



Review Article

Tsunami risk reduction – are we better prepared today than in 2004?



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ABSTRACT

With over 220,000 fatalities, the 26 December 2004 Indian Ocean tsunami was one of the deadliest natural hazard events ever, and represents a landmark in disaster risk reduction governance in several ways. The 2004 Indian Ocean tsunami led to a better understanding of the likelihood of tsunami occurrence and potential tsunami inundation. For example, the Hyogo Framework Agreement was a direct result of this event. Since December 2004, Indonesia, Samoa, Chile and Japan were hit by altogether six destructive tsunamis in 2006, 2007, 2009, 2010 and 2011.

This article looks into the progress (or lack thereof) made in tsunami risk reduction at the local level during the past ten years, with focus on the densely populated coastal regions of Indonesia and Sri Lanka. The experience from other countries, as well as the progress made in the state of the art for assessment of tsunami hazard, vulnerability, exposure and risk are also summarized. In addition, extensive new warning systems enabling a rapid assessment of the potential coastal impact of a tsunami have been developed and implemented. However, the experience from the tsunami events in October 2010 in Indonesia and March 2011 in Japan clearly demonstrated that the tsunami risk mitigation measures implemented to date are far from adequate. The article also examines the progress in assessing and factoring in vulnerability aspects in tsunami risk reduction, highlighted through two case studies in Padang (Indonesia) and Galle (Sri Lanka). In this regard, societal awareness and behavioural response to tsunamis are addressed. Recommendations about how the improved knowledge about tsunami hazard, vulnerability and exposure assessment gained over the past decade could be better implemented into tsunami risk reduction measures are provided at the end of the article.

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1. Introduction

Recent disasters triggered by natural hazards provide further evidence of the need for disaster risk reduction (DRR) strategies that address the mitigation of hazard impact and reduction of vulnerability and its root causes. This need is also stressed by the post-2015 Hyogo Framework for Action (HFA) process. In this context, tsunamis have played an important role due to their devastating impacts, exemplifying the tremendous number of fatalities and losses that could have been reduced by effective risk reduction activities. With over 220,000 fatalities, the 26 December 2004 Indian Ocean tsunami was one of the deadliest disasters triggered by a natural hazard event ([67]). It demonstrated the need for more research, improved planning activities, awareness raising, as well as the need for establishing early warning systems [105]. The Indian Ocean tsunami provided important lessons for developing the HFA and sharpened the commitment for its implementation [103,106]. Although a variety of tsunami risk reduction measures such as the ongoing establishment of the Indian Ocean tsunami early warning system have been implemented since December 2004, the tsunamis that occurred during the last decade illustrated remaining deficiencies. The 11th March 2011 Tohoku Earthquake and subsequent tsunami, which caused a nuclear catastrophe, is just the most recent example (Table 1). The tsunami hitting the Mentawai Islands in Indonesia on 24 th October 2010 is another. Both events occurred in regions where tsunami risk prevention measures had been implemented.

In hindsight, the 2004 Indian Ocean tsunami should not have come as a surprise [82]. Old historical events occurring two centuries ago provided a warning sign that was raised a short time before the disaster hit [18]. Recent paleotsunami deposits have revealed evidence for past events in pre-historical times [44], meaning that the 2004 Indian Ocean tsunami is not an isolated event. The 2004 Indian Ocean tsunami did introduce a paradigm change in the sense that previous models for constraining earthquake magnitudes along fault zones are now refuted [90].

As a consequence, megathrust earthquakes emerging from any of the large subduction zones in the world should not be ruled out.

The tsunamis that hit Japan in 2011 and Mentawai Islands in 2010 [34] have revealed weaknesses in the way society deals with tsunami hazard information. At that time, a new warning system was at place in Indonesia, but there were no tsunami sirens located along the most exposed shorelines near the Sumatra trench. Here, the population did not self-evacuate, maybe because of many false warnings and earlier tremors, and perhaps also due to the lack of proper systems for conveying the warnings [94]. A similar lack of awareness was demonstrated in by the Samoa tsunami in 2009, where many people drowned in their cars when they could have evacuated by foot [94]. The 2011 Tohoku tsunami was more severe than the tsunami barriers were designed for [20]. According to Ogasawara et al. [74], 25 of 55 tsunami barriers in Iwate prefecture were damaged and also almost half of the disaster prevention infrastructure has been destroyed. Even the breakwater installed in Kamaishi, being the deepest breakwater in the world (1950 m long and 63 m deep), was heavily damaged. Although seawalls were partly overtopped and dikes were heavily damaged, these structures reduced the wave height and avoided a greater damage [29,84]. The Japanese tsunami hazard maps were largely based on historical earthquake records limiting the earthquake moment magnitude to about 8, one order of magnitude lower than the 2011 event [37]. Recent analyses have in fact shown that a tsunami of this size may have a return period of about 500 years and should by no means have been a surprise [46]. A 500-year return period is well below the typical return periods of the extreme events nuclear power plants are designed to withstand. Still, one should keep in mind that the Japan, like Indonesia and Sri Lanka, faced run-up exceeding 10 m over large areas, with horizontal inundation extending one or sometimes several kilometres, leaving many cities almost totally destroyed. The fact that the relative death toll in Japan was one order of magnitude lower than that caused by the Indian Ocean tsunami is one of the strongest indicators that the exposed

Table 1

Tsunamis worldwide and related economic losses and fatalities between 2004 and 2013 (Sources: MunichRE 2013a, 2013b and [17]).

Date	Country/ies affected	Economic losses (million US\$)	Fatalities
26 December 2004	Sri Lanka, Indonesia, Thailand, India, Bangladesh, Myanmar, Maldives, Malaysia	11,200	220,000
17 July 2006	Indonesia	55	802
2 April 2007	Solomon Islands	Several millions	112
29 September 2009	Samoa and American Samoa	150	177
27 February 2010	Chile	30,000	520
24 October 2010	Indonesia	n.a.	530
11 March 2011	Japan	210,000	15,840

population in Japan was far better prepared. Even in retrospect, it is hard to see how the physical damage that Japan suffered in 2011 could have been avoided. The age composition of those who perished following the Tohoku tsunami showed that 46.5% were older than 70 years, and 77.6% older than 50 years, which may indicate that they could not evacuate themselves as fast as younger ones [108]. Preparedness programs, evacuation plans, loudspeakers, and hard coastal protection structures were in place [28,1]. However, much stronger precautions should have been applied when designing nuclear power plants in the exposed areas. Although parts of the scientific community had expressed concern about the possible scale of the threat, the political will for more stringent precautions may not have been sufficient. A more elaborate analysis of the Tohoku tsunami is given by NGI [72].

In the past decade, tremendous efforts have been made by the international community to develop DRR methodologies and strategies that allow policy makers and practitioners to actively engage in disaster risk management (DRM). These encompass, for example, the identification of areas at risk including hazard mapping activities [47]. On the other hand, it is realized that disaster risk is determined by additional factors than hazard intensity and extension of inundated areas. This has led to the integration of susceptibility and coping factors into risk assessment methodologies (Liverman 1990, [13,19,6] and most recently also IPCC, 2012).

