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TESIS DOCTORAL

HACIA UNA GESTIÓN INTEGRADA DEL RIESGO DE DESASTRES POR INUNDACIÓN COSTERA

Towards an integrated disaster risk management due to coastal flooding

DOCTORANDA:

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Agradezco a mis directores de tesis su apoyo durante el todo el proceso. A Raúl Medina le agradezco su apoyo desde que me incorporé al IH Cantabria (el GIOC en su día) para trabajar en gestión costera, su confianza, sus buenos consejos y el tiempo dedicado. A Mauricio González le agradezco la oportunidad de meterme en el mundo de los tsunamis y los riesgos costeros, tema que me apasiona y disfruto muchísimo, así como el reconocimiento a mi trabajo y la confianza depositada en mí. A mi equipo cercano de trabajo, Oscar y Nacho al principio y ahora María también, por el trabajo compartido durante tanto tiempo en gestión costera y riesgos, y porque me encanta compartir proyectos, mesa y el día a día con vosotros. A Nacho, porque parte de esta tesis ha sido gracias al esfuerzo conjunto en otros proyectos, a la visión común que tenemos del tema del riesgo y a nuestro genial trabajo en equipo.

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Foreword

Format of the PhD Thesis: thesis by publications

The regulation for the preparation of doctoral thesis as a compendium of articles in the Department of Science and Technology of Water and Environment (CYTAMA), University of Cantabria, provides the following conditions:

- Minimum number of required articles: two articles in the same line of research published in the scientific journals included in the Journal of Citation Reports-Science Edition.
- Maximum age of publications: articles must be published or accepted for publication from the year of commencement of graduate studies
- Mechanisms to guarantee the PhD candidate authorship and the originality of the work: a copy of the published articles must be provided

The work presented in this thesis has resulted in four scientific articles that are attached as Annex I to this document. Two of them are already published while the other two have been submitted and are under review.

González-Riancho, P., Aguirre-Ayerbe, I., García-Aguilar, O., Medina, R., González, M., Aniel-Quiroga, I., Gutiérrez, O. Q., Álvarez-Gómez, J. A., Larreynaga, J., and Gavidia, F.: Integrated tsunami vulnerability and risk assessment: application to the coastal area of El Salvador, Nat. Hazards Earth Syst. Sci. 14:1223–1244, 2014.

Impact factor: 1.826 (2013)

González-Riancho, P., Aguirre-Ayerbe, I., Aniel-Quiroga, I., Abad, S., González, M., Larreynaga, J., Gavidia, F., Gutiérrez, O. Q., Álvarez-Gómez, J. A., and Medina, R.: Tsunami evacuation modelling as a tool for risk reduction: application to the coastal area of El Salvador, Nat. Hazards Earth Syst. Sci., 13, 3249-3270, doi:10.5194/nhess-13-3249-2013, 2013.

Impact factor: 1.826 (2013)

González-Riancho, P., Aliaga, B., Hettiarachchi, S., González, M., and Medina, R.: 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). *Submitted to Nat. Hazards Earth Syst. Sci., September 2014, under review.*

Impact factor: 1.826 (2013)

P. González-Riancho, B. Gerkensmeier, B. Ratter, M. Gonzalez and R. Medina. Storm surge risk perception and resilience: a pilot study in the German North Sea Coast, *Ocean & Coastal Management OCMA-D-14-00389, under review.*

Impact factor: 1.769 (2013)

Chapter 1. Introduction

This introductory chapter presents the motivation of the thesis, the thesis research questions and objectives, the thesis structure and a note on experiences, references and projects regarding the scientific contribution of the work.

1.1 Motivation / description of the problem

Advances in the understanding and prediction of natural hazards impacts allow the development of risk reduction strategies for hazard-prone areas. Risk assessments are essential for the identification of the exposed areas and of the most vulnerable communities and elements, with the hazard, vulnerability and risk results being critical for the formulation of adequate, site-specific and vulnerability-oriented risk management options.

Risk-related works in the literature differ according to the risk component analyzed (i.e. hazard, exposure, vulnerability, impacts, resilience, coping capacity, etc.), the risk dimension dealt with (i.e. human, infrastructural, environmental, social, economic, administrative, legal, etc.), and the spatial scale tackled (i.e. regional, national, local, etc.), thereby proving the complexity associated to risk assessment and management.

Individual risk, hazard and/or vulnerability assessments can be partial, sectoral or specific. However, risk management requires an integrated and holistic understanding of the coupled human and natural system (CHANS) dealt with; otherwise management options can produce unexpected and sometimes undesired results. According to Rotmans and Dowlatabadi (1998), the integrated assessment is aimed at combining, interpreting and communicating knowledge from diverse scientific fields in order to comprehensively tackle an environmental problem by stressing its cause-effect links in their entirety. Integration refers here to the understanding and combination of risk components, dimensions and scales affecting a CHANS, one of the major challenges being the systematic combination and aggregation of different types of data and information (i.e. quantitative vs. qualitative) from various disciplines, scales and data acquisition methodologies.

Vulnerability is multi-dimensional and differential, as it varies across physical space and among and within social groups; scale dependent regarding time, space and analysis units; and dynamic, as the characteristics and driving forces of vulnerability change over time (Vogel and O'Brien, 2004). The current literature encompasses several different definitions and concepts to systematize vulnerability, such as those provided by Chambers (1989), Bohle (2001), Wisner et al. (2003), Downing et al. (2006), UN/ISDR (2004), Pelling (2003), Luers (2005), Green (2004), UN-Habitat (2003), Schneiderbauer and Ehrlich (2004), van Dillen (2004), Turner et al. (2003), Cardona (2004). Many conceptual frameworks for vulnerability analysis have been also developed, such as the Bohle's double structure of vulnerability (Bohle, 2001), the sustainable livelihood framework (DFID, 1999), the conceptual framework to identify disaster risk (Davidson, 1997; Bollin et al., 2003), the risk framework as a result of vulnerability, hazard and deficiencies in preparedness (Villagrán de León, 2001/2004), the ISDR framework for disaster risk reduction (UN/ISDR, 2004), the Turner et al.'s Vulnerability Framework (Turner et al., 2003), the onion framework (Bogardi and Birkmann, 2004), the Pressure and Release (PAR) model (Wisner et al., 2003), the theoretical framework and model for holistic approach to disaster risk assessment and management (Cardona and Barbat, 2000), the BBC conceptual framework (Bogardi and Birkmann 2004 and Cardona 1999/2001), among others. Although the international community does not formulate guidelines on how to develop indicators or indicator systems to assess vulnerability (Birkman, 2006), the Hyogo Framework for Action (UN/ISDR, 2013) underlines the fact that impacts of disasters on social, economic, and environmental conditions should be examined through such indicators.

Despite the existing amount of academic work on the topic, very little information is provided about how to apply the different existing theoretical and conceptual frameworks and how to integrate the different risk-related concepts. Furthermore, risk assessment results sometimes do not provide conclusions on how to reduce the risk at the identified areas, lacking a clear correlation between risk assessment and management.

In summary, there are multiple risk and vulnerability frameworks and definitions, however, most of them are too theoretical and have low or difficult applicability. The vulnerability and risk assessment works found in the literature show a lack of integrated approach to understand complex systems and a need for clarifying the definition of vulnerability indicators. Finally, a gap has been found between science and management, since risk assessment results are not automatically connected to options for risk reduction.

1.2 Thesis research questions and objectives

The thesis is driven by two general problems, which always arise while dealing with the management of complex coastal systems located in natural hazards prone areas. These two general problems can be formulated with the following questions:

How can we understand and describe the complexity of coastal systems to better measure their vulnerability and risk to different natural hazards?

How can we translate the scientific work carried out to assess the risk into more useful and practical information for coastal managers and policy-makers?

Therefore, the scientific topic dealt with within this thesis is the **vulnerability and risk assessment of coastal complex systems to natural hazards in order to move towards an integrated and holistic disaster risk management approach.** This idea is represented in Figure 1.1.

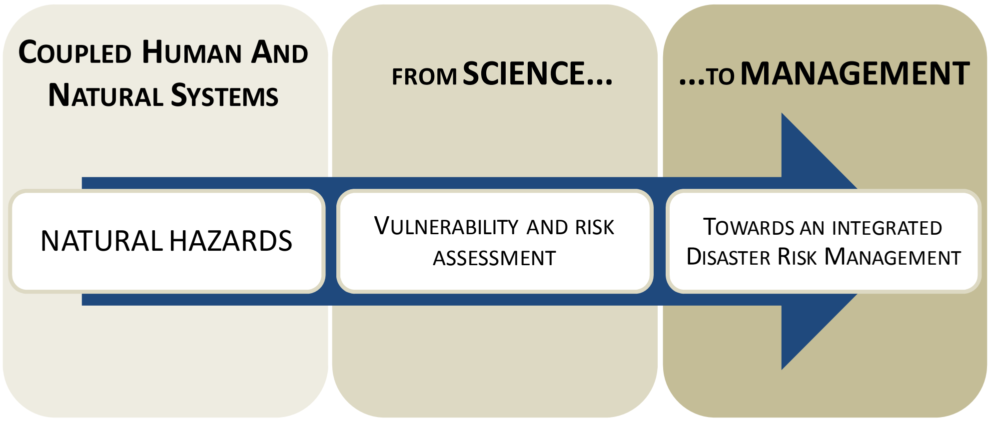

Figure 1.1 Thesis research questions

Due to the large array of terms on risk and vulnerability and the often unclear relationships between them, it is essential to first clarify the main definitions to better understand the thesis objectives.

Risk is defined as the probability of expected harmful consequences or losses resulting from interactions between natural or human-induced hazards and vulnerable conditions (UN/ISDR, 2004), the mentioned *consequences* being the negative effects of disaster expressed in terms of human, economic, environmental, infrastructural and social impacts (adapted from ISO, 2009). Therefore, risk depends on the specific impact analyzed (e.g. loss of human lives), the characteristics of the threat (e.g. flooding), the exposure of the studied elements (e.g. people in urban areas) and their vulnerability (sensitive groups and resilience).

The *Hazard* as a dangerous phenomenon (UN/ISDR, 2009) is analyzed based on the different associated *threats* (which are characterized by their location, intensity, duration, frequency and probability) together with their *dynamics*, i.e. variables and physical processes, involved in their generation. As an example, the specific threats to deal with when analyzing climate change hazard could be, among others, sea level rise or an increase in tropical cyclones and droughts; while the dynamics to study would be waves, tides, sea level, sea temperature, precipitation, etc.

Exposure refers to people, property, systems, or other elements present in hazard zones that are thereby subject to potential losses (UN/ISDR, 2009), while *vulnerability* 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). These vulnerability conditions are here understood to be of two types, internal (unchangeable individual conditions, such as the age of the population) and external (changeable community conditions, improvable through learning and experience, such as the risk preparedness within the communities), the improvement of the latter being a possible countermeasure to reduce the vulnerability of highly sensitive areas. Accordingly, *sensitivity* refers to the intrinsic characteristics of the exposed elements that make them potentially affected by physical or socio-economic changes, including damage and losses (adapted from UN/ISDR, 2004); while *resilience* is the ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions (UN/ISDR, 2009).

The thesis focuses on the entire risk assessment process, covering each of the risk components mentioned before, to link the scientific results with site-specific and vulnerability-oriented risk reduction measures (Figure 1.2).

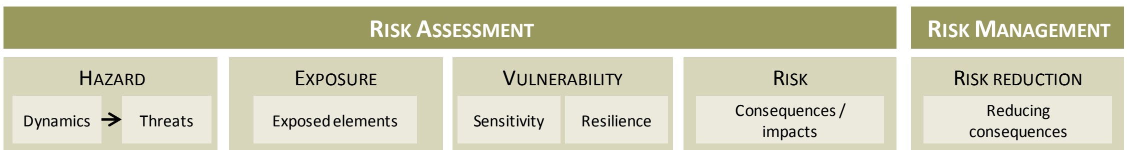

Figure 1.2 Thesis research line

The success or failure of many policies and management practices is based on their ability to take into account complexities of coupled human and natural systems –CHANS- (Liu et al., 2007). Understanding the interrelationships between human societies and their behaviour patterns, coastal resources and their uses, as well as policies and institutions that govern human activities is essential for an adequate coastal management. This requires an integrated and multidisciplinary approach to analyze the entire system in order to understand the feedback loops that manage its behaviour and equilibrium instead of simply considering specific aspects of a single sector or scientific discipline.

Based on this background and on the research questions raised above, the general objectives (G.O.) of the thesis are the following:

- To progress in assessing the potential impacts in complex socio-ecological systems due to various natural hazards (G.O.1.).
- To bridge the gap between risk science and management to facilitate the use of final scientific inputs by coastal managers and policy-makers (G.O.2.).

The specific objectives (S.O.) of the thesis are the following:

- Proposal of a multidimensional and integrated risk assessment framework for CHANS that connects the technical risk assessment with management options (S.O.1)
- Proposal of a framework for tsunami evacuation planning as a specific type of risk reduction measures for the human dimension of the coastal system (S.O.2)
- Contribution to the definition of vulnerability indicators (S.O.3).
  - S.O.3a Sensitivity: validation of the indicators currently proposed by the scientific community to measure tsunami human vulnerability.
  - S.O.3b Resilience: proposal of a resilience framework to understand the capacity of a community to organize itself before, during and after a potential coastal flooding event in order to minimize the impacts.

1.3 Thesis structure

This thesis is organized into 8 chapters. This Chapter 1 is introductory to the core of the thesis. Each of the next four chapters (Chapters 2-5) is associated to an article published or submitted to scientific journals, being self-contained with its own scientific objectives, state-of-the-art review, methodology, results and conclusions. Throughout the text, methodologies are applied to specific case studies to improve reader’s understanding and support the methodological approach proposed by this thesis. Chapter 6 includes a Spanish summary of the articles presented here and Chapter 7 provides a global summary and discussion of the main results as well as the most relevant aspects of the work carried out. Chapter 8 presents the references used in the development of the thesis. Annex I includes a copy of the original published articles.

The first scientific article, on **Integrated tsunami vulnerability and risk assessment**, is presented in Chapter 2 and proposes a methodology to deal with the complexity and variability of coastal zones by means of (i) an integral approach to cover the entire risk-related process from the hazard, vulnerability and risk assessments to the final risk management; (ii) an integrated approach to combine and aggregate the information stemming from the different dimensions of coupled human and natural systems; and (iii) a dynamic and scale-dependent approach to integrate the spatiotemporal variability considerations. This work also aims at establishing a clear connection to translate the vulnerability and risk assessment results into adequate target-oriented risk reduction measures, trying to bridge the gap between science and management for the tsunami hazard. This work has resulted in a scientific paper published in the journal Natural Hazards and Earth System Sciences with the following reference:

> *González-Riancho, P., Aguirre-Ayerbe, I., García-Aguilar, O., Medina, R., González, M., Aniel-Quiroga, I., Gutiérrez, O. Q., Álvarez-Gómez, J. A., Larreynaga, J., and Gavidia, F.: Integrated tsunami vulnerability and risk assessment: application to the coastal area of El Salvador, Nat. Hazards Earth Syst. Sci. 14:1223–1244, 2014.*

The second article (Chapter 3) presents a **framework for the formulation of tsunami evacuation plans based on tsunami vulnerability assessment and evacuation modelling**. This framework considers (i) the hazard aspects, i.e. tsunami flooding characteristics and arrival time, (ii) the characteristics of the exposed area, i.e. people, shelters and road network, (iii) the current tsunami warning procedures and timing, (iv) the time needed to evacuate the population, and (v) the identification of measures to improve the evacuation process. The proposed methodological framework aims to bridge between risk assessment and risk management in terms of tsunami evacuation, as it allows for an estimation of the degree of evacuation success of specific management options, as well as for the classification and prioritization of the gathered information, in order to formulate an optimal evacuation plan. The methodology is applied in this thesis to the case study of El Salvador. This work has resulted in a scientific paper published in the journal Natural Hazards and Earth System Sciences with the following reference:

> *González-Riancho, P., Aguirre-Ayerbe, I., Aniel-Quiroga, I., Abad, S., González, M., Larreynaga, J., Gavidia, F., Gutiérrez, O. Q., Álvarez-Gómez, J. A., and Medina, R.: Tsunami evacuation modelling as a tool for risk reduction: application to the coastal area of El Salvador, Nat. Hazards Earth Syst. Sci., 13, 3249-3270, doi:10.5194/nhess-13-3249-2013, 2013.*

The third article (Chapter 4) focuses on the **validation, in light of past tsunami events, of the indicators currently proposed by the scientific community to measure human vulnerability.** This work validates the human vulnerability indicators currently used by the scientific community, 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. This work has resulted in a scientific paper submitted to the journal Natural Hazards and Earth System Sciences with the following reference:

> *González-Riancho, P., Aliaga, B., Hettiarachchi, S., González, M., and Medina, R.: 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). Submitted to Nat. Hazards Earth Syst. Sci, September 2014.*

The fourth article (Chapter 5) focuses on the analysis of **risk perception and resilience to understand the capacity of a community to organize itself before, during and after a potential coastal flooding event** in order to minimize the impacts. This refers to the disaster management cycle (prevention-preparedness-response-recovery capacities) in the short-term and to the adaptive capacity in the long-term. A questionnaire has been developed to explore the perception of stakeholders regarding the risk and emergency management processes as well as psychological and social factors conditioning individual and community preparedness. The methodology is applied in this thesis to the storm surge hazard and to the case study of the German North Sea Coast. This work has resulted in a scientific paper submitted to the journal Ocean & Coastal Management with the following reference:

> *P. González-Riancho, B. Gerkensmeier, B. Ratter, M. Gonzalez and R. Medina. Storm surge risk perception and resilience: a pilot study in the German North Sea Coast. Ocean & Coastal Management OCMA-D-14-00389, under review.*

As a summary, Table 1.1 shows the contents of each chapter detailing the main topic, the hazard analyzed, the study area and the thesis objectives dealt with.

Table 1.1 Thesis structure: summary

Chapter	Topic	Hazard	Study area	Objectives
1	Integrated risk assessment	Tsunami	El Salvador	G.O.1-2 S.O.1
2	Risk reduction: evacuation modelling	Tsunami	El Salvador	G.O.1-2 S.O.2
3	Vulnerability indicators	Tsunami	Sri Lanka and Thailand (2004), Samoa (2009), Chile (2010), Japan (2011)	G.O.1-2 S.O.3a
4	Resilience and risk perception	Storm surge	German North Sea Coast	G.O.1-2 S.O.3b

Figure 1.3 shows the relationship between chapters/articles within the thesis. Article 1/Chapter 2 provides the overall risk assessment framework, the next articles/chapters focusing into different theoretical and methodological aspects of this framework.

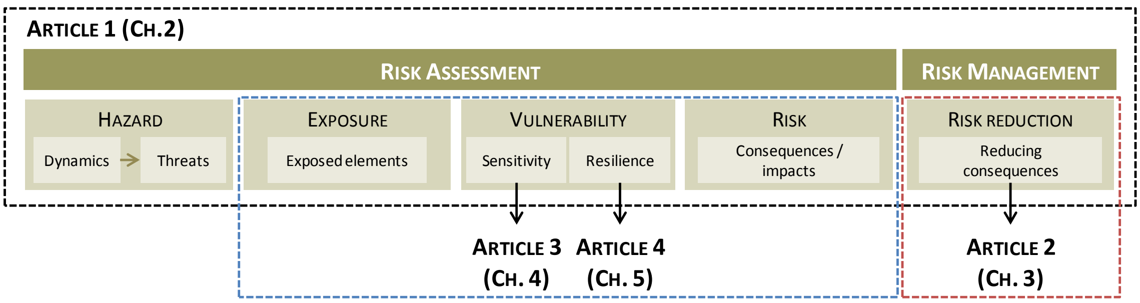

Figure 1.3 Thesis structure: relationship between thesis articles/chapters

1.4 Thesis contribution

This thesis is based on an extended research carried out in the field of coastal vulnerability and risk, and on lessons learnt in the last few years in different practical experiences. The research encompasses the revision of the major experiences in the international coastal risks science and coastal policy arena and has been conducted in parallel with projects which have given a decisive contribution to the results of this work.

1.4.1 Scientific projects

The projects that influenced or have been influenced by the present work, covering the areas of coastal vulnerability and risk to different natural hazards such as tsunami, storm surge, and coastal/river floods, among others, are the following:

Table 1.2 Projects that influenced or have been influenced by this thesis work

TITLE	Tsunami Risk Assessment on the coast of El Salvador (Phase II: Vulnerability and Risk)
SPONSOR	Spanish Agency for International Cooperation for Development (AECID)
DURATION	2010-2012
THESIS CONTRIBUTION	*Development of the research that resulted in **papers 1 and 2.** The review of the state-of-the-art in vulnerability indicators inspired **paper 3.** The resilience assessment carried out inspired **paper 4.***
TITLE	Probabilistic Hazard and Vulnerability Assessment Report based on Climate Change Projections (Peru, El Salvador, Trinidad and Tobago)
SPONSOR	Inter-American Development Bank (IADB)
DURATION	2012
THESIS CONTRIBUTION	*Application of the conceptual framework and methodology developed in **paper 1** to climate change-related flooding in Peru, El Salvador, Trinidad and Tobago. New research: aggregation of vulnerability indicators through k-means method.*
TITLE	Assessment of Coastal Hazards, Vulnerability and Risk for the Coast of Oman (tsunamis and storm surge), in the framework of the "National Multi-Hazard Early Warning System (NMHEWS)"
SPONSOR	Directorate General of Meteorology and Air Navigation (DGMAN), Sultanate of Oman
DURATION	2013-2014
THESIS CONTRIBUTION	*Application of the conceptual framework and methodology developed in **paper 1** to tsunamis and storm surge in Oman and its 9 local study sites. New research: probabilistic hazard assessment, and implementation in an early warning system (NMHEWS).*
TITLE	Assessment, Strategy And Risk Reduction for Tsunamis in Europe (ASTARTE Project)
SPONSOR	European commission. Seventh Framework Programme (FP7)
DURATION	2013-2016
THESIS CONTRIBUTION	*Application of the conceptual framework and methodology developed in **paper 2** to the project study sites. New research: adaptation of the evacuation framework to include both shortest-distance-path (small scale) and agent-based (large scale) evacuation modelling.*

TITLE	Enhancing risk management partnerships for catastrophic natural disasters in Europe (ENHANCE Project)
SPONSOR	European commission. Seventh Framework Programme (FP7)
DURATION	PhD internship, Jan-May 2014
THESIS CONTRIBUTION	*Development of the research that resulted in* ***paper 4*** *(storm surge risk perception and resilience)****.*** *Ongoing replication of this study along the North Sea coast, including the whole trilateral Wadden Sea region (Germany, The Netherlands and Denmark), by the PhD internship host institute (Helmholtz Zentrum Geesthacht, Institute of Coastal Research, Department of Human Dimensions of Coastal Areas).*
TITLE	Disaster Risk Profile for floods, drought and fires in Paraguay
SPONSOR	Inter-American Development Bank (IADB)
DURATION	2014-2015
THESIS CONTRIBUTION	*Implementation of the integrated vulnerability assessment developed in* ***paper 1.*** *New research: aggregation of vulnerability indicators through k-means method to identify the vulnerability patterns of the country and find the method to extrapolate the results obtained in some local detailed analyses to the entire country.*
TITLE	Strengthening of the Caribbean Disaster Emergency Management Agency (CDEMA) in the technical areas of earthquakes and tsunamis
SPONSOR	Spanish Agency for International Cooperation for Development (AECID)
DURATION	2014-2015
THESIS CONTRIBUTION	*Capacity building of the CDEMA on the conceptual frameworks and methodologies developed in* ***papers 1*** *(integrated tsunami vulnerability and risk assessment)* ***and 2*** *(Tsunami evacuation modelling as a tool for risk reduction)*

1.4.2 Scientific production

1.4.2.1 Scientific journals

The work in this thesis translates in 4 scientific articles published and/or submitted to several scientific journals:

1. **González-Riancho, P.**, Aguirre-Ayerbe, I., García-Aguilar, O., Medina, R., González, M., Aniel-Quiroga, I., Gutiérrez, O. Q., Álvarez-Gómez, J. A., Larreynaga, J., and Gavidia, F.: Integrated tsunami vulnerability and risk assessment: application to the coastal area of El Salvador, Nat. Hazards Earth Syst. Sci. 14:1223–1244, 2014.
2. **González-Riancho, P.**, Aguirre-Ayerbe, I., Aniel-Quiroga, I., Abad, S., González, M., Larreynaga, J., Gavidia, F., Gutiérrez, O. Q., Álvarez-Gómez, J. A., and Medina, R.: Tsunami evacuation modelling as a tool for risk reduction: application to the coastal area of El

Salvador, Nat. Hazards Earth Syst. Sci., 13, 3249-3270, doi:10.5194/nhess-13-3249-2013, 2013.

3. **González-Riancho, P.**, Aliaga, B., Hettiarachchi, S., González, M., and Medina, R.: 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). *Submitted to Nat. Hazards Earth Syst. Sci. in September 2014, under review.*
4. **P. González-Riancho**, B. Gerkensmeier, B. Ratter, M. Gonzalez and R. Medina. Storm surge risk perception and resilience: a pilot study in the German North Sea Coast. *Ocean & Coastal Management OCMA-D-14-00389, under review.*

1.4.2.2 International and national scientific congresses and conferences

Besides, the work offered in this thesis has been presented in several scientific congresses and conferences:

1. I. Aguirre-Ayerbe, F. Fernández Pérez, **P. González-Riancho**, M. S. Jara, Í. Aniel-Quiroga, J.A. Álvarez-Gómez, M. González, R. Medina, S. Al-Yahyai, and G. Al-Rawas. Tsunami vulnerability and risk assessment for the development of planning tools in Oman. *Reducing Tsunami Risk in the Western Indian Ocean: A Regional Conference in Muscat, Oman*. Jointly organised by the Intergovernmental Oceanographic Commission of UNESCO and Oman's Directorate General of Meteorology, Public Authority for Civil Aviation. Oman, March 2015.
2. Aniel-Quiroga, Í., Álvarez-Gómez, J.A., González, M., Aguirre-Ayerbe, I., Fernández Pérez, F., Jara, M. S., **González-Riancho, P.**, Medina, R., Al-Harthy, S., Al-Yahyai, S., and Al-Hashmi, S. Tsunami Hazard assessment and Scenarios Database development for the Tsunami Warning System for the coast of Oman. *Reducing Tsunami Risk in the Western Indian Ocean: A Regional Conference in Muscat, Oman*. Jointly organised by the Intergovernmental Oceanographic Commission of UNESCO and Oman's Directorate General of Meteorology, Public Authority for Civil Aviation. Oman, March 2015.
3. Ignacio Aguirre-Ayerbe, **Pino González-Riancho**, Iñigo Aniel-Quiroga, Mauricio González, Omar Q. Gutiérrez, José A. Álvarez, J. Larreynaga, F. Gavidia. Integrated Tsunami Risk assessment and evacuation planning as a tool for risk management: application to the coastal area of El Salvador. *International Conference Coastal Risks: Hazards, Issues, Representations, Management*, IUEM, Brest, July 3-4 2014.
4. **Pino Gonzalez-Riancho**, Ignacio Aguirre-Ayerbe, Iñigo Aniel-Quiroga, Sheila Abad, Mauricio González Rodriguez, Jeniffer Larreynaga, Francisco Gavidia, Omar Quetzalcoalt Gutiérrez, Jose Antonio Álvarez-Gómez, Raúl Medina Santamaría. Tsunami evacuation analysis, modelling and planning: application to the coastal area of El Salvador. *European Geosciences Union (EGU) General Assembly* 2014, Vienna; 05/2014.
5. **González-Riancho Calzada, P**., Aguirre-Ayerbe, I., Larreynaga, J., González Rodríguez, M., Aniel-Quiroga, I., Gutierrez Gutierrez, O., García-Aguilar, O., Álvarez, J.A., Gavidia, F. Integrated tsunami risk assessment and evacuation planning: application to the coastal

area of El Salvador. *International Tsunami Symposium ITS* 2013. Fethiye-Gocek, Turkey and Rhodes, Greece on September 25-28, 2013.
6. Aguirre Ayerbe, **P. González-Riancho Calzada**, M. González Rodríguez, I. Aniel-Quiroga Zorrilla, O. García Aguilar, O. Gutiérrez Gutiérrez, J. A. Álvarez Gómez, F. Gavidia Medina, J. Larreynaga Murcia. Metodología para la evaluación de la vulnerabilidad y el riesgo ante tsunamis: aplicación a la costa de El Salvador. *XII Jornadas de Ingeniería de Costas y Puertos*, Cartagena (España), mayo 2013.
7. **González-Riancho Calzada, P.,** González Rodríguez, M., Gutierrez Gutierrez, O., García-Aguilar, O., Aniel-Quiroga, I., Aguirre-Ayerbe, I., Álvarez, J., Gavidia, F., Jaimes, I., & Larreynaga, J. (2012). A methodology for tsunami hazard and risk assessment: application to the coastal area of El Salvador. Coastal Engineering Proceedings [Online], Volume 1 Number 33 (25 October 2012). *International Conference on Coastal Engineering (ICCE)*. Santander (Spain), 1-6 July 2012. ISSN: 2156-1028. doi:10.9753/icce.v33.management.11.
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1.4.2.3 Scientific educational activities

The work in this thesis has also contributed to the design and development of various educational activities:

1. A Real Summer Abroad Experience, Summer School on Challenges And Opportunities For Engineering In The Ocean. Lecture on *Tsunami Vulnerability & Risk Assessment and evacuation modelling*. Santander (Spain), 19th June 2014.
2. Science Week of the Universidad de Cantabria. Lecture on *Tsunamis* for school students. Santander (Spain), 11th November 2013.
3. International Conference on Coastal Engineering (ICCE 2012). Lecture on *Tsunami Vulnerability & Risk Assessment* within the course "*Tsunami Modeling and Hazard/Risk Assessment*". Santander (Spain), July 2012.

Chapter 2. Integrated tsunami vulnerability and risk assessment

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Natural Hazards and Earth System Sciences

Integrated tsunami vulnerability and risk assessment: application to the coastal area of El Salvador

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Abstract. Advances in the understanding and prediction of tsunami impacts allow for the development of risk reduction strategies for tsunami-prone areas. This paper presents a tsunami vulnerability and risk assessment for the case study of El Salvador, the applied methodology dealing with the complexity and variability of coastal zones by means of (i) an integral approach to cover the entire risk-related process from the hazard, vulnerability and risk assessments to the final risk management; (ii) an integrated approach to combine and aggregate the information stemming from the different dimensions of coupled human and natural systems; and (iii) a dynamic and scale-dependent approach to integrate the spatiotemporal variability considerations. This work also aims at establishing a clear connection to translate the vulnerability and risk assessment results into adequate target-oriented risk reduction measures, trying to bridge the gap between science and management for the tsunami hazard. The approach is applicable to other types of hazards, having been successfully applied to climate-change-related flooding hazard.

2.1 Introduction

Advances in the understanding and prediction of tsunami impacts allow for the development of risk reduction strategies for tsunami-prone areas. Tsunami risk assessments are essential for the identification of the exposed areas and of the most vulnerable communities and elements, with the hazard, vulnerability and risk results being critical for the formulation of adequate, site-specific and vulnerability-oriented risk management options.

Risk-related works in the literature differ according to the risk component analysed (i.e. hazard, exposure, vulnerability, impacts, resilience, coping capacity, etc.), the risk dimension dealt with (i.e. human, infrastructural, environmental, social, economic, etc.), and the spatial scale tackled (i.e. regional, national, local, etc.), thereby proving the complexity associated to risk assessment and management. Regarding the existing literature on tsunami risk, several authors centre their work on the tsunami hazard itself, trying to understand its evolution from the generation and propagation phases until its arrival at the coastal area with the aim of predicting the tsunami location, magnitude, duration and probability (Gosenberg and Schlurmann, 2009; Harbitz et al., 2012; Álvarez-Gómez, 2013), while others propose a methodology for the integration of various hazards (Greiving et al., 2006). On the other hand, some authors' analyses are oriented towards the calculation of vulnerability and/or impacts at a specific location (UNDP, 2011; UNU-EHS, 2009; Villagrán de León, 2008) or on specific elements at that location such as the population (Sugimoto et al., 2003; Sato et al., 2003; Koshimura et al., 2006; Jonkman et al., 2008; Strunz et al., 2011), the exposed buildings and infrastructures (Tinti et al., 2011; Dall'Osso et al., 2009; Cruz et al., 2009; Grezio et al., 2012; Koeri et al., 2009; Jelínek et al., 2009), the environmental resources (Fundación-Terram, 2012; ECLAC, 2003) or the socioeconomic system (ECLAC, 2003). Many deal with resilience, coping capacities, preparedness, etc. (UNESCO, 2009a; Wegscheider et al., 2011; US IOTWSP, 2007), with some of them concentrating on tsunami evacuation modelling (Van Zuilekom et al., 2005; Aboelata and Bowles, 2005; Mück, 2008; Clerveaux et al., 2008; Alvear Brito et al., 2009; Kolen et al., 2010).

Individual risk, hazard and/or vulnerability assessments can be partial, sectoral or specific. However, risk management requires an integrated and holistic understanding of the coupled human and natural system (CHANS) dealt with, otherwise management options can produce unexpected and sometimes undesired results. According to Rotmans and Dowlatabadi (1998), the integrated assessment is aimed at combining, interpreting and communicating knowledge from diverse scientific fields in order to comprehensively tackle an environmental problem by stressing its cause–effect links in their entirety. Integration refers in this paper to the understanding and combination of risk components, dimensions and scales affecting a CHANS, one of the major challenges being the systematic combination and aggregation of different types of data and information (i.e. quantitative vs. qualitative) from various disciplines, scales and data acquisition methodologies.

Vulnerability is multi-dimensional and differential, as it varies across physical space and among and within social groups; scale dependent regarding time, space and analysis units; and dynamic, as the characteristics and driving forces of vulnerability change over time (Vogel and O'Brien, 2004). The current literature encompasses several different definitions, concepts, frameworks and methods to systematise vulnerability (Birkmann, 2006), very little information being provided about how to apply the different existing theoretical and conceptual frameworks and how to integrate the different risk-related concepts. Furthermore, risk assessment results sometimes do not provide conclusions on how to reduce the risk at the identified areas, lacking a clear correlation between risk assessment and management.

The starting point of this work is the existing theoretical frameworks and approaches such as the MOVE framework (Birkmann et al., 2013), Turner et al. (2003) or the BBC conceptual framework (Birkmann, 2006). The main expected contribution is to provide a straightforward method to facilitate the implementation of some theoretical concepts to case studies, as this is sometimes complex due to site-specific problems, lack of data or the lack of information about particular methodological aspects. The final aim of the risk assessment is the identification of the expected impacts on each dimension as input for the formulation of adequate target-oriented risk reduction measures.

The objectives and structure of this paper are the presentation of the integrated tsunami vulnerability and risk assessment carried out in El Salvador, considering the different risk components, dimensions and spatiotemporal scales and the methodological process to integrate them (Sect. 2), and the establishment of a clear connection to translate the vulnerability and risk assessments into risk reduction measures, trying to bridge the gap between science and management for the tsunami hazard, and its application to the coastal area of El Salvador (Sect. 3). Finally, some conclusions are presented in Sect. 4.

2.2 Integrated tsunami risk assessment for El Salvador

Due to the large array of terms on risk and vulnerability and the often unclear relationships between them, it is essential to first clarify the conceptual framework applied in this paper. Regarding the risk components, this methodology is based on the definition of *risk* as the probability of expected harmful consequences or losses resulting from interactions between natural or human-induced hazards and vulnerable conditions (UN/ISDR, 2004), the mentioned consequences being the negative effects of disaster expressed in terms of human, economic, environmental, infrastructural and social impacts (adapted from ISO, 2009). Therefore, risk depends on the specific impact analysed (e.g. loss of human lives), the characteristics of the threat (e.g. flooding), the exposure of the studied elements (e.g. people in urban areas) and their vulnerability (sensitive groups and resilience).

The *hazard* as a dangerous phenomenon (UN/ISDR, 2009) is analysed based on the different associated threats (which are characterised by their location, intensity, duration, frequency and probability) together with their dynamics – i.e. variables and physical processes, involved in their generation. As an example, the specific threats to deal with when analysing climate change hazard could be, among others, sea level rise or an increase in tropical cyclones and droughts, while the dynamics to study would be waves, tides, sea level, sea temperature, precipitation, etc.

Exposure refers to people, property, systems, or other elements present in hazard zones that are thereby subject to potential losses (UN/ISDR, 2009), while *vulnerability* to the conditions is 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). These vulnerability conditions are here understood to be of two types, internal (unchangeable individual conditions, such as the age of the population) and external (changeable community conditions, improvable through learning and experience, such as risk preparedness within the communities), the improvement of the latter being a possible countermeasure to reduce the vulnerability of highly sensitive areas. Accordingly, *sensitivity* refers to the intrinsic characteristics of the exposed elements that make them potentially affected by physical or socioeconomic changes, including damage and losses (adapted from UN/ISDR, 2004), while *resilience* is the ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions (UN/ISDR, 2009).

The success or failure of many policies and management practices is based on their ability to take into account complexities of CHANS (Liu et al., 2007). Understanding the interrelationships between human societies and their behavior patterns, coastal resources and their uses, as well as policies and institutions that govern human activities is essential for adequate coastal management. This requires an integrated and multidisciplinary approach to analyse the entire system in order to understand the feedback loops that manage its behavior and equilibrium instead of simply considering specific aspects of a single sector or scientific discipline. This approach is applied here throughout the exposure and vulnerability assessments, as they are fragmented to incorporate different coastal dimensions (human, environmental, socioeconomic and infrastructural dimensions) within the tsunami risk assessment, based on EC (2010), the Hyogo Framework for Action (UN, 2005) and the impacts generated in recent tsunami events. Contrary to other previous works found in the literature, the human and socioeconomic dimensions are separated here on purpose, as the information regarding the human dimension will directly feed the evacuation planning of the area (González-Riancho et al., 2013), while the socioeconomic dimension focuses on livelihoods and economic losses. The elements at risk vary with time and space, as both factors will change the amount and type of exposed and vulnerable elements. For this reason, and according to EC (2010), impact assessments are defined based on a reference space-time window.

Figure 2.1 shows the entire process to integrate the risk components, dimensions and spatial scales. Regarding the integration of dimensions and according to EC (2010), two types of results are provided, partial and aggregated results. The former allow having the analysed impacts available separately for the different dimensions and components, while the latter combines all the dimensions. Based on the results of the risk assessment and according to UNESCO (2009b), the risk can be mitigated by reducing the vulnerability to the hazard and improving preparedness. Within the work presented here, this translates into the formulation of risk reduction measures to reduce the partial exposure and sensitivity, and to enhance the resilience at the municipality level.

As shown through the colour-coded arrows, the construction of aggregated indices – i.e. exposure, sensitivity and vulnerability, is performed through weighted aggregation (blue vertical arrows) while the risk calculation, both partial and aggregated results, is performed through the risk matrix (red horizontal arrows). The main advantage of this approach is the generation of partial and aggregated results as well as the possibility of disaggregating them again into risk components, dimensions and indicators, in order to understand the precise cause of the obtained results, and thereby provide essential information for risk management (black arrows).

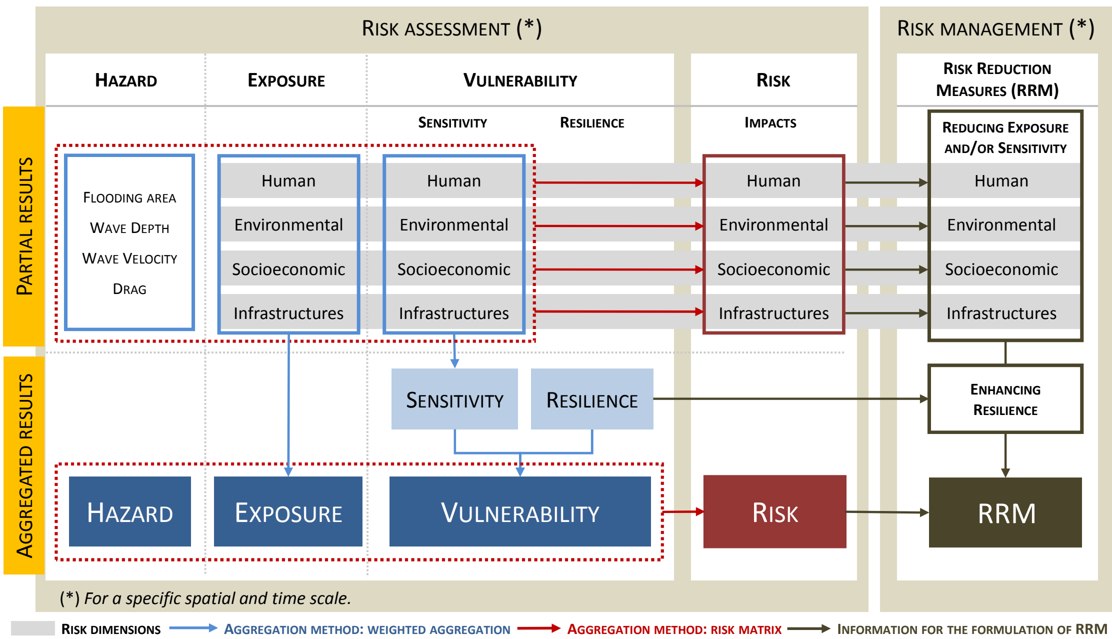

Figure 2.1. Structure of the risk assessment and different kind of results to be obtained (RRM = risk reduction measures).

This approach, although presented in this paper for the tsunami hazard, can be used for other types of hazards, having been already applied by IH Cantabria to climate change-related flooding in Peru and El Salvador within the framework of the Inter-American Development Bank project Probabilistic Hazard and Vulnerability Assessment Report based on Climate Change Projections (2012).

2.2.1 Case study

El Salvador is located in an area of high seismic activity which was hit by 15 tsunamis between 1859 and 2012, 9 of which were recorded in the 20th century. All of the tsunamis were generated by earthquakes, and two of them were highly destructive; one in 1902 that affected the eastern coast of the country and one in 1957 that affected Acajutla. The most recent, albeit of lesser magnitude, occurred in August 2012, affecting Jiquilisco Bay (IH Cantabria-MARN, 2012). The work presented here is framed within a project for assessing the tsunami risk in coastal areas worldwide, and applied specifically to the coast of El Salvador during the 2009–2012 period.

Table 2.1 shows the specific structure of the tsunami risk assessment applied to the coastal area of El Salvador, which is based on the pre-established expected consequences that are of interest to the Ministry of Environment and Natural Resources (MARN) of El Salvador; it is according to them that the vulnerability indicators (described in Sect. 2.3) are defined.

The spatial scale considers the national and local levels, the municipality being the planning unit. The national level includes the 29 coastal municipalities, while the local scale focuses on 3 specific areas that include 10 municipalities: the Western Coastal Plain (San Francisco Menéndez, Jujutla and Acajutla municipalities), La Libertad municipality and Jiquilisco Bay (Jiquilisco, Puerto El Triunfo, Usulután, San Dionisio, Jucuarán and Concepción Batres municipalities). As proposed by Turner et al. (2003), different factors shaping the risk at various spatio-temporal scales are considered, the population movements due to holiday patterns (rainy season/dry season, week/weekend) in the human system and the migration patterns or breeding/nesting periods for the environmental system.

The hazard assessment is carried out through a deterministic analysis to understand the worst possible case scenario, as carried out by Jelínek et al. (2009) and Wijetunge (2014). The use of a deterministic approach does not allow for the provision of the risk results in terms of a probability of negative consequences for different tsunami return periods; instead it permits the identification, location and quantification of the expected negative consequences or impacts for the worst possible credible scenario as the main outcome of the risk assessment. To calculate the expected consequences, the threat analysis differs according to each dimension to better understand the potential impacts or due to the lack of detailed information and/or methods in the literature to assess the specific damage levels. As a result, in this case study drag is applied to the human dimension, water depth to buildings, and flooded area to the environmental, socioeconomic and infrastructural dimensions.

Table 2.1. Structure of the Tsunami Risk Assessment applied to El Salvador coastal area.

Risk			Hazard			Exposure	Vulnerability	
Consequences	Time scale	Spatial scale	Probability	Dynamics	Threat	Exposed elements	Sensitivity	Resilience
Loss of lives due to: • reduced mobility • difficulties understanding a warning message • bad housing materials and lack of recovery capacity • difficulties in receiving a warning and evacuating in badly connected areas • difficulties in performing a coordinated evacuation	Annual Seasonal	National Local	Deterministic analysis (aggregation of the 23 worst credible tsunami cases)	Tsunamigenic sources Sea level Tsunami waves Tides	Drag	People	Sensitive age groups Illiteracy Extreme poverty Disability (physical/intellectual) Isolation Critical evacuation	Information & awareness Warning & evacuation Emergency response Recovery
Loss of protected ecosystems Loss of unique ecosystems (coral reef) Loss of ecosystem services (mangrove) Loss of endangered species Permanent destruction of ecosystems	Annual Seasonal	National Local			Flooding area	Ecosystems	Protection Singularity Threat Degradation	
Loss of area of socioeconomic activities Loss of jobs Loss of gross domestic product (GDP) Loss of foreign trade	Annual	National Local			Flooding area	Socioeconomic activities	Job generation Contribution to GDP Contribution to Foreign Trade	
Pollution of wells, hindering long-term water supply to local communities Loss of essential evacuation routes Generation of cascading impacts due to hazardous/dangerous industries Loss of emergency and health services, essential during the event	Annual	National Local			Flooding area	Infrastructures	Water supply (wells) Roads Hazardous/dangerous industries Emergency/health infrastructures	
Impacts on critical buildings (housing large population) Loss of potential vertical shelters Destruction of buildings	Annual	Local			Water Depth	Buildings	Critical buildings Vertical evacuation Building materials	

Accordingly, the national assessment focuses on the identification of the most critical municipalities in terms of likelihood of impacts for the worst credible event, which facilitates their prioritisation regarding further detailed studies, risk management efforts and resources (Fletcher, 2005). The likelihood of impacts within this qualitative risk assessment derives from the vulnerability variability and uncertainties. The local assessment aims at the calculation of specific expected impacts on the different dimensions by municipality. These worst-credible-event results allow the authorities organizing and managing the risk to provide the most protective situation, so that the formulation of measures is on the side of safety and as conservative as possible in order to ensure their validity for different scenarios. Some of the results obtained for the national level and the Western Coastal Plain are presented in this paper

2.2.2 Tsunami hazard assessment

The hazard assessment is based on propagation models for earthquake-generated tsunamis, developed through the characterization of tsunamigenic sources – seismotectonic faults – and other dynamics such as tsunami waves, sea level, etc. Simulations of historical and potential tsunamis with greater or lesser impacts on the country's coast have been performed (Figure 2.2), including distant sources (distances greater than 2000 km to the coast, with tsunami travel times greater than 4 h), regional sources (between 700 and 2000 km with tsunami travel times between 1 and 4 h), and local sources (located in the subduction trench off the country's coast with tsunami travel times of less than 1 h).

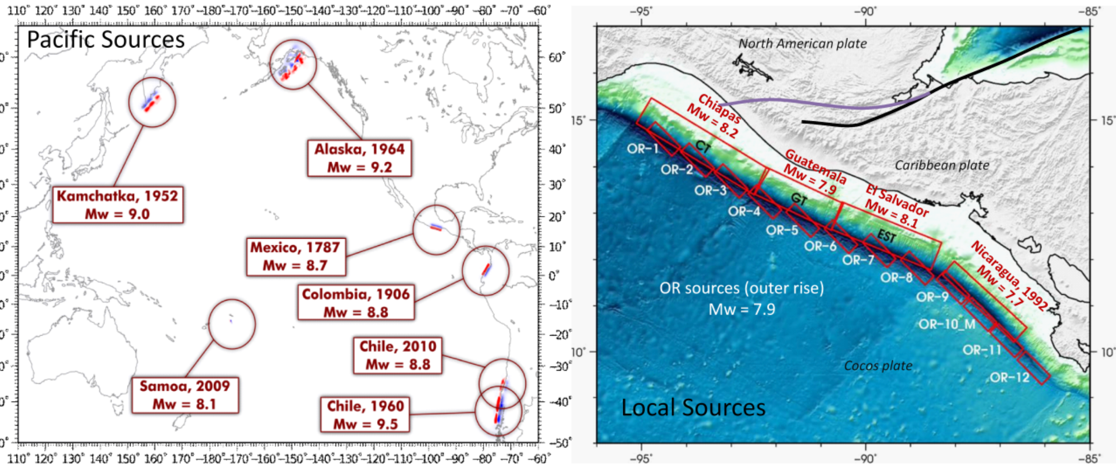

Figure 2.2. Distant, regional and local tsunamigenic sources of historical and potential tsunamis that could impact on the Salvadoran coast have been aggregated for the deterministic hazard assessment.

The numerical propagations have been simulated using the C3 model "Cantabria–Comcot–Tsunami–Claw model" (Olabarrieta et al., 2011). This model was developed by IH Cantabria and it combines two models: COMCOT and Tsunami–Claw (LeVeque et al., 2011) in order to solve nonlinear shallow water equations (NSWE). C3 is a finite differences numerical model validated and applied to several historical tsunami events such as the 1960 Chilean tsunami (Liu et al., 1994), the 1992 Flores Islands (Indonesia) tsunami, the 2004 Indian Ocean tsunami and the Algerian tsunami 2003 (Wang and Liu, 2005). Additionally, the model has been validated using the benchmark cases proposed within the framework of the European Tsunami Project TRANSFER (Tsunami Risk And Strategy For the European Region). C3 is especially designed to simulate tsunami events. The parameters of the earthquake can be introduced via the Okada fault model (Okada, 1985). The model then solves the NSWE using a gridded domain. It provides data such as free surface elevation at every point on the grid, or temporal series of velocity and total depth at each point. In the case studied in this paper, 4 levels of nested grids have been used in order to obtain a cell size of 30mon the coast of El Salvador. The run-up calculation at the areas where no local grids were available has been carried out using the Synolakis (1987) validated empirical formulations. Further information on this hazard assessment is provided by Álvarez-Gómez et al. (2013) and IH Cantabria-MARN (2010).

As mentioned above, a deterministic analysis which aggregates the 23 worst credible cases of tsunamis that could impact on the Salvadoran coast (see Fig. 2) has been carried out, with the main output being different hazard maps along the coast of El Salvador and at some relevant locations with high-resolution analysis. The generated hazard maps include the following: maximum wave height elevation, maximum water depth, minimum tsunami arrival time, maximum flooding level or "run-up", and maximum potential drag (understood as the hazard degree for human instability based on incipient water velocity and depth). Fig. 5a shows one of the tsunami hazard maps generated at the national level, which allows for the identification of the areas subjected to higher tsunami water depths and consequently to a higher impact.

2.2.3 Tsunami vulnerability and risk assessment

The hazard area calculated allows identifying the number and type of exposed elements for the four dimensions (i.e. human, environmental, socioeconomic and infrastructural). The exposure assessment identifies the elements located in the hazard area, while the vulnerability assessment measures the characteristics of the exposed elements that make them susceptible to suffering the selected impacts. Thus, vulnerability focuses on the expected impacts by municipality on the different dimensions and their potential worsening implications for the populations due to existing feedback loops (for example, the loss of household income due to loss of livelihood-related natural resources, the loss of recovery capacity of the country due to the loss of area of specific socioeconomic activities, or the lack of long-term water resources for some coastal communities due to the affection of coastal wells, among others). This is the main justification for the mixed indicator approach presented below. A partial human analysis could seem enough for reducing life losses; however, understanding all the potential implications of a tsunami event in a specific area will help in promoting awareness and preparedness. On the other hand, this global understanding of the system has the disadvantage of sometimes resulting in a superficial analysis of some of the impacts analysed.

Two different and complementary aspects for feedback loops existing in CHANS are perceived depending on the reference to specific static assessments or to holistic and time-evolving management. As described by Cutter et al. (2008) for the antecedent conditions of resilience, the sensitivity assessment is carried out in this work for a specific moment, it can be seen as a snapshot in time or a statistic state, the result being a precise value for each partial sensitivity (human, environmental, etc.) independently of the existing feedback loops within the system. Feedback loops are essential and are considered in this work as the only way to understand the behaviour of the system and to correctly manage it in terms of risk reduction, this being the reason for designing the set of indicators through the integrated approach.

2.2.3.1 Definition of exposure and vulnerability indicators

A set of indices and indicators are developed to calculate the exposure and sensitivity of the coastal dimensions as well as the resilience of the society and communities at risk. To carry this task out, several mathematical–statistical procedures are applied in order to produce comparable and combinable information. A Geographic Information System allows supporting every decision with geo-referenced information, being an essential tool for the combination of partial maps related to each dimension and particularly useful for evacuation modelling and planning (González-Riancho et al., 2013). The following sections describe the set of indicators and the methodology used to integrate them.

Based on the steps suggested by the Handbook on Constructing Composite Indicators (OECD, 2008), the proposed set of indicators is presented in Table 2.2. This set is adapted to different spatiotemporal scales: the spatial scale includes both national and local levels, while the timescale considers the movements caused by holiday patterns in the human population. It is important to point out the analytical soundness of all the indicators, the independence among them and the relevance of the measured phenomenon. The robustness, sensitivity and transparency of the indicator system allow managing the information at the index level as well as separating them into the different indicators and working directly with the base data, which is essential for not losing information while aggregating results, and for the formulation of adequate risk reduction measures.

The human sensitivity indicators (S1–S6) are oriented to measure the municipalities' weaknesses in terms of evacuation and recovery capacities of the exposed population. Accordingly, difficulties in understanding a warning message (S1, S2, S4-intellectual disability), problems with mobility and reduced evacuation speed (S1, S4-physical disability), difficulties with evacuation related to the built environment and coordinated evacuations (S6), difficulties with receiving a warning message and reaching the safe area before the tsunami arrives (S5); and the difficulties in recovering after a disaster (S3) are analysed.

The environmental sensitivity indicators (S7–S10) aim to assess the potential environmental impacts by municipality in terms of loss of ecosystems and the subsequent loss of livelihood-related ecosystem services. Thus, the loss of relevant ecosystems (S7, S8, S9), the potential permanent destruction of ecosystems (S10), and the loss of livelihood-related ecosystem services, such as coral reefs and mangroves (S8) is assessed. The potential capacity of mangroves to mitigate the hazard is included in this work through the hazard assessment, as a higher roughness coefficient was assigned to mangrove areas.

The socioeconomic sensitivity indicators (S11–S13) are oriented to measure the potential social and economic impacts by municipality in terms of loss of income at the household level and economic losses for the country, respectively. The social impacts (S11) are calculated through the number of jobs that would be lost per socioeconomic activity, while the economic impacts (S12, S13) are expressed in millions of dollars lost per socioeconomic activity in case of having a percentage of its area affected.

The infrastructures sensitivity indicators (S14–S17) measure the number of critical infrastructures and buildings that would be affected by municipality and the subsequent implications for the population, the term critical applied to those elements that if affected would worsen the situation both during and after the event. Accordingly, S14 calculates the potential number of polluted wells hindering long-term water supply to local communities, loss of essential evacuation routes, generation of cascading impacts due to affected hazardous/dangerous industries, and loss of emergency and health services which are essential during the event. S15 provides the number of buildings that would require a coordinated and previously planned evacuation due to the high number of people (in some cases sensitive population) in them, such as hospitals, schools, clinics for elderly people, malls, stadiums, churches, hotels, etc. S16 and S17 measure the number of buildings not able to provide shelter for the population, due to the number of floors or to the weak materials. S17 permits the calculation of the buildings damage level according to the materials and the water depth (based on SCHEMA methodology by Tinti et al., 2011). The damage level of the specific infrastructures (water, energy, industrial, transport, emergency) is not included in this study.

Table 2.2. Tsunami Exposure and Vulnerability indices and indicators (N = national scale, L = local scale, GDP = gross domestic product).

Aggre-gate index	Partial indices	Indicators	Variables	Spatial scale
Exposure	Human Exposure	E1 - Exposed population	Number of persons permanently exposed	N - L
			Number of persons temporally exposed (holidays)	N - L
	Environmental Exposure	E2 - Exposed ecosystems	Area of exposed ecosystems	N - L
	Socioeconomic Exposure	E3 - Exposed socioeconomic activities	Area of exposed activities (agriculture and herding, fishing, aquaculture, tourism, industry, trade, services)	N - L
	Infrastructures Exposure	E4 - Exposed infrastructures	Number of exposed infrastructures (water, energy, waste treatment, transport, industrial, emergency)	N - L
		E5 - Exposed buildings	Number of exposed buildings	L
Sensitivity	Human Sensitivity	S1 - Sensitive age groups	Number of persons under 10 years	N - L
			Number of persons over 65 years	N - L
		S2 - Illiteracy	Number of illiterate persons	N - L
		S3 - Extreme poverty	Number of persons in extreme poverty conditions	N - L
		S4 - Disability	Number of disabled persons (physical / intellectual)	L
		S5 - Isolation	Number of persons in isolated areas	L
		S6 - Critical evacuation	Number of persons in critical buildings	L
	Environmental Sensitivity	S7 - Protection	Area of protected ecosystems	N - L
		S8 - Singularity	Area of singular ecosystems (ecosystem services)	N - L
		S9 - Threat	Area of threatened ecosystems	N - L
		S10 - Degradation	Area of degraded ecosystems	L
	Socioeconomic Sensitivity	S11 - Job generation	Number of workers per activity	N - L
		S12 - Contribution to GDP	Millions of dollars contributed per activity	N - L
		S13 - Contribution to foreign trade	Millions of dollars contributed per activity	N - L
	Infrastructures Sensitivity	S14 - Critical infrastructures	Number of water supply infrastructures (wells)	N - L
			Number of transport infrastructures (evacuation)	N - L
			Number of dangerous/hazardous infrastructures	N - L
			Number of emergency infrastructures	N - L
		S15 - Critical buildings	Number of critical buildings (hospitals, schools, hotels, malls, stadiums, churches, etc.)	L
		S16 - Vertical evacuation	Number of buildings with less than 3 stories	L
		S17 - Building materials	Number of non-resistant buildings	L
Resilience	Resilience	R1 - Coping capacity	Information and awareness level	N - L
			Warning and evacuation level	N - L
			Emergency response level	N - L
		R2 - Recovery capacity	Post-disaster recovery level	N - L

Data collection for exposure and sensitivity indicators is based on the best available information for the human[1], environmental[2], socioeconomic[3] and infrastructural[4] dimensions in El Salvador. Besides this, field work was carried out to produce the information that was not officially available or that was incomplete, such as the one regarding isolated communities (with the help of local authorities and Civil Protection local departments), critical buildings, building materials and vertical evacuation.

The consideration of factors shaping risk at various scales (as proposed by Turner et al., 2003) is considered in this paper through the variable "Number of persons exposed temporarily (holidays)" within the human exposure indicator, which permitted the comparison of specific areas at different times of the year (spatio-temporal variability) and showing higher exposure and vulnerability values in holiday periods. This effect in specific hotspots is explained by holiday movements of foreigners to very specific sites and associated for example with surf promotion campaigns developed at the national level. These overcrowded places are likely to be higher risk areas in holiday periods. Other factors that could be considered are the planned coastal development for the coming years in exposed areas, or national initiatives (like the one resulting in this paper) which are aimed at reducing the vulnerability of communities at the local level. Further research work is needed in order to properly include these types of factors within risk assessments.

An additional explanation is provided for the resilience assessment. The resilience of a community with respect to potential hazard events is determined by the degree to which the community has the necessary resources and is capable of absorbing disturbance and reorganising into a fully functioning system (Cutter et al., 2008). This is understood as the capacity of a community to organise itself before, during and after the event in order to minimise the impacts. Thus, two of society's capacities are analysed to evaluate the resilience: coping capacity, as the ability of people, organizations and systems, using available skills and resources, to face and manage adverse conditions, emergencies or disasters (UN/ISDR, 2009) before and during the event; and recovery capacity, as the ability of the system to recover after a disaster. These two indicators are assessed through the analysis of the four phases of emergency management: information and awareness, warning and evacuation, emergency response, and disaster recovery.

Due to the lack of thematic and geographically homogeneous data regarding resilience, data collection for the construction of the resilience index has been carried out through a short

[1] Censo de Población 2007, Encuesta de Hogares de Propósitos Múltiples 2011 (Dirección General de Estadística y Censos DIGESTYC), Ministerio de Turismo MITUR
[2] Ministerio de Medio Ambiente y Recursos Naturales MARN
[3] DIGESTYC 2007, Banco Central de Reserva BCR
[4] Asociación Nacional de Acueductos y Alcantarillados ANDA, Comisión Hidroeléctrica del Rio Lempa CEL, Comisión Ejecutiva Portuaria Autónoma CEPA, Ministerio de Obras Públicas MOP, Ministerio de Economía MINEC, Centro de Desarrollo de la Pesca y la Acuicultura CENDEPESCA, Ministerio de Agricultura y Ganadería, Fuerza Naval, and Ministerio de Turismo MITUR

questionnaire which identifies the degree of organization and response within a community in case of an emergency. The type of questionnaire applied is based on the assessment of the level of implementation of Integrated Coastal Zone Management (ICZM) in Europe, proposed by Pickaver et al. (2004) and carried out through a questionnaire with three possible answers (yes/no/no answer) against each ICZM action and for three spatial levels to identify the main existing gaps in ICZM implementation and a trend through time. Using appropriate questionnaires for the resilience assessment solves the commonly faced problem regarding the limits of measurability and the collection of quantitative data to be analysed together with the sensitivity data. Table 2.3 shows the relation between the elements of resilience, the phases of emergency management and the questionnaire.

Table 2.3. Resilience assessment: society's capacities, related emergency phases and questionnaire applied.

Society's capacities	Emergency management phases (description based on U.S. IOTWS, 2007)	Resilience questionnaire
Coping capacity	<u>Information and awareness.</u> Leadership and community members are aware of hazards and risk information is utilized when making decisions.	1. Existence of social awareness 2. Existence of institutional awareness
	<u>Warning and evacuation</u>. Community is capable of receiving notifications and alerts of coastal hazards, warning at-risk populations, and individuals acting on the alert.	3. Existence of tsunami Early Warning System 4. Existence of evacuation routes 5. Existence of maps / drawings with hazard areas and critical spots 6. Development of evacuation drills in institutions and communities
	<u>Emergency response</u>. Mechanisms and networks are established and maintained to respond quickly to coastal disasters and address emergency needs at the community level.	7. Proper functioning of the Municipal Commission of Civil Protection 8. Existence of a contingency plan 9. Existence of Communal Committees for risk management 10. Existence of coordination networks at departmental / national levels 11. Existence of sufficient emergency human resources
Recovery capacity	<u>Disaster recovery</u>. Plans are in place prior to hazard events that accelerate disaster recovery, engage communities in the recovery process, and minimize negative environmental, social, and economic impacts.	12. Existence of temporary shelters 13. Existence of municipal funds to cover immediate expenses 14. Existence of catastrophe insurance 15. Existence of sufficient medical and public health human resources 16. Existence of sufficient development human resources

The resilience questionnaire offers three response alternatives, yes/no/partially, together with space for fuller comments, and has been filled in by 34 stakeholders. Although the statistical sample could be considered small, the coherence of the assessment is ensured at the national level through the answers of those responsible for emergency management in every coastal municipality (Municipal Civil Protection Committees). Additional stakeholders were interviewed for the local studies, such as some nongovernmental organisations, companies and business associations, and community leaders; in case of contradictory answers (“yes/no”) the intermediate value (“partially”) has been finally assigned, the incoherence between authorities’ and society’s perception about the preparedness of the municipality being automatically identified as a critical issue for resilience enhancement measures.

The complexity of having the resilience as a component inversely proportional to risk (a higher resilience reduces the risk) in a multidisciplinary study, which combines different risk components, dimensions and timescales and therefore indicators from various disciplines, sources and units, highlights the need to translate this factor into a directly proportional one. Therefore, the authors propose the use of a new component named “lack of resilience”, as applied by the MOVE framework (Birkmann et al., 2013). Consequently, the indicators coping capacity and recovery capacity will analyse the lack of resilience and focus on the negative responses of the questionnaire. The aggregation of each type of answer multiplied by its coefficient and divided by the total number of questions providing the value of the lack of resilience index, the coefficients being 0, 1 and 0.5 for positive, negative and intermediate answers, respectively. This is necessary for aggregation purposes (i.e. aggregating sensitivity and resilience to build the vulnerability); however, to analyse the resilience itself, the lack of resilience is translated again into the resilience concept through the expression Resilience = 1−Lack of resilience.

2.2.3.2 Integration of risk concepts

The method for the integration of risk concepts included in the process from the exposure and vulnerability data collection and processing up to the risk assessment is explained in the next paragraphs. This method has several steps: (i) building indicators through normalizations; (ii) building partial and aggregated indices through weighted aggregation, (iii) index classification via the natural breaks method; and (iv) risk assessment using the risk matrix.

Based on OECD (2008), in order to correct the imbalance caused by the different variable units, thus allowing for their comparison and combination, the transformation of the variables range of values is carried out through the minimum–maximum (Min–Max) method, which normalises the indicators so as to obtain an identical range [0,1]. A weighted aggregation is applied to them in order to build the partial (for each dimension) and aggregated indices. Weights are assigned in this work using participatory methods: a workshop has allowed the authors to collect the opinions of different experts, with the participation of 10 technicians from the *MARN* (Ministry of Environment and Natural Resources, El Salvador) and the team from *IH Cantabria* (Environmental Hydraulics Institute, Spain), in order to reflect political and social priorities, technical factors related to the tsunami hazard and the reliability of the data used.

As carried out by Damm (2010) and the World Risk Report (Alliance Development Works, 2012), among others, the indices are classified considering the data distribution and translated into five classes linked to a colour code geographically representing the information. The natural breaks classification method, based on the Jenk’s optimisation algorithm, implemented in ArcGIS® software and designed to provide the best arrangement of values into different classes, is applied. The method reduces the variance within classes and maximises the variance between classes (Jenks, 1967) and has been selected after testing other methods (such as the equal interval, defined interval, quantile, geometrical interval, standard deviation, etc.), as it permits grouping within the same class the municipalities that have similar values, that is those that behave in the same way and which are expected to need similar risk reduction measures. Since this method of classification depends on the distribution of the data, the study of any index evolution over time must maintain the ranges established in the initial analysis.

As conducted by Greiving et al. (2006) and Jelínek et al. (2009), the risk is calculated through a risk matrix by combining the classes obtained for the hazard and the vulnerability indices, or hazard and sensitivity indices in the case of partial results. The sensitivity and vulnerability are calculated on the exposed elements; therefore, the exposure is implicitly incorporated into the matrix. Once the municipalities with higher risk values are identified, in other words those which are expected to have serious negative consequences due to the combination of the hazard scenario modelled and the vulnerability conditions, the calculation of the specific expected impacts at the local level is carried out. The different methods applied to the Western Coastal Plain of El Salvador are described in Sect. 2.3.3 together with the obtained results.

2.2.3.3 Results and discussion

The vulnerability results for the coastal area of El Salvador are analysed and mapped in Figure 2.3. The municipalities are organized geographically within the graphs, thereby facilitating the comparison of numerical and cartographic results.

The sensitivity index numerical and cartographic results explain how sensitive the exposed municipalities are regarding the different dimensions. The sensitivity is represented through the graph columns and the colour code on the maps. The identification of the causes that make each municipality more or less susceptible to the hazard is based on the sensitivity indicators, with the different colours within the columns representing the contribution of the different indicators to their index. For example, one can differentiate the reasons why two municipalities have similar socioeconomic sensitivity, identifying whether it is due to the potential loss of contribution to foreign trade or GDP. The results obtained will feed the risk reduction measures for each dimension.

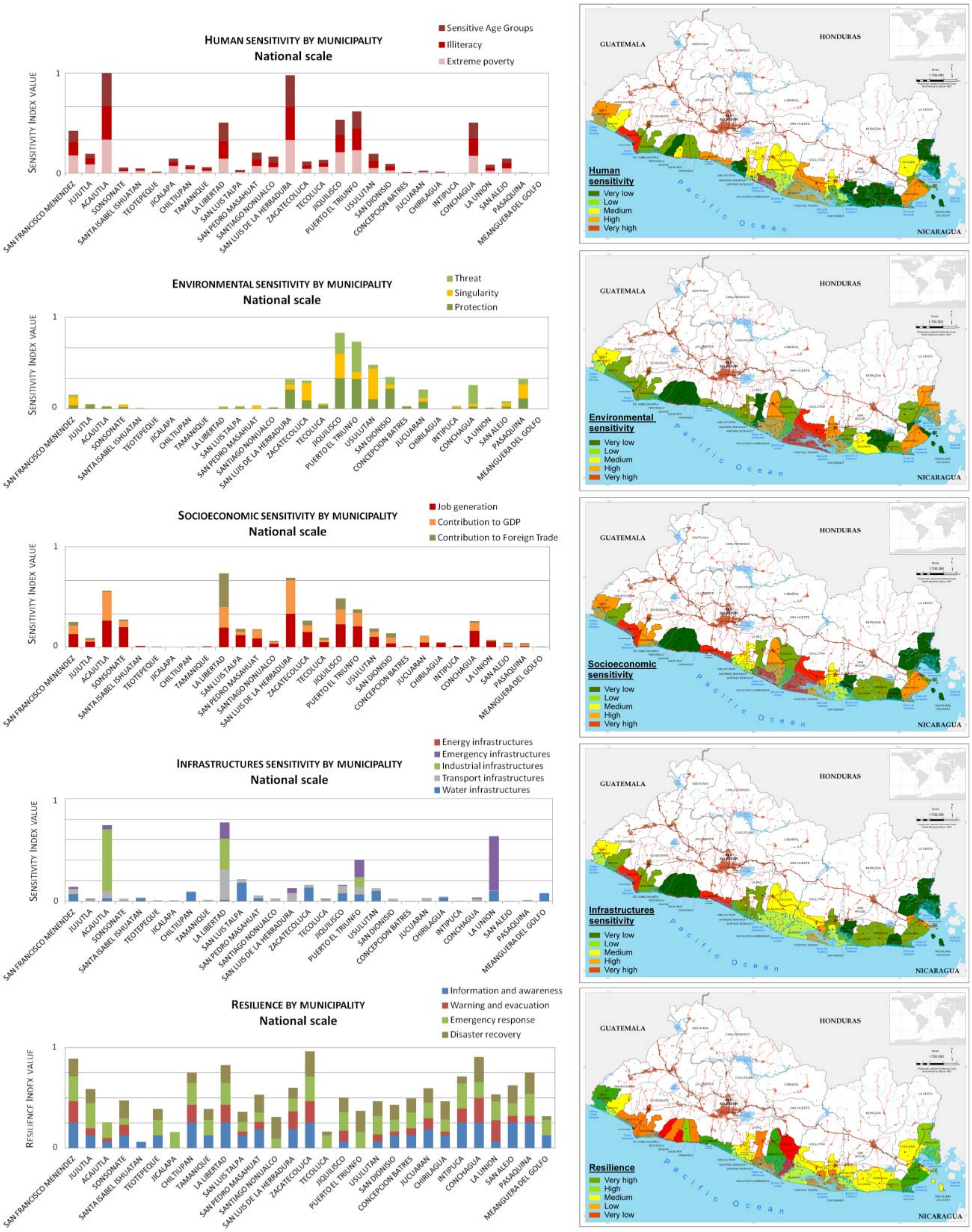

Figure 2.3. Vulnerability results for the El Salvadoran coastal area at the national scale by municipality: (from top to bottom) (i) human, (ii) environmental, (iii) socioeconomic and (iv) infrastructural sensitivity, and (v) community resilience.

The results of the resilience index at the national level allow an understanding, in a general and preliminary way, of the main weaknesses in emergency management, in order to design further detailed analyses to propose weakness-oriented site-specific corrective measures. The main shortcomings regarding the emergency phases can be identified and consequently tackled, both at the municipality level (e.g. Acajutla does not have temporary tsunami shelters) and transversally for a more coherent regional planning (e.g. the country lacks a tsunami insurance or a properly implemented tsunami EWS, although some respondents stated that the existing flooding warning procedures could be easily incorporated to the tsunami EWS), as shown in Figure 2.4. Quantitative information for the indicators would nonetheless provide more detailed results to analyse the coastal municipalities in terms of, for instance, the number of temporary shelters or doctors by population density and municipality.

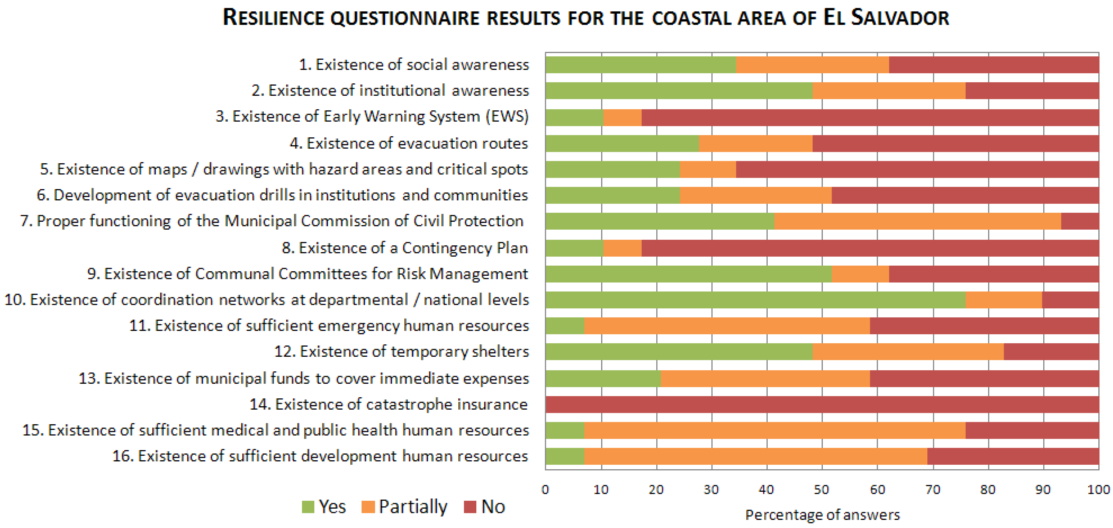

Figure 2.4. Resilience questionnaire results for tsunami hazard on the coastal area of El Salvador.

The importance of each indicator or variable and the critical role of some of them within the assessment have been considered through the weighted aggregation. Accordingly, in the case of resilience, coping capacity is weighted more than the recovery capacity due to the prioritisation of saving lives, and resilience is weighted less than sensitivity due to the use of more subjective information. The workshop made evident the difficulties in weighting the different resilience variables: the first impulse for almost everyone was to give higher weights to early warning system and evacuation routes; however, a lack of social awareness regarding evacuation (question 1) or a communication and coordination malfunction between the different warning responsible levels (questions 7, 9, 10) could turn a tsunami warning ineffective. Regarding social awareness in the case of a local tsunami, a community informed and trained about the tsunami hazard would start evacuating just after feeling the earthquake, which could save valuable time before the warning is issued and, hopefully, lives.

The aggregated result (sensitivity or resilience) per se should not be understood as the final aim of the work, but the generation of information for the formulation of risk reduction measures; i.e. the assessments allow the identification of site-specific topics that should be managed before a tsunami event happens. In other words, and as an example, the resilience assessment identifies in which municipalities one should work on designing evacuation routes and in which ones the focus should be on social awareness or an early warning system. Similarly, the sensitivity results identify in which municipalities specific attention must be paid regarding the evacuation of critical buildings such as schools, hospitals, etc., where an alternative water supply for coastal communities with potential polluted wells must be planned, or where specific information and training campaigns must be designed for isolated areas or municipalities with a large amount of people with difficulties understanding a warning message.

The national risk assessment (Figure 2.5c), obtained from the combination of hazard and vulnerability results (Figure 2.5a and b, respectively), allowed for the identification of the critical areas in which a more detailed analysis is needed. The specific expected impacts have been calculated for the three local areas framed by black squares in the figure, with some of the results for the Western Coastal Plain being presented next. The calculation of the extent of the negative consequences (damage levels) varies according to the available methodologies in literature and information, not being defined for every dimension or exposed element in a homogeneous way. The specific results, which differ in format and scope, cover the different dimensions as well, providing essential knowledge for risk management and the formulation of adequate risk reduction measures.

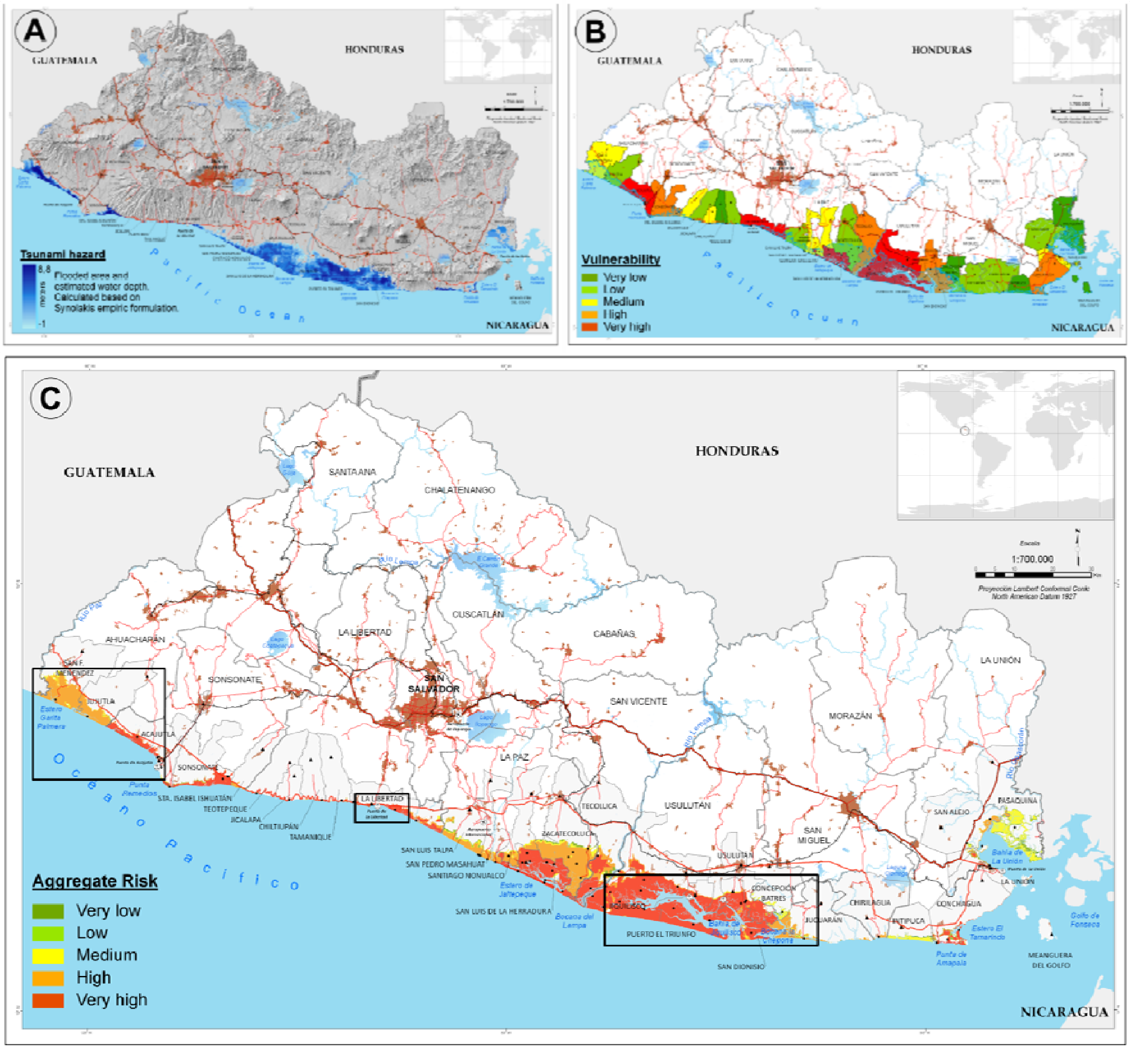

Figure 2.5. National tsunami risk assessment in El Salvador: **(a)** hazard assessment: flooded area and water depth results; **(b)** vulnerability assessment by municipality including the human, environmental, socioeconomic and infrastructural dimensions; **(c)** risk assessment combining hazard and vulnerability results via the risk matrix (the areas framed by black squares show the local studies carried out; from left to right: Western Coastal Plain, La Libertad municipality and Jiquilisco Bay).

