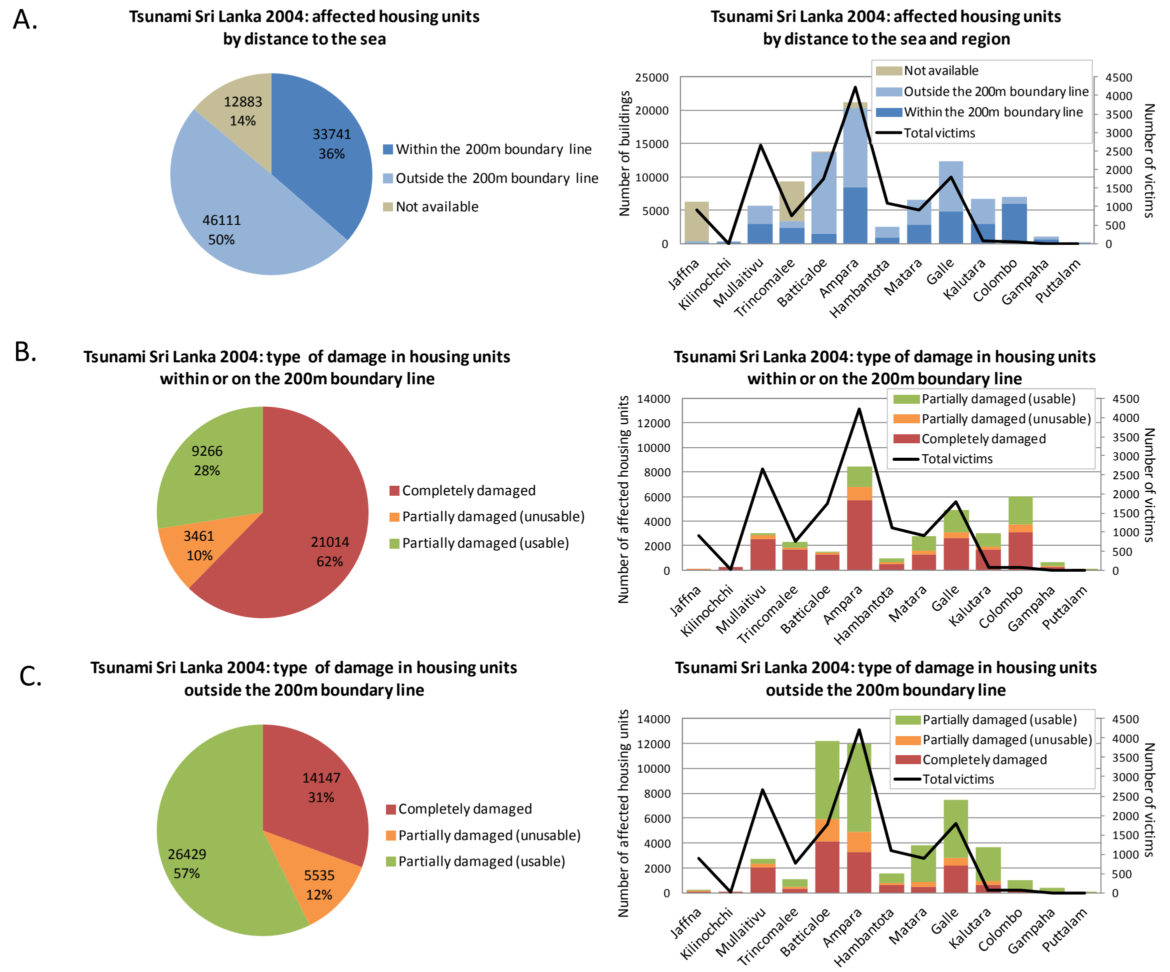

Fig. 12. Correlation between number of tsunami victims, buildings' type of damage and distance to the sea (Sri Lanka 2004).