Existing work on tsunami resilient communities conducted was recently reviewed in the EU 7-FP ASTARTE project, Dogulu et al. [25]. They find that the technical component of tsunami resilience may be relatively well covered in certain aspects, e.g., developing existing and new tsunami early warning systems (e.g. the Pacific Tsunami Warning Center, <http://ptwc.weather.gov/>, the North-Eastern Atlantic and Mediterranean Tsunami Information Centre, <http://neamtic.ioc-unesco.org/neamtwts>), evacuation planning (e.g. [39]), evacuation mapping (e.g. [22]). Yet, similar efforts in social science aspects have been less explored. Therefore, Dogulu et al. [25] further emphasized the need for further, and more focused, research in the social science branch of tsunami resilience. As available sociological studies of tsunami resilience so far have been focussing on the individual, they stress that more emphasis should be devoted to the collective dimensions. Finally, they found that most of the available studies stem from South East Asia and the Pacific, and that corresponding studies in Europe are sparse.

Although there exist tools for tsunami hazard and vulnerability assessment from a scientific point of view,

it remains unclear whether they are actually used in national and regional DRR efforts. It is thus the aim of this article to review the application of DRR methodologies with regard to tsunami hazard and risk. We start with a general review of existing hazard mapping and physical vulnerability methods in Sections 2 and 3, respectively. In Sections 4–6, we provide a review dedicated to two case studies, in Galle (Sri Lanka), and in Padang (Indonesia), respectively. Here, we review the existing methodologies in societal vulnerability, implementation of the tsunami vulnerability risk and vulnerability information, and finally on the identification of gaps. Recommendations for bridging the potential implementation gap are also discussed.

2. Progress in understanding and mapping tsunami hazard

Before 2004, and for a few years after the Indian Ocean Tsunami, tsunami hazard assessment was mainly based on worst-case scenario analysis [99,53,42,58,75,107,57]. Worst-case scenarios are used to delineate the possible impact of high consequence events of a relatively small likelihood. In the design of the tsunami sources, information regarding the seismicity and tectonics are utilized if available. As tsunamis having long return periods are believed to dominate the risk [69], the worst-case scenario approaches may sometimes be preferable due to the large uncertainty linked to events having return periods of hundreds or even thousands of years. Furthermore, scenarios are often useful in areas having a complex tectonic or geological setting with too limited information to conduct a proper probabilistic analysis [59].

Throughout the last decade, probabilistic methods for estimating the tsunami hazard have become increasingly popular. The Probabilistic Hazard Assessment method (PTHA) was developed during the eighties [54,80], but was sparsely used before the 2004 Indian Ocean tsunami. PTHA is largely based on Probabilistic Seismic Hazard Analysis (PSHA) originally proposed by Cornell [16] and is well documented in many references (e.g. [89]). The application of PTHA was revitalized following the Indian Ocean Tsunami, largely due to the developments of Geist and Parsons [36]. In recent years, PTHA has been utilized to quantify the probability of the tsunami metric (usually the run-up height) in a number of areas [4,14,78,38,98,87]. The PTHA framework is usually implemented by assuming linearity, which allows construction of events by superposition from a large amount of unit sources. By

pre-computing and storing the tsunami waveforms at points along the coast generated by each sub-fault for a unit slip, the tsunami waveforms are synthesized for any slip distribution by summing the individual sub-fault tsunami waveforms (weighted by their slip). This approach makes it feasible to use superposition, easing the computational load. Probabilities may be assigned to each source through a recurrence model. The linear assumption holds for small amplitude-to-depth ratios, but extra measures have to be taken to allow for simulating shoaling and inundation.

A crucial element in PTHA is the estimation of the frequency of occurrence and maximum magnitudes of large tsunami-generating earthquakes in each source region. Due to the short historical record for megathrusts and other large earthquakes in relation to their recurrence times, it is not possible to base such constraints directly on the observed seismicity. In recent history, we have not seen events similar to the size of the 2004 Indian Ocean tsunami and the 2011 Tohoku tsunami locally in these regions. However, we now know that megathrust events such as the 1960 Chile and 1964 Alaska along other faults zones should have been sufficient to warrant caution. Although subduction zones are different, the potential for large megathrust events should therefore not be ruled out along any large subduction zone as our present understanding on how to discriminate them is still limited [90]. For tsunami hazard assessment, a possible conservative strategy is to take into account the tectonic convergence rate and assume fault locking over the entire return period. This method has been utilized in the methodology for estimating the tsunami hazard for the UN-ISDR Global Assessment reports in 2009 and 2013 ([103]; [60]; [104]; [61]).

Although the various approaches developed for tsunami hazard and exposure assessment build on the same principles and physical laws, the results obtained with these approaches for the same scenario may differ significantly because of the simplifications made for implementation. Appendix A provides an example of the problems that arise from this variability and how they could be dealt with in practice.

3. Progress in understanding and assessing physical vulnerability

Vulnerability is a multi-faceted concept that has different definitions depending on the context and discipline. In natural sciences and engineering, vulnerability often refers to the physical vulnerability of the exposed population or elements at risk that are coupled with hazard characteristics to quantify of the potential for loss and damage¹ on a scale of 0 (no damage and/or very little chance of being killed) to 1 (complete destruction and/or certain death). Following Einstein and Sousa [30], the physical vulnerability $P[C|T]$ relates to the hazard $P[T]$ (the temporal probability of a threat T) and enters the probabilistic

definition of the expected risk R as

$$R = P[T] \cdot P[C|T] \cdot u(C)$$

Here, $u(C)$ is the **loss** or **utility** of a set of consequences C , all certain to happen. Following this risk definition, the risk may change non-linearly as a function of the hazard and vulnerability parameters as they may be linked. Nadim and Glade [69] and Løvholt et al. [60] have argued that this non-linearity is particularly prominent for tsunamis, as both the hazard and vulnerability may change abruptly with the return period.

In social sciences, the term “vulnerability” refers to societal vulnerability, which is related to exposure and susceptibility of the society, as well its capacity to react to a hazardous event. Both concepts are important in understanding and reducing the risk posed by tsunamis and great progress has been made on both fronts since 2004.

3.1. Hazard characteristics related to physical vulnerability

Physical vulnerability to tsunamis is a relatively unexplored discipline, and few reliable models exist. There is thus a need for improving the tsunami vulnerability models. However, this is also a field where substantial development is currently being made.

The Tsunami Pilot Study Working Group [100] lists the following tsunami parameters as possible impacts metrics (intensity measures) that may enter as important hazard parameters in tsunami models for assessment mortality risk, building damage and forces on structures:

- Tsunami flow depth
- Wave current speed
- Wave current acceleration
- Wave current inertia component (product of acceleration and flow depth)
- The momentum flux (product of squared wave current speed and flow depth). In many circumstances, this is the best damage indicator.

The above-mentioned hazard parameters are important in estimating the expected number of fatalities for a tsunami scenario, as well as the wave forces on structures. The selection of the flow depth is obvious, being a direct measure of the thickness of the flowing water; the flow depth is also influencing the current velocity. The fluid force on a structure is proportional to the momentum flux, as well as impact forces of flotsam, and hence also a natural possibility as an impact metric. Perhaps more surprising is the inclusion of the wave current acceleration. However, a tsunami wave that run-up on the beach will often accelerate when it hits the shoreline after breaking [93], and this effect may be counterintuitive for a layperson observing the tsunami, leading to a misinterpretation of the escape time. The physical vulnerability would determine the risk of mortality as well as fragility or the different likelihoods of buildings to collapse.