The zoning for the expected human damage in the Western Coastal Plain (Figure 2.6a), is calculated through the combination of tsunami drag (based on Jonkman et al., 2008) and human sensitivity. An overall 20 429 persons are exposed to this tsunami event, 75% of them being located in very high and high human damage areas. This information is very useful for evacuation planning, as the critical areas in terms of hazard, exposure and sensitivity are identified. One could argue that evacuation planning as well as other type of measures, such as the identification of evacuation routes and shelter areas, could proceed without such detailed information; however, the more information is collected, the better management options can be applied. Knowing the evacuation speed of the population, which can depend on the age, disabilities, etc., will allow modelling the evacuation in order to identify critical areas where people would not be able to reach a shelter before the tsunami reaches the coast. Knowing where the sensitive population in terms of evacuation is located facilitates planning alternative measures for them.

Figure 2.6b shows the number of buildings exposed to the tsunami event by census segment (blue colour code) and the expected impacts on buildings (pie charts) calculated through the adaptation of the SCHEMA methodology to El Salvador based on water depth and building materials (Tinti et al., 2011). In total, 6557 buildings are exposed in the Western Coastal Plain, 26% of them being included among the important damage and partial failure classes.

The area and location of ecosystems and related ecosystem services that would be affected by a potential event, as well as the local communities depending on them have been identified. The area, number of jobs and economic contribution to be lost for the different socioeconomic activities exposed to the hazard is provided in Figure 2.7a. It shows that the largest area of socioeconomic activity that would be lost is mainly agricultural land in the three municipalities; this implies practically the entire expected loss of contribution to foreign trade. The other smaller exposed socioeconomic area is dedicated to tourism, trade, construction and services, mainly in urban areas, and especially in Acajutla municipality. This small multi-activity area would imply the biggest impacts in terms of loss of jobs and loss of contribution to GDP.

Figure 2.7b shows some examples of the analysis of impacts on infrastructures for the Western Coastal Plain, based on the identification and location of the sensitive infrastructures potentially affected, implying various consequences to the population, such as the reduction of possible evacuation roads, the potential pollution of wells hindering long-term supply to coastal communities, the affect on dangerous/hazardous industrial infrastructures that could worsen the tsunami impacts, or the exposure of all the emergency infrastructures present in the study area, which probably will not be able to help the population in case of a tsunami event.

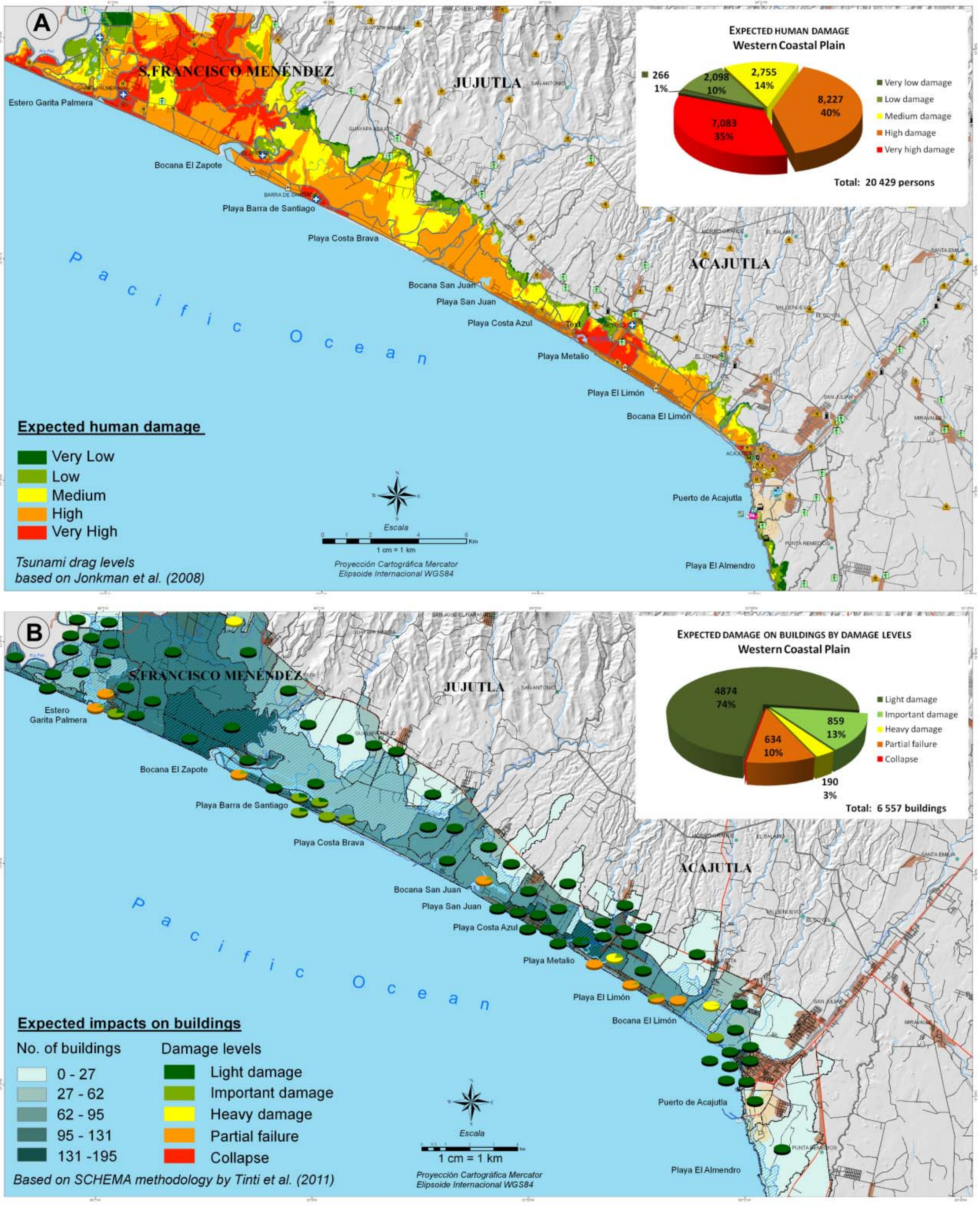

Figure 2.6. Expected impacts in the Western Coastal Plain of El Salvador: **(a)** zoning for expected human damage, and **(b)** expected impacts on buildings by census segment.

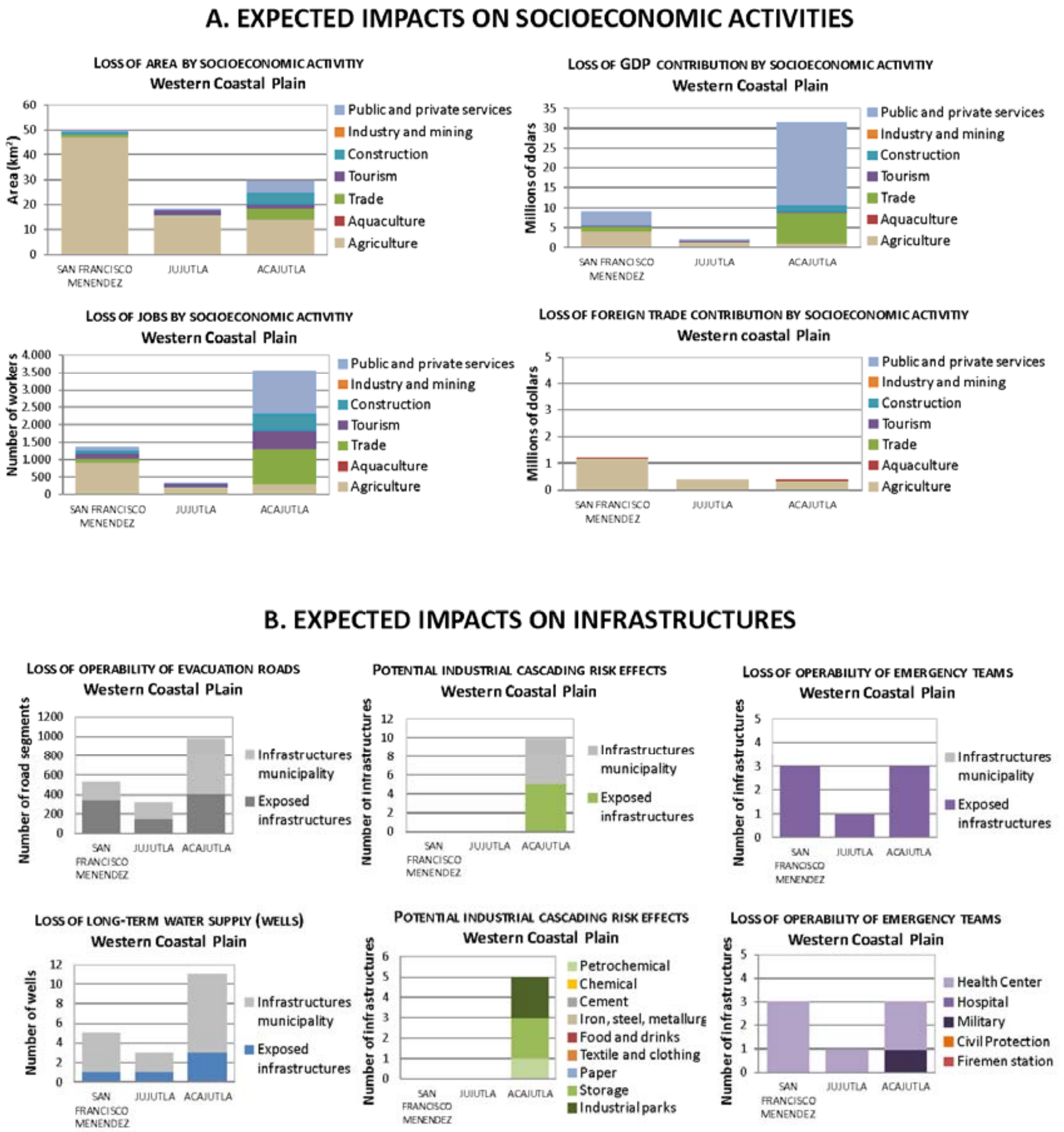

Figure 2.7. Expected impacts in the Western Coastal Plain of El Salvador: **(a)** impacts on socioeconomic activities, and **(b)** impacts on infrastructures.

2.3 Tsunami risk management: application to El Salvador

Scientific risk assessment studies are frequently characterized by a linear structure that goes from the hazard and vulnerability assessments to the final risk calculation, very few of them providing specific risk reduction options. This linear structure and the lack of a clear and straightforward link with the disaster risk management (DRM) may generate a lack of connection between the authorities' decision-making and the technical results obtained from the risk assessment. This section focuses on how to enhance the value of the gathered knowledge to translate the results into something closer to the management options the decision-maker needs. Figure 2.8 shows how the risk assessment process can directly feed the various steps within the risk management process. Once the connection between both processes is identified, the structures of the studies are reoriented in order to have the DRM as the main goal to achieve. The scheme on the right, in a dartboard shape, shows that the closer a study arrives to the centre of the dartboard, the more useful it becomes for the managers.

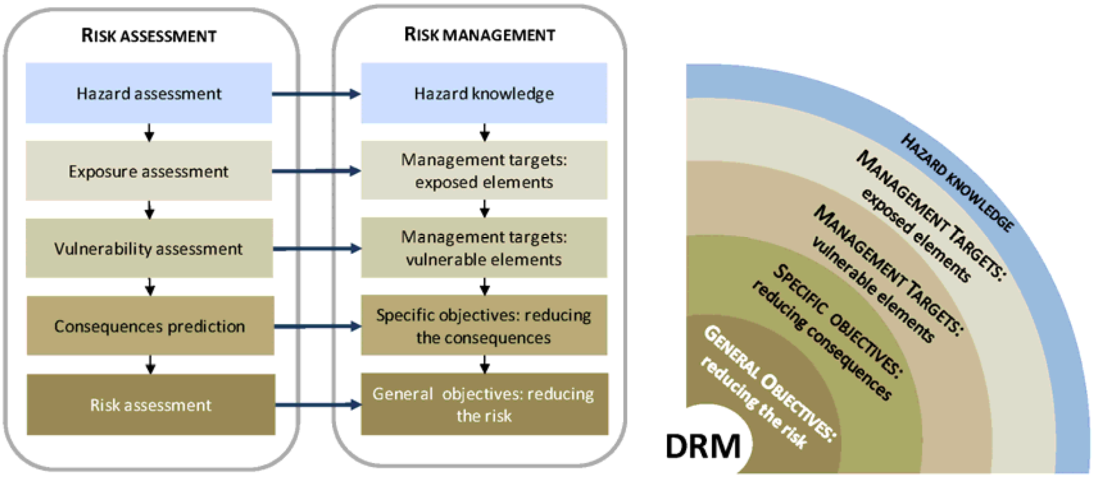

Figure 2.8. Left: translating vulnerability and risk results into a management framework. Right: disaster risk management (DRM) dartboard framework.

Based on the results of the national and local risk assessment carried out for El Salvador and the main expected impacts due to the modelled tsunami event, different adaptation and mitigation measures can be proposed. It is here understood that mitigation measures aim to reduce the hazard's effect on the coastal system, while adaptation measures basically aim to reduce the vulnerability by reducing the sensitivity or enhancing the resilience-identified shortcomings. The overlap of mitigation and adaptation measures on the exposure component is due to territorial and time factors – i.e. a risk reduction measure aimed at reducing the exposure will be a mitigation measure if it intends to change the location of existing elements, but can be considered an adaptation measure if it intends to plan the future location of elements so as to limit as much as possible their presence in the area.

DRM must be site-specific and needs to be detailed and individually applied to the different study areas. Figure 2.9 shows an example of general planning structure based on some of the results presented. The main goal is the DRM in the centre of the figure, and to achieve it different tasks are needed: (i) knowledge acquisition about the hazard; (ii) identification and location of the exposed elements of that hazard to be considered; (iii) from the exposed ones, analysis of the vulnerable elements as management targets; (iv) formulation of DRM-specific objectives to reduce the expected negative consequences on each dimension; and (v) DRM general objectives to guide the management of the study area. Focusing for example on the human dimension in Figure 2.9, the general objective is reducing human risk by ensuring effective evacuation, this can be achieved by minimising the population evacuation and reaction time. Table 4 shows the translation of the tsunami risk results obtained in Acajutla municipality into risk reduction measures by following the steps suggested in Fig. 8. According to this approach, specific risk reduction measures are proposed to address each of the identified impacts in every dimension. However, it is normally politically and economically difficult for a country to implement them all, a prioritisation of measures being required.

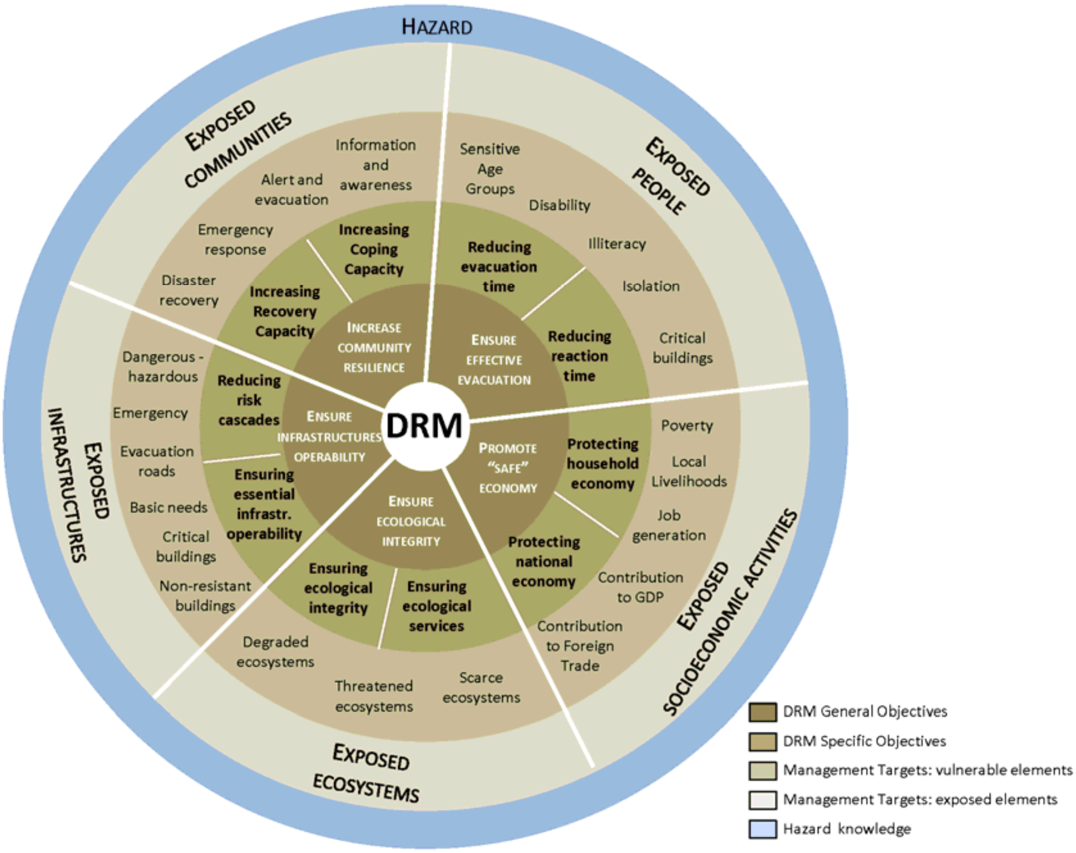

Figure 2.9. Example of risk management framework for tsunami hazard in El Salvador.

DRM, as a complex process, deals with a huge amount of information including different kinds of data on hazards, exposed elements, dimensions, vulnerabilities, spatiotemporal scales, specific problems, scenarios, stakeholders, governance, resilience, emergency protocols, early warning systems, etc. This information must be properly prioritized in order to optimise the management process, select the most urgent and relevant issues to solve and once the first objectives have been fulfilled, address the next ones. Therefore, after the definition of the risk management structure, the next task would be identifying the key factors affecting or controlling the system (i.e. leverage points) as they can be used to bring about major changes in the system with minimum effort (Martín García, 2006), the system dynamics being a potential tool to achieve this objective (Sterman, 2002, 2006; Meadows, 2008).

Table 2.4. Translation of human risk results into DRM options (Acajutla, Western Coastal Plain, El Salvador). Further information provided by González-Riancho et al. (2013).

DRM phases and related risk assessment results	Risk management options
A. Hazard knowledge. Flooded area, water depth (up to 4m), velocity (up to 10 m/s, very high drag levels, tsunami arrival time (25-30 min.)	*Hazard mitigation measures* • Construction of flood defence structures • Ocean wave barriers • Reforestation • Restoration of mangroves
B. *Management targets: exposed and vulnerable elements*. 9262 people exposed 70% located at very high/high risk areas 30% sensitive age 67% illiterate 32% extreme poverty 4% disability 37% isolated areas 15% critical evacuation *C. Specific objectives: reducing the consequences.* Minimizing potential loss of lives by reducing the population evacuation and reaction time. This depends on potential reduced mobility, difficulties for understanding a warning message, difficulties for receiving a warning and/or for evacuating in badly connected areas, and difficulties for performing a coordinated evacuation *D. General objective: reducing the risk.* Reducing human risk by ensuring effective evacuation	*Early warning system (EWS)* • Enhancing EWS for regional and local tsunamis • Optimization of communication system: networking, technology, mobile, warning speakers, etc. • Tsunami warning network in collaboration with local communities • Official tsunami reports regularly issued to the public. *Information, awareness, capacity building campaigns for local communities, including tailored campaigns for:* • people with difficulties for understanding a warning message • slow groups (elderly, disabled, pregnant women and children) • people in isolated areas • critical buildings (schools, hospitals, etc.) *Evacuation planning* • Community-based evacuation design and organization • Evacuation drills • Specific evacuation training for critical buildings staff • Specific help for slow groups and isolated areas (e.g. transport services) • Warning time prioritization to isolated areas • Construction of vertical evacuation shelters in strategic locations.

Figure 2.10a shows the system dynamics modelled for the analysis of tsunami impacts in Acajutla based on the participatory contribution of the various technicians from MARN and IH Cantabria. The impact of a tsunami event on the exposed and vulnerable elements (capital letters and blue font text, respectively) produce different cause-effect relationships and feedback loops (arrows) within the system generating the various negative consequences under study (text in boxes). These causal relationships show some kind of relevance roles and priorities between the elements in terms of management, which means that by working on some of them, results can be obtained on the others. The feedback loops between the final consequences highlight those that can worsen other impacts in the same or other dimensions and that, consequently, should be tackled first. For example, the generation of risk-cascading effects and the loss of infrastructures' operability generate human casualties and

environmental impacts; analogously, the loss of ecological integrity reduces the capability of generating ecological services, which affects the socioeconomic dimension.

Understanding the behaviour of the system and the interrelationships between the elements allows for the proposal of different management scenarios to understand the effects of the decision-making and to optimise the DRM. Figure 2.10b shows the causal relationships and tsunami impacts partially tackled by three risk reduction measures (orange boxes) proposed here: (i) promotion of population information and awareness campaigns tailored to the local sensitivity characteristics; (ii) protection and reforestation of mangroves; (iii) relocation or reinforcement of the seven critical buildings, and one dangerous-hazardous and three emergency infrastructures identified. It also shows how these three measures affect various causal relationships and feedbacks between the elements, and allow obtaining parallel extra results to those that were originally planned. The orange arrows represent the flows set in motion due to the risk reduction measure, while the yellow boxes show the consequences that are affected or improved somehow by these flows.

This example aims to show that one single action may have many results in complex systems, which is an interesting idea to bring forward in risk management. Working with complex systems is complicated, as many aspects, dimensions and variables should be considered and dealt with. However, once the system is understood, one can take advantage of this complexity to generate better results with less effort. Therefore, the understanding of complex systems allows for optimising the effort and getting the best results from the management options applied.

Working with scenarios provides the opportunity to understand the current system, predict the consequences of different plausible management options and, consequently, promote an adequate risk reduction plan for the studied area. It can be therefore a dynamic assessment of policy options and their response to existing feedback loops.

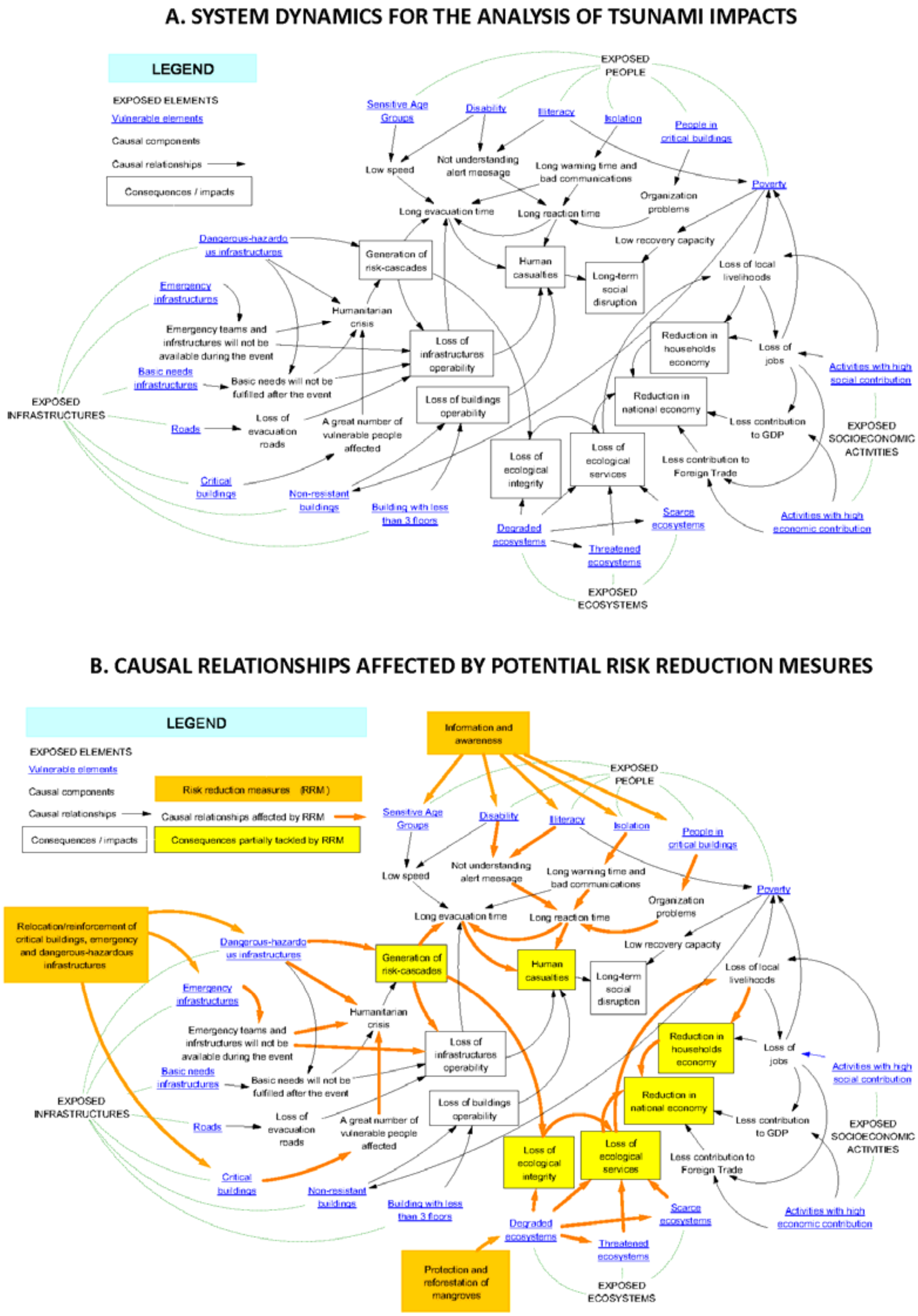

Figure 2.10. **(a)** System dynamics for the analysis of tsunami impacts in El Salvador; **(b)** causal relationships and tsunami impacts affected by potential risk reduction measures (Vensim® Software).

2.4 Conclusions

Advances in the understanding and prediction of tsunami impacts allow for the development of risk reduction strategies for tsunami-prone areas. Based on existing vulnerability and risk frameworks and approaches, the main expected contribution is to provide a straightforward method to facilitate their implementation. The method deals with the complexity and variability of CHANS by means of an integral approach to cover the entire process from the risk assessment to the risk management; an integrated approach to combine and aggregate the information stemming from the different dimensions; and a dynamic and scale-dependent approach to integrate the spatiotemporal variability considerations.

Risk assessment at the national level aims at comparing and prioritising municipalities in terms of risk reduction efforts (see Figure 2.5), while the assessment at the local level of the prioritised municipalities is aimed at calculating the specific expected impacts by dimension (see Figure 2.6 and Figure 2.7).

The deterministic hazard assessment based on propagation models for earthquake-generated tsunamis provided different hazard maps along the coast of El Salvador. This permitted the identification of the main tsunami flood-prone areas, that is, the Western Coastal Plain and the coastal stretch between La Libertad and Jucuaran municipalities, with the Lempa river mouth and Jiquilisco and Jaltepeque wetlands being especially relevant in terms of flooded area. The proposed exposure and vulnerability mixed indicator approach has proved to be useful to identify and locate the elements in the hazard area, as well as to measure the human, environmental, socioeconomic and infrastructural characteristics that make the municipalities more susceptible to the selected impacts.

The qualitative resilience assessment identified (through a short questionnaire) the degree of organisation and response within a community in case of an emergency. The analysis of a single municipality may not require a resilience index (i.e. numerical); however, when a comparison between municipalities is required (which was the aim of the national assessment), the resilience index seems to be a possible approach to have a general idea of the state of each municipality in terms of their preparedness and emergency management in order to design further detailed analyses to propose weakness-oriented, site-specific corrective measures.

A clear connection to translate the vulnerability and risk assessments into risk reduction measures is offered, trying to bridge the gap between science and management for the tsunami hazard. The risk assessment process directly feeds the required information to develop the risk management process, by reorienting its usual linear structure in order to have the DRM as the main goal to achieve. The approach, together with system dynamics modelling, facilitates the identification and prioritisation of ways to reduce the sensitivity of municipalities regarding various dimensions and to enhance the resilience of communities. Regarding the practical application of the RRM to the case study of El Salvador, and based on the risk results presented above, several measures are already being developed by the MARN, such as public tsunami hazard bulletins and monthly reports, information and awareness campaigns for local communities, a network of local observers to warn the communities in collaboration with the Ministry and Civil Protection, and community-based evacuation planning (further information is provided by González-Riancho et al., 2013).

A dynamic model to update the risk results is expected to be incorporated into the methodology as an effective tool for adaptive risk management. It is intended to gradually update the set of indicators, as the risk reduction measures are being implemented, allowing the systematic modification of the exposure, vulnerability and risk results and the understanding and utilising of the interrelation and feedback loops controlling the behaviour of the coupled human and natural system.

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Chapter 3. Tsunami evacuation modelling as a tool for risk reduction

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Tsunami evacuation modelling as a tool for risk reduction: application to the coastal area of El Salvador

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Abstract. Advances in the understanding and prediction of tsunami impacts allow the development of risk reduction strategies for tsunami-prone areas. This paper presents an integral framework for the formulation of tsunami evacuation plans based on tsunami vulnerability assessment and evacuation modelling. This framework considers (i) the hazard aspects (tsunami flooding characteristics and arrival time), (ii) the characteristics of the exposed area (people, shelters and road network), (iii) the current tsunami warning procedures and timing, (iv) the time needed to evacuate the population, and (v) the identification of measures to improve the evacuation process. The proposed methodological framework aims to bridge between risk assessment and risk management in terms of tsunami evacuation, as it allows for an estimation of the degree of evacuation success of specific management options, as well as for the classification and prioritization of the gathered information, in order to formulate an optimal evacuation plan. The framework has been applied to the El Salvador case study, demonstrating its applicability to site-specific response times and population characteristics.

3.1 Introduction

Tsunamis are relatively infrequent phenomena, but they nonetheless represent an important threat and cause the loss of thousands of human lives and extensive damage to coastal infrastructure around the world (González et al., 2012). Advances in the understanding and prediction of tsunami impacts allow the development of risk reduction strategies for tsunami-prone areas.

Conducting risk assessments is essential to identify the exposed areas and the most vulnerable communities. Hazard, vulnerability and risk assessment results allow the identification of adequate, site-specific and vulnerability-oriented risk management options, with the formulation of a tsunami evacuation plan being one of the main expected results. An evacuation plan requires the analysis of the territory and an evaluation of the relevant elements (hazard, population, evacuation routes, and shelters), the modelling of the evacuation, and the proposal of alternatives for those communities located in areas with limited opportunities for evacuation. This information facilitates the decision-making regarding tsunami risk management.

Several previous works dealing with different aspects of the evacuation process for a tsunami hazard exist. Some authors focus on hazard aspects, such as the calculation of the tsunami wave height, the flooded area, run-up, or arrival time, while others deal with tsunami-related human aspects, such as the calculation of loss of lives, potential casualties, mortality vs. safety, human damage prediction, etc. Some analyse road characteristics as input information for evacuation modelling, while others predict the impacts on buildings using damage functions. Several authors focus on the evacuation itself, dealing with the identification of critical areas, the calculation of the evacuation time, or the assessment of warning procedures, among others. Many are oriented to the development of specific evacuation modelling software. Very few authors focus on precisely how to plan a tsunami evacuation. Some examples of the previous works are briefly analysed here.

Regarding the human damage prediction caused by flooding-related disasters, including tsunamis, Sugimoto et al. (2003) presented a tsunami human damage prediction method employing numerical calculation and GIS for a town in a high-risk area. The number of deaths as a result of a tsunami was estimated from the accumulated death toll, taking into account the time necessary to begin to seek refuge after an earthquake, tsunami inundation depth on land, flow velocity and evacuation speed. Jonkman et al. (2008a, b) proposed a method for the estimation of loss of life due to flooding of low-lying areas protected by flood defences, which is given based on the flood characteristics, the exposed population and evacuation, and the mortality amongst the exposed population, using new mortality functions developed by analysing empirical information from historical floods. Koshimura et al. (2006) estimated the number of casualties that may occur while people evacuate from a tsunami inundation zone, based on a simple model of hydrodynamic forces as they affect the human body. The method uses a tsunami casualty index computed at each grid point of a numerical tsunami model to determine locations and times where tsunami evacuation is not possible, and therefore where casualties are most likely to occur. This, combined with population density information, allows for the calculation of the potential number of casualties, which is useful information to identify locations which ought to be excluded from evacuation routes. Sato et al. (2003) proposed a simplified method for tsunami risk assessment without wave run-up analysis, to qualitatively estimate the safety of residents, and examine the effectiveness of tsunami prevention facilities. Two normalized values are evaluated: the ratio of calculated maximum tsunami height to seawall height, and the ratio of the time between tsunami over-topping and evacuation completion to the total time required for evacuation.

Concerning the analysis of specific evacuation issues, Strunz et al. (2011), within the framework of the tsunami risk assessment for the German Indonesian Tsunami Early Warning System (GITEWS), analysed the evacuation of several Indonesian islands, considering vulnerability as the probability of not reaching safe areas in time. Alvear Brito et al. (2009) calculated the population evacuation time through a GIS-based numerical model, in which the critical zones (where the population will not have sufficient time to reach the security areas) are identified by considering factors such as the distance to security zones, the land slope, and accessibility of roads. Clerveaux and Katada (2008) presented a tsunami scenario simulator, which combines the hydrodynamic simulation of tsunamis with warning and human response simulations for evacuation, mainly focusing on alert communication aspects.

Works on evacuation modelling software may be grouped into three categories, according to the FLOODsite project (HR Wallingford, 2006): (i) traffic simulation models, (ii) evacuation behaviour models, and (iii) timeline/critical path management diagrams. The evacuation modelling shown in this paper fits into the third category. Kolen et al. (2010) described the *EvacuAid* probabilistic evacuation model, which determines the expected value and bandwidth for the success and loss of life of evacuation strategies based on four parameters: the available time, the behaviour of people, the behaviour of authorities and the available infrastructure and resources. Van Zuilekom et al. (2005) developed the *Evacuation Calculator* to compute how much time is required for evacuation, and to determine the effect of traffic management during the evacuation process on the required evacuation time. It focuses on traffic flows, and not on individual people or vehicles, and requires data about the average vehicle speed, the capacity of the exit point, the source zones and exits, the distance between them, and the number of people present in each source zone. BC Hydro (2004) developed the *Life SafetyModel* which allows dynamic interaction between the receptors (e.g. people, vehicles and buildings) and the flood hazard. It requires data about the location of individual properties, vehicles and people, the flood depths and velocities from a two-dimensional hydraulic model, and details of the road network and other pathways. Aboelata and Bowles (2005) proposed the *LIFESim* model for the estimation of potential loss of life from natural and man-made (dam and levee failure) floods, which comprises three modules: loss of shelter, warning and evacuation, and loss of life.

As far as evacuation planning is concerned, Scheer et al. (2011a), within the framework of the SCHEMA project and the Handbook on Tsunami Evacuation Planning, presented the local tsunami risk assessment and all subsequent implications for evacuation planning, based on the expected tsunami wave height, and the arrival time of the first devastating tsunami wave. This work defines a cost surface layer, evacuation shelter points, a time map, the area covered by each shelter point, the time distance from the closest shelter, the area served by exit/escape points, and the time distance to reach the closest escape point. Scheer et al. (2011b) propose optimizing tsunami evacuation plans through the use of building damage scenarios to identify potential vertical shelters. Garside et al. (2009) state that all at-risk facilities should have appropriate emergency response planning which would include (i) warning notification protocols and systems; (ii) evaluation and mapping of evacuation routes, with signage to designated assembly points; (iii) consideration of evacuation timing; and (iv) staff training and evacuation plan exercising. Besides the existing scientific works, many of the official evacuation plans reviewed (Tokyo's earthquake survival manual[5], Oregon's tsunami evacuation brochures[6], Chile's tsunami inundation map[7], etc.) are oriented to provide citizens from a city/province/country with strategic information such as an evacuation map and some general guidelines about what to do in case of emergency, as opposed to being a tool for decision makers to plan the proper evacuation of the area.

As mentioned above, different partial aspects of tsunami risk and evacuation are addressed in the literature. With a view to the successful planning of the evacuation of the population located in a tsunami prone area, several gaps in the prevailing science are identified: (i) no direct relationship between the specific evacuation-related assessments carried out and the formulation of risk reduction measures and/or an evacuation plan exists, even though some general connections are usually established; (ii) an assessment of the characteristics of the population and communities to be evacuated is not usually undertaken, (iii) the evacuation time is sometimes calculated without considering the tsunami arrival time, resulting in a lack of information regarding the degree of success that the identified evacuation time represents for the population; (iv) an analysis of the time needed by the responsible administrations to issue the tsunami warning and to inform the population is sometimes not considered, although this is essential information for determining the real time available for the population to evacuate; (v) the evacuation modelling results sometimes do not identify, propose or suggest conclusions about how to reduce the risk of the populations identified in critical areas, regarding successful evacuation; and (vi) proposals for improvements in the evacuation process are frequently inadequate, lacking identification of locations to build new vertical shelters and evacuation routes, and omitting warning time reduction strategies, etc.

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[5] Tokyo Metropolitan Government: Earthquake survival manual

[6] Oregon Department of Emergency Management and Oregon Department of Geology and Mineral Industries: Tsunami Evacuation Brochures

[7] Gobierno de Chile: Carta de Inundación Por Tsunami, Zona Urbana Coronel Costa (in Spanish)

Based on this analysis, the objective of this paper is to present a framework which aims to eliminate the above-identified gaps, providing a global picture of what is required for the adequate formulation of evacuation plans of a study area, and to present evacuation modelling as an essential tool for risk management. This methodological framework proposes an integral approach to considering (i) the hazard aspects (tsunami flooding characteristics and arrival time), (ii) the characteristics of the exposed area (people, shelters and road network), (iii) the current tsunami warning procedures and timing, (iv) the evacuation time needed by the population, and (v) the identification of measures to improve the evacuation. It thus aims to bridge the gap between risk assessment and management in tsunami evacuation. Finally, an application of this framework to the coastal area of El Salvador, and specifically to the Western Coastal Plain, is presented in this paper along with a discussion on the major findings.

3.2 Framework for tsunami evacuation planning

Evacuation plans, which are developed by the responsible authorities and decision makers, would benefit from a clear and straightforward connection between the scientific and technical information from tsunami risk assessments and the subsequent risk reduction options. Scientifically-based evacuation plans would translate into benefits for the society in terms of mortality reduction. Figure 3.1 shows the methodological framework proposed for evacuation planning, which is divided into three phases: analysis, modelling and planning. This framework and its three phases are intended to be supported by participatory processes involving the local communities, the Civil Protection, emergency-related NGOs and responsible authorities, among others. These processes aim to (i) inform the stakeholders about the work, (ii) involve them in the overall evacuation planning process, from the preliminary designs to the validation of the evacuation strategy and maps, (iii) include their knowledge in the analysis, and (iv) thereby improve the final planning results.

The analysis phase aims to examine the territory and communities exposed to the tsunami flooding in order to identify critical elements from the point of view of the evacuation, by examining the characteristics of the population, the characteristics of the road network and the availability of safe areas in case of tsunami events. These three components (population, routes and shelters) are identified and weighted based on several evacuation-relevant criteria (reaction time, travel speed and isolation of the exposed population; travel difficulty and safety of the road network; and capacity, safety and accessibility of shelters), to obtain essential information for the preparation of a preliminary evacuation proposal that distributes the population among the different shelters identified. This preliminary proposal is intended to then be discussed and reviewed with the exposed local communities in order to include and benefit from their experience, perception and knowledge.

The modelling phase aims to refine and update the preliminary evacuation proposal to identify the critical areas that would not be able to be evacuated and that should therefore be priority candidates for risk reduction measures. The evacuation modelling considers the distances to be travelled and the evacuation speeds of the population, the tsunami arrival time and the current risk management procedures, such as the warning time needed by the responsible authorities and the reaction time of the population. This information is best obtained through consultations with the involvement of the responsible authorities, in order to include their experience and knowledge about existing warning protocols and the main difficulties faced in emergency events. Once the critical areas have been identified, alternatives dealing with reducing the distances to be travelled and/or increasing the available time are proposed to reduce risk. These proposals are also modelled to ensure that the critical areas are gradually reduced, and this process is repeated until these areas are eliminated.

The planning phase aims to gather all the information produced in the analysis and modelling phases as inputs for a comprehensive tsunami evacuation plan. The analysis of the exposed population will result in measures to ensure the proper evacuation of the entire population, by reducing the limitations produced by the reaction time, the travel speed and the isolation of communities. Analysis of the road network and safe areas will result in measures to improve both elements, by increasing the capacity, safety and accessibility of roads and shelters. The evacuation modelling will provide conclusions about the need for reducing (i) the distances that the population has to travel until they reach a safe area, (ii) the authorities' response time (detection, analysis and warning time) and (iii) the population reaction time, and consequently the measures are oriented to these issues. This framework permits interactive and adaptive planning and management, as once the above-mentioned measures have been implemented, the three evacuation indices (population evacuation index, evacuation routes index and safe areas index) will be improved towards their optimal status.

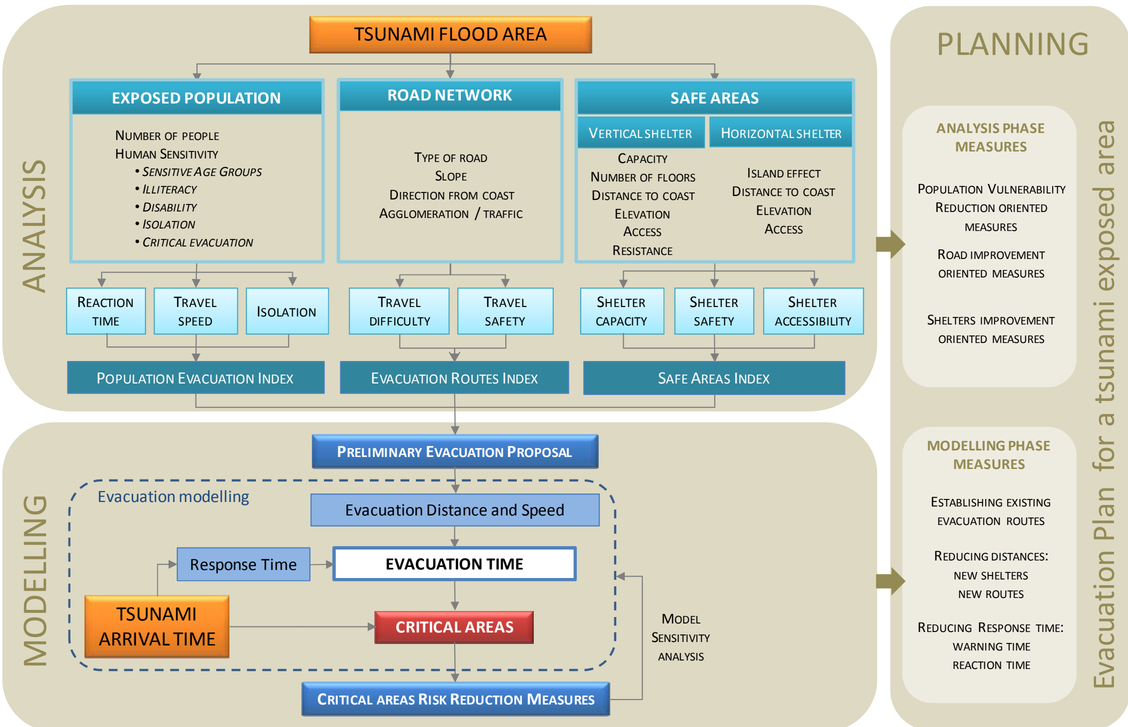

Figure 3.1. Tsunami evacuation planning framework.

Based on this framework, the chapter is divided into six sections: (1) identification of the potential tsunami-flooded area, (2) analysis of the exposed population, safe areas and evacuation routes, (3) time calculation, (4) evacuation modelling, (5) proposal of alternatives for critical areas, and (6) evacuation planning.

3.2.1 Identification of the potential tsunami-flooded area

A proper identification of the potential tsunami-flooded area requires a hazard assessment based on tsunami propagation models through the characterization of tsunamigenic sources and other oceanic and coastal dynamics. Simulations of historical and potential tsunamis with variable impact on the coast should be performed including distant, regional and local sources. Probabilistic or deterministic analyses can be carried out to generate different hazard maps such as the maximum wave height elevation, the maximum water depth, the maximum flooding level or run-up, the minimum tsunami arrival time, and the maximum potential drag, understood as the hazard degree for human instability based on incipient water velocity and depth.

A specific methodology for the hazard assessment is not detailed in this section, as this paper focuses on evacuation planning. For further methodological information see Álvarez-Gómez et al. (2013).

3.2.2 Analysis of the exposed population, safe areas and road network

Once the potential tsunami-flooded area has been identified and consequently the exposed communities and infrastructures are known and geographically located, a characterization of the exposed population, the safe (not-flooded) areas and the road network to reach these areas is performed.

The analysis of the exposed population in terms of evacuation is based on the population evacuation index (PEI) and a series of evacuation indices and indicators. For the calculation of the PEI, (i) the reaction time index considers the number of illiterate people (related to not understanding a warning message) and the number of people located in critical buildings, understood as those that house large numbers of people to be organized jointly in case of evacuation (hospitals, schools); (ii) the travel speed index is based on the number of disabled and sensitive age people (children and the elderly); and (ii) the isolation index considers the expected number of people that may have difficulties evacuating due to the characteristics of their territory. In conclusion, gathering knowledge about the number of people to be evacuated, their location and their characteristics and limitations regarding evacuation, is extremely useful to successfully manage their evacuation and to foster their preparedness in a specificity-oriented manner.

Evacuation to safe areas distinguishes between horizontal and vertical shelters. Horizontal evacuation refers to the strategy for arriving in the areas that are not flooded which are outside the hazard zone or on accessible high grounds. Vertical evacuation refers to the strategy for escaping within the hazard zone by going up to higher floors in buildings or other artificial structures. Tsunami numerical modelling defines the potentially flooded area, which then permits the establishment of horizontal security zoning. The security zoning is proposed to be comprised of the following zones:

- Tsunami-flooded area: area with larger flood depths and flow velocities near the coast and lower depths and flow velocities further inland. Evacuation from this area is strongly recommended.
- Medium-security area: this zone is established between the maximum flood level in the study area and a security level specifically determined for each zone and defined by elevation. This area would be the minimum evacuation objective to be achieved by the population in order to ensure their safety.
- High-security area: from the medium-security zone onwards. This area is the evacuation objective for those located in the medium-security zone when the alert is received and for anyone able to reach this area in the available time.

Potential vertical shelters located within the tsunami hazard area are identified, analysed and prioritized based on the above-shown criteria, i.e. capacity, safety and accessibility. The current road network is also analysed to identify the existing evacuation routes in the study area, and to select those roads that connect populated areas with medium-security areas and prioritized in terms of ease of travel and safety.

The set of indicators proposed for the analysis of the exposed people, road network and safe areas is shown in Table 3.1, with several mathematical–statistical procedures being applied to them in order to generate comparable and combinable information. The following paragraphs describe the methodology used to integrate the indicators.

The indicators proposed for the assessment of the exposed population, road network and safe areas help in (i) identifying specific weaknesses to be addressed within a tsunami preparedness program, and (ii) prioritizing routes and shelters. The indicators for the assessment of safe areas also provide, through the binary indicators, information used to reject some shelters from the planning process (for example, non-resistant vertical shelters, island effects on horizontal shelters, and no available access to either kind of shelter results in a direct rejection).

Following OECD/EC-JRC (2008), the process for the integration of the evacuation indicators and indices has the following steps: (i) building indicators through normalization; (ii) building indices through weighted aggregation, and (iii) indices classification through the natural breaks method. The transformation of the variables range of values is carried out using the minimum–maximum (Min–Max) method, which normalizes the indicators to an identical range [0,1] by subtracting the minimum value and dividing by the range of the indicator values. The indices are built through the weighted aggregation of the normalized indicators, the weights being associated with (i) the importance it represents for the index to which it belongs, and (ii) the reliability of the information (for example, although the type of road – in terms of materials, width and conservation – is considered important for an efficient evacuation, it is common to find that a high percentage of the roads that must be used are not the best type of roads, therefore in such cases this indicator should be low-weighted). The partial indices obtained are also weighted and aggregated to build the composite index. The indices are classified and translated into 5 classes, this ranking being linked to a colour code to represent the information geographically. The Natural Breaks classification method, based on the Jenk's optimization algorithm, implemented in the ArcGIS® software and designed to determine the best arrangement of values into different classes is applied. The method reduces the variance within classes and maximizes the variance between classes (Jenks, 1967) by minimizing each class's average deviation from the class mean, while maximizing each class's deviation from the means of the other groups. It has been selected after testing other methods (such as the equal interval, defined interval, quantile, geometrical interval, standard deviation, etc.), as it permits grouping within the same class the planning units (e.g. municipalities) that have similar values, i.e. that behave in the same way and which are expected to need similar measures. Since this method of classification depends on the distribution of the data, the study of any index evolution over time must maintain the ranges established in the initial analysis (González-Riancho et al., 2013).

Table 3.1. Set of indices and indicators for the analysis of exposed population, road network and safe areas (*V* = vertical shelter; *H* = horizontal shelter).

Composite indices	Indices	Indicators	Variables
Population Evacuation Index	Reaction time	Illiteracy	Number of illiterate people
		Critical evacuation	Number of people in critical buildings
	Travel speed	Sensitive Age Groups	Number of people below 10 yr, and above 65 yr
		Disability	Number of people with physical/intellectual disability
	Isolation	Isolation	Number of people located in isolated areas
Evacuation Routes index	Travel difficulty	Type of road	Number of road segments (per evacuation route) below a predefined site-specific level of quality
		Slope	Number of road segments (per evacuation route) with more than 9% slope (based on Cano et al., 2011 and Laghi et al., 2006)
		Agglomeration/traffic	Number of road segments (per evacuation route) with common agglomeration/traffic bottlenecks
	Travel safety	Direction from the coast	Number of road segments (per evacuation route) and distances to travel parallel to the coast
Safe Areas Index	Shelter Capacity	Capacity (V)	Number of people that can be hosted per vertical shelter
	Shelter Safety	Number of floors (V)	Number of floors per vertical shelter
		Resistance (V)	Materials resistance per vertical shelter (yes/no)
		Distance to the coast (V/H)	Distance (m) from the shelter to the coast
		Elevation (V/H)	Elevation (m) from the sea level per shelter
		Island effect (H)	Horizontal safe area surrounded by flooding (yes/no)
	Shelter Accessibility	Access (V/H)	Open access to the shelter by road (yes/no)

3.2.3 Time calculation

Some time-related concepts essential to understanding the study are as follows (Figure 3.2):

- *Tsunami arrival time* ($T_{Tsunami}$): time from the tsunami generation until the first wave arrives at the coastal area. The tsunami arrival time map is represented by time contour lines and a colour code.
- *Total evacuation time*: time from the tsunami generation until the entire population reaches a safe area. It consists of two concepts:

a. *Response time* ($T_{Response}$): time from the tsunami generation until the population begins to evacuate. This time includes:

   i. *Detection and warning time*: time from the earthquake detection and the analysis of its characteristics until the tsunami warning is issued by the responsible authority.

ii. *Alert transmission time*: time from the reception of the alert by the intermediate authorities in charge of crisis management (such as Civil Protection) at the national level and its transmission to those responsible at the local level.
iii. *Alert reception time*: time from the reception of the alert by those responsible at the local level until the entire community is informed.
iv. *Population reaction time*: time elapsed from the instant the population receives the alert until they start to evacuate.

b. Evacuation time ($T_{Evacuation}$): time from the beginning of the evacuation until the population arrives in a safe zone (walking evacuation time).

The tsunami arrival time is calculated based on the hazard assessment described in Sect. 2.1 by means of the generation of a set of tsunami arrival time maps through numerical modelling. The response time can be obtained from the existing emergency protocols or from direct work with the responsible authorities, at least the information regarding the detection and warning, alert transmission and reception times. The reaction time of the population, if no information is available, may be assumed to be 15 min for prepared/aware people, based on Post et al. (2009) and Strunz et al. (2011), despite being a simplification as not the whole population would evacuate at the same time. The evacuation time is to be obtained from the evacuation modelling considering the tsunami arrival time and response time.

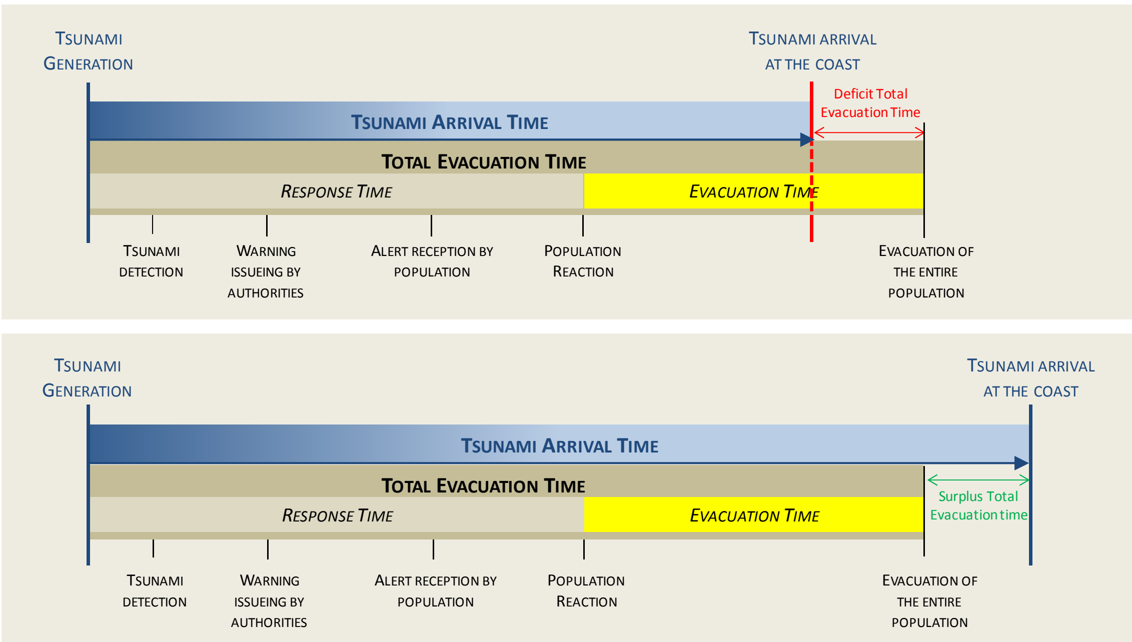

Figure 3.2. Tsunami evacuation timelines: to ensure the evacuation of the entire exposed population the Total Evacuation Time –TET-, which includes the response and the evacuation times, must be lower than the time the tsunami needs to arrive at the coast (Surplus TET, image below). The opposite situation (Deficit TET, image above) implies potential human impacts.

A deficit in the total evacuation time is generated when the time needed for evacuation is greater than the time the tsunami takes to arrive at the coast. A surplus is obtained when the opposite situation happens (see Figure 3.2). As the tsunami arrival time cannot be controlled, the only option to reduce the risk for coastal communities depends on the management (reduction) of the response and evacuation time. The evacuation time depends on the distances to be travelled and the population speeds; assuming that no improvements to evacuation time (such as building new shorter routes, organizing specific help for slow populations, etc.) can be implemented at the moment, then the current evacuation success will mainly depend on the response time: the lower the response time, the more time will be available for the evacuation and to reach a safe area before the first tsunami wave arrives. The evacuation corresponding to various response times should be analysed and modelled in order to identify the critical one for which the population would not be able to evacuate in time.

3.2.4 Evacuation modelling

An evacuation modelling is carried out to identify optimal evacuation routes and the time needed for the population to evacuate, based on the tsunami arrival time, the security zoning and the road network. For the evacuation modelling applied within the framework proposed in this paper, the network analyst extension of the ArcGIS® 10.1 software is used to create a network database and perform various analyses considering the definition of attributes and connectivity standards. Based on this extension, the "closest facility" analysis is applied to measure the travelling cost between origin and destination points. The following factors are considered for modelling:

- Evacuation distances: the aim is to obtain the minimum distance a person has to walk (L) from each evacuation point of origin (located at every road intersection inside the flooded area and based on the spatial analysis of the distribution of population) to the destination point (located where each road gets out of the flood sheet).
- Evacuation speed (V): based on Sugimoto et al. (2003) and Mück (2008), two types of people with different speeds (V1, V2) are considered:
    i. Fast population, generally associated with adults, with an evacuation speed of $V1=1ms^{-1}$.
    ii. Slow population, associated with the elderly, children and the disabled, with an evacuation speed of $V2=0.7ms^{-1}$.
- Evacuation time ($T_{Evacuation}$): the time needed to travel the length L to the safe area (destination point); it depends on the different speeds considered ($T_{Evacuation1}$, $T_{Evacuation2}$):
    i. Fast population: $T_{Evacuation1} = L/V1$.
    ii. Slow population: $T_{Evacuation2} = L/V2$.
- A slope slows the evacuation (slope = (Za−Zo)/L; Za being the highest point and Zo the lowest point on the evacuation route). Thus, according to Laghi et al. (2006) and Cano (2011), speeds are corrected based on the slope (see Table 3.2), and consequently the evacuation times are also corrected. The slope calculation considers the difference of elevation between the origin and destination points, assuming that the latter points are always located on higher ground.

Table 3.2. Evacuation speed correction based on the slope (Laghi et al., 2006).

Slope (%)	Speed value (%)
0-3	100%
3-6	85%
6-9	70%
9-12	55%
12-5	45%
15-18	40%
18-21	35%
21-24	30%
24-27	25%
27-30	20%
30-33	15%
33-36	14%
36-39	13%
39-42	12%
42-45	11%
45 or more	10%

– Response time ($T_{Response}$) =time from the occurrence of the tsunamigenic event until the population begins to evacuate
– Total evacuation time (T) for each type of population by speeds (T1, T2):
    i. Fast population: $T1 = T_{Response} + T_{Evacuation1}$.
    ii. Slow population: $T2 = T_{Response} + T_{Evacuation2}$.

According to the response time modelled in each case, the model provides the shortest path from each origin point to the destination point, calculates the time required for walking the shortest path identified, and colours the origin point depending on the result obtained. Table 3.3 shows the colour code used to represent these results, depending on whether the total evacuation time of the fast population (T1) and the slow population (T2) are less than or greater than the tsunami arrival time ($T_{Tsunami}$).

As the number of exposed people is known, this modeling also permits the calculation of the evacuation balance, understood as the percentage of people getting evacuated by census tract for the response time analysed. The evacuation balance depends on both the distance to be travelled and the population speed.

Table 3.3. Results for the relationships between tsunami arrival time and total evacuation time.

	Total Evacuation Time (T1<T2)		Result	Colour code (evacuation origin points)
	Fast population T1	Slow population T2		
Tsunami Arrival Time	$T1 > T_{Tsunami}$	$T2 > T_{Tsunami}$	No one starting from this origin point would evacuate	Red
	$T1 < T_{Tsunami}$	$T2 > T_{Tsunami}$	Only the fast population group would evacuate	Orange
		$T2 < T_{Tsunami}$	Everyone starting from this origin point would evacuate	Green

3.2.5 *Proposal of alternatives for critical areas: a sensitivity analysis of the evacuation model*

Depending on the evacuation results obtained for a specific response time, the formulation of particular measures to improve the evacuation of the area may be required. These measures can be of two types:

- The reduction in the response time, which would increase the time available for evacuation.
- The reduction in the distance to be travelled by communities which are currently not able to evacuate in time, by means of building vertical evacuation shelters and/or new evacuation routes.

After the proposals for alternatives to reduce the response time and/or the distances to be travelled are implemented, the evacuation shall be modelled again in order to confirm that the critical area is being reduced and that more of the population is being evacuated. Further measures should be applied and modelled until the entire area evacuates successfully. This sensitivity analysis of the evacuation model represents a powerful tool for managers to reduce the risk of specific areas, by ensuring the successful evacuation of the population, as it allows for the prediction and assessment of the results of specific management options.

Regarding the identification of possible locations for vertical evacuation shelters in the study areas, once a lower (than the initial) response time is modelled and the critical areas have been identified, the following steps are required:

i. Identification of areas where the population that would be unable to evacuate for this lower response time ($T_{Response}$) is concentrated (the selection of the initial response time and subsequent reductions to model is context-specific and depends on the modelled tsunami arrival time and the minimum potential response time for the case study).
ii. Location of towers at strategic points in that area. Designers must select the initial location of towers based on the following information: the number and distribution of people along the flooded area with special attention to the people located seaward of

the shelter, the tsunami arrival time at the coastline, the geomorphologic characteristics of the territory and the subsequent effects on the tsunami.

iii. Calculation of the arrival time of the tsunami ($T_{Tsunami}$) at each tower. Assuming that a warning will be issued -the modelling is based on a predefined response time-, the arrival time at the tower is calculated in order to understand the available time to reach it. Knowing the tsunami arrival time at the coast and the location of the various communities, the selection of the tower location must ensure that the tsunami arrival time at the tower is higher than the added reaction and evacuation times of the population located seaward to the shelter.

iv. Calculation of the time available for evacuation at that point, i.e. the time that people have to arrive at the tower before it is reached by the first tsunami wave ($T_{Evacuation} = T_{Tsunami} - T_{Response}$).

v. Calculation of the distance that can be travelled for that evacuation time for the two considered speeds ($V1= ms^{-1}$, $V2=0.7ms^{-1}$).

vi. Modification of tower locations, based on the obtained results for each tower, i.e. the initial position is maintained or modified to improve results in terms of number of people reaching the shelter. Any improvement implies going back to steps iii, iv, v and vi until the final location satisfies designer.

Note that in this work, this iterative procedure has been performed heuristically and based on designer experience. However, the methodology could be settled like a mathematical programming problem and solved by standard optimization procedures. The tower locations and its number would be the optimization or decision variables, and the problem could be stated in two different forms: (i) minimize the tower costs subject to the constraint that all inhabitants would have time enough to reach shelter on time; this case assumes that there are no budget limitations; or (ii) maximize the number of people reaching shelter on time, constraint by a limited budget. Although the first option is preferable, reality makes the second option most likely. This automatic selection of the number and location of towers is a subject for further research. In spite of how this selection if performed, at the end of the process the following information (Figure 3.3) is provided for each tower: the tsunami arrival time ($T_{Tsunami}$); the response time ($T_{Response}$); the time available to evacuate ($T_{Evacuation}$); and the reception distance for both population speeds, which is represented by the green and red concentric rings surrounding the towers (the population located in the green ring would reach the tower in the available time, regardless of whether they belong to the fast or slow population; from the population located in the red ring only the fast population would reach the tower in time).

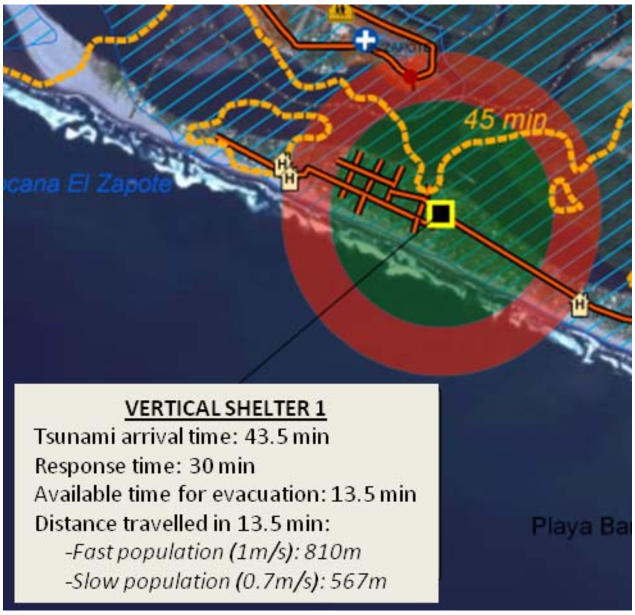

Figure 3.3. Example of the information provided for a vertical evacuation shelter.

3.2.6 *Evacuation planning*

The above-described process provides essential information for tsunami risk management, including the formulation of an evacuation plan. The analysis phase provides measures oriented to (i) reducing the limitations of populations in terms of evacuation, (ii) improving the road network and (ii) improving the existing shelters; while the modelling phase offers measures oriented to (iv) the reduction of current evacuation distances to be travelled and (v) reducing the current response time. Based on this, Table 3.4 presents an example of an evacuation plan structure and measures.

Table 3.4. Evacuation plan structure.

General objectives	Specific objectives	Examples of measures
Enhancing the tsunami preparedness of the population	Reduction of the vulnerability of the population regarding evacuation	Reaction time measures - Information, awareness, capacity building and specific help for people who have difficulties understanding a warning message - Specific evacuation training for critical buildings staff (schools, geriatrics, hospitals, etc.) Travel speed measures - Information, awareness and capacity building for slow groups (elderly, disabled, pregnant women and children) - Community organization and specific help for slow groups Isolation measures - Information, awareness and training for isolated areas - Specific help (transport services) for isolated areas - Warning time prioritization to isolated areas
Consolidation of the existing evacuation infrastructures	Consolidation of the existing evacuation routes	Travel difficulty measures - Urban traffic management to avoid bottleneck areas - Removal of potential bottlenecks (i.e. markets) from evacuation routes Travel safety measures - Improve/fix existing roads to facilitate the evacuation
	Consolidation of the existing evacuation shelters	Shelter capacity measures - Increasing the capacity of certain shelters when possible Shelter safety measures - Structural reinforcement of existing structures Shelter accessibility measures - Improve accessibility to existing shelters, eliminate barriers to evacuation
Risk reduction in critical areas	Reducing evacuation distances to travel	Building new routes - Building new routes to shorten the current evacuation distances Building new shelters - Building new shelters to shorten the distances to travel by the communities that currently are not able to evacuate - Special help for the slow population located on the red ring
	Reducing response time	Reducing warning time - Early warning system - Capacity building in critical areas - Optimization of communication system: networking, technology (mobile, tsunami warning speakers, etc.) Reducing reaction time - Information and awareness campaigns in critical areas - Training, evacuation drills in critical areas

3.3 Application to the coastal area of El Salvador

This chapter presents the application of the described methodological framework for evacuation planning to the coastal area of El Salvador. Of the tsunamis that have hit the Pacific coast of Central America, only 4 have been generated by distant sources (including the two recent tsunamis of Chile 2010 and Japan 2011) versus 30 local events, 7 of which were damaging (Álvarez-Gómez et al., 2012). According to Álvarez-Gómez et al. (2012), MARN (2009), Fernández et al. (2004, 2000) and Fernández (2002), the study area is located in an area of high seismic activity which has been hit by 15 tsunamis between 1859 and 2012 (Figure 3.4 and Table 3.5), with all of them having been generated by earthquakes, and two of them being highly destructive; one in 1902 that affected the eastern coast of the country and one in 1957 that affected Acajutla. The most recent, albeit of lesser magnitude, occurred in August 2012, affecting Jiquilisco Bay (IH Cantabria-MARN, 2012).

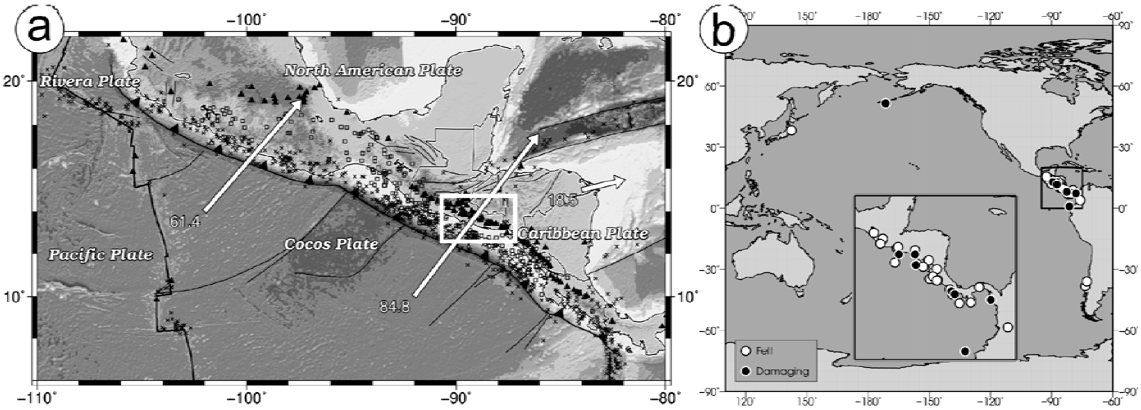

Figure 3.4. Location of El Salvador, fault zones and epicentres of past earthquakes (figure and caption modified from Álvarez-Gómez, 2012). **(a)** Tectonic setting of the Middle America Trench. The white square shows the location of El Salvador; the arrows illustrate the direction and magnitude of the plate motions taking the North American Plate; the label is the motion magnitude in mm/year; the triangles show the position of the Holocene volcanoes; cross symbols represent the shallow seismicity (b50 km) and squares the rest of the seismic Global CMT Catalog. **(b)** Tsunami catalog of the pacific coast of Central America; white circles: epicentres of non-destructive tsunamis; black circles: epicentres of damaging tsunamis.

Table 3.5. Catalogue of historical tsunamis affecting the coast of El Salvador. Data from MARN (2009), Fernández (2002) and USGS Earthquake Hazards Program (http://earthquake.usgs.gov).

Date	Country	Earthquake location	Earthquake magnitude	Tsunami impact location
1859/08/25	Guatemala	13.0N 87.5W	6.2	La Unión
1859/12/08	Guatemala	13.0N 89.8W	7.0	Acajutla
1902/02/26	Guatemala	13.5N 89.5W	8.3	Acajutla
				Barra de Santiago
				La Paz
1906/01/31	Ecuador	1.0N 80.0W	8.6	All the coast
1919/06/29	Nicaragua	13.50N 87.50W	6.7	La Unión
1950/10/05	Costa Rica	11.0N 85.0W	7.7	La Libertad
				La Unión
1950/10/23	Guatemala	14.3N 91.7W	7.1	La Unión
1952/11/04	Russia	52.8N 159.5W	9.0	La Libertad
1957/03/10	USA	51.3N 175.6W	8.1	Acajutla
				La Unión
1960/05/22	Chile	39.5S 74.5W	9.5	La Unión
1964/03/28	USA	61.1N 147.5W	9.2	Acajutla
				La Unión
1985/09/19	Chile	18.19N 102.53W	8.0	Acajutla
1992/09/01	Nicaragua	11.73N 87.39W	7.7	Golfo de Fonseca
2004/12/26	Indonesia	3.29N 95.98E	9.0	Acajutla
2012/08/26	El Salvador	12.28N 88.53W	**7.3**	Bahía de Jiquilisco (Isla de Mendez)

The work presented here is framed within a comprehensive methodology for assessing the tsunami risk in coastal areas worldwide, and applied specifically to the coast of El Salvador during the period 2009–2012. Two spatial scales have been applied for the risk assessment in the project, a global analysis for the national scale, and a local and more detailed analysis for three specific areas at higher risk: the Western Coastal Plain, La Libertad and the Bahía de Jiquilisco. Evacuation has been modelled for the three local studies. The results obtained for the Western Coastal Plain are presented in this paper.

3.3.1 Identification of the tsunami-flooded area

The hazard assessment is based on propagation models for earthquake-generated tsunamis, developed through the characterization of tsunamigenic sources – seismotectonic faults – and other dynamics (waves, sea level, etc.). Simulations of historical and potential tsunamis that affect the coast to a greater or lesser extent have been performed, including distant sources (distances greater than 2000 km to the coast, with tsunami travel times greater than 4 h), regional sources (between 700 and 2000 km with tsunami travel times between 1 and 4 h), and local sources (located in the subduction trench off the country's coast with tsunami travel times of less than 1 h).

A deterministic analysis (aggregated analysis that combines the 23 worst credible cases of tsunamis that could impact on the Salvadoran coast, see Figure 3.5) has been carried out, considering local seismic sources located in the Middle America Trench, characterized seismotectonically, and distant sources in the rest of Pacific Basin, using historical and recent earthquakes and tsunamis. The earthquakes magnitude ranges between Mw7.7 for some local sources and Mw9.5 for distant sources (Álvarez-Gómez et al., 2013). According to the methodology proposed by the SCHEMA project (Tinti et al., 2011), when applying the worst-case credible scenario approach to the tsunami hazard assessment the process of aggregation of the results obtained for the single tsunami sources consists in selecting for each position of the map the extreme value (the highest or the lowest) computed for the individual cases. The main outputs (Figure 3.6) are different hazard maps (maximum wave height elevation, maximum water depth, maximum flow velocity, minimum tsunami arrival time, maximum flooding level or "run-up", and maximum potential drag along the coast of El Salvador and at some relevant locations with high resolution analysis. Further information on this deterministic hazard assessment is provided by Álvarez-Gómez et al. (2013).

For evacuation analysis purposes the drag hazard map has been used, as it allows understanding the potential human instability based on incipient water velocity and depth to better explain the human risk caused by the tsunami. Regarding the drag calculation, the drag value at each point of the grid and for each event modelled is obtained by multiplying the flow velocity (u) value by the flow depth (h) value at each instant, and calculating the maximum value of the product, i.e. max (h×u), which is different than considering the maximum value of the velocity at that point (i.e. max (u)×h). The drag value at each point of the grid for the aggregated case is the maximum drag value obtained among the 23 events.

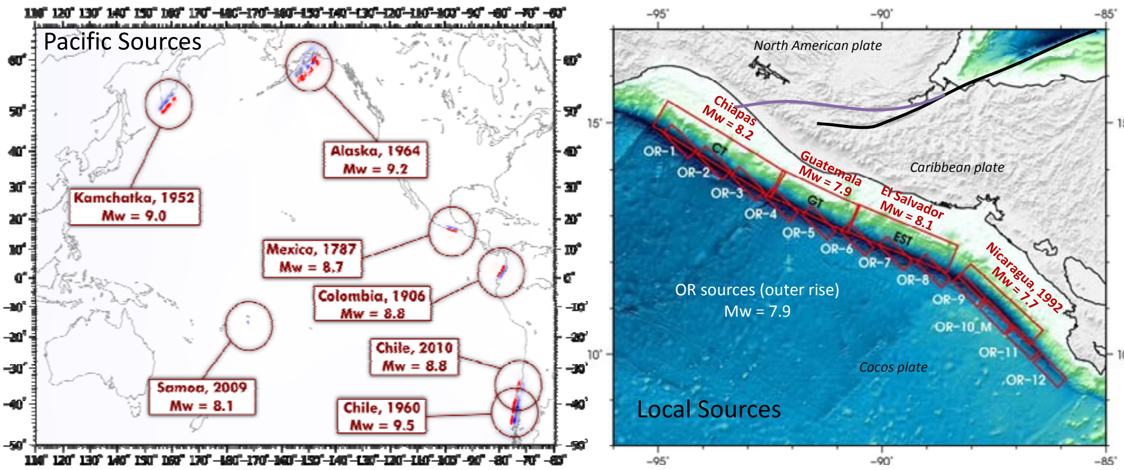

Figure 3.5. Tsunamigenic sources aggregated for the deterministic analysis.

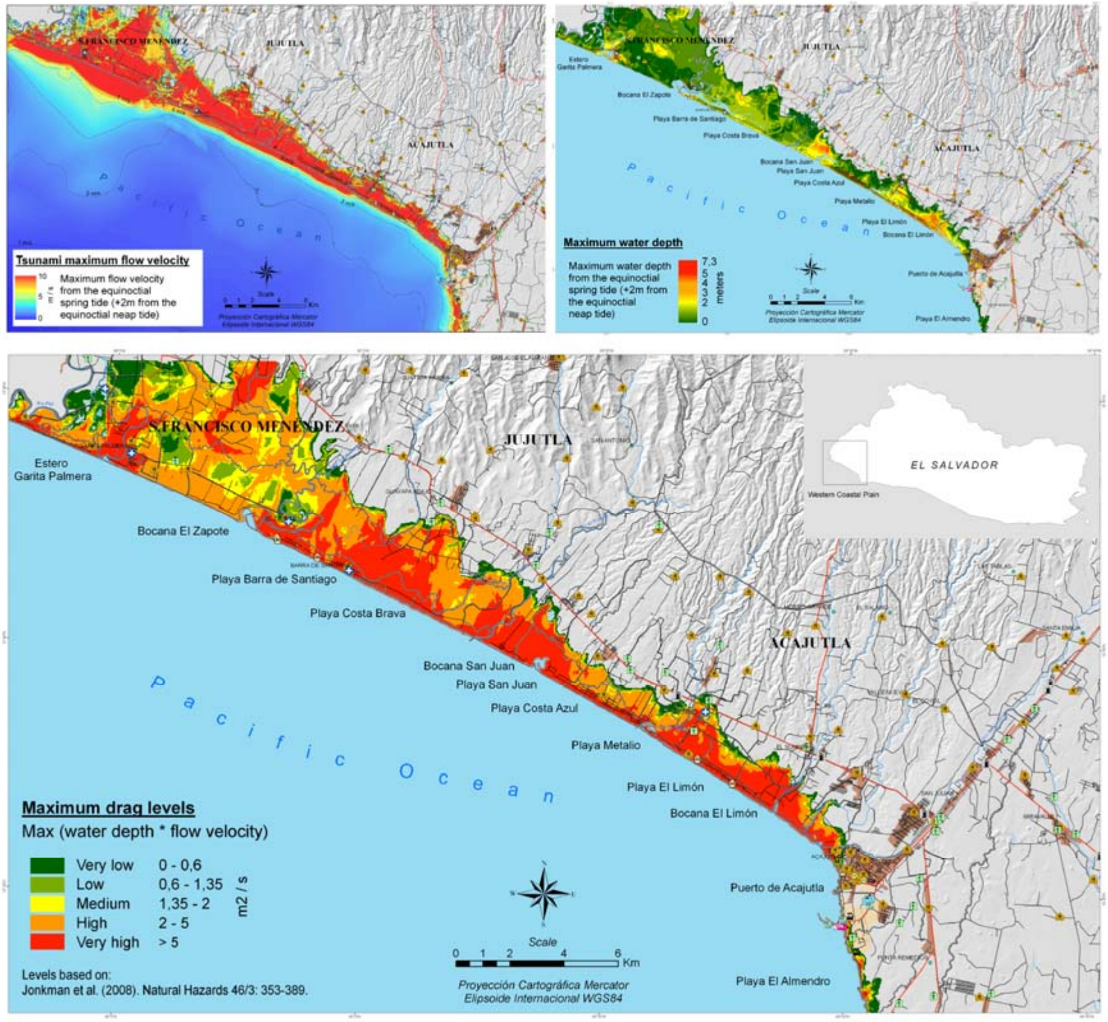

Figure 3.6. Hazard maps for the Western Coastal Plain of El Salvador: maximum flow velocity (above left), maximum water depth (above right) and maximum drag (below).

3.3.2 Analysis of exposed population, safe areas and road network

The analysis of the exposed population in terms of evacuation has been carried out using the exposure and vulnerability information gathered for the tsunami risk assessment (González-Riancho et al., 2013), with the census tract being the analysis unit at the local level. Based on the methodology presented in Sect. 2 and a geographic information system, several partial and aggregated maps have been generated to better understand the population evacuation index (PEI). Figure 3.7 shows the PEI map, together with the three indices composing it: (i) the reaction time index of each census tract exposed to the hazard has been calculated, aggregating the number of illiterate people and the number of people located in critical buildings, including schools, hospitals, health centres, hotels, geriatrics, churches, malls, sports and leisure centres; (ii) the travel speed index is based on the number of disabled persons, as well as children below 10 yr and persons above 65 yr; and (iii) the isolation index considers the number of people located in badly connected road areas, or those that frequently get isolated due to other extreme events such as river and coastal flooding. Ultimately, the number of people to be evacuated, their location, and their characteristics regarding difficulties for evacuation are known.

