Earth-Science Reviews 110 (2012) 58–73

Contents lists available at SciVerse ScienceDirect

Earth-Science Reviews

journal homepage: www.elsevier.com/locate/earscirev

# Tsunami hazard and exposure on the global scale

Finn Løvholt [a,b,*], Sylfest Glimsdal [a,b], Carl B. Harbitz [a,b], Natalia Zamora [b,i], Farrokh Nadim [a,b], Pascal Peduzzi [c], Hy Dao [c,d], Helge Smebye [a,b]

[a] NGI, P.O. Box 3930, 0806 Ullevål Stadion, Oslo, Norway
[b] International Centre for Geohazards, co NGI, Oslo, Norway
[c] United Nations Environment Programme, DEWA/GRID-Europe, 11, ch. Anémones, 1219 Chatelaine Geneva, Switzerland
[d] University of Geneva, Switzerland

ARTICLE INFO

*Article history:*
Received 25 January 2011
Accepted 8 October 2011
Available online 28 October 2011

*Keywords:*
Tsunamis
Hazard assessment
Population exposure
Global study
Literature review

ABSTRACT

In the aftermath of the 2004 Indian Ocean tsunami, a large increase in the activity of tsunami hazard and risk mapping is observed. Most of these are site-specific studies with detailed modelling of the run-up locally. However, fewer studies exist on the regional and global scale. Therefore, tsunamis have been omitted in previous global studies comparing different natural hazards. Here, we present a first global tsunami hazard and population exposure study. A key topic is the development of a simple and robust method for obtaining reasonable estimates of the maximum water level during tsunami inundation. This method is mainly based on plane wave linear hydrostatic transect simulations, and validation against results from a standard run-up model is given. The global hazard study is scenario based, focusing on tsunamis caused by megathrust earthquakes only, as the largest events will often contribute more to the risk than the smaller events. Tsunamis caused by non-seismic sources are omitted. Hazard maps are implemented by conducting a number of tsunami scenario simulations supplemented with findings from literature. The maps are further used to quantify the number of people exposed to tsunamis using the Landscan population data set. Because of the large geographical extents, quantifying the tsunami hazard assessment is focusing on overall trends.



**Contents**



* Corresponding author at: NGI, Oslo, Norway. Tel.: +47 22023043, +47 95793100 (cell); fax: +47 22022348.
*E-mail addresses:* finn.lovholt@ngi.no (F. Løvholt), Sylfest.glimsdal@ngi.no (S. Glimsdal), carl.bonnevie.harbitz@ngi.no (C.B. Harbitz), n_zamoras@hotmail.com (N. Zamora), farrokh.nadim@ngi.no (F. Nadim), pascal.peduzzi@unepgrid.ch (P. Peduzzi), hy.dao@unepgrid.ch (H. Dao), helge.smebye@ngi.no (H. Smebye).
[i] Previously at ICG, now at GFZ German Research Centre for Geosciences.

0012-8252/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.earscirev.2011.10.002

## 1. Introduction

The devastating 2004 Indian Ocean tsunami led to increased awareness of the destructing capabilities of tsunamis. The focus on and implementation of Tsunami Early Warning Systems (e.g. Rudloff et al., 2009; Behrens et al., 2010; Lauterjung et al., 2010), awareness building, physical mitigation measures, and hazard and risk mapping (e.g. Berryman et al., 2005; Borrero et al., 2006; Løvholt et al., 2006; Burbidge and Cummins, 2007; Power et al., 2007; Lorito et al., 2008; McCloskey et al.;, 2008; Okal and Synloakis, 2008; Sengara et al., 2008; Gonzalez et al., 2009; Parsons and Geist, 2009; Post et al., 2009; Brune et al., 2010; Gayer et al., 2010; Roemer et al., 2010; Harbitz et al., in press; Løvholt et al., submitted to) have been strengthened in many countries. This paper presents a study related to the global tsunami hazard and population exposure, a first step towards an estimate of the global mortality tsunami risk. The study was a contribution to the UN-ISDR Global Assessment Report on Disaster Risk Reduction (GAR) assessing most natural hazards (UN-ISDR, 2009). It is, to the authors knowledge in contrast to earlier local and regional studies, the first of its kind extending globally.

The Hyogo Framework for Action (HFA) was adopted in January 2005 by 168 governments at the World Conference on Disaster Reduction and includes six priorities for reducing disaster risk. This research addresses priority 2 of the HFA and aims to *identify, assess and monitor disaster risks and enhance early warning*, by *generating risk assessments and maps, elaboration and dissemination of multi-risk*.