¹ The mortality or damage function is also sometimes defined as physical vulnerability, however, in this article we intend to define hazard and vulnerability as separate components that interact to build risk.

3.2. Risk of mortality

In a national tsunami risk evaluation for New Zealand, Berryman et al. [5] suggested an empirically derived mortality model solely based on the flow depth of the tsunami (Fig. 1). A similar model based on the flow depth was suggested by Reese et al. [79], also shown in Fig. 1. The latter model includes all casualties (both injuries and fatality). Another model distinguishing between fatalities and injuries are included also in Berryman et al. [5] (not shown). The latter model is a typical example of most mortality models in current practice, assuming that no warning systems are available. It parameterizes the amount of people present in buildings at nighttime or daytime. Apparent from both models shown in Fig. 1, there is large spread in the mortality and casualty as a function of the flow depth, suggesting that other factors than the flow depth influences the risk of mortality (Fig. 2).

3.3. Building fragility and risk of building damage

The vast destruction caused by the 2004 Indian Ocean and 2011 Tohoku tsunamis have led to a number of studies on re-analysis of building damage from tsunami (e.g. [91,92]). In these studies, the degree of building damage is linked to the overland flow depth of the tsunami, as this is the indicator that would usually be available from a post-tsunami field survey. Suppasri et al. [91] studied the building damage in Thailand following the 2004 Indian Ocean tsunami. They used an inundation model to estimate current velocities and forces on structures, and compared these to the probability of damage. Suppasri et al. [92] compiled a wide range of data for building damage in Japan following the Tohoku tsunami.

The study by Koshimura [50] in the city of Banda Aceh quantifies mortality and building damage due to tsunami as a function of distance from the coast.

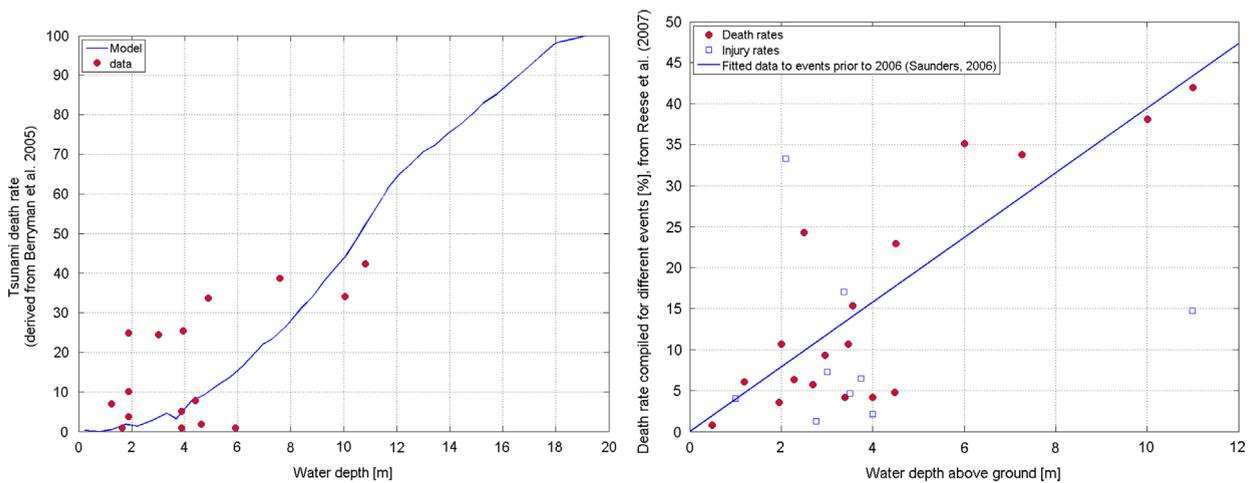


Fig. 1. Left: Empirical mortality model of Berryman et al. [5]. Right: Empirical injuries and death rate in per cent, red and blue markers indicate casualties caused by the 2006 Java tsunami, black markers other events. Plots derived from [79].

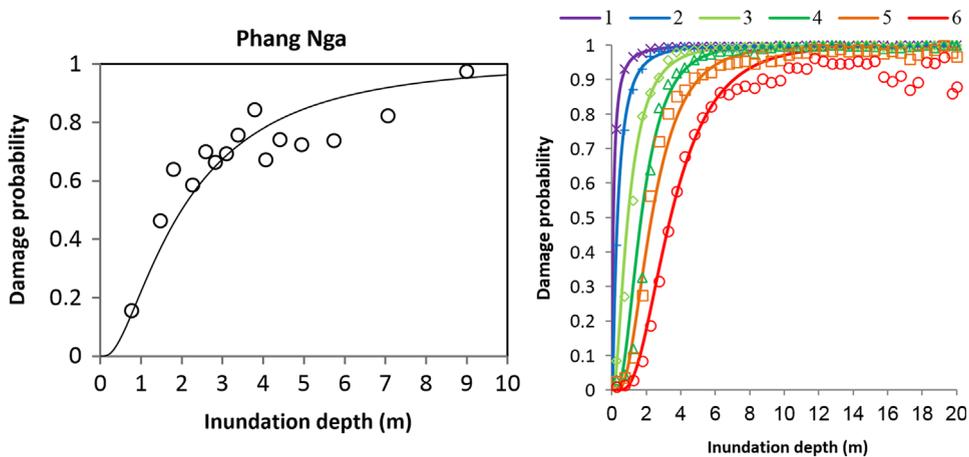


Fig. 2. Left, building damage probability as a function of the overland depth for Phang Nga in Thailand, figure from [50]. Right, building damage probability as a function of the overland depth for different damage classes (1 – minor damage to 6 – washed away) compiled for a range of locations in Japan following the 2011 Tohoku tsunami, figure from [91].

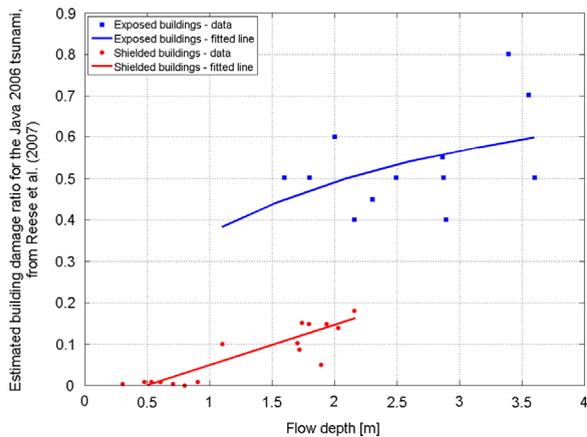


Fig. 3. Example of building fragility models due to the 2006 Java tsunami, damage ratio for traditional brick buildings with reinforced concrete columns following the 2006 Java tsunami, plot derived from [79].

Reese et al. [79] established a fragility model for building damage based on damage observations following the 2006 Java tsunami. They investigated the damage ratio (cost to repair/cost to replace) for four different building types as a function of the flow depth. An example of the observed damage ratio for traditional brick buildings with reinforced concrete is shown in Fig. 3.

It should be noted that the one parameter models described above are too simplistic. In general, a reliable quantification of expected mortality and damage rate should take into account all important factors that could possibly affect the elements at risk. These include all the damage metrics listed above, but also parameters like tsunami warning time, time of day, population distribution, population age, population awareness, building design, etc. Many of these factors are represented by the societal vulnerability.