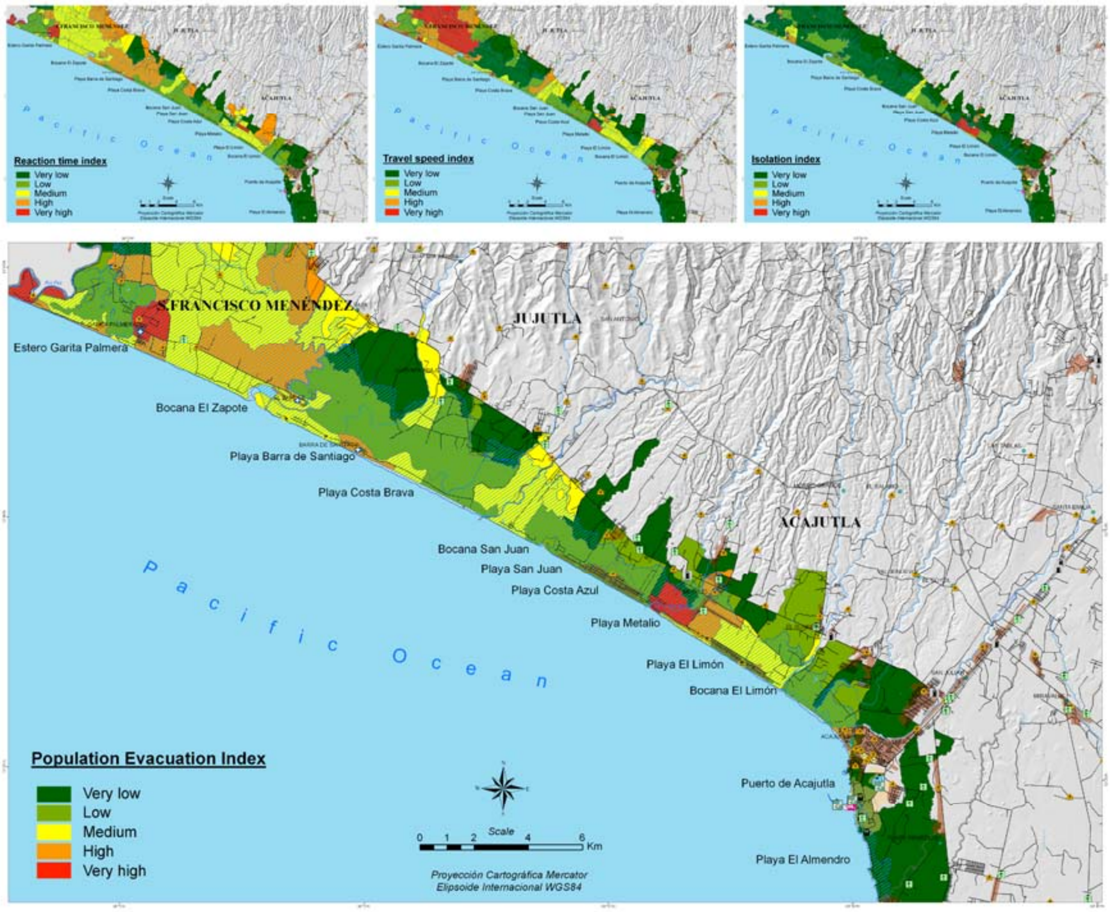

Figure 3.7. Population Evacuation Index (PEI) and related indices: reaction time (above left), travel speed (above centre), isolation (above right) – Western Coastal Plain (El Salvador).

The analysis of the safe areas has considered both horizontal and vertical shelters. Regarding the horizontal evacuation and based on the potentially flooded area, Figure 3.8 shows the proposed security zoning for the Western Coastal Plain of El Salvador, which is composed of (i) the tsunami-flooded area (in blue); (ii) the medium-security area (in yellow), established between the maximum flood level in the study area and a security level specifically determined for this zone (20ma.s.l.); and (iii) the high-security area (in green) from this level onwards. Potential vertical shelters located within the different tsunami hazard areas in the three local studies have been identified, analysed and prioritized based on their capacity, safety, and accessibility. In the case of the Western Coastal Plain, analysed here, no vertical shelters were found. The current road network has been analysed, in collaboration with local community leaders through participatory workshops, to identify the existing evacuation routes in the study area, with those roads that connect populated areas with medium-security areas being selected and prioritized in terms of ease of travel and safety. Figure 8 also shows the two specific locations selected in the Western Coastal Plain to be analysed in detail. The results presented in this paper refer to the Barra de Santiago Area (the box outlined on the left).

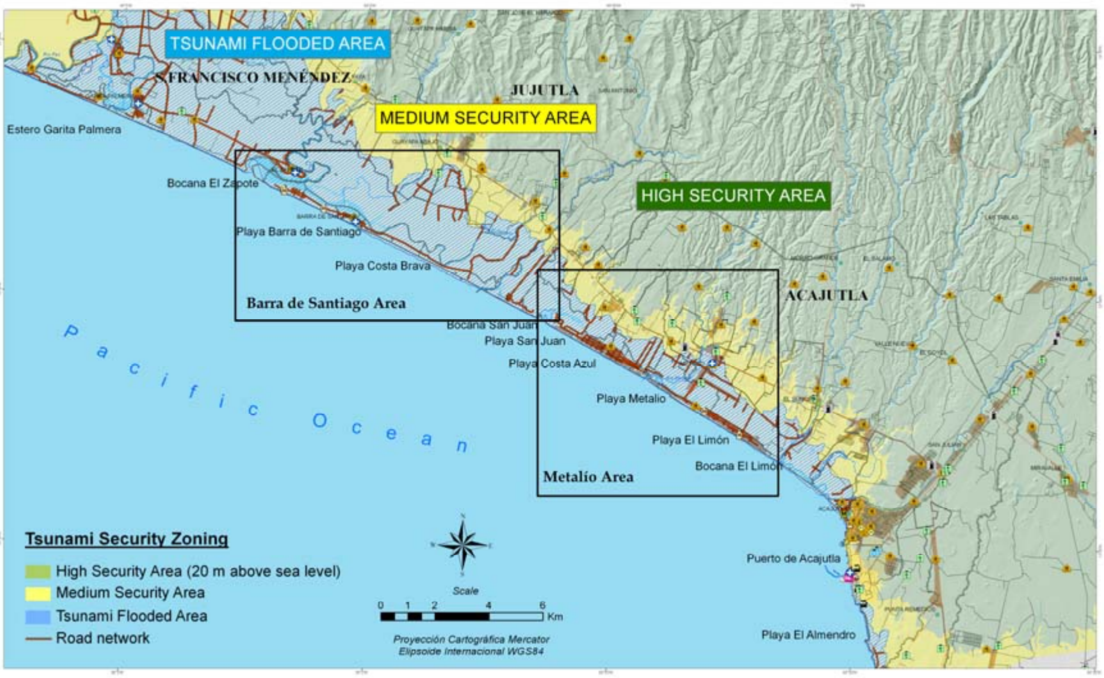

Figure 3.8. Tsunami security zoning and existing road network – Western Coastal Plain (El Salvador). Black rectangles show the areas where a detailed analysis has been carried out to identify the evacuation routes, the results for the Barra de Santiago Area being presented in this paper.

The Barra de Santiago area, located within Jujutla and San Francisco Menéndez municipalities (Ahuachapán region), is characterized by a 9 km-long sand spit that protects the estuary (Estero El Zapote) of the Aguachapío, Guayapa and El Naranjo rivers. The wetland includes an important mangrove area and belongs to the Complejo Barra de Santiago ANP (Protected Natural Area). According to the census (*VI Censo de Población y V de Vivienda*, DIGESTYC, 2007) and the hazard modelling results, the number of people located in the tsunami-flooded area is around 3300, 75% being located on the sand spit (Barra de Santiago canton), which was affected by the tsunami of 1902 (see Table 3.5) and where, according to the local knowledge, only 5 persons survived the event. Figure 3.9 shows, for the Barra de Santiago area, (i) the main existing evacuation routes (in purple) and the connecting paths (in red); (ii) the location of all the critical infrastructures which must be considered when planning the evacuation, i.e. critical buildings such as schools, hotels, health centres, etc., together with their capacity, and basic needs supply infrastructures such as wells; and (iii) the number of people by census tract (it must be pointed out here that the population-related coloured dots are located exactly in the centroid of each census tract polygon, which represents the location of the coastal communities quite accurately for the small census tracts but not for the big ones, this being the case with the brown-dot census tract whose population is located in the medium-security area, i.e. the yellow area). It is necessary to model and analyse whether the routes allow for the evacuation of people in the time available, or if it is necessary to propose alternative routes.

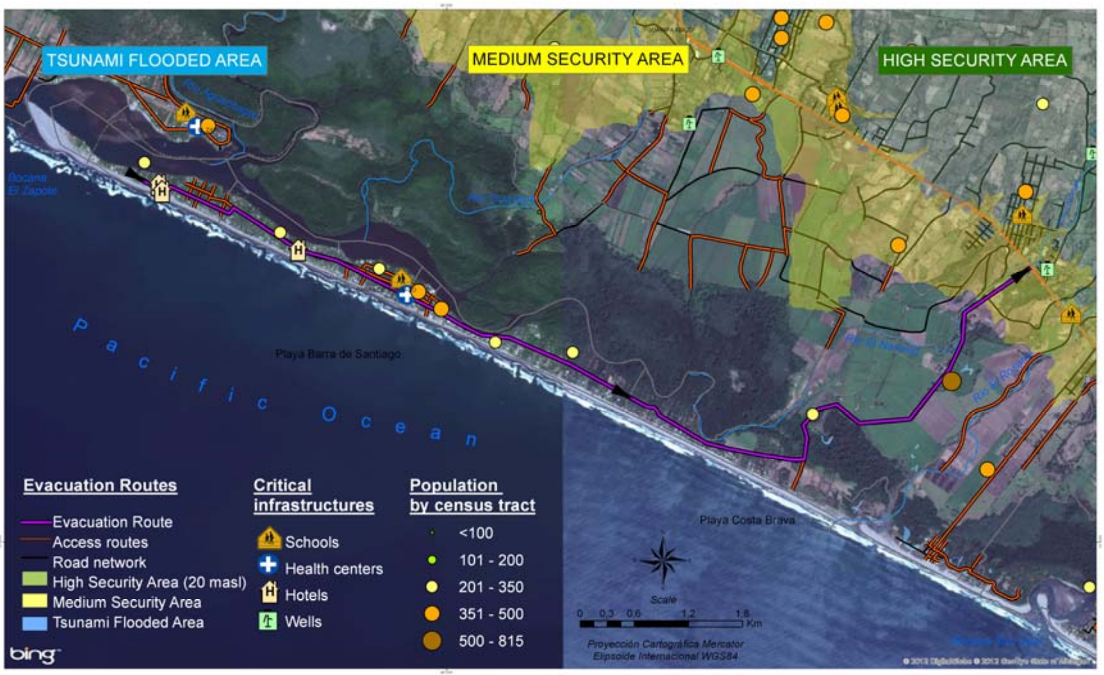

Figure 3.9. Existing evacuation routes, critical infrastructures and population by census tract – Barra de Santiago, Western Coastal Plain (El Salvador).

3.3.3 Time calculation

The tsunami arrival time and the response time calculated for the study area are presented here. A set of tsunami arrival time maps has been generated through numerical modelling, based on a deterministic analysis that combines the 23 worst credible cases of tsunamis that could impact on the Salvadoran coast. This worst credible case correctly corresponds to a tsunami generated by nearby sources due to an earthquake originating in the subduction zone (Cocos Plate–Caribbean Plate) off the coast of El Salvador. Accordingly the tsunami arrival time presented in this paper is related to a locally generated tsunami, representing the most conservative case in terms of evacuation time and, consequently, safety for the population. In the case of a tsunami caused by a more distant source, these times would obviously increase.

Considering this tsunami scenario, Figure 3.10 shows the tsunami arrival time for the Western Coastal Plain which varies between 25 and 45 min depending on the zone, with the 25 entire coast of El Salvador being exposed to this time range. The first tsunami wave would arrive in the area of the Barra de Santiago 40 min after the tsunami generation time.

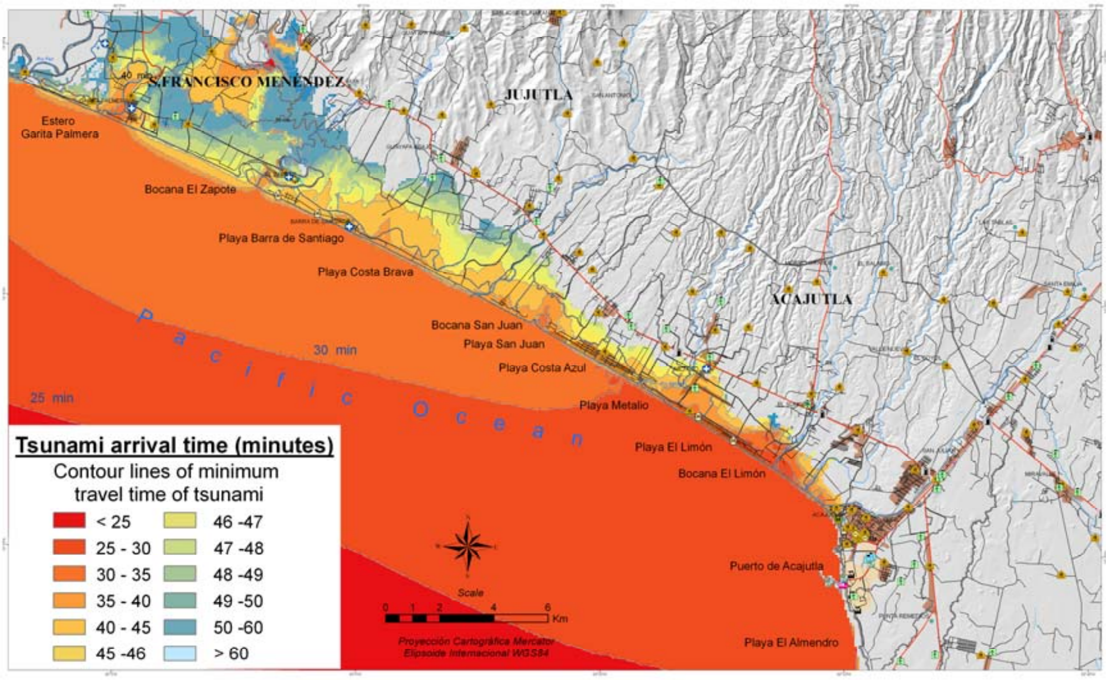

Figure 3.10. Tsunami arrival time for the worst-case credible scenario (i.e. aggregated case combining the 23 worst credible cases of tsunami that could impact on the Salvadorian coast) – Western Coastal Plain (El Salvador).

To calculate the response time, several workshops were held with the authorities responsible for the management of different aspects of a tsunami emergency in El Salvador. These workshops allowed for the collection and compilation of the appropriate information and knowledge concerning the approximate duration of the different time intervals involved in this concept:

- The time including (i) the earthquake detection and characterization by the Ministry of Environment and Natural Resources (MARN), (ii) the issuing of the tsunami warning by MARN, (iii) the reception of the alert by the Directorate General of Civil Protection, and (iv) its transmission to the different Civil Protection levels (Departmental, Municipal and Communal Civil Protection committees), takes a total of approximately 13min.
- Based on experience gained in previous emergency processes for other coastal risks that frequently affect the study area (coastal and river flooding), the time required to transmit the alert to all the people in the community by those responsible in the Communal Civil Protection Committee, is estimated to be 17 min.
- Due to the lack of information regarding the reaction time of the population and recognizing the simplification applied, as there is a strong likelihood that the whole population would not evacuate at the same time, the time elapsed from the moment they are alerted until they begin to evacuate is assumed to be 15 min according to Post et al. (2009) and Strunz et al. (2011).

In conclusion, the current response time in El Salvador for a tsunami event is therefore approximately 45 (13+17+15) min. The next task is to calculate the evacuation time which corresponds to this response time, using evacuation modelling.

3.3.4 Evacuation modelling

Based on the tsunami arrival time, the security zoning and the road network, evacuation modelling allows the identification of the optimal evacuation routes and the time the population needs to evacuate. For this case study, the origin points are located at every road intersection inside the flooded area according to the spatial distribution and number of people by canton/census tracts and the location of critical buildings. Therefore, depending on the existing road intersections, each origin point will represent a variable number of people. Having this information in mind is essential for further steps (evacuation balance, designing of vertical evacuation shelters, etc.).

The evacuation of the population has been modelled for an initial response time of 45 min (RT45), equivalent to the current response time calculated for El Salvador (Figure 3.11). The contour line of 45 min for the first tsunami wave arrival is shown in orange inside the flooded area. It is clear that RT45 means that when the warning arrives in the communities, the tsunami has already reached the coast, and is spreading through the exposed area. The main conclusion obtained from the RT45 results is that most of the exposed population would not be able to evacuate for a response time of 45 min. Results are also presented in pie charts by census tract (Figure 3.12), with the green colour representing the percentage of people who evacuate and the red colour representing the percentage who do not; the census tracts showing both options highlight the fact that the evacuation time is also a function of a person’s speed (i.e. the fast ones would evacuate, the slow ones would not), and is not only determined by the distance to be travelled in the available time.

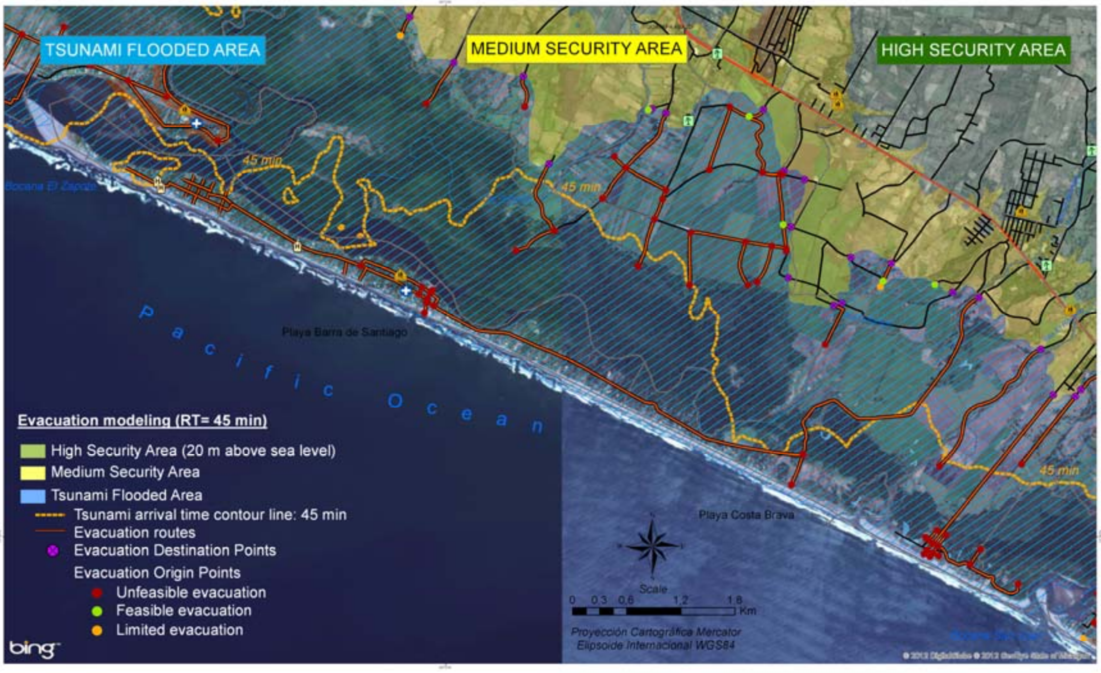

Figure 3.11. Evacuation time modelling for a response time of 45 min (RT45) – Barra de Santiago, Western Coastal Plain (El Salvador).

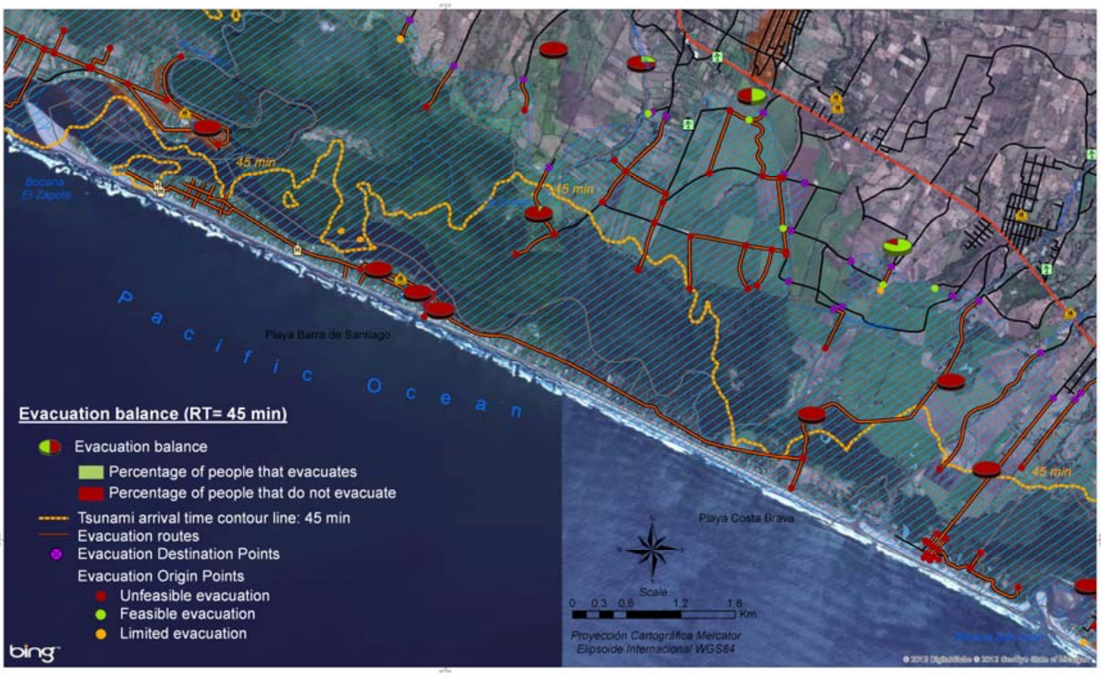

Figure 3.12. Evacuation balance for a response time of 45 min (RT45) and by census tract – Barra de Santiago, Western Coastal Plain (El Salvador).

3.3.5 Proposals of alternatives for critical areas

Based on the evacuation results obtained (i.e. most of the exposed population would not be able to evacuate for a response time of 45 min), the formulation of particular measures to improve the evacuation of the area is necessary. These measures include (i) the reduction of the response time, and (ii) the reduction of the distance to be travelled by the population. These two proposed measures are then tested using evacuation modelling until it is confirmed that the critical area is eliminated and that the entire area evacuates successfully.

A new modelling has been performed for a response time of 30 min (RT30) in order to understand the implications, in terms of people affected, of taking less time to (i) detect the tsunami, (ii) warn the people, and (iii) start evacuating, since this situation would then result in increased time being available for evacuation (Figure 3.13). The selection of the several response times to model is site-specific and should be adapted to each case study; the example applied to this case (RT30) and presented below does not imply that this is a suitable time threshold for all cases, or even for El Salvador. The idea is to reduce the response time as much as possible, combined with further measures to reduce the distance to be travelled.

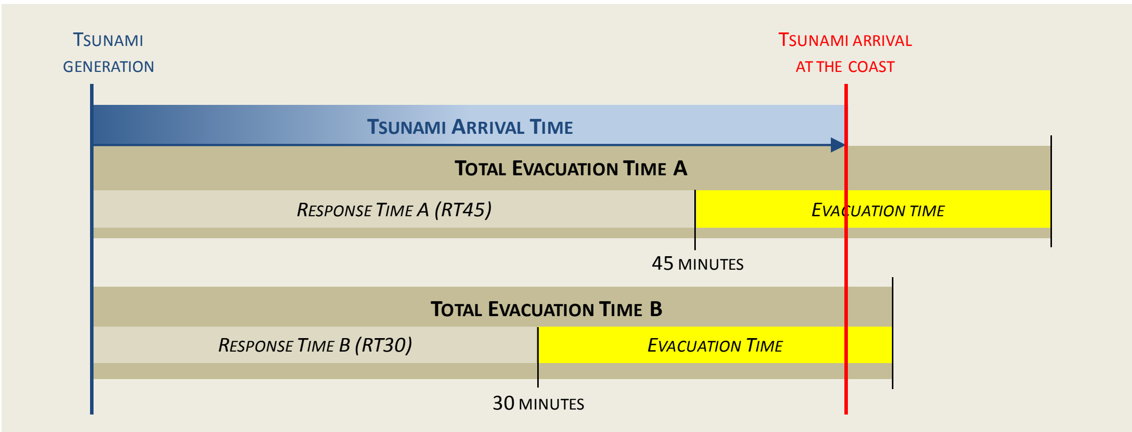

Figure 3.13. Response time modelled: 45 and 30 min. The Total evacuation Time (TET) A considers the current situation in El Salvador (RT45, response time of 45min). The evacuation modelling showed that most of the coastal population would not be able to evacuate. The TET B considers a lower response time (RT30) in order to model and understand if this reduction would be enough to achieve a successful evacuation for the whole coast or further RT reductions are required.

Compared to the evacuation modelling for RT45 (Figure 3.11), the modelling for RT30 (Figure 3.14) shows that the communities located close to safe areas and above the tsunami arrival time contour line of 45 min, would more or less successfully evacuate for this new response time (origin points changed to green and orange). The communities located below the 45 min contour line, however, would not evacuate (origin points still in red) even with the 15 additional minutes afforded by RT30.

For these latter communities which would not able to evacuate in time, further measures are proposed, i.e. the reduction of the distance to be travelled by these communities, by means of building vertical evacuation shelters and/or new evacuation routes. These measures are represented in Figure 3.14 by yellow-black elements, with squares representing the new vertical shelters, and lines representing the new evacuation routes. As explained in the methodology, the green and red concentric rings surrounding the towers represent the reception distance for both population speeds. Special attention is paid to the critical buildings (1 school, 3 hotels and 1 health centre in Barra de Santiago) in order to have them included in the reception area of the towers. The combination of this information, together with the amount of people to be evacuated, indicates the number of persons that these shelters should be designed to accommodate (in this case, 2500 persons between towers 1 and 2, and 800 in tower 3, approximately).

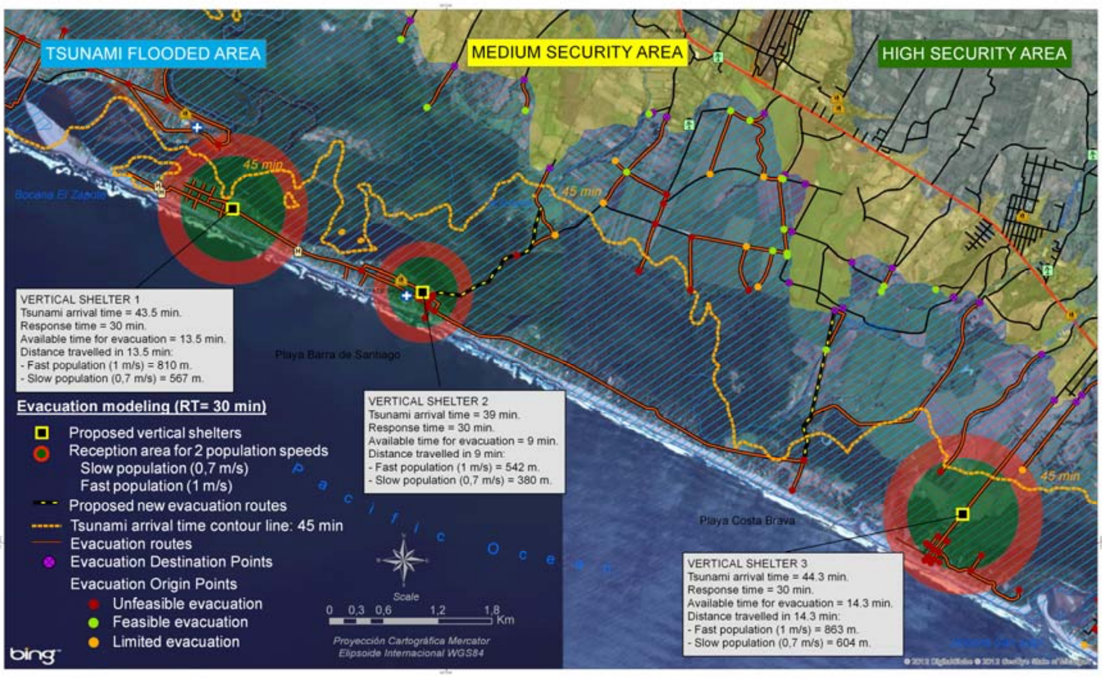

Figure 3.14. Evacuation time modelling for a response time of 30 min (RT30) and proposal of alternatives for critical areas – Barra de Santiago, Western Coastal Plain (El Salvador).

The iterative modelling of subsequent measures ensures that all the starting evacuation points change to green, indicating the evacuation of the entire exposed population in the time available.

It is important to point out that these analyses and mapping resources are oriented to and designed for risk and emergency managers, in order to provide them with technically sound information to assist in the formulation of optimal evacuation planning for specific areas. The evacuation maps which are to be provided to the exposed local communities, based on the results obtained from the presented framework, must however be simplified to ensure they are intuitive and can be easily understood by the members of the communities.

3.4 Conclusions

Advances in the understanding and prediction of tsunami impacts allow the development of risk reduction strategies for tsunami-prone areas, with evacuation planning being an essential requirement to save lives during emergencies. This paper presents an integral framework for the formulation of tsunami evacuation plans based on tsunami hazard and vulnerability assessment and evacuation modelling. This methodology considers (i) the hazard aspects (tsunami flooding characteristics and arrival times), (ii) the characteristics of the exposed area (people, shelters and road network), (iii) the current tsunami warning procedures and timing, (iv) the time needed to evacuate the population, and (v) the identification of measures to improve the evacuation process. The presented framework aims to bridge the gap between science and management in terms of tsunami evacuation and presents evacuation modelling as a vital tool for disaster risk management and evacuation planning. The framework has been applied to the El Salvador case study, demonstrating its applicability to site-specific response times and population characteristics.

The hazard assessment, through the tsunami numerical modelling, permits the generation of different hazard maps (i.e. maximum wave height elevation, maximum water depth, minimum tsunami arrival time, maximum flooding level or "run-up", and maximum drag regarding people instability) which provides knowledge about the exposed area, the locations which would receive higher impacts and the tsunami first wave arrival time, all being critical information for evacuation purposes. The worst case scenario is the most conservative in terms of risk management.

The vulnerability assessment of the exposed population assists in the designing of specificity-oriented measures in order to deal with specific weaknesses in terms of evacuation (see Table 3.1). Several characteristics of the population have been analysed: (i) the total number of exposed people, (ii) the number of people in critical buildings (schools, hospitals, geriatrics, hotels, etc.), together with illiteracy and intellectual disability, providing information about reaction times; (iii) slow groups (the elderly and children) and physical disability which are directly related to the travel speed; and (iv) badly connected areas which translate into community isolation, impacting both the reception of an alert and the subsequent evacuation. The analysis of the existing road network and safe areas provides knowledge about the current evacuation infrastructure and may highlight the need for repairs and improvements.

The proposed evacuation modelling helps by identifying (i) the shortest routes that people have to travel from their places of origin to destination points, considering the slope and different population speeds, and (ii) the evacuation degree of success for the available evacuation time. This modeling also considers the response time, understood as the time from the tsunami generation until the population begins to evacuate: (i) the current emergency protocols and the experience of the responsible authorities both provide essential information about the time needed for tsunami detection, issuing of warnings, alert transmission and reception, all of which are extremely important for the population, as a shorter response time directly translates into longer time available for the population to evacuate; (ii) the population reaction time is assumed to be 15min (Post et al., 2009; Strunz et al., 2011). It is important to mention that the proposed framework permits the application of more complex evacuation models as required and/or further research advances such as those regarding the slope calculation or the optimization process for shelter location. Modelling the current response time gives the real evacuation situation, which is the starting point for risk management. The evacuation degree of success obtained for the current response time helps in defining alternatives for those communities that do not have options to evacuate in the current situation, by means of reducing the response time and/or shortening the distances to be travelled (through additional routes and/or shelters). This sensitivity analysis of the evacuation model represents a powerful tool for managers to reduce the risk in specific areas, by ensuring the successful evacuation of the population, as it allows predicting the results of specific management options.

A method for the identification of possible locations for vertical evacuation shelters is proposed, providing useful information for each shelter, such as the tsunami arrival time, the response time, the time available to evacuate, and the reception distance for both population speeds. The combination of this information with the amount of people to be evacuated indicates the capacity that these shelters should accommodate.

Finally, the proposed framework permits the organization, classification and prioritization of the gathered information, in order to better define the several risk management measures to be included in an evacuation plan.

Regarding some of the results obtained for El Salvador, the evacuation modelling for the current response time of 45 min (RT45; i.e. warning time 30 min, reaction time 15 min) highlighted that improvements to the warning process must be made to ensure the success of the evacuation, as most of the coastal communities would be reached by the tsunami before being warned about it. A reduction of 15 min in the response time (RT30) showed that a higher percentage of populations evacuates (proving the importance of working on this issue); however, the communities located closer to the coastline would not be able to reach the safe areas. For these communities an attempt to identify alternative measures to ensure their evacuation is proposed, such as building new evacuation routes and new vertical shelters. These combined measures (reducing response time and reducing distances to travel) have been demonstrated to be useful for achieving the desired results. The repetition of the evacuation modeling for each group of measures proposed ensures the control and reduction of critical areas.

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Chapter 4. Tsunami human vulnerability indicators

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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.

4.1 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.

4.2 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 4.1 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.

4.3 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 4.2. 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[8], Chile[9], Samoa[10], Sri Lanka[11], and

[8] **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

[9] **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.

[10] **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.

[11] **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

Thailand[12]). Table 4.3 summarizes the indicators presented in Table 1 that can be validated in this work based on the information provided by these sources.

Table 4.1. 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]

[12] **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.

	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 4.2. 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 4.3. 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

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 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 Northern 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.

4.3.1 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 (Figure 4.1). 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.

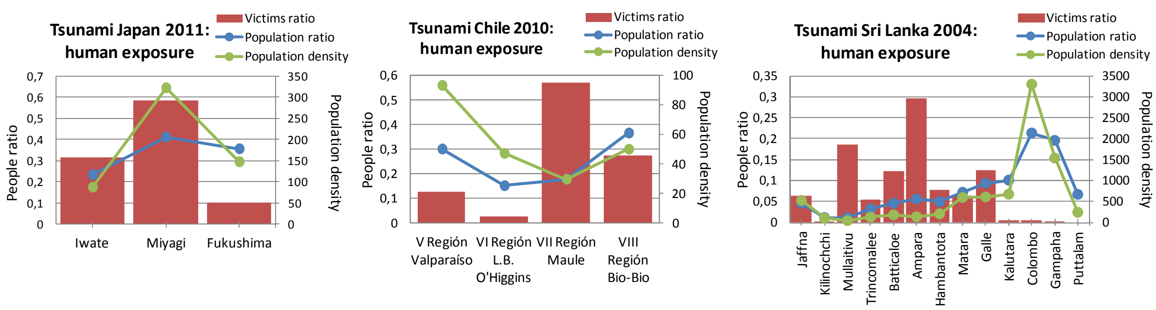

Figure 4.1. Correlation between tsunami victims ratio, population ratio and population density (Japan 2011, Chile 2010 and Sri Lanka 2004).

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.

4.3.2 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 4.3 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[13]). 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).

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

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 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.

4.3.3 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 4.3, age, gender, disability and dependency indicators are analyzed and validated in this section.

4.3.3.1 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, Figure 4.2 jointly analyzes the percentage of human losses by age groups for the four tsunami events (Figure 4.2b), together with the age groups structure in the country before each event based on the immediately preceding census (Figure 4.2a). 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.

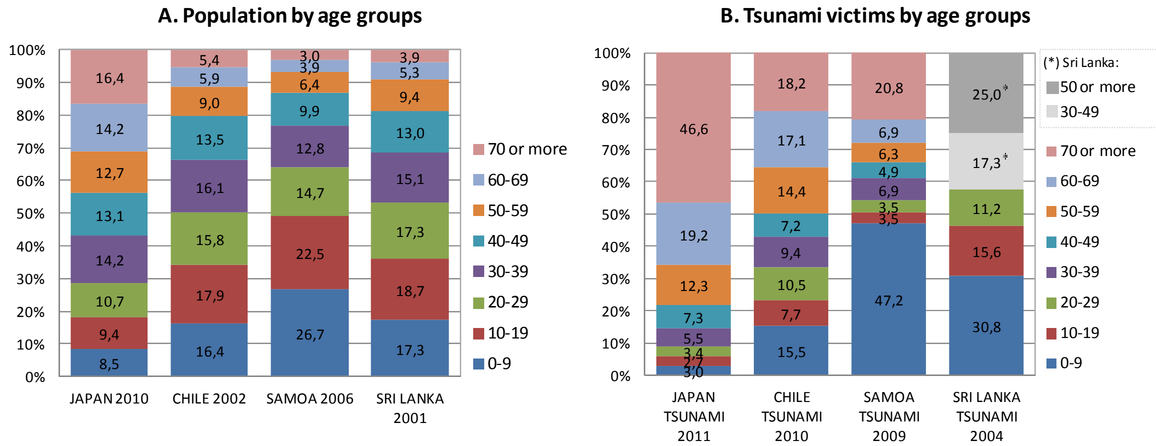

Figure 4.2. Age groups analysis for several past tsunami events (Japan 2011, Chile 2010, Samoa 2009 and Sri Lanka 2004). A: pre-tsunami census, B: tsunami victims. The age of tsunami victims over 30 years old in Sri Lanka is not available disaggregated in ranges of 10 yr.

Figure 4.3c and Table 4.4 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 (Figure 4.3b) by the percentage of population for each age group (Figure 4.3a). 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.

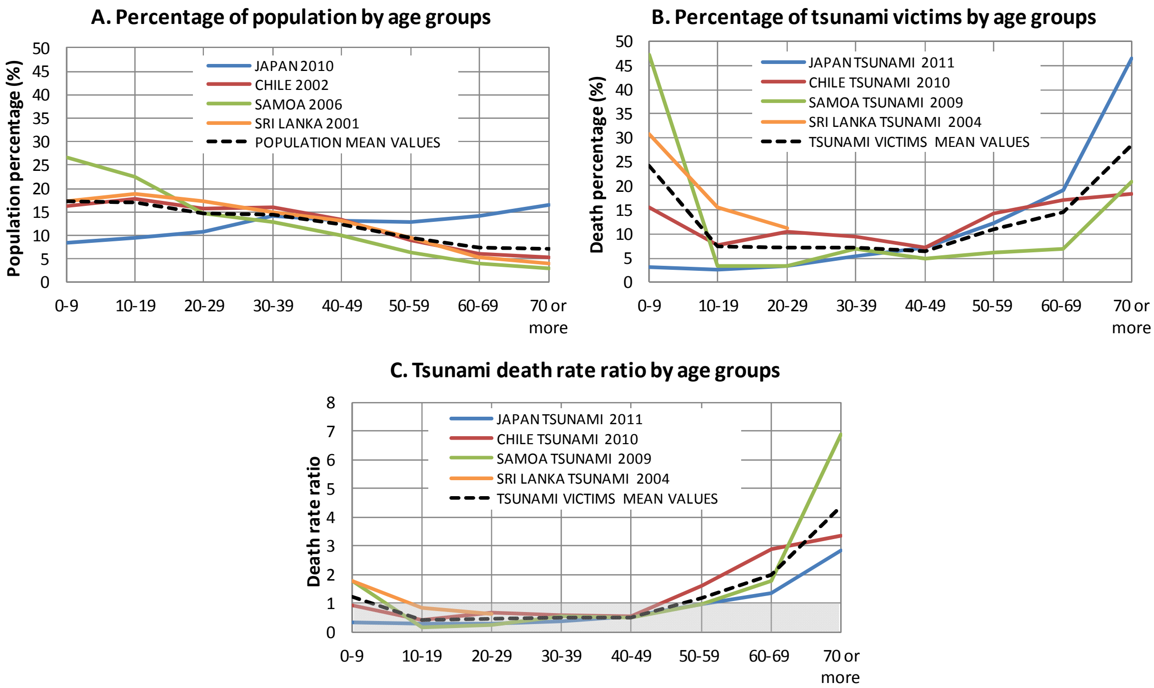

Figure 4.3. Analysis of mortality by age groups (Japan 2011, Chile 2010, Samoa 2009 and Sri Lanka 2004). A: pre-tsunami census; B: tsunami victims; C: tsunami death rate ratio (C=B/A). The age of tsunami victims over 30 years old in Sri Lanka is not available disaggregated in ranges of 10 yr, consequently 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.

Table 4.4. 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

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 (Figure 4.4). 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.

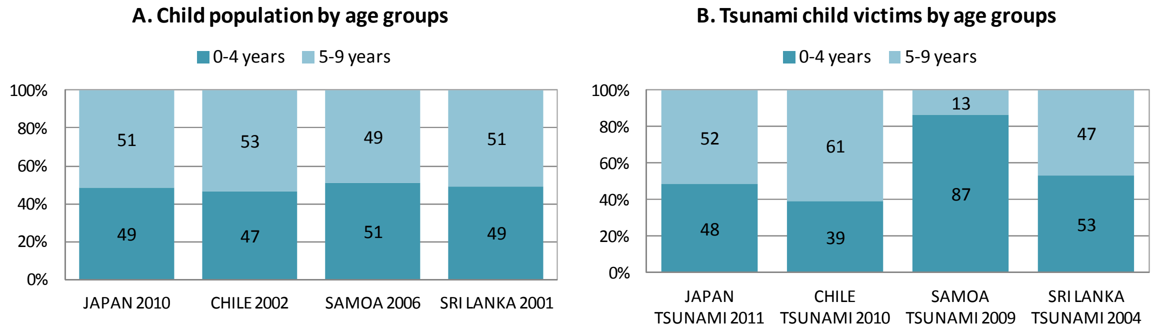

Figure 4.4. Analysis of child age groups (Japan 2011, Chile 2010, Samoa 2009 and Sri Lanka 2004). A: pre-tsunami census, B: tsunami victims.

4.3.3.2 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[14]. 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

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

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 4.1).

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 4.5 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-disaggregated format. Figure 4.6 shows the population pyramids for the four countries and both pre- and post-tsunami censuses, illustrating the distribution of age groups by sex.

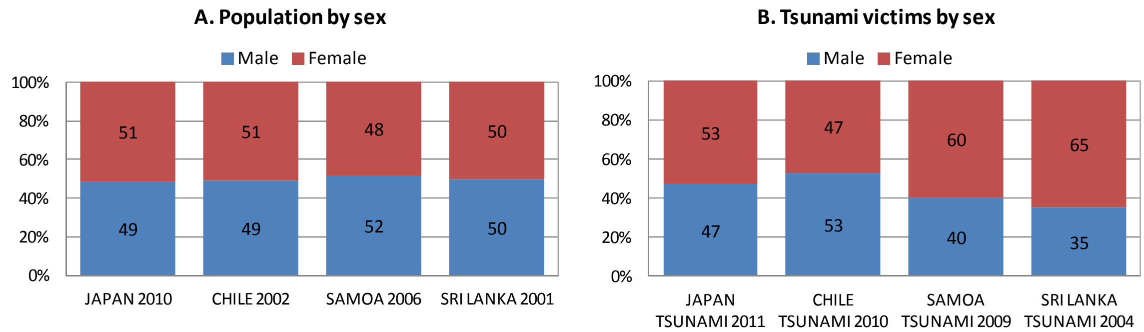

Figure 4.5. Gender analysis (Japan 2011, Chile 2010, Samoa 2009 and Sri Lanka 2004). A: pre-tsunami census, B: tsunami victims.

As far as the age analysis in Figure 4.6 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 right 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 Figure 4.7 which presents population rates and tsunami mortality rates by type of population pyramid.

Back to Figure 4.6 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.

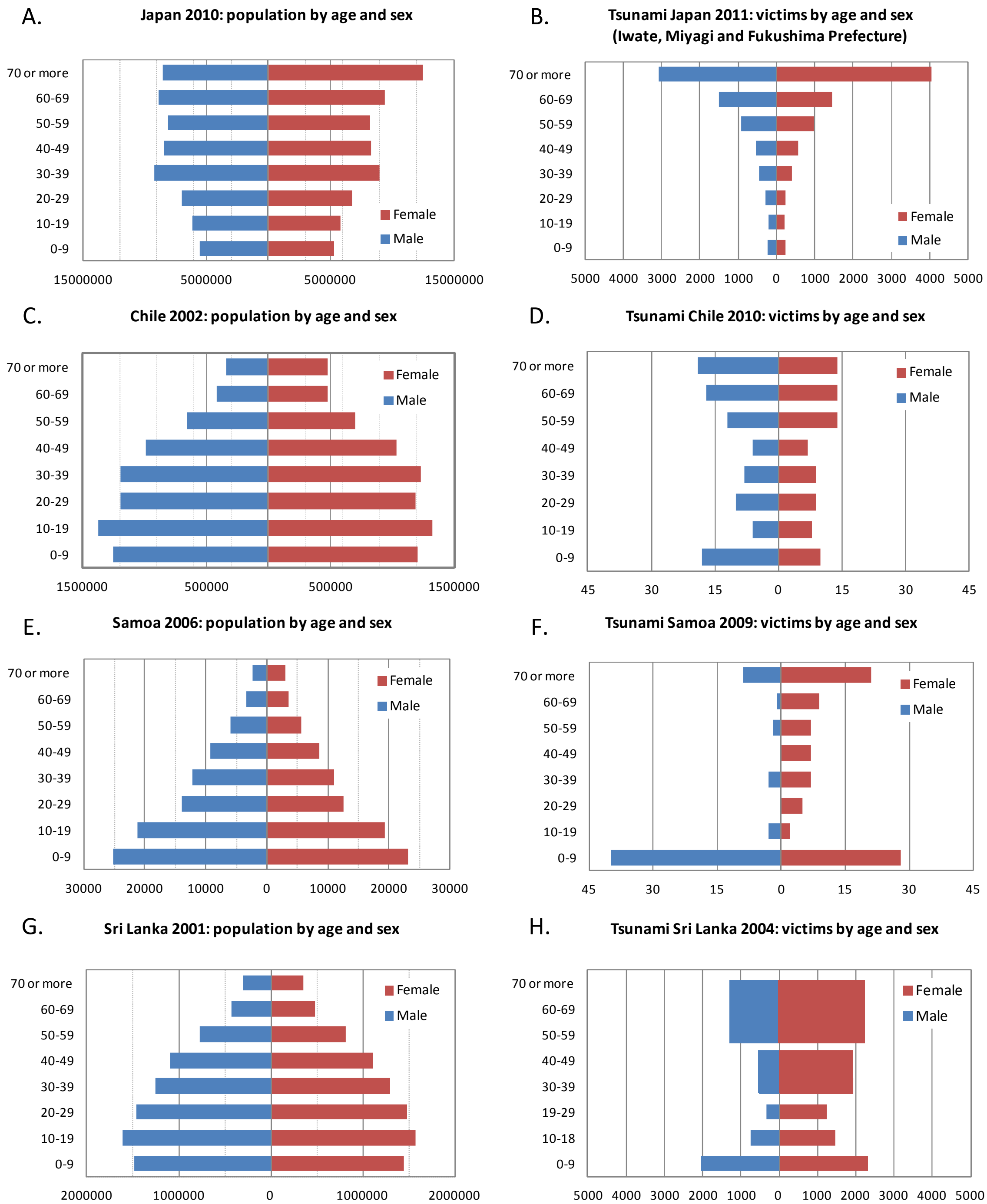

Figure 4.6. Population pyramids (left: pre-tsunami census, right: tsunami victims). The age of tsunami victims over 30 years old in Sri Lanka is not available disaggregated in ranges of 10 yr (Fig. 6H)

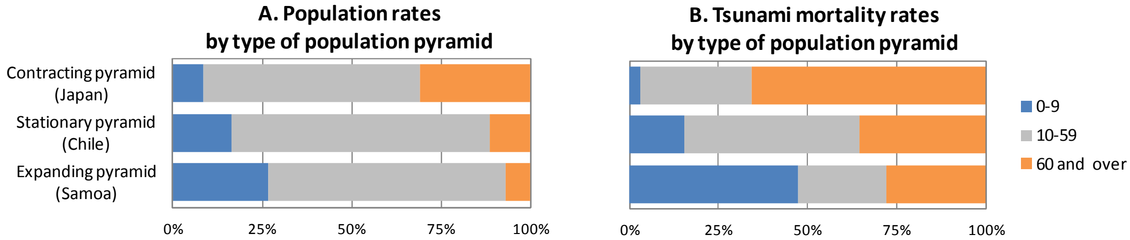

Figure 4.7. Comparison between population rates (A) and tsunami mortality rates (B) by type of population pyramid.

4.3.3.3 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 (Figure 4.8) 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.

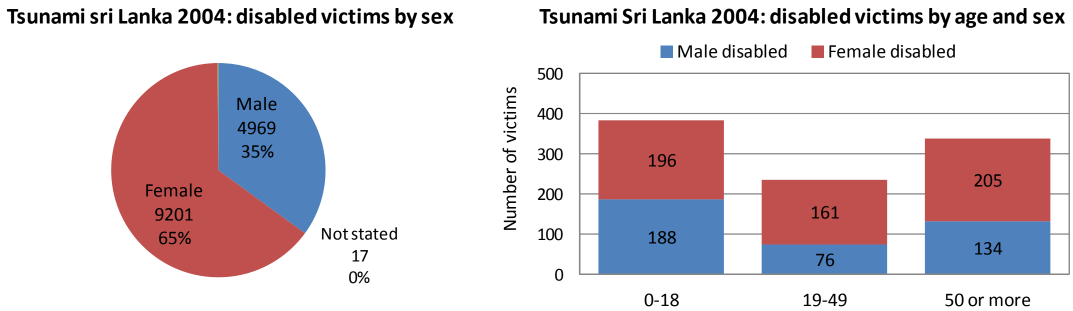

Figure 4.8. Tsunami disabled victims by age and sex (Sri Lanka 2004).

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 Figure 4.9. 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.

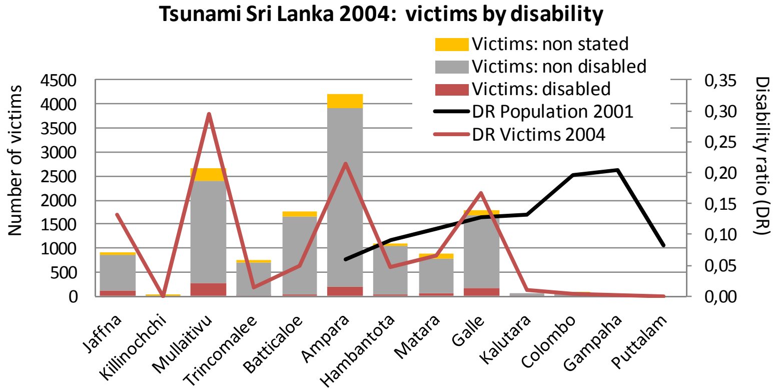

Figure 4.9. Tsunami victims in the different affected coastal divisions in Sri Lanka (2004) by disability and pre-/post-disability ratios (disability ratio = disabled by district/total disabled). No data about disabled population in the tamil districts (Jaffna-Batticaloe) is available in the census 2001.

4.3.3.4 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 Figure 4.10 presents the female mortality considering first all age groups (Figure 4.10a) and then only the active female population that might be in charge of taking care of family members (Figure 4.10b). 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 (Figure 4.10b), 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 Figure 4.10a 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).

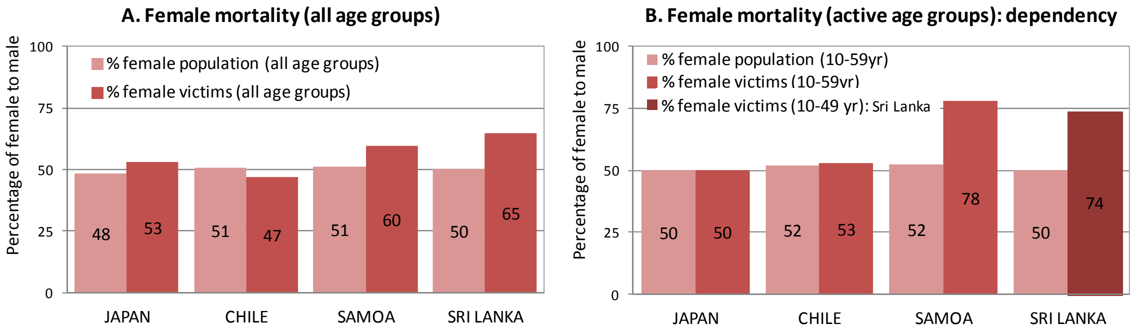

Figure 4.10. Female mortality for different tsunami events and its relationship with the concept of dependency (Japan 2011, Chile 2012, Samoa 2009 and Sri Lanka 2004). Pre-tsunami censuses appear in light red and tsunami victims in dark red. A: female mortality considering all age groups, B: female mortality 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.

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.

4.3.4 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 Figure 4.11 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.

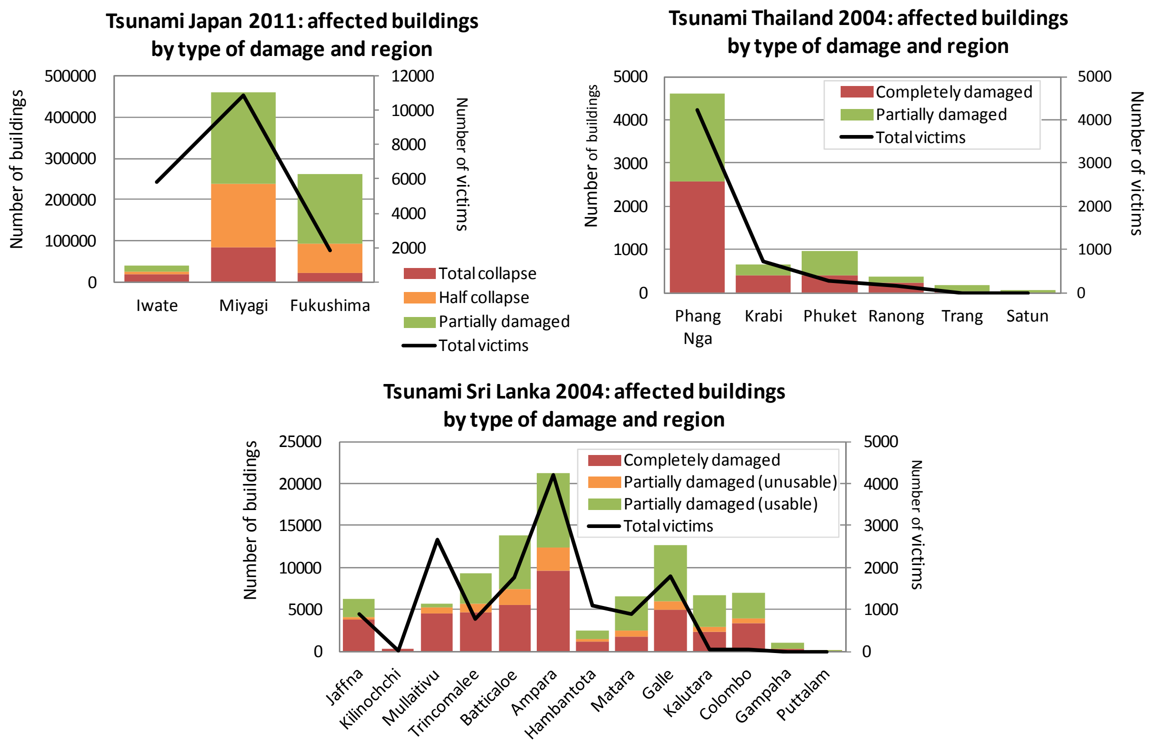

Figure 4.11. Correlation between total tsunami victims and affected buildings by type of damage and region (Japan 2011, Thailand 2004 and Sri Lanka 2004).

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.

4.3.4.1 Distance to the sea

Figure 4.12 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 (Figure 4.12b): 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 (Figure 4.12b) to the 57% outside the boundary line (Figure 4.12c). 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.

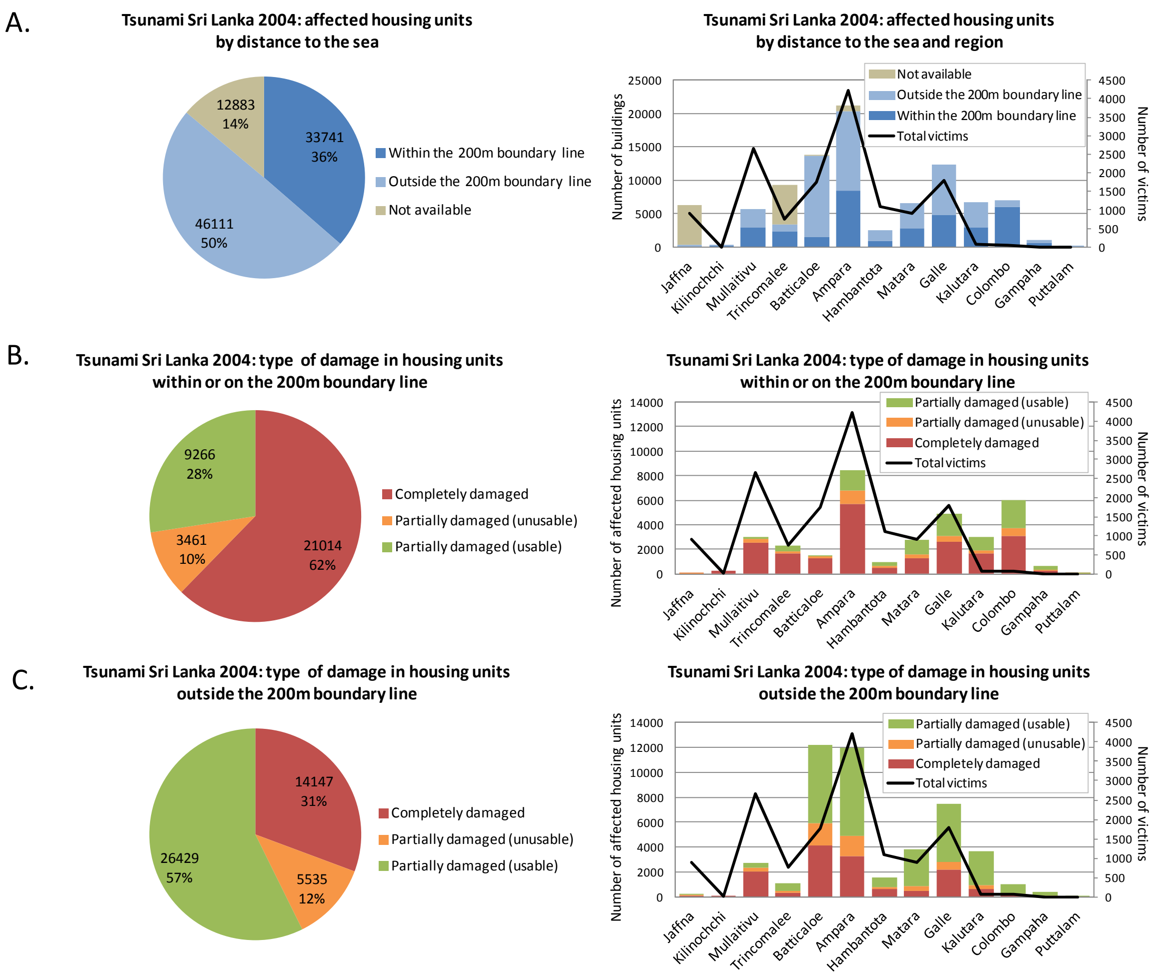

Figure 4.12. Correlation between number of tsunami victims, buildings' type of damage and distance to the sea (Sri Lanka 2004).

4.3.4.2 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 kilometres by coastal lagoons and local topography-related tsunami effects contributed to the huge death tolls in the area (72% of the victims).

4.3.4.3 Type of building

Figure 4.13a 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.

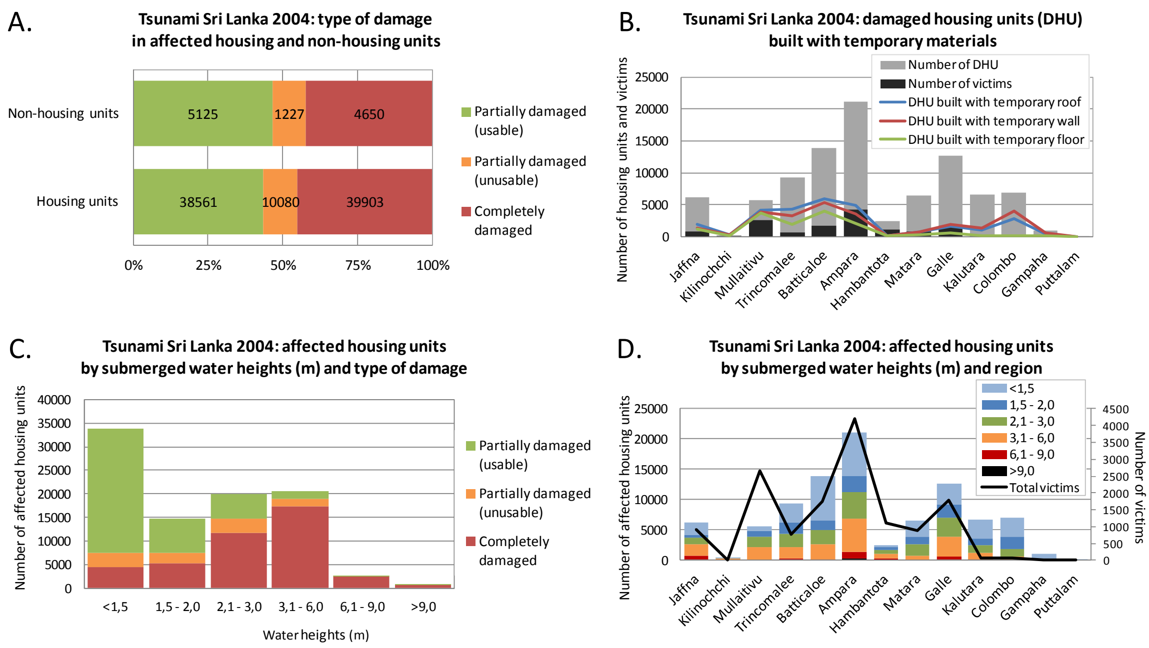

Figure 4.13. Analysis of damaged buildings in Sri Lanka 2004. A: comparison between number of housing units (HU) and non-housing units (NHU) affected by type of damage. B: correlation between numbers of tsunami victims, damaged HU and building materials. C-D: correlation between numbers of tsunami victims, buildings' type of damage and water depths.

4.3.4.4 Building materials and water depths

Figure 4.13b 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.

Figure 4.13c 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. Figure 4.13d 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.

4.3.4.5 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.

4.3.5 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 4.3 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 4.1). 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 4.14 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.

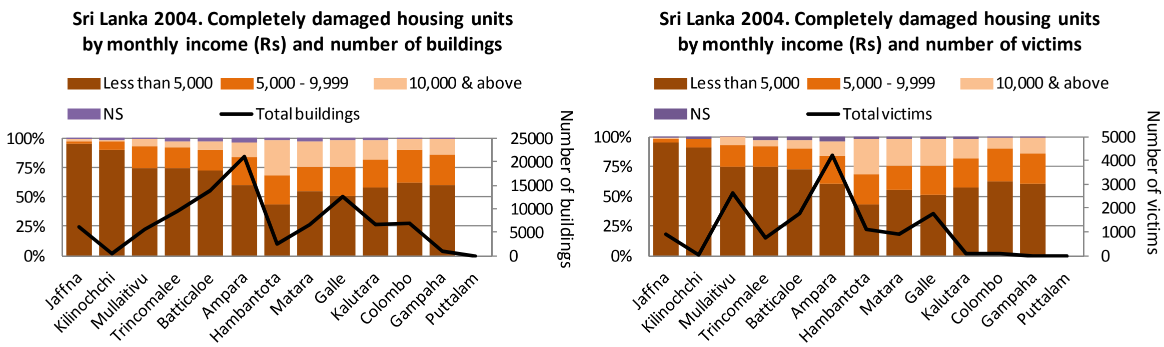

Figure 4.14. Percentage distribution of completely damaged housing units (left) and number of tsunami victims (right) by reported monthly income of the housing unit in Sri Lanka 2004 (5000Rs = 27.71€, on 2014/07/10).

Figure 4.15a 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 4.15b 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.

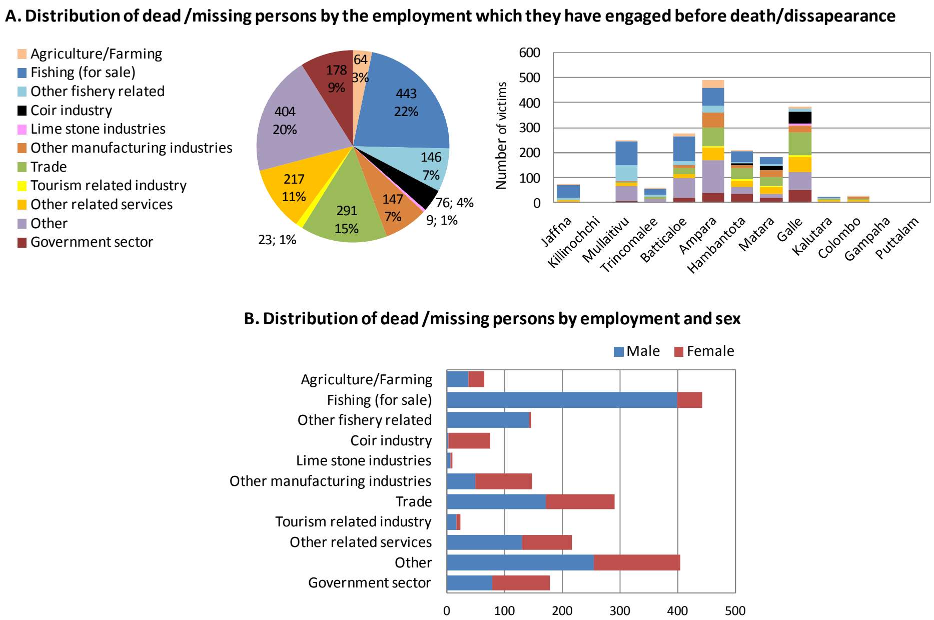

Figure 4.15. Distribution of tsunami victims by employment and district in Sri Lanka 2004. A: distribution of dead/missing persons by the employment they have engaged before death/disappearance. B: distribution of dead/missing persons by employment and sex.

4.4 Discussion

Table 4.5 summarizes the main results obtained from the analyses presented in this work.

Table 4.5. 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

4.5 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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Chapter 5. Storm surge risk perception and resilience

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Storm surge risk perception and resilience: a pilot study in the German North Sea coast

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Abstract. Resilience is defined as the capacity of a community to organise itself before, during and after a dangerous/hazardous event in order to minimise the impacts. A conceptual framework is proposed to assess the resilience of a community by understanding and integrating the institutional, legal and social capacities to cope and recover from a natural hazardous event in order to minimize the impacts in the short-term and to adapt to the risk in the long-term. A survey-based method and a specific resilience questionnaire is proposed to explore the perception of stakeholders regarding the risk and emergency management processes as well as psychological and social factors conditioning individual and community preparedness. Although some questions may need some type of adaptation to fit adequately to other study sites, the conceptual and methodological framework could be applied worldwide, the application to the Dithmarschen district in the German North Sea Coast being presented in this work. The study area and its population are characterized by their continuous interaction with the ocean, with the continuous transformation and reclamation of land for agricultural and other purposes, the constant reshaping of the coastline and frequent coastal inundation by storm surge flooding. The assessment allows identifying the main characteristics of the study area in terms of stakeholders' risk perception, intention to prepare, individual and societal behavioural patterns, as well as their opinion regarding authorities' decision-making on emergency and risk management. It also addresses potential improvement in emergency and risk management in terms of multi-sector partnerships and additional adaptation measures for the area. The deficiencies and incoherencies between society's and administration's answers detected in the analysis point towards the challenges to deal with - in

order to foster an adequate community preparedness and adaptation to storm surge risk. Some of the results that the proposed method permitted to obtain in the study area show (i) the need for a better information strategy to enhance society's awareness and preparedness; (ii) the respondents' current proactive behaviour and preference on participatory risk management options, despite fully participatory schemes are not yet set by the authorities; (iii) the need for awareness campaigns regarding the relevance and benefits of the integrated approach in potential partnerships, and (iv) the need for tailored and site-specific adaptation instruments and measures due to the current society's disagreement with some of the options currently provided. The results are useful to improve risk reduction initiatives by means of including society's opinions from the beginning of the management process.

5.1 Introduction

Resilience is defined as the ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner, including the preservation and restoration of its essential basic structures and functions (UN/ISDR, 2009). Cutter et al. (2008) defines resilience as the degree to which the community has the necessary resources and is capable of absorbing disturbance and reorganising into a fully functioning system. This refers to the capacity of a community to organise itself before, during and after the event in order to minimise the impacts (González-Riancho et al., 2014), and is directly linked to risk reduction, understood as the development and implementation of activities aimed at mitigation, preparedness, response and recovery (Mileti, 1999). The ability of a system, community or society, implies the recognition of both institutional and social/individual abilities. Resilience assessments focus on the changeable collective conditions improvable through learning and experience, such as risk preparedness within the communities, in contrast to the unchangeable conditions such as the age of the population (González-Riancho et al., 2014).

Accordingly, a resilient society is aware of the hazard, is prepared for its impacts and is able to recover. These capacities are referring to both institutional and social spheres of the community. In the field of resilience, some authors have focused on the institutional performance and preparedness (IOTWS, 2007; Birkmann et al., 2013; González-Riancho et al., 2014), while others focus on the preparedness and protective behaviour of the individuals (Fishbein and Ajzen, 1975; Rogers, 1983; Schwarzer, 1992; Paton 2003, 2005, 2010; Becker et al., 2011, 2013; Lindell and Perry, 2012) or on how factors like risk perception may influence the behavioural adjustment and preparedness (Douglas and Wildawsky, 1982; Renn, 2008; Solberg et al., 2010; Birkmann et al.,2012a, 2012b). Table 5.1 presents a summary on the behavioural factors studied by several authors to predict preparedness and/or measure resilience. These factors having their origin in theories from health and social psychology, being applied and adapted afterwards to the natural hazards discipline.

The objective of this work is to propose a conceptual framework to assess the resilience of a community by understanding and integrating the institutional, legal and social capacities to cope and recover from a natural hazardous event in order to minimize the impacts in the short-term and to adapt to the risk in the long-term. By means of a proposed survey-based method we explore the perception of stakeholders regarding the risk and emergency management processes as well as psychological and social factors conditioning individual and community preparedness.

The conceptual framework and method presented in this paper has been applied for its validation in a small area (Dithmarschen district, Schleswig-Holstein) exposed to storm surge hazard on the German North Sea coast. It will be replicated along the whole trilateral Wadden Sea region, including the Netherlands and Denmark, in the framework of the ongoing FP7 ENHANCE Project (Enhancing risk management partnerships for catastrophic natural disasters in Europe, www.enhanceproject.eu). This project is aimed at developing and analysing new ways to enhance society's resilience to catastrophic natural hazard impacts, by providing new scenarios for selected hazard cases in close collaboration with stakeholders, and contribute to the development of new Multi-Sector Partnerships (MSPs) to reduce or redistribute risk.

Table 5.1. Review of previous works dealing with preparedness/protective behaviours [1], risk perception [2] and resilience [3].

Theory/framework	Predictor	Factors considered
Theory of Planned Behaviour / Reasoned Action (Fishbein and Ajzen, 1975)	[1]	Beliefs, attitudes, norms, and intentions
Cultural Theory of Risk (Douglas and Wildawsky, 1982)	[2]	Ways of life: Individualism vs. Communitarianism, Hierarchy vs. Egalitarism
Protection Motivation Theory (Rogers, 1983)	[1]	Threat appraisal: perceived severity of a threatened event, and perceived probability of occurrence or perceived vulnerability of the individual. Coping appraisal: perceived response efficacy, perceived self-efficacy.
Health Action Process Approach (Schwarzer, 1992)	[1]	Threat appraisal: perceived severity of a threatened event, perceived vulnerability of the individual. Coping appraisal: perceived response efficacy, perceived self-efficacy, and individual and social outcome expectancies.
Social-cognitive preparation model (Paton, 2003)	[1]	Precursors: critical awareness, risk perception, hazard anxiety Intention formation: outcome expectancy, self efficacy, problem-focused coping, response efficacy, intention to prepare Linking intentions and preparedness: perceived responsibility, sense of community, timing of hazard activity, normative factors (trust, empowerment), response efficacy, adjustment/ adoption/ preparation
The preparedness process (Paton, 2005)	[1]	Precursors: critical awareness, risk perception, anxiety Development of intentions: outcome expectancy, self efficacy, action coping, intention to prepare Convert intention to action: preparation/action
Disaster Resilience of Place DROP model (Cutter et al., 2008)	[3]	Antecedent conditions: place-specific social, natural and built environment systems, including both inherent vulnerability and resilience. Event characteristics: frequency, duration, intensity, magnitude, and rate of onset Absorptive capacities: presence/absence of mitigating actions and coping responses (directly associated with antecedent conditions).
Risk governance (Renn, 2008)	[2]	Categories: personal manifestations and collective influences Factors: cultural background, social-political institutions, cognitive-affective factors, and heuristics of information processing
Tsunami resilient communities (IOTWS, 2009)	[3]	Governance, society and economy, coastal resource management, land use and structural design, risk knowledge, warning and evacuation, emergency response, and disaster recovery.
Social sustainability (Magis, 2010)	[3]	Resource development, community resources, active agents, collective action, strategic action, equity, impact, resource engagement

Adaptive capacity/ resilience model (Paton, 2010)	[3]	Individual level: negative outcome expectancy (denial/fatalism), positive outcome expectancy, action coping, self-efficacy, critical awareness. Community level: place attachment, sense of community, community participation, collective efficacy Societal/agency level: empowering settings, trust. Resilience/adaptive capacity: immediate impact (safeguard home/contents), impact (resources, self-reliance, psychological preparedness), response (community plans, collective action), recovery/rebuilding (collective action, inter-dependencies with civil agencies).
Community resilience framework (Becker et al., 2011)	[3]	Individual indicators: self-efficacy, outcome expectancy, critical awareness, action coping. Community indicators: community participation, articulating problems Institutional/societal indicators: community empowerment, trust
The Protective Action Decision Model (Lindell and Perry, 2012)	[1]	Source/message/receiver characteristics, channel access and preference, social/environmental cues. Pre-decision processes (exposure, attention, comprehension), stakeholders/ threat/protective action perceptions, protective action decision-making. Situational facilitators/impediments, behavioural response (information search, protective response, emotion-focused coping).
Embrace project (Birkmann et al., 2012a)	[2]	Interpretation of danger, understanding and knowledge of the cause, proximity, exposure, direct personal threat, personal experiences, people's priorities, experimental factors, environmental values.
Embrace project (Birkmann et al., 2012b)	[3]	Psychological, organizational and institutional, ecological and socio-ecological, critical infrastructure, and community-based
Community resilience framework (Becker et al., 2013)	[3]	Self-efficacy, critical awareness, positive/negative outcome expectancy, action coping, community participation, articulating problems, empowerment, social norms, trust, planning, personal responsibility, social responsibility, sense of community, leadership, collective efficacy, place attachment, experience, resourcing, psychological preparedness.
MOVE framework (Birkmann et al., 2013)	[3]	Capacity to anticipate: health and rescue human resources, residents risk awareness, insurance Capacity to cope: emergency plan, hospital beds, health human resources, rescue and firemen manpower Capacity to recover: development level, mean of subsistence, origin, education level, size of companies, female employment, etc.
Tsunami resilience (González-Riancho et al, 2014)	[3]	Coping capacity: information & awareness, warning & evacuation, emergency response Recovery capacity: disaster recovery

5.2 Storm surge resilience assessment

This section includes the description of a conceptual framework to understand the factors affecting the resilience of a community exposed to risks from natural hazards. The conceptual and methodological framework could be applied worldwide, although some questions may need some adaptation to fit adequately to other risks and study sites. The application to storm surge risks at the Dithmarschen district in the German North Sea Coast is presented here. Moreover, the proposed methodology allows analyzing each of the relevant factors to enhance disaster risk management and adaptation policies.

5.2.1 A framework for assessing resilience

A conceptual framework is proposed to assess the resilience of a community by understanding its short-term coping capacity and long-term adaptive capacity, the former referring to the emergency/disaster management cycle, i.e. preparedness, response and recovery phases, while the latter refers to the adjustments in the human-natural system needed to respond properly to the existing threat. Figure 5.1 conceptualizes and summarizes all the aspects considered in the storm surge resilience assessment presented here and that will be explained along this section.

Preparedness is defined as the knowledge and capacities developed by governments, professional response and recovery organizations, communities and individuals to effectively anticipate, respond to, and recover from the impacts of likely, imminent or current hazard events or conditions (UNISDR, 2009). The performance in this phase will determine the success in the subsequent emergency and recovery phases. Therefore, it must be based on a sound risk analysis as well as supported by formal institutional, legal and budgetary capacities. Accordingly, to better understand the organizational capacity of a community, institutional, social and legal dimensions should be considered since a failure or a shortage/deficit of a specific ability in one of them could turn the risk management and/or the emergency process partially ineffective or invalid for the worst case.

The institutional adaptation to the storm surge risk implies the improvement of every task included in the disaster management cycle (IOTWS, 2009; González-Riancho et al., 2014), such as flood protection measures, vertical and horizontal coordination, public information and awareness, early warning system, evacuation planning, emergency protocols, contingency planning, etc., as well as a range of recovery options. Most of the tasks of the institutional adaptation are requirements defined in obligatory documents (which are included in the legal dimension in this framework). The institutional awareness and knowledge regarding the storm surge risk as well as the existing mandatory conditions to manage it will affect the level of implementation of each step.

The social adaptation, however, is voluntary and more complex to understand due to existing society's values, risk cultures, perceptions and dynamics. The voluntarism associated to a society's behaviour make necessary to analyze its potential adaptation to the storm surge risk in terms of "intentions", which are understood as the cognitive representation of a person's readiness to perform a given behaviour, and considered to be the immediate antecedent of behaviour (Ajzen, 1991). Besides the individual protective behaviour as predictor of preparedness, developing community participation to achieve community goals is considered essential for effective disaster management (Perry & Lindell, 2003; Wisner et al., 2003; UN/ISDR, 2005; Paton, 2006; US IOTWS, 2007; Basolo et al., 2009; Solberg et al., 2010). It is therefore important to understand the capacity of the society to work in a collaborative way and if this networking and the results obtained from it are supported by coordination and empowerment mechanisms promoted by the authorities (Becker et al., 2011). The intention to prepare at both individual and collective levels is determined here through the analysis of the behavioural conditioning factors presented in the conceptual framework (orange boxes), which are inspired by the work carried out by Paton (2003, 2005, 2010), Becker et al. (2011, 2013) and Birkmann et al. (2012a).