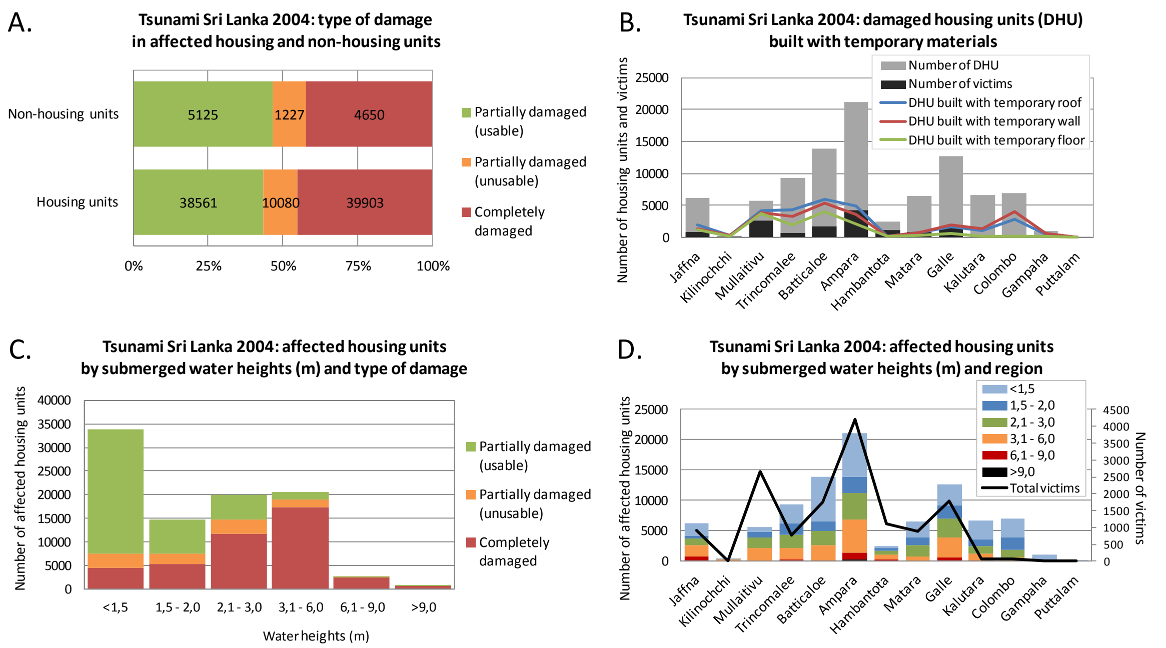

Fig. 13. Analysis of damaged buildings in Sri Lanka 2004. A: comparison between number of housing units (HU) and non-housing units (NHU) affected by type of damage. B: correlation between numbers of tsunami victims, damaged HU and building materials. C-D: correlation between numbers of tsunami victims, buildings' type of damage and water depths.

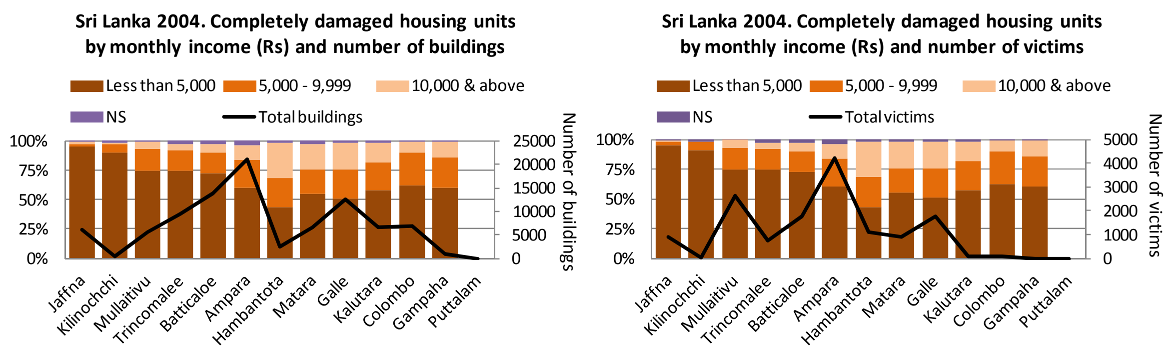

Fig. 14. Percentage distribution of completely damaged housing units (left) and number of tsunami victims (right) by reported monthly income of the housing unit in Sri Lanka 2004 (5000Rs = 27.71€, on 2014/07/10).

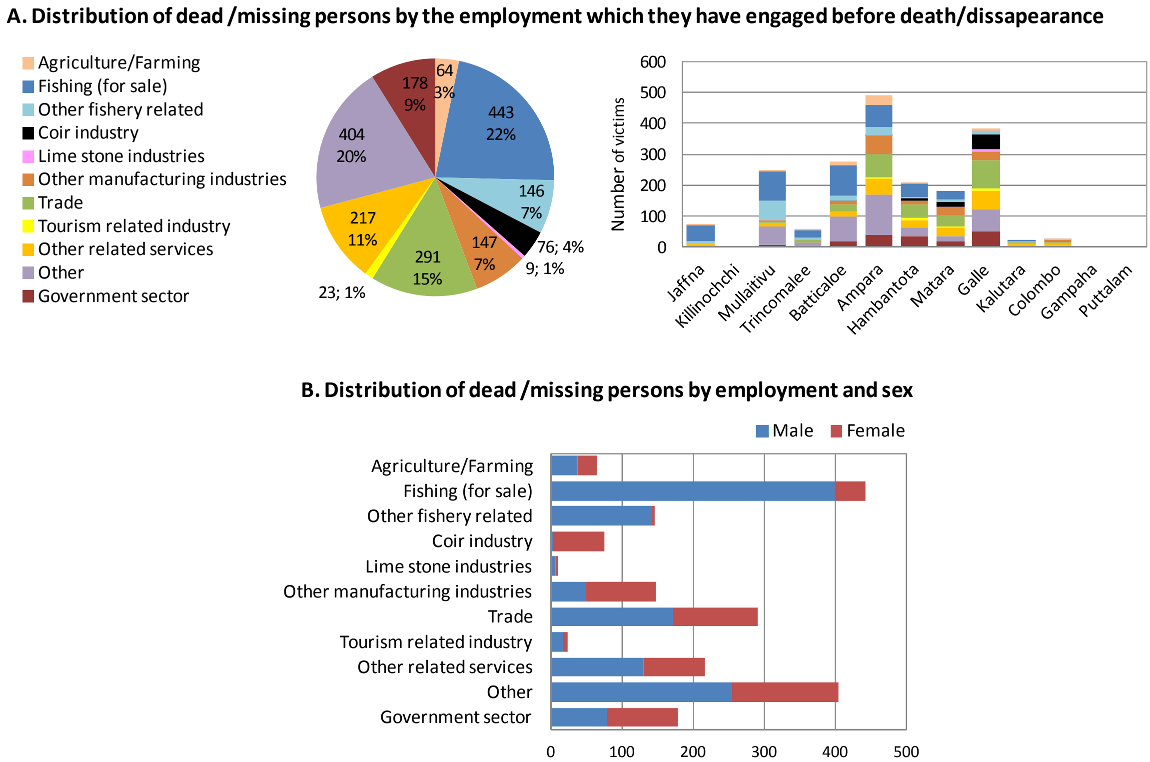

Fig. 15. Distribution of tsunami victims by employment and district in Sri Lanka 2004. A: distribution of dead/missing persons by the employment they have engaged before death/disappearance. B: distribution of dead/missing persons by employment and sex.