Early methods to quantify tsunami vulnerability and risk were developing immediately before the 2004 Indian Ocean tsunami [111,112]. The PTVA models (see e.g. [111]; [26]; and [27]), all based on the work of Papathoma et al. [111], are hybrid models addressing tsunami risk using indicators which have been popular for the last 10 years or so. They are engineering type models and are largely based on classification of buildings, but also bring in other indicators such as economic, demographic, and social indicators. The PTVA model has been consistently validated and updated, for instance against building fragility data in the Maldives following the 2004 Indian Ocean Tsunami [26]. Furthermore, the PTVA and similar types of models are growingly used to quantify tsunami risk in various parts of the world such as in Sydney [21], Aeolian Islands [23], Seaside Oregon State [27] and in Casablanca [77]. However, the validation of the PTVA model available in literature lack a clear quantitative analysis and the validity of the model therefore remains largely unclear. For instance, we have not found any method for conveying the building fragility data to risk indicators. Another possible weakness of this type of model is that because a link between the fragility and risk does not exist, it is not clear how losses may be derived. Assessment of the

mortality is also not included. Although these tsunami risk models provide a first step, further work is therefore needed in physical tsunami risk modelling to derive quantitative and traceable links between the tsunami load and the resulting losses.

4. Progress in understanding societal vulnerability – the case studies from Indonesia and Sri Lanka

From the social science perspective, vulnerability assessment focuses strongly on people, their intrinsic propensity and the social processes that increase exposure and vulnerability of population groups and their livelihoods (see e.g. [113]). There have also been various concepts and methods to assess societal vulnerability to natural hazards, qualitatively and quantitatively. In the context of tsunami, as in physical vulnerability, there has been much progress in understanding the societal vulnerability factors, as well as in development of assessment methodologies in recent years. Some important vulnerability factors were particularly revealed by the Indian Ocean Tsunami in 2004, which devastated the Province of Aceh, Indonesia (221,291 dead including missing), and many coastal districts of Sri Lanka (35,368 dead including missing). In both countries, but also other affected countries in the region, high spatial exposure of various social groups to tsunamis and very low – if any – awareness and response capability of the impacted regions to such an extreme tsunami event have been recognized as contributors to high number of victims. In addition to such “revealed” societal vulnerability factors related to mortality, a better understanding has emerged related to societal vulnerability assessment and factors specifically linked to tsunami risk reduction measures after the event. Further factors have been identified in the ongoing process of the development of an end-to-end tsunami early warning system and tsunami preparedness in the Indian Ocean region, as well as implementation of buffer zone regulation in the coastal areas. The following section presents important indicators and assessment methods of societal vulnerability on the basis of the existing studies following the 2004 Indian Ocean Tsunami, particularly in Indonesia and Sri Lanka. Furthermore, specific factors related to tsunami early warning and relocation as part of tsunami recovery and risk reduction are discussed based on two in-depth case studies in the tsunami-prone city of Padang, Indonesia [95,85,12] and in cities of Galle and Batticaloa, Sri Lanka [9,11,10,31,32].

Fig. 4 shows the location of the case study areas. The first case study in Indonesia dealt with vulnerability assessment and important factors for people-centred early warning in the city that prepares themselves for potential tsunamis in the future. It views vulnerability as “the conditions which influence the level of exposure and capability of people to respond to the warning and conduct appropriate evacuation, and in the long term, to change those conditions and enhance their response capability” [85]. The second case study in Sri Lanka dealt with the vulnerability and challenges of recovery, particularly relocation measures due to buffer zone regulation to reduce exposure to tsunamis. It introduced vulnerability as “exposure to various forced resettlement-related stresses and risks that

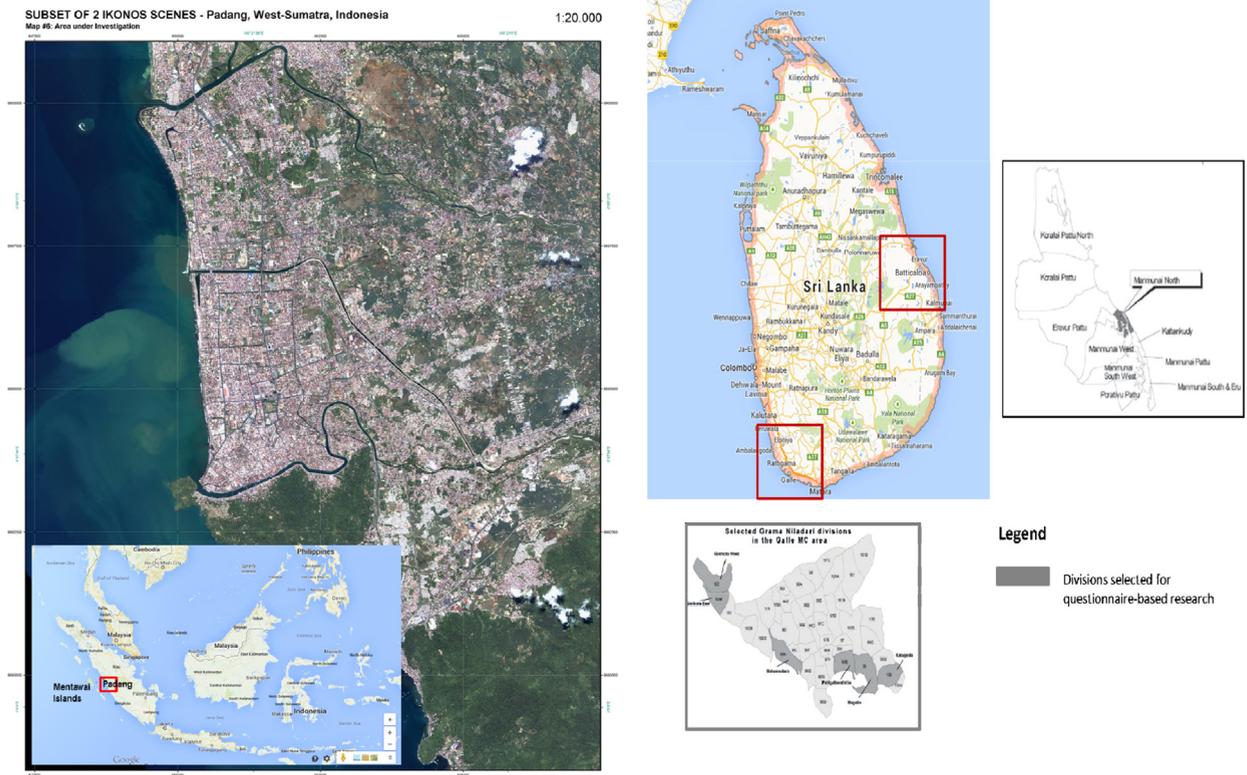


Fig. 4. Location maps of in-depth case studies in Indonesia and Sri Lanka (left: study area in Padang city, Indonesia; right: Galle, Sri Lanka).

affected the households and the difficulty in coping with such issues" (Fernando 2010). Both in-depth case studies used various quantitative and qualitative data collection and analysis methods to identify and assess the vulnerability indicators, combining existing statistical and spatial data, as well as additional data from household surveys, non-structured and in-depth interviews, and focus group discussions (further information on the data, methodology, and analysis results can be found in the above-mentioned references). In both studies, the quantitative methods to assess societal vulnerability indicators were mostly using demographic and socio-economic composite indicators, which are associated with the potential loss of lives and difficulties to recover after tsunami events. On the other hand, complementary relevant qualitative information was used to provide context information on the indicators and understanding on intangible factors, such as concerns of the community, and perception issues. Although these studies do not capture all the progress made in understanding societal vulnerability in the region, they do provide a better understanding on some important factors and development of qualitative and quantitative methods to measure them emerging after the tsunami event.