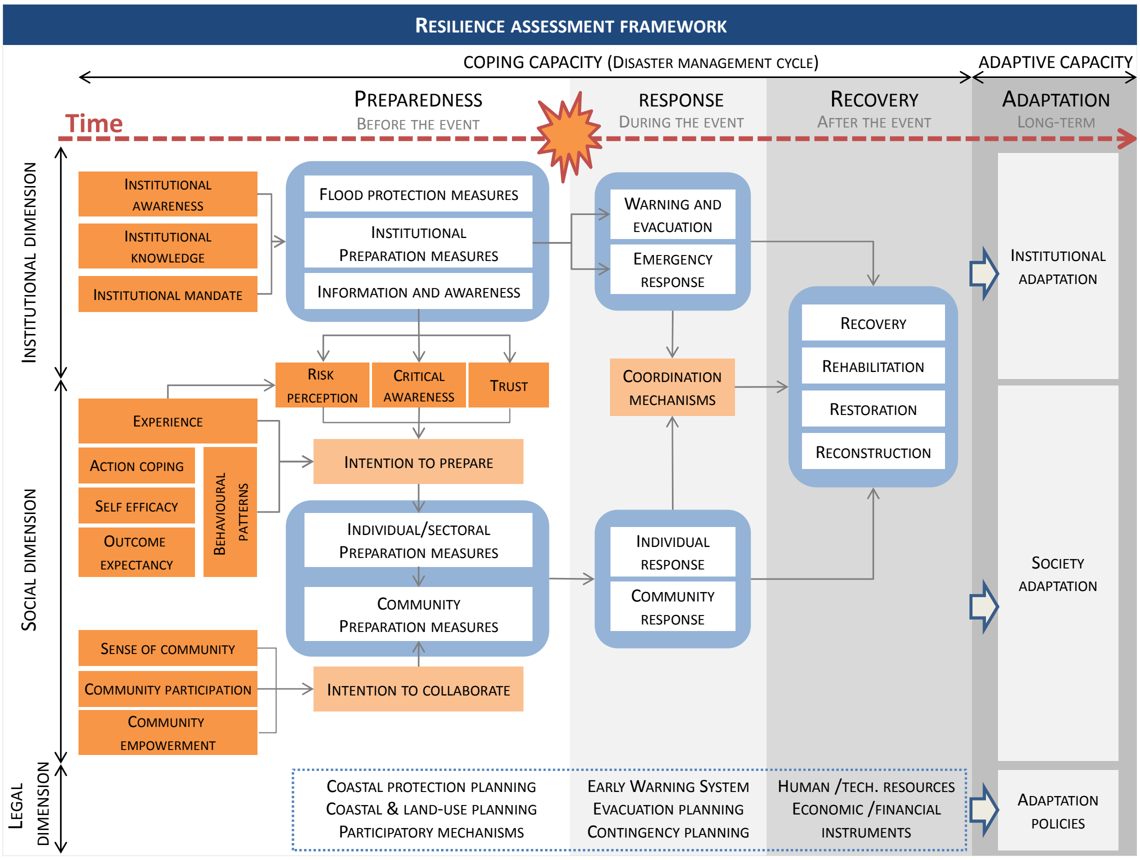

Figure 5.1. Resilience conceptual framework applied to understand the coping and adaptive capacities through time and dimensions (institutional, social and legal), and to design the questionnaire accordingly. The various preparedness, response and recovery steps to be accomplished by the institutions and society, as well as policy instruments required for it, are shown in blue boxes. Orange boxes represent the factors conditioning the action-taking by both institutions and society.

The fulfilment of both social and institutional requirements is essential to enhance society's resilience to catastrophic storm surge events. The close collaboration between governmental authorities, sectoral stakeholders and the community, for example through new Multi-Sector Partnerships to reduce or redistribute risk, is proposed in this framework to be a needed step towards improved risk management options. This institutional-social coupled assessment, similarly applied by Becker et al. (2011), is complemented by the legal dimension in order to incorporate policy requirements and instruments conditioning the adaptation. These policies are the basis above all for most tasks included in the institutional dimension. The deficiencies detected in the analysis will point towards the challenges to deal with to foster an adequate community adaptation to storm surge risk.

To summarize, the framework shows the linkages between the institutional, social and legal dimensions within risk management to enhance community preparedness, emergency management and long-term adaptation. It provides an appraisal through time (short-term vs. long-term) and analyzes psychological and social factors conditioning individual and collective preparedness.

5.2.2 Methodology and resilience questionnaire

Based on the conceptual framework presented in Figure 5.1, a questionnaire has been designed to assess the storm surge resilience (Table 5.2). To understand the capacity of the community to organize itself before, during and after a potential event in order to minimize the impacts, an analysis of the opinion of various stakeholders on several topics must be carried out. The entire questionnaire and its questions are clearly linked to the information the coastal manager obtains to improve risk management, and it can be easily adapted to analyze the risk perception and resilience of a community regarding other type of hazards.

The perceived institutional preparedness can be explored through the analysis of the current hazard mitigation measures and emergency management phases, the availability of storm surge risk information (hazard probability, potential impacts, responsible authorities on risk management, etc.) and its consideration in the decision-making process. The individual as well as the sectoral preparedness can be understood through the analysis of stakeholders' potential intention to prepare and the currently undertaken preparation measures; while the community preparedness can be studied through the analysis of the sense of community and community involvement levels. Finally, the feasibility of coordination mechanisms (partnerships) and various potential policy options allows connecting potential institutional measures and social acceptance to understand their expected degree of success and implementation challenges.

It is important to conduct the survey in both institutional and social spheres since incoherencies between authorities' and society's perceptions are automatically identified as a critical issue for resilience enhancement measures (González-Riancho et al., 2014). Accordingly, the questionnaire aims to understand the perceived (1) institutional and social preparedness, and (2) feasibility of coordination mechanisms and policy options. This allows identifying potential misunderstandings between those who make the rules and those whose life and activities are regulated based on them. This lack of coordination may generate potential failures in risk and emergency management.

Following the recommendations provided by EC (2002) to conduct an integrated stocktaking of stakeholders, the identification of survey participants should analyse which major actors and institutions in the exposed area influence or are affected by the risk management of their coastal zone. The inventory should consider all administrative levels and economic sectors; analyse interests and concerns of citizens, nongovernmental organisations (NGOs) and the business sector; and identify relevant inter-regional organisations and cooperation structures.

Table 5.2. Questionnaire applied, including for each question the resilience criteria and the output information for the formulation of risk management measures.

Resilience criteria		Question about:	Output information for the formulation of risk management measures. Knowledge about:
About risk information and institutional preparedness	Expected impacts	Q1. The impacts that could be generated in case of storm surge flooding.	The need for improving the risk communication strategy based on the degree of awareness on potential impacts and the disagreements/incoherencies between the answers
	Information & knowledge	Q2. The storm surge-related information provided by the responsible authorities.	The need for improving the risk communication strategy to increase risk awareness and fulfil society's expectations.
	Knowledge-based decision-making	Q3. The extent the storm surge risk is considered in the decision-making.	The need for integrating risk knowledge within sectoral decision-making and sectoral interests within risk management. Additionally the need for better information about it if already happens.
	Flood protection measures	Q4. The effectiveness of the currently applied flood protection measures.	The need for fostering society's knowledge, awareness and acceptance of the various flood protection options.
	Preparedness and recovery options	Q5. The availability of preparedness and recovery options for storm surge flooding.	The need for implementing specific options in the area if they do not exist yet or the need for better information about them if they already exist.
	Warning	Q6. The type of warning currently being issued in case of a storm surge event.	The need for enhancing society's knowledge about warning mechanisms, or the need for establishing new ones based on society's suggestions.
	Responsible authorities	Q7. The responsible authorities for the various processes within storm surge risk management.	The need for clarifying the roles of each institution within risk management, so that society knows what to expect and how to behave in case of emergency.
About sectoral and community preparedness	Critical awareness	Q8. The main problems the stakeholders worry about.	The significance of society's perception of risks in the context of daily life issues, and the need for increased awareness to foster society's intention to prepare.
	Trust	Q9. The extent stakeholders trust the institutions, mechanisms and structures related to storm surge management.	The need for increased society's trust on the management system and authorities in order to facilitate the adoption of protective behaviours.
	Experience	Q10. The experience with major storm surge flooding events.	The extent life experiences may influence society's risk perception and intention to prepare.
	Risk perception	Q11. The risk perception of stakeholders regarding their public/private sector and living/working activities.	The society's threat feelings as a predictor of intention to prepare.
	Intentional patterns	Q12. The level of involvement that the stakeholders think their sector should have within risk management.	The sectors / stakeholders willingness and attitude towards participative management approaches and the preferred type of participation extent.
	Behavioural patterns	Q13. The current proactive/reactive behaviour of the various sectors and stakeholders and the extent it is considered by the authorities.	The society's current preparedness behaviour and its acceptance and internalization by the authorities. It includes the concepts of outcome expectancy, self-efficacy and action coping as predictors of intention.
	Preparation measures	Q14. The accomplishment of different preparation measures and the main constraints faced by stakeholders.	The need for institutional support to enhance and facilitate the adoption of site-specific and plausible measures.
	Community participation	Q15. The level of participation and involvement of community members and sectors within risk management.	The need for enhancing sense of community and institutional support for community participation.
	Active stakeholders	Q16. The stakeholders/persons currently having an active role in storm surge protection within the community.	The relevant stakeholders that could help encouraging a participative approach in the preparedness of the community.
About coordination mechanisms and policy options	Partnerships structure	Q17. The involvement of several listed stakeholders in a potential partnership for risk reduction.	The need for raising awareness about the relevance of integrated approaches in risk management, involving public and private sectors and civil society organizations.
	Partnerships benefits	Q18. The main benefits that these partnerships could bring.	The perceived benefits in risk management to foster the partnerships.
	Partnerships difficulties	Q19. The main foreseen challenges/difficulties that these partnerships could face.	The perceived difficulties to anticipate them and propose preventive solutions.
	Potential risk reduction measures	Q20. The adequacy of various economic instruments, measures and policy options.	The potential level of acceptance of the various measures by society and consequent prioritization of measures, as well as the need for raising awareness on benefits and disadvantages.

The questionnaire includes different types of questions (scoring, selection, and open-ended), all of them composed of various items. Once the questionnaire is completed, each item may be analyzed separately or aggregated to create a score for each question. Different types of questions require different aggregation methods (Table 5.3). Based on OECD (2008), a weighted aggregation is applied to the scoring questions items in order to build the item value. The range of values is normalized through the minimum–maximum (Min–Max) method to obtain an identical range [0,1], thus allowing for their comparison and combination. The selection questions are analyzed through the selection ratio, while open-ended questions are analyzed qualitatively.

Table 5.3. Aggregation methods by type of question. The score weighting of those questions implying denial (e.g. "no information", "not available", etc.) includes the null weight for the lowest category. N/A= No answer/I don't know.

Type of question		Questions	Aggregation method
Scores	5 scores	1, 4, 9, 15, 20	Item value: scores weighted aggregation. Min-Max normalization. Score Weights: *Non-denial scoring (Q1, Q4, Q9): Very Low=1, Very High=5, N/A=0.* *Denial scoring (Q15, Q20): Very Low=0, Very High=4, N/A=0.* Question value: mean value of the normalized items
	3 scores	2, 3, 5, 17	Item value: scores weighted aggregation. Min-Max normalization. Score Weights: *Non-denial scoring (Q17): Low=1, High=3, N/A=0.* *Denial scoring (Q2, Q3, Q5): Low=0, High=2, N/A=0.* Question value: mean value of the normalized items
Selection	1 option	10, 12, 13	Selection ratio.
	Many options	6, 8, 11	Selection ratio.
		7, 14, 18, 19, 20	Selection ratio. Qualitative analysis
Open-ended	question	16	Qualitative analysis

Based on the above-described methodological considerations, the application of the proposed resilience questionnaire and method to the pilot case is presented in Section 3.

5.3 Application to the case study: the German North Sea coast

The German North Sea coast and its population are characterized by their continuous interaction with the ocean. The coastal area has been reclaimed and transformed for agricultural and settlement purposes by the population, while the sea has been constantly reshaping the coastline and flooding settled marshlands. This continuous human-nature interaction has resulted into a unique landscape and cultural-historical heritage in the area where, according to Bauer et al. (2001), until today the local population feels strong bonds to its history.

The rural district[15] of Dithmarschen in Schleswig-Holstein (SH) is located on the German North Sea coast, embraced by the Eider estuary to the north, the Elbe estuary to the south, and the Kiel Canal to both the east and southeast. It is a rather flat countryside that was once full of fens and swamps and has a maximum north-south length of 54 km and an east-west length of 41 km. It has 1,428 km^2 and hosts about 133,000 inhabitants according to the census of 2011[16], which represents less than 1% of the population in about 9% of the total area of the state of Schleswig-Holstein. The population density is of 94 inhabitants per km^2, considerably lower than the state's average of 179[17].

The Dithmarschen economy consists mainly of agriculture, tourism, and energy. Dithmarschen has an outstanding soil quality, which can easily be cultivated, and a favourable climate. The forms of agricultural operations include extensive and intensive farming of grain crops and vegetables (Bauer et al., 2001). The touristic infrastructure predominates in Büsum and Friedrichskoog communities, the industry is mainly based in Brunsbüttel community being fostered by the North Sea-Baltic Sea canal, and there are numerous wind parks shaping the Dithmarschen coastal scenery.

According to Bauer et al. (2001), as a result of the development patterns the contemporary cultural landscape of the Dithmarschen marshes can be divided into three sections seawards: (i) the old sea marsh which was enclosed in dykes in the High Middle Ages, with its substantial village mounds, (ii) the low-lying Sietland, which was made arable in the Middle Ages, with its elongated linear settlements, and (iii) the new sea marsh with its modern dyke constructions.

The resilience assessment presented in this document has been carried out on the 19 coastal communities of Dithmarschen. In total, these coastal communities have a population of around 33,300 inhabitants along a 70km long coastal stretch. The 4 most populated communities (Büsum, Meldorf, Friedrichskoog and Brunsbüttel) host the 81% of the coastal population, which reflects the low population density along most of the study area.

5.3.1 Storm surge flooding and disaster risk management

The region is exposed to different hazards. For centuries storm surges and sea level rise represent the major threat to coastal settlements and agricultural land, forcing the inhabitants to adopt several coastal protection measures and strategies. Some of the most relevant storm surge events are presented in Table 5.4. The most famous one is probably the Grote Mandränke or 'Great Drowning' of 1362 which devastated the entire Wadden Sea region with around 100,000 casualties, the disappearance of villages and islands and the reshape of the entire coastline, such as the first embayment of the Dollart bay (NLWKN, 2007). The last disastrous event was in February 1962, which caused 340 casualties in the German North Sea coast and Hamburg. The flooded area in Dithmarschen due to the last 4 events of this Table

[15] Federal States (*Lander*) in Germany are divided into districts (*Kreis*) and communities (*Gemeinde*), districts being grouped in counties (*Amt*).

[16] "Statistikamt Nord – Bevölkerung der Gemeinden in Schleswig-Holstein 4. Quartal 2012] (XLS-Datei) (Fortschreibung auf Basis des Zensus 2011)". Statistisches Amt für Hamburg und Schleswig-Holstein (in German). 25 July 2013.

[17] www.dithmarschen.de

5.4 is shown in Figure 5.2, together with the current coastal protection dyke line. Additional risks are related to heavy storm and rainfall events with subsequent flooding events in the hinterland, which increase the risks of high discharge rates and raise the challenge of draining the land in the low-lying areas behind the dikes.

Table 5.4. Summary of important historic storm surge events at the German North Sea Coast (extract from NLWKN 2007). The flooded area in Dithmarschen due to the last 4 events is shown in Figure 2.

Date	Description	Countries/ areas affected	Number of casualties
16/01/1219	1st *Marcellus flood.* Huge flooding in the River Elbe area and elsewhere; first historically transmitted eye-witness account	German North Sea Coast	36,000
16/01/1362	2nd *Marcellus flood/ "Grote Mandrenke".* First embayment of the Dollart bay between northern Netherlands and Germany; destruction of a huge part of North Frisia	North Frisia	100,000
11/10/1634	2nd *"Mandrenke".* Island of "Strand" destroyed, remnants of Strand are Nordstrand and Pellworm islands	Germany, North Frisia	8,000
24-25/12/1717	*Christmas flood.* Highest and most disastrous storm surge event of its time	Netherlands, Germany and Denmark	11,150
3-4/02/1825	Many dyke breaches and heavy losses of dunes on islands; marked the highest storm surge level (e.g. in Hamburg) until 1962	German North Sea Coast	800
16-17/02/1962	*February Flood 1962/ 2nd Julian flood*. Heavy storms flood in the North Sea coast, mainly around Hamburg	German North Sea Coast and Hamburg	340
3/01/1976	Highest storm surge level at many tidal gauges, dyke breaches along the coast of SH and the Elbe river	German North Sea Coast	0

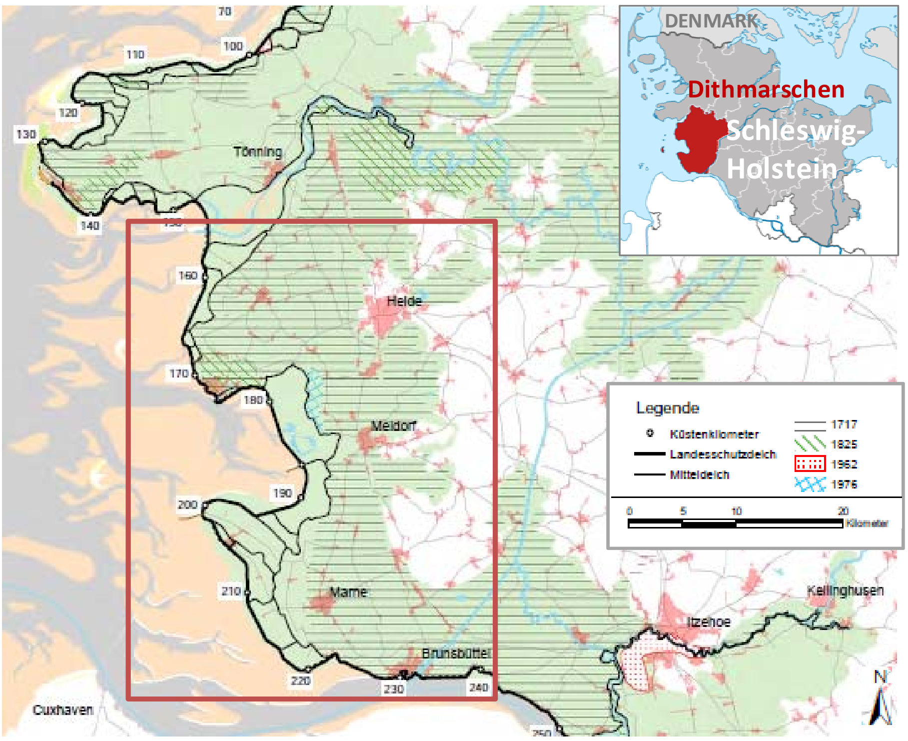

Figure 5.2. Current coastal protection and historical flooded areas for the storm surge events of 1717, 1826, 1962 and 1976 in Dithmarschen. The black lines show the main and secondary dyke lines. (Source: modified from Generalplan Küstenschutz des Landes Schleswig-Holstein, MELUR 2012)

The disastrous storm surge events triggered large changes in coastal protection strategies over the centuries (dwelling mounds, ring dykes, closed dyke lines, etc.). Simultaneously with the process of continuous enhancement of protection facilities, an increase in population and the amount of goods and values in this region has been documented. In this regard institutional arrangements, responsibilities and distributions of mandates played an important role in risk management over centuries and resulted in the currently applied, comprehensive risk management of storm surge risks along the German North Sea coast.

As an introduction to the coastal management of the study area and in order to better understand some of the results presented in this work, some basic information about laws, responsibilities, funding and the distribution of mandates and tasks in the study area is summarized here.

The Basic Constitutional Law of the Federal Republic of Germany identifies coastal protection as an issue of concurrent legislation[18], and assigns the Federal States the responsibility for it. According to NLWKN (2007) the public funding for coastal protection is distributed between the German Government (70% of the costs) and the federal states (30%) for the main dyke line (NLWKN 2007). Maintenance of dykes and other coastal protection facilities are paid by the federal state in Schleswig-Holstein. Regarding private investments and insurance, storm surge damages are not insurable in Germany, being officially and explicitly excluded from both building insurance (VGB, 2008) and home content insurance (AStB, 2008).

In SH, the organizational structure and distribution of competencies among authorities/associations involved in coastal protection, shown in Table 5.5, reflects the embedded risk culture of the study area, based on a modified coastal landscape, the land reclamation patterns and related need for drainage, the storm surge hazard and the coastal protection dykes.

Table 5.5. Organizational structure and distribution of competencies among authorities/associations involved in coastal protection and emergency management in Schleswig-Holstein (German North Sea coast).

Institution	Mandate
Ministry of Energy Transition, Agriculture, Environment and Rural Areas (*Ministerium für Energiewende, Landwirtschaft, Umwelt und ländliche Räume, MELUR*)	Strategic planning of coastal protection issues. In 2012 the State Governmental Master Plan for Coastal Risk Management in SH (*MELUR, 2012)* was updated in order to consider new projections of climate change and sea level rise and to implement the EU-Floods Directive (Hofstede, 2014)
Agency for Coastal Protection, National Parks and Ocean Protection (*Landesbetrieb Küstenschutz, Nationalpark und Meeresschutz, LKN*)	Guidance and supervision of construction and maintenance of coastal protection facilities
Water Boards and Land Associations (*Landesverband Wasser - und Bodenverbände, LVB*)	Dike maintenance (guided and supervised by LKN; MLR, 2001), pumping station operation, water, sanitation, wind/water protection and irrigation, and take additional tasks of nature conservation.

[18] Concurrent legislation means that the Federal States have the power of legislation processes as long as the State does not make use of its (superordinate) right of legislation on the issue.

Main Dyke and Sluice Association (*Deich- und Hauptsielverein, DHSV*)	Maintenance of water resources and dikes, operation and maintenance of pumping stations, implementation of the EU Water Framework Directives, nature conservation and landscape management, sewage treatment plants and coordination of several Dykes Associations at the local level.
Federal Maritime and Hydrographic Agency (*Bundesamt für Seeschifffahrt und Hydrographie, BSH*) in connection with the German Weather Service (*Deutsche Wetterdienst, DWD*)	Issuing and publishing the flood warnings in case of a storm surge event through the radio, internet (www.bsh.de) and TV. If evacuation of vulnerable areas is necessary, the warning is issued by radio or television, loudspeakers also being used for announcements of local police or fire department, together with sirens in some regions
Federal Agency for Technical Relief (*Technisches Hilfswerk, THW*) from the Ministry of Interior	Emergency operations, supported by partners such as the fire departments, the Red Cross, the Federal Police and the Army

In view of the long-lasting historic experience in managing risks along the coast and the continuous interaction between the population and the ocean, the experience on coastal protection and hazard mitigation measures is recognized in the study area; devastation incidents were at the order of the time. Performance of preparedness, response and recovery phases as well as the perception of society on storm surge risk issues have not been found documented and became an issue in rather recent time.

5.3.2 Stakeholders sample

Following the EC (2002) guidelines to stock take the main actors, the following types of stakeholders were identified in Dithmarschen:

- Main socioeconomic sectors: agriculture, tourism, industry, culture and environment.
- Relevant administrative actors: coastal protection, emergency management, local administration.
- Relevant non-administrative actors: NGOs, business sector.
- Administrative levels: national, state (Lander), county (Amt), district (Kreis), community (Gemeinde).

Several interviews with experts on the storm surge hazard and emergency management and/or in the socio-economy of the study area, helped to develop an inventory of stakeholders in Dithmarschen including those involved in management processes and those whose activities could be potentially affected by the storm surge impacts. 43 stakeholders were identified due to their representativeness and relevance in the region and contacted by phone and/or email, 16 of them answered the questionnaire. The interviewed stakeholders are shown in Table 5.6, including their type, spatial scope and sector. The statistical sample could be considered small, but is still representative of the study area including all types of stakeholders, the administrative levels and sectors. At the next stage individual citizens will be also included in the analysis, since the validated method will be replicated along the whole trilateral Wadden Sea region in the framework of the ongoing FP7 ENHANCE Project.

Table 5.6. Stakeholders interviewed in Dithmarschen categorized by type of stakeholder, scope and sector (scope: N=national, S=state, D=district, C=county, CM=community). The name of the organizations is not provided due to questionnaire-related confidentiality conditions.

No.	Type	Scope					Sector
		N	S	D	C	CM	
1	Administration			x			Administration
2	Authority, Administration			x			Emergency
3	Authority				x		Environment
4	Authority, Administration				x	x	Coastal protection, emergency, tourism
5	Public agency					x	Tourism
6	Authority		x				Coastal protection
7	Authority	x					Emergency
8	Authority				x		Emergency, Environment
9	Authority			x	x	x	Emergency
10	Cultural			x			Emergency
11	Authority					x	Emergency
12	NGO			x			Emergency
13	Business/ socioeconomic activity			x			Tourism
14	Business/ socioeconomic activity					x	Tourism
15	Business/ socioeconomic activity			x			Agriculture and farming
16	Business/ socioeconomic activity	x		x			Administration, industry, water supply

5.3.3 Storm surge risk perception and resilience in Dithmarschen

This section presents the results obtained in the pilot study area which are organized according to the structure presented in Table 3, which includes (1) risk information and institutional preparedness, (2) sectoral and community preparedness, and (3) coordination and policy options. Results are supported by the pertinent references and methodological background needed to understand the main conclusions obtained.

5.3.3.1 Risk information and institutional preparedness

According to Patton (2005), risk communication based on information provision alone will fail to engage people in ways that facilitate their ability to make decisions. Instead, personalizing hazard information and disseminating it in ways that involve engaging people in debate encourages people to interact with and to interpret information relative to its implications for themselves, their family and the activities they deem important (Paton and Johnston, 2006). The first group of questions dealt with the knowledge of the stakeholders about the storm surge hazard, such as potential impacts, what to do in case of an event, responsible authorities, flood protection and preparedness/recovery options. The availability, quality and use of the existing storm surge risk information in sectoral planning were analyzed together with the perception of the stakeholders regarding the institutional preparedness.

The major expected impacts (Q1, Figure 5.3) in Dithmarschen are on the infrastructural, economic and social dimensions, while human losses and environmental impacts are secondarily positioned by the stakeholders. To understand the degree to which knowledge and awareness could translate into preparedness behaviour (Johnston et al., 2005), the stakeholders were asked about the availability of storm surge risk information (Q2, Figure 5.3). Almost half of the respondents don't know if there is available information for each of the issues. About half stated that no/little information is available, this percentage increasing for the potential socio/economic impacts and for risk reduction measures. Very low rates were given to the "Excellent information" category, which indicates a lack of appropriate information on the topic being provided to stakeholders (and consequently also to the local population) to better cope with the hazard. The question on knowledge-based decision-making (Q3, Figure 5.3) aimed to evaluate the extent the risk information is considered in the sectoral planning in the study area. More than half of the respondents (10-12) think it is fully considered in coastal protection planning but not in spatial planning, tourism development and location of transport infrastructures. These results suggest that there is a lack of risk knowledge-based sectoral planning which could imply a higher amount of people and infrastructures in flood-prone areas. Being asked to rate the effectiveness of the currently applied flood protection measures (Q4, Figure 5.3), most of the stakeholders have agreed on the high effectiveness of hard protection measures, i.e. dykes system and flood gates (13-14 rated them with high/very high effectiveness). However, soft protection and spatial planning measures, i.e. coastal nourishment, building codes and coastal setbacks, receive lower effectiveness values. This result shows the higher credibility on engineering measures prevailing in the study area.

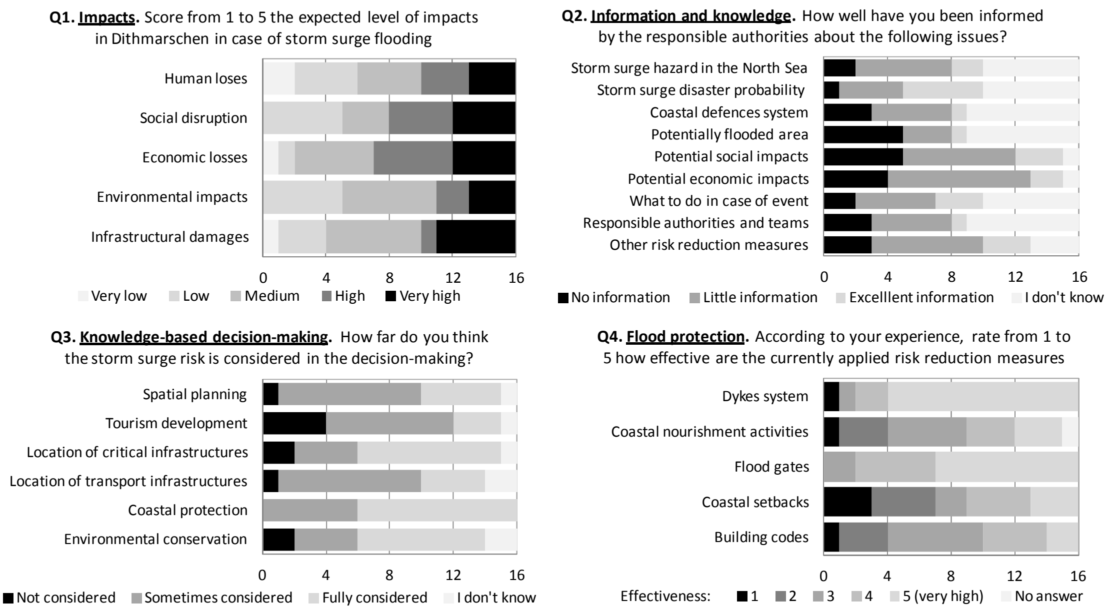

Figure 5.3. Results about availability of information and institutional preparedness (questions 1-4). Q1: expected impacts, Q2: available information/knowledge, Q3: knowledge-based decision-making, Q4: flood protection measures.

Regarding the preparedness and recovery options (Q5, Figure 5.4) available in Dithmarschen, 14 respondents guaranteed that an early warning system and contingency plans are fully/somewhat available. For evacuation plans, drills and temporary shelters that certainty decreases resulting in contradictory responses that should be considered for better information strategies. Most of the respondents (14-15) do not know if economic instruments are available to deal with the risk. These results show a lack of clear information about preparedness and recovery options provided to the public, which could hinder the community preparedness options. Focusing on the storm surge early warning system (Q6, Figure 5.4), the interviewed stakeholders effectively identified the available official warning mechanisms, with the radio, TV and internet being the most known ones, followed by sirens and loudspeakers, and then by street signs and SMS. Some stakeholders suggested additional warning systems such as Facebook/Twitter (social media), sirens in those places where is not currently available and firemen-related warning. Regarding the responsible authorities within storm surge management (Q7, Figure 5.4), as several answers were possible the stakeholders identified those authorities they think are involved in each process, and not only the responsible ones. MELUR and LKN are identified as the main responsible authorities for planning the coastal defences system, although the Dykes Association, Ministry of Interior, BSH, DWD, and majors are also linked to this task. Every presented authority is expected by the stakeholders to provide information to the society, the DWD and the North German Climate Office (Norddeutsches Klimabüro, a science information office of HZG), involved in dissemination of information to the public, not being particularly highlighted compared to the others. The DWD and the BSH are identified as those in charge of issuing a warning, although MELUR, Ministry of Interior, LKN and Majors are also identified. Emergency coordination is assigned to the Ministry of Interior, THW, firemen, police, etc., but also to LKN, MELUR, Dykes association and Majors. The clear conclusion obtained from this question is that the different tasks within storm surge risk management are not completely understood nowadays and that should be clarified to the stakeholders and to the society in general.

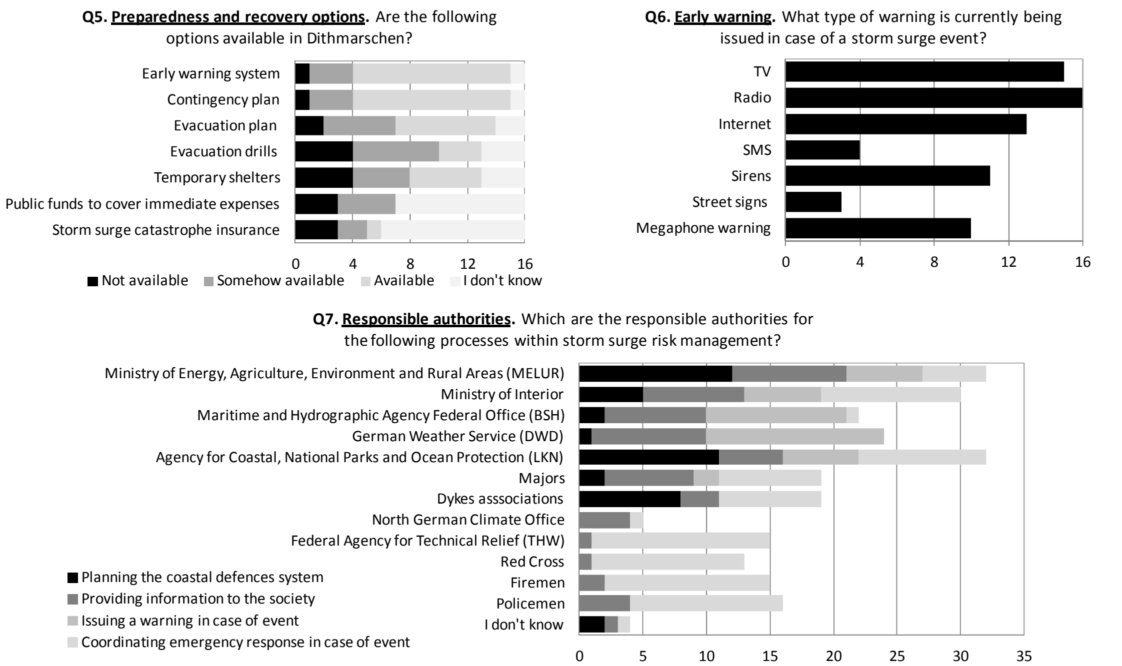

Figure 5.4. Results about availability of information and institutional preparedness (questions 5- 7). Q5: preparedness and recovery options, Q6: early warning, Q7: responsible authorities (several answers possible).

5.3.3.2 Sectoral and community preparedness

This second group of questions dealt with the sectoral and community preparedness for storm surge risks, including several factors conditioning behavioural patterns, protective behaviours as well as community interaction.

Risk perception has been long considered a protective behaviour predictor in health and natural hazards literature (Douglas and Wildawsky, 1982, Lindell and Perry, 2000; Sjöberg, 2004, Renn, 2008; Birkmann et al., 2012a). The extent risk is perceived in the society is conditioned by previous experiences (Birkmann et al.,2012a; Becker et al., 2013) as well as on the information provided by the authorities regarding the hazard itself, the potential impacts and the risk reduction options applied and/or promoted. The information provided will affect the extent the hazard is a salient topic within the society's discourse as well as the extent the society trusts the information itself, the responsible institutions and the measures applied. Dalton (2001), Patton (2003, 2005, 2010) and Becker et al. (2011, 2013), among others, identified the critical awareness as a conditioning factor for the perception of risk and the intention to act. The critical awareness describes the extent to which people think and talk about a specific source of adversity or hazard within their environment (Paton, 2003), reflects how important this problem is compared to others and provides an insight about the intention to develop a protective behaviour. The storm surge critical awareness (Q8, Figure 5.5) has been found very low according to the answers obtained. The three main problems affecting the stakeholders in Dithmarschen are livelihood-related difficulties, demographic change and migration, and climate change. Not a single stakeholder selected storm surge or river flooding as a problem they worry about, which suggests that storm surge is not considered an urgent problem. It could be discussed that daily problems as livelihood-related issues, for example, are most likely to be highlighted; however, climate change appears as the third most important problem for the stakeholders, which may be related to the effectiveness of climate change awareness campaigns worldwide and the lack of them for storm surge hazard in particular. The fact of not considering storm surge as an urgent problem may be the cause for the prevalence of temporary short-term protection measures to cope with it.

Research has found that people are more likely to adopt protective measures if they trust the source that is providing the information, as well as to be supportive of civic agencies if they trust the way the manage risk and they think they are competent (Paton 2003, 2010; Paton et al., 2006; Basolo et al., 2009; Becker et al., 2011). The question about trust (Q9, Figure 5.5) shows higher trust levels in coastal engineering measures than in other type of measures, mechanisms and authorities. The trust in coastal defences is definitely proved with 13 respondents assigning very high and high trust, although lower trust is given to the same coastal defences for future climate scenarios. Regarding experience (Q10, Figure 5.5), the stakeholders are familiar with major storm surge events although not with storm surge disasters. No one experienced a disastrous event although most of them have experienced a major storm surge event with minor impacts. The answers to the risk perception (Q11, Figure 5.5) question show that storm surge risk is perceived in Dithmarschen, since 11-12 respondents feel personally threatened as their living/working activities are located at a potentially flooded area. About half of the survey participants feel that his/her sector is threatened and that it could be potentially disrupted. In spite of the perceived risk, only 2 stakeholders are looking for information to better cope with the storm surge hazard. However, according to Paton (2005) the intention to seek information does not directly lead to protective behaviours as does the intention to prepare.

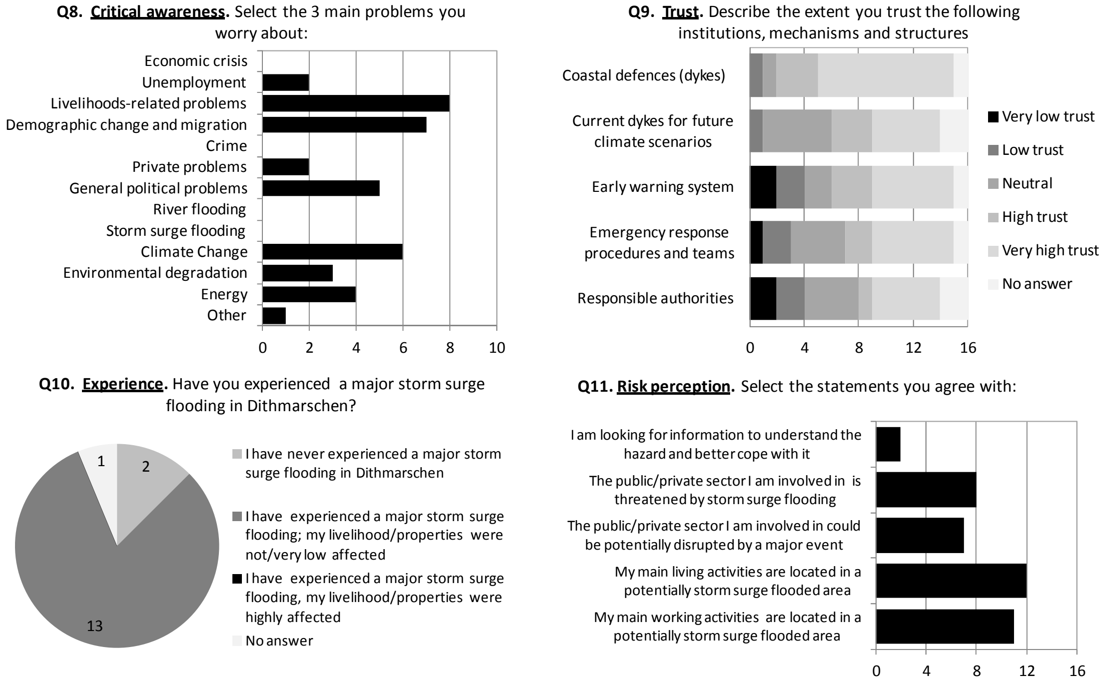

Figure 5.5. Results about sectoral and community preparedness (questions 8-11). Q8: critical awareness, Q9: trust, Q10: experience, Q11: risk perception.

The question on intentional patterns (Q12, Figure 5.6) deals with the level of involvement the stakeholders think their sector should have within risk management. Half of the respondents suggest a more participative and integrated approach in storm surge risk management as they believe they can actively contribute with their knowledge and actions. The 68% prefers a participatory risk management, although with different involvement levels. The question on behavioural patterns (Q13, Figure 5.6) includes on the one hand the concepts of outcome expectancy, self-efficacy and action coping applied by previous authors as predictors of intention formation (Paton, 2005, 2010; Becker et al., 2011, Becker et al., 2013). On the other hand it assesses whether the authorities are considering in some way the actions taken by the stakeholders to reduce the risk. Outcome expectancy refers to the perceptions of whether personal actions will effectively mitigate or reduce a problem, self-efficacy to the beliefs regarding personal capacity to act effectively, and action coping (or "problem-focused coping" as per Paton, 2003) to the predisposition to choose action directed at changing a situation (Paton, 2003). The answers to this question show that 4 respondents believe they cannot do anything to reduce the risk as this totally depends on the authorities' actions and infrastructures. This attitude has been psychologically described as fatalism by several authors in disaster research (McClure et al., 1999; Asgary and Willis, 1997; Flynn et al. 1999, Paton, 2010; Şimşekoğlu, 2013). When people perceive others as being responsible for their safety, they are less likely to convert intentions to actions (Ballantyne et al., 2000). Besides, the dissemination of information on structural mitigation to the public has been found to lead to a reduction in levels of household and personal preparedness and a transfer of responsibility for safety to civic authorities (Paton et al., 2000). The perceived high effectiveness (Q4) and the high trust (Q9) associated to the dyke system call attention to a possible safety feeling among the society. However, a proactive behaviour in risk reduction is detected in the 75% of responses to this question. Half of the stakeholders are already working on risk reduction, the actions and interests of 7 of them being already considered by the risk management authorities. 3 respondents are already aware that their sector can do something to reduce the risk, although not working on it yet.

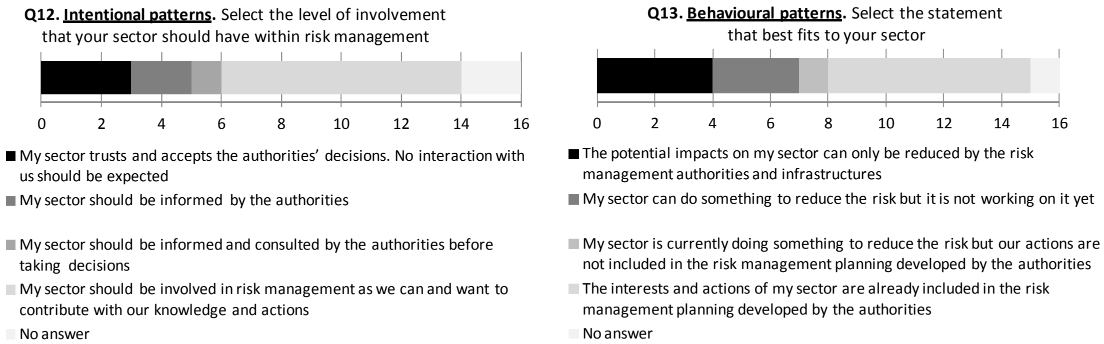

Figure 5.6. Results about sectoral and community preparedness (questions 12-13). Q12: Intentional patterns, Q13: behavioural patterns.

In order to move from intentions and behavioural patterns to implemented protective behaviours, the stakeholders were asked about the type of preparation measures (Q14, Figure 5.7) being already undertaken by them together with the main constraints faced (or potentially faced) to accomplish them, the latter aspect being related to the situational facilitators/impediments proposed by Lindell and Perry (2012). The preparation measures undertaken by the stakeholders - from agriculture & farming, industry, emergency and administration sectors - are mainly temporary (6), such as sandbag storage, time being the main constraint faced to accomplish it. Very few undertake permanent structural protection, evacuation measures or have their belongings covered against flooding by insurance. Besides cost/time constraints, the stakeholders identify a lack of support by authorities and insurance to accomplish temporary protection and evacuation measures as well as to insure their belongings.

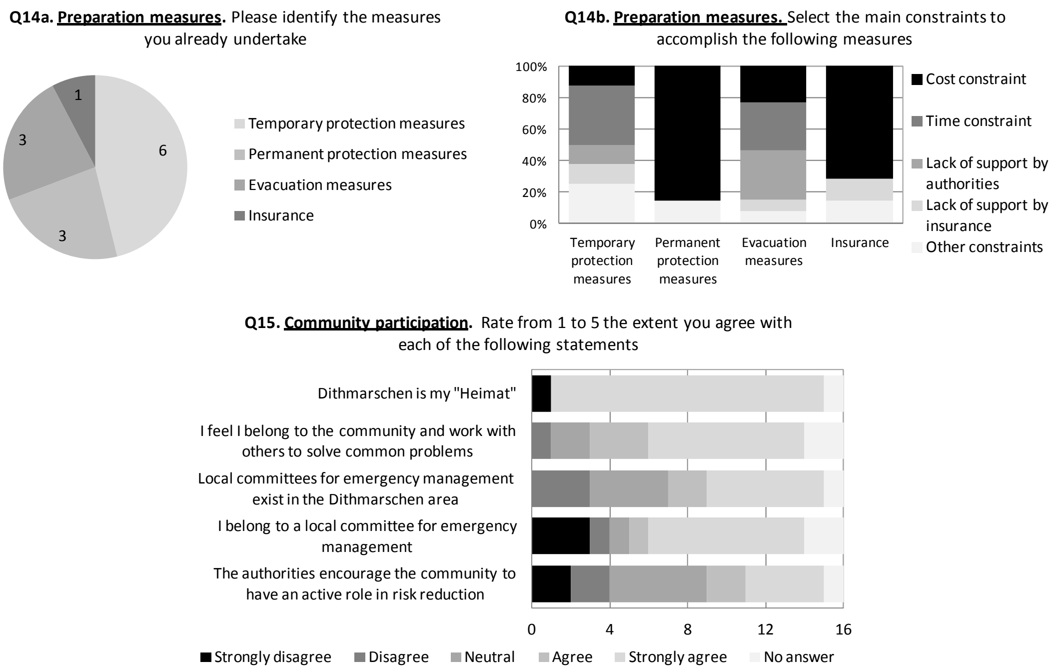

Figure 5.7. Results about sectoral and community preparedness (questions 14-15). Q14: preparation measures (several answers possible), Q15: community participation.

The enhancement of community resilience depends on the promotion of mitigation and preparedness behaviours and the implementation of collaboration and empowerment mechanisms to connect local communities with disaster risk management agencies. Based on this idea, the question on community participation (Q15, Figure 5.7) includes queries about the feelings of the respondent concerning the study area (using the German concept of Heimat) and the local community, to then ask about the existence of emergency management local committees, his/her involvement in them and their acceptance and support by the authorities. Ratter and Gee (2012) confirmed the concept of Heimat as a multi-faceted and highly relevant term in the German context and explicitly along the North Sea coast for approaching place values, sense of place and attachment to place. The concept links place to social relations through a strong emotional component related to the perceived intangible place values or “spirit of place”. Their results demonstrated that this feeling of belonging has inherent qualities to foster the people to act as well as to strengthen participative processes. The answers to Q15 show that there is a sense of community in the study area, since 14 respondents feel home and place-attached (Dithmarschen is my Heimat) and 11 work with others to solve common problems. Around the half stated that local committees for emergency management exist and they belong to one of them. However, more than half stated that the authorities are not encouraging enough the community to have an active role in risk management, more support from authorities being therefore expected.

The stakeholders identified by the respondents as active in storm surge management in Dithmarschen (Q16) are the authorities at the various administrative levels, the Main Dyke and Sluice Association and local Dykes Associations, the Trade Ministry, the Coastal, Natural Parks, and Ocean Protection Agency (LKN), the Water Boards and Land Associations (LVB), the fire brigades, and the farmers. These stakeholders should be considered in potential participatory approaches and partnerships, and all of them having been contacted for carrying out this questionnaire.

5.3.3.3 Coordination and policy options

The third and final group of questions dealt with the potential coordination mechanisms along with policy and economic options to foster the adaptation to the storm surge hazard in Dithmarschen.

One of the main lessons in the aftermath of hurricane Katrina 2005 or the tsunami of 2004 and seen in other coastal hazards is that single-sector development planning cannot solve the complexity of problems posed by natural hazards nor build resilience to them (US IOTWS, 2007). Partnerships involving the public and private sectors and civil society organizations are currently seen as a way of sharing responsibilities to significantly improve disaster risk management and an increased support and understanding of the chosen direction and solutions (Swart et al., 2014; OECD, 2010; UN/ISDR, 2005). Most of the stakeholders interviewed (14-15 out of 16), when asked about the structure of a potential partnership to deal with risk management (Q17, Figure 5.8), highly agreed on the involvement of those stakeholders related to the emergency (i.e. THW, Red Cross, Fire brigade, etc.) and coastal protection (LKN, Dykes association). The highest disagreements are related to the involvement of sectoral stakeholders (such as the agriculture/livestock, tourism and industry private sectors), the environmental stakeholders (Wadden Sea National Park and environmental conservation organizations) and NGOs. The involvement of authorities (ministries, mayors and communities) also counts with some disagreement. The main conclusion arising here is that if Multi-Sector Partnerships are to be fostered in the region, previous awareness campaigns about the relevance of this integrated approach should be promoted.

The stakeholders were asked to identify the 3 main benefits and challenges from potential partnerships, this allowing rank/prioritize the provided options. The main expected benefits from a potential partnership (Q18, Figure 5.8) are the increased collaboration and responsibility-sharing between stakeholders, and the gain of knowledge in risk management. Long-term planning, increased budget available, and the involvement of the society are considered next. These are followed by increased discussion about risk management, risk sharing and, finally, the involvement of sectoral objectives in management. The main expected difficulties to be faced by a potential partnership (Q19, Figure 5.8) are related to people’s time and commitment, and the effective implementation of the decisions potentially taken. Budget, guidance and knowledge are also challenges to be considered. These are followed by collaboration and empowerment issues. The identified and ranked challenges are essential information to design and manage the partnership in such way that these problems are minimized.

The last question dealt with potential policy options or economic instruments that could be applied in the region to adapt to the storm surge risk (Q20, Figure 5.9). The stakeholders were asked to rate the extent they agree with the adequacy of the following measures to

Dithmarschen: land use taxes/dykes taxes [19], tax exemption [20], grants/subsidies [21], incentives/compensation [22], public contracts [23], service concessions [24], insurance [25], and catastrophe bonds[26]. Around the half of the respondents rated very inadequate/inadequate all of the measures. Land use taxes are considered very inadequate by most (10) of the stakeholders. The options that received some acceptance (adequate/very adequate), even with low percentages, were grants/subsidies and insurance, followed by tax exemptions. The lowest acceptance was detected for service concessions and catastrophe bonds. Potential economic instruments and adaptation options should consider the current disagreement with some of the presented options, in order to design tailored and site-specific measures.

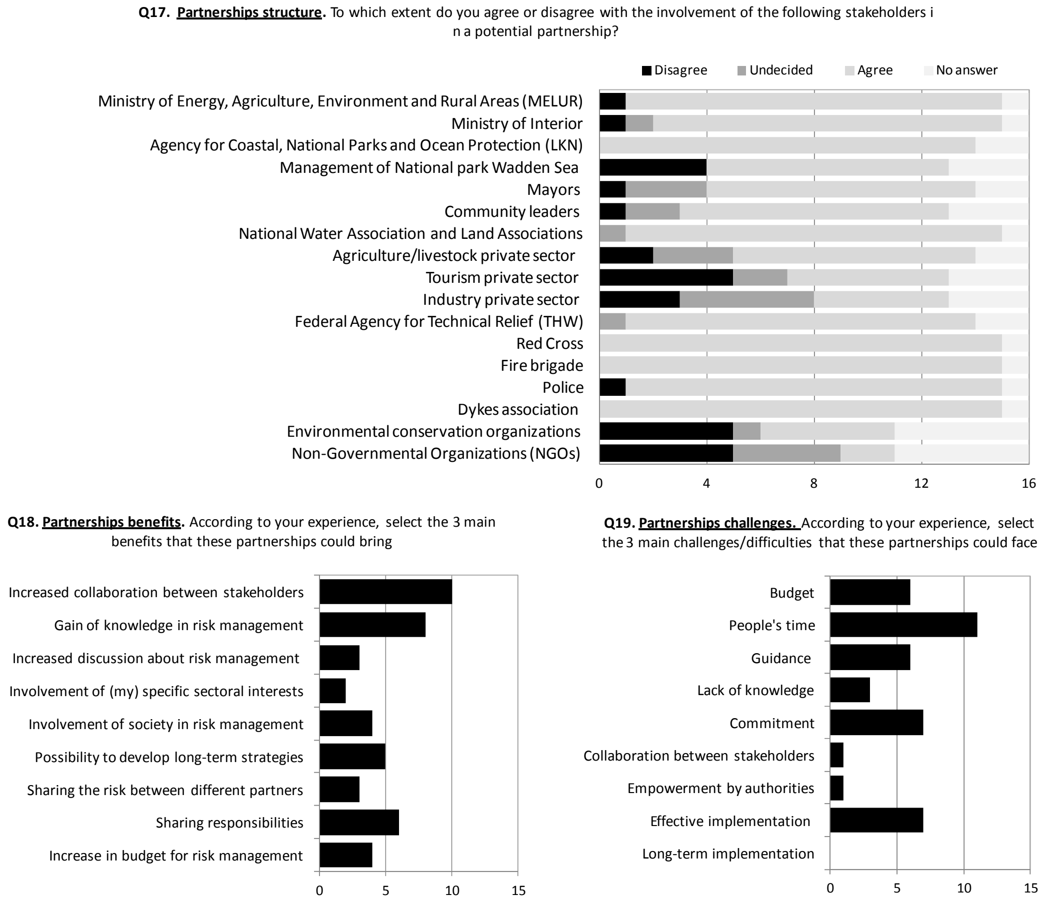

Figure 5.8. Results about coordination and policy options (question 18 and 19). Q17: partnerships structure, Q18: partnership benefits, Q19: partnership challenges (Q18 and Q19: only 3 options possible).

[19] Flood prone land owners finance coastal protection
[20] Tax exemption for private investment in permanent flood protection
[21] Grants/ subsidies as financial support for private investment in permanent flood protection
[22] Incentives/compensation for giving up land
[23] Public contracts to perform a particular task that benefit the community funded by government funds
[24] Service concessions to have the exclusive right to operate, maintain and carry out the investment in a public utility for a given number of years, this including the right to charge the final users of the product
[25] Insurance financing losses caused by storm surge events
[26] Disaster risks are securitized in the financial markets, the investor receiving a return if a catastrophe does not occur during the contract, but sacrificing interest or part of the principal if the event does occur

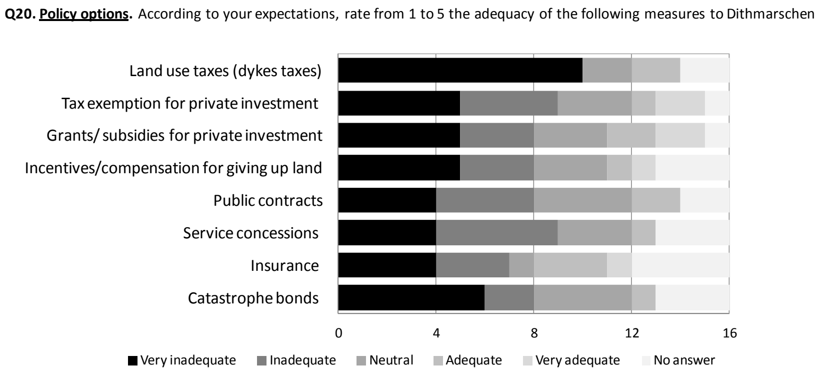

Figure 5.9. Results about coordination and policy options (question 20). Q20: policy options

5.3.3.4 *Discussion on the main results: the risk culture of the pilot study*

The assessment carried out permitted to identify the main characteristics of the study area in terms of stakeholders' risk perception, individual/collective intention to prepare and behavioural patterns, as well as their opinion regarding the authorities' decision-making. This provided a very useful insight about the risk culture of the area, defined by Douglas and Wildawsky, (1982) as the predominance in society of individual or collective approaches and the preference for hierarchies or. egalitarism. The main findings of the analysis, presented below, allow understanding the site-specific institutional, sectoral and community preparedness in Dithmarschen and the options for enhancing its resilience.

Based on the aggregation methods presented in Table 3, the following values by question have been obtained for the study area (Table 5.7). These values have been classified in 5 classes from very low to very high to better understand the extent risk reduction measures may be needed. The specific results obtained for each item within each question have been presented in the previous section and are summarized next.

Table 5.7. Resilience assessment results by question

Resilience question	Type of question	Value	Class (5)
Q1. Expected impacts	Scores (5)	0,67	High
Q2. Information and knowledge	Scores (3)	0,32	Medium
Q3. Knowledge-based decision-making	Scores (3)	0,61	High
Q4. Flood protection effectiveness	Scores (5)	0,73	High
Q5. Preparedness and recovery options	Scores (3)	0,35	Medium
Q6. Early warning	Selection (any)	0,92	Very High
Q7. Responsible authorities	Selection (any)	Qualitative	Low
Q8. Critical awareness	Selection (any)	0	Very low
Q9. Trust	Scores (5)	0,69	High
Q10. Experience	Selection (1)	0,58	Medium
Q11. Risk perception	Selection (any)	0,50	Medium
Q12. Intentional patterns	Selection (1)	0,66	High
Q13. Behavioural patterns	Selection (1)	0,64	High
Q14. Preparation measures	Selection (any)	Qualitative	Medium

Q15. Community participation	Scores (5)	0,67	High
Q16. Active stakeholders	Open question	Qualitative	Not applicable
Q17. Partnerships structure	Scores (3)	Qualitative	Low
Q18. Partnership benefits	Selection (any)	Qualitative	Not applicable
Q19. Partnership challenges	Selection (any)	Qualitative	Not applicable
Q20. Adequacy of policy options	Scores (5)	0,26	Low

High storm surge impacts are expected in Dithmarschen, the higher damages being related to the infrastructural and socio-economic dimensions. To some extent there is some storm surge risk-related information available but it is not enough for raising awareness in the society and for a better preparedness. The information that should be improved concerns (i) the potential impacts of a major storm surge event, (ii) preparedness/recovery options, (iii) responsible authorities of the different tasks within storm surge risk management, and (iv) the consideration of storm surge risk in sectoral planning. Warning mechanisms are known by the stakeholders, some new additional having been suggested.

A clear reflect of the risk culture of the area is shown by a higher credibility and trust levels on engineering-based protection measures, than on soft protection and spatial planning measures, as well as on authorities and teams. The stakeholders have some experience with major storm surge events, and storm surge risk is indeed perceived in Dithmarschen, as the 75% of the respondents feel personally threatened as their living/working activities are located at a potentially flooded area; and around the half feels that his/her sector is threatened and that it could be potentially disrupted. Nevertheless, few stakeholders are looking for information to better cope with the storm surge hazard.

Despite the experience and the risk perception, storm surge is not considered an urgent/important problem by the stakeholders. It could be discussed that only daily problems such as livelihood-related difficulties or demographic change and migration are highlighted; however, climate change appears as the third most important problem for the stakeholders, which suggests the important role and effectiveness of climate change awareness campaigns worldwide and the lack of them for storm surge hazard in particular. The fact of not considering storm surges as an urgent problem may be the cause for the prevalence of temporary short-term protection measures to cope with it. Besides cost/time constraints, a lack of authorities and insurance support to accomplish temporary protection and evacuation measures, as well as insurance support could be identified as an important obstacle in order to increase resilience against storm surges in Dithmarschen.

Most of the respondents prefers a participatory risk management and shows a proactive behaviour in risk reduction (68% and 75%, respectively), though fully participatory schemes are not yet established by the authorities. Most of the stakeholders works with others to solve common problems, although more support from authorities is expected in terms of community participation and involvement. However, a lack of awareness about the relevance/usefulness of the integrated approach and the vertical and horizontal coordination, i.e. various administrative levels and various sectors respectively, is recognized when asked about the structure of this potential partnership. There is a high consensus on the involvement of those stakeholders related to the emergency and coastal protection in a potential partnership. The highest disagreements are related to the involvement of sectoral stakeholders (such as the agriculture/livestock, tourism and industry private sectors), the environmental stakeholders and the NGOs. The involvement of authorities also counts with some disagreement. Therefore, if multi-sector-partnerships are to be fostered in the region, previous awareness campaigns should be promoted regarding the relevance of the mentioned integrated approach. Several stakeholders have been identified as already active on risk reduction, which should be definitely considered in potential participatory approaches and partnerships. Finally, regarding potential policy options and economic instruments to cope with the storm surge, around the half of the respondents rated very inadequate/inadequate all of the measures that were offered as an answer. Strong disagreement of the involved stakeholders with currently discussed and proposed measures and instruments highlights the need for tailored and site-specific potential economic instruments and adaptation measures for Dithmarschen. This need represent a major future challenge in storm surge management.

5.4 Conclusions

A resilient society is aware of the hazard, is prepared for its impacts and is able to recover, these capacities referring to both institutional and social spheres of the community. A conceptual and methodological framework is proposed to understand the factors affecting the resilience of a community exposed to risks from natural hazards. The framework shows the linkages between the institutional, social and legal dimensions within risk management to enhance community preparedness, emergency management and long-term adaptation. The proposed survey-based method and the specific resilience questionnaire allows exploring the perception of stakeholders regarding the risk and emergency management processes as well as psychological and social factors conditioning individual and community preparedness.

Both framework and questionnaire could be applied worldwide, although some questions may need some adaptation to fit adequately to other risks and study sites. The application to storm surge risks at the Dithmarschen district in the German North Sea Coast has been presented here. The assessment carried out in the pilot case permitted to identify the main characteristics of the study area in terms of stakeholders' risk perception, individual/collective intention to prepare and behavioural patterns, as well as their opinion regarding the authorities' decision-making. This provided a very useful insight about the risk culture of the area to guide future site-specific options for enhancing its resilience.

Both institutional and social preparedness are analyzed since a failure or a shortage/deficit of a specific ability in one of them could turn the risk management and/or the emergency process partially ineffective or invalid for the worst case. The deficiencies and the incoherencies between society's and administration's answers detected in the analysis point towards the challenges to tackle in order to foster an adequate community preparedness and adaptation to storm surge risk. As an example, some of the results obtained from the pilot study in Dithmarschen analyzed in this work show (i) the need for a better information strategy in some specific topics in order to enhance society's awareness and preparedness; (ii) the respondents' current proactive behaviour and preference on participatory risk management options, despite fully participatory schemes are not yet set by the authorities; (iii) the need for awareness campaigns regarding the relevance and benefits of the integrated approach in potential partnerships, and (iv) the need for tailored and site-specific adaptation instruments and measures due to the current disagreement of society with some of the options provided. This type of results is very useful to improve risk reduction initiatives by means of including society's opinions from the beginning of the management process.

The various conclusions on the risk culture, perception and preparedness of the study area validate the usefulness of the questionnaire applied to enhance community resilience and risk reduction. The conceptual framework and method presented will be replicated along the region of the Wadden Sea, including the Dutch, German and Danish North Sea Coast, in the framework of the ongoing FP7 ENHANCE Project.

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Chapter 6. Summary of scientific articles (in Spanish)

6.1 Introducción

De acuerdo a la normativa para la elaboración de tesis doctorales como compendio de artículos en el Departamento de Ciencias y Técnicas del agua y del Medio Ambiente (CYTAMA) de la Universidad de Cantabria, se presenta en este capítulo un resumen en español de los artículos publicados en otro idioma (en este caso, inglés) y que se listan a continuación.

- González-Riancho et al.: Integrated tsunami vulnerability and risk assessment: application to the coastal area of El Salvador, Nat. Hazards Earth Syst. Sci. 14:1223–1244, 2014.
- González-Riancho et al.: Tsunami evacuation modelling as a tool for risk reduction: application to the coastal area of El Salvador, Nat. Hazards Earth Syst. Sci. 13:3249-3270, 2013.
- González-Riancho et al.: 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). *Nat. Hazards Earth Syst. Sci., enviado en septiembre 2014, en revisión.*
- González-Riancho et al.: Storm surge risk perception and resilience: a pilot study in the German North Sea Coast. *Ocean & Coastal Management OCMA-D-14-00389, en revisión.*

Los resúmenes son lo suficientemente extensos para poder evaluar el contenido y la calidad de los mismos y cuentan con una estructura homogénea que incluye título y autores, antecedentes y objetivos, metodología y resultados, y conclusiones.

6.2 Integrated tsunami vulnerability and risk assessment (scientific article 1)

6.2.1 Título y autores

Evaluación integrada de la vulnerabilidad y el riesgo ante tsunami: aplicación a la zona costera de El Salvador (*Integrated Tsunami Vulnerability and Risk Assessment: application to the coastal area of El Salvador*)

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6.2.2 Antecedentes y objetivos

Los avances en el conocimiento y la predicción de los impactos debidos a potenciales tsunamis facilitan el desarrollo de estrategias de reducción de riesgos en zonas propensas a este tipo de eventos. Actualmente se están consiguiendo grandes progresos en la evaluación del riesgo ante tsunami, tanto para caracterizar correctamente el evento físico en sí como para la identificación de las zonas expuestas y de las comunidades y elementos más vulnerables, siendo estos resultados científico-técnicos críticos para la formulación de medidas de reducción de riesgo específicas para cada lugar.

Se muestra en el artículo una revisión de los trabajos existentes en el ámbito de los riesgos naturales, los cuales difieren según el componente del riesgo analizado (amenaza, exposición, vulnerabilidad, impactos, resiliencia, capacidad de respuesta, etc.), la dimensión del riesgo tratado (humana, de infraestructuras, ambiental, social, económica, etc.), y la escala espacial abordada (regional, nacional, local, etc.), lo que manifiesta la complejidad asociada a la evaluación y gestión de riesgos. Tal como refleja la variedad de trabajos revisados, las evaluaciones de vulnerabilidad y riesgo pueden perfectamente ser parciales, sectoriales o específicas, sin embargo, la gestión del riesgo requiere una comprensión integrada y holística del sistema socio-ecológico (*Coupled Human And Natural System*, CHANS) evaluado; de lo contrario las alternativas de gestión propuestas pueden producir resultados inesperados e incluso no deseados.

Según Rotmans y Dowlatabadi (1998), la evaluación integrada tiene como objetivo combinar, interpretar y comunicar el conocimiento de diversos campos científicos con el fin de abordar de manera sostenible un problema ambiental, destacando sus vínculos de causa-efecto en su totalidad. La integración se refiere en este trabajo a la comprensión y la combinación de los componentes, dimensiones y escalas del riesgo que afectan a un CHANS, debidos principalmente a la complejidad de la vulnerabilidad, y siendo uno de los principales desafíos la combinación sistemática y la agregación de diferentes tipos de datos e información proveniente de diversas disciplinas, escalas y metodologías de adquisición de datos (cuantitativa versus cualitativa).

La vulnerabilidad es multidimensional y diferencial, ya que varía tanto en el espacio físico como entre grupos sociales y dentro de los mismos; es dependiente de la escala temporal y espacial; y es dinámica, debido a la variabilidad temporal de los factores que la generan (Vogel y O'Brien, 2004). La literatura actual abarca varias definiciones, marcos conceptuales y métodos de sistematización de la vulnerabilidad (Birkmann, 2006), incluyendo muchos de ellos referencias claras a su multidimensionalidad. Sin embargo, existe muy poca información relativa a la aplicación práctica de los diferentes marcos teóricos y conceptuales y a la integración de los diferentes conceptos relacionados con el riesgo. Por otra parte, los resultados de la evaluación de riesgo no suelen ofrecer una traducción metódica y directa hacia la reducción del riesgo en las áreas identificadas, es decir, carecen de una clara correlación entre la evaluación y la gestión del riesgo. La principal contribución de este trabajo es la propuesta de un método claro y directo para facilitar la aplicación de algunos de los mencionados conceptos teóricos al estudio de casos prácticos, ya que multitud de veces es complicado debido a problemas específicos de la zona de estudio, la falta de datos o la falta de información sobre determinados aspectos metodológicos.

Los objetivos de este trabajo son (i) la propuesta de un marco para la evaluación integrada de la vulnerabilidad y el riesgo ante tsunami y su aplicación para el caso de estudio de El Salvador, teniendo en cuenta los diferentes componentes, dimensiones y escalas espacio-temporales del riesgo así como el proceso metodológico para integrarlos; y (ii) el establecimiento de una conexión clara para traducir los resultados de vulnerabilidad y riesgo en medidas concretas de reducción de riesgo, tratando de conectar ciencia y gestión en el ámbito del riesgo ante tsunami.

6.2.3 Metodología y resultados

La Figure 6.1 muestra el proceso propuesto para integrar componentes y dimensiones del riesgo en cada escala espacial estudiada. De acuerdo con las directrices presentadas en el documento *Risk Assessment and Mapping Guidelines for Disaster Management* (EC, 2010), se proponen dos tipos de resultados, parciales y agregados. Los primeros permiten analizar los impactos por separado para las diferentes dimensiones y componentes, mientras que el segundo combina todas las dimensiones. Según UNESCO (2009b), el riesgo puede ser mitigado mediante la reducción de la vulnerabilidad y mejorando la preparación. En el trabajo que aquí se presenta, esto se traduce en la formulación de medidas de gestión del riesgo para reducir la exposición parcial y la sensibilidad, y para mejorar la resiliencia a nivel municipal.

Como se muestra en la figura a través de las flechas de color, la construcción de los índices de agregados - es decir, la exposición, la sensibilidad y la vulnerabilidad, se lleva a cabo mediante la agregación ponderada (flechas verticales de color azul), mientras que el cálculo del riesgo, tanto los resultados parciales y agregados, se lleva a cabo a través de la matriz de riesgo (flechas horizontales rojas). La principal ventaja de este enfoque es la generación de los resultados parciales y agregados, así como la posibilidad de desagregarlos de nuevo en componentes, dimensiones e indicadores de riesgo, a fin de comprender la causa precisa de los resultados obtenidos, y de ese modo proporcionar información esencial para la gestión del riesgo (flechas negras).

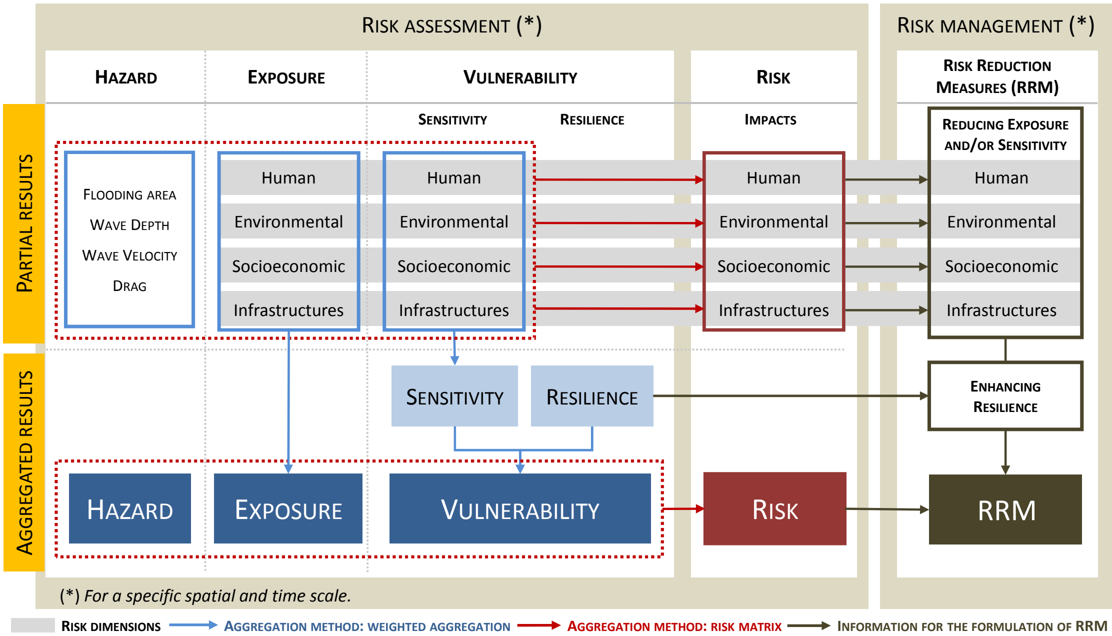

Figure 6.1. Marco para la evaluación del riesgo y diferentes tipos de resultados (RRM = medidas de reducción del riesgo).

La Table 6.1 muestra la estructura concreta aplicada para la evaluación del riesgo ante tsunami en el caso de estudio de El Salvador. Esta estructura se fundamenta en las consecuencias esperadas, que son de interés para el Ministerio de Medio Ambiente y Recursos Naturales (MARN) de El Salvador, y que son establecidas con anterioridad. Los indicadores de vulnerabilidad se definen.de acuerdo a estas consecuencias.

Table 6.1Estructura de la evaluación del riesgo ante tsunami aplicada en la costa de El Salvador

Riesgo			Amenaza			Exposición	Vulnerabilidad	
Consecuencias	Escala temporal	Escala espacial	Probabilidad	Dinámicas	Amenaza	Elementos expuestos	Sensibilidad	Resiliencia
Pérdida de vidas debido a: • movilidad reducida • dificultades para entender un mensaje de alerta • viviendas frágiles y falta de capacidad de recuperación • dificultades para recibir una alerta y evacuar en zonas mal conectadas • dificultades asociadas a una evacuación coordenada	Anual Estacional	Nacional Local	Análisis determinista (agregación de los 23 peores casos creíbles de tsunami)	Fuentes tsunamigénicas Nivel del mar Ola de tsunami Mareas	Arrastre	Personas	Grupos de edad sensible Analfabetismo Pobreza extrema Discapacidad (física/intelectual) Aislamiento Evacuación crítica	Información y concienciación Alerta y evacuación Respuesta de emergencia Recuperación post-desastre
Pérdida de ecosistemas protegidos Pérdida de ecosistemas únicos (arrecifes) Pérdida de servicios ecosistémicos (manglares) Pérdida de especies en peligro de extinción Destrucción permanente de los ecosistemas	Anual Estacional	Nacional Local			Área inundada	Ecosistemas	Protección Singularidad Amenaza Degradación	
Pérdida de área de actividades socioeconómicas Pérdida de puestos de trabajo Pérdida de producto interno bruto (PIB) Pérdida de comercio exterior	Anual	Nacional Local			Área inundada	Actividades socioeconómicas	Generación de empleo Contribución al PIB Contribución al comercio exterior	
Contaminación de pozos dificultando el suministro de agua a las comunidades locales a largo plazo Pérdida de rutas de evacuación esenciales Generación de impactos en cascada debido a industrias peligrosas Pérdida de servicios de emergencia y de salud, esenciales durante el evento	Anual	Nacional Local			Área inundada	Infraestructuras	Abastecimiento de agua (pozos) Carreteras Industrias peligrosas Infraestructura de salud/emergencia	
Impactos en edificios críticos (gran número de población) Pérdida de potenciales refugios verticales Destrucción de edificios	Anual	Local			Profundidad	Edificios	Edificios críticos Evacuación vertical Materiales de los edificios	

Evaluación de la amenaza

La evaluación de la amenaza se basa en modelos de propagación de tsunamis generados por terremoto. Para realizar el modelado se han caracterizado las fuentes tsunamigénicas (fallas sismotectónicas) y otras dinámicas como las olas del tsunami, el nivel del mar, etc. Se han desarrollado varias simulaciones de tsunamis históricos y potenciales con mayor o menor impacto sobre la costa del país, incluidas las fuentes lejanas (a distancias superiores a 2000 km de la costa, con tiempos de viaje del tsunami mayores que 4 h), fuentes regionales (entre 700 y 2000 km, con tiempos de viaje del tsunami entre 1 y 4 h), y fuentes locales (ubicadas en la fosa de subducción frente a la costa del país, con tiempos de viaje de menos de una hora).

A partir de estas simulaciones, se ha desarrollado un análisis determinista que agrega los 23 peores casos creíbles de tsunamis que podrían impactar en la costa salvadoreña, obteniendo como resultado diferentes mapas de riesgo a lo largo de toda la costa de El Salvador así como análisis de alta resolución en algunos lugares relevantes. Los mapas generados incluyen el área inundada, la elevación máxima de la altura de ola, la profundidad máxima de la columna de agua, el tiempo mínimo de llegada del tsunami, el nivel máximo de inundación o "run-up", y el máximo potencial de arrastre (entendido como el nivel de riesgo asociado a la inestabilidad del ser humano en base a la velocidad del agua incipiente y la profundidad).

Evaluación de la vulnerabilidad y el riesgo

El área inundada calculada anteriormente permite localizar, inventariar y caracterizar los elementos expuestos en las cuatro dimensiones (humana, ambiental, socioeconómica y de infraestructuras). La evaluación de la exposición identifica por tanto los elementos situados en el área de la amenaza, mientras que la evaluación de la vulnerabilidad mide aquellas características de estos elementos expuestos que los hacen susceptibles de sufrir los impactos seleccionados o de interés. Se ha propuesto y desarrollado un set de indicadores (Table 6.2) para calcular la exposición y la sensibilidad ante tsunami para las distintas dimensiones costeras, así como la resiliencia de la sociedad y las comunidades en riesgo. Este set de indicadores ha sido sometido a varios procedimientos matemático-estadísticos con el fin de producir información comparable y combinable, y está reforzado a su vez por un sistema de información geográfica que permite basar cada decisión en información geo-referenciada, siendo una herramienta esencial para la combinación de mapas parciales y particularmente útil para el modelado y planificación de la evacuación.

Table 6.2Indicadores de exposición y vulnerabilidad ante tsunami (N = escala nacional, L = escala local, PIB = producto interior bruto).

Índice agregado	Índices parciales	Indicadores	Variables	Escala espacial
Exposición	Exposición humana	E1 – Población expuesta	Nº de personas permanentemente expuestas	N - L
			Nº de personas temporalmente expuestas (vacaciones)	N - L
	Exposición ambiental	E2 – Ecosistemas expuestos	Área de ecosistemas expuestos	N - L
	Exposición socioeconómica	E3 – Actividades socioeconómicas expuestas	Área de actividades expuestas (agricultura y pastoreo, pesca, acuacultura, turismo, industria, comercio, servicios)	N - L
	Exposición infraestructuras	E4 – Infraestructuras expuestas	Nº de infraestructuras expuestas (agua, energía, tratamiento de residuos, transporte, industrial, emergencia)	N - L
		E5 – Edificios expuestos	Nº de edificios expuestos	L
Sensibilidad	Sensibilidad humana	S1 – Grupos de edad sensible	Nº de personas menores de 10 y mayores de 65 años	N - L
		S2 - Analfabetismo	Nº de personas analfabetas	N - L
		S3 – Pobreza extrema	Nº de personas en condiciones de extrema pobreza	N - L
		S4 - Discapacidad	Nº de personas discapacitadas (física / intelectual)	L
		S5 - Aislamiento	Nº de personas en zonas aisladas	L
		S6 – Evacuación crítica	Nº de personas en edificios críticos	L
	Sensibilidad ambiental	S7 - Protección	Área de ecosistemas protegidos	N - L
		S8 - Singularidad	Área de ecosistemas singulares (servicios ecosistémicos)	N - L
		S9 - Amenaza	Área de ecosistemas amenazados	N - L
		S10 - Degradación	Área de ecosistemas degradados	L
	Sensibilidad socioeconómica	S11 – Generación de empleo	Nº de trabajadores por actividad	N - L
		S12 – Contribución al PIB	Millones de dólares aportados por actividad	N - L
		S13 - Contribución al comercio exterior	Millones de dólares aportados por actividad	N - L
	Sensibilidad infraestructuras	S14 – Infraestructuras críticas	Nº de infraestructuras de abastecimiento de agua (pozos)	N - L
			Nº de infraestructuras de transporte (evacuación)	N - L
			Nº de infraestructuras peligrosas	N - L
			Nº de infraestructuras de emergencia	N - L
		S15 – Edificios críticos	Nº de edificios críticos (hospitales, colegios, hoteles, centros comerciales, estadios, iglesias, etc.)	L
		S16 – Evacuación vertical	Nº de edificios con menos de 3 plantas	L
		S17 – Materiales de los edificios	Nº de edificios no resistentes	L
Resiliencia	Resiliencia	R1 – Capacidad de respuesta	Nivel de información y concienciación	N - L
			Nivel de alerta y evacuación	N - L
			Nivel de respuesta de emergencia	N - L
		R2 – Capacidad de recuperación	Nivel de recuperación post-desastre	N - L

Los *indicadores de sensibilidad humana* están orientados a medir las debilidades de los municipios en materia de evacuación y de las capacidades recuperación de la población expuesta. Los *indicadores de sensibilidad ambiental* tienen como objetivo evaluar los posibles impactos ambientales por municipio en términos de pérdida de los ecosistemas y consiguiente pérdida de servicios ecosistémicos y modos de vida asociados. Los *indicadores de sensibilidad socioeconómica* están orientados a medir los potenciales impactos sociales y económicos por municipio en base a la pérdida de empleos por actividad socio-económica afectada, y la pérdida de ingresos a nivel de hogar y a nivel de país. Los *indicadores de sensibilidad de infraestructuras* miden el número de infraestructuras críticas y los edificios que se verían afectados por el municipio, así como las consecuencias para la población. El término crítico se emplea en aquellas infraestructuras que, si se vieran afectadas, agravarían el impacto sufrido, tanto durante como tras el evento. Así, se identifica el número potencial de pozos contaminados que dificultarían el suministro a largo plazo de agua a las comunidades locales, la pérdida de las rutas de evacuación esenciales, la generación de impactos en cascada debido a la afección a industrias peligrosas/peligrosas, y la pérdida de los servicios de emergencia y de salud que son imprescindibles durante el evento. Se calcula también el número de edificios que requieren una evacuación coordinada y planificada con anterioridad, debido al gran número de personas (en algunos casos población sensible) que albergan, como hospitales, escuelas, geriátricos, centros comerciales, estadios, iglesias, hoteles, etc. Se mide asimismo el número de edificios no adecuados para refugiar a la población, debido a un número de pisos insuficiente o a materiales de construcción frágiles.