The result of this study is a first assessment of the tsunami hazard and population exposure. The study focuses on tsunamis caused by megathrust earthquakes only, as the largest events will often contribute more to the risk than the smaller events (Nadim and Glade, 2006). Tsunamis caused by landslides, rockslides, and volcanoes were not covered in the study. This is mainly due to lack of reliable models for quantifying tsunami hazard and particularly return periods globally for such sources.

Emphasis is given to producing regional hazard maps for less developed countries rather than for countries clearly able to cope with tsunami risk themselves. The results from the scenario simulations were supplemented by information from available reports and scientific papers. The GAR was completed within a fast track scheme by medio 2008. As a result, the reports and publications completed at later dates could not be included in the current study. Moreover, the effects of major events such as the 2009 Maule (e.g. Madariaga et al., 2010) and the 2011 Tohoku-Oki (e.g. Geller, 2011; Ozawa et al., 2011) earthquakes are not taken into account.

This paper has a strong focus on the methodology, but it also provides an elaborate overview over previous local and regional tsunami hazard studies around the world. A key topic is the development of a simple and robust method for obtaining reasonable estimates of the maximum water level during tsunami inundation, which is referred to as the method of amplification factors. Combined with numerical tsunami analyses, the method of amplification factors allows the quantification of the coastal tsunami impact for coastlines covering a large portion of the globe due to its low computational cost. The methodology is crude and does not provide results that are applicable on the local scale. Its focus is on overall trends rather than details, a natural objective due to the various and large uncertainties that admittedly exist in a study of this kind.

## 2. Methodologies for the tsunami hazard and population exposure

The tsunami hazard at a given location is defined as the temporal probability of occurrence of a given tsunami metric at that location, e.g. the annual probability of a run-up exceeding a given threshold. Here, the purpose is producing regional hazard maps, presenting the maximum water levels for a return period of 475 years, or a 10% exceedance probability in 50 years. Reliable estimates of the hazard at such large return periods are not easily established, particularly given the geographical extent of the problem and various sources of error and uncertainty. Hence, the reference return period dealt with in this paper (475 years) is indicative to the order of magnitude only (generally ranging from 100 to 1000 years). By including the population exposure, the current study is a first step towards quantifying the global tsunami mortality risk. We intersected the probability of hazard occurrence with models of population density (Landscan, 2007) and economical values located in tsunami-prone areas in order to compute the average yearly exposure. We note that quantifying the tsunami risk, defined as the product of the hazard, population exposure and the vulnerability (degree of loss to an element at risk) is beyond the scope of this paper.

### 2.1. Tsunami hazard and risk assessment

Tsunami hazard analysis is traditionally scenario-based (Tinti and Armigliato, 2003; Løvholt et al., 2006; Okal et al., 2006; Lorito et al., 2008; McCloskey et al., 2008; Okal and Synloakis, 2008) defined as events that could occur in the future and often related to poorly constrained probabilities or return periods. In the aftermath of the 2004 Indian Ocean tsunami, the Probabilistic Tsunami Hazard Analysis (PTHA) methodology has been developed and put to use (Geist and Parsons, 2006; Annaka et al., 2007; Thio et al., 2007). However, Nadim and Glade (2006) suggested that the scenario based approach is best suited for tsunami hazard and risk assessment. Based on their conclusions and taking into account the geographical extent of the problem, among others, it was decided to use the scenario based approach and not to include the vulnerability in the analysis. Below, we briefly review some of the key findings of Nadim and Glade (2006), as well as adding some new points:

- The numerical resources needed in PTHA are much higher than in the Probabilistic Seismic Hazard Assessment (PSHA) owing to the need in performing forward wave modelling. Nevertheless, recent attempts on performing PTHA for a large number of tsunami simulations covering large areas are promising (Sørensen et al., in press).
- For tsunamis, it is likely that there is a threshold for the tsunami metric (i.e. flow depth) where the consequence (i.e. mortality) changes rapidly, indicating a strong non-linearity in the relation between the metric and the consequence. In addition, the non-linear increase in the tsunami hazard and exposure (as exemplified below for the city of Seaside, Oregon, by Gonzalez et al., 2009) magnifies the non-linearity.
- The least probable events may cause huge losses, and hence dominate the risk. It is clear that the hazard for the scenario events with return periods of several hundred years or more is extremely uncertain. In a PTHA analysis, increased uncertainty is therefore expected for the largest return periods.