4.1. Spatial exposure and demographic factors

The relevant factors for exposure are particularly the density of development in the coastal areas and its relation with the existence of vulnerable groups (cf. Oxfam International [76]; [81,7,8]).

In Indonesia, the **spatial exposure** of the population and buildings in the coastal areas, which are located near the coastline, contributed to the magnitude of fatalities and damages. Similarly in Sri Lanka, people within the 100-m zone from the shoreline were more likely to die and to be seriously injured than people living outside this zone, although inundation in many cases stretched inland across the 200 and 300 m zones. The same pattern was observed for housing damage. Using the example of the district of Galle, about 50% of the houses within the 100m zone were totally damaged, or partially damaged but could not be used anymore, as compared to about 20% outside this area (Fig. 4) [9,11]. Although the building damage rate relates to the physical vulnerability (fragility of the building), it is important to consider the distribution of social groups in the exposed areas that will also determine the quality and density of the exposed housings.

Moreover, many reports mentioned that the differences in the mortality rates among different population groups were correlated with **demographic factors**, especially age and gender [76,81]. In Aceh, the number of female, children and elderly victims was much higher, and these groups were less likely to survive compared to other population groups. This seems to relate with their differentiated exposure [76] – many male population conducted activities outside exposed areas and women were carrying children with them – and their physical capability. For Sri Lanka, using the example of Galle, also showed that **age** and **gender** played a significant role. While among the dead and missing people, children younger than 9 years

(25%) as well as people aged 40 or older (44%) were most vulnerable,² two-thirds of the dead and missing were women.³

Exposure in various hazard zones was mapped using remote sensing data and geo-information systems combining the hazard information with the existing population (and others like buildings, critical facilities, etc.) data. Population data is attainable from the available statistical data (population census) at lowest administrative level, while data at the building level is made available by means of remote sensing analysis (e.g. [97]).

4.2. Tsunami awareness

Knowledge and education about tsunamis are essential with regard to taking evacuation action. It is obvious that there was hardly any knowledge about tsunamis in the affected areas in Indonesia and Sri Lanka prior to 2004. In Aceh, an ADRC Survey in October–December 2005 [2] in Banda Aceh and Aceh Besar showed that most of the Aceh population had never heard about tsunamis before the Indian Ocean Tsunami (88.50%). The others (11.50%) said that they have heard about a big sea wave coming to land (from Islamic story telling) from family, friends, books, from schools or television. In Sri Lanka, less than 10% of the respondents had any tsunami knowledge before 2004 ([45], p. 47). Such lack of knowledge consequently led to lack of preparedness to such an extreme event. This was identified as an important contributor to the high number of fatalities – specifically as many people ran to the beach to watch the setback of the sea ([3], p. 50).

4.3. Factors related with early warning and evacuation

The factors related to early warning and evacuation were particularly explored further and methods to assess them were developed for the case study of Padang, Indonesia. Especially, social factors were found to be associated with spatial and technical requirements of early warning and evacuation facilities. Thus, such analysis provided more insights and information for tsunami early warning and evacuation planning from societal perspective.

Access to safe places or available infrastructure (transportation networks) for evacuation also determine the evacuation time. For example, various modelling methods were developed and utilized to estimate the evacuation time and identifying the need for evacuation measures in the city of Padang like additional bridges, roads, vertical shelters (cf. [51,24,66]). Furthermore, locations with high proportion of vulnerable people, like women, children, elderly, and low-income groups (informal settlements, schools, hospitals, and lower class settlement areas) have shown the spatial considerations for priorities in provision and specific design of evacuation shelters, improvement of evacuation routes, and provision of vehicle support [85].

² In absolute terms, the youngest age group showed the most fatalities.

³ Similar findings were also generated through studies in India (Guha-Sapir et al. 2006)

Access to warning was assessed using household survey, survey of critical facilities and spatial data on location of warning devices showing different levels of access to warning due to dynamic population distribution [85]. Moreover, access and utilization of private devices to receive warning information is proven to be related with socio-economic characteristics (income, gender, age) [85]. Thus, the allocation of public broadcasting devices needs to take into consideration such conditions.

Evacuation behaviour determines the utilization and effectiveness of the existing infrastructure and technical measures. The data analysis in Padang showed that evacuation bottlenecks are likely to occur due to the potential delays in evacuation decisions at household level, lack of harmonized evacuation arrangements, gaps in knowledge of recommended safe places, and the preferred use of available motorized vehicles as mode of evacuation [85]. Moreover, correlation and regression analysis of the **cognitive factors** derived from household surveys showed a significant influence of these factors influencing the intention to conduct reactive (evacuation after a warning) and proactive (support and participation in the improvement of evacuation infrastructures) action [85]. Various cognitive factors related to objective knowledge (e.g. indicators of tsunami occurrence) and socio-psychological factors (e.g. recognition of lack of preparedness, concerns of livelihoods) need to be incorporated into the development of risk communication strategies [85].

An exposure analysis in a context of evacuation for the city of Padang was conducted for population groups with different evacuation (physical) capability, using activity diary as part of household surveys, combined with local statistics and building data from remote sensing analysis [86]. It emphasizes differentiated exposure due to spatial distribution of the city functions (building uses) and characteristics of the population such as working activities, gender, and income groups [85]. Overall, the case study of Padang revealed that the **gender, age, income level, and ethnic groups** played a role in response capability of the population, such as differentiated exposure, level of awareness, access to existing measures and facilities [85]. This has put more emphasis on different strategies to meet the needs of different social groups.

4.4. Factors related with reconstruction and restoring livelihoods

On this aspect, additional susceptibility and coping factors, especially in the phase of recovery, were identified particularly in the case study of Sri Lanka. Here, **income and employment** were revealed as important factors. Low-income groups considerably lost income in the aftermath of the tsunami and were more likely to lose their jobs than those households with comparatively high income (21,000 rupees or more) ([9,11], p. 30 f).

The **economic and financial status** also played an important role with respect to *coping* with the tsunami impacts since low-income households require a longer period of time to reconstruct housing and/or replace other damages ([9,11], p. 32, [110]). In this respect, the occupation of the household head played an important role.