La *resiliencia* de una comunidad con respecto a potenciales amenazas se refiere a la capacidad de la comunidad para acceder a los recursos necesarios para hacer frente a la amenaza, absorber las perturbaciones y volver a organizarse en un sistema en pleno funcionamiento (Cutter et al. 2008). En otras palabras, la resiliencia se refiere a la capacidad de una comunidad para organizarse antes, durante y después del evento con el fin de minimizar los impactos. Para poder medir la resiliencia se evalúan dos indicadores, la capacidad de respuesta (*coping capacity*) y la capacidad de recuperación (*recovery capacity*), mediante el análisis de la gestión de emergencias (información y sensibilización, alerta y evacuación, respuesta de emergencia y recuperación de desastres). La recopilación de datos para la construcción del índice resiliencia se ha realizado a través de un breve cuestionario que identifica el grado de organización y respuesta dentro de una comunidad en caso de una emergencia.

El método para la integración de los distintos conceptos de riesgo tiene varios pasos: construcción de indicadores normalizados, construcción de índices parciales y agregados a través de agregaciones ponderadas, clasificación de índices mediante el método Natural Breaks, y evaluación de riesgos utilizando la matriz de riesgo que combina las clases obtenidas para la amenaza y la vulnerabilidad. Una vez que se identifican los municipios con mayores valores de riesgo, se calculan impactos específicos a nivel local para cada dimensión.

Se presentan a continuación algunos de los resultados obtenidos, si bien la totalidad de resultados así como el análisis detallado de los mismos aparece en el artículo. La Figure 6.2 muestra los resultados de vulnerabilidad obtenidos a escala nacional. Los municipios se han organizado geográficamente en las gráficas, lo que facilita la comparación de los resultados numéricos y cartográficos. La Figure 6.3 muestra algunos de los resultados relativos a impactos específicos a escala local.

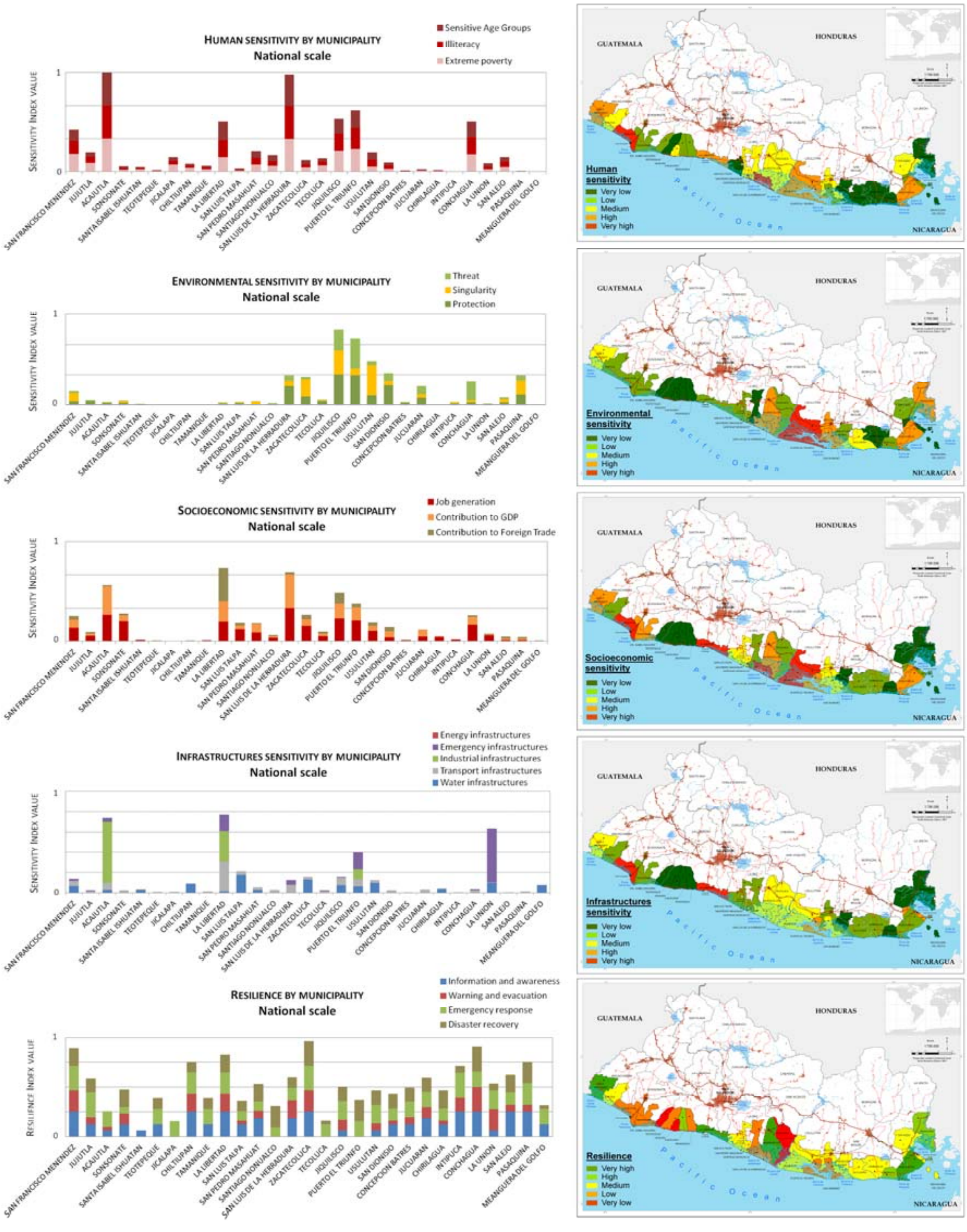

Figure 6.2 Resultados de vulnerabilidad ante tsunami en los municipios costeros de El Salvador: (de arriba abajo) humana, ambiental, socioeconómica, de infraestructuras y resiliencia.

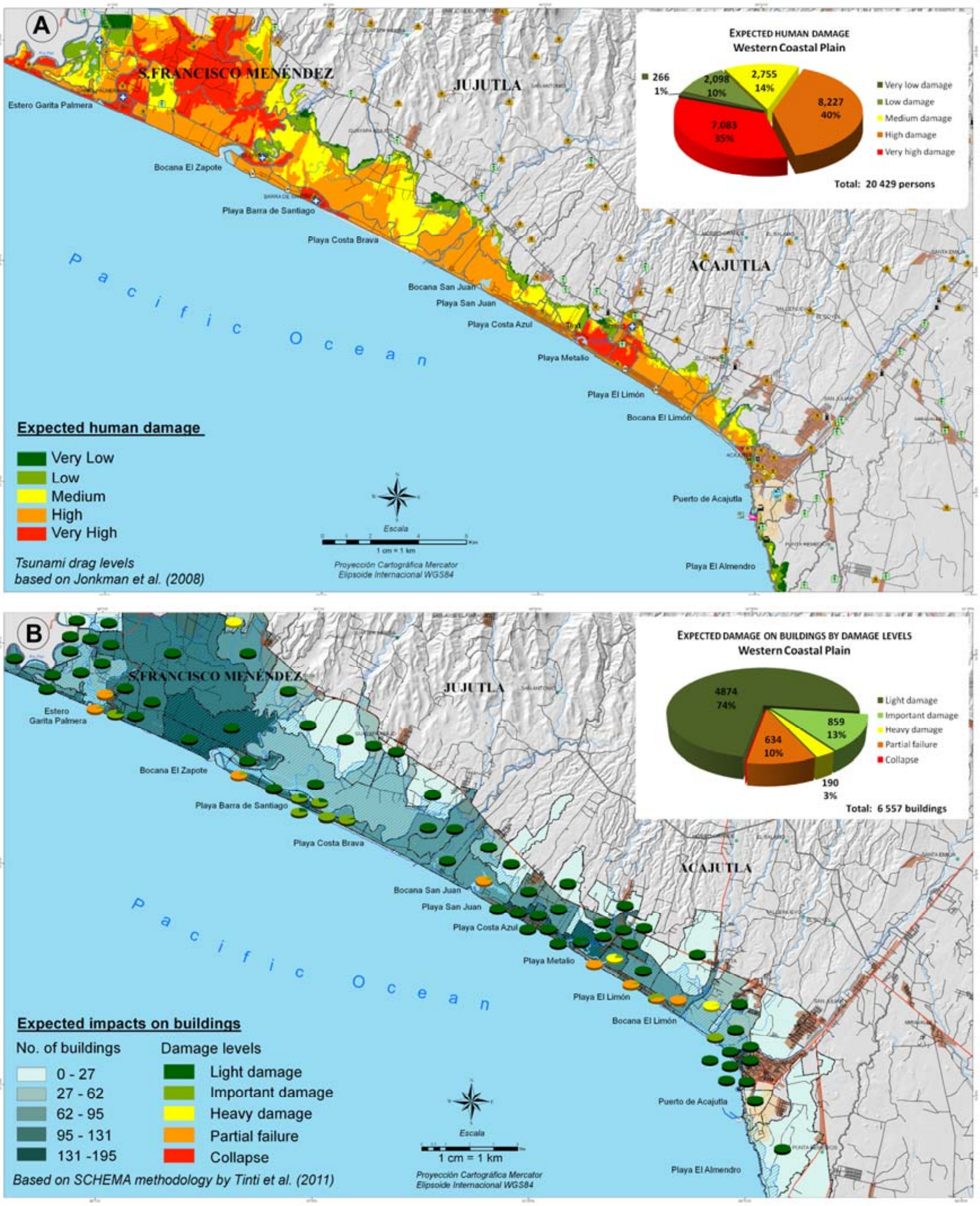

Figure 6.3 Impactos esperados en la llanura costera occidental de El Salvador por segmento censal: (a) zonificación de daños humanos esperados, (b) impactos esperados en edificios.

Gestión del riesgo ante tsunami

Los estudios científico-técnicos sobre evaluación de riesgos se caracterizan frecuentemente por una estructura lineal que va desde el análisis de la amenaza y la vulnerabilidad hasta el cálculo final de riesgo, proporcionando muy pocos de ellos opciones específicas para la reducción del mismo. Esta estructura lineal y la falta de una relación clara y directa con la gestión del riesgo de desastres (DRM) pueden dificultar o imposibilitar la implementación por parte de los beneficiarios de los trabajos de muchos de los resultados científico-técnicos generados en proyectos y que son esenciales para reducir el riesgo.

Esta sección se centra en cómo potenciar el valor de los conocimientos científico-técnicos generados en la evaluación del riesgo para poder traducir los resultados a algo más próximo a las alternativas de gestión que necesita el gestor o responsable de la toma de decisiones. Se presenta un marco conceptual que muestra (Figure 6.4) cómo el proceso de evaluación del riesgo alimenta directamente los distintos pasos requeridos en el proceso de gestión del mismo y cómo una vez que se identifica la conexión entre ambos procesos, la estructura de los estudios se reorienta con el fin de tener la DRM como objetivo principal. El marco conceptual, en forma de diana, permite entender que cuanto más cerca del centro de la diana llega un estudio más útil será para los gestores. Se muestra en esta sección un ejemplo de estructura de planificación basada en los resultados presentados para El Salvador (Figure 6.5).

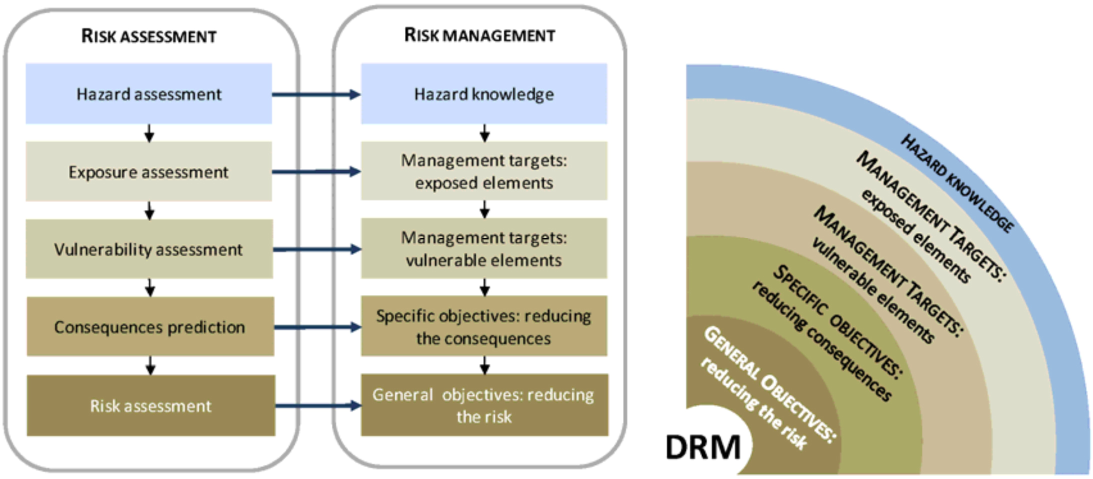

Figure 6.4 Izquierda: traducción de los resultados de vulnerabilidad y riesgo en información para la gestión. Derecha: marco en forma de diana para gestión del riesgo de desastres (DRM).

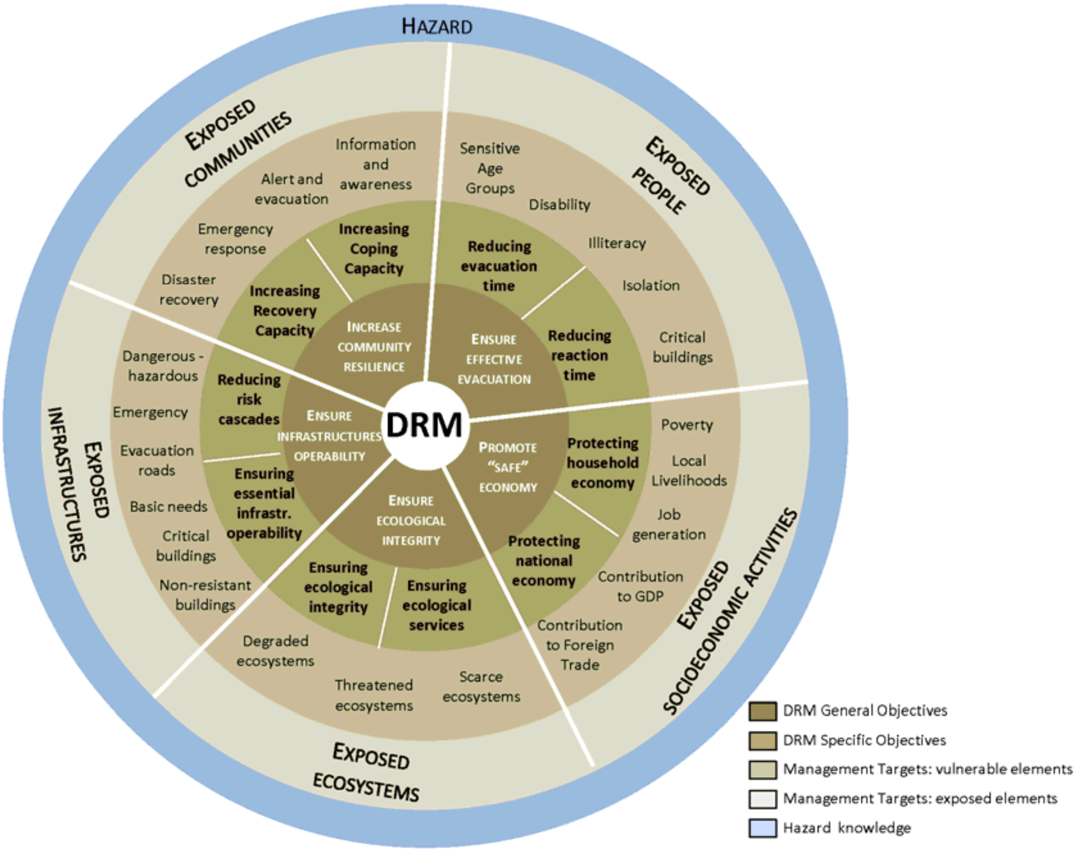

Figure 6.5 Ejemplo de marco de gestión del riesgo ante tsunami para El Salvador.

Según el marco presentado, se proponen medidas específicas de reducción de riesgo para hacer frente a cada uno de los impactos identificados en cada dimensión. Sin embargo, suele ser política y económicamente difícil poner en práctica todos ellos, por lo que se requiere una priorización de las medidas.

La gestión del riesgo de desastres, como proceso complejo, se ocupa de una gran cantidad de información, incluyendo los diferentes tipos de datos sobre las amenazas, elementos expuestos, dimensiones, vulnerabilidades, escalas espacio-temporales, problemas específicos, escenarios, stakeholders, gobernanza, capacidad de recuperación, protocolos de emergencia, sistemas de alerta temprana, etc. Esta información debe ser priorizada adecuadamente para optimizar el proceso de gestión, lo cual implica seleccionar los temas más urgentes y relevantes por resolver y una vez que los primeros objetivos se han cumplido atacar los siguientes. Por lo tanto, después de la definición de la estructura de gestión del riesgo, la siguiente tarea conlleva identificar los factores clave que afectan o controlan el comportamiento del sistema mediante el análisis de la dinámica del sistema (Sterman, 2002, 2006; Meadows, 2008). La dinámica de sistemas permite priorizar elementos mediante la identificación de los *leverage points* o puntos de influencia, que pueden ser utilizados para llevar a cabo importantes cambios en el sistema con el mínimo esfuerzo (Martín García, 2006).

Entender el comportamiento del sistema y las interrelaciones entre los elementos (Figure 6.6a) permite proponer diferentes escenarios de gestión para entender los efectos de la toma de decisiones y para optimizar la DRM. La Figure 6.6b muestra las relaciones causales y los efectos del tsunami parcialmente abordados por 3 ejemplos de medidas de reducción del riesgo: (i) promoción de campañas de información y sensibilización de la población adaptadas a las características de sensibilidad local; (ii) la protección y reforestación de los manglares; (iii) la reubicación o el refuerzo de los edificios e infraestructuras críticas identificadas. Este ejemplo pretende mostrar que una acción individual puede tener muchos resultados en sistemas complejos, siendo esta una idea interesante para promover en la gestión de riesgos.

Trabajar con sistemas complejos es complicado, ya que se deben considerar al mismo tiempo muchos aspectos, dimensiones y variables. Sin embargo, una vez que se entiende el sistema se puede aprovechar esta complejidad para generar mejores resultados con menos esfuerzo. Por lo tanto, la comprensión de sistemas complejos permite la optimización de esfuerzos y conseguir mejores resultados de las medidas de gestión aplicadas. Trabajar con escenarios ofrece la oportunidad de entender el sistema actual, predecir las consecuencias de diferentes medidas de gestión y, en consecuencia, promover planes de reducción de riesgos adecuados para el área estudiada. Permiten, por tanto, una evaluación dinámica de posibles políticas o medidas de gestión y su respuesta a los flujos de retroalimentación existentes.

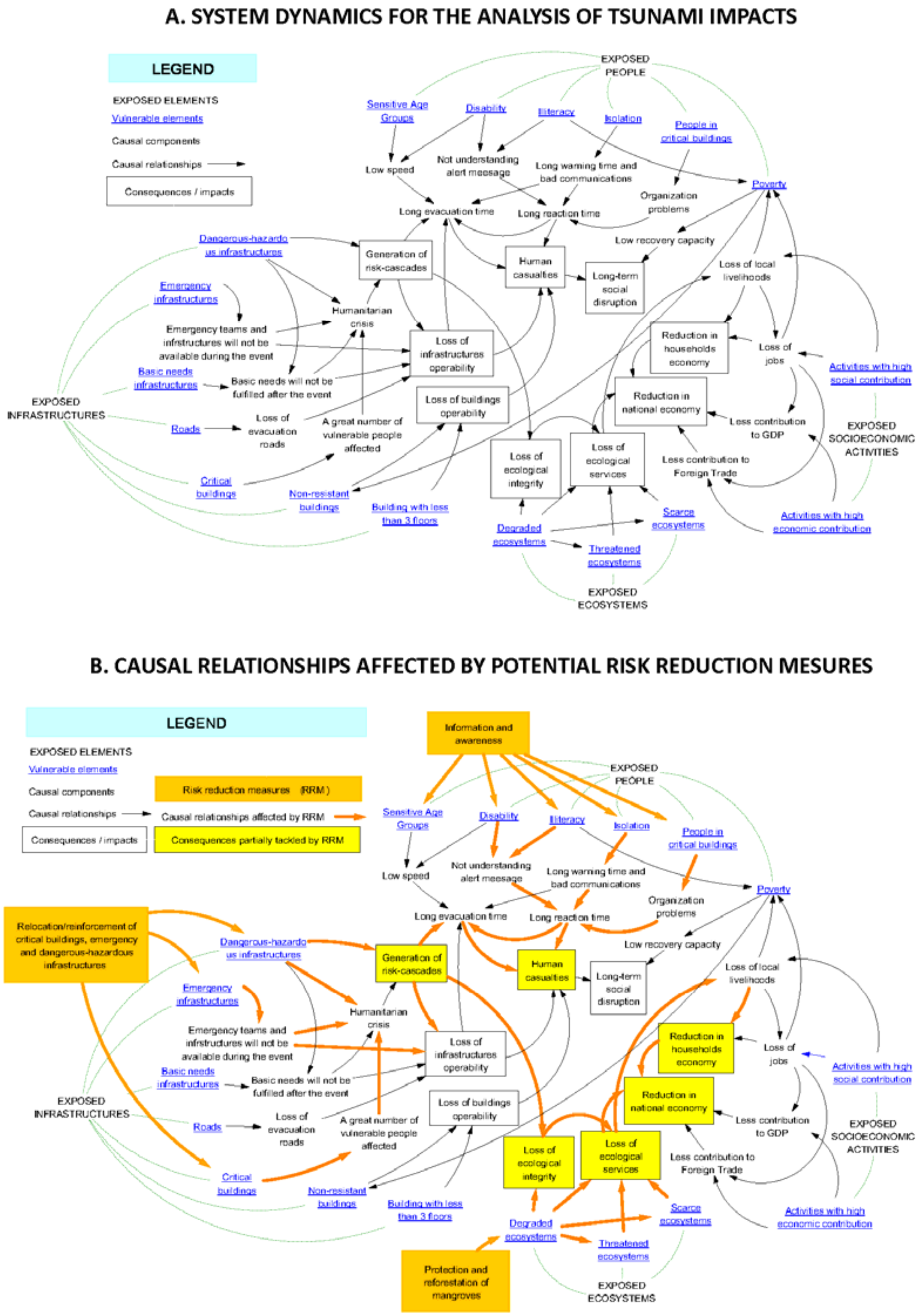

Figure 6.6 (a) Dinámica de sistemas para el análisis de los impactos de tsunami en El Salvador; (b) relaciones causales y reducción de impactos por potenciales medidas de reducción de riesgos (Vensim® Software).

6.2.4 Conclusiones

Los avances en el conocimiento y la predicción de los impactos del tsunami permiten el desarrollo de las estrategias de reducción de riesgos para las zonas propensas a los tsunamis. Sobre la base de los marcos de vulnerabilidad y riesgo existentes, la principal contribución de este trabajo es proporcionar un método que facilite la aplicación de los mismos. El método trata la complejidad y variabilidad de CHANS por medio de un enfoque integral que cubre todo el proceso desde la evaluación hasta la gestión de riesgos; un enfoque integrado para combinar y agregar la información derivada de las diferentes dimensiones; y un enfoque dinámico y dependiente de la escala para integrar la variabilidad espacio-temporal.

La evaluación de riesgos a nivel nacional tiene como objetivo comparar y priorizar los municipios en relación a los esfuerzos necesarios para la reducción del riesgo, mientras que la evaluación en el ámbito local de los municipios priorizados está dirigido a calcular los impactos esperados específicos por dimensión.

La evaluación determinista de la amenaza, basada en la generación del peor caso de tsunami, proporciona diferentes mapas a lo largo de la costa de El Salvador que han permitido identificar las principales áreas expuestas a las inundaciones del tsunami: la llanura costera occidental y el tramo costero entre La Libertad y el municipio de Jucuaran, siendo especialmente relevantes la desembocadura del río Lempa y los humedales de Jiquilisco y Jaltepeque. El enfoque propuesto para medir la exposición y la vulnerabilidad ha demostrado ser útil para identificar y localizar a los elementos en peligro, así como para medir las características humanas, ambientales, socioeconómicas y de infraestructura que hacen los municipios más susceptibles a los impactos seleccionados. La evaluación de la resiliencia, a través de un breve cuestionario, mide el grado de organización y de respuesta dentro de una comunidad en caso de una emergencia y permite comparar el nivel de preparación de los distintos municipios ante un potencial tsunami e identificar las principales carencias sobre las que realizar un análisis más detallado con el fin de corregirlas.

Se ha establecido una conexión clara para traducir los resultados de las evaluaciones de vulnerabilidad y riesgo en medidas concretas y específicas de reducción de riesgo, tratando de conectar ciencia y gestión en el ámbito del riesgo ante tsunami. El enfoque, junto con la dinámica de sistemas, facilita la identificación y priorización de medidas para reducir la sensibilidad y mejorar la resiliencia de los municipios. En cuanto a la aplicación práctica y real de los resultados presentados en este trabajo, varias de las medidas propuestas se están ya desarrollando en El Salvador lideradas por el MARN, contraparte y coautor del trabajo. Algunos ejemplos incluyen los boletines e informes mensuales de peligro de tsunami, campañas de información y sensibilización para las comunidades locales, una red de observadores locales para advertir a las comunidades, en colaboración con el Ministerio y Protección Civil, y los planes de evacuación definidos conjuntamente con las comunidades locales (González-Riancho et al., 2013).

6.3 Tsunami evacuation modelling as a tool for risk reduction (scientific article 2)

6.3.1 Título y autores

Modelado de la evacuación ante tsunami como herramienta para la reducción de riesgos: aplicación a la zona costera de El Salvador (*Tsunami evacuation modelling as a tool for risk reduction: application to the coastal area of El Salvador*)

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6.3.2 Antecedentes y objetivos

La evaluación del riesgo ante tsunami es una tarea esencial para poder identificar las áreas expuestas y las comunidades más vulnerables y formular medidas de gestión específicas para cada lugar y enfocadas a reducir la vulnerabilidad de las mismas, siendo la formulación de planes de evacuación ante tsunami uno de los principales resultados esperados para reducir el riesgo humano. Un plan de evacuación requiere analizar y caracterizar el territorio y una serie de elementos relevantes (relativos a la amenaza, la población, las rutas de evacuación y los refugios), el modelado de la evacuación, y la propuesta de alternativas para las comunidades ubicadas en áreas con limitadas oportunidades para la evacuación. Esta información facilita la toma de decisiones sobre la gestión del riesgo de tsunami.

Los trabajos previos existentes en la literatura cubren distintos aspectos relacionados con el proceso de evacuación ante tsunami, incluyendo (i) el análisis de la amenaza, como el cálculo de la altura de las olas del tsunami, la zona inundada, el run-up, o el tiempo de llegada; (ii) los potenciales impactos humanos relacionados con el tsunami; (iii) el análisis de las características de las rutas como información de entrada para el modelado de evacuación; (iv) la predicción de los impactos sobre edificios mediante funciones de daño; (v) la propia evacuación, incluyendo la identificación de áreas críticas, el cálculo del tiempo de evacuación, o la evaluación de los procedimientos de alerta, etc.; (vi) el desarrollo de software de diseño de evacuación. Habiendo revisado toda esta literatura se puede afirmar que existe escasísima información relativa a la planificación de la evacuación de tsunami.

Con vistas a la planificación adecuada de la evacuación de la población ubicada en un área propensa a los tsunamis, se han detectado varias lagunas en la literatura: (i) no existe una relación directa entre el análisis de los diferentes aspectos relacionados con la evacuación y la formulación de planes de evacuación, a pesar de que suelen establecerse algunas conexiones generales; (ii) no se suele realizar una caracterización de la población a ser evacuada, (iii) el tiempo de evacuación se calcula a veces sin tener en cuenta el tiempo de llegada del tsunami, lo que genera una falta de información sobre el grado de éxito en la evacuación de la población; (iv) a veces no se analiza el tiempo que necesitan las administraciones responsables para emitir la alerta de tsunami y para informar a la población, siendo una información esencial para determinar el tiempo real disponible para evacuar; (v) los resultados del modelado de evacuación no suelen ir concluir a proponer cómo reducir el riesgo de las poblaciones ubicadas en áreas críticas; y (vi) las propuestas de mejoras en el proceso de evacuación son frecuentemente insuficientes, carentes de identificación de lugares potenciales para construir nuevos refugios verticales y rutas de evacuación, y de estrategias de reducción de tiempo de alerta, etc.

Basándonos en este análisis, el objetivo de este trabajo es proponer un marco conceptual y metodológico para eliminar las lagunas técnicas identificadas anteriormente, proporcionando una visión global de lo que se requiere para la adecuada formulación de planes de evacuación, y presentando el modelado de evacuación como una herramienta esencial para la gestión del riesgo. Este marco metodológico propone un enfoque integral para considerar (i) los aspectos de la amenaza (características de inundación de tsunami y el tiempo de llegada), (ii) las características de la zona expuesta (personas, refugios y red viaria), (iii) la actual gestión del riesgo de tsunami (tiempo necesario para advertir a las comunidades locales por parte de las autoridades responsables), (iv) el tiempo de evacuación que necesita la población, y (v) la identificación de medidas para mejorar la evacuación. Por lo tanto, tiene como objetivo conectar evaluación y gestión de riesgos en el ámbito de la evacuación ante tsunami. Se presenta en este documento la aplicación de este marco de trabajo a la zona costera de El Salvador, y en concreto a la llanura costera occidental, junto con una discusión sobre las principales conclusiones.

6.3.3 Metodología y resultados

Los planes de evacuación ante tsunami los desarrollan normalmente las autoridades y gestores responsables de los riesgos en zonas costeras; sin embargo, no existe actualmente una relación clara entre los resultados de las evaluaciones de vulnerabilidad y riesgo y las decisiones de gestión a tomar en base a estos resultados, lo cual se traduciría en un mejor plan de evacuación, y por lo tanto en beneficios para la sociedad. El marco metodológico propuesto para la planificación de la evacuación (Figure 6.7) se divide en 3 fases: análisis, modelización y planificación. Este marco técnico se sustenta a lo largo de sus fases en procesos de participación con comunidades locales, autoridades responsables, protección civil, y organizaciones no gubernamentales relacionadas con las emergencias, entre otros. Estos procesos participativos tienen por objeto (i) informar a los interesados acerca del riesgo ante tsunami y la planificación de la evacuación, (ii) involucrarlos en el proceso general planificación, desde los diseños preliminares hasta la validación de mapas y estrategias de evacuación, (iii) incluir sus conocimientos en el análisis, y (iv) mejorar así los resultados finales de la planificación.

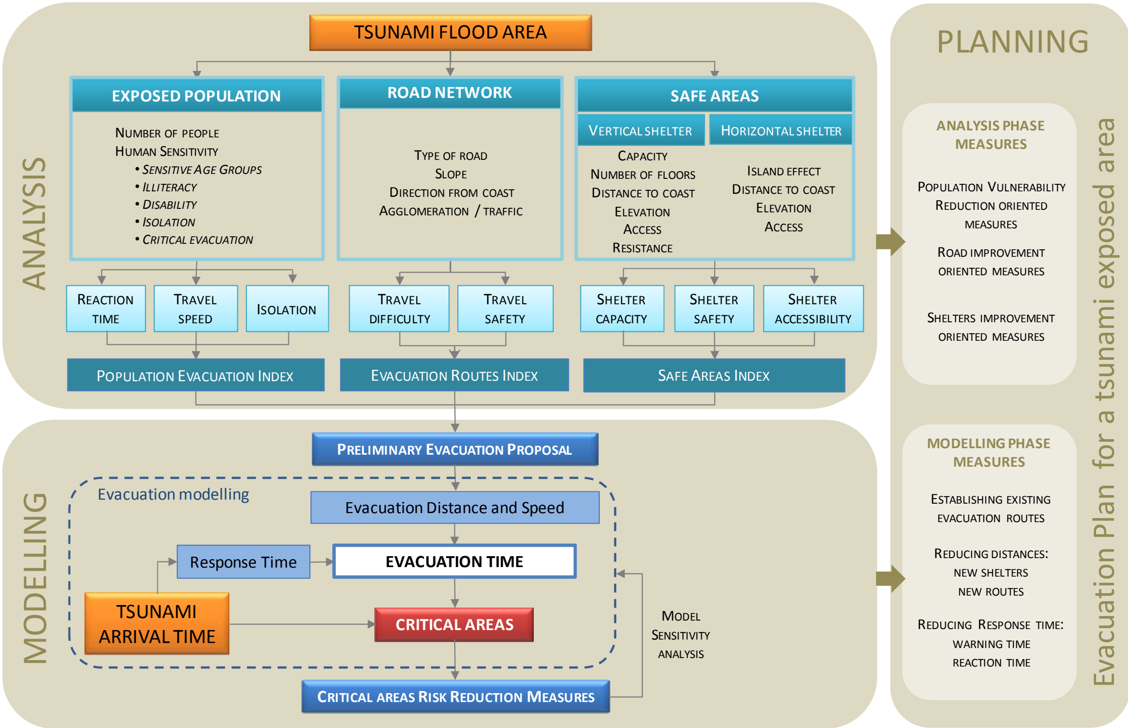

Figure 6.7. Marco de planificación de la evacuación ante tsunami

La fase de análisis tiene como objetivo examinar el territorio y las comunidades expuestas a la inundación de tsunami con el fin de identificar elementos críticos desde el punto de vista de la evacuación. Para ello, se identifica y caracteriza la población, la red de carreteras y la disponibilidad de zonas seguras en el caso de los tsunamis. Estos tres componentes se ponderan y priorizan en función de varios criterios de evacuación (tiempo de reacción, velocidad de desplazamiento y aislamiento de la población expuesta; dificultad y seguridad de la red de carreteras; capacidad, seguridad y accesibilidad de los refugios). Esta priorización permite formular una propuesta preliminar de evacuación que distribuya la población entre los diferentes refugios identificados, y será revisada, discutida y validada con las comunidades locales con el fin de incluir su experiencia, percepción y conocimiento.

La fase de modelado tiene como objetivo perfeccionar y actualizar la propuesta de evacuación preliminar para identificar aquellas áreas críticas en las que la población no sería capaz de evacuar a tiempo y que, por lo tanto, deben ser candidatas prioritarias de medidas de reducción del riesgo. El modelado de evacuación considera las distancias a recorrer y las velocidades de evacuación de la población, el tiempo de llegada del tsunami y los procedimientos actuales de gestión de riesgo, como el tiempo requerido para dar la alerta y el tiempo de reacción de la población. Esta información se obtiene a través de la participación de las autoridades competentes, con el fin de incluir su experiencia y conocimiento acerca de los protocolos de alerta existentes y las principales dificultades a las que se enfrentan en situaciones de emergencia. Una vez que se han identificado las áreas críticas, se proponen alternativas para reducir el riesgo bien mediante la reducción de las distancias a recorrer y / o el incremento del tiempo disponible para la evacuación. Estas propuestas se modelan para garantizar que las áreas críticas se reducen gradualmente, repitiendo este proceso hasta que se eliminan totalmente.

La fase de planificación tiene como objetivo recopilar toda la información que se produce en el las fases de análisis y modelado como inputs para un plan integral de evacuación ante tsunami. El análisis de la población expuesta se traducirá en medidas para asegurar la correcta evacuación de toda la población, mediante la reducción de las limitaciones producidas por el tiempo de reacción, la velocidad de desplazamiento y el aislamiento de las comunidades. El análisis de la red de carreteras y las zonas seguras se traducirá en medidas para mejorar ambos elementos, mediante el aumento de la capacidad, la seguridad y la accesibilidad de rutas y refugios. El modelado de evacuación permitirá identificar la necesidad de reducir las distancias a recorrer por la población, el tiempo de respuesta de las autoridades (detección, análisis y alerta) y el tiempo de reacción de la población. Este marco permite la planificación y una gestión iterativa y adaptativa, ya que la aplicación las medidas antes mencionadas permitirá llevar los tres índices de evacuación (índice de evacuación de la población, índice de rutas de evacuación e índice de zonas seguras) gradualmente hacia a su estado óptimo.

En base a este marco, el artículo se estructura en dos capítulos, mostrando primero el desarrollo metodológico y aplicándolo posteriormente a la costa oeste de El Salvador. Ambos capítulos se dividen a su vez en seis secciones:

- identificación del área potencial inundada por el tsunami (Figure 6.8),
- análisis de la población expuesta (Figure 6.9),
- análisis de las zonas de seguridad (Figure 6.10) y las rutas de evacuación (Figure 6.11),
- cálculo de los tiempos de llegada de tsunami y de evacuación (Figure 6.12)
- modelado de la evacuación (Figure 6.13)
- propuesta de alternativas para áreas críticas (Figure 6.14)
- plan de evacuación (Table 6.3 Estructura de un plan de evacuación ante tsunami.Table 6.3).

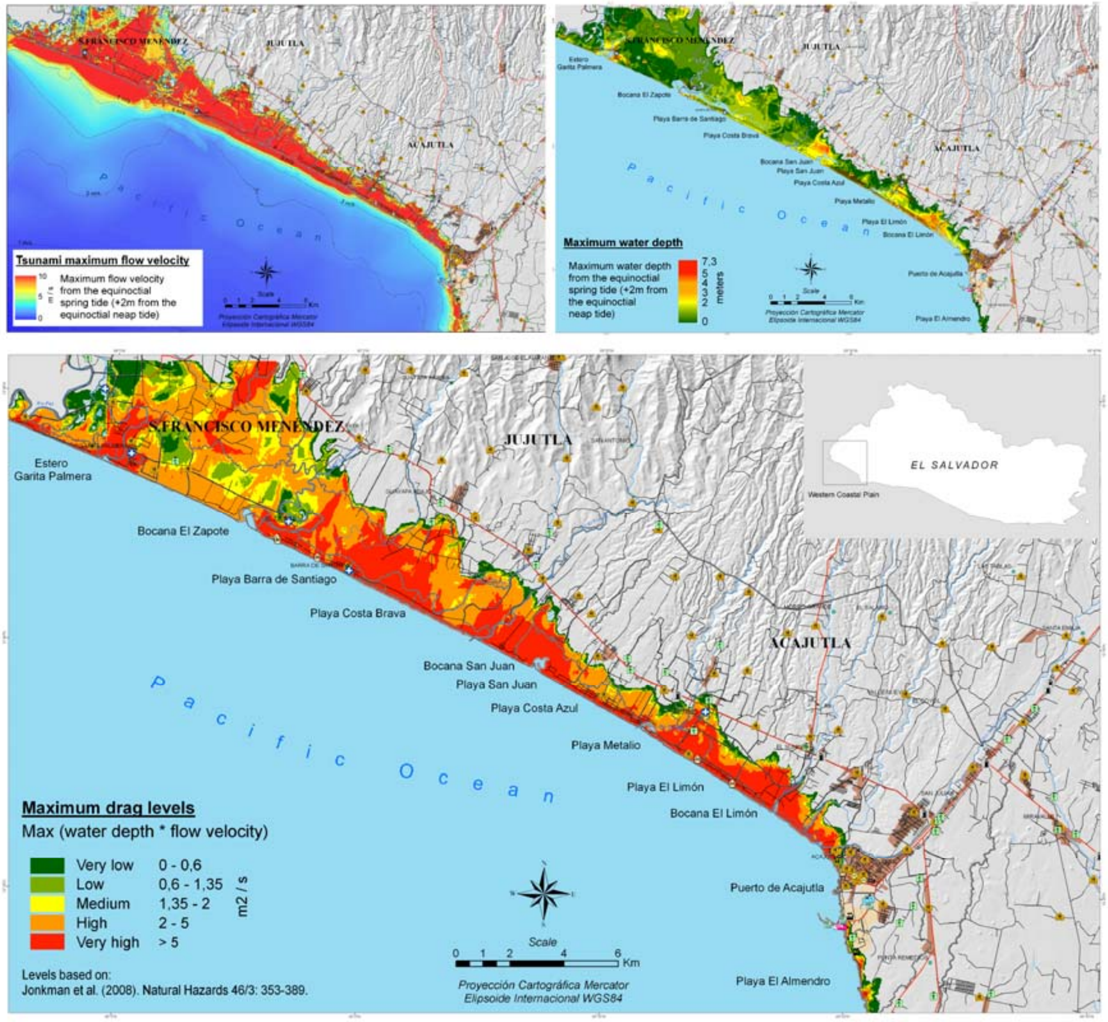

Figure 6.8 Mapas de riesgo para la llanura costera occidental de El Salvador: velocidad máxima de flujo (arriba a la izquierda), profundidad máxima del agua (arriba a la derecha) y arrastre máximo (abajo).

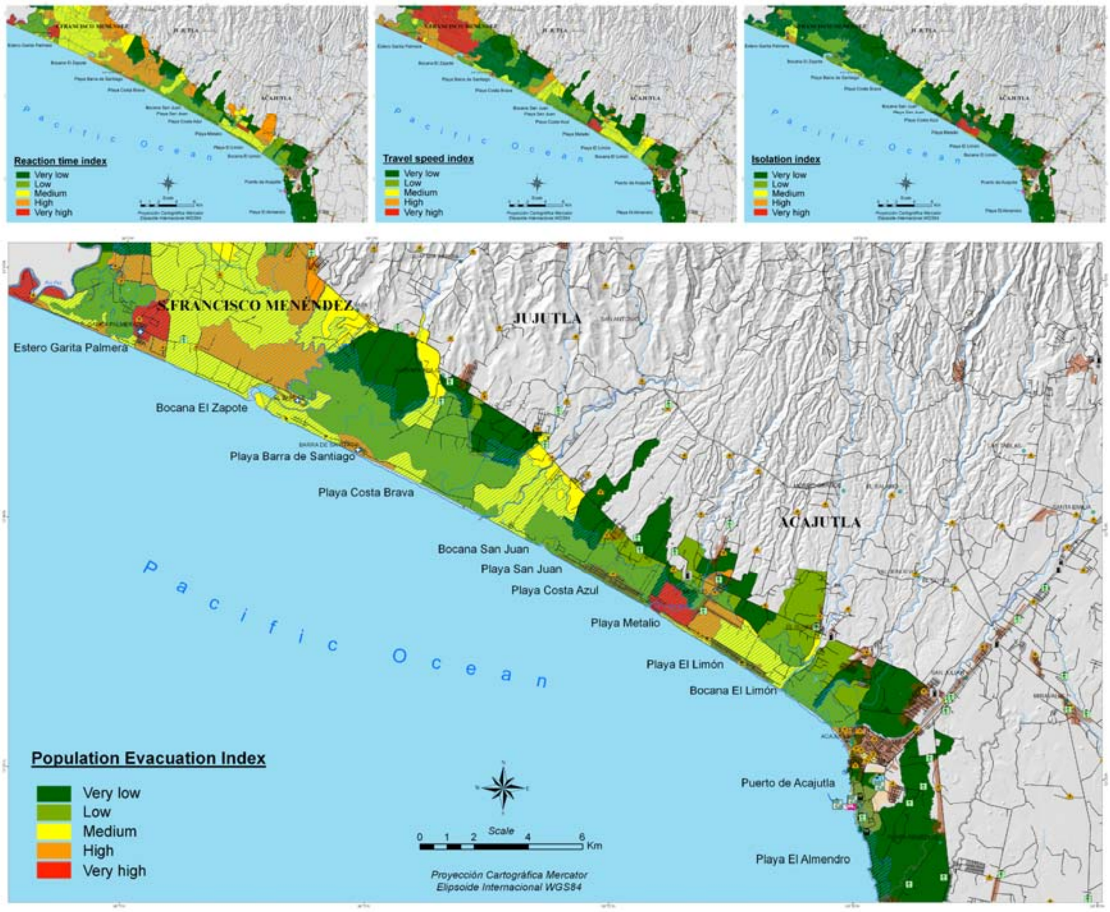

Figure 6.9 Índice de Evacuación de Población (PEI) e índices relacionados: tiempo de reacción, velocidad de desplazamiento y aislamiento (arriba de izquierda a derecha) - Llanura Costera Occidental (El Salvador).

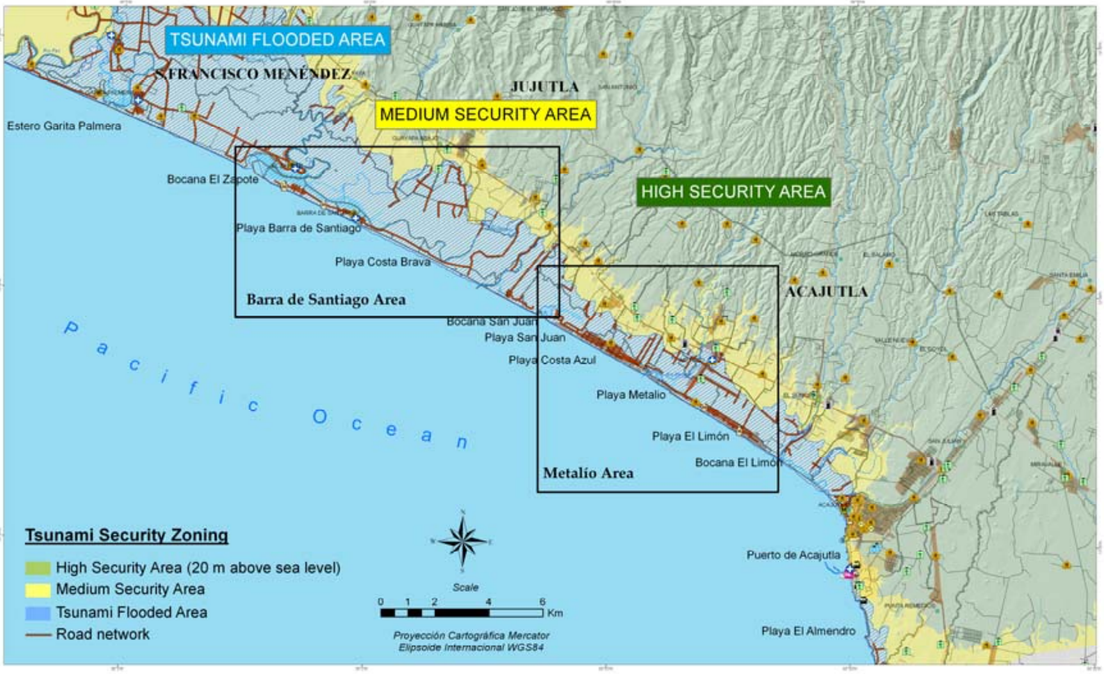

Figure 6.10 Zonificación de seguridad y red de carreteras existente - Llanura Costera Occidental (El Salvador). Los rectángulos negros indican las áreas en las que se ha realizado un análisis detallado para identificar las rutas de evacuación. Se presentan los resultados obtenidos para la zona Barra de Santiago.

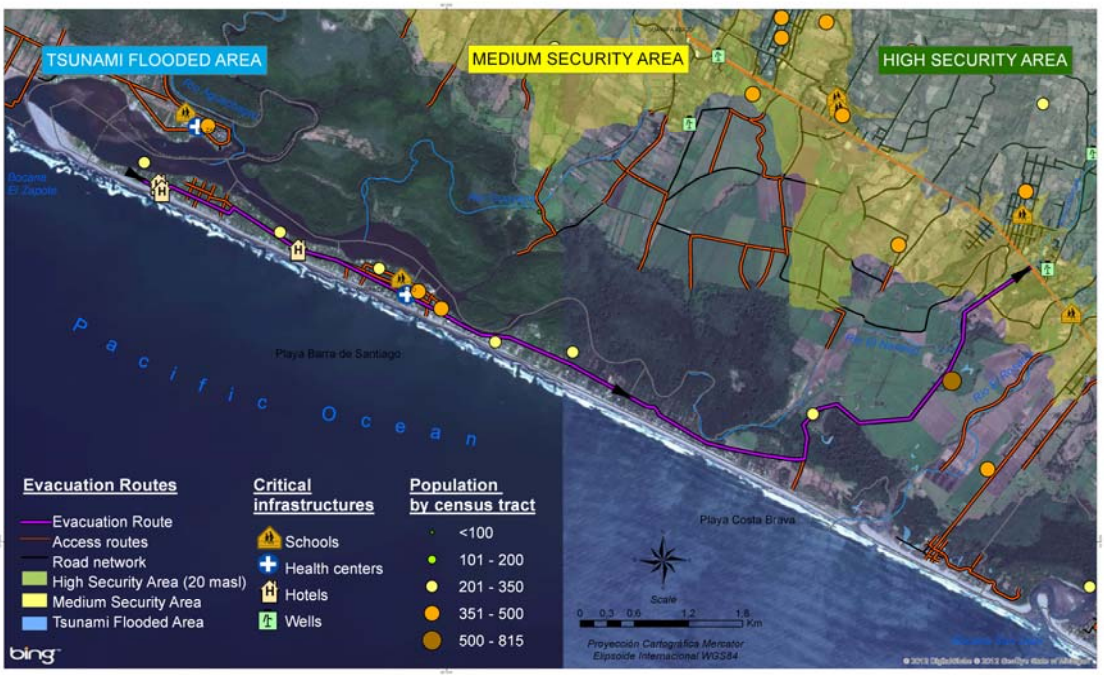

Figure 6.11 Rutas de evacuación existentes, infraestructuras críticas y población por segmento censal - Barra de Santiago, Llanura Costera Occidental (El Salvador).

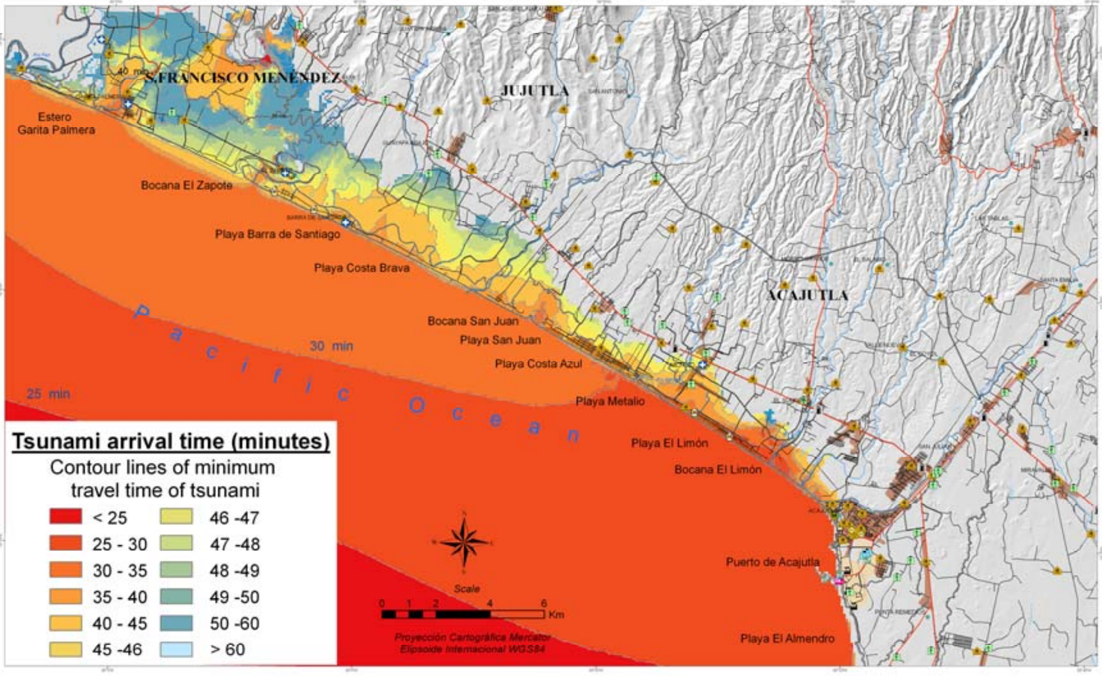

Figure 6.12 Tiempo de llegada del tsunami para el peor escenario creíble (combinación de los 23 peores casos creíbles) - Llanura Costera Occidental (El Salvador).

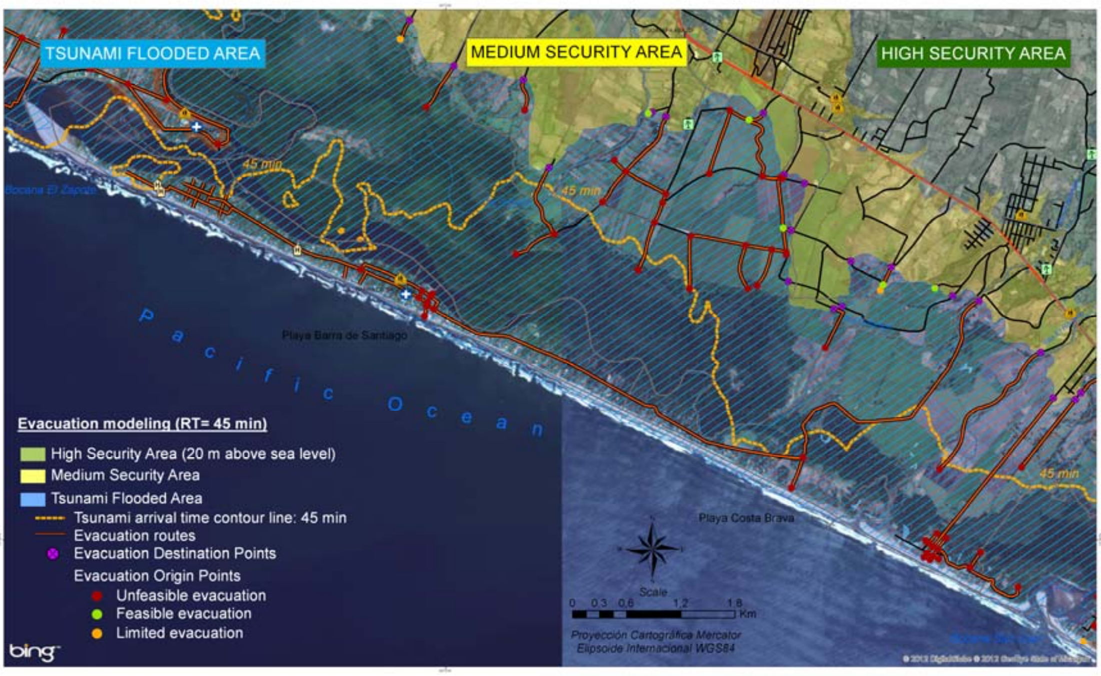

Figure 6.13 Modelado de evacuación para un tiempo de respuesta de 45 min (RT45) - Barra de Santiago, Llanura Costera Occidental (El Salvador).

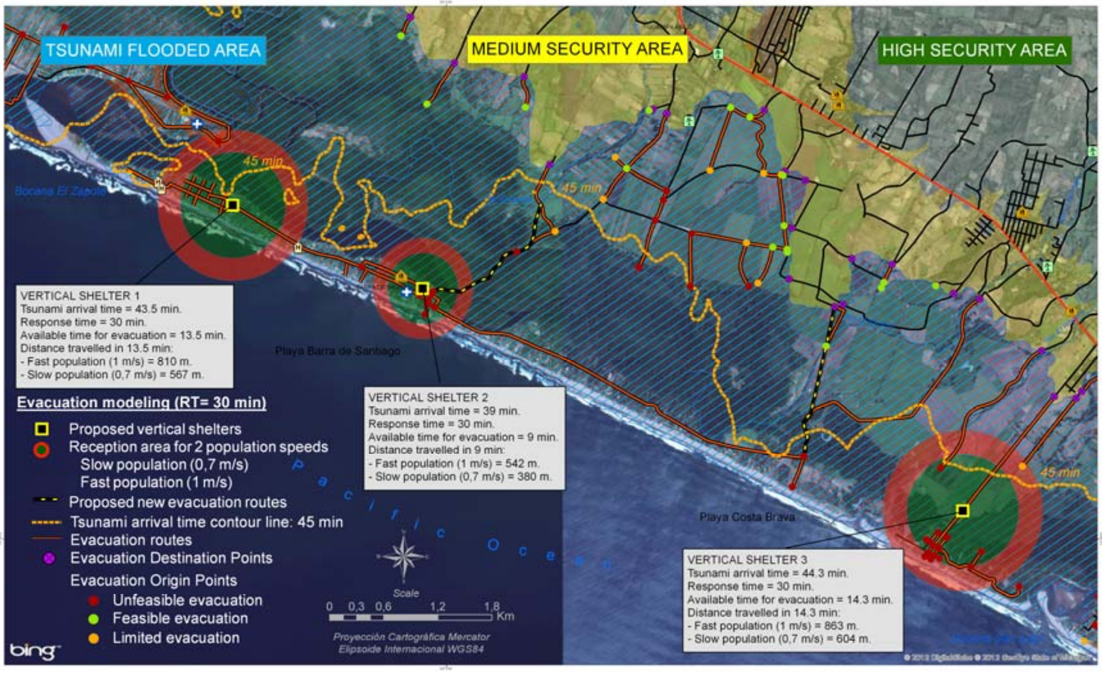

Figure 6.14 Modelado de evacuación para un tiempo de respuesta de 30 min (RT30) y propuesta de alternativas para zonas críticas - Barra de Santiago, Llanura Costera Occidental (El Salvador).

Table 6.3 Estructura de un plan de evacuación ante tsunami.

Objetivos generales	Objetivos específicos	Ejemplos de medidas
Mejorar la preparación de la población ante tsunami	Reducción de la vulnerabilidad de la población con respecto a la evacuación	Medidas relacionadas con el tiempo de reacción • Información, sensibilización, capacitación y ayuda específica para personas con dificultades para entender un mensaje de alerta • Entrenamiento específico en evacuación para el personal de los edificios críticos (escuelas, geriátricos, hospitales, etc.) Medidas relacionadas con la velocidad de viaje • Información, sensibilización y entrenamiento para grupos lentos (mujeres, ancianos, discapacitados embarazadas y niños) • Organización comunitaria y ayuda específica para grupos lentos Medidas relacionadas con el aislamiento • Información, sensibilización y formación en zonas aisladas • Ayuda específica (servicios de transporte) para zonas aisladas • Priorización de tiempo de alerta en zonas aisladas
Consolidación de las infraestructuras existentes de evacuación	Consolidación de las rutas de evacuación existentes	Medidas relacionadas con la dificultad de viaje: • Gestión del tráfico urbano para evitar zonas de cuello de botella • Eliminación de potenciales cuellos de botella de las rutas de evacuación (p.ej. mercados) Medidas relacionadas con la seguridad de viaje: • Mejorar / reparar las carreteras existentes para facilitar la evacuación
	Consolidación de los refugios de evacuación existentes	Medidas relacionadas con la capacidad de los refugios: • Incrementar la capacidad de los refugios existentes cuando sea posible Medidas relacionadas con la seguridad de los refugios: • Reforzar estructuralmente los refugios existentes Medidas relacionadas con la accesibilidad a los refugios: • Mejorar la accesibilidad a los refugios existentes, eliminar barreras a la evacuación
Reducción del riesgo en áreas críticas	Reducción de las distancias de evacuación a recorrer	Medidas relacionadas con la construcción de nuevas rutas de evacuación: • Construir nuevas rutas para acortar las distancias a recorrer Medidas relacionadas con la construcción de nuevos refugios: • Construir nuevos refugios para acortar las distancias a recorrer por las comunidades que actualmente no consiguen evacuar • Prestar ayuda especial a la población lenta ubicada en el anillo rojo de las torres de evacuación
	Reducción del tiempo de respuesta	Medidas relacionadas con la reducción del tiempo de alerta: • Sistema de alerta temprana • Capacitación en áreas críticas • Optimización del sistema de comunicación: networking, tecnología (telefonía, altavoces, etc.) Medidas relacionadas con la reducción del tiempo de reacción: • Campañas de información y concienciación en áreas críticas • Entrenamiento, simulacros de evacuación en áreas críticas

6.3.4 Conclusiones

La evaluación de la amenaza, a través de la modelización numérica del tsunami, permite la generación de diferentes mapas de riesgo que proporcionan conocimientos sobre la zona expuesta, los lugares que recibirían mayores impactos y el tsunami primera vez ola de llegada, información crítica para la evacuación. El peor escenario es el más conservador en términos de gestión de riesgos.

La evaluación del número total de personas expuestas y su vulnerabilidad en términos de evacuación ayuda en el diseño de medidas específicas para hacer frente a las debilidades identificadas. Así, el número de personas en edificios críticos (escuelas, hospitales, hoteles, etc.), el analfabetismo y la discapacidad intelectual, indican los grupos de población con mayores tiempos de reacción; la discapacidad física y los grupos de edad asociados a ancianos y niños se relacionan directamente con una menor velocidad de desplazamiento; y aquellas áreas mal conectadas se traducen en aislamiento de la comunidad, afectando tanto a la recepción de una alerta como a la posterior evacuación. El análisis de la red de carreteras y zonas seguras permite conocer la situación actual de los mismos y poner de relieve la necesidad de reparaciones y mejoras.

El modelado de evacuación ha permitido identificar (i) las rutas de evacuación más cortas, teniendo en cuenta la pendiente y diferentes velocidades de población, y (ii) el grado de éxito para el tiempo de evacuación actual. Se ha considerado el tiempo de respuesta, entendido como el tiempo que transcurre desde la generación de un tsunami hasta que la población comienza a evacuar, que incluye: los protocolos de emergencia actuales y la experiencia de las autoridades responsables, y el tiempo de reacción de la población. Modelar el tiempo de respuesta actual permite entender las posibilidades reales de evacuación, que es el punto de partida para la gestión del riesgo. Así, el modelado de evacuación en El Salvador para el tiempo de respuesta actual de 45 min (RT45: tiempo de alerta 30 minutos, tiempo de reacción 15 min) puso de relieve la necesidad de mejorar el proceso de alerta para asegurar el éxito de la evacuación, ya que en la mayoría de las comunidades costeras el tsunami alcanzaría la costa antes de ser alertadas. Una reducción de 15 minutos en el tiempo de respuesta (RT30) mostró un mayor porcentaje de población evacuada, demostrando la importancia de esta cuestión; sin embargo, las comunidades más cercanas a la costa no serían capaces de llegar a las zonas seguras. Para estas comunidades, se proponen medidas alternativas para asegurar su evacuación, tales como la construcción de nuevas vías de evacuación y refugios de evacuación vertical. Estas medidas combinadas (reducir el tiempo de respuesta y las distancias a recorrer) han demostrado ser útiles para lograr los resultados deseados. La repetición del modelado de evacuación para cada grupo de medidas propuesto garantiza el control y la reducción de las áreas críticas. Este análisis de sensibilidad del modelo de evacuación representa una poderosa herramienta para reducir el riesgo en áreas críticas, asegurando la evacuación de la población, ya que permite predecir los resultados de las opciones de gestión propuestas.

Se propone un método para la identificación de posibles ubicaciones para los refugios de evacuación vertical, proporcionando información útil para cada refugio, tal como el tiempo de llegada del tsunami, el tiempo de respuesta modelado, el tiempo disponible para evacuar, y la distancia de recepción de la torre para ambas velocidades de población. La combinación de esta información con la cantidad de personas a ser evacuadas indica la capacidad que estos refugios deben acomodar.

Por último, el marco propuesto permite a la organización, clasificación y priorización de la información recogida, con el fin de definir mejor las diversas medidas de gestión de riesgos que deben incluirse en un plan de evacuación. Es importante mencionar que el marco permite la aplicación de modelos de evacuación más complejos si es necesario y/o nuevos avances de investigación, tales como los relativos al cálculo de la pendiente o el proceso de optimización para la ubicación del refugio.

6.4 Tsunami human vulnerability indicators (scientific article 3)

6.4.1 *Título y autores*

Contribución para la selección de indicadores de vulnerabilidad humana ante tsunamis: conclusiones de los impactos sufridos en Sri Lanka y Thailand (2004), Samoa (2009), Chile (2010) and Japan (2011) *(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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6.4.2 *Antecedentes y objetivos*

Los desastres naturales son provocados por fenómenos naturales extremos y se convierten en desastres debido a una mayor vulnerabilidad de las personas y los lugares donde se producen (Mazurana et al., 2011). La vulnerabilidad se refiere a las condiciones físicas, sociales, económicas y ambientales, que aumentan la susceptibilidad de los elementos expuestos al impacto de la amenaza (adaptado de la UN/ISDR, 2004).

Tras varios tsunamis con consecuencias desastrosas en todo el mundo, los países costeros son conscientes de la necesidad de estar preparados ante este tipo de eventos para minimizar tanto la mortalidad humana como los daños en recursos e infraestructura costera, y en los modos y medios de vida asociados a los mismos. Actualmente la comunidad científica internacional está orientando gran esfuerzo a desarrollar y validar metodologías para evaluar el riesgo ante tsunami, incluyendo el análisis de la amenaza y de la vulnerabilidad de las comunidades costeras para entender aquellas condiciones que pueden exacerbar los impactos de potenciales tsunamis.

Siendo la vulnerabilidad multidimensional, dinámica y dependiente de la escala (Vogel y O'Brien, 2004), de acuerdo con el alcance de cada trabajo los autores precedentes se centran bien en una dimensión específica (humana, ecológica, socioeconómica, etc.) o en enfoques integrados al tratar sistemas socio-ecológicos complejos. La mayoría de los estudios de vulnerabilidad se llevan a cabo mediante la definición de un conjunto de índices e indicadores que son normalizados, ponderados, agregados y clasificados a través de diferentes métodos matemático-estadísticos para posteriormente representar geográficamente la información.

Los indicadores de vulnerabilidad seleccionados difieren claramente entre los autores, en base a literatura previa, el conocimiento y los avances científicos, lecciones aprendidas de desastres de tsunami anteriores, el alcance del estudio y la disponibilidad de la información. Las ideas y conceptos medidos por todos estos indicadores son, sin embargo, muy similares. Esto refleja una visión común al respecto en la comunidad científica pero implica una necesidad de validación de los indicadores para dar coherencia a las distintas evaluaciones de riesgo ante tsunami.

El objetivo de este trabajo es validar, a la luz de eventos de tsunami pasados, los indicadores propuestos actualmente por la comunidad científica para medir la vulnerabilidad humana. Se pretende mejorar la definición de indicadores de vulnerabilidad y analizar su validez para diferentes perfiles de desarrollo de los países. Los eventos analizados en este trabajo son el gran tsunami de Tohoku de 2011, el tsunami chileno de 2010, el tsunami de Samoa 2009 y el tsunami del Océano Índico de 2004. El trabajo se centra en el análisis de estos eventos para comprender las condiciones de vulnerabilidad que agravaron el impacto humano del tsunami e integrarlos en un marco válido para futuros trabajos.

6.4.3 Metodología y resultados

Se presenta en el artículo una revisión exhaustiva de los trabajos existentes en materia de evaluación de la vulnerabilidad ante tsunami basados en indicadores para identificar aquellos utilizados actualmente para evaluar la vulnerabilidad humana. La mayoría de los autores coinciden en el uso de algunos indicadores como edad, analfabetismo, discapacidad, edificios críticos, número de pisos, etc., algunos de ellos aportando además cierta creatividad al análisis para incorporar otros aspectos relacionados con la preparación y respuesta ante este tipo de eventos por parte de las comunidades, como por ejemplo mecanismos de coordinación, conocimiento y concienciación social, etc.

Aunque los diversos autores proponen y aplican diferentes indicadores de acuerdo con el alcance de su trabajo y de la información disponible, la totalidad de los indicadores de exposición y vulnerabilidad aplicados siguen áreas temáticas muy específicas y se pueden agrupar en cuatro categorías principales y diez temas clave. Las 4 categorías son: exposición, capacidad de alerta, capacidad de evacuación y emergencia, y capacidad de recuperación. Los 10 temas clave son:

(i) exposición humana,
(ii) recepción de un mensaje de alerta,
(iii) comprensión de un mensaje de alerta,
(iv) movilidad y velocidad de evacuación,
(v) seguridad de los edificios,
(vi) dificultades en la evacuación relacionados con el entorno construido,
(vii) capacidad de respuesta de la sociedad,
(viii) recursos económicos del hogar,

(ix) apoyo externo para la recuperación,
(x) impactos esperados con potencial afección a la recuperación.

Se presenta en el artículo un resumen de todos los indicadores recopilados, los cuales están organizados dentro de las categorías y temas clave propuestos, detallando las referencias en las que han sido aplicados en trabajos anteriores.

Para validar los indicadores se han analizado los impactos generados por tsunamis pasados en varios países (Japón, Chile, Samoa, Sri Lanka y Tailandia). La validación se basa en la comparación en cada país de los efectos del tsunami sobre la población con los datos censales disponibles inmediatamente anteriores al evento, para comprender si las tendencias de la mortalidad asociada al tsunami están relacionadas con el evento en sí o con patrones de población y características de vulnerabilidad existentes anteriormente al tsunami. Para ello, se han analizado censos oficiales pre- y post-tsunami para los distintos países. En base a la información disponible en estos censos se han validado los indicadores mostrados en la Table 6.4. Se presentan a continuación algunos de los resultados gráficos obtenidos, si bien el análisis detallado de los mismos aparece en el artículo.

Table 6.4 Indicadores validados en este trabajo en base a la información disponible. Celdas sombreadas: indicadores no validados, aunque la información está disponible, ya que los países no emitieron una alerta de tsunami antes de que la primera ola llegara a la costa.

Vulnerabilidad humana ante tsunami – temas clave	Indicadores	Japón 2011	Chile 2010	Samoa 2009	Sri Lanka 2004	Tailandia 2004
I. Exposición humana	Número de personas expuestas	X	X		X	
	Densidad de población	X	X		X	
II. Recepción de un mensaje de alerta	Sistema de alerta temprana	SI	NO	SI	NO	NO
III. Comprensión de un mensaje de alerta	Edad	X	X	X	X	
	Nivel de educación				X	
	Analfabetismo				X	
	Inmigración				X	
	Conocimiento del idioma				X	
	Etnicidad				X	
IV. Movilidad y velocidad de evacuación	Edad	X	X	X	X	
	Género	X	X	X	X	
	Discapacidad				X	
	Dependencia	X	X	X	X	
V. Seguridad de los edificios	Tipo de edificio				X	
	Materiales				X	
	Distancia a costa				X	
VIII. Recursos económicos	Salario, ahorros, pobreza				X	
	Empleo, tipo de ocupación				X	
X. Impactos esperados con potencial afección a la recuperación	Socioeconómicos: pérdida de empleos /estilos de vida/PIB				X	
	Infraestructuras (viviendas /edificios): nivel de daño	X			X	X

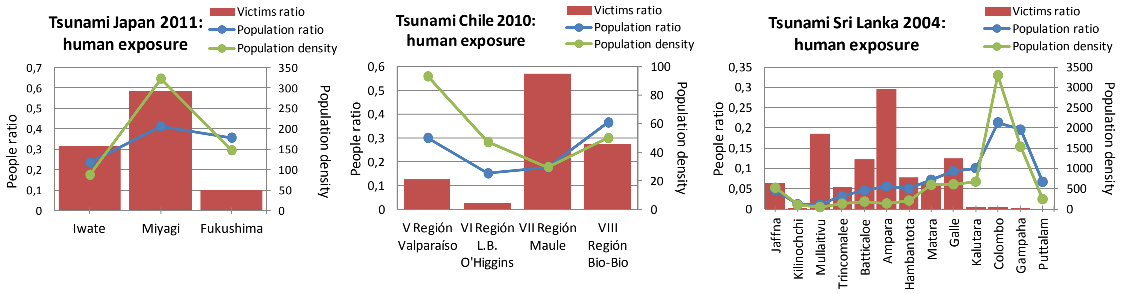

Figure 6.15 Correlación entre el número de víctimas, el ratio de población y la densidad de población (Japón 2011, Chile 2010 y Sri Lanka 2004)

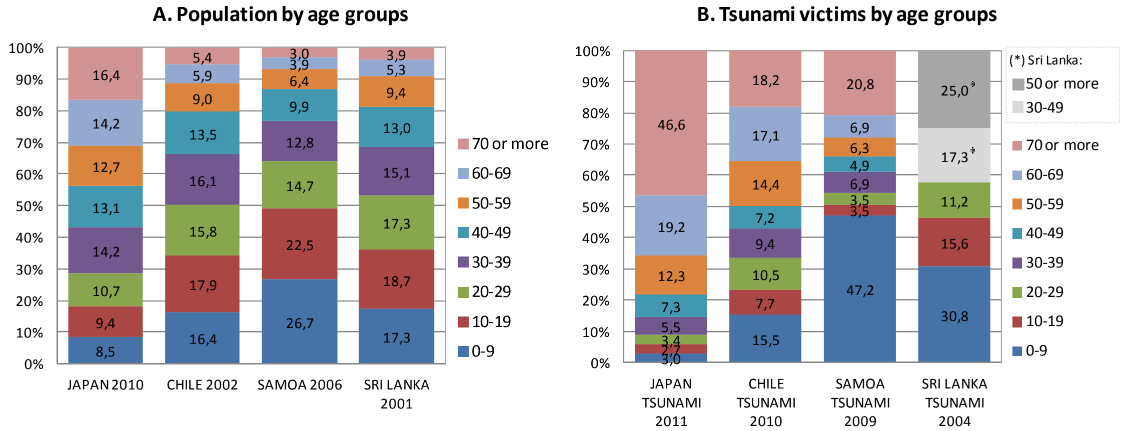

Figure 6.16 Análisis de los grupos de edad (Japón 2011, Chile 2010, Samoa 2009 y Sri Lanka 2004). A: censo, B: víctimas del tsunami.

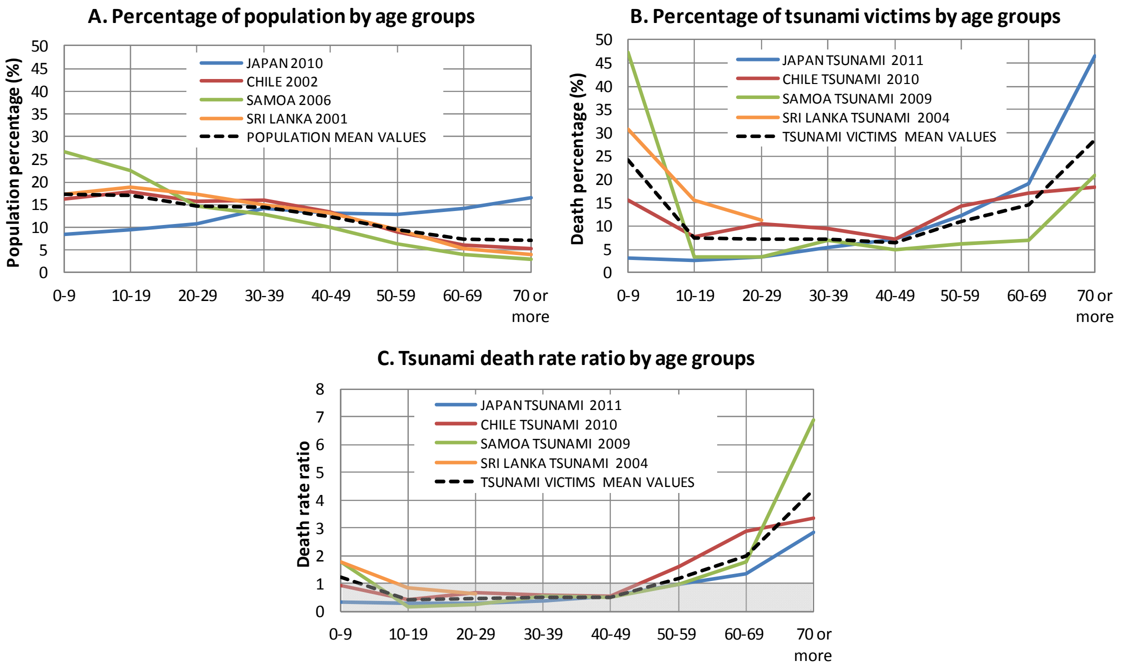

Figure 6.17 Análisis de la mortalidad por grupos de edad (Japón 2011, Chile 2010, Samoa 2009 y Sri Lanka 2004). A: censo pre-tsunami, B: víctimas del tsunami, C: tasa de mortalidad por tsunami, C=B/A).

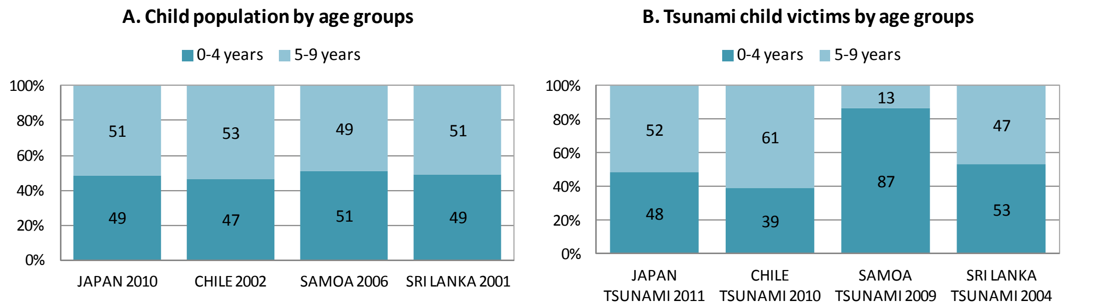

Figure 6.18 Análisis de los grupos de edad infantil (Japón 2011, Chile 2010, Samoa 2009 y Sri Lanka 2004). A: censo pre-tsunami, B: víctimas del tsunami.

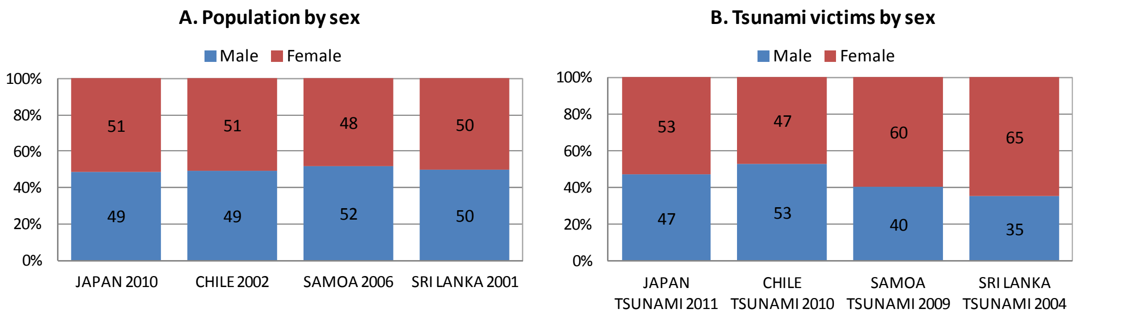

Figure 6.19 Análisis de género (Japón 2011, Chile 2010, Samoa 2009 y Sri Lanka 2004). A: censo pre-tsunami, B: víctimas del tsunami.