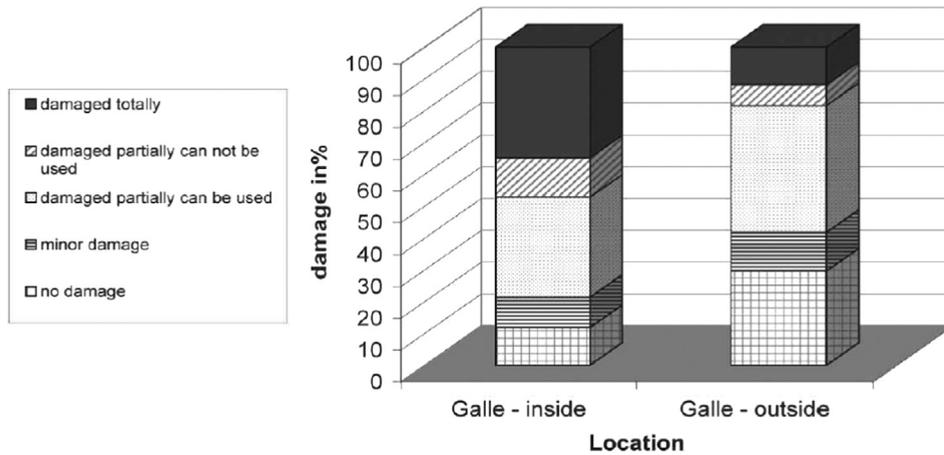


Fig. 5. Housing damage inside and outside the 100-m zone in Galle (Source: [9,11], p. 29).

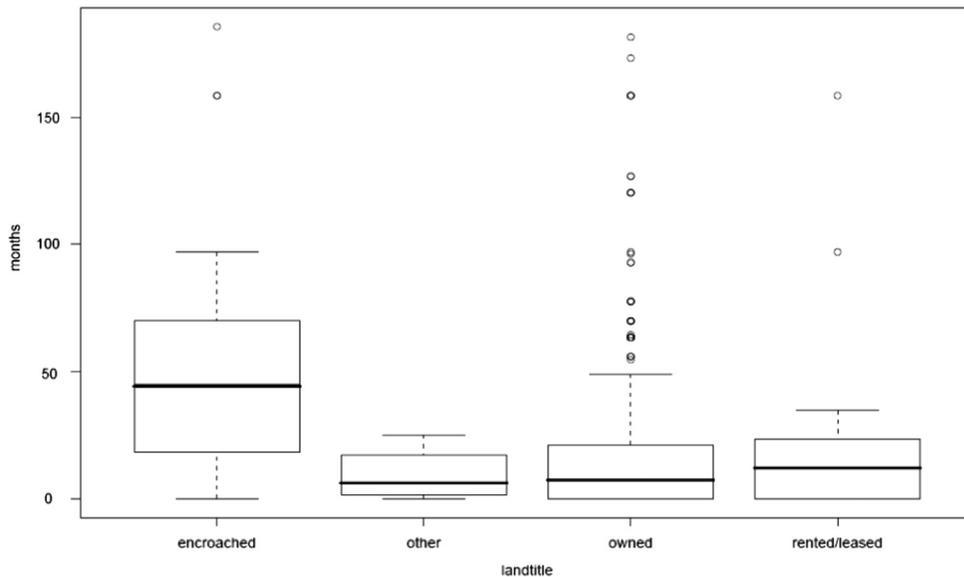


Fig. 6. House damage and land title (Source: [9,11], p. 35).

Specifically, those households with a lower economic and financial status were overproportionally exposed in the 100 zone as compared to higher income groups. The **land title** is an additional factor being closely related to financial status and the marginal living spaces of lower income groups (the number of illegal settlers is twice as high in the 100-m high risk zone than outside of it [10], p. 97) and was also found to play an important role with respect to recovery. While house owners or those renting housing needed about a year to recover from the tsunami, those living in informal settlement needed almost four times as long (based on the median of answers) (Fig. 5). Households without a land title can also be regarded as potentially more vulnerable since it serves also as economic and livelihood resource which can even be sold in times of crisis [83] (Fig. 6).

Comparing the case studies of Galle and Batticaloa, people in Batticaloa were found to have difficulties in recovering from the hazard impact due to lower job

diversity, an overall lower income and limited options for opening an employment – all results of the armed conflict of the past two decades ([45], p. 45).

5. Progress in using hazard and vulnerability information

5.1. Case studies from Indonesia and Sri Lanka

The research conducted in the two case study areas of Padang and Galle showed that a variety of factors are important for tsunami risk and impact. These include generic factors such as distance to the sea, and DRM-specific factors such as early warning, evacuation and resettlement strategies. Various tsunami risk reduction measures have been developed since 2004, especially with regard to improvement of urban planning, tsunami early warning system, and tsunami awareness. Consideration of hazard and vulnerability aspects in urban planning.

The tsunami loss and lack of coping capacity have been found to be markedly different within 100 m of the coastline compared to other areas. Accordingly, the development of a *buffer or no construction zone*, where construction and development are restricted by urban development regulations, has been suggested as a tsunami risk reduction measure ([10], p. 99). In Sri Lanka, buffer zones of 100 m and 200 m were initially discussed, but were later reduced to 50 m after the election in 2007 [10] causing insecurity with respect to (individual) investment decisions and tensions ([10], p. 53). Accordingly, buffer zones have to be developed consistently and transparently while considering the needs of different household types such as fishermen (ibid.). Overall, the implementation of buffer zones can be a challenge due to the scarcity of land close to the original settlements, especially in urban areas ([7,8], p. 63 f).

With regard to exposure reduction, tsunami hazard considerations were integrated into the city spatial plan of the Indonesian city of Padang (RTRW 2010–2030). Based on the new plan, the area where the tsunami hazard level is high should be used as open space. The development in the coastal areas should also be oriented rather towards non-settlement development with lower density. The seismic building code is more strictly applied especially for new buildings in the hazard zone. The current plans seem to already take into consideration the tsunami hazard and vulnerability to some extent. However, specific protection standards for facilities or buildings with more vulnerable people (hospitals, schools, even settlements), for example, are still needed.

With respect to the establishment of buffer zones and exposure reduction, resettlement played an important role in the aftermath of the 2004 tsunami and the respective reconstruction efforts. This is also the case in the already densely built coastal areas with high tsunami hazard level (like in the case of Padang). However, resettlement strategies are still discussed in the context of the establishment of no construction/development in the hazardous areas. In Padang, possible relocation due to tsunami risk reduction was perceived as difficult [85]. The UNU-EHS Household Survey in 2008 showed that household income is associated with perception of ease to move and find job in case of relocation and suggested difficulties especially for the lower-income group (ibid.). Resettlement decision can thereby be influenced by a variety of factors. In Galle, Sri Lanka the decision was for example shaped by characteristics such as the lack of a land title ([10], p. 100) or the level of destruction of the housing [40]. It appears that immediately after the tsunami event the affected households might have been traumatized and not being able to start a new life at a different location (ibid., p. 72). Relatives in the resettlement areas instead served as pull factors ([40], p. 74).

Supporting studies [9,11,31] on the case study of Sri Lanka demonstrated that most of the people displaced due to tsunami – except for the households in the buffer zone that were engaged in fishery – preferred to move outside the affected areas, but still wanted to keep their access to the previous locations. In contrast, the enforcement of the buffer zone regulation by the Sri Lankan government

forced those people to move to new settlements far away from their previous locations, due to limited available space [31]. In spite of government's efforts to implement an inclusive resettlement policy, most of the relocatees were not fully involved in the relocation process. Identification of beneficiaries to handover houses was done by the government officials through a process that was not transparent. No proper vulnerability assessment was conducted by either the donors or the government officials among the selected beneficiaries in order to identify those households with inherent or other socio-economic vulnerabilities who needed more assistance in the relocation process to gradually adapt to the new location [32]. The resettlement process caused multiple stress factors such as long distance to the city, lack of employment opportunities in the new place, lack of common services, conflicts between new and old settlers for common property resources, more expenses for electricity, water and transportation, and poor quality houses, which especially affected the vulnerable households [31]. This in turn forced many of the relocatees to move back to the buffer zone illegally by renting, closing or selling their new houses in the new settlements several years after the relocation. Consequently, they are once again exposed to tsunami and other coastal hazards [31]. This highlights the need for a people-centred resettlement process from the beginning in order to ensure an effective disaster risk reduction [32].