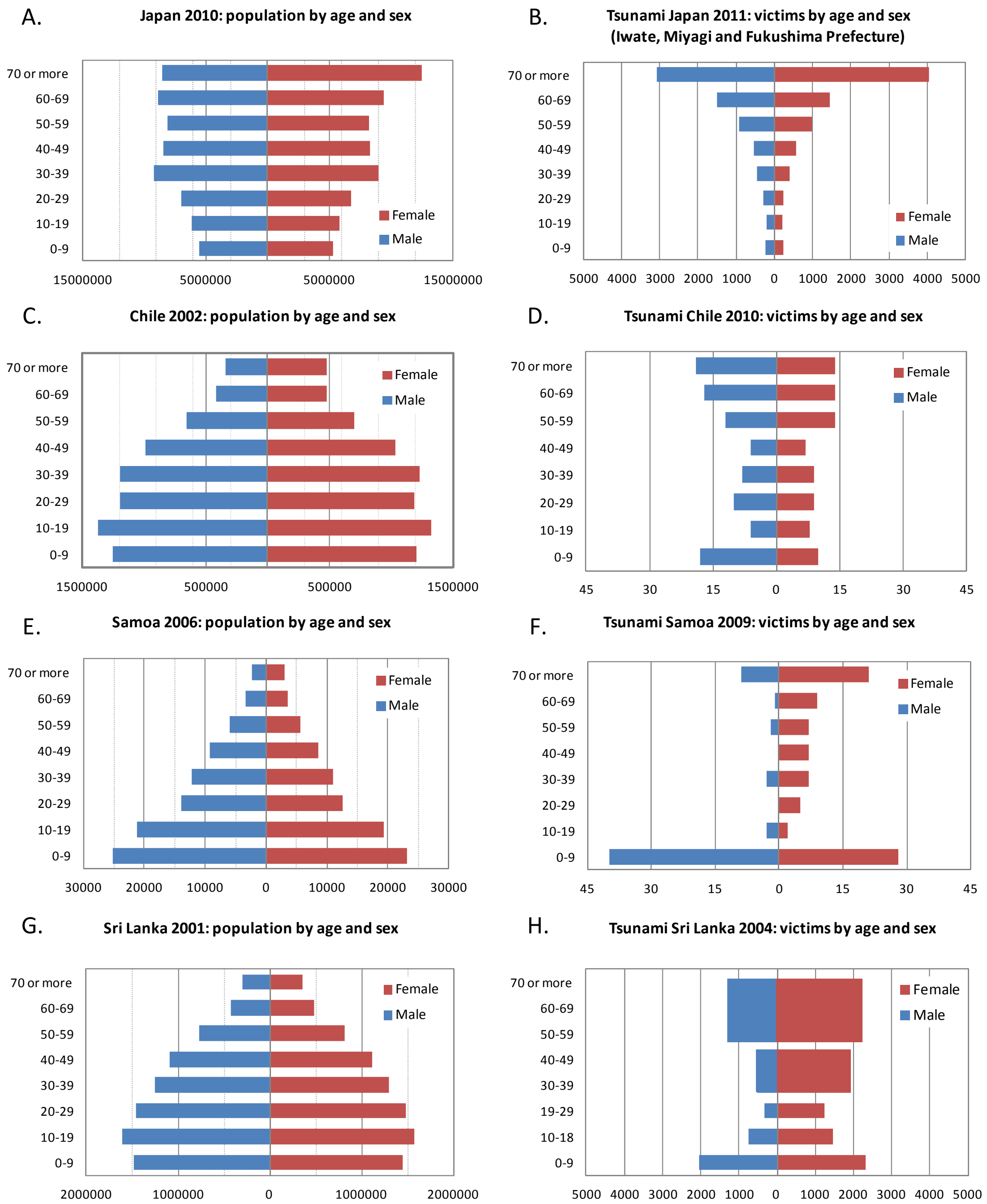

Figure 6.20 Pirámides de población (izquierda: censo pre-tsunami, derecha: víctimas del tsunami).

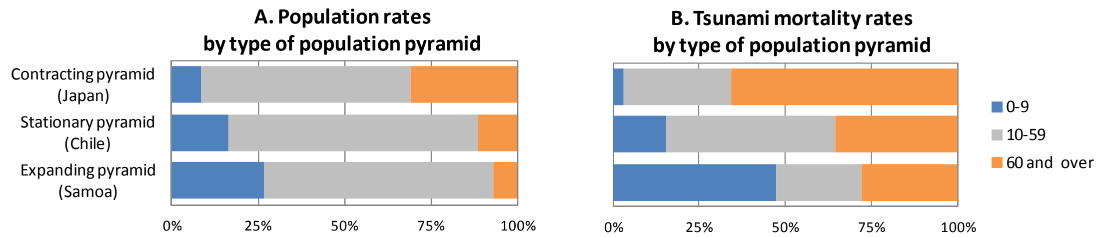

Figure 6.21 Tasas de población (A) y las tasas de mortalidad por tsunami (B) según tipo de pirámide de población

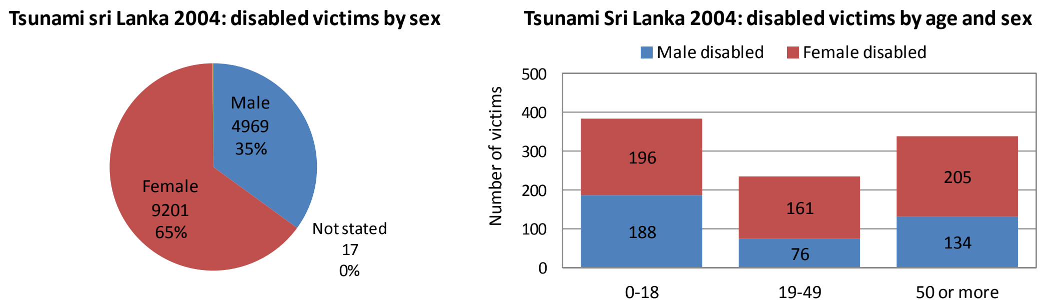

Figure 6.22 Víctimas con discapacidad por edad y sexo (tsunami Sri Lanka 2004)

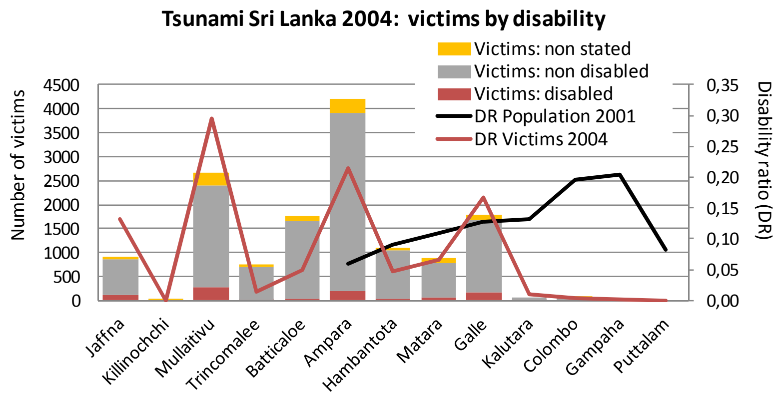

Figure 6.23 Víctimas según discapacidad y tasas de discapacidad pre- y post-tsunami en las diferentes divisiones costeras afectadas (tsunami Sri Lanka 2004).

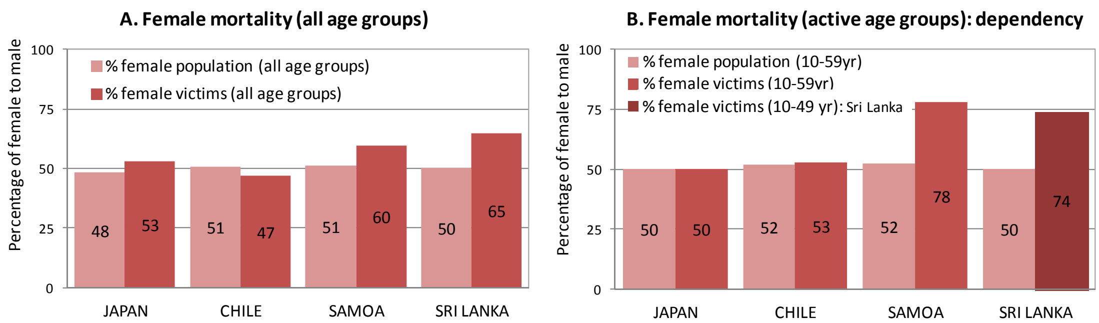

Figure 6.24 Mortalidad femenina y su relación con el concepto de dependencia. A: mortalidad femenina teniendo en cuenta todos los grupos de edad, B: mortalidad femenina considerando sólo los grupos de edad "activos" asumiendo que las mujeres en este rango de edad pudieron haber estado a cargo de miembros de la familia como niños y ancianos.

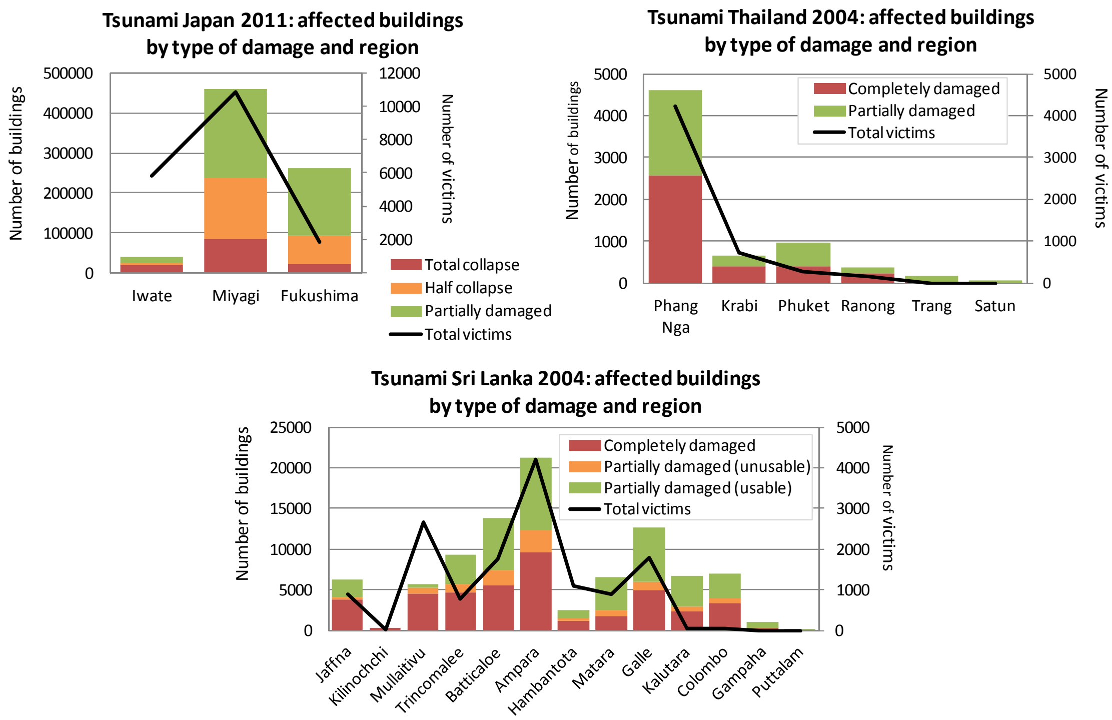

Figure 6.25 Correlación entre el total de víctimas y los edificios afectados según tipo de daño y región (Japón 2011, Tailandia 2004 y Sri Lanka 2004)

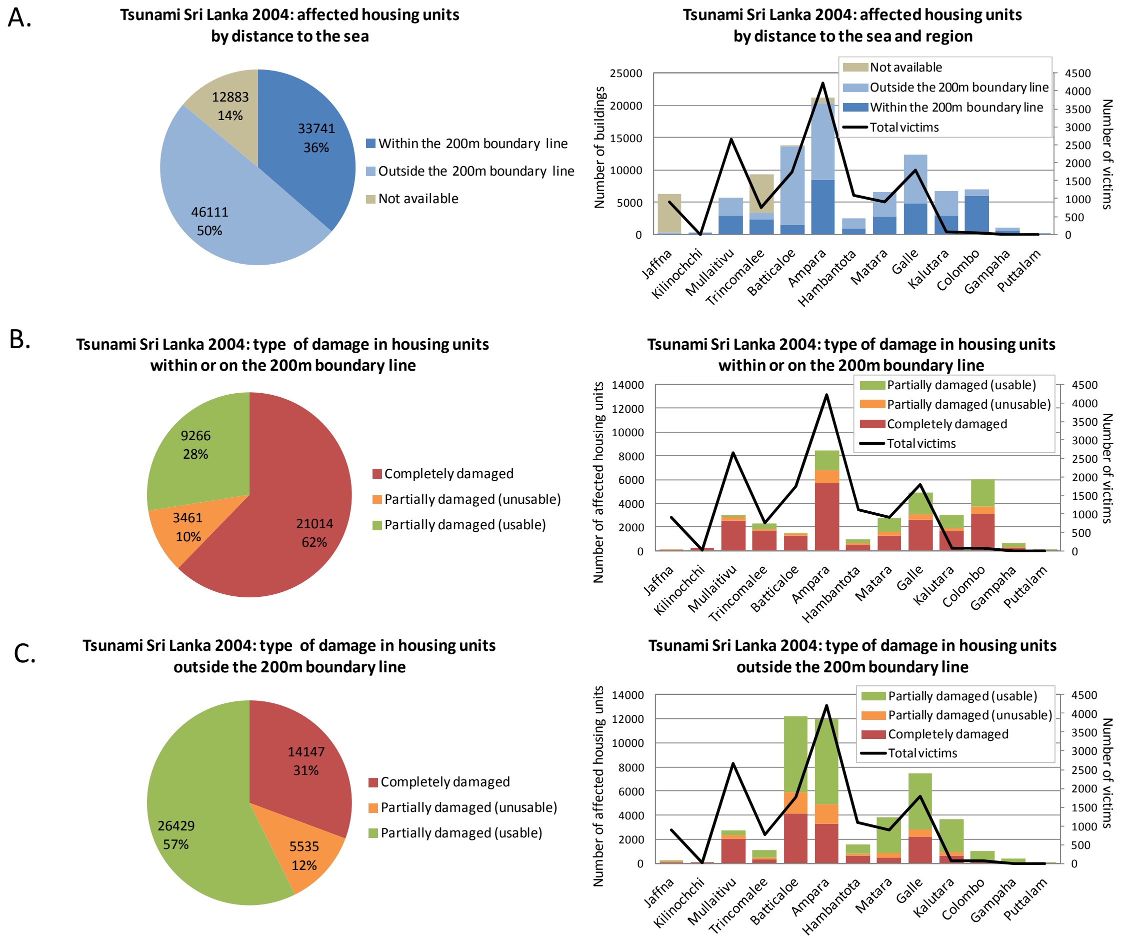

Figure 6.26 Correlación entre el número de víctimas, el tipo de daños en edificios y la distancia hasta el mar (tsunami de Sri Lanka 2004)

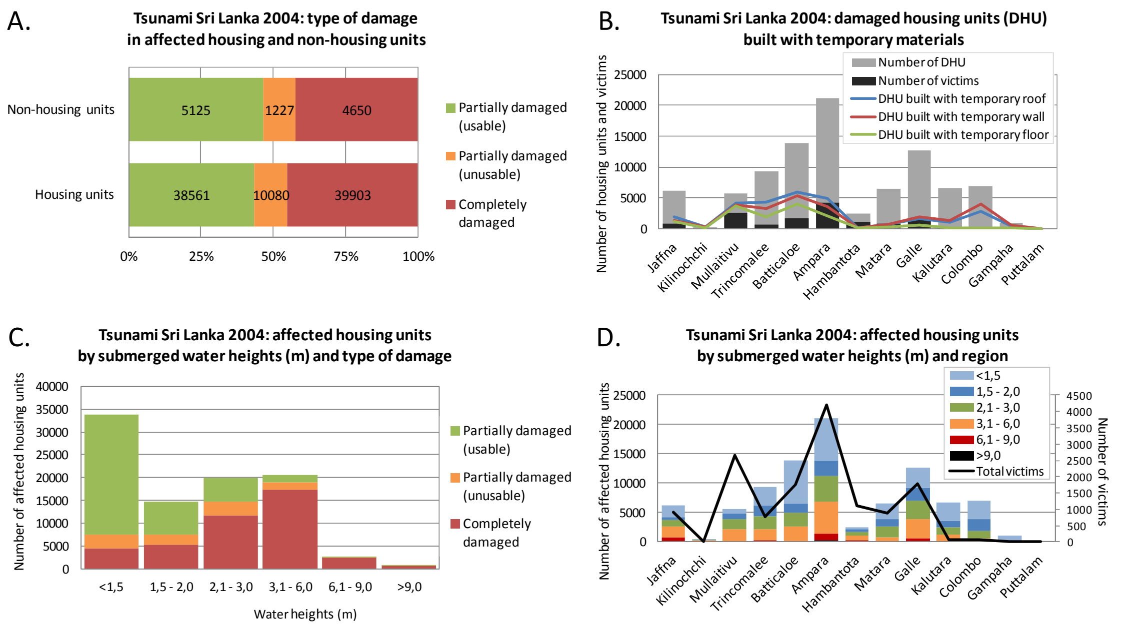

Figure 6.27 Análisis de los edificios afectados en Sri Lanka 2004 A: comparación entre el número de vivienda (HU) y las unidades no utilizadas como vivienda (NHU) afectados por tipo de daño. B: correlación entre el número de víctimas, daños en HU y materiales de construcción. C-D: correlación entre el número de víctimas, el tipo de daño en edificios y la profundidad alcanzada por la columna de agua.

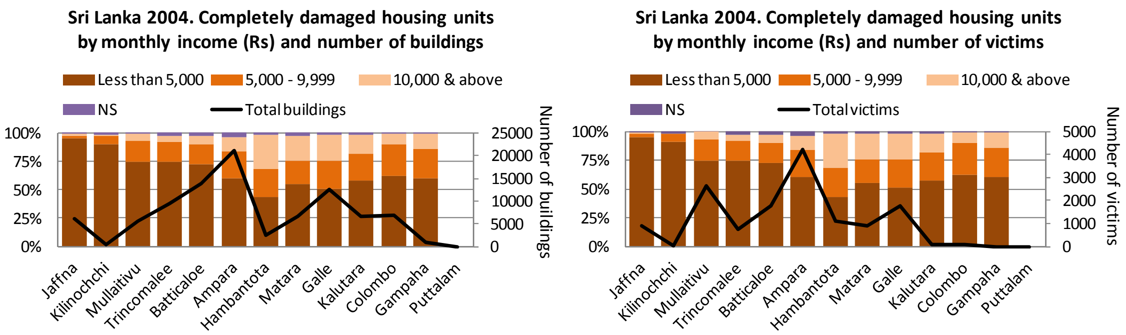

Figure 6.28 Distribución porcentual de viviendas totalmente dañadas (A) y número de víctimas (B) por ingreso mensual reportado (5000Rs = 27,71 €, en 10/07/2014)

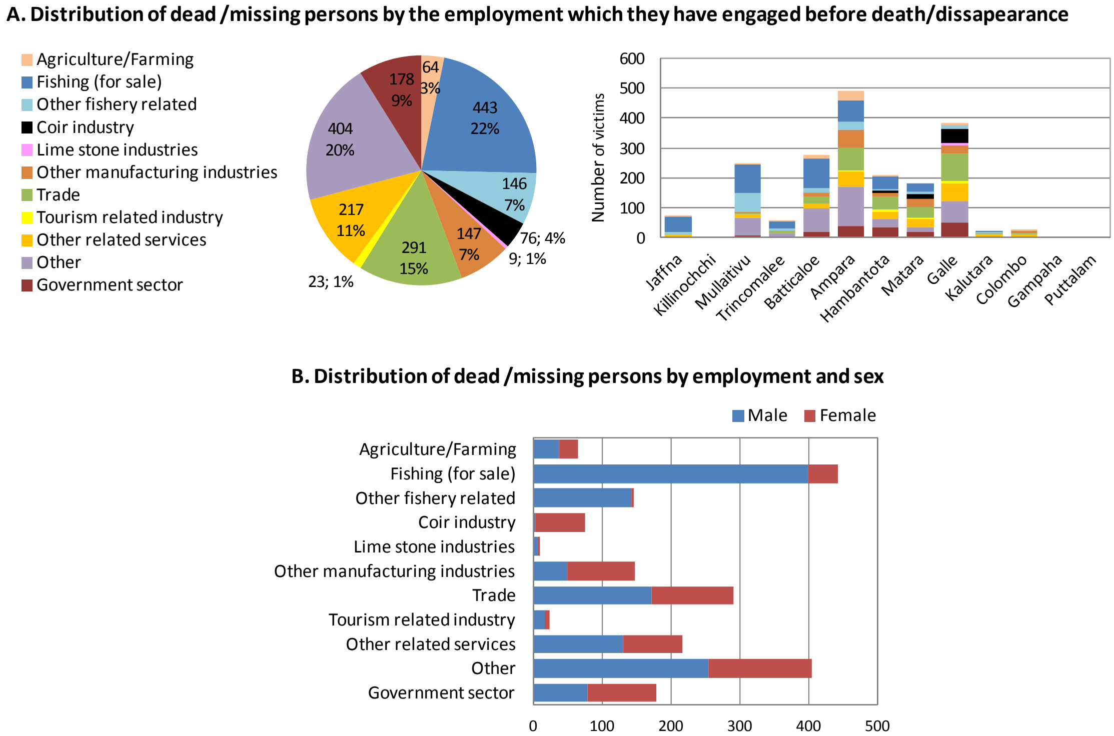

Figure 6.29 Distribución de las víctimas del tsunami según empleo y distrito (Sri Lanka 2004). A: víctimas según empleo. B: víctimas según empleo y sexo.

6.4.4 Conclusiones

Se presentan a continuación algunas conclusiones obtenidas de los resultados de este trabajo.

La exposición humana permanente, entendida como el número de comunidades/personas normalmente ubicadas en la zona de peligro, no sólo se relaciona con la densidad de población de la unidad administrativa (que es el indicador aplicado normalmente), sino con la densidad de la zona expuesta. Por esta razón es esencial desarrollar un modelado numérico de la amenaza asociada al tsunami, es decir la zona potencialmente inundada, para identificar las comunidades en riesgo. La exposición humana temporal se relaciona con los modos de vida específicos del lugar, las tradiciones culturales y los roles de género, que tienen variabilidad diaria/semanal/ mensual, y requiere el estudio de los patrones temporales de la comunidad antes de proponer indicadores de vulnerabilidad. Este es el caso por ejemplo de los impactos del tsunami en Sri Lanka en una mañana de domingo, en la que las mujeres y los niños estaban en la playa, mientras los hombres estaban pescando.

Centrándonos en los indicadores basados en la población, se ha demostrado que la edad es determinante en la evaluación de la vulnerabilidad. Se proporcionan en este trabajo los ratios en las tasas de mortalidad (Death Rate Ratios, DRR) por grupos de edad para comprender si la muerte asociada a cada grupo de edad se debe a una mayor vulnerabilidad ante el evento de tsunami o a la estructura de la población previa al evento. Las DRR están condicionadas por el perfil de desarrollo del país (pirámides de población). Los resultados confirman que los grupos de edad más vulnerables son los adultos mayores y los niños; sin embargo, los primeros tienen tasas de mortalidad mucho más altas que los niños, siendo especialmente alto para los grupos de edad por encima de 60 años de edad e incrementando con la edad. La mortalidad de los otros grupos de edad únicamente se relaciona con la estructura de la población antes de un evento. Los grupos de edad infantil (0-4 y 5-9 año) son igualmente vulnerables en eventos de tsunami con un elevado número de muertes. En cuanto a cuestiones de sexo/ género, se ha encontrado que la mortalidad femenina no siempre es mayor que la masculina, tal y como señalan muchos de los estudios previos. En consecuencia, para caracterizar la vulnerabilidad femenina se necesita realizar estudios específicos sobre el perfil de desarrollo del país y la pirámide de población asociada, la longevidad femenina, los roles de género, la dependencia, las tradiciones culturales, etc. Además, la mortalidad femenina no siempre se relaciona con la dependencia (sólo en Samoa en este trabajo). La dependencia y los roles de género parecen estar asociados en mayor medida a los países sub-desarrollados y en desarrollo. En cuanto a la discapacidad, mayores números de personas con discapacidad no se tradujeron en un mayor número de víctimas en los distritos afectados de Sri Lanka.

Además, basándonos en los resultados globales obtenidos está claro que la mortalidad no sólo se relaciona con las características de la población, sino también de los edificios. En este sentido, se ha encontrado una alta correlación entre edificios afectados y número de víctimas, siendo muy alta para edificios completamente dañados. Se han analizado los factores que determinan el tipo de daño en los edificios y se pueden agrupar en dos categorías: la ubicación del edificio y la fragilidad de la construcción. En cuanto a la ubicación del edificio, la distancia a la costa es un factor altamente correlacionado con el daño a la infraestructura y, consiguientemente, con el número de víctimas. En cuanto a la fragilidad de la construcción, los materiales y la profundidad de la columna de agua han confirmado una alta correlación con el tipo de daño, lo que coincide con y refuerza trabajos anteriores sobre el tema en diferentes países (Tinti et al, 2011; Supasri et al, 2013). El cálculo de la profundidad esperada de la inundación requiere el modelado numérico de la amenaza.

Como se destaca en este apartado, el modelado numérico del tsunami es esencial para identificar el área y las comunidades expuestas, así como la profundidad de la inundación, ambos claros condicionantes del número esperado de víctimas.

Los resultados y conclusiones presentados en este trabajo validan a la luz de los acontecimientos pasados de tsunami algunos de los indicadores propuestos actualmente por la comunidad científica para medir la vulnerabilidad humana y permiten mejorar la definición de indicadores específicos para cada zona de estudio en futuras evaluaciones de vulnerabilidad ante tsunami.

6.5 Storm surge risk perception & resilience (scientific article 4)

6.5.1 Título y autores

Percepción del riesgo y resiliencia ante inundaciones causadas por tormentas: estudio piloto en la costa norte alemana (*Storm surge risk perception and resilience: a pilot study in the German North Sea Coast*)

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6.5.2 Antecedentes y objetivos

En el ámbito de la gestión de desastres, la resiliencia se define como la capacidad de un sistema, comunidad o sociedad expuestos a una amenaza para resistir, absorber, adaptarse y recuperarse de los efectos de la misma de un modo oportuno y eficiente, preservando y restaurando sus estructuras básicas y funciones esenciales (UN/ISDR, 2009). Cutter et al. (2008) la define como el grado en que la comunidad cuenta con los recursos necesarios y es capaz de absorber las perturbaciones y reorganizarse en un sistema en pleno funcionamiento. En otras palabras, la resiliencia se refiere a la capacidad de una comunidad para organizarse antes, durante y después del evento, a fin de minimizar los impactos (González-Riancho et al., 2014) y, por lo tanto, está directamente relacionada con la reducción del riesgo, entendida como el desarrollo e implementación de actividades dirigidas a la mitigación, preparación, respuesta y recuperación (Mileti, 1999).

El hecho de hablar de la capacidad de un sistema, comunidad o sociedad, implica analizar y entender tanto las capacidades institucionales como las de la sociedad para hacer frente al evento. Otro aspecto a considerar en relación al concepto de la resiliencia es su carácter extrínseco y variable, así como mejorable a través del aprendizaje y la experiencia mediante por ejemplo la preparación ante desastres dentro de las comunidades, en contraste con las condiciones individuales, internas e inmutables de la sociedad, como la edad de la población o el nivel de pobreza (González-Riancho et al., 2014).

Así, una sociedad resiliente es consciente del peligro, está preparada ante potenciales impactos y es capaz de recuperarse, estas capacidades refiriéndose tanto a los ámbitos institucionales como sociales de la comunidad. Coherentemente, en la bibliografía relativa a la resiliencia algunos autores se han centrado en el desempeño y la preparación institucional ante una amenaza (IOTWS, 2007; Birkmann et al, 2013; González-Riancho et al, 2014), mientras que otros en el comportamiento de los individuos en términos de preparación y protección (Fishbein y Ajzen, 1975; Rogers, 1983; Schwarzer, 1992; Paton 2003, 2005, 2010; Becker et al, 2011, 2013; Lindell y Perry, 2012) o en cómo factores como la percepción del riesgo pueden influir en el ajuste del comportamiento y la preparación (Douglas y Wildawsky, 1982; Renn, 2008; Solberg et al, 2010; Birkmann et al, 2012a, 2012b). Se muestra en el artículo un resumen de los factores de comportamiento estudiados por diversos autores para predecir la preparación y/o medir la capacidad de recuperación, que con origen en las teorías de la salud y la psicología social, se han adaptado y aplicado posteriormente a la disciplina de las amenazas naturales.

El objetivo de este trabajo es proponer un marco conceptual para evaluar la resiliencia de una comunidad mediante la comprensión e integración de las capacidades institucionales, legales y sociales para hacer frente y recuperarse de una amenaza natural con el fin de minimizar los impactos en el corto plazo y adaptarse a largo plazo al riesgo existente. Para ello se propone un método basado en encuestas para explorar la percepción de la comunidad sobre los procesos de gestión del riesgo y la emergencia, así como los factores psicológicos y sociales que condicionan la preparación individual y de la comunidad.

El marco conceptual y el método presentados en este trabajo son válidos para cualquier zona de estudio si bien las preguntas del cuestionario propuesto pueden adaptarse a las especificidades de cada lugar. Así, se presenta en este documento la aplicación del cuestionario en una pequeña zona de la costa alemana del Mar del Norte (distrito de Dithmarschen, estado Schleswig-Holstein). El área de estudio ha sufrido fuertes transformaciones antropogénicas y naturales de la línea de costa y su población se caracteriza por su continua interacción con el océano. Por un lado las poblaciones costeras han ido ganando tierras al mar para fines agrícolas y, por otro, varios episodios de inundación por tormenta (storm surge) de diversa índole han ido remodelando la línea de costa.

El método se ha validado en la zona de estudio descrita y se está replicando actualmente en la región del Mar de Frisia (Wadden Sea), incluyendo las costas holandesa, alemana y danesa del Mar del Norte, en el marco del proyecto FP7 ENHANCE (*Enhancing risk management partnerships for catastrophic natural disasters in Europe*, www.enhanceproject.eu). Este proyecto tiene como objetivo desarrollar y analizar nuevas formas de mejorar la resiliencia de la sociedad a impactos catastróficos asociados a amenazas naturales, proporcionar nuevos escenarios e información en varios casos de estudio en estrecha colaboración con actores costeros, y contribuir al desarrollo de nuevas asociaciones multisectoriales (*Multi-Sector Partnerships*, MSP) para reducir o redistribuir el riesgo.

6.5.3 Metodología y resultados

Marco conceptual de resiliencia

Para evaluar la capacidad de una comunidad para organizarse antes, durante y después de un potencial evento a fin de minimizar los impactos, se necesita entender los conceptos de capacidad de respuesta (*coping capacity*) en el corto plazo y capacidad de adaptación (*adaptive capacity*) en el largo plazo. El primero se refiere al ciclo de gestión de desastres, es decir, a las fases de prevención, preparación, respuesta y recuperación. La Figure 6.30 conceptualiza y resume todos los aspectos considerados en la evaluación de la resiliencia ante eventos de inundación por tormenta, que se explicarán a lo largo de esta sección. El marco muestra los vínculos entre las dimensiones institucional y social relacionados con los procesos de gestión del riesgo y la emergencia, los factores psicológicos y sociales que condicionan la preparación individual y de la comunidad, así como los requisitos legales para mejorar tanto la preparación de la comunidad como la gestión del riesgo y la adaptación a largo plazo.

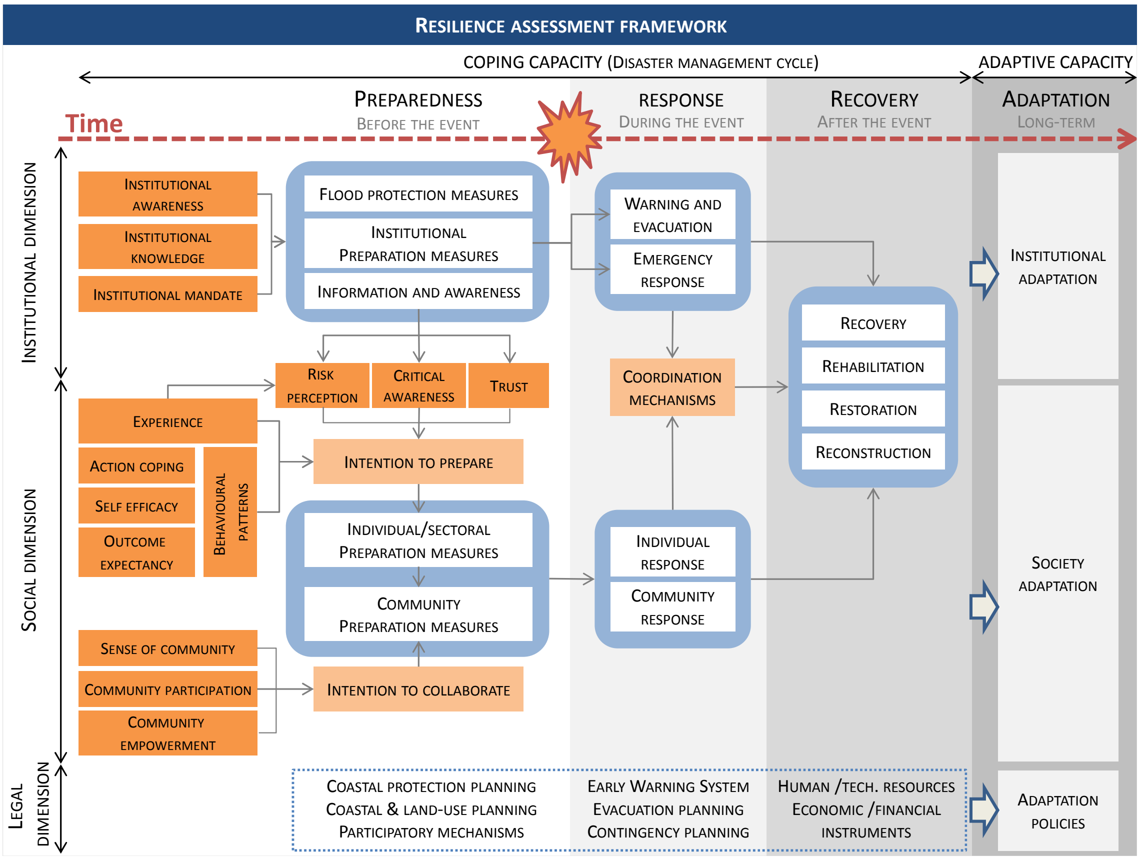

Figure 6.30 Marco conceptual para la evaluación de la resiliencia que integra el ciclo de la gestión de la emergencia, la capacidad de adaptación y las dimensiones del sistema analizado. Las diversas etapas de preparación, respuesta y recuperación a llevar a cabo por las instituciones y la sociedad, así como las políticas necesarias para ello, se muestran en cajas azules. Las cajas de color naranja representan los factores que condicionan la intención de preparación de instituciones y sociedad.

Además de esta valoración temporal en el corto y el largo plazo, el análisis de la capacidad de organización de una comunidad debe considerar diferentes dimensiones para comprender mejor la complejidad del sistema. La preparación ante desastres se define como el conocimiento y las capacidades desarrolladas por gobiernos, profesionales de la emergencia, organizaciones para la recuperación post-desastre, comunidades y personas para prever, hacer frente y recuperarse de los impactos de los eventos de amenazas probables, inminentes o actuales (UNISDR, 2009). Por lo tanto, se debe analizar tanto la actuación institucional como la social, ya que un déficit en una habilidad específica en cualquiera de estas dimensiones podría implicar una gestión parcialmente ineficaz, o nula en el peor de los casos. Esta evaluación conjunta institucional-social, similar al la propuesta por Becker et al., (2011), se complementa con la dimensión legal con el fin de incorporar las políticas que condicionan y ayudan en la adaptación. Las deficiencias encontradas en el análisis se señalan los desafíos a los que una comunidad se enfrenta a la hora de fomentar una adaptación adecuada.

La adaptación institucional implica la mejora de cada tarea relativa al ciclo de la gestión de desastres (IOTWS, 2009; González-Riancho et al, 2014), como las medidas de prevención/mitigación (p.ej. protección contra inundaciones), de preparación (coordinación vertical/ horizontal, información y sensibilización del público), de alerta y evacuación (sistemas de alerta temprana, planes de evacuación), de respuesta a emergencias (protocolos de emergencia, planes de contingencia, etc.) y de recuperación (equipos, presupuesto económico, etc.). La concienciación y el conocimiento sobre el riesgo por parte de las instituciones, así como el mandato específico para su gestión, van a afectar el nivel de ejecución de cada fase.

La adaptación de la sociedad, sin embargo, es voluntaria y más compleja de entender debido a la diversidad de valores, culturas de riesgo, percepciones y dinámicas sociales. El voluntarismo asociado a la conducta de una sociedad hace necesario analizar la potencial adaptación al riesgo en términos de "intenciones", entendidas como la representación cognitiva de la disposición de una persona para realizar una conducta determinada, y considerada el antecedente inmediato del comportamiento (Ajzen, 1991). Además del comportamiento individual de protección como predictor de la preparación, es importante entender la capacidad de la sociedad en su conjunto para trabajar de forma colaborativa y si esta colaboración se apoya en mecanismos de coordinación y empoderamiento promovidos por las autoridades (Becker et al., 2011). El cumplimiento de ambos requisitos, sociales e institucionales, es esencial para el desarrollo de posibles asociaciones para mejorar la resiliencia de la sociedad ante eventos catastróficos. Los factores condicionantes del comportamiento, la intención y la motivación para actuar que se presentan en el marco conceptual se inspiran en el trabajo realizado por Paton (2003, 2005, 2010), Becker et al. (2011, 2013) y Birkmann et al. (2012a).

Método y cuestionario de resiliencia

Partiendo de las consideraciones teóricas y el marco conceptual presentado en la Figure 6.30, se ha diseñado un cuestionario para evaluar la resiliencia ante inundación por tormenta (Table 6.5). Este cuestionario analiza la opinión de diversos actores (stakeholders) y la percepción sobre: (1) la preparación institucional, individual/sectorial y comunitaria, y (2) la viabilidad de potenciales figuras de coordinación, mecanismos económicos y políticas para la reducción del riesgo.

Table 6.5. Cuestionario aplicado, incluyendo los criterios de resiliencia tratados cada pregunta.

Criterios de resiliencia		Pregunta sobre:
Información sobre riesgos y preparación institucional	Impactos esperados	Los impactos que podría generarse en caso de evento de inundación por storm surge
	Información y conocimiento	La información sobre storm surge actualmente provista por las autoridades
	Toma de decisiones basada en conocimiento técnico	La medida en que el riesgo de storm surge está siendo considerada en la toma de decisiones sectorial.
	Medidas de protección frente a inundaciones	La efectividad de las actuales medidas de protección frente a inundaciones
	Opciones de preparación y recuperación	La disponibilidad de opciones de preparación y recuperación frente a inundaciones
	Alerta	El tipo de alerta utilizada actualmente en caso de evento de storm surge.
	Autoridades responsables	Las autoridades responsables de los distintos procesos en la gestión del riesgo ante storm surge.
Preparación sectorial y comunitaria	Concienciación crítica	Los principales problemas por los que los stakeholders se preocupan.
	Confianza	La medida en que los stakeholders confían en las instituciones, mecanismos y estructuras relacionadas con la gestión del riesgo ante storm surge.
	Experiencia	La experiencia con eventos importantes de inundación por storm surge.
	Percepción del riesgo	La percepción del riesgo que tienen los stakeholders en relación a su sector público/privado, actividades laborales y residencia.
	Patrones intencionales	El nivel de participación que los stakeholders creen que su sector debe tener dentro de la gestión de riesgos.
	Patrones de comportamiento	El actual comportamiento proactivo / reactivo de los diversos sectores y stakeholders y la medida en que es considerado por las autoridades.
	Medidas de preparación	La realización de diferentes medidas de preparación y las principales limitaciones a las que se enfrentan los stakeholders.
	Participación de la comunidad	El nivel de participación e implicación de los miembros y sectores de la comunidad en la gestión de riesgo.
	Stakeholders activos	Los stakeholders/personas que actualmente tienen un papel activo en la protección ante storm surge dentro de la comunidad.
Mecanismos de coordinación y opciones de política costera	Estructura de las asociaciones	La posible participación de varios stakeholders seleccionados en una potencial asociación para la reducción de riesgos.
	Beneficios de las asociaciones	Los principales beneficios que estas asociaciones podrían generar.
	Dificultades de las asociaciones	Los principales desafíos/dificultades a las que estas asociaciones podrían enfrentarse.
	Potenciales medidas de reducción de riesgo	La adecuación de los diversos instrumentos económicos, medidas y opciones políticas.

Las incoherencias detectadas entre la percepción de las autoridades y la sociedad se identifican automáticamente como un tema crítico para las medidas de mejora de la resiliencia (González-Riancho et al., 2014). A raíz de las recomendaciones formuladas por la CE (2002), para efectuar un inventario integrado de stakeholders, la identificación de los participantes de la encuesta debería determinar los principales actores e instituciones en el área expuesta que influyen o se ven afectados por la gestión de riesgos de sus zonas costeras. El inventario debe considerar todos los niveles administrativos y sectores económicos; analizar los intereses y preocupaciones de los ciudadanos, las organizaciones no gubernamentales (ONG) y el sector empresarial; e identificar las organizaciones inter-regionales y estructuras de cooperación relevantes.

El cuestionario incluye diferentes tipos de preguntas (puntuación, selección y respuesta abierta), todas ellas compuestas por varias sub-preguntas. Una vez completado el cuestionario, cada sub-pregunta puede ser analizada por separado o agregada para crear una puntuación por pregunta. Se muestran en el artículo los diferentes métodos de agregación aplicado para cada tipo de pregunta.

Resultados

La evaluación realizada permitió identificar las principales características de la zona de estudio en cuanto a las partes interesadas la percepción del riesgo, la intención de preparar y pautas de comportamiento, así como su opinión sobre las autoridades de la toma de decisiones. Esto proporcionó una visión muy útil sobre la preparación institucional, sectorial y comunitaria en Dithmarshen y las opciones para aumentar su capacidad de recuperación.

Se presentan a continuación algunos de los resultados gráficos obtenidos, si bien el análisis detallado de los mismos aparece en el artículo.

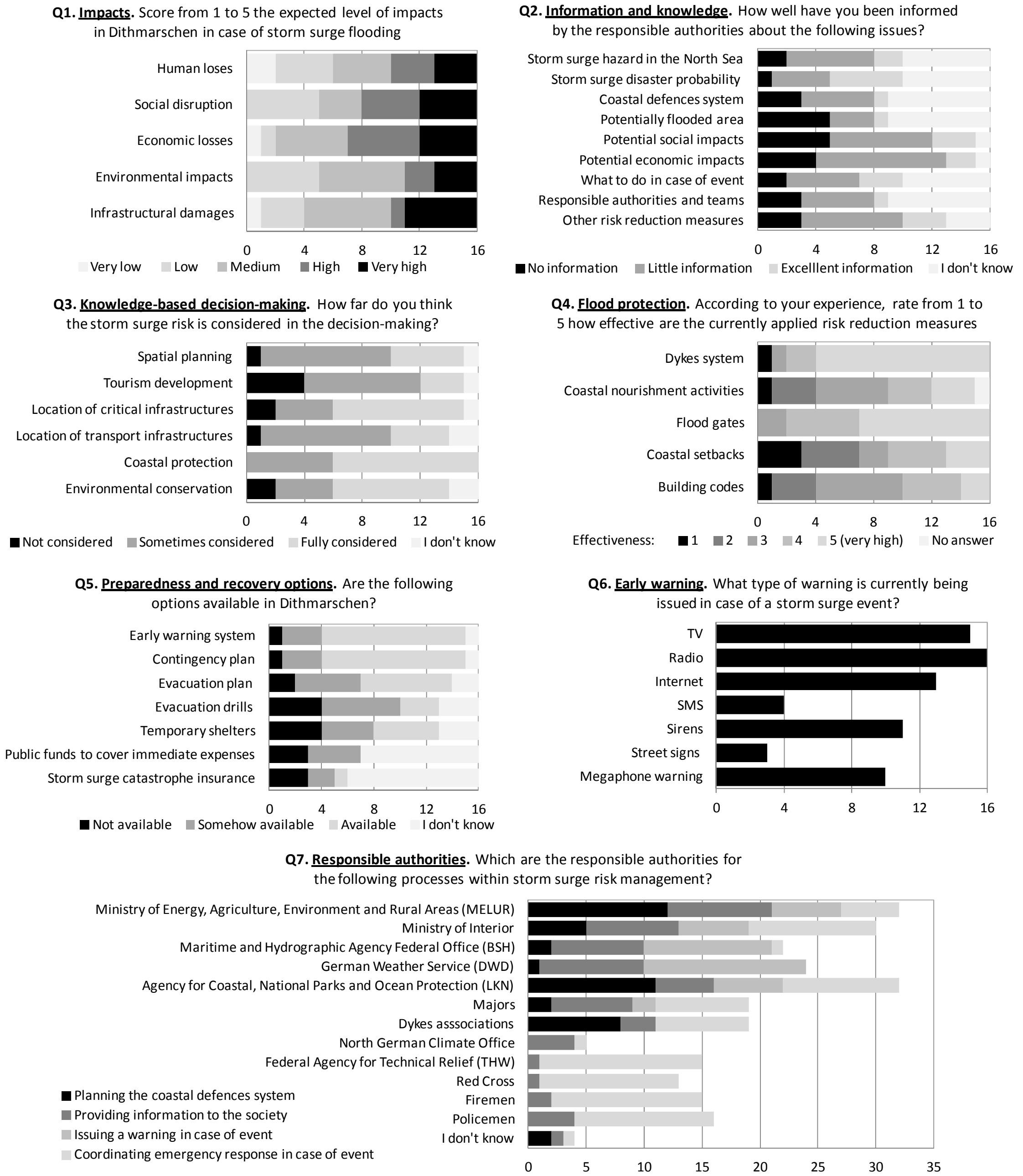

Figure 6.31 Información sobre el riesgo y preparación institucional

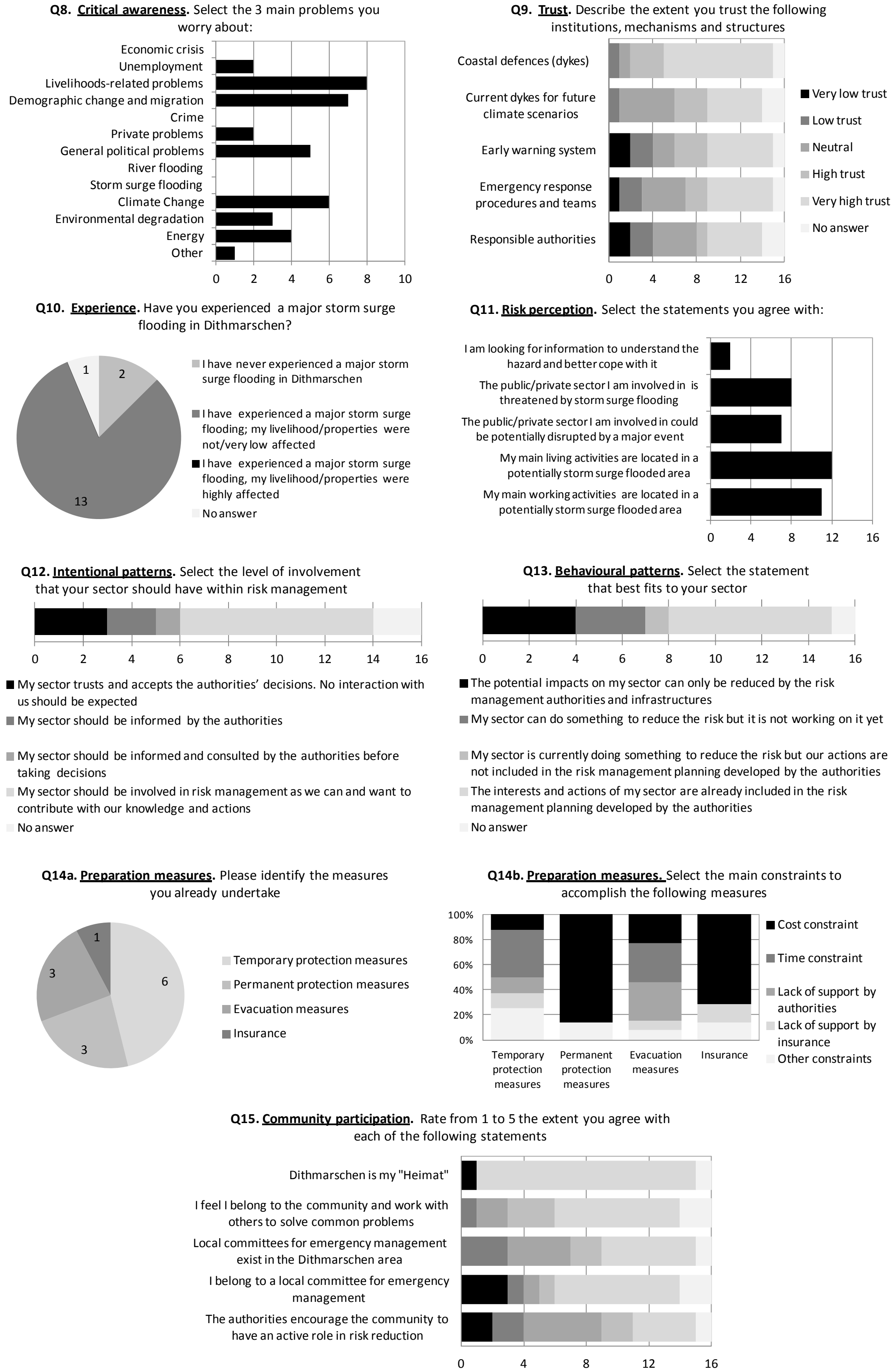

Figure 6.32 Preparación sectorial y comunitaria

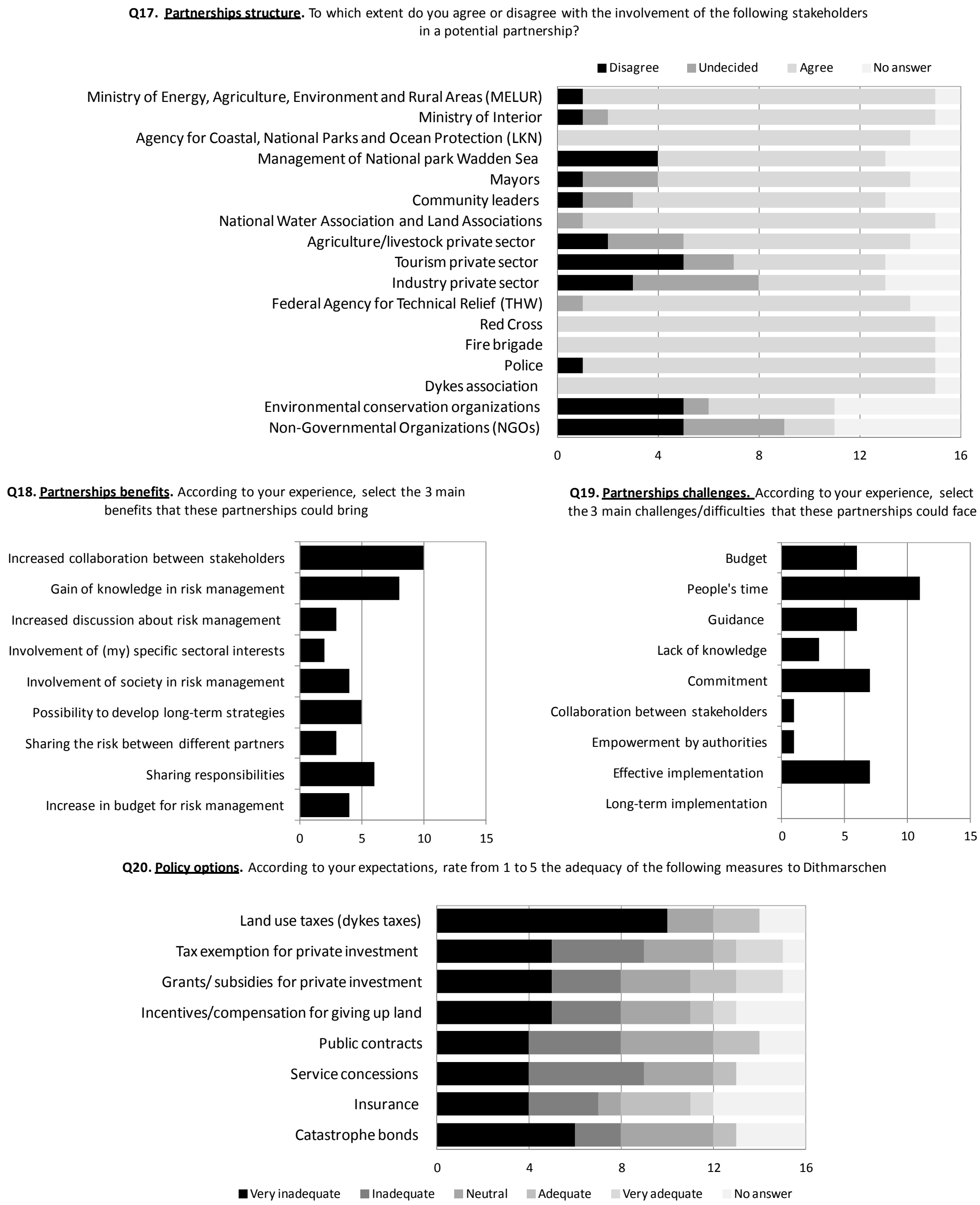

Figure 6.33 Mecanismos de coordinación y opciones de política costera

En base a los métodos de agregación presentados en el artículo, se han obtenido para el área de estudio los siguientes valores por pregunta (Table 6.6). Estos valores se han clasificado en 5 clases, de muy bajo a muy alto, para entender mejor el grado en que pueden ser necesarias medidas de reducción de riesgo. Los resultados específicos obtenidos para cada pregunta y sub-pregunta se presentan de manera detallada en el artículo y se resumen a continuación.

Table 6.6 Resultados del cuestionario por pregunta

Pregunta de resiliencia	Tipo de pregunta	Valor	Clase (5)
Q1. Impactos esperados	Puntuación (5)	0,67	Alta
Q2. Información y conocimiento	Puntuación (3)	0,32	Media
Q3. Toma de decisiones basada en conocimiento técnico	Puntuación (3)	0,61	Alta
Q4. Medidas de protección frente a inundaciones	Puntuación (5)	0,73	Alta
Q5. Opciones de preparación y recuperación	Puntuación (3)	0,35	Media
Q6. Alerta	Selección (varias)	0,92	Muy alta
Q7. Autoridades responsables	Selección (varias)	Cualitativo	Baja
Q8. Concienciación crítica	Selección (varias)	0	Muy baja
Q9. Confianza	Puntuación (5)	0,69	Alta
Q10. Experiencia	Selección (1)	0,58	Media
Q11. Percepción del riesgo	Selección (varias)	0,50	Media
Q12. Patrones intencionales	Selección (1)	0,66	Alta
Q13. Patrones de comportamiento	Selección (1)	0,64	Alta
Q14. Medidas de preparación	Selección (varias)	Cualitativo	Media
Q15. Participación de la comunidad	Puntuación (5)	0,67	Alta
Q16. Stakeholders activos	Respuesta abierta	Cualitativo	No aplicable
Q17. Estructura de las asociaciones	Puntuación (3)	Cualitativo	Baja
Q18. Beneficios de las asociaciones	Selección (varias)	Cualitativo	No aplicable
Q19. Dificultades de las asociaciones	Selección (varias)	Cualitativo	No aplicable
Q20. Potenciales medidas de reducción de riesgo	Puntuación (5)	0,26	Baja

Las conclusiones del análisis, se presentan a continuación, proporcionan información esencial para la comprensión de la cultura de riesgo de la zona y contribuir a la promoción de los procesos de gestión de riesgos específicos del lugar.

De acuerdo a los resultados del cuestionario, la comunidad de la zona de estudio espera impactos elevados en Dithmarschen debido a potenciales eventos de storm surge, los mayores daños estando asociados a las infraestructuras y la dimensión socio-económica. Según los encuestados, existe algo de información disponible relacionada con algunos aspectos relativos al riesgo de storm surge, pero definitivamente no es suficiente para crear conciencia y mejorar la preparación de la sociedad. Alrededor del 80% de los encuestados declaró para cada tema analizado que no existe, hay poca o que no saben si hay información disponible. Más de la mitad de los encuestados no sabe, por ejemplo, si existen instrumentos económicos disponibles para hacer frente al riesgo. La información a mejorar incluye la relativa a (1) los impactos potenciales de un evento importante de storm surge, (2) las opciones de preparación / recuperación, (3) las autoridades responsables de las diferentes tareas dentro de la gestión del riesgo y la emergencia, y (4) la consideración de riesgo en la planificación sectorial. Los mecanismos de alerta son bien conocidos por todos los encuestados, algunos de los cuales sugirieron otras adicionales como redes sociales, sirenas en aquellas zonas donde no están actualmente disponibles y la alerta asociada a bomberos.

Un claro reflejo de la cultura característica en la zona, ligada a la continua ganancia de tierras al mar y protección frente a inundaciones, se muestra en una mayor credibilidad y confianza en medidas de protección ingenieriles (sistema de diques y compuertas), respecto a medidas blandas de protección (ordenación del territorio), y procedimientos, autoridades y equipos. Las defensas costeras actuales para futuros escenarios climáticos cuentan, sin embargo, con menor confianza. Los encuestados muestran cierta experiencia con eventos de storm surge pues el 81% ha experimentado un evento importante aunque con impactos menores. El riesgo de storm surge es, en efecto, percibido en Dithmarschen ya que el 75% de los encuestados se sienten personalmente amenazados debido a la localización de sus actividades laborales o su residencia en zonas potencialmente inundadas; y alrededor de la mitad siente que su sector está amenazado y que podría sufrir impactos. Sin embargo, son pocos (12%) los que están buscando información para afrontar mejor el riesgo.

A pesar de la experiencia y la percepción del riesgo, el storm surge no se considera un problema urgente o importante por los encuestados, ya que nadie lo seleccionó entre los tres principales problemas que les preocupan. Cabe pensar que en los 3 principales problemas que preocupan a la gente aparezcan asuntos cotidianos que dificulten el día a día como los relacionados con los medios de subsistencia, el cambio demográfico y la migración, o la criminalidad, por ejemplo. Sin embargo, el cambio climático aparece como el tercer problema más importante, lo que quizás sugiere el importante papel y la eficacia de las campañas de sensibilización sobre el cambio climático en todo el mundo y la falta de los mismos para storm surge en particular. El hecho de no considerar el storm surge como un problema urgente puede ser la causa de la prevalencia de las medidas de protección temporales y a corto plazo. Además de las limitaciones coste/tiempo, los encuestados señalan la falta de apoyo institucional y de las compañías de seguros para implementar muchas de las medidas, como la evacuación o la protección económica de sus pertenencias.

La mayoría de los encuestados prefiere una gestión participativa del riesgo y muestra un comportamiento proactivo en la reducción del riesgo, aunque las autoridades no hayan establecido aún esquemas de participación plena. La mayoría se siente “en casa”, tiene apego por Dithmarschen y trabaja con otros para resolver problemas comunes, a pesar de que esperan un mayor apoyo por parte de las autoridades en términos de participación de la comunidad.

En relación a potenciales asociaciones de stakeholders, se identificaron como los 3 principales beneficios el aumento de la colaboración, la responsabilidad compartida, y la ganancia de los conocimientos en la gestión de riesgos. Sin embargo, en la respuesta sobre la estructura de una potencial alianza se detecta una falta de concienciación acerca de la relevancia/utilidad de un enfoque integrado en estas asociaciones. Este enfoque integrado se refiere a la coordinación vertical y horizontal de los stakeholders (distintos niveles administrativos y diversos sectores). Existe un alto consenso sobre la participación de actores relacionados con la emergencia y la protección costera. Sin embargo, existe un elevado desacuerdo con la participación de actores sectoriales (como los sectores privados de la agricultura / ganadería, el turismo y la industria), los stakeholders ambientales y las ONG. La participación de las autoridades también cuenta con cierto desacuerdo. Por lo tanto, si el objetivo es fomentar asociaciones multi-sectoriales para la gestión del riesgo en la región es imprescindible realizar primero campañas de sensibilización respecto de la pertinencia del mencionado enfoque integrado. Los encuestados han identificado varios stakeholders como actualmente activos en la reducción del riesgo en Dithmarschen, incluyendo diversas autoridades administrativas, la asociación principal de diques y compuertas, las asociaciones locales de diques, el ministerio de comercio, la agencia de protección de costas, parques naturales y océano (LKN), las juntas de agua y las asociaciones de la tierra (LVB), el cuerpo de bomberos, y los agricultores. Estos stakeholders deberían ser definitivamente considerados en posibles asociaciones y enfoques participativos. Los 3 principales desafíos a los que los encuestados creen que se enfrentarían estas asociaciones son el tiempo y el compromiso de las personas, y la aplicación efectiva de las decisiones.

Por último, respecto a las posibles políticas e instrumentos económicos para hacer frente al riesgo de storm surge, alrededor de la mitad de los encuestados calificaron como inadecuadas/muy inadecuadas todas las medidas. Las tasas asociadas al uso del suelo (impuestos de dique) se consideran muy inadecuadas por la mayoría. Las opciones que reciben cierta aceptación (adecuado/muy adecuado), aunque con bajos porcentajes son las exenciones fiscales, subsidios/subvenciones, y los seguros, seguido de incentivos/compensación por abandonar terrenos costeros y los contratos públicos. En el momento e que se quieran implementar medidas de adaptación e instrumentos económicos en Dithmarschen, se debe tener en cuenta el actual desacuerdo con las opciones presentadas aquí, con el fin de diseñar medidas específicas para la zona de estudio.

6.5.4 Conclusiones

El marco conceptual propuesto permite evaluar la resiliencia de una comunidad mediante la comprensión y la integración de las capacidades institucionales, legales y sociales para hacer frente y recuperarse de un evento natural peligroso con el fin de minimizar los impactos en el corto plazo y adaptarse al riesgo a largo plazo. El método propuesta basado en el cuestionario de resiliencia ha demostrado ser válido para explorar la percepción de los stakeholders en relación a los procesos de gestión del riesgo y la emergencia, así como los factores psicológicos y sociales que condicionan la preparación individual y de la comunidad.

Las incoherencias detectadas entre la percepción de las autoridades y la sociedad se identifican automáticamente como un tema crítico para las medidas de mejora de la resiliencia. A modo de ejemplo, algunos de los resultados obtenidos del estudio piloto analizado en este trabajo muestran (i) la necesidad de una mejor estrategia de información en algunos temas específicos con el fin de mejorar el conocimiento y la preparación de la sociedad; (ii) el comportamiento proactivo actual y la preferencia por formas participativas de gestión de riesgos, a pesar de que aún no existen estrategias de participación plena promovidas por las autoridades; (iii) la necesidad de campañas de sensibilización respecto a la importancia y los beneficios del enfoque integrado en potenciales asociaciones, y (iv) la necesidad de diseñar instrumentos de adaptación a medida y específicos para la zona, ya que existe por parte de la sociedad un desacuerdo actual claro con algunas de las opciones de las que se dispone . Este tipo de resultados es muy útil para mejorar las iniciativas de reducción de riesgos por medio de la inclusión de las opiniones de la sociedad desde el inicio del proceso de gestión.

Las distintas conclusiones sobre la cultura del riesgo, la percepción y la preparación de la zona de estudio validan la utilidad del cuestionario aplicado para mejorar la resiliencia y la reducción de riesgos. Aunque algunas preguntas pueden necesitar algún tipo de adaptación para ajustarse adecuadamente a otras zonas de estudio, el marco conceptual y metodológico podría aplicarse en todo el mundo. El marco conceptual y el método presentado en este trabajo ha sido validado en el distrito de Dithmarschen, en la costa del Mar del Norte de Alemania, y se replican junto la región del Mar de Frisia, incluido el holandés, alemán y danés Costa del Mar del Norte, en el marco del proyecto FP7 ENHANCE.

Chapter 7. Conclusions

7.1 Introduction

Advances in the understanding and prediction of impacts allow for the development of risk reduction strategies for areas prone to natural hazards. Risk assessments are essential for the identification of the exposed areas and of the most vulnerable communities and elements, with the hazard, vulnerability and risk results being critical for the formulation of adequate, site-specific and vulnerability-oriented risk management options.

Risk-related works differ according to the risk component analyzed (i.e. hazard, exposure, vulnerability, impacts, resilience, coping capacity, etc.), the risk dimension dealt with (i.e. human, infrastructural, environmental, social, economic, administrative, legal, etc.), and the spatial scale tackled (i.e. regional, national, local, etc.), thereby proving the complexity associated to risk assessment and management.

Multiple risk and vulnerability frameworks and definitions exist; however, most of them are too theoretical and have low or difficult applicability. The vulnerability and risk assessment works found in the literature show a lack of integrated approach to understand complex systems and a need for clarifying the definition of vulnerability indicators. Finally, a gap has been found between science and management, since risk assessment results are not automatically connected to options for risk reduction.

This thesis deals with the vulnerability and risk assessment of coastal complex systems in order to move towards an integrated and holistic disaster risk management approach. The research carried out has resulted in 4 scientific papers published in different scientific journals included in the Journal of Citation Reports-Science Edition. The thesis covers the entire process from risk assessment to risk management, each of the scientific articles focusing on different risk components on which gaps in literature were identified. Figure 7.1 provides an overview of the thesis structure, where Article 1 provides the overall risk assessment framework and the next articles focus into different theoretical and methodological aspects of this framework.

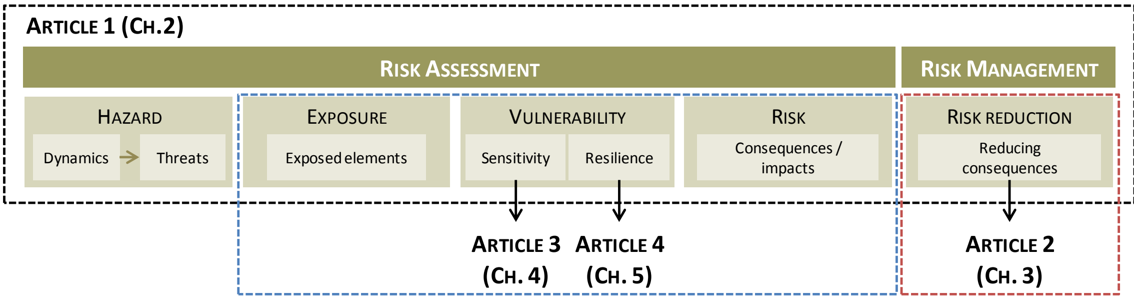

Figure 7.1 Overview of the thesis structure: relationship between thesis articles/chapters

The proposed methods can be applied to different natural hazards and different study areas; however, in order to improve reader's understanding and support the methodological approaches each scientific article presents the application of the proposed methods to specific hazards and study areas. Accordingly:

An integrated vulnerability and risk assessment framework has been proposed (article 1), together with a clear connection to translate the vulnerability and risk assessment results into adequate target-oriented risk reduction measures. The use of system's dynamics to understand the behaviour of the system and the interrelationships between the elements has been proved to allow for the proposal of different management scenarios to understand the effects of the decision-making and to optimise the DRM. The method has been applied and proved to be valid to the tsunami hazard in El Salvador, being adaptable to other hazards and study areas.

A framework for the formulation of tsunami evacuation plans based on tsunami vulnerability assessment and evacuation modelling has been proposed (article 2). It connects in a straightforward manner the scientific work with planning options, bridging the gap between risk assessment and risk management in terms of tsunami evacuation, as it allows for an estimation of the degree of evacuation success of specific management options, as well as for the classification and prioritization of the gathered information, in order to formulate an optimal evacuation plan. The method has been applied to the tsunami hazard in El Salvador and proved to be valid, being also adaptable to other flooding-related hazards and study areas.

The indicators currently proposed by the scientific community to measure human vulnerability have been validated in light of past tsunami events, to improve their definition and selection as well as to analyse their validity for different country development profiles (article 3). 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 are useful for future tsunami risk assessments worldwide.

A conceptual framework has been proposed to assess the resilience of a community by understanding and integrating the institutional, legal and social capacities to cope and recover from a natural hazardous event in order to minimize the impacts in the short-term and to adapt to the risk in the long-term (article 4). A survey-based method and a specific resilience questionnaire has been proposed to explore the perception of stakeholders regarding the risk and emergency management processes as well as psychological and social factors conditioning individual and community preparedness. The method has been applied and proved to be valid to the storm surge hazard in the German North Sea coast, being adaptable to other hazards and study areas.

This Chapter 7 provides a summary and a discussion on the major findings of the 4 scientific papers in order to capture the main conclusions from the research, as well as drivers for further research based on this work.

7.2 Summary of major findings

The main results from the thesis are related to (1) a better understanding and description of the complexity of coastal systems to adequately measure their vulnerability and risk to different natural hazards; and (2) a direct translation of the scientific work carried out to assess the risk into more useful and practical information for coastal managers and policy-makers. Based on this idea, the major findings of the various papers are the following:

7.2.1 On tsunami vulnerability and risk assessment

Multiple risk and vulnerability frameworks and definitions exist, however, very little information is provided about how to apply the existing theoretical and conceptual frameworks to a specific study-site and how to integrate the different risk-related concepts. Furthermore, risk assessment results sometimes do not provide conclusions on how to reduce the risk at the identified areas, lacking a clear correlation between risk assessment and management.

This paper presents the proposed integrated vulnerability and risk assessment framework for tsunami hazard and applies it to the case study of El Salvador. The methodology deals with the complexity and variability of coastal zones by means of:

- an integral approach to cover the entire risk-related process from the hazard, vulnerability and risk assessments to the final risk management
- an integrated approach to combine and aggregate the information stemming from the different dimensions of coupled human and natural systems
- a dynamic and scale-dependent approach to integrate the spatiotemporal variability considerations.

The approach is applicable to other types of hazards, having been successfully applied to river flooding and storm surge hazards.

This work also establishes a clear connection to translate the vulnerability and risk assessment results into adequate target-oriented risk reduction measures, bridging the gap between science and management for the tsunami hazard.

The use of systems dynamics to understand the behaviour of the system and the interrelationships between the elements has been proved to allow for the proposal of different management scenarios to understand the effects of the decision-making and to optimise the DRM. The example presented in the paper shows that one single action may have many results in complex systems, which is an interesting idea to bring forward in risk management. Working with complex systems is complicated, as many aspects, dimensions and variables should be considered and dealt with. However, once the system is understood, one can take advantage of this complexity to generate better results with less effort. Therefore, the understanding of complex systems allows for optimising the effort and getting the best results from the management options applied.

Working with scenarios provides the opportunity to understand the current system, predict the consequences of different plausible management options and, consequently, promote an adequate risk reduction plan for the studied area. It can be therefore a dynamic assessment of policy options and their response to existing feedback loops.

7.2.2 On tsunami evacuation modelling

Different partial aspects of tsunami risk and evacuation are addressed in the literature. With a view to the successful planning of the evacuation of the population located in a tsunami prone area, several gaps in the prevailing science are identified:

- no direct relationship between the specific evacuation-related assessments carried out and the formulation of risk reduction measures and/or an evacuation plan exists, even though some general connections are usually established
- an assessment of the characteristics of the population and communities to be evacuated is not usually undertaken
- the evacuation time is sometimes calculated without considering the tsunami arrival time, resulting in a lack of information regarding the degree of success that the identified evacuation time represents for the population
- an analysis of the time needed by the responsible administrations to issue the tsunami warning and to inform the population is sometimes not considered, although this is essential information for determining the real time available for the population to evacuate

- the evacuation modelling results sometimes do not identify, propose or suggest conclusions about how to reduce the risk of the populations identified in critical areas, regarding successful evacuation
- proposals for improvements in the evacuation process are frequently inadequate, lacking identification of locations to build new vertical shelters and evacuation routes, and omitting warning time reduction strategies, etc.

The objective of this paper is to present a framework that eliminates the above-identified gaps, providing a global picture of what is required for the adequate formulation of evacuation plans of a study area, and to present evacuation modelling as an essential tool for risk management. Accordingly, it presents an integral framework for the formulation of tsunami evacuation plans based on tsunami vulnerability assessment and evacuation modelling. This framework considers the following:

- the hazard aspects (tsunami flooding characteristics and arrival time)
- the characteristics of the exposed area (people, shelters and road network)
- the current tsunami warning procedures and timing
- the time needed to evacuate the population
- the identification of measures to improve the evacuation process.

A method for the identification of possible locations for vertical evacuation shelters has been proposed, providing useful information for each shelter, such as the tsunami arrival time, the response time, the time available to evacuate, and the reception distance for both population speeds. The combination of this information with the amount of people to be evacuated indicates the capacity that these shelters should accommodate.

The proposed methodological framework connects in a straightforward manner the scientific work with planning options, bridging the gap between risk assessment and risk management in terms of tsunami evacuation, as it allows for an estimation of the degree of evacuation success of specific management options, as well as for the classification and prioritization of the gathered information, in order to formulate an optimal evacuation plan.

The framework has been applied to the El Salvador case study, demonstrating its applicability to site-specific response times and population characteristics.

7.2.3 On tsunami human vulnerability indicators

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.

This work validates 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.

7.2.4 On storm surge risk perception and resilience

Resilience is defined as the capacity of a community to organise itself before, during and after a dangerous/hazardous event in order to minimise the impacts. A conceptual framework is proposed to assess the resilience of a community by understanding and integrating the institutional, legal and social capacities to cope and recover from a natural hazardous event in order to minimize the impacts in the short-term and to adapt to the risk in the long-term.

A survey-based method and a specific resilience questionnaire is proposed to explore the perception of stakeholders regarding the risk and emergency management processes as well as psychological and social factors conditioning individual and community preparedness. The entire questionnaire and its questions are clearly linked to the information the coastal manager obtains for a better risk management. Although some questions may need some type of adaptation to fit adequately to other study sites, the conceptual and methodological framework could be applied worldwide, the application to the Dithmarschen district in the German North Sea Coast being presented in this work. The study area and its population are characterized by their continuous interaction with the ocean, with the continuous transformation and reclamation of land for agricultural purposes by the population and the constantly reshape of the coastline and coastal inundation by several storm surge flooding episodes.

The assessment allows identifying the main characteristics of the study area in terms of stakeholders' risk perception, intention to prepare and behavioural patterns, as well as their opinion regarding authorities' decision-making on emergency and risk management, and potential multi-sector partnerships or adaptation measures for the area. The deficiencies and/or the incoherencies between society's and administration's answers found out in the analysis point out the challenges to deal with in order to foster an adequate community preparedness and adaptation to storm surge risk. Some of the results in the study area show:

- the need for a better information strategy to enhance society's awareness and preparedness
- the respondents' current proactive behaviour and preference on participatory risk management options, despite fully participatory schemes are not yet set by the authorities
- the need for awareness campaigns regarding the relevance and benefits of the integrated approach in potential partnerships
- the need for tailored and site-specific adaptation instruments and measures due to the current disagreement of society with some of the options provided.

This type of results is very useful to improve risk reduction initiatives by means of including society's opinions from the beginning of the management process. The framework and the questionnaire can be easily adapted to analyze the risk perception and resilience of the community regarding other type of hazards.

7.3 Drivers of further research

The present thesis draws the attention to the potential of different fields of knowledge and techniques to be used for reducing the risk due to natural hazards, and coastal flooding specifically, in future research.

Regarding the integrated vulnerability and risk assessment framework, the following lines of research are suggested:

- Validation of different methods to aggregate vulnerability indicators, such as weighted aggregation, k-means, etc., in order to identify advantages and disadvantages, as well as the factors conditioning the use of each method in specific study sites.
- A method to properly assess the system dynamics in order to prioritize risk reduction measures.
- A dynamic model to update the risk results may be incorporated into the methodology as an effective tool for adaptive risk management. It would be intended to gradually update the set of indicators, as the risk reduction measures are being implemented, allowing the systematic modification of the exposure, vulnerability and risk results and the understanding and utilising of the interrelation and feedback loops controlling the behaviour of the coupled human and natural system.

- Analysis of advantages and disadvantages of the use of deterministic and probabilistic hazard results for the risk assessment, as well as the factors conditioning the use of each method in specific study sites.

Regarding the integral framework for evacuation planning, the following lines of research are suggested:

- The application of different complex evacuation models within the framework, such as agent-based modelling for example, in order to identify advantages and disadvantages, as well as the factors conditioning the use of one or another in specific study sites.
- The slope calculation for a better evacuation modelling.
- The optimization process for shelter location. The methodology could be settled like a mathematical programming problem and solved by standard optimization procedures. The tower locations and its number would be the optimization or decision variables, and the problem could be stated in two different forms: (i) minimize the tower costs subject to the constraint that all inhabitants would have time enough to reach shelter on time; this case assumes that there are no budget limitations; or (ii) maximize the number of people reaching shelter on time, constraint by a limited budget. Although the first option is preferable, reality makes the second option most likely.
- Analysis of advantages and disadvantages of the use of deterministic and probabilistic hazard results for the evacuation planning, as well as the factors conditioning the use of each method in specific study sites.

Regarding the tsunami human vulnerability indicators, the following lines of research are suggested:

- Validation of further vulnerability indicators when additional databases are available.
- Identification of the combination of indicators that exacerbates the vulnerability to the tsunami hazard.
- Validation of the indicators related to understanding a warning message (age, education level, illiteracy, immigration, language skills and ethnicity) based on an existing EWS and several drill scenarios. The scenarios aim to capture the response of society to different levels of awareness and training.
- Identification of the human vulnerability drivers for other type of hazards.

Regarding the risk perception and resilience assessment, the following lines of research are suggested:

- Analysis of the connection between intention to prepare and actual implementation of preparedness measures.
- Analysis of the differences of perception between individual citizens and stakeholders from administration, private business, NGOs, etc., in order to identify potential gaps in information flows, imbalanced support from authorities, differences in intentions to

prepare and preparedness difficulties, etc. This information allows for a better definition of risk reduction and adaptation policies.

- Multi-sector partnerships
- Analysis of potential configurations and procedures for multi-sector partnerships, as a way of improving disaster risk management through sharing responsibilities and increasing support and understanding of the chosen direction and solutions.
- Analysis of methods to increase the awareness about the relevance of integrated approaches in multi-sector partnerships in order to increase the acceptance of different type of stakeholders stemming from different sectors.

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Integrated tsunami vulnerability and risk assessment: application to the coastal area of El Salvador

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Abstract. Advances in the understanding and prediction of tsunami impacts allow for the development of risk reduction strategies for tsunami-prone areas. This paper presents a tsunami vulnerability and risk assessment for the case study of El Salvador, the applied methodology dealing with the complexity and variability of coastal zones by means of (i) an integral approach to cover the entire risk-related process from the hazard, vulnerability and risk assessments to the final risk management; (ii) an integrated approach to combine and aggregate the information stemming from the different dimensions of coupled human and natural systems; and (iii) a dynamic and scale-dependent approach to integrate the spatiotemporal variability considerations. This work also aims at establishing a clear connection to translate the vulnerability and risk assessment results into adequate target-oriented risk reduction measures, trying to bridge the gap between science and management for the tsunami hazard. The approach is applicable to other types of hazards, having been successfully applied to climate-change-related flooding hazard.

1 Introduction

Advances in the understanding and prediction of tsunami impacts allow for the development of risk reduction strategies for tsunami-prone areas. Tsunami risk assessments are essential for the identification of the exposed areas and of the most vulnerable communities and elements, with the hazard, vulnerability and risk results being critical for the formulation of adequate, site-specific and vulnerability-oriented risk management options.

Risk-related works in the literature differ according to the risk component analysed (i.e. hazard, exposure, vulnerability, impacts, resilience, coping capacity, etc.), the risk dimension dealt with (i.e. human, infrastructural, environmental, social, economic, etc.), and the spatial scale tackled (i.e. regional, national, local, etc.), thereby proving the complexity associated to risk assessment and management. Regarding the existing literature on tsunami risk, several authors centre their work on the tsunami hazard itself, trying to understand its evolution from the generation and propagation phases until its arrival at the coastal area with the aim of predicting the tsunami location, magnitude, duration and probability (Gosenberg and Schlurmann, 2009; Harbitz et al., 2012; Álvarez-Gómez, 2013), while others propose a methodology for the integration of various hazards (Greiving et al., 2006). On the other hand, some authors' analyses are oriented towards the calculation of vulnerability and/or impacts at a specific location (UNDP, 2011; UNU-EHS, 2009; Villagrán de León, 2008) or on specific elements at that location such as the population (Sugimoto et al., 2003; Sato et al., 2003; Koshimura et al., 2006; Jonkman et al., 2008; Strunz et al., 2011), the exposed buildings and infrastructures (Tinti et al., 2011; Dall'Osso et al., 2009; Cruz et al., 2009; Grezio et

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al., 2012; Koeri et al., 2009; Jelínek et al., 2009), the environmental resources (Fundación-Terram, 2012; ECLAC, 2003) or the socioeconomic system (ECLAC, 2003). Many deal with resilience, coping capacities, preparedness, etc. (UNESCO, 2009a; Wegscheider et al., 2011; US IOTWSP, 2007), with some of them concentrating on tsunami evacuation modelling (Van Zuilekom et al., 2005; Aboelata and Bowles, 2005; Mück, 2008; Clerveaux et al., 2008; Alvear Brito et al., 2009; Kolen et al., 2010).

Individual risk, hazard and/or vulnerability assessments can be partial, sectoral or specific. However, risk management requires an integrated and holistic understanding of the coupled human and natural system (CHANS) dealt with, otherwise management options can produce unexpected and sometimes undesired results. According to Rotmans and Dowlatabadi (1998), the integrated assessment is aimed at combining, interpreting and communicating knowledge from diverse scientific fields in order to comprehensively tackle an environmental problem by stressing its cause–effect links in their entirety. Integration refers in this paper to the understanding and combination of risk components, dimensions and scales affecting a CHANS, one of the major challenges being the systematic combination and aggregation of different types of data and information (i.e. quantitative vs. qualitative) from various disciplines, scales and data acquisition methodologies.

Vulnerability is multi-dimensional and differential, as it varies across physical space and among and within social groups; scale dependent regarding time, space and analysis units; and dynamic, as the characteristics and driving forces of vulnerability change over time (Vogel and O'Brien, 2004). The current literature encompasses several different definitions, concepts, frameworks and methods to systematise vulnerability (Birkmann, 2006), very little information being provided about how to apply the different existing theoretical and conceptual frameworks and how to integrate the different risk-related concepts. Furthermore, risk assessment results sometimes do not provide conclusions on how to reduce the risk at the identified areas, lacking a clear correlation between risk assessment and management.

The starting point of this work is the existing theoretical frameworks and approaches such as the MOVE framework (Birkmann et al., 2013), Turner et al. (2003) or the BBC conceptual framework (Birkmann, 2006). The main expected contribution is to provide a straightforward method to facilitate the implementation of some theoretical concepts to case studies, as this is sometimes complex due to site-specific problems, lack of data or the lack of information about particular methodological aspects. The final aim of the risk assessment is the identification of the expected impacts on each dimension as input for the formulation of adequate target-oriented risk reduction measures.

The objectives and structure of this paper are the presentation of the integrated tsunami vulnerability and risk assessment carried out in El Salvador, considering the different risk components, dimensions and spatiotemporal scales and the methodological process to integrate them (Sect. 2), and the establishment of a clear connection to translate the vulnerability and risk assessments into risk reduction measures, trying to bridge the gap between science and management for the tsunami hazard, and its application to the coastal area of El Salvador (Sect. 3). Finally, some conclusions are presented in Sect. 4.

2 Integrated tsunami risk assessment for El Salvador

Due to the large array of terms on risk and vulnerability and the often unclear relationships between them, it is essential to first clarify the conceptual framework applied in this paper. Regarding the risk components, this methodology is based on the definition of *risk* as the probability of expected harmful consequences or losses resulting from interactions between natural or human-induced hazards and vulnerable conditions (UN/ISDR, 2004), the mentioned consequences being the negative effects of disaster expressed in terms of human, economic, environmental, infrastructural and social impacts (adapted from ISO, 2009). Therefore, risk depends on the specific impact analysed (e.g. loss of human lives), the characteristics of the threat (e.g. flooding), the exposure of the studied elements (e.g. people in urban areas) and their vulnerability (sensitive groups and resilience).

The *hazard* as a dangerous phenomenon (UN/ISDR, 2009) is analysed based on the different associated threats (which are characterised by their location, intensity, duration, frequency and probability) together with their dynamics – i.e. variables and physical processes, involved in their generation. As an example, the specific threats to deal with when analysing climate change hazard could be, among others, sea level rise or an increase in tropical cyclones and droughts, while the dynamics to study would be waves, tides, sea level, sea temperature, precipitation, etc.

Exposure refers to people, property, systems, or other elements present in hazard zones that are thereby subject to potential losses (UN/ISDR, 2009), while *vulnerability* to the conditions is 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). These vulnerability conditions are here understood to be of two types, internal (unchangeable individual conditions, such as the age of the population) and external (changeable community conditions, improvable through learning and experience, such as risk preparedness within the communities), the improvement of the latter being a possible countermeasure to reduce the vulnerability of highly sensitive areas. Accordingly, *sensitivity* refers to the intrinsic characteristics of the exposed elements that make them potentially affected by physical or socioeconomic changes, including damage and losses (adapted from UN/ISDR, 2004), while *resilience* is the ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions (UN/ISDR, 2009).

The success or failure of many policies and management practices is based on their ability to take into account complexities of CHANS (Liu et al., 2007). Understanding the interrelationships between human societies and their behaviour patterns, coastal resources and their uses, as well as policies and institutions that govern human activities is essential for adequate coastal management. This requires an integrated and multidisciplinary approach to analyse the entire system in order to understand the feedback loops that manage its behaviour and equilibrium instead of simply considering specific aspects of a single sector or scientific discipline. This approach is applied here throughout the exposure and vulnerability assessments, as they are fragmented to incorporate different coastal dimensions (human, environmental, socioeconomic and infrastructural dimensions) within the tsunami risk assessment, based on EC (2010), the Hyogo Framework for Action (UN, 2005) and the impacts generated in recent tsunami events. Contrary to other previous works found in the literature, the human and socioeconomic dimensions are separated here on purpose, as the information regarding the human dimension will directly feed the evacuation planning of the area (González-Riancho et al., 2013), while the socioeconomic dimension focuses on livelihoods and economic losses. The elements at risk vary with time and space, as both factors will change the amount and type of exposed and vulnerable elements. For this reason, and according to EC (2010), impact assessments are defined based on a reference space-time window.

Figure 1 shows the entire process to integrate the risk components, dimensions and spatial scales. Regarding the integration of dimensions and according to EC (2010), two types of results are provided, partial and aggregated results. The former allow having the analysed impacts available separately for the different dimensions and components, while the latter combines all the dimensions. Based on the results of the risk assessment and according to UNESCO (2009b), the risk can be mitigated by reducing the vulnerability to the hazard and improving preparedness. Within the work presented here, this translates into the formulation of risk reduction measures to reduce the partial exposure and sensitivity, and to enhance the resilience at the municipality level.

As shown through the colour-coded arrows, the construction of aggregated indices – i.e. exposure, sensitivity and vulnerability, is performed through weighted aggregation (blue vertical arrows) while the risk calculation, both partial and aggregated results, is performed through the risk matrix (red horizontal arrows). The main advantage of this approach is the generation of partial and aggregated results as well as the possibility of disaggregating them again into risk components, dimensions and indicators, in order to understand the precise cause of the obtained results, and thereby provide essential information for risk management (black arrows).

This approach, although presented in this paper for the tsunami hazard, can be used for other types of hazards, having been already applied by IH Cantabria to climate change-related flooding in Peru and El Salvador within the framework of the Inter-American Development Bank project Probabilistic Hazard and Vulnerability Assessment Report based on Climate Change Projections (2012).

2.1 Case study

El Salvador is located in an area of high seismic activity which was hit by 15 tsunamis between 1859 and 2012, 9 of which were recorded in the 20th century. All of the tsunamis were generated by earthquakes, and two of them were highly destructive; one in 1902 that affected the eastern coast of the country and one in 1957 that affected Acajutla. The most recent, albeit of lesser magnitude, occurred in August 2012, affecting Jiquilisco Bay (IH Cantabria-MARN, 2012). The work presented here is framed within a project for assessing the tsunami risk in coastal areas worldwide, and applied specifically to the coast of El Salvador during the 2009–2012 period.

Table 1 shows the specific structure of the tsunami risk assessment applied to the coastal area of El Salvador, which is based on the pre-established expected consequences that are of interest to the Ministry of Environment and Natural Resources (MARN) of El Salvador; it is according to them that the vulnerability indicators (described in Sect. 2.3) are defined.

The spatial scale considers the national and local levels, the municipality being the planning unit. The national level includes the 29 coastal municipalities, while the local scale focuses on 3 specific areas that include 10 municipalities: the Western Coastal Plain (San Francisco Menéndez, Jujutla and Acajutla municipalities), La Libertad municipality and Jiquilisco Bay (Jiquilisco, Puerto El Triunfo, Usulután, San Dionisio, Jucuarán and Concepción Batres municipalities). As proposed by Turner et al. (2003), different factors shaping the risk at various spatio-temporal scales are considered, the population movements due to holiday patterns (rainy season/dry season, week/weekend) in the human system and the migration patterns or breeding/nesting periods for the environmental system.

The hazard assessment is carried out through a deterministic analysis to understand the worst possible case scenario, as carried out by Jelínek et al. (2009) and Wijetunge (2014). The use of a deterministic approach does not allow for the provision of the risk results in terms of a probability of negative consequences for different tsunami return periods; instead it permits the identification, location and quantification of the expected negative consequences or impacts for the worst possible credible scenario as the main outcome of the risk assessment. To calculate the expected consequences, the

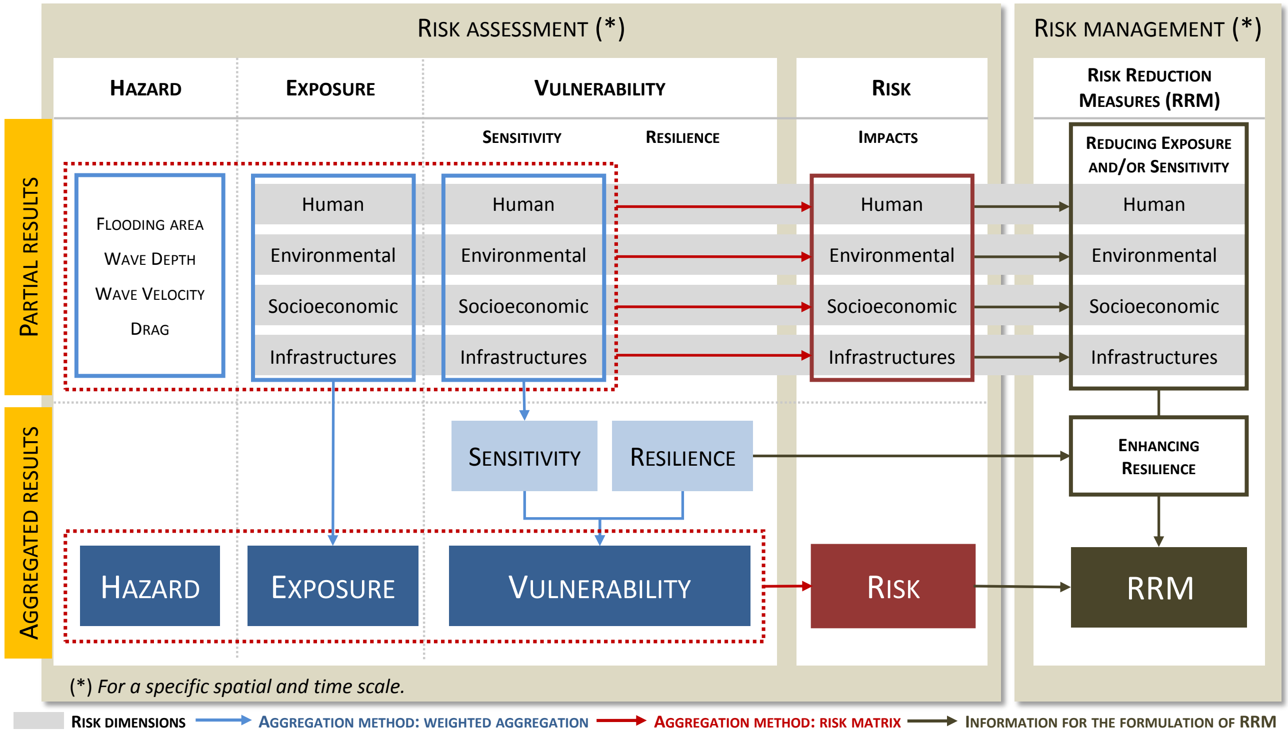

Figure 1. Structure of the risk assessment and different kind of results to be obtained (RRM = risk reduction measures).

threat analysis differs according to each dimension to better understand the potential impacts or due to the lack of detailed information and/or methods in the literature to assess the specific damage levels. As a result, in this case study drag is applied to the human dimension, water depth to buildings, and flooded area to the environmental, socioeconomic and infrastructural dimensions.

Accordingly, the national assessment focuses on the identification of the most critical municipalities in terms of likelihood of impacts for the worst credible event, which facilitates their prioritisation regarding further detailed studies, risk management efforts and resources (Fletcher, 2005). The likelihood of impacts within this qualitative risk assessment derives from the vulnerability variability and uncertainties. The local assessment aims at the calculation of specific expected impacts on the different dimensions by municipality. These worst-credible-event results allow the authorities organising and managing the risk to provide the most protective situation, so that the formulation of measures is on the side of safety and as conservative as possible in order to ensure their validity for different scenarios. Some of the results obtained for the national level and the Western Coastal Plain are presented in this paper.

2.2 Tsunami hazard assessment

The hazard assessment is based on propagation models for earthquake-generated tsunamis, developed through the characterisation of tsunamigenic sources – seismotectonic faults – and other dynamics such as tsunami waves, sea level, etc. Simulations of historical and potential tsunamis with greater or lesser impacts on the country's coast have been performed (Fig. 2), including distant sources (distances greater than 2000 km to the coast, with tsunami travel times greater than 4 h), regional sources (between 700 and 2000 km with tsunami travel times between 1 and 4 h), and local sources (located in the subduction trench off the country's coast with tsunami travel times of less than 1 h).

The numerical propagations have been simulated using the C3 model "Cantabria–Comcot–Tsunami–Claw model" (Olabarrieta et al., 2011). This model was developed by IH Cantabria and it combines two models: COMCOT and Tsunami–Claw (LeVeque et al., 2011) in order to solve nonlinear shallow water equations (NSWE). C3 is a finite differences numerical model validated and applied to several historical tsunami events such as the 1960 Chilean tsunami (Liu et al., 1994), the 1992 Flores Islands (Indonesia) tsunami, the 2004 Indian Ocean tsunami and the Algerian tsunami 2003 (Wang and Liu, 2005). Additionally, the model has been validated using the benchmark cases proposed within the framework of the European Tsunami Project TRANSFER (Tsunami Risk And Strategy For the European Region). C3 is especially designed to simulate tsunami events. The parameters of the earthquake can be introduced via the Okada fault model (Okada, 1985). The model then solves the NSWE using a gridded domain. It provides data such as free surface

Table 1. Structure of the Tsunami Risk Assessment applied to El Salvador coastal area.

Risk			Hazard			Exposure	Vulnerability	
Consequences	Time-scale	Spatial scale	Probability	Dynamics	Threat	Exposed elements	Sensitivity	Resilience
Loss of lives due to • reduced mobility • difficulties understanding a warning message • bad housing materials and lack of recovery capacity • difficulties in receiving a warning and evacuating in badly connected areas • difficulties in performing a coordinated evacuation	Annual Seasonal	National Local	Deterministic analysis (aggregation of the 23 worst credible tsunami cases)	Tsunamigenic sources Sea level Tsunami waves Tides	Drag	People	Sensitive age groups Illiteracy Extreme poverty Disability (physical/intellectual) Isolation Critical evacuation	Information & awareness Warning & evacuation Emergency response Recovery
Loss of protected ecosystems Loss of unique ecosystems (coral reef) Loss of ecosystem services (mangrove) Loss of endangered species Permanent destruction of ecosystems	Annual Seasonal	National Local			Flooding area	Ecosystems	Protection Singularity Threat Degradation	
Loss of area of socioeconomic activities Loss of jobs Loss of gross domestic product (GDP) Loss of foreign trade	Annual	National Local			Flooding area	Socioeconomic activities	Job generation Contribution to GDP Contribution to foreign trade	
Pollution of wells, hindering long-term water supply to local communities Loss of essential evacuation routes Generation of cascading impacts due to hazardous/dangerous industries Loss of emergency and health services, essential during the event	Annual	National Local			Flooding area	Infrastructures	Water supply (wells) Roads Hazardous/dangerous industries Emergency/health infrastructures	
Impacts on critical buildings (housing large population) Loss of potential vertical shelters Destruction of buildings	Annual	Local			Water Depth	Buildings	Critical buildings Vertical evacuation Building materials	

elevation at every point on the grid, or temporal series of velocity and total depth at each point. In the case studied in this paper, 4 levels of nested grids have been used in order to obtain a cell size of 30 m on the coast of El Salvador. The run-up calculation at the areas where no local grids were available has been carried out using the Synolakis (1987) validated empirical formulations. Further information on this hazard assessment is provided by Álvarez-Gómez et al. (2013) and IH Cantabria-MARN (2010).

As mentioned above, a deterministic analysis which aggregates the 23 worst credible cases of tsunamis that could impact on the Salvadoran coast (see Fig. 2) has been carried out, with the main output being different hazard maps along the coast of El Salvador and at some relevant locations with high-resolution analysis. The generated hazard maps include the following: maximum wave height elevation, maximum water depth, minimum tsunami arrival time, maximum flooding level or "run-up", and maximum potential drag (understood as the hazard degree for human instability based on incipient water velocity and depth). Fig. 5a shows one of the tsunami hazard maps generated at the national level, which allows for the identification of the areas subjected to higher tsunami water depths and consequently to a higher impact.

2.3 Tsunami vulnerability and risk assessment

The hazard area calculated allows identifying the number and type of exposed elements for the four dimensions (i.e. human, environmental, socioeconomic and infrastructural). The exposure assessment identifies the elements located in the hazard area, while the vulnerability assessment measures the characteristics of the exposed elements that make them

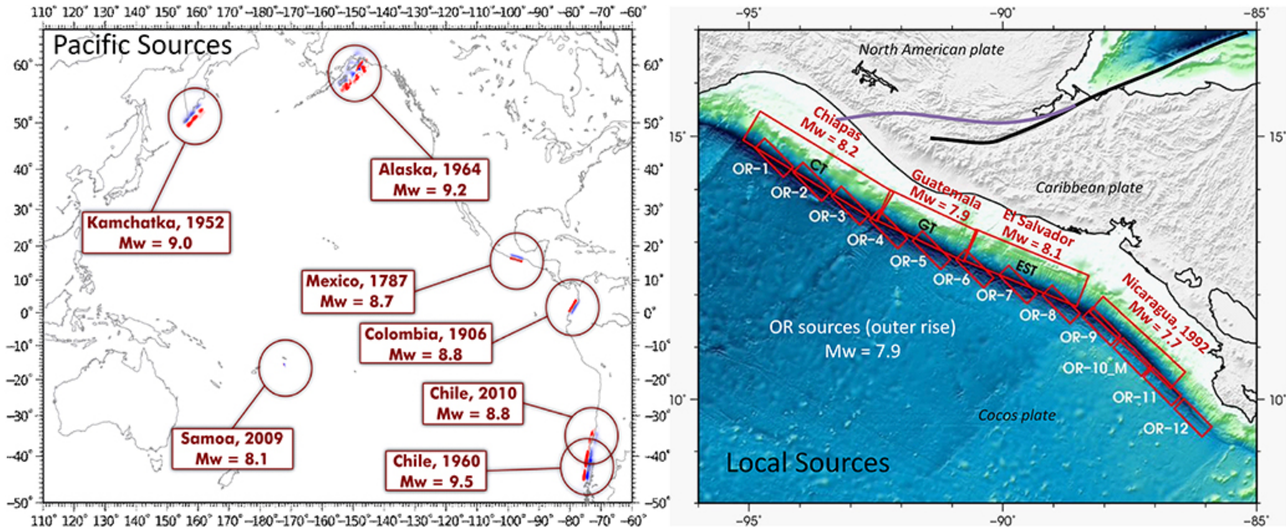

Figure 2. Distant, regional and local tsunamigenic sources of historical and potential tsunamis that could impact on the Salvadoran coast have been aggregated for the deterministic hazard assessment.

susceptible to suffering the selected impacts. Thus, vulnerability focuses on the expected impacts by municipality on the different dimensions and their potential worsening implications for the populations due to existing feedback loops (for example, the loss of household income due to loss of livelihood-related natural resources, the loss of recovery capacity of the country due to the loss of area of specific socioeconomic activities, or the lack of long-term water resources for some coastal communities due to the affection of coastal wells, among others). This is the main justification for the mixed indicator approach presented below. A partial human analysis could seem enough for reducing life losses; however, understanding all the potential implications of a tsunami event in a specific area will help in promoting awareness and preparedness. On the other hand, this global understanding of the system has the disadvantage of sometimes resulting in a superficial analysis of some of the impacts analysed.

Two different and complementary aspects for feedback loops existing in CHANS are perceived depending on the reference to specific static assessments or to holistic and time-evolving management. As described by Cutter et al. (2008) for the antecedent conditions of resilience, the sensitivity assessment is carried out in this work for a specific moment, it can be seen as a snapshot in time or a statistic state, the result being a precise value for each partial sensitivity (human, environmental, etc.) independently of the existing feedback loops within the system. Feedback loops are essential and are considered in this work as the only way to understand the behaviour of the system and to correctly manage it in terms of risk reduction, this being the reason for designing the set of indicators through the integrated approach.

2.3.1 Definition of exposure and vulnerability indicators

A set of indices and indicators are developed to calculate the exposure and sensitivity of the coastal dimensions as well as the resilience of the society and communities at risk. To carry this task out, several mathematical–statistical procedures are applied in order to produce comparable and combinable information. A Geographic Information System allows supporting every decision with geo-referenced information, being an essential tool for the combination of partial maps related to each dimension and particularly useful for evacuation modelling and planning (González-Riancho et al., 2013). The following sections describe the set of indicators and the methodology used to integrate them.

Based on the steps suggested by the Handbook on Constructing Composite Indicators (OECD, 2008), the proposed set of indicators is presented in Table 2. This set is adapted to different spatiotemporal scales: the spatial scale includes both national and local levels, while the timescale considers the movements caused by holiday patterns in the human population. It is important to point out the analytical soundness of all the indicators, the independence among them and the relevance of the measured phenomenon. The robustness, sensitivity and transparency of the indicator system allow managing the information at the index level as well as separating them into the different indicators and working directly with the base data, which is essential for not losing information while aggregating results, and for the formulation of adequate risk reduction measures.

The human sensitivity indicators (S1–S6) are oriented to measure the municipalities' weaknesses in terms of evacuation and recovery capacities of the exposed population. Accordingly, difficulties in understanding a warning message

Table 2. Tsunami Exposure and Vulnerability indices and indicators (N = national scale, L = local scale, GDP = gross domestic product).

Aggregate index	Partial indices	Indicators	Variables	Spatial scale
Exposure	Human Exposure	E1 – Exposed population	Number of persons permanently exposed Number of persons temporally exposed (holidays)	N–L N–L
	Environmental Exposure	E2 – Exposed ecosystems	Area of exposed ecosystems	N–L
	Socioeconomic Exposure	E3 – Exposed socioeconomic activities	Area of exposed activities (agriculture and herding, fishing, aquaculture, tourism, industry, trade, services)	N–L
	Infrastructures Exposure	E4 – Exposed infrastructures	Number of exposed infrastructures (water, energy, waste treatment, transport, industrial, emergency)	N–L
		E5 – Exposed buildings	Number of exposed buildings	L
Sensitivity	Human Sensitivity	S1 – Sensitive age groups	Number of persons under 10 years Number of persons over 65 years	N–L N–L
		S2 – Illiteracy	Number of illiterate persons	N–L
		S3 – Extreme poverty	Number of persons in extreme poverty conditions	N–L
		S4 – Disability	Number of disabled persons (physical/intellectual)	L
		S5 – Isolation	Number of persons in isolated areas	L
		S6 – Critical evacuation	Number of persons in critical buildings	L
	Environmental Sensitivity	S7 – Protection	Area of protected ecosystems	N–L
		S8 – Singularity	Area of singular ecosystems (ecosystem services)	N–L
		S9 – Threat	Area of threatened ecosystems	N–L
		S10 – Degradation	Area of degraded ecosystems	L
	Socioeconomic Sensitivity	S11 – Job generation	Number of workers per activity	N–L
		S12 – Contribution to GDP	Millions of dollars contributed per activity	N–L
		S13 – Contribution to foreign trade	Millions of dollars contributed per activity	N–L
	Infrastructures Sensitivity	S14 – Critical infrastructures	Number of water supply infrastructures (wells) Number of transport infrastructures (evacuation) Number of dangerous/hazardous infrastructures Number of emergency infrastructures	N–L N–L N–L N–L
		S15 – Critical buildings	Number of critical buildings (hospitals, schools, hotels, malls, stadiums, churches, etc.)	L
		S16 – Vertical evacuation	Number of buildings with less than three stories	L
		S17 – Building materials	Number of non-resistant buildings	L
Resilience	Resilience	R1 – Coping capacity	Information and awareness level Warning and evacuation level Emergency response level	N–L N–L N–L
		R2 – Recovery capacity	Post-disaster recovery level	N–L

(S1, S2, S4-intellectual disability), problems with mobility and reduced evacuation speed (S1, S4-physical disability), difficulties with evacuation related to the built environment and coordinated evacuations (S6), difficulties with receiving a warning message and reaching the safe area before the tsunami arrives (S5); and the difficulties in recovering after a disaster (S3) are analysed.

The environmental sensitivity indicators (S7–S10) aim to assess the potential environmental impacts by municipality in terms of loss of ecosystems and the subsequent loss of livelihood-related ecosystem services. Thus, the loss of relevant ecosystems (S7, S8, S9), the potential permanent destruction of ecosystems (S10), and the loss of livelihood-related ecosystem services, such as coral reefs and mangroves (S8) is assessed. The potential capacity of mangroves to mitigate the hazard is included in this work through the hazard assessment, as a higher roughness coefficient was assigned to mangrove areas.

The socioeconomic sensitivity indicators (S11–S13) are oriented to measure the potential social and economic impacts by municipality in terms of loss of income at the household level and economic losses for the country, respectively. The social impacts (S11) are calculated through the number of jobs that would be lost per socioeconomic activity, while the economic impacts (S12, S13) are expressed in millions of dollars lost per socioeconomic activity in case of having a percentage of its area affected.

The infrastructures sensitivity indicators (S14–S17) measure the number of critical infrastructures and buildings that would be affected by municipality and the subsequent implications for the population, the term critical applied to those elements that if affected would worsen the situation both during and after the event. Accordingly, S14 calculates the potential number of polluted wells hindering long-term water supply to local communities, loss of essential evacuation routes, generation of cascading impacts due to affected hazardous/dangerous industries, and loss of emergency and health services which are essential during the event. S15 provides the number of buildings that would require a coordinated and previously planned evacuation due to the high number of people (in some cases sensitive population) in them, such as hospitals, schools, clinics for elderly people, malls, stadiums, churches, hotels, etc. S16 and S17 measure the number of buildings not able to provide shelter for the population, due to the number of floors or to the weak materials. S17 permits the calculation of the buildings damage level according to the materials and the water depth (based on SCHEMA methodology by Tinti et al., 2011). The damage level of the specific infrastructures (water, energy, industrial, transport, emergency) is not included in this study.

The Pearson correlation coefficient was calculated to select the indicators. Most of the indicators had low correlation except extreme poverty & illiteracy ($r = 0.92$), environmental threat & protection ($r = 0.68$), and GDP contribution & job generation ($r = 0.90$). These relationships between variables were carefully evaluated to consider the removal of some of them; however, their analytical relevance and differentiation prevailed to the correlation result, as agreed by the assistants in a participatory workshop and for the sake of better refined risk reduction measures. In this sense, (i) poverty gives information about areas which would struggle more after the event due to the lack of financial resources to recover, while illiteracy provides information about the ability to understand a warning message during the event; (ii) maintaining both threat and protection indicators permitted the identification of areas where unprotected endangered species were located and formulate specific measures for these areas; (iii) maintaining both GDP contribution and job generation permitted a clear differentiation between social and economic impacts of the event to understand the medium to long-term effects of the tsunami. Weights have been carefully assigned to these indicators to correct the doubling effects when aggregating.

Data collection for exposure and sensitivity indicators is based on the best available information for the human[1], environmental[2], socioeconomic[3] and infrastructural[4] dimensions in El Salvador. Besides this, field work was carried out to produce the information that was not officially available or that was incomplete, such as the one regarding isolated communities (with the help of local authorities and Civil Protection local departments), critical buildings, building materials and vertical evacuation.

The consideration of factors shaping risk at various scales (as proposed by Turner et al., 2003) is considered in this paper through the variable "Number of persons exposed temporarily (holidays)" within the human exposure indicator, which permitted the comparison of specific areas at different times of the year (spatio-temporal variability) and showing higher exposure and vulnerability values in holiday periods. This effect in specific hotspots is explained by holiday movements of foreigners to very specific sites and associated for example with surf promotion campaigns developed at the national level. These overcrowded places are likely to be higher risk areas in holiday periods. Other factors that could be considered are the planned coastal development for the coming years in exposed areas, or national initiatives (like the one resulting in this paper) which are aimed at reducing the vulnerability of communities at the local level. Further research work is needed in order to properly include these types of factors within risk assessments.

An additional explanation is provided for the resilience assessment. The resilience of a community with respect to potential hazard events is determined by the degree to which the community has the necessary resources and is capable of absorbing disturbance and reorganising into a fully functioning system (Cutter et al., 2008). This is understood as the capacity of a community to organise itself before, during and after the event in order to minimise the impacts. Thus, two of society's capacities are analysed to evaluate the

[1]Censo de Población 2007, Encuesta de Hogares de Propósitos Múltiples 2011 (Dirección General de Estadística y Censos DIGESTYC), Ministerio de Turismo MITUR

[2]Ministerio de Medio Ambiente y Recursos Naturales MARN

[3]DIGESTYC 2007, Banco Central de Reserva BCR

[4]Asociación Nacional de Acueductos y Alcantarillados ANDA, Comisión Hidroeléctrica del Rio Lempa CEL, Comisión Ejecutiva Portuaria Autónoma CEPA, Ministerio de Obras Públicas MOP, Ministerio de Economía MINEC, Centro de Desarrollo de la Pesca y la Acuicultura CENDEPESCA, Ministerio de Agricultura y Ganadería, Fuerza Naval, and Ministerio de Turismo MITUR

resilience: coping capacity, as the ability of people, organisations and systems, using available skills and resources, to face and manage adverse conditions, emergencies or disasters (UN/ISDR, 2009) before and during the event; and recovery capacity, as the ability of the system to recover after a disaster. These two indicators are assessed through the analysis of the four phases of emergency management: information and awareness, warning and evacuation, emergency response, and disaster recovery.

Due to the lack of thematic and geographically homogeneous data regarding resilience, data collection for the construction of the resilience index has been carried out through a short questionnaire which identifies the degree of organisation and response within a community in case of an emergency. The type of questionnaire applied is based on the assessment of the level of implementation of Integrated Coastal Zone Management (ICZM) in Europe, proposed by Pickaver et al. (2004) and carried out through a questionnaire with three possible answers (yes/no/no answer) against each ICZM action and for three spatial levels to identify the main existing gaps in ICZM implementation and a trend through time. Using appropriate questionnaires for the resilience assessment solves the commonly faced problem regarding the limits of measurability and the collection of quantitative data to be analysed together with the sensitivity data. Table 3 shows the relation between the elements of resilience, the phases of emergency management and the questionnaire.

The resilience questionnaire offers three response alternatives, yes/no/partially, together with space for fuller comments, and has been filled in by 34 stakeholders. Although the statistical sample could be considered small, the coherence of the assessment is ensured at the national level through the answers of those responsible for emergency management in every coastal municipality (Municipal Civil Protection Committees). Additional stakeholders were interviewed for the local studies, such as some non-governmental organisations, companies and business associations, and community leaders; in case of contradictory answers (“yes/no”) the intermediate value (“partially”) has been finally assigned, the incoherence between authorities’ and society’s perception about the preparedness of the municipality being automatically identified as a critical issue for resilience enhancement measures.

The complexity of having the resilience as a component inversely proportional to risk (a higher resilience reduces the risk) in a multidisciplinary study, which combines different risk components, dimensions and timescales and therefore indicators from various disciplines, sources and units, highlights the need to translate this factor into a directly proportional one. Therefore, the authors propose the use of a new component named “lack of resilience”, as applied by the MOVE framework (Birkmann et al., 2013). Consequently, the indicators coping capacity and recovery capacity will analyse the lack of resilience and focus on the negative responses of the questionnaire. The aggregation of each type of answer multiplied by its coefficient and divided by the total number of questions providing the value of the lack of resilience index, the coefficients being 0, 1 and 0.5 for positive, negative and intermediate answers, respectively. This is necessary for aggregation purposes (i.e. aggregating sensitivity and resilience to build the vulnerability); however, to analyse the resilience itself, the lack of resilience is translated again into the resilience concept through the expression Resilience = 1 − Lack of resilience.

2.3.2 Integration of risk concepts

The method for the integration of risk concepts included in the process from the exposure and vulnerability data collection and processing up to the risk assessment is explained in the next paragraphs. This method has several steps: (i) building indicators through normalizations; (ii) building partial and aggregated indices through weighted aggregation, (iii) index classification via the natural breaks method; and (iv) risk assessment using the risk matrix.

Based on OECD (2008), in order to correct the imbalance caused by the different variable units, thus allowing for their comparison and combination, the transformation of the variables range of values is carried out through the minimum–maximum (Min–Max) method, which normalises the indicators so as to obtain an identical range [0,1]. A weighted aggregation is applied to them in order to build the partial (for each dimension) and aggregated indices. Weights are assigned in this work using participatory methods: a workshop has allowed the authors to collect the opinions of different experts, with the participation of 10 technicians from the *MARN* (Ministry of Environment and Natural Resources, El Salvador) and the team from *IH Cantabria* (Environmental Hydraulics Institute, Spain), in order to reflect political and social priorities, technical factors related to the tsunami hazard and the reliability of the data used.

As carried out by Damm (2010) and the World Risk Report (Alliance Development Works, 2012), among others, the indices are classified considering the data distribution and translated into five classes linked to a colour code geographically representing the information. The natural breaks classification method, based on the Jenk’s optimisation algorithm, implemented in ArcGIS® software and designed to provide the best arrangement of values into different classes, is applied. The method reduces the variance within classes and maximises the variance between classes (Jenks, 1967) and has been selected after testing other methods (such as the equal interval, defined interval, quantile, geometrical interval, standard deviation, etc.), as it permits grouping within the same class the municipalities that have similar values, that is those that behave in the same way and which are expected to need similar risk reduction measures. Since this method of classification depends on the distribution of the data, the study of any index evolution over time must maintain the ranges established in the initial analysis.

Table 3. Resilience assessment: society's capacities, related emergency phases and questionnaire applied.

Society's capacities	Emergency management phases (description based on US IOTWS, 2007)	Resilience questionnaire
Coping capacity	**Information and awareness.** Leadership and community members are aware of hazards and risk information is utilised when making decisions.	1. Existence of social awareness 2. Existence of institutional awareness
	Warning and evacuation. Community is capable of receiving notifications and alerts of coastal hazards, warning at-risk populations, and individuals acting on the alert.	3. Existence of tsunami Early Warning System 4. Existence of evacuation routes 5. Existence of maps/drawings with hazard areas and critical spots 6. Development of evacuation drills in institutions and communities
	Emergency response. Mechanisms and networks are established and maintained to respond quickly to coastal disasters and address emergency needs at the community level.	7. Proper functioning of the Municipal Commission of Civil Protection 8. Existence of a contingency plan 9. Existence of Communal Committees for risk management 10. Existence of coordination networks at departmental/national levels 11. Existence of sufficient emergency human resources
Recovery capacity	**Disaster recovery.** Plans are in place prior to hazard events that accelerate disaster recovery, engage communities in the recovery process, and minimise negative environmental, social, and economic impacts.	12. Existence of temporary shelters 13. Existence of municipal funds to cover immediate expenses 14. Existence of catastrophe insurance 15. Existence of sufficient medical and public health human resources 16. Existence of sufficient development human resources

As conducted by Greiving et al. (2006) and Jelínek et al. (2009), the risk is calculated through a risk matrix by combining the classes obtained for the hazard and the vulnerability indices, or hazard and sensitivity indices in the case of partial results. The sensitivity and vulnerability are calculated on the exposed elements; therefore, the exposure is implicitly incorporated into the matrix. Once the municipalities with higher risk values are identified, in other words those which are expected to have serious negative consequences due to the combination of the hazard scenario modelled and the vulnerability conditions, the calculation of the specific expected impacts at the local level is carried out. The different methods applied to the Western Coastal Plain of El Salvador are described in Sect. 2.3.3 together with the obtained results.

2.3.3 Results and discussion

The vulnerability results for the coastal area of El Salvador are analysed and mapped in Fig. 3. The municipalities are organised geographically within the graphs, thereby facilitating the comparison of numerical and cartographic results.

The sensitivity index numerical and cartographic results explain how sensitive the exposed municipalities are regarding the different dimensions. The sensitivity is represented through the graph columns and the colour code on the maps. The identification of the causes that make each municipality more or less susceptible to the hazard is based on the sensitivity indicators, with the different colours within the columns representing the contribution of the different indicators to their index. For example, one can differentiate the reasons why two municipalities have similar socioeconomic sensitivity, identifying whether it is due to the potential loss of contribution to foreign trade or GDP. The results obtained will feed the risk reduction measures for each dimension.

The results of the resilience index at the national level allow an understanding, in a general and preliminary way, of the main weaknesses in emergency management, in order to design further detailed analyses to propose weakness-oriented site-specific corrective measures. The main shortcomings regarding the emergency phases can be identified and consequently tackled, both at the municipality level (e.g. Acajutla does not have temporary tsunami shelters) and transversally for a more coherent regional planning (e.g. the country lacks a tsunami insurance or a properly implemented tsunami EWS, although some respondents stated that the existing flooding warning procedures could be easily incorporated to the tsunami EWS), as shown in Fig. 4. Quantitative information for the indicators would nonetheless provide more detailed results to analyse the coastal municipalities in

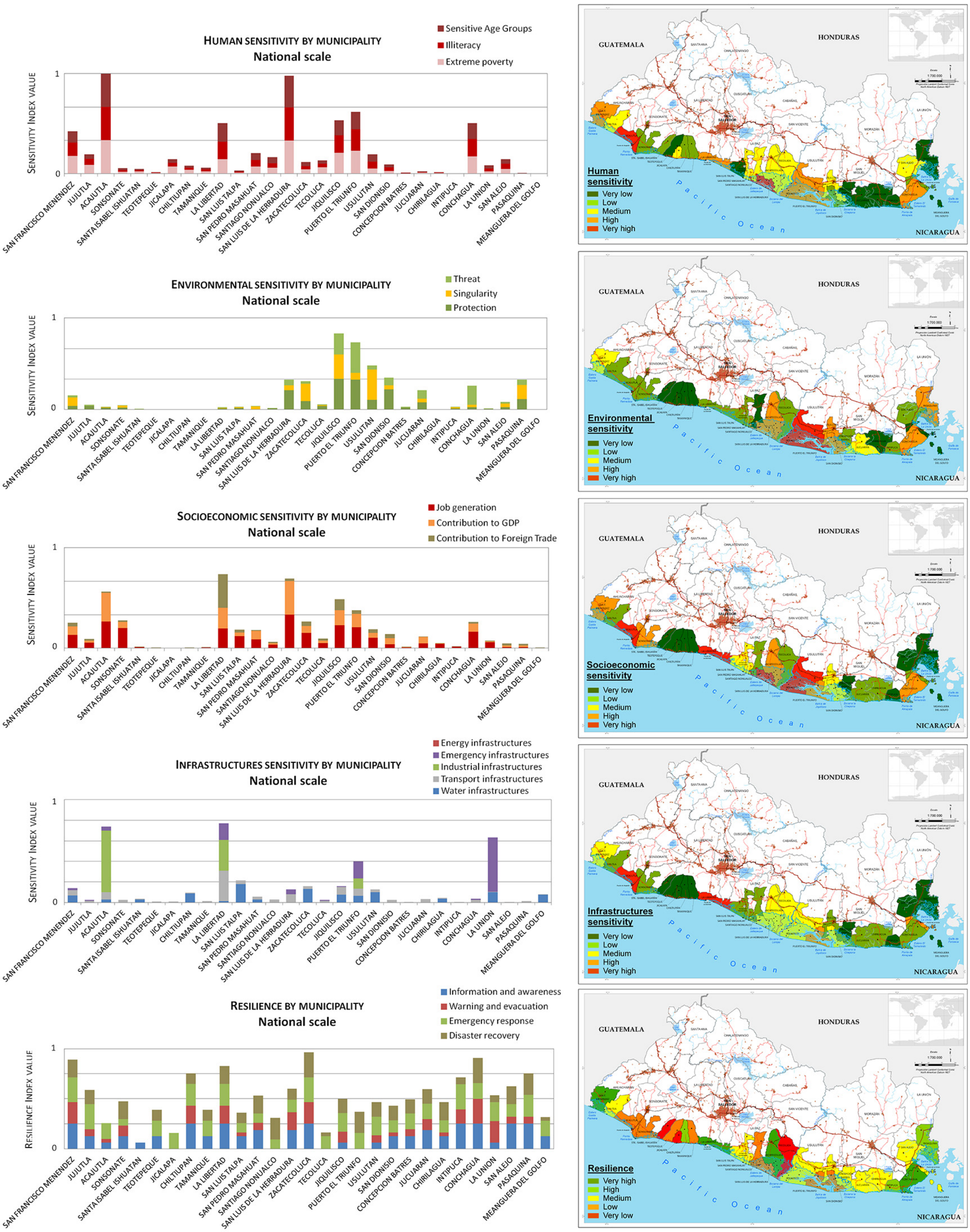

Figure 3. Vulnerability results for the El Salvadoran coastal area at the national scale by municipality: (from top to bottom) (i) human, (ii) environmental, (iii) socioeconomic and (iv) infrastructural sensitivity, and (v) community resilience.

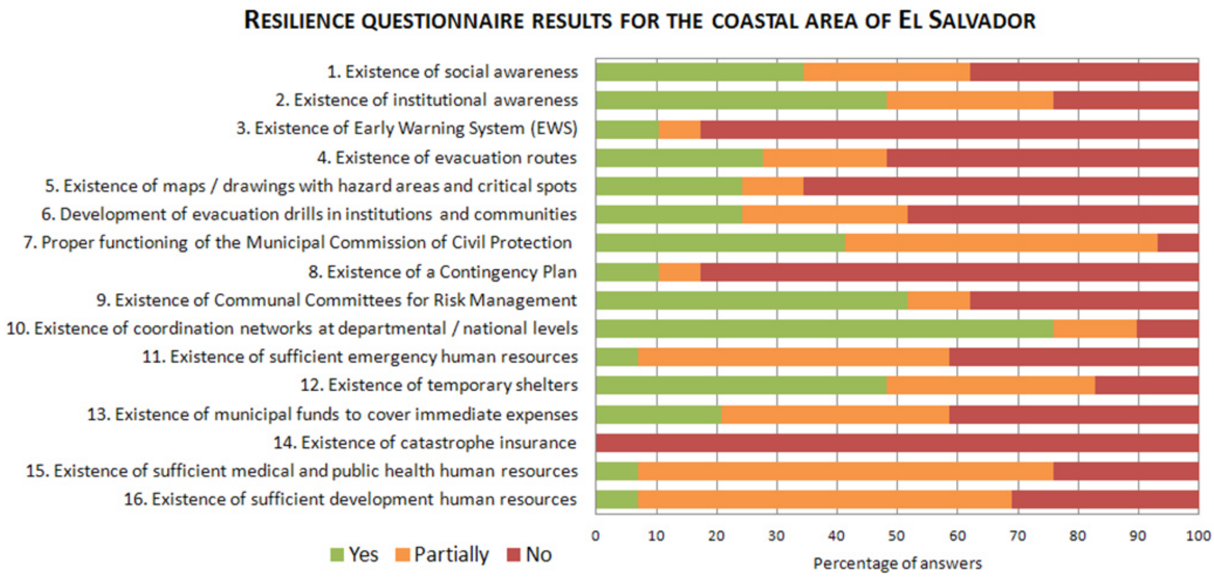

Figure 4. Resilience questionnaire results for tsunami hazard on the coastal area of El Salvador.

terms of, for instance, the number of temporary shelters or doctors by population density and municipality.

The importance of each indicator or variable and the critical role of some of them within the assessment have been considered through the weighted aggregation. Accordingly, in the case of resilience, coping capacity is weighted more than the recovery capacity due to the prioritisation of saving lives, and resilience is weighted less than sensitivity due to the use of more subjective information. The workshop made evident the difficulties in weighting the different resilience variables: the first impulse for almost everyone was to give higher weights to early warning system and evacuation routes; however, a lack of social awareness regarding evacuation (question 1) or a communication and coordination malfunction between the different warning responsible levels (questions 7, 9, 10) could turn a tsunami warning ineffective. Regarding social awareness in the case of a local tsunami, a community informed and trained about the tsunami hazard would start evacuating just after feeling the earthquake, which could save valuable time before the warning is issued and, hopefully, lives.

The aggregated result (sensitivity or resilience) per se should not be understood as the final aim of the work, but the generation of information for the formulation of risk reduction measures; i.e. the assessments allow the identification of site-specific topics that should be managed before a tsunami event happens. In other words, and as an example, the resilience assessment identifies in which municipalities one should work on designing evacuation routes and in which ones the focus should be on social awareness or an early warning system. Similarly, the sensitivity results identify in which municipalities specific attention must be paid regarding the evacuation of critical buildings such as schools, hospitals, etc., where an alternative water supply for coastal communities with potential polluted wells must be planned, or where specific information and training campaigns must be designed for isolated areas or municipalities with a large amount of people with difficulties understanding a warning message.

The national risk assessment (Fig. 5c), obtained from the combination of hazard and vulnerability results (Fig. 5a and b, respectively), allowed for the identification of the critical areas in which a more detailed analysis is needed. The specific expected impacts have been calculated for the three local areas framed by black squares in the figure, with some of the results for the Western Coastal Plain being presented next. The calculation of the extent of the negative consequences (damage levels) varies according to the available methodologies in literature and information, not being defined for every dimension or exposed element in a homogeneous way. The specific results, which differ in format and scope, cover the different dimensions as well, providing essential knowledge for risk management and the formulation of adequate risk reduction measures.

The zoning for the expected human damage in the Western Coastal Plain (Fig. 6a), is calculated through the combination of tsunami drag (based on Jonkman et al., 2008) and human sensitivity. An overall 20 429 persons are exposed to this tsunami event, 75 % of them being located in very high and high human damage areas. This information is very useful for evacuation planning, as the critical areas in terms of hazard, exposure and sensitivity are identified. One could argue that evacuation planning as well as other type of measures, such as the identification of evacuation routes and shelter areas, could proceed without such detailed information; however, the more information is collected, the better

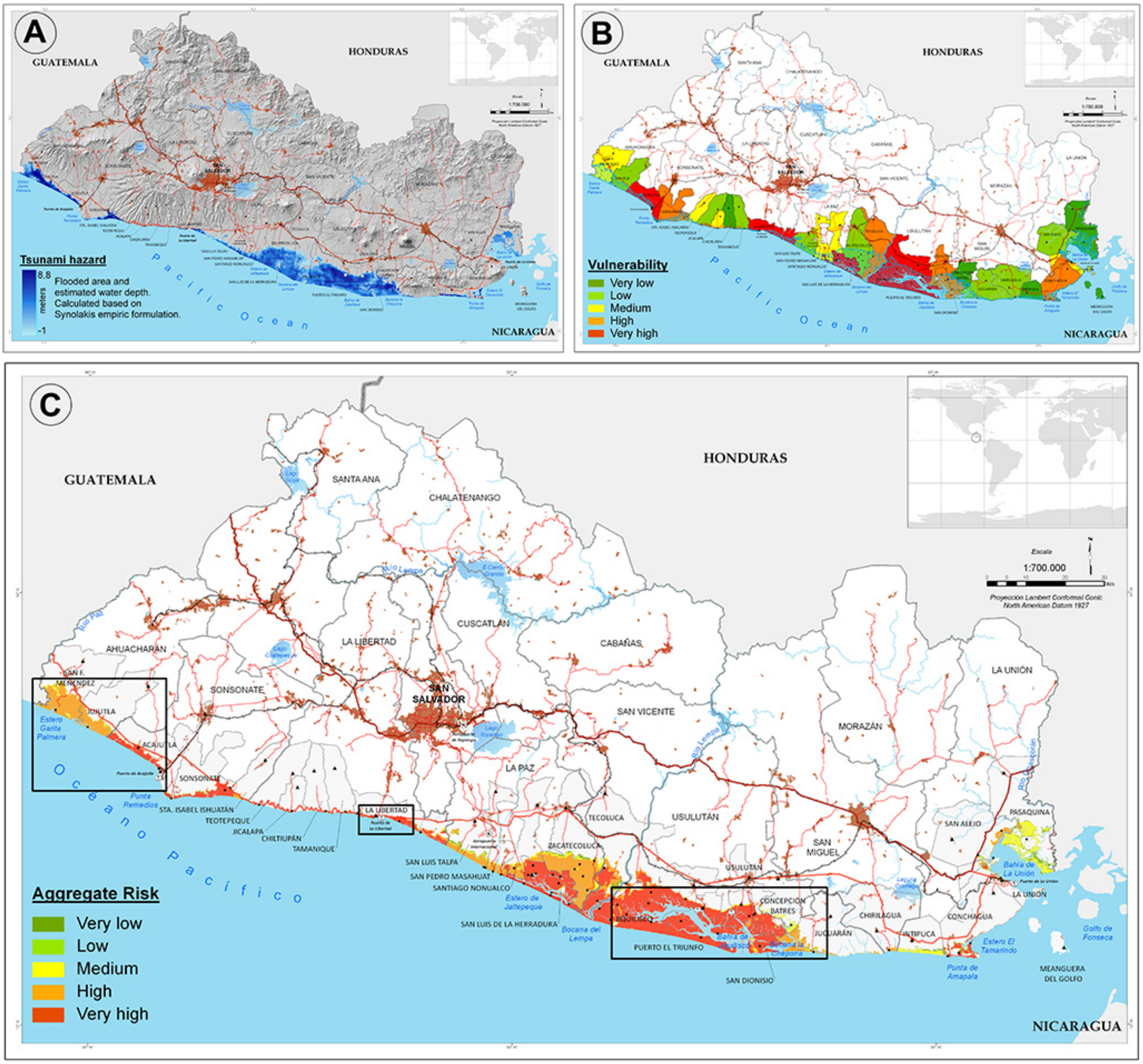

Figure 5. National tsunami risk assessment in El Salvador: **(a)** hazard assessment: flooded area and water depth results; **(b)** vulnerability assessment by municipality including the human, environmental, socioeconomic and infrastructural dimensions; **(c)** risk assessment combining hazard and vulnerability results via the risk matrix (the areas framed by black squares show the local studies carried out; from left to right: Western Coastal Plain, La Libertad municipality and Jiquilisco Bay).

management options can be applied. Knowing the evacuation speed of the population, which can depend on the age, disabilities, etc., will allow modelling the evacuation in order to identify critical areas where people would not be able to reach a shelter before the tsunami reaches the coast. Knowing where the sensitive population in terms of evacuation is located facilitates planning alternative measures for them.

Figure 6b shows the number of buildings exposed to the tsunami event by census segment (blue colour code) and the expected impacts on buildings (pie charts) calculated through the adaptation of the SCHEMA methodology to El Salvador based on water depth and building materials (Tinti et al., 2011). In total, 6557 buildings are exposed in the Western Coastal Plain, 26 % of them being included among the important damage and partial failure classes.

The area and location of ecosystems and related ecosystem services that would be affected by a potential event, as well as the local communities depending on them have been identified. The area, number of jobs and economic contribution to be lost for the different socioeconomic activities exposed to the hazard is provided in Fig. 7a. It shows that the largest area of socioeconomic activity that would be lost

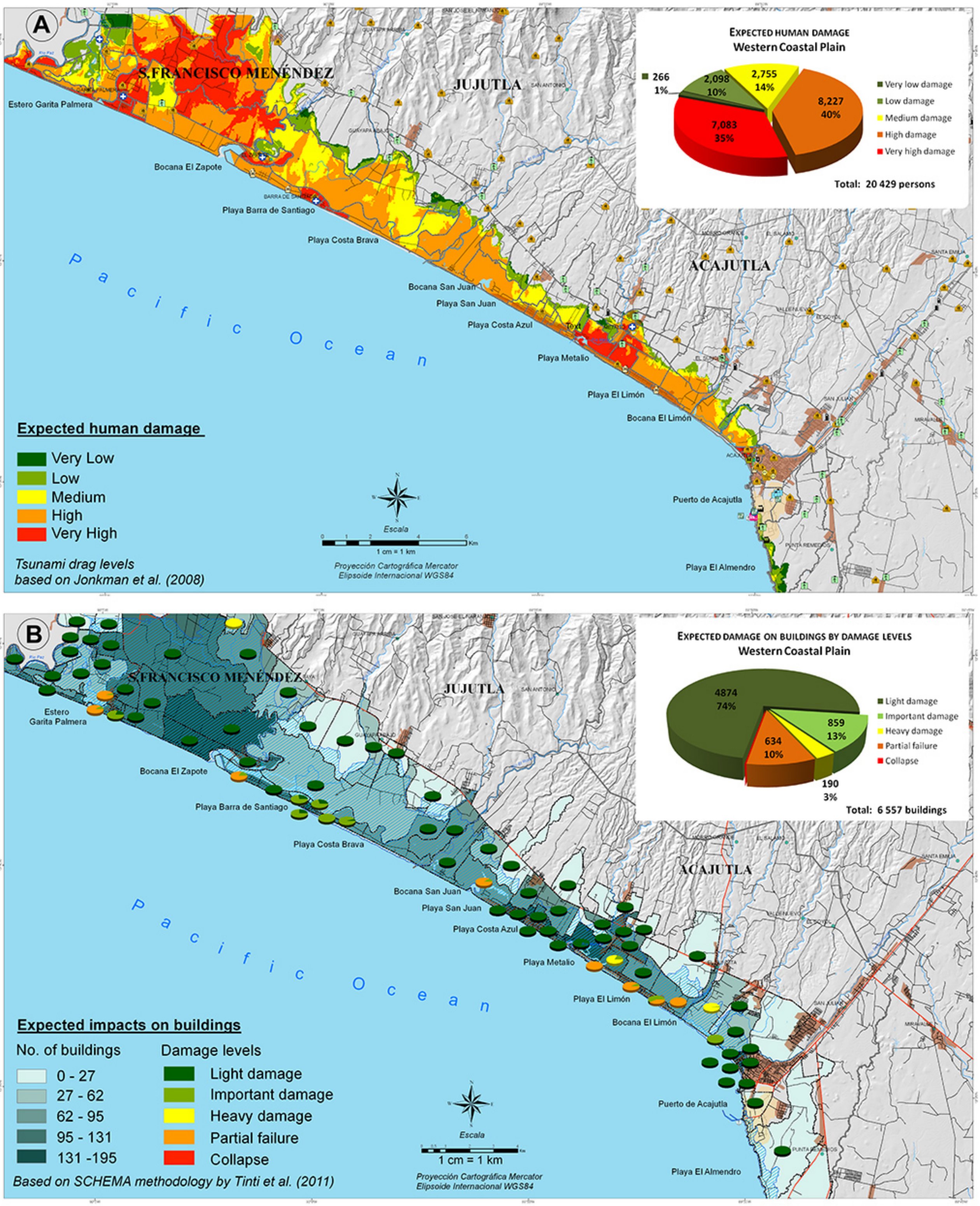

Figure 6. Expected impacts in the Western Coastal Plain of El Salvador: **(a)** zoning for expected human damage, and **(b)** expected impacts on buildings by census segment.

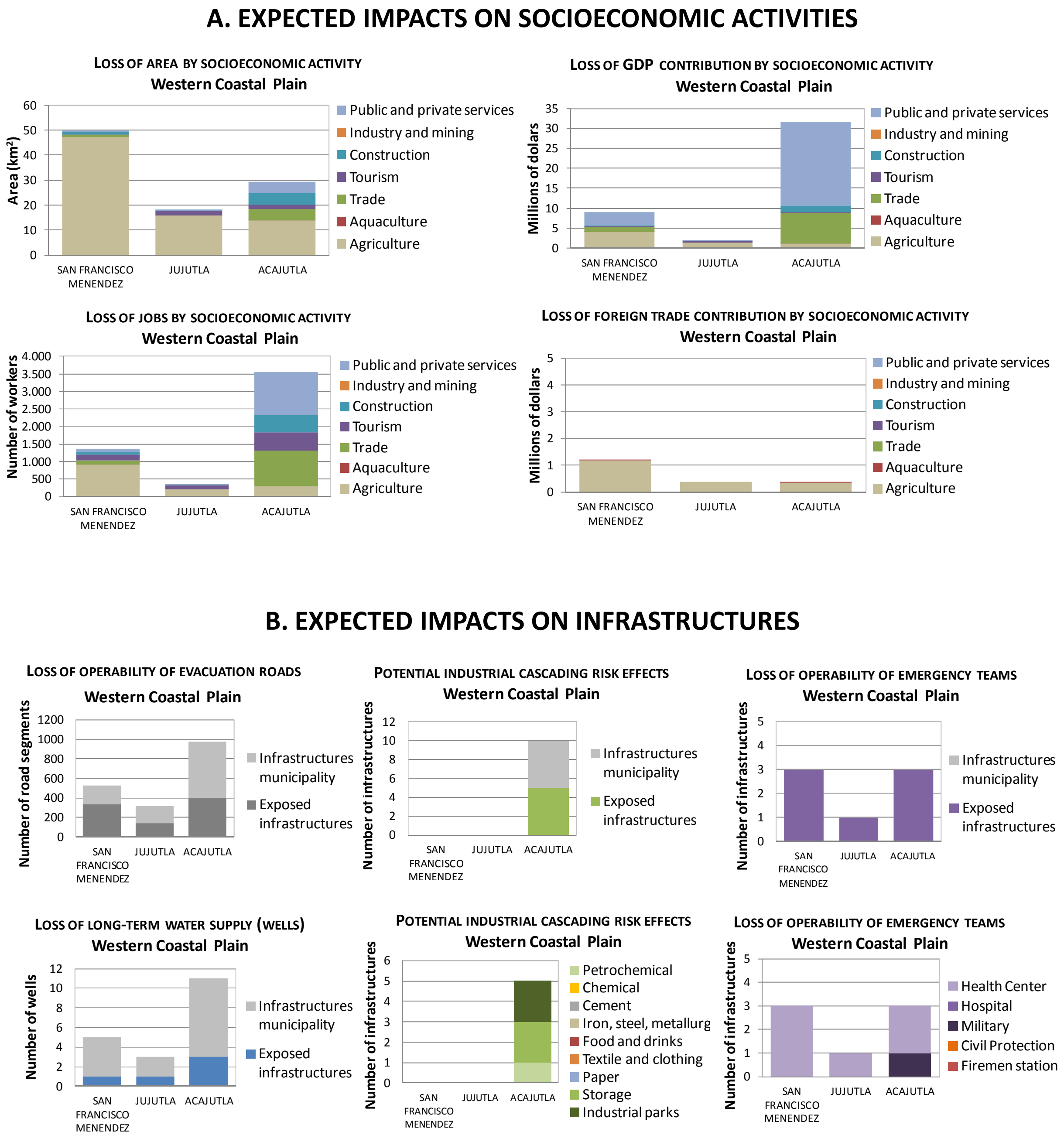

Figure 7. Expected impacts in the Western Coastal Plain of El Salvador: **(a)** impacts on socioeconomic activities, and **(b)** impacts on infrastructures.

is mainly agricultural land in the three municipalities; this implies practically the entire expected loss of contribution to foreign trade. The other smaller exposed socioeconomic area is dedicated to tourism, trade, construction and services, mainly in urban areas, and especially in Acajutla municipality. This small multi-activity area would imply the biggest impacts in terms of loss of jobs and loss of contribution to GDP.

Figure 7b shows some examples of the analysis of impacts on infrastructures for the Western Coastal Plain, based on the identification and location of the sensitive infrastructures potentially affected, implying various consequences to the population, such as the reduction of possible evacuation roads, the potential pollution of wells hindering long-term supply to coastal communities, the affect on dangerous/hazardous industrial infrastructures that could worsen the tsunami impacts, or the exposure of all the emergency infrastructures

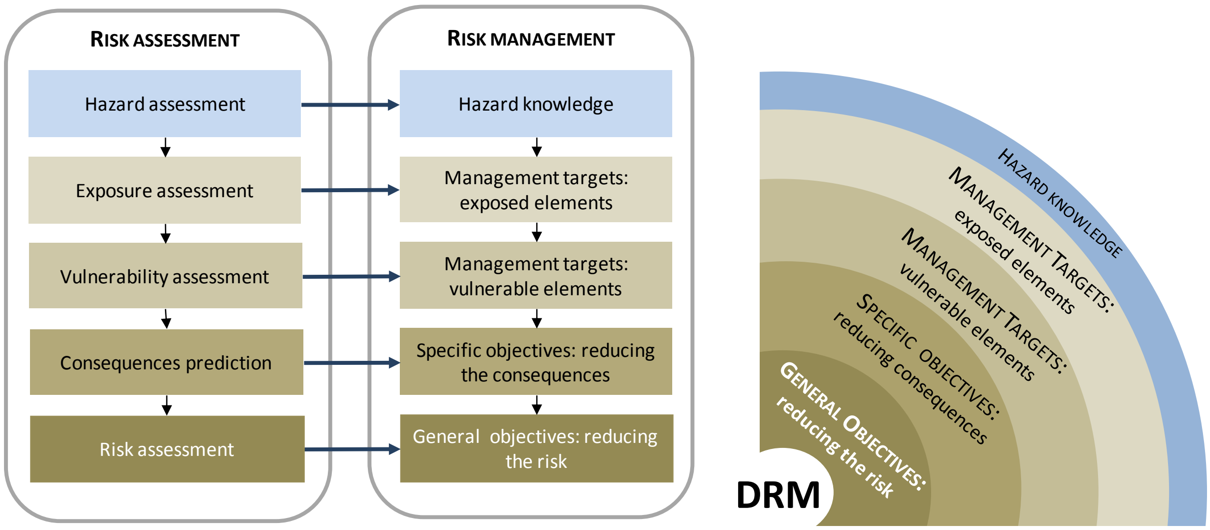

Figure 8. Left: translating vulnerability and risk results into a management framework. Right: disaster risk management (DRM) dartboard framework.

present in the study area, which probably will not be able to help the population in case of a tsunami event.

3 Tsunami risk management: application to El Salvador

Scientific risk assessment studies are frequently characterised by a linear structure that goes from the hazard and vulnerability assessments to the final risk calculation, very few of them providing specific risk reduction options. This linear structure and the lack of a clear and straightforward link with the disaster risk management (DRM) may generate a lack of connection between the authorities' decision-making and the technical results obtained from the risk assessment. This section focuses on how to enhance the value of the gathered knowledge to translate the results into something closer to the management options the decision-maker needs. Figure 8 shows how the risk assessment process can directly feed the various steps within the risk management process. Once the connection between both processes is identified, the structures of the studies are reoriented in order to have the DRM as the main goal to achieve. The scheme on the right, in a dartboard shape, shows that the closer a study arrives to the centre of the dartboard, the more useful it becomes for the managers.

Based on the results of the national and local risk assessment carried out for El Salvador and the main expected impacts due to the modelled tsunami event, different adaptation and mitigation measures can be proposed. It is here understood that mitigation measures aim to reduce the hazard's effect on the coastal system, while adaptation measures basically aim to reduce the vulnerability by reducing the sensitivity or enhancing the resilience-identified shortcomings. The overlap of mitigation and adaptation measures on the exposure component is due to territorial and time factors – i.e. a risk reduction measure aimed at reducing the exposure will be a mitigation measure if it intends to change the location of existing elements, but can be considered an adaptation measure if it intends to plan the future location of elements so as to limit as much as possible their presence in the area.

DRM must be site-specific and needs to be detailed and individually applied to the different study areas. Fig. 9 shows an example of general planning structure based on some of the results presented. The main goal is the DRM in the centre of the figure, and to achieve it different tasks are needed: (i) knowledge acquisition about the hazard; (ii) identification and location of the exposed elements of that hazard to be considered; (iii) from the exposed ones, analysis of the vulnerable elements as management targets; (iv) formulation of DRM-specific objectives to reduce the expected negative consequences on each dimension; and (v) DRM general objectives to guide the management of the study area. Focusing for example on the human dimension in Fig. 9, the general objective is reducing human risk by ensuring effective evacuation, this can be achieved by minimising the population evacuation and reaction time. Table 4 shows the translation of the tsunami risk results obtained in Acajutla municipality into risk reduction measures by following the steps suggested in Fig. 8. According to this approach, specific risk reduction measures are proposed to address each of the identified impacts in every dimension. However, it is normally politically and economically difficult for a country to implement them all, a prioritisation of measures being required.

DRM, as a complex process, deals with a huge amount of information including different kinds of data on hazards, exposed elements, dimensions, vulnerabilities, spatio-temporal scales, specific problems, scenarios, stakeholders,

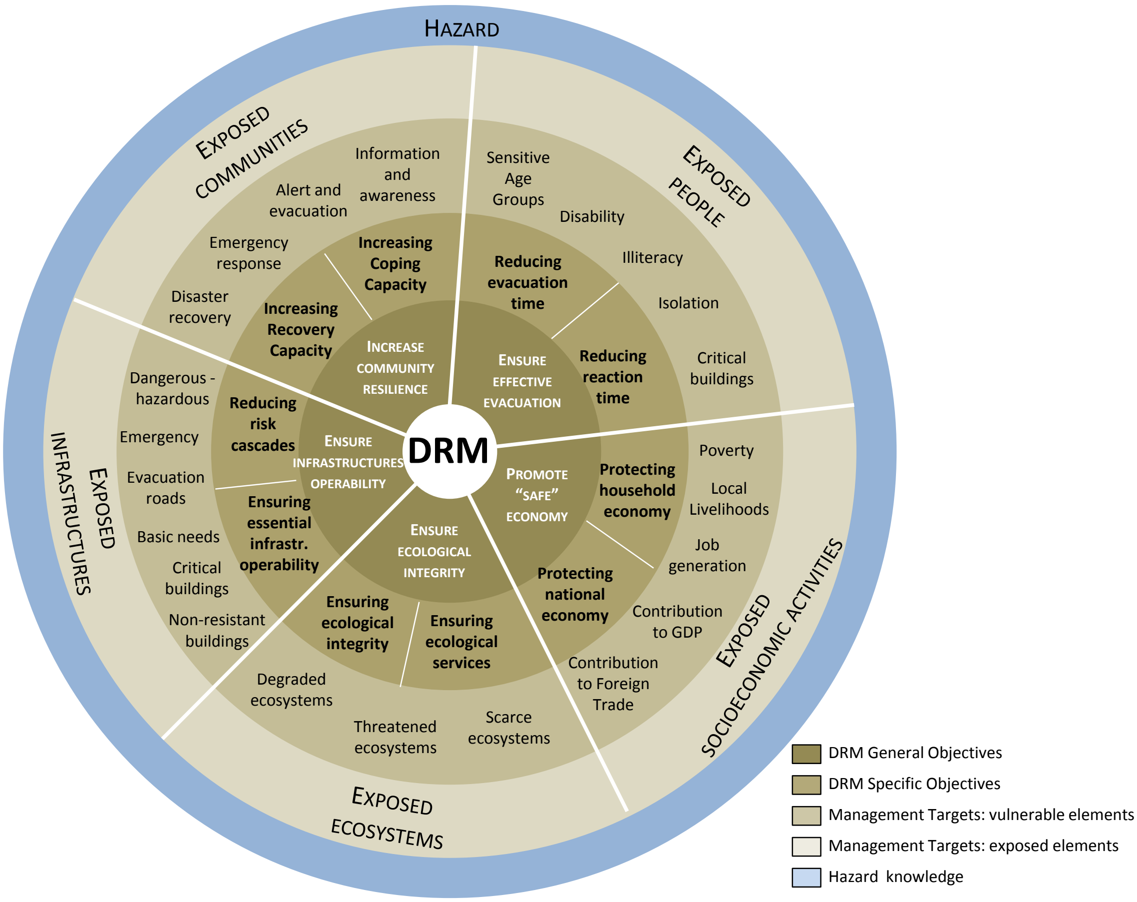

Figure 9. Example of risk management framework for tsunami hazard in El Salvador.

governance, resilience, emergency protocols, early warning systems, etc. This information must be properly prioritised in order to optimise the management process, select the most urgent and relevant issues to solve and once the first objectives have been fulfilled, address the next ones. Therefore, after the definition of the risk management structure, the next task would be identifying the key factors affecting or controlling the system (i.e. leverage points) as they can be used to bring about major changes in the system with minimum effort (Martín García, 2006), the system dynamics being a potential tool to achieve this objective (Sterman, 2002, 2006; Meadows, 2008).

Figure 10a shows the system dynamics modelled for the analysis of tsunami impacts in Acajutla based on the participatory contribution of the various technicians from MARN and IH Cantabria. The impact of a tsunami event on the exposed and vulnerable elements (capital letters and blue font text, respectively) produce different cause-effect relationships and feedback loops (arrows) within the system generating the various negative consequences under study (text in boxes). These causal relationships show some kind of relevance roles and priorities between the elements in terms of management, which means that by working on some of them, results can be obtained on the others. The feedback loops between the final consequences highlight those that can worsen other impacts in the same or other dimensions and that, consequently, should be tackled first. For example, the generation of risk-cascading effects and the loss of infrastructures' operability generate human casualties and environmental impacts; analogously, the loss of ecological integrity reduces the capability of generating ecological services, which affects the socioeconomic dimension.

Understanding the behaviour of the system and the interrelationships between the elements allows for the proposal of different management scenarios to understand the effects of the decision-making and to optimise the DRM. Fig. 10b shows the causal relationships and tsunami impacts partially tackled by three risk reduction measures (orange boxes) proposed here: (i) promotion of population information and awareness campaigns tailored to the local sensitivity characteristics; (ii) protection and reforestation of mangroves; (iii) relocation or reinforcement of the seven critical buildings, and one dangerous-hazardous and three emergency infrastructures identified. It also shows how these three measures affect various causal relationships and feedbacks between the elements, and allow obtaining parallel extra results to those

Table 4. Translation of human risk results into DRM options (Acajutla, Western Coastal Plain, El Salvador). Further information provided by González-Riancho et al. (2013).

DRM phases and related risk assessment results	Risk management options
A. Hazard knowledge. Flooded area, water depth (up to 4 m), velocity (up to 10 m/s, very high drag levels, tsunami arrival time (25-30 min.)	Hazard mitigation measures • Construction of flood defence structures • Ocean wave barriers • Reforestation • Restoration of mangroves
B. Management targets: exposed and vulnerable elements. 9262 people exposed 70% located at very high/high risk areas 30% sensitive age 67% illiterate 32% extreme poverty 4% disability 37% isolated areas 15% critical evacuation *C. Specific objectives: reducing the consequences.* Minimising potential loss of lives by reducing the population evacuation and reaction time. This depends on potential reduced mobility, difficulties understanding a warning message, difficulties receiving a warning and/or evacuating in badly connected areas, and difficulties performing a coordinated evacuation *D. General objective: reducing the risk.* Reducing human risk by ensuring effective evacuation	Early warning system (EWS) • Enhancing EWS for regional and local tsunamis • Optimization of communication system: networking, technology, mobile, warning speakers, etc. • Tsunami warning network in collaboration with local communities • Official tsunami reports regularly issued to the public. Information, awareness, capacity building campaigns for local communities, including tailored campaigns for: • people with difficulties for understanding a warning message • slow groups (elderly, disabled, pregnant women and children) • people in isolated areas • critical buildings (schools, hospitals, etc.) Evacuation planning • Community-based evacuation design and organization • Evacuation drills • Specific evacuation training for critical buildings staff • Specific help for slow groups and isolated areas (e.g. transport services) • Warning time prioritization to isolated areas • Construction of vertical evacuation shelters in strategic locations.

that were originally planned. The orange arrows represent the flows set in motion due to the risk reduction measure, while the yellow boxes show the consequences that are affected or improved somehow by these flows.

This example aims to show that one single action may have many results in complex systems, which is an interesting idea to bring forward in risk management. Working with complex systems is complicated, as many aspects, dimensions and variables should be considered and dealt with. However, once the system is understood, one can take advantage of this complexity to generate better results with less effort. Therefore, the understanding of complex systems allows for optimising the effort and getting the best results from the management options applied.

Working with scenarios provides the opportunity to understand the current system, predict the consequences of different plausible management options and, consequently, promote an adequate risk reduction plan for the studied area. It can be therefore a dynamic assessment of policy options and their response to existing feedback loops.

4 Conclusions

Advances in the understanding and prediction of tsunami impacts allow for the development of risk reduction strategies for tsunami-prone areas. Based on existing vulnerability and risk frameworks and approaches, the main expected contribution is to provide a straightforward method to facilitate their implementation. The method deals with the complexity and variability of CHANS by means of an integral approach to cover the entire process from the risk assessment to the risk management; an integrated approach to combine and aggregate the information stemming from the different dimensions; and a dynamic and scale-dependent approach to integrate the spatiotemporal variability considerations.

Risk assessment at the national level aims at comparing and prioritising municipalities in terms of risk reduction

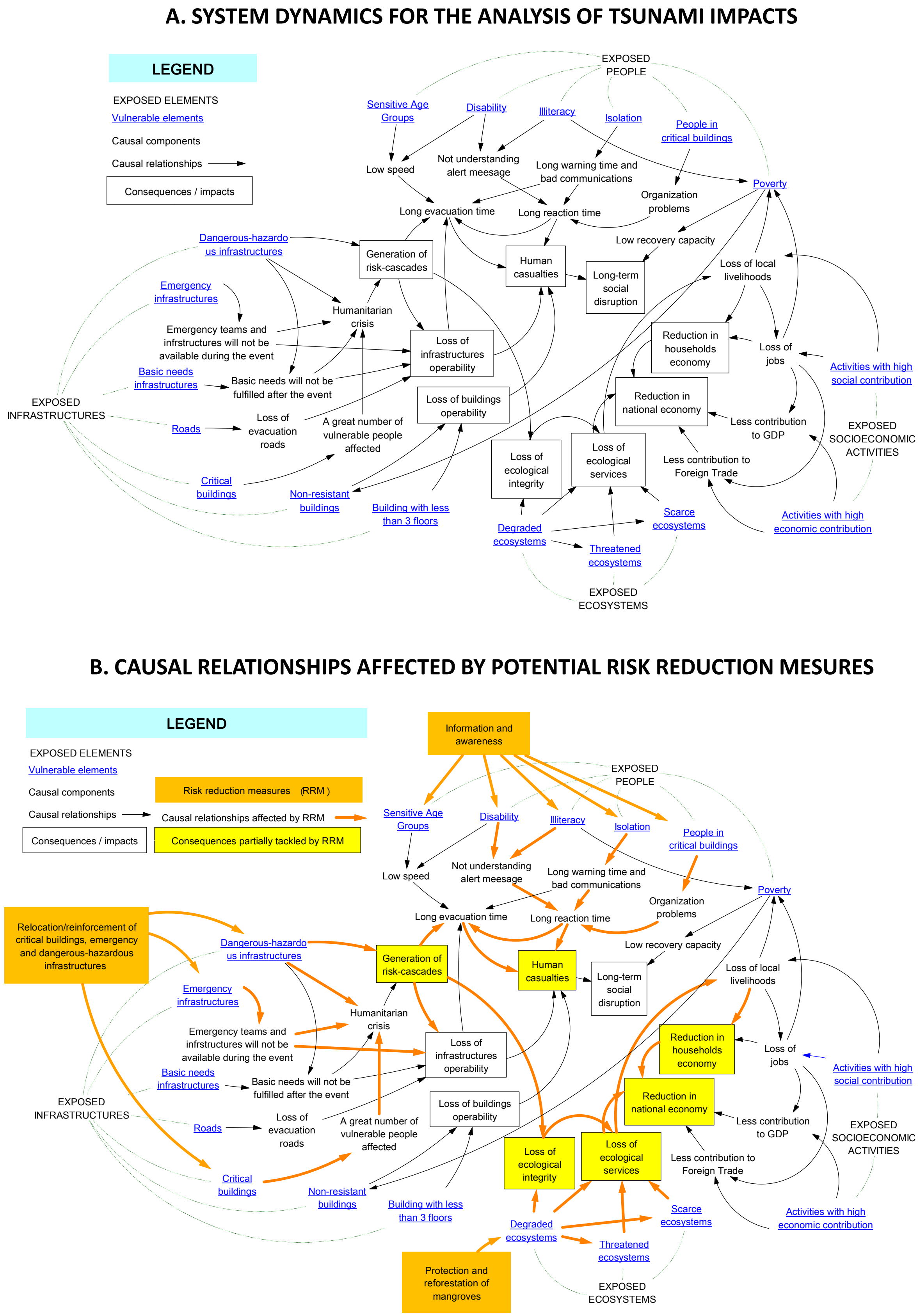

Figure 10. (a) System dynamics for the analysis of tsunami impacts in El Salvador; **(b)** causal relationships and tsunami impacts affected by potential risk reduction measures (Vensim® Software).

efforts (see Fig. 5), while the assessment at the local level of the prioritised municipalities is aimed at calculating the specific expected impacts by dimension (see Figs. 6 and 7).

The deterministic hazard assessment based on propagation models for earthquake-generated tsunamis provided different hazard maps along the coast of El Salvador. This permitted the identification of the main tsunami flood-prone areas, that is, the Western Coastal Plain and the coastal stretch between La Libertad and Jucuaran municipalities, with the Lempa river mouth and Jiquilisco and Jaltepeque wetlands being especially relevant in terms of flooded area. The proposed exposure and vulnerability mixed indicator approach has proved to be useful to identify and locate the elements in the hazard area, as well as to measure the human, environmental, socioeconomic and infrastructural characteristics that make the municipalities more susceptible to the selected impacts.

The qualitative resilience assessment identified (through a short questionnaire) the degree of organisation and response within a community in case of an emergency. The analysis of a single municipality may not require a resilience index (i.e. numerical); however, when a comparison between municipalities is required (which was the aim of the national assessment), the resilience index seems to be a possible approach to have a general idea of the state of each municipality in terms of their preparedness and emergency management in order to design further detailed analyses to propose weakness-oriented, site-specific corrective measures.