5.2. Consideration of hazard and vulnerability aspects in early warning

Overall, Indonesia has made significant progress in incorporating early warning systems (including tsunami) in development planning. Development of early warning systems is among the five key priorities in the National Action Plan for Disaster Reduction 2006–2009 [101]. The development of **Tsunami Early Warning System** in Indonesia, in cooperation with local authorities and disaster management bodies, has been advancing in the past decade. In the city of Padang, the new disaster management body (BPBD) was established in 2009, and it has been coordinating with various local governmental and non-governmental actors in tsunami risk reduction efforts. The tsunami hazard map was utilized as a basis of evacuation planning (an official evacuation map was developed based on the agreed hazard zone and urban physical boundaries), which were disseminated through street billboards and leaflets to the community.

Additionally, the needs of vertical evacuation structures in the coastal districts, including in the city of Padang, were recognized and funding have been allocated by the National Disaster Management Agency (BNPB). In this respect, several new vertical evacuation structures were constructed especially after the earthquake event in September 2009 in Padang as part of reconstruction activities, mostly in form of multi-functional, multi-storey buildings (e.g. schools), as well as large space for evacuation hills were allocated. It was also mentioned in the spatial plan, that the planning of evacuation shelters need to take into account the women, children, and elderly. Thus, specific

information on factors related with early warning and evacuation such as spatio-temporal distribution of vulnerable groups, but also evacuation behaviour can be used for the future planning of such facilities.

Despite of these developments – which are still concentrated in regions where national and international projects took place as in the city of Padang, the tsunami that hit Mentawai Islands in 2010, killing more than 500 persons, demonstrated that significant challenges remain in designing a successful early warning system for tsunamis. Although a tsunami warning was issued, only a few people were able to evacuate at Mentawai [94]. This shows that more progress needs to be made both with respect to the warning architecture in poorly developed regions and with respect to increasing tsunami awareness in exposed areas.

5.3. Consideration of hazard and vulnerability aspects in awareness raising

Various awareness raising and community preparedness activities were arranged by local NGOs in the city of Padang. Different approaches were applied (involvement of religious and community leaders, focusing on emergency training, community evacuation planning, etc.) and various social groups in the city were covered. School and community education started to include information about earthquake and tsunami hazard characteristics and natural signs, although there is still limited common knowledge available at the moment. Additionally, city-wide tsunami drills were conducted regularly, and tsunami knowledge is now incorporated in school activities (to be institutionalized as a formal curricula). Information and criteria from the analysis of early warning and evacuation factors related to cognitive factors of various social groups have also been used to assess the impact of community capacity building activities. However, this has only been done in a pilot scale.

6. Identified gaps

From a methodological perspective, important progress has been made in the last decade advancing from hazard mapping to the identification of vulnerability factors and the development of methodologies to analyse the overall tsunami risk. Different methodologies in assessing vulnerability, such as engineering and social scientific approach discussed in the previous sections, have been identified and they provide useful information for different planning purposes. Some of these tools are applied in DRM activities at national and local levels. However, in the actual planning activities, the use of such information often encompass the use of hazards maps only for the establishment of buffer zones without any further planning of construction/development areas or evacuation routes. More advanced methodologies encompassing vulnerability factors have not been fully integrated into risk management activities. In addition, the incorporation of the existing vulnerability information into DRM is still low and existing information is not translated systematically into action. As discussed in the previous section, the assessment of (societal, in particular) vulnerability has pointed out gaps in the ongoing tsunami risk reduction, such as specific consideration of

social groups in providing early warning and evacuation facilities or lack of involvement of vulnerable groups in case of relocation.

The systematic utilization of vulnerability information related to people's response capability (exposure map, early warning access map, analysis of evacuation behaviour) for planning was also not clearly indicated. Specific recommendations derived from the vulnerability assessment (e.g. potential locations and considerations for evacuation shelters) were not fully materialized presently, due to limited financial resources available with regard to many other competitive development needs (Setiadi, non-structure interviews in 2009, review of local planning documents and newsletters). Information and assessment for example on the cognitive factors was utilized to monitor awareness raising activities, however only for pilot project activities. Instead, the planning of evacuation shelters focused rather on physical construction of the shelters, but has not fully considered specific aspects such as evacuation behaviour, utilizations by various social groups as revealed in the vulnerability assessment previously. It is crucial to ensure the position and role of vulnerability and risk assessment in ongoing development planning.

The same holds true for the case studies in Sri Lanka. Although a variety of vulnerability indicators such as socio-economic factors, the lack of land title or information of resettlement decisions were identified, the respective information did not translate into DRM. This was partially reflected in the failed resettlement processes. Even though the 2006 Disaster Management Roadmap identified the need for integrating DRM and land use planning ([62], p. 172), guidelines have been developed while concrete codes are lacking (e.g. [63,64]). Existing guidelines are, however, not applied consistently. The resettlement policy for development activities developed in 2001 was not used when relocating tsunami-displaced households under the buffer zone regulation. Nowadays, additional topics such as climate change adaptation and other, more frequent hazards, such as landslides or floods seem to compete for attention and financial resources [63].

It also needs to be mentioned that some putative risk reduction measures might also create second-order vulnerabilities, calling for detailed analysis and careful implementation in DRM. Regarding resettlement policies, livelihood aspects such as land tenure as well as proximity to livestock, access to fishing grounds and farmland have to be integrated into resettlement planning in order to avoid worsening the individual situation of households ([49] or [52]). Nevertheless, access to physical and social infrastructure was disrupted through resettlement processes and not sufficiently represented at the resettlement sites [7,8,31].

Another challenge of vulnerability assessment found from the case study of Padang, Indonesia, was the inexistence of a centralized database and information sharing among different agencies and local and regional institutions in the city. The information is often scattered or stored locally, and consequently it is difficult to use and update vulnerability information systematically. At the moment there are several, but no common, guidelines on tsunami vulnerability and risk assessment (cf. [55,73,70]),

that may impede continuous monitoring of vulnerability to tsunamis. There is also trade-off between the level of detail of assessment and the costs/technical requirements: more detail, more cost intensive and requires higher technical capacity. Costs of vulnerability assessment should be properly budgeted to ensure its sustainability.

7. Conclusions and recommendations

Ten years after the 2004 Indian Ocean Tsunami, it is evident that Indonesia has taken major steps to improve its preparedness for dealing with the tsunami threat in its most populated coastal communities, as demonstrated in this paper for Padang. In this respect, the international assistance and cooperation among different countries have been essential. Yet most people in the nearby Mentawai Islands were unprepared when the tsunami hit those islands in October 2010. It seems that despite the alarming reports above, it is difficult to build tsunami awareness in areas not previously affected by tsunamis. Yet, it has been demonstrated by for example Gaillard et al. [35] and Fritz and Kalligeris [33] that ancestral heritage lead to larger self-evacuation and reduced mortality for the both the 2004 Indian Ocean Tsunami (island of Simeulue) and the 2007 Solomon Island tsunami, respectively. The long-term recurrence rate associated with the destructive tsunamis makes it challenging for the population to build this experience. In many situations, unprecedented factors play a major role in large future disasters. For instance, could a tsunami triggered by a large submarine landslide cause the next great disaster in a coastal region with low seismic activity (see [41] for a discussion). Such unprecedented events would certainly pose new challenges to vulnerable coastal communities.

In the past decade, progress was made in the understanding and quantification of vulnerability that can form the basis for the development of disaster risk reducing strategies. However, systematic utilization of vulnerability information for development of tsunami risk reduction in the DRM as demonstrated in the study areas of Padang and Galle is still limited. Well-designed early warning systems, as well as evacuation and land use strategies are still lacking in many tsunami-exposed regions. Additionally, second-order vulnerability like that revealed in case of relocation due to tsunamis is hardly considered in the planning process.

For the post-Hyogo process this is relevant in three ways: (1) More stringent implementation of existing priorities and actions under the HFA, for example, in the context of land use planning (Action 4–3), (2) Identification of new indicators and criteria to promote the continuous monitoring and use of hazard and vulnerability information in actual planning, and (3) Increasing and monitoring continuous awareness of the exposed population.

Regarding the implementation of existing HFA priorities, there is a need for more detailed studies on why they were not applied. Limitations in the availability of (centralized) data, financial resources, and lack of capacities might play a role. Planning regulations should provide a strong institutional basis to clarify the role and requirements of vulnerability and risk information in the planning process. Furthermore, a clarification of the roles of various stakeholders (government

agencies, local community and private sector) is needed in many places.

More work on the development of indicators and criteria to determine the use of vulnerability information in disaster risk management, that also allows assessing the effectiveness of key strategies and tools, like people-centred 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. Furthermore, respective indicators and criteria (e.g. specifically developed for the use of vulnerability aspects in early warning and resettlement strategies) will allow for the identification and reduction of the causes of disaster risk. While global databases and indicators might allow for analysis of risk or vulnerability profile on a national or regional level, the lack of conserving vulnerability aspects in evacuation plans or missing building codes are not reflected in such assessments. Effective application of the knowledge about vulnerability aspects is thus needed for successful implementation of DRR measures. Finally, the development of risk and vulnerability indicators and assessment methodologies are of little help if no or hardly any use is made of them at the national and local level.

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Appendix A. Stakeholders' involvement in development of the tsunami hazard map in Padang city, Indonesia

The city of Padang, Indonesia, has been recognized as a tsunami-prone area, where a potential major earthquake and tsunami could occur in the near future. As part of the

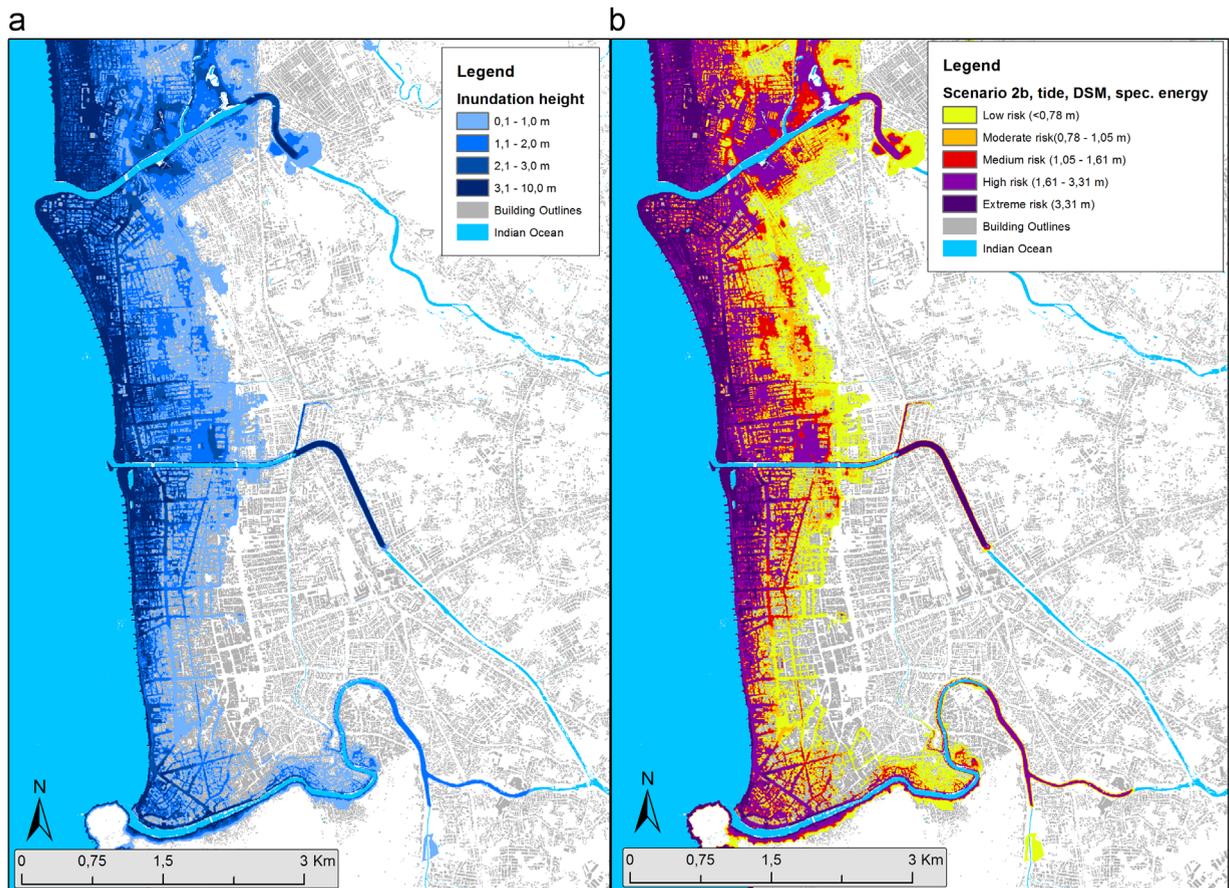


Fig. A1. A set of maps developed by Taubenböck et al. (2013) [95] for a tsunami scenario hitting Padang: (a) inundation height and (b) specific wave energy of the tsunami [95].

tsunami risk reduction efforts in the city, various international scientific groups as well as local actors developed tsunami hazard maps as basis for mitigation and evacuation planning (e.g., Figure A1). However, the hazard information contained in the maps (hazard and exposure zones) was significantly different due to different approaches and basis data used. As of August 2008, at least eight different hazard maps were identified (GTZ, personal communication 2008).

The so-called “Padang consensus” meetings were conducted as a platform for different groups of international and national scientists, as well as local decision makers, to discuss the most acceptable hazard scenario and mapping approach for the city. Agreement was reached on the following major issues: earthquake source scenario (e.g. most plausible worst case, multi-scenario probability approach), basis data (topographical, bathymetry), and modelling parameters (e.g. consideration of roughness coefficient, consideration of buildings that modify the tsunami wave energy and potentially inundated areas). Despite ongoing discussion on the most suitable planning basis and existing uncertainty, such a process has provided an opportunity of reconciling various state-of-the-art scientific findings and has been a showcase of a science policy platform in advancing tsunami hazard information.

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