A clear connection to translate the vulnerability and risk assessments into risk reduction measures is offered, trying to bridge the gap between science and management for the tsunami hazard. The risk assessment process directly feeds the required information to develop the risk management process, by reorienting its usual linear structure in order to have the DRM as the main goal to achieve. The approach, together with system dynamics modelling, facilitates the identification and prioritisation of ways to reduce the sensitivity of municipalities regarding various dimensions and to enhance the resilience of communities. Regarding the practical application of the RRM to the case study of El Salvador, and based on the risk results presented above, several measures are already being developed by the MARN, such as public tsunami hazard bulletins and monthly reports, information and awareness campaigns for local communities, a network of local observers to warn the communities in collaboration with the Ministry and Civil Protection, and community-based evacuation planning (further information is provided by González-Riancho et al., 2013).

A dynamic model to update the risk results is expected to be incorporated into the methodology as an effective tool for adaptive risk management. It is intended to gradually update the set of indicators, as the risk reduction measures are being implemented, allowing the systematic modification of the exposure, vulnerability and risk results and the understanding and utilising of the interrelation and feedback loops controlling the behaviour of the coupled human and natural system.

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Tsunami evacuation modelling as a tool for risk reduction: application to the coastal area of El Salvador

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Abstract. Advances in the understanding and prediction of tsunami impacts allow the development of risk reduction strategies for tsunami-prone areas. This paper presents an integral framework for the formulation of tsunami evacuation plans based on tsunami vulnerability assessment and evacuation modelling. This framework considers (i) the hazard aspects (tsunami flooding characteristics and arrival time), (ii) the characteristics of the exposed area (people, shelters and road network), (iii) the current tsunami warning procedures and timing, (iv) the time needed to evacuate the population, and (v) the identification of measures to improve the evacuation process. The proposed methodological framework aims to bridge between risk assessment and risk management in terms of tsunami evacuation, as it allows for an estimation of the degree of evacuation success of specific management options, as well as for the classification and prioritization of the gathered information, in order to formulate an optimal evacuation plan. The framework has been applied to the El Salvador case study, demonstrating its applicability to site-specific response times and population characteristics.

1 Introduction

Tsunamis are relatively infrequent phenomena, but they nonetheless represent an important threat and cause the loss of thousands of human lives and extensive damage to coastal infrastructure around the world (González et al., 2012). Advances in the understanding and prediction of tsunami impacts allow the development of risk reduction strategies for tsunami-prone areas.

Conducting risk assessments is essential to identify the exposed areas and the most vulnerable communities. Hazard, vulnerability and risk assessment results allow the identification of adequate, site-specific and vulnerability-oriented risk management options, with the formulation of a tsunami evacuation plan being one of the main expected results. An evacuation plan requires the analysis of the territory and an evaluation of the relevant elements (hazard, population, evacuation routes, and shelters), the modelling of the evacuation, and the proposal of alternatives for those communities located in areas with limited opportunities for evacuation. This information facilitates the decision-making regarding tsunami risk management.

Several previous works dealing with different aspects of the evacuation process for a tsunami hazard exist. Some authors focus on hazard aspects, such as the calculation of the tsunami wave height, the flooded area, run-up, or arrival time, while others deal with tsunami-related human aspects, such as the calculation of loss of lives, potential casualties, mortality vs. safety, human damage prediction, etc. Some analyse road characteristics as input information for evacuation modelling, while others predict the impacts on buildings using damage functions. Several authors focus on the

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evacuation itself, dealing with the identification of critical areas, the calculation of the evacuation time, or the assessment of warning procedures, among others. Many are oriented to the development of specific evacuation modelling software. Very few authors focus on precisely how to plan a tsunami evacuation. Some examples of the previous works are briefly analysed here.

Regarding the human damage prediction caused by flooding-related disasters, including tsunamis, Sugimoto et al. (2003) presented a tsunami human damage prediction method employing numerical calculation and GIS for a town in a high-risk area. The number of deaths as a result of a tsunami was estimated from the accumulated death toll, taking into account the time necessary to begin to seek refuge after an earthquake, tsunami inundation depth on land, flow velocity and evacuation speed. Jonkman et al. (2008a, b) proposed a method for the estimation of loss of life due to flooding of low-lying areas protected by flood defences, which is given based on the flood characteristics, the exposed population and evacuation, and the mortality amongst the exposed population, using new mortality functions developed by analysing empirical information from historical floods. Koshimura et al. (2006) estimated the number of casualties that may occur while people evacuate from a tsunami inundation zone, based on a simple model of hydrodynamic forces as they affect the human body. The method uses a tsunami casualty index computed at each grid point of a numerical tsunami model to determine locations and times where tsunami evacuation is not possible, and therefore where casualties are most likely to occur. This, combined with population density information, allows for the calculation of the potential number of casualties, which is useful information to identify locations which ought to be excluded from evacuation routes. Sato et al. (2003) proposed a simplified method for tsunami risk assessment without wave run-up analysis, to qualitatively estimate the safety of residents, and examine the effectiveness of tsunami prevention facilities. Two normalized values are evaluated: the ratio of calculated maximum tsunami height to seawall height, and the ratio of the time between tsunami over-topping and evacuation completion to the total time required for evacuation.

Concerning the analysis of specific evacuation issues, Strunz et al. (2011), within the framework of the tsunami risk assessment for the German Indonesian Tsunami Early Warning System (GITEWS), analysed the evacuation of several Indonesian islands, considering vulnerability as the probability of not reaching safe areas in time. Alvear Brito et al. (2009) calculated the population evacuation time through a GIS-based numerical model, in which the critical zones (where the population will not have sufficient time to reach the security areas) are identified by considering factors such as the distance to security zones, the land slope, and accessibility of roads. Clerveaux and Katada (2008) presented a tsunami scenario simulator, which combines the hydrodynamic simulation of tsunamis with warning and human-response simulations for evacuation, mainly focusing on alert communication aspects.

Works on evacuation modelling software may be grouped into three categories, according to the FLOODsite project (HR Wallingford, 2006): (i) traffic simulation models, (ii) evacuation behaviour models, and (iii) timeline/critical path management diagrams. The evacuation modelling shown in this paper fits into the third category. Kolen et al. (2010) described the *EvacuAid* probabilistic evacuation model, which determines the expected value and bandwidth for the success and loss of life of evacuation strategies based on four parameters: the available time, the behaviour of people, the behaviour of authorities and the available infrastructure and resources. Van Zuilekom et al. (2005) developed the *Evacuation Calculator* to compute how much time is required for evacuation, and to determine the effect of traffic management during the evacuation process on the required evacuation time. It focuses on traffic flows, and not on individual people or vehicles, and requires data about the average vehicle speed, the capacity of the exit point, the source zones and exits, the distance between them, and the number of people present in each source zone. BC Hydro (2004) developed the *Life SafetyModel* which allows dynamic interaction between the receptors (e.g. people, vehicles and buildings) and the flood hazard. It requires data about the location of individual properties, vehicles and people, the flood depths and velocities from a two-dimensional hydraulic model, and details of the road network and other pathways. Aboelata and Bowles (2005) proposed the *LIFESim* model for the estimation of potential loss of life from natural and man-made (dam and levee failure) floods, which comprises three modules: loss of shelter, warning and evacuation, and loss of life.

As far as evacuation planning is concerned, Scheer et al. (2011a), within the framework of the SCHEMA project and the Handbook on Tsunami Evacuation Planning, presented the local tsunami risk assessment and all subsequent implications for evacuation planning, based on the expected tsunami wave height, and the arrival time of the first devastating tsunami wave. This work defines a cost surface layer, evacuation shelter points, a time map, the area covered by each shelter point, the time distance from the closest shelter, the area served by exit/escape points, and the time distance to reach the closest escape point. Scheer et al. (2011b) propose optimizing tsunami evacuation plans through the use of building damage scenarios to identify potential vertical shelters. Garside et al. (2009) state that all at-risk facilities should have appropriate emergency response planning which would include (i) warning notification protocols and systems; (ii) evaluation and mapping of evacuation routes, with signage to designated assembly points; (iii) consideration of evacuation timing; and (iv) staff training and evacuation plan exercising. Besides the existing scientific works, many of the official evacuation plans reviewed (Tokyo's earthquake survival manual[1], Oregon's tsunami evacuation brochures[2], Chile's tsunami inundation map[3], etc.) are oriented to provide citizens from a city/province/country with strategic information such as an evacuation map and some general guidelines about what to do in case of emergency, as opposed to being a tool for decision makers to plan the proper evacuation of the area.

As mentioned above, different partial aspects of tsunami risk and evacuation are addressed in the literature. With a view to the successful planning of the evacuation of the population located in a tsunami prone area, several gaps in the prevailing science are identified: (i) no direct relationship between the specific evacuation-related assessments carried out and the formulation of risk reduction measures and/or an evacuation plan exists, even though some general connections are usually established; (ii) an assessment of the characteristics of the population and communities to be evacuated is not usually undertaken, (iii) the evacuation time is sometimes calculated without considering the tsunami arrival time, resulting in a lack of information regarding the degree of success that the identified evacuation time represents for the population; (iv) an analysis of the time needed by the responsible administrations to issue the tsunami warning and to inform the population is sometimes not considered, although this is essential information for determining the real time available for the population to evacuate; (v) the evacuation modelling results sometimes do not identify, propose or suggest conclusions about how to reduce the risk of the populations identified in critical areas, regarding successful evacuation; and (vi) proposals for improvements in the evacuation process are frequently inadequate, lacking identification of locations to build new vertical shelters and evacuation routes, and omitting warning time reduction strategies, etc.

Based on this analysis, the objective of this paper is to present a framework which aims to eliminate the above-identified gaps, providing a global picture of what is required for the adequate formulation of evacuation plans of a study area, and to present evacuation modelling as an essential tool for risk management. This methodological framework proposes an integral approach to considering (i) the hazard aspects (tsunami flooding characteristics and arrival time), (ii) the characteristics of the exposed area (people, shelters and road network), (iii) the current tsunami warning procedures and timing, (iv) the evacuation time needed by the population, and (v) the identification of measures to improve the evacuation. It thus aims to bridge the gap between risk assessment and management in tsunami evacuation. Finally, an application of this framework to the coastal area of El Salvador, and specifically to the Western Coastal Plain, is presented in this paper along with a discussion on the major findings.

[1]Tokyo Metropolitan Government: Earthquake survival manual

[2]Oregon Department of Emergency Management and Oregon Department of Geology and Mineral Industries: Tsunami Evacuation Brochures

[3]Gobierno de Chile: Carta de Inundación Por Tsunami, Zona Urbana Coronel Costa (in Spanish)

2 Framework for tsunami evacuation planning

Evacuation plans, which are developed by the responsible authorities and decision makers, would benefit from a clear and straightforward connection between the scientific and technical information from tsunami risk assessments and the subsequent risk reduction options. Scientifically-based evacuation plans would translate into benefits for the society in terms of mortality reduction. Figure 1 shows the methodological framework proposed for evacuation planning, which is divided into three phases: analysis, modelling and planning. This framework and its three phases are intended to be supported by participatory processes involving the local communities, the Civil Protection, emergency-related NGOs and responsible authorities, among others. These processes aim to (i) inform the stakeholders about the work, (ii) involve them in the overall evacuation planning process, from the preliminary designs to the validation of the evacuation strategy and maps, (iii) include their knowledge in the analysis, and (iv) thereby improve the final planning results.

The analysis phase aims to examine the territory and communities exposed to the tsunami flooding in order to identify critical elements from the point of view of the evacuation, by examining the characteristics of the population, the characteristics of the road network and the availability of safe areas in case of tsunami events. These three components (population, routes and shelters) are identified and weighted based on several evacuation-relevant criteria (reaction time, travel speed and isolation of the exposed population; travel difficulty and safety of the road network; and capacity, safety and accessibility of shelters), to obtain essential information for the preparation of a preliminary evacuation proposal that distributes the population among the different shelters identified. This preliminary proposal is intended to then be discussed and reviewed with the exposed local communities in order to include and benefit from their experience, perception and knowledge.

The modelling phase aims to refine and update the preliminary evacuation proposal to identify the critical areas that would not be able to be evacuated and that should therefore be priority candidates for risk reduction measures. The evacuation modelling considers the distances to be travelled and the evacuation speeds of the population, the tsunami arrival time and the current risk management procedures, such as the warning time needed by the responsible authorities and the reaction time of the population. This information is best obtained through consultations with the involvement of the responsible authorities, in order to include their experience and knowledge about existing warning protocols and the main difficulties faced in emergency events. Once the critical areas

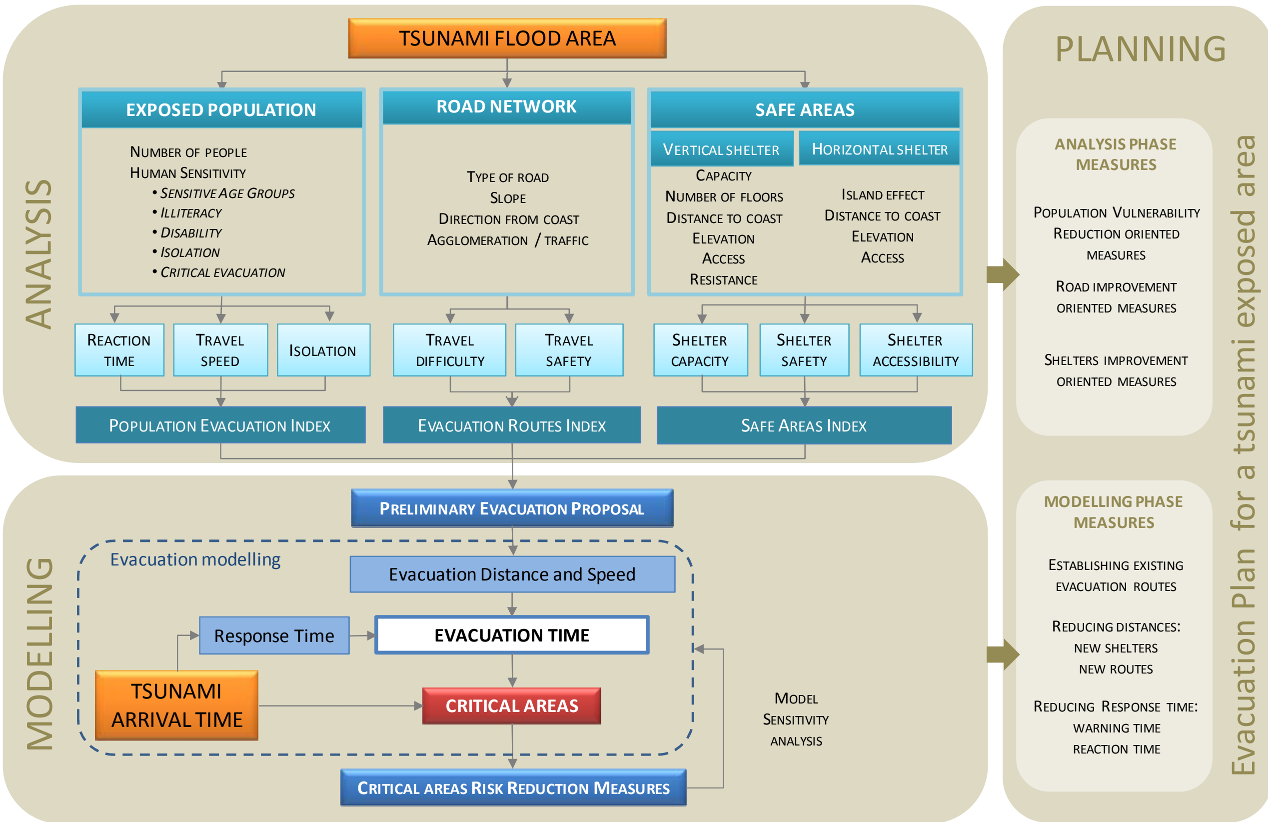

Fig. 1. Tsunami evacuation planning framework.

have been identified, alternatives dealing with reducing the distances to be travelled and/or increasing the available time are proposed to reduce risk. These proposals are also modelled to ensure that the critical areas are gradually reduced, and this process is repeated until these areas are eliminated.

The planning phase aims to gather all the information produced in the analysis and modelling phases as inputs for a comprehensive tsunami evacuation plan. The analysis of the exposed population will result in measures to ensure the proper evacuation of the entire population, by reducing the limitations produced by the reaction time, the travel speed and the isolation of communities. Analysis of the road network and safe areas will result in measures to improve both elements, by increasing the capacity, safety and accessibility of roads and shelters. The evacuation modelling will provide conclusions about the need for reducing (i) the distances that the population has to travel until they reach a safe area, (ii) the authorities' response time (detection, analysis and warning time) and (iii) the population reaction time, and consequently the measures are oriented to these issues. This framework permits interactive and adaptive planning and management, as once the above-mentioned measures have been implemented, the three evacuation indices (population evacuation index, evacuation routes index and safe areas index) will be improved towards their optimal status.

Based on this framework, the chapter is divided into six sections: (1) identification of the potential tsunami-flooded area, (2) analysis of the exposed population, safe areas and evacuation routes, (3) time calculation, (4) evacuation modelling, (5) proposal of alternatives for critical areas, and (6) evacuation planning.

2.1 Identification of the potential tsunami-flooded area

A proper identification of the potential tsunami-flooded area requires a hazard assessment based on tsunami propagation models through the characterization of tsunamigenic sources and other oceanic and coastal dynamics. Simulations of historical and potential tsunamis with variable impact on the coast should be performed including distant, regional and local sources. Probabilistic or deterministic analyses can be carried out to generate different hazard maps such as the maximum wave height elevation, the maximum water depth, the maximum flooding level or run-up, the minimum tsunami arrival time, and the maximum potential drag, understood as the hazard degree for human instability based on incipient water velocity and depth.

A specific methodology for the hazard assessment is not detailed in this section, as this paper focuses on evacuation planning. For further methodological information see Álvarez-Gómez et al. (2013).

2.2 Analysis of the exposed population, safe areas and road network

Once the potential tsunami-flooded area has been identified and consequently the exposed communities and infrastructures are known and geographically located, a characterization of the exposed population, the safe (not-flooded) areas and the road network to reach these areas is performed.

The analysis of the exposed population in terms of evacuation is based on the population evacuation index (PEI) and a series of evacuation indices and indicators. For the calculation of the PEI, (i) the reaction time index considers the number of illiterate people (related to not understanding a warning message) and the number of people located in critical buildings, understood as those that house large numbers of people to be organized jointly in case of evacuation (hospitals, schools); (ii) the travel speed index is based on the number of disabled and sensitive age people (children and the elderly); and (ii) the isolation index considers the expected number of people that may have difficulties evacuating due to the characteristics of their territory. In conclusion, gathering knowledge about the number of people to be evacuated, their location and their characteristics and limitations regarding evacuation, is extremely useful to successfully manage their evacuation and to foster their preparedness in a specificity-oriented manner.

Evacuation to safe areas distinguishes between horizontal and vertical shelters. Horizontal evacuation refers to the strategy for arriving in the areas that are not flooded which are outside the hazard zone or on accessible high grounds. Vertical evacuation refers to the strategy for escaping within the hazard zone by going up to higher floors in buildings or other artificial structures. Tsunami numerical modelling defines the potentially flooded area, which then permits the establishment of horizontal security zoning. The security zoning is proposed to be comprised of the following zones:

- Tsunami-flooded area: area with larger flood depths and flow velocities near the coast and lower depths and flow velocities further inland. Evacuation from this area is strongly recommended.

- Medium-security area: this zone is established between the maximum flood level in the study area and a security level specifically determined for each zone and defined by elevation. This area would be the minimum evacuation objective to be achieved by the population in order to ensure their safety.

- High-security area: from the medium-security zone onwards. This area is the evacuation objective for those located in the medium-security zone when the alert is received and for anyone able to reach this area in the available time.

Potential vertical shelters located within the tsunami hazard area are identified, analysed and prioritized based on the above-shown criteria, i.e. capacity, safety and accessibility. The current road network is also analysed to identify the existing evacuation routes in the study area, and to select those roads that connect populated areas with medium-security areas and prioritized in terms of ease of travel and safety.

The set of indicators proposed for the analysis of the exposed people, road network and safe areas is shown in Table 1, with several mathematical–statistical procedures being applied to them in order to generate comparable and combinable information. The following paragraphs describe the methodology used to integrate the indicators.

The indicators proposed for the assessment of the exposed population, road network and safe areas help in (i) identifying specific weaknesses to be addressed within a tsunami preparedness program, and (ii) prioritizing routes and shelters. The indicators for the assessment of safe areas also provide, through the binary indicators, information used to reject some shelters from the planning process (for example, non-resistant vertical shelters, island effects on horizontal shelters, and no available access to either kind of shelter results in a direct rejection).

Following OECD/EC-JRC (2008), the process for the integration of the evacuation indicators and indices has the following steps: (i) building indicators through normalization; (ii) building indices through weighted aggregation, and (iii) indices classification through the natural breaks method. The transformation of the variables range of values is carried out using the minimum–maximum (Min–Max) method, which normalizes the indicators to an identical range [0,1] by subtracting the minimum value and dividing by the range of the indicator values. The indices are built through the weighted aggregation of the normalized indicators, the weights being associated with (i) the importance it represents for the index to which it belongs, and (ii) the reliability of the information (for example, although the type of road – in terms of materials, width and conservation – is considered important for an efficient evacuation, it is common to find that a high percentage of the roads that must be used are not the best type of roads, therefore in such cases this indicator should be low-weighted). The partial indices obtained are also weighted and aggregated to build the composite index. The indices are classified and translated into 5 classes, this ranking being linked to a colour code to represent the information geographically. The Natural Breaks classification method, based on the Jenk's optimization algorithm, implemented in the ArcGIS® software and designed to determine the best arrangement of values into different classes is applied. The method reduces the variance within classes and maximizes the variance between classes (Jenks, 1967) by minimizing

Table 1. Set of indices and indicators for the analysis of exposed population, road network and safe areas (V = vertical shelter; H = horizontal shelter).

Composite indices	Indices	Indicators	Variables
Population evacuation index	Reaction time	Illiteracy	Number of illiterate people
		Critical evacuation	Number of people in critical buildings
	Travel speed	Sensitive age groups	Number of people below 10 yr, and above 65 yr
		Disability	Number of people with physical/intellectual disability
	Isolation	Isolation	Number of people located in isolated areas
Evacuation routes index	Travel difficulty	Type of road	Number of road segments (per evacuation route) below a predefined site-specific level of quality
		Slope	Number of road segments (per evacuation route) with more than 9 % slope (based on Cano et al., 2011 and Laghi et al., 2006)
		Agglomeration/traffic	Number of road segments (per evacuation route) with common agglomeration/traffic bottlenecks
	Travel safety	Direction from the coast	Number of road segments (per evacuation route) and distances to travel parallel to the coast
Safe areas index	Shelter capacity	Capacity (V)	Number of people that can be hosted per vertical shelter
	Shelter safety	Number of floors (V)	Number of floors per vertical shelter
		Resistance (V)	Materials resistance per vertical shelter (yes/no)
		Distance to the coast (V/H)	Distance (m) from the shelter to the coast
		Elevation (V/H)	Elevation (m) from the sea level per shelter
		Island effect (H)	Horizontal safe area surrounded by flooding (yes/no)
	Shelter accessibility	Access (V/H)	Open access to the shelter by road (yes/no)

each class's average deviation from the class mean, while maximizing each class's deviation from the means of the other groups. It has been selected after testing other methods (such as the equal interval, defined interval, quantile, geometrical interval, standard deviation, etc.), as it permits grouping within the same class the planning units (e.g. municipalities) that have similar values, i.e. that behave in the same way and which are expected to need similar measures. Since this method of classification depends on the distribution of the data, the study of any index evolution over time must maintain the ranges established in the initial analysis (González-Riancho et al., 2013).

2.3 Time calculation

Some time-related concepts essential to understanding the study are as follows (Fig. 2):

- *Tsunami arrival time* (T_{Tsunami}): time from the tsunami generation until the first wave arrives at the coastal area. The tsunami arrival time map is represented by time contour lines and a colour code.

- *Total evacuation time*: time from the tsunami generation until the entire population reaches a safe area. It consists of two concepts:

a. *Response time* (T_{Response}): time from the tsunami generation until the population begins to evacuate. This time includes:

   i. *Detection and warning time*: time from the earthquake detection and the analysis of its characteristics until the tsunami warning is issued by the responsible authority.

   ii. *Alert transmission time*: time from the reception of the alert by the intermediate authorities in charge of crisis management (such as Civil Protection) at the national level and its transmission to those responsible at the local level.

   iii. *Alert reception time*: time from the reception of the alert by those responsible at the local level until the entire community is informed.

   iv. *Population reaction time*: time elapsed from the instant the population receives the alert until they start to evacuate.

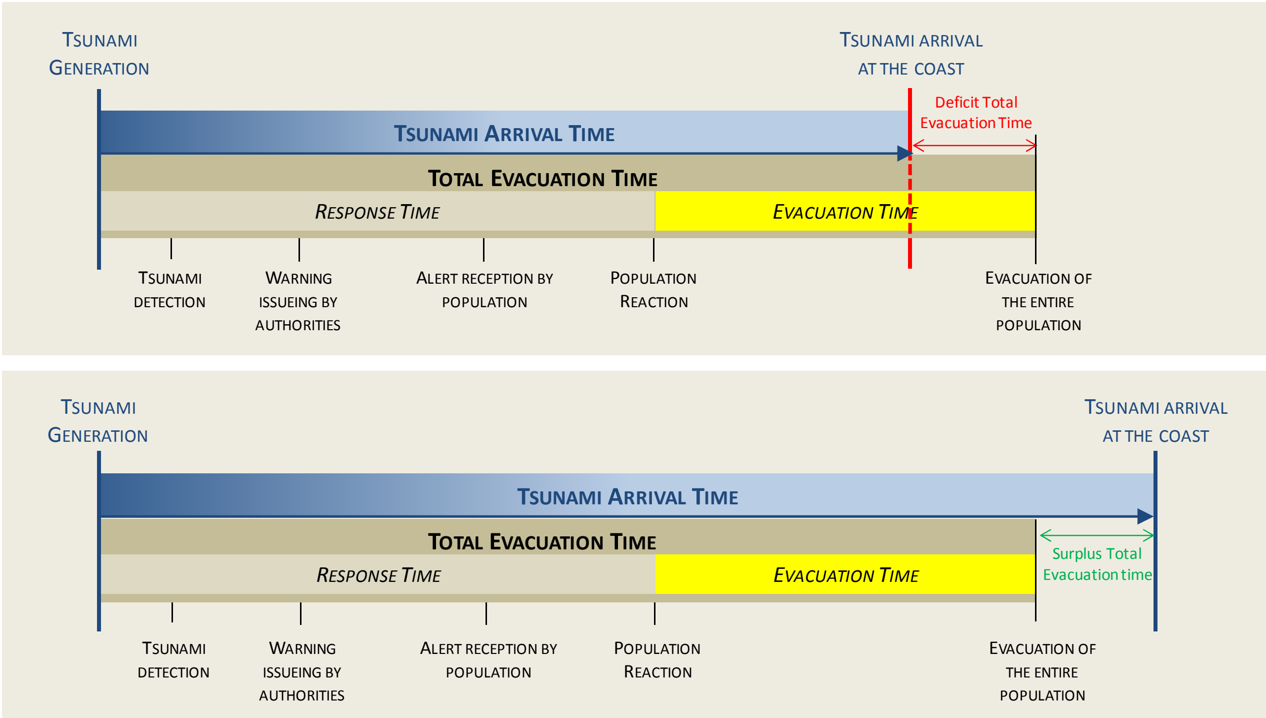

Fig. 2. Tsunami evacuation timelines: to ensure the evacuation of the entire exposed population, the Total Evacuation Time – TET –, which includes the response and the evacuation times, must be lower than the time the tsunami needs to arrive at the coast (Surplus TET, image below). The opposite situation (Deficit TET, image above) implies potential human impacts.

b. *Evacuation time* ($T_{Evacuation}$): time from the beginning of the evacuation until the population arrives in a safe zone (walking evacuation time).

The tsunami arrival time is calculated based on the hazard assessment described in Sect. 2.1 by means of the generation of a set of tsunami arrival time maps through numerical modelling. The response time can be obtained from the existing emergency protocols or from direct work with the responsible authorities, at least the information regarding the detection and warning, alert transmission and reception times. The reaction time of the population, if no information is available, may be assumed to be 15 min for prepared/aware people, based on Post et al. (2009) and Strunz et al. (2011), despite being a simplification, as not the whole population would evacuate at the same time. The evacuation time is to be obtained from the evacuation modelling considering the tsunami arrival time and response time.

A deficit in the total evacuation time is generated when the time needed for evacuation is greater than the time the tsunami takes to arrive at the coast. A surplus is obtained when the opposite situation happens (see Fig. 2). As the tsunami arrival time cannot be controlled, the only option to reduce the risk for coastal communities depends on the management (reduction) of the response and evacuation time. The evacuation time depends on the distances to be travelled and the population speeds; assuming that no improvements to evacuation time (such as building new shorter routes, organizing specific help for slow populations, etc.) can be implemented at the moment, then the current evacuation success will mainly depend on the response time: the lower the response time, the more time will be available for the evacuation and to reach a safe area before the first tsunami wave arrives. The evacuation corresponding to various response times should be analysed and modelled in order to identify the critical one for which the population would not be able to evacuate in time.

2.4 Evacuation modelling

An evacuation modelling is carried out to identify optimal evacuation routes and the time needed for the population to evacuate, based on the tsunami arrival time, the security zoning and the road network. For the evacuation modelling applied within the framework proposed in this paper, the network analyst extension of the ArcGIS® 10.1 software is used to create a network database and perform various analyses considering the definition of attributes and connectivity standards. Based on this extension, the "closest facility" analysis is applied to measure the travelling cost between origin and destination points. The following factors are considered for modelling:

– Evacuation distances: the aim is to obtain the minimum distance a person has to walk (L) from each evacuation point of origin (located at every road intersection inside the flooded area and based on the spatial analysis of the distribution of population) to the destination point (located where each road gets out of the flood sheet).

– Evacuation speed (V): based on Sugimoto et al. (2003) and Mück (2008), two types of people with different speeds ($V1$, $V2$) are considered:

  i. Fast population, generally associated with adults, with an evacuation speed of $V1 = 1\,\mathrm{m\,s^{-1}}$.

  ii. Slow population, associated with the elderly, children and the disabled, with an evacuation speed of $V2 = 0.7\,\mathrm{m\,s^{-1}}$.

– Evacuation time ($T_{\mathrm{Evacuation}}$): the time needed to travel the length L to the safe area (destination point); it depends on the different speeds considered ($T_{\mathrm{Evacuation1}}$, $T_{\mathrm{Evacuation2}}$):

  i. Fast population: $T_{\mathrm{Evacuation1}} = L/V1$.

  ii. Slow population: $T_{\mathrm{Evacuation2}} = L/V2$.

– A slope slows the evacuation (slope = (Za−Zo)/L; Za being the highest point and Zo the lowest point on the evacuation route). Thus, according to Laghi et al. (2006) and Cano (2011), speeds are corrected based on the slope (see Table 2), and consequently the evacuation times are also corrected. The slope calculation considers the difference of elevation between the origin and destination points, assuming that the latter points are always located on higher ground.

– Response time (T_{Response}) = time from the occurrence of the tsunamigenic event until the population begins to evacuate

– Total evacuation time (T) for each type of population by speeds ($T1$, $T2$):

  i. Fast population: $T1 = T_{\mathrm{Response}} + T_{\mathrm{Evacuation1}}$.

  ii. Slow population: $T2 = T_{\mathrm{Response}} + T_{\mathrm{Evacuation2}}$.

According to the response time modelled in each case, the model provides the shortest path from each origin point to the destination point, calculates the time required for walking the shortest path identified, and colours the origin point depending on the result obtained. Table 3 shows the colour code used to represent these results, depending on whether the total evacuation time of the fast population ($T1$) and the slow population ($T2$) are less than or greater than the tsunami arrival time (T_{Tsunami}).

As the number of exposed people is known, this modelling also permits the calculation of the evacuation balance, understood as the percentage of people getting evacuated by census tract for the response time analysed. The evacuation balance depends on both the distance to be travelled and the population speed.

Table 2. Evacuation speed correction based on the slope (Laghi et al., 2006).

Slope (%)	Speed value
0–3	100 %
3–6	85 %
6–9	70 %
9–12	55 %
12–5	45 %
15–18	40 %
18–21	35 %
21–24	30 %
24–27	25 %
27–30	20 %
30–33	15 %
33–36	14 %
36–39	13 %
39–42	12 %
42–45	11 %
45 or more	10 %

2.5 Proposal of alternatives for critical areas: a sensitivity analysis of the evacuation model

Depending on the evacuation results obtained for a specific response time, the formulation of particular measures to improve the evacuation of the area may be required. These measures can be of two types:

– The reduction in the response time, which would increase the time available for evacuation.

– The reduction in the distance to be travelled by communities which are currently not able to evacuate in time, by means of building vertical evacuation shelters and/or new evacuation routes.

After the proposals for alternatives to reduce the response time and/or the distances to be travelled are implemented, the evacuation shall be modelled again in order to confirm that the critical area is being reduced and that more of the population is being evacuated. Further measures should be applied and modelled until the entire area evacuates successfully. This sensitivity analysis of the evacuation model represents a powerful tool for managers to reduce the risk of specific areas, by ensuring the successful evacuation of the population, as it allows for the prediction and assessment of the results of specific management options.

Regarding the identification of possible locations for vertical evacuation shelters in the study areas, once a lower (than the initial) response time is modelled and the critical areas have been identified, the following steps are required:

Table 3. Results for the relationships between tsunami arrival time and total evacuation time.

	Total Evacuation Time ($T1 < T2$)		Result	Colour code (evacuation origin points)
	Fast population $T1$	Slow population $T2$		
Tsunami Arrival Time	$T1 > T_{\mathrm{Tsunami}}$	$T2 > T_{\mathrm{Tsunami}}$	No one starting from this origin point would evacuate	Red
	$T1 < T_{\mathrm{Tsunami}}$	$T2 > T_{\mathrm{Tsunami}}$	Only the fast population group would evacuate	Orange
		$T2 < T_{\mathrm{Tsunami}}$	Everyone starting from this originpoint would evacuate	Green

i. Identification of areas where the population that would be unable to evacuate for this lower response time (T_{Response}) is concentrated (the selection of the initial response time and subsequent reductions to model is context-specific and depends on the modelled tsunami arrival time and the minimum potential response time for the case study).

ii. Location of towers at strategic points in that area. Designers must select the initial location of towers based on the following information: the number and distribution of people along the flooded area with special attention to the people located seaward of the shelter, the tsunami arrival time at the coastline, the geomorphologic characteristics of the territory and the subsequent effects on the tsunami.

iii. Calculation of the arrival time of the tsunami (T_{Tsunami}) at each tower. Assuming that a warning will be issued -the modelling is based on a predefined response time-, the arrival time at the tower is calculated in order to understand the available time to reach it. Knowing the tsunami arrival time at the coast and the location of the various communities, the selection of the tower location must ensure that the tsunami arrival time at the tower is higher than the added reaction and evacuation times of the population located seaward to the shelter.

iv. Calculation of the time available for evacuation at that point, i.e. the time that people have to arrive at the tower before it is reached by the first tsunami wave ($T_{\mathrm{Evacuation}} = T_{\mathrm{Tsunami}} - T_{\mathrm{Response}}$).

v. Calculation of the distance that can be travelled for that evacuation time for the two considered speeds ($V1 = \mathrm{m\,s^{-1}}$, $V2 = 0.7\,\mathrm{m\,s^{-1}}$).

vi. Modification of tower locations, based on the obtained results for each tower, i.e. the initial position is maintained or modified to improve results in terms of number of people reaching the shelter. Any improvement implies going back to steps iii, iv, v and vi until the final location satisfies designer.

Note that in this work, this iterative procedure has been performed heuristically and based on designer experience. However, the methodology could be settled like a mathematical programming problem and solved by standard optimization procedures. The tower locations and its number would be the optimization or decision variables, and the problem could be stated in two different forms: (i) minimize the tower costs subject to the constraint that all inhabitants would have time enough to reach shelter on time; this case assumes that there are no budget limitations; or (ii) maximize the number of people reaching shelter on time, constraint by a limited budget. Although the first option is preferable, reality makes the second option most likely. This automatic selection of the number and location of towers is a subject for further research.

In spite of how this selection if performed, at the end of the process the following information (Fig. 3) is provided for each tower: the tsunami arrival time (T_{Tsunami}); the response time (T_{Response}); the time available to evacuate ($T_{\mathrm{Evacuation}}$); and the reception distance for both population speeds, which is represented by the green and red concentric rings surrounding the towers (the population located in the green ring would reach the tower in the available time, regardless of whether they belong to the fast or slow population; from the population located in the red ring only the fast population would reach the tower in time).

2.6 Evacuation planning

The above-described process provides essential information for tsunami risk management, including the formulation of an evacuation plan. The analysis phase provides measures oriented to (i) reducing the limitations of populations in terms of evacuation, (ii) improving the road network and (ii) improving the existing shelters; while the modelling phase offers measures oriented to (iv) the reduction of current evacuation distances to be travelled and (v) reducing the current response time. Based on this, Table 4 presents an example of an evacuation plan structure and measures.

Table 4. Evacuation plan structure.

General objectives	Specific objectives	Examples of measures
Enhancing the tsunami preparedness of the population	Reduction of the vulnerability of the population regarding evacuation	Reaction time measures – Information, awareness, capacity building and specific help for people who have difficulties understanding a warning message – Specific evacuation training for critical buildings staff (schools, geriatrics, hospitals, etc.) Travel speed measures – Information, awareness and capacity building for slow groups (elderly, disabled, pregnant women and children) – Community organization and specific help for slow groups Isolation measures – Information, awareness and training for isolated areas – Specific help (transport services) for isolated areas – Warning time prioritization to isolated areas
Consolidation of the existing evacuation infrastructures	Consolidation of the existing evacuation routes	Travel difficulty measures – Urban traffic management to avoid bottleneck areas – Removal of potential bottlenecks (i.e. markets) from evacuation routes Travel safety measures – Improve/fix existing roads to facilitate the evacuation
	Consolidation of the existing evacuation shelters	Shelter capacity measures – Increasing the capacity of certain shelters when possible Shelter safety measures – Structural reinforcement of existing structures Shelter accessibility measures – Improve accessibility to existing shelters, eliminate barriers to evacuation
Risk reduction in critical areas	Reducing evacuation distances to travel	Building new routes – Building new routes to shorten the current evacuation distances Building new shelters – Building new shelters to shorten the distances to travel by the communities that currently are not able to evacuate – Special help for the slow population located on the red ring
	Reducing response time	Reducing warning time – Early warning system – Capacity building in critical areas – Optimization of communication system: networking, technology, mobile, tsunami warning speakers, etc. Reducing reaction time – Information and awareness campaigns in critical areas – Training, evacuation drills in critical areas

3 Application to the coastal area of El Salvador

This chapter presents the application of the described methodological framework for evacuation planning to the coastal area of El Salvador. Of the tsunamis that have hit the Pacific coast of Central America, only 4 have been generated by distant sources (including the two recent tsunamis of Chile 2010 and Japan 2011) versus 30 local events, 7 of which were damaging (Álvarez-Gómez et al., 2012). According to Álvarez-Gómez et al. (2012), MARN (2009), Fernández et al. (2004, 2000) and Fernández (2002), the study area is located in an area of high seismic activity which has been hit by 15 tsunamis between 1859 and 2012 (Fig. 4 and Table 5), with all of them having been generated by earthquakes, and two of them being highly destructive; one in 1902 that affected the eastern coast of the country and one in 1957 that affected Acajutla. The most recent, albeit of lesser

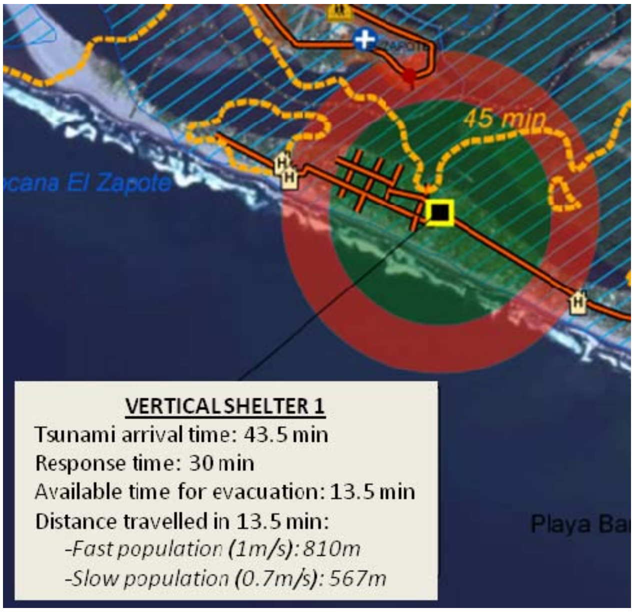

Fig. 3. Example of the information provided for a vertical evacuation shelter.

magnitude, occurred in August 2012, affecting Jiquilisco Bay (IH Cantabria-MARN, 2012).

The work presented here is framed within a comprehensive methodology for assessing the tsunami risk in coastal areas worldwide, and applied specifically to the coast of El Salvador during the period 2009–2012. Two spatial scales have been applied for the risk assessment in the project, a global analysis for the national scale, and a local and more detailed analysis for three specific areas at higher risk: the Western Coastal Plain, La Libertad and the Bahía de Jiquilisco. Evacuation has been modelled for the three local studies. The results obtained for the Western Coastal Plain are presented in this paper.

3.1 Identification of the tsunami-flooded area

The hazard assessment is based on propagation models for earthquake-generated tsunamis, developed through the characterization of tsunamigenic sources – seismotectonic faults – and other dynamics (waves, sea level, etc.). Simulations of historical and potential tsunamis that affect the coast to a greater or lesser extent have been performed, including distant sources (distances greater than 2000 km to the coast, with tsunami travel times greater than 4 h), regional sources (between 700 and 2000 km with tsunami travel times between 1 and 4 h), and local sources (located in the subduction trench off the country's coast with tsunami travel times of less than 1 h).

A deterministic analysis (aggregated analysis that combines the 23 worst credible cases of tsunamis that could impact on the Salvadoran coast, see Fig. 5) has been carried out, considering local seismic sources located in the Middle America Trench, characterized seismotectonically, and distant sources in the rest of Pacific Basin, using historical and recent earthquakes and tsunamis. The earthquakes magnitude ranges between Mw 7.7 for some local sources and Mw 9.5 for distant sources (Álvarez-Gómez et al., 2013). According to the methodology proposed by the SCHEMA project (Tinti et al., 2011), when applying the worst-case credible scenario approach to the tsunami hazard assessment the process of aggregation of the results obtained for the single tsunami sources consists in selecting for each position of the map the extreme value (the highest or the lowest) computed for the individual cases. The main outputs (Fig. 6) are different hazard maps (maximum wave height elevation, maximum water depth, maximum flow velocity, minimum tsunami arrival time, maximum flooding level or "run-up", and maximum potential drag along the coast of El Salvador and at some relevant locations with high resolution analysis. Further information on this deterministic hazard assessment is provided by Álvarez-Gómez et al. (2013).

For evacuation analysis purposes the drag hazard map has been used, as it allows understanding the potential human instability based on incipient water velocity and depth to better explain the human risk caused by the tsunami. Regarding the drag calculation, the drag value at each point of the grid and for each event modelled is obtained by multiplying the flow velocity (u) value by the flow depth (h) value at each instant, and calculating the maximum value of the product, i.e. max ($h \times u$), which is different than considering the maximum value of the velocity at that point (i.e. max (u) $\times$ h). The drag value at each point of the grid for the aggregated case is the maximum drag value obtained among the 23 events.

3.2 Analysis of exposed population, safe areas and road network

The analysis of the exposed population in terms of evacuation has been carried out using the exposure and vulnerability information gathered for the tsunami risk assessment (González-Riancho et al., 2013), with the census tract being the analysis unit at the local level. Based on the methodology presented in Sect. 2 and a geographic information system, several partial and aggregated maps have been generated to better understand the population evacuation index (PEI). Figure 7 shows the PEI map, together with the three indices composing it: (i) the reaction time index of each census tract exposed to the hazard has been calculated, aggregating the number of illiterate people and the number of people located in critical buildings, including schools, hospitals, health centres, hotels, geriatrics, churches, malls, sports and leisure centres; (ii) the travel speed index is based on the number of disabled persons, as well as children below 10 yr and persons above 65 yr; and (iii) the isolation index considers the number of people located in badly connected road areas, or those that frequently get isolated due to other extreme events

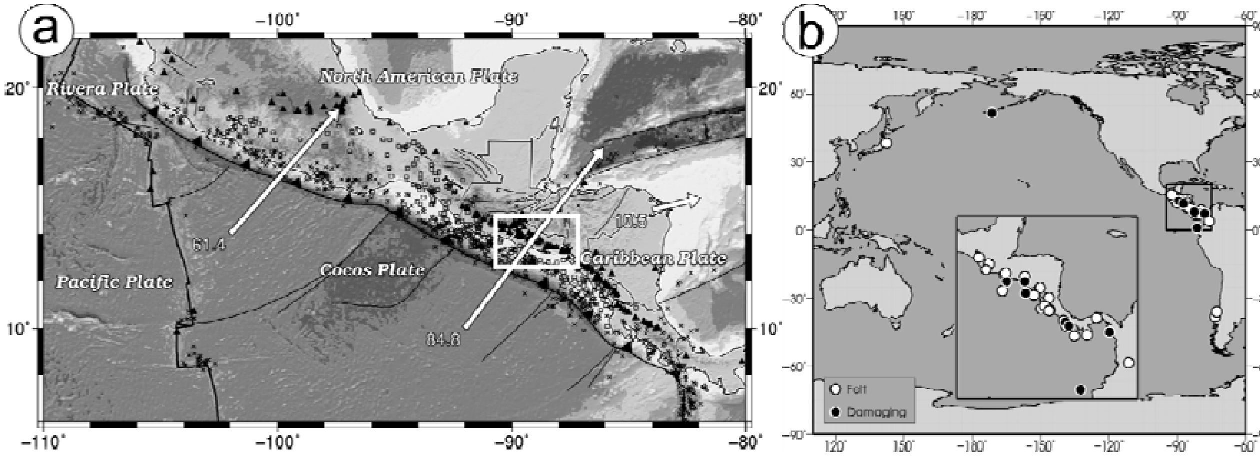

Fig. 4. Location of El Salvador, fault zones and epicentres of past earthquakes (figure and caption modified from Álvarez-Gómez, 2012). **(a)** Tectonic setting of the Middle America Trench. The white square shows the location of El Salvador; the arrows illustrate the direction and magnitude of the plate motions taking the North American Plate; the label is the motion magnitude in mm/year; the triangles show the position of the Holocene volcanoes; cross symbols represent the shallow seismicity (b50 km) and squares the rest of the seismic Global CMT Catalog. **(b)** Tsunami catalog of the pacific coast of Central America; white circles: epicentres of non-destructive tsunamis; black circles: epicentres of damaging tsunamis.

Table 5. Catalogue of historical tsunamis affecting the coast of El Salvador. Data from MARN (2009), Fernández (2002) and USGS Earthquake Hazards Program (http://earthquake.usgs.gov).

Date	Country	Earthquake location	Earthquake magnitude	Tsunami impact location
1859/08/25	Guatemala	13.0° N 87.5W	6.2	La Unión
1859/12/08	Guatemala	13.0° N 89.8W	7.0	Acajutla
1902/02/26	Guatemala	13.5° N 89.5W	8.3	Acajutla Barra de Santiago La Paz
1906/01/31	Ecuador	1.0° N 80.0° W	8.6	All the coast
1919/06/29	Nicaragua	13.50° N 87.50° W	6.7	La Unión
1950/10/05	Costa Rica	11.0° N 85.0° W	7.7	La Libertad La Unión
1950/10/23	Guatemala	14.3° N 91.7° W	7.1	La Unión
1952/11/04	Russia	52.8° N 159.5° W	9.0	La Libertad
1957/03/10	USA	51.3° N 175.6° W	8.1	Acajutla La Unión
1960/05/22	Chile	39.5S 74.5° W	9.5	La Unión
1964/03/28	USA	61.1° N 147.5° W	9.2	Acajutla La Unión
1985/09/19	Chile	18.19° N 102.53° W	8.0	Acajutla
1992/09/01	Nicaragua	11.73° N 87.39° W	7.7	Golfo de Fonseca
2004/12/26	Indonesia	3.29° N 95.98E	9.0	Acajutla
2012/08/26	El Salvador	12.28° N 88.53° W	7.3	Bahía de Jiquilisco (Isla de Mendez)

such as river and coastal flooding. Ultimately, the number of people to be evacuated, their location, and their characteristics regarding difficulties for evacuation are known.

The analysis of the safe areas has considered both horizontal and vertical shelters. Regarding the horizontal evacuation and based on the potentially flooded area, Fig. 8 shows the proposed security zoning for the Western Coastal Plain of El Salvador, which is composed of (i) the tsunami-flooded area (in blue); (ii) the medium-security area (in yellow), established between the maximum flood level in the study area and a security level specifically determined for this zone (20 m a.s.l.); and (iii) the high-security area (in green) from

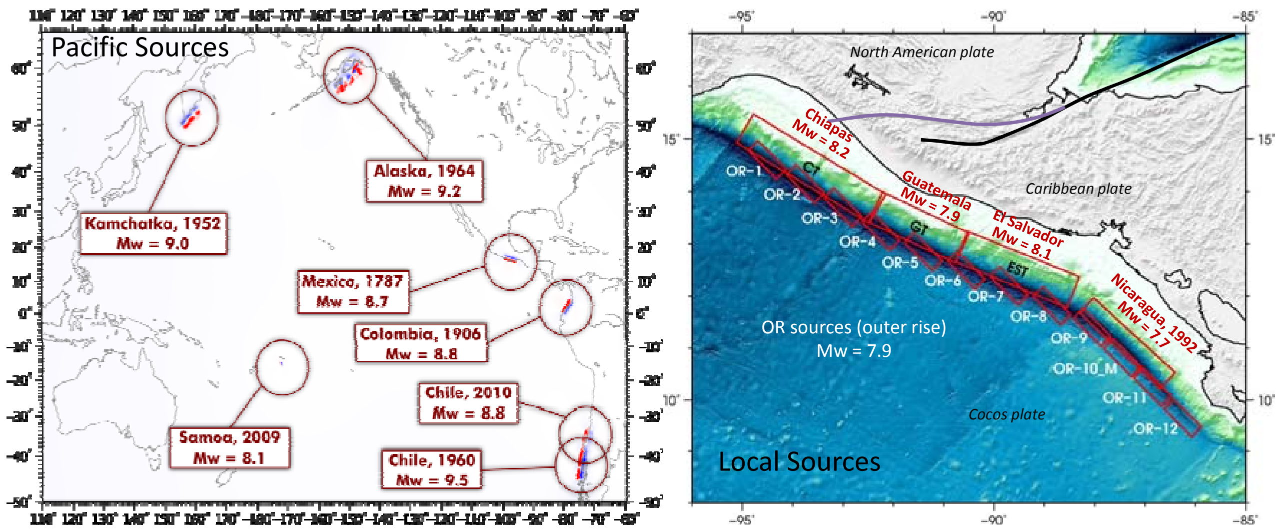

Fig. 5. Tsunamigenic sources aggregated for the deterministic analysis.

this level onwards. Potential vertical shelters located within the different tsunami hazard areas in the three local studies have been identified, analysed and prioritized based on their capacity, safety, and accessibility. In the case of the Western Coastal Plain, analysed here, no vertical shelters were found. The current road network has been analysed, in collaboration with local community leaders through participatory workshops, to identify the existing evacuation routes in the study area, with those roads that connect populated areas with medium-security areas being selected and prioritized in terms of ease of travel and safety. Figure 8 also shows the two specific locations selected in the Western Coastal Plain to be analysed in detail. The results presented in this paper refer to the Barra de Santiago Area (the box outlined on the left).

The Barra de Santiago area, located within Jujutla and San Francisco Menéndez municipalities (Ahuachapán region), is characterized by a 9 km-long sand spit that protects the estuary (Estero El Zapote) of the Aguachapío, Guayapa and El Naranjo rivers. The wetland includes an important mangrove area and belongs to the Complejo Barra de Santiago ANP (Protected Natural Area). According to the census (*VI Censo de Población y V de Vivienda*, DIGESTYC, 2007) and the hazard modelling results, the number of people located in the tsunami-flooded area is around 3300, 75 % being located on the sand spit (Barra de Santiago canton), which was affected by the tsunami of 1902 (see Table 5) and where, according to the local knowledge, only 5 persons survived the event. Figure 9 shows, for the Barra de Santiago area, (i) the main existing evacuation routes (in purple) and the connecting paths (in red); (ii) the location of all the critical infrastructures which must be considered when planning the evacuation, i.e. critical buildings such as schools, hotels, health centres, etc., together with their capacity, and basic needs supply infrastructures such as wells; and (iii) the number of people by census tract (it must be pointed out here that the population-related coloured dots are located exactly in the centroid of each census tract polygon, which represents the location of the coastal communities quite accurately for the small census tracts but not for the big ones, this being the case with the brown-dot census tract whose population is located in the medium-security area, i.e. the yellow area). It is necessary to model and analyse whether the routes allow for the evacuation of people in the time available, or if it is necessary to propose alternative routes.

3.3 Time calculation

The tsunami arrival time and the response time calculated for the study area are presented here. A set of tsunami arrival time maps has been generated through numerical modelling, based on a deterministic analysis that combines the 23 worst credible cases of tsunamis that could impact on the Salvadoran coast. This worst credible case correctly corresponds to a tsunami generated by nearby sources due to an earthquake originating in the subduction zone (Cocos Plate–Caribbean Plate) off the coast of El Salvador. Accordingly the tsunami arrival time presented in this paper is related to a locally generated tsunami, representing the most conservative case in terms of evacuation time and, consequently, safety for the population. In the case of a tsunami caused by a more distant source, these times would obviously increase.

Considering this tsunami scenario, Fig. 10 shows the tsunami arrival time for the Western Coastal Plain which varies between 25 and 45 min depending on the zone, with the 25 entire coast of El Salvador being exposed to this time range. The first tsunami wave would arrive in the area of the Barra de Santiago 40 min after the tsunami generation time.

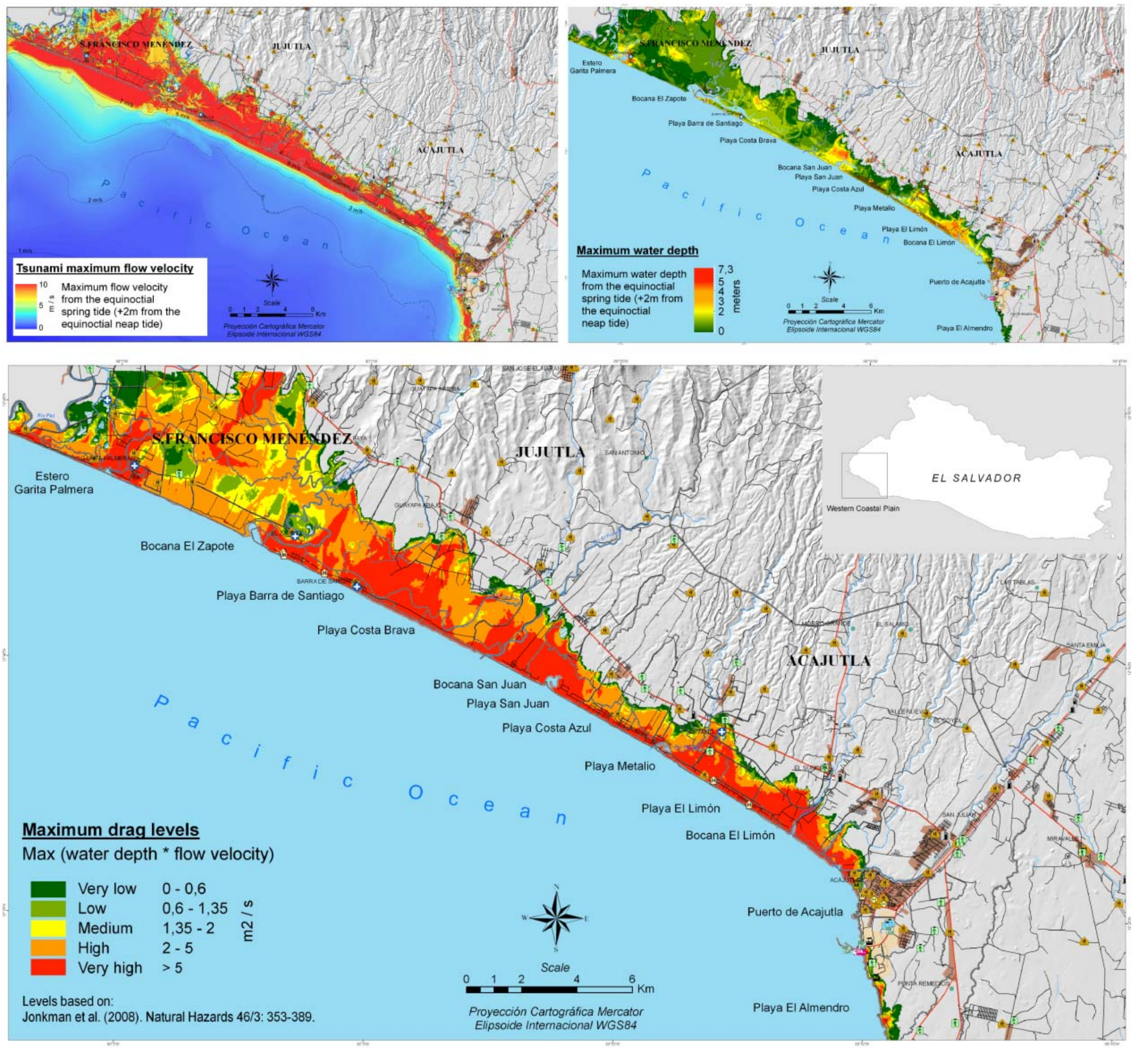

Fig. 6. Hazard maps for the Western Coastal Plain of El Salvador: maximum flow velocity (above left), maximum water depth (above right) and maximum drag (below).

To calculate the response time, several workshops were held with the authorities responsible for the management of different aspects of a tsunami emergency in El Salvador. These workshops allowed for the collection and compilation of the appropriate information and knowledge concerning the approximate duration of the different time intervals involved in this concept:

– The time including (i) the earthquake detection and characterization by the Ministry of Environment and Natural Resources (MARN), (ii) the issuing of the tsunami warning by MARN, (iii) the reception of the alert by the Directorate General of Civil Protection, and (iv) its transmission to the different Civil Protection levels (Departmental, Municipal and Communal Civil Protection committees), takes a total of approximately 13 min.

– Based on experience gained in previous emergency processes for other coastal risks that frequently affect the study area (coastal and river flooding), the time required to transmit the alert to all the people in the community by those responsible in the Communal Civil Protection Committee, is estimated to be 17 min.

– Due to the lack of information regarding the reaction time of the population and recognizing the simplification applied, as there is a strong likelihood that the whole population would not evacuate at the same time, the time elapsed from the moment they are alerted until they begin to evacuate is assumed to be 15 min according to Post et al. (2009) and Strunz et al. (2011).

In conclusion, the current response time in El Salvador for a tsunami event is therefore approximately 45 $(13 + 17 + 15)$ min. The next task is to calculate the evacuation time

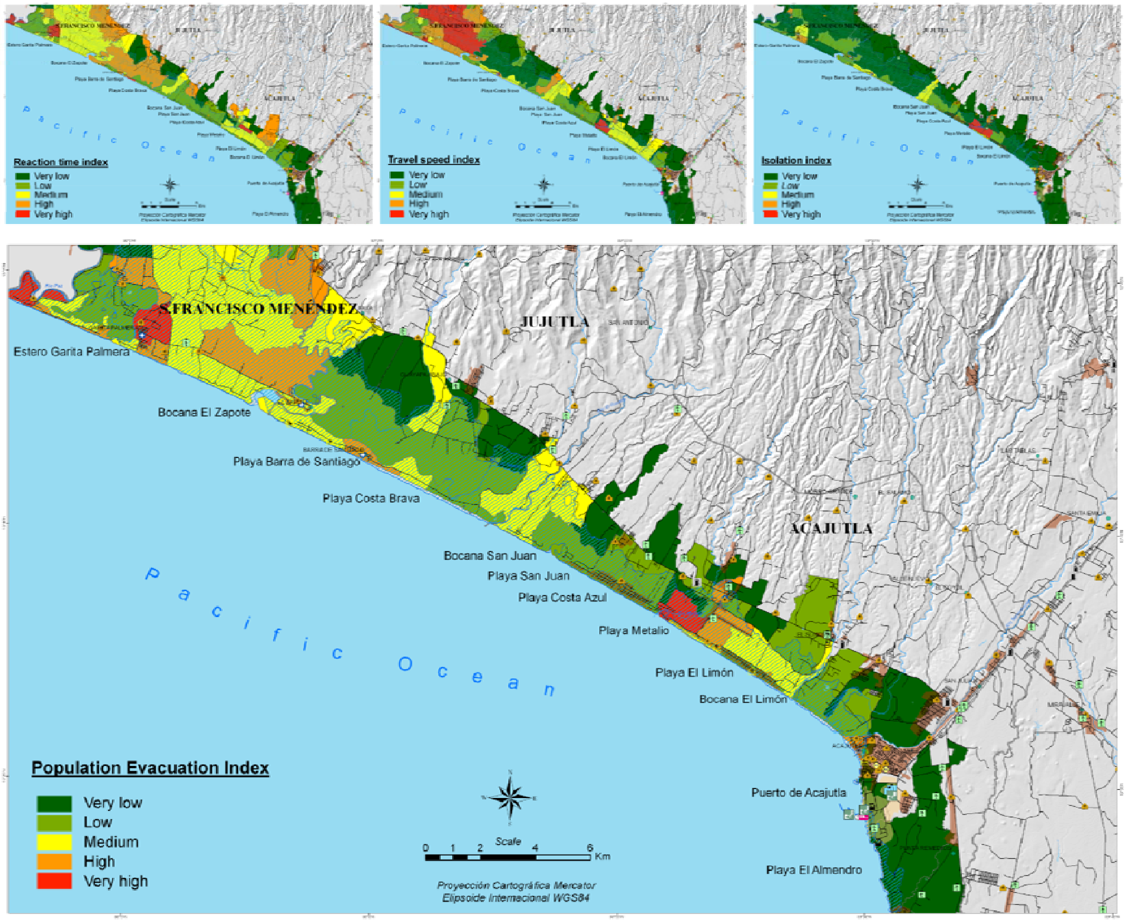

Fig. 7. Population evacuation index (PEI) and related indices: reaction time (above left), travel speed (above centre), isolation (above right) – Western Coastal Plain (El Salvador).

which corresponds to this response time, using evacuation modelling.

3.4 Evacuation modelling

Based on the tsunami arrival time, the security zoning and the road network, evacuation modelling allows the identification of the optimal evacuation routes and the time the population needs to evacuate. For this case study, the origin points are located at every road intersection inside the flooded area according to the spatial distribution and number of people by canton/census tracts and the location of critical buildings. Therefore, depending on the existing road intersections, each origin point will represent a variable number of people. Having this information in mind is essential for further steps (evacuation balance, designing of vertical evacuation shelters, etc.).

The evacuation of the population has been modelled for an initial response time of 45 min (RT45), equivalent to the current response time calculated for El Salvador (Fig. 11). The contour line of 45 min for the first tsunami wave arrival is shown in orange inside the flooded area. It is clear that RT45 means that when the warning arrives in the communities, the tsunami has already reached the coast, and is spreading through the exposed area. The main conclusion obtained from the RT45 results is that most of the exposed population would not be able to evacuate for a response time of 45 min. Results are also presented in pie charts by census tract (Fig. 12), with the green colour representing the percentage of people who evacuate and the red colour representing the percentage who do not; the census tracts showing both options highlight the fact that the evacuation time is also a function of a person's speed (i.e. the fast ones would evacuate, the slow ones would not), and is not only determined by the distance to be travelled in the available time.

3.5 Proposals of alternatives for critical areas

Based on the evacuation results obtained (i.e. most of the exposed population would not be able to evacuate for a response time of 45 min), the formulation of particular measures to improve the evacuation of the area is necessary.

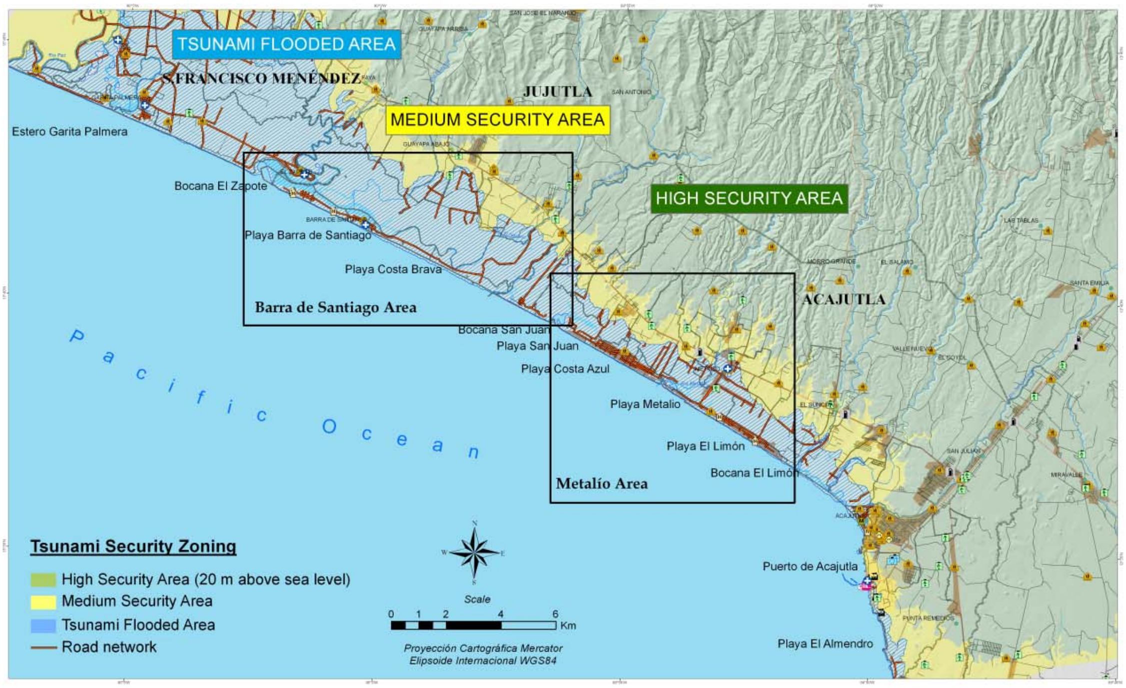

Fig. 8. Tsunami security zoning and existing road network – Western Coastal Plain (El Salvador). Black rectangles show the areas where a detailed analysis has been carried out to identify the evacuation routes, the results for the Barra de Santiago Area being presented in this paper.

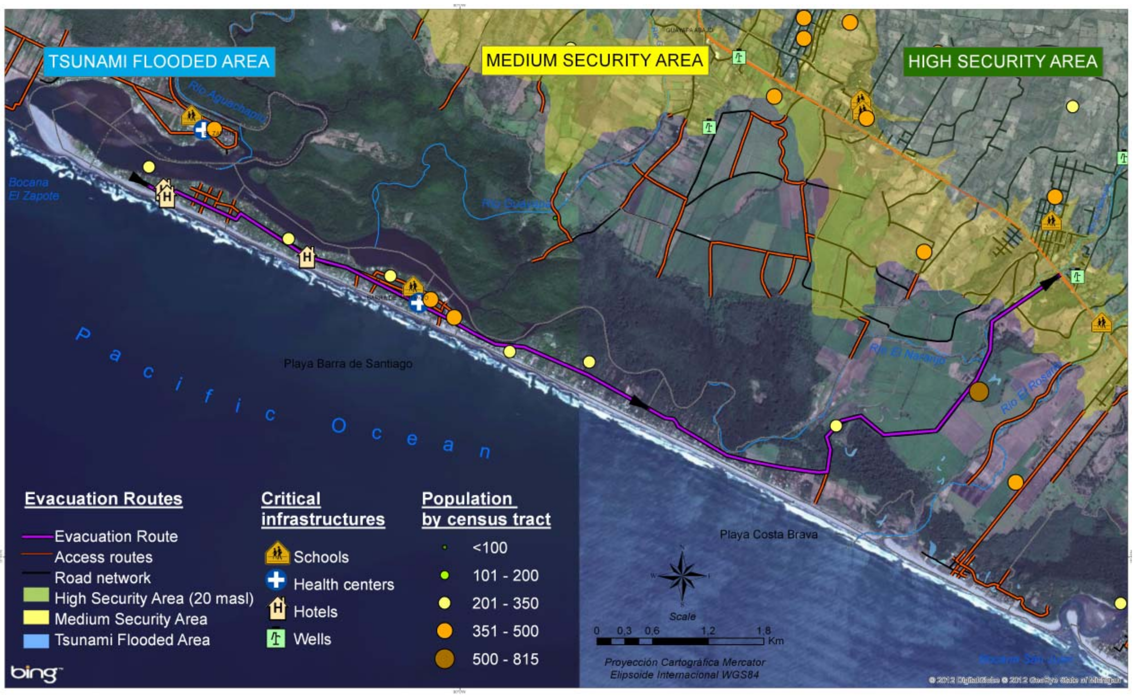

Fig. 9. Existing evacuation routes, critical infrastructures and population by census tract – Barra de Santiago, Western Coastal Plain (El Salvador).

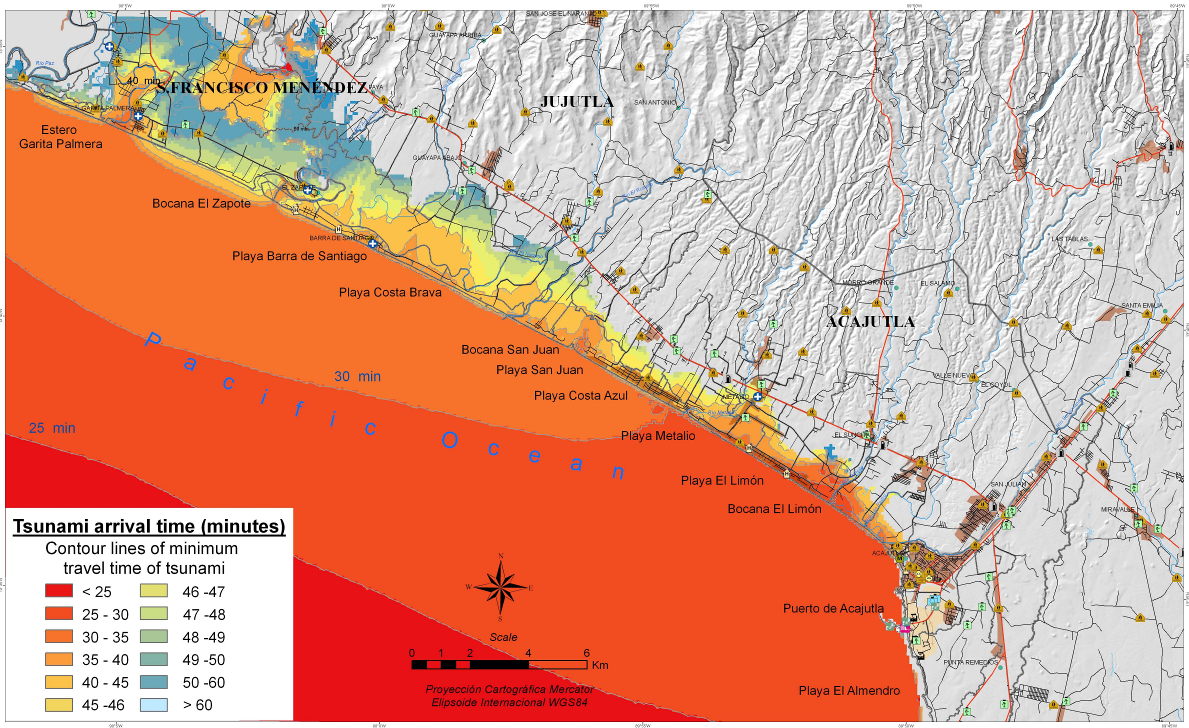

Fig. 10. Tsunami arrival time for the worst-case credible scenario (i.e. aggregated case combining the 23 worst credible cases of tsunami that could impact on the Salvadorian coast) – Western Coastal Plain (El Salvador).

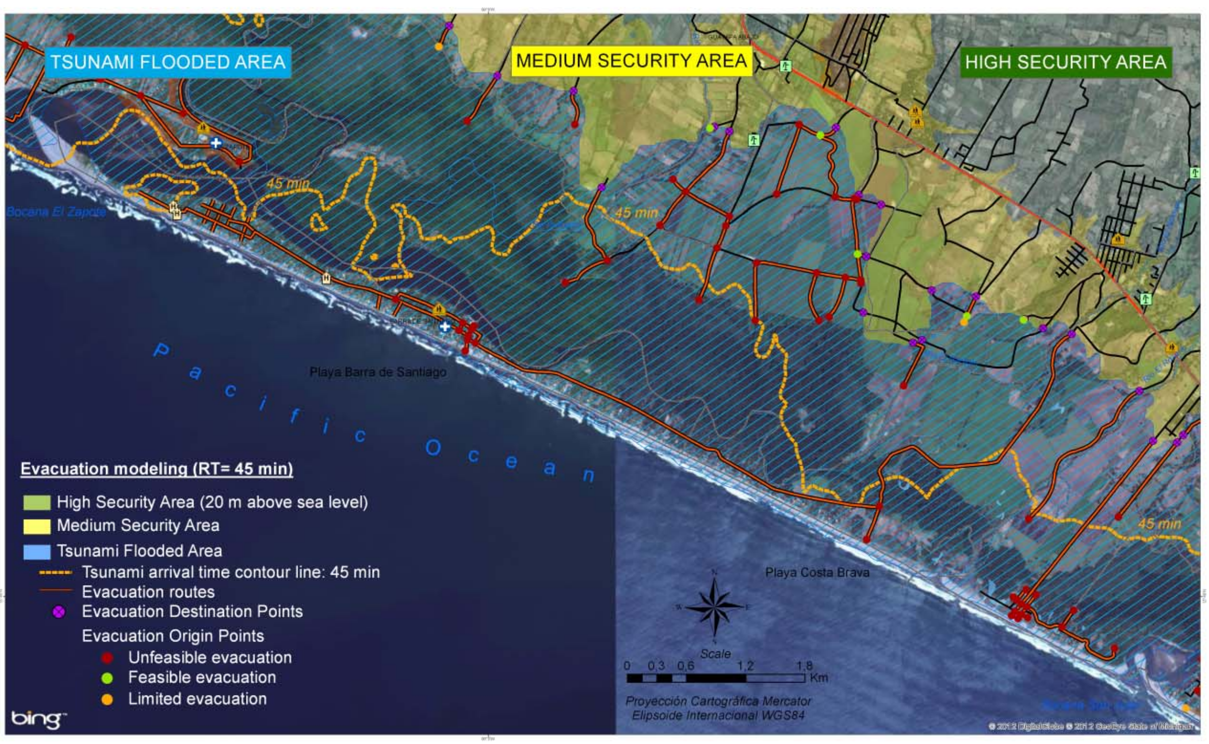

Fig. 11. Evacuation time modelling for a response time of 45 min (RT45) – Barra de Santiago, Western Coastal Plain (El Salvador).

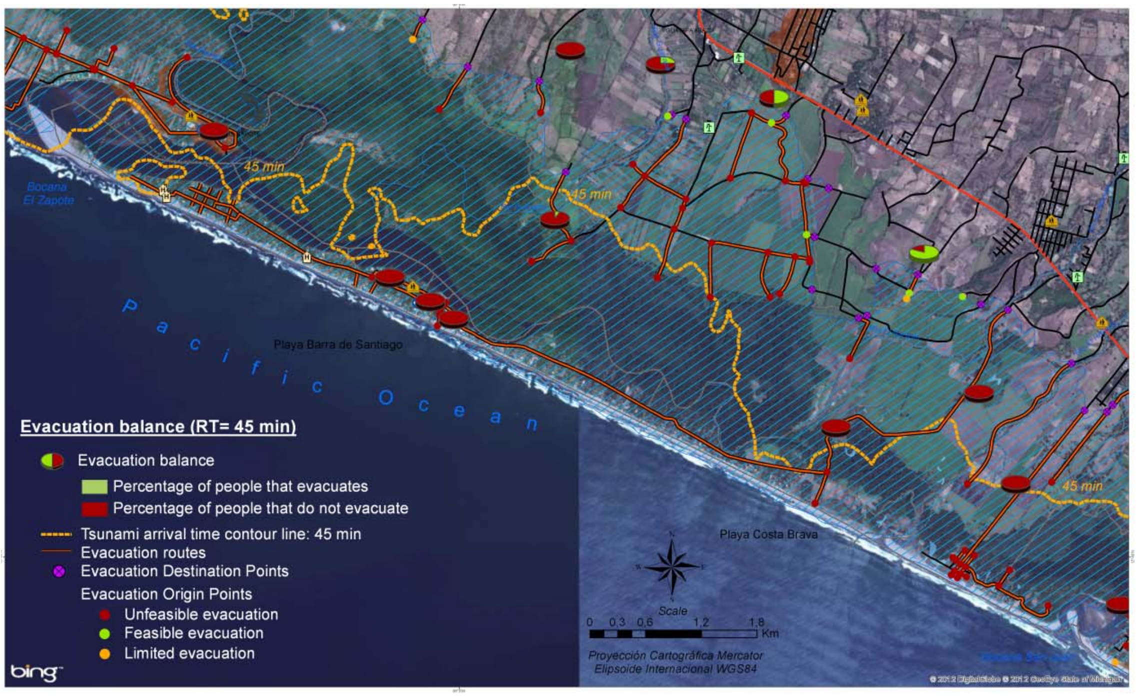

Fig. 12. Evacuation balance for a response time of 45 min (RT45) and by census tract – Barra de Santiago, Western Coastal Plain (El Salvador).

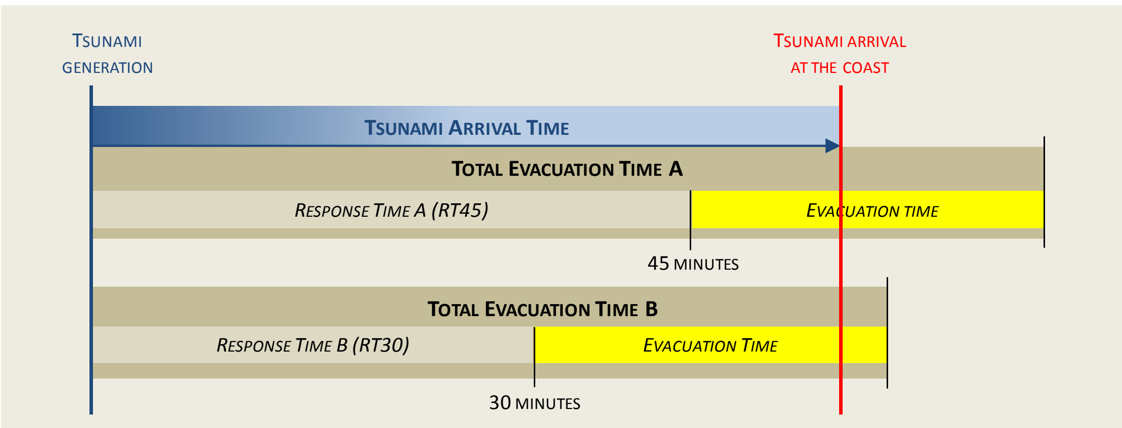

Fig. 13. Response time modelled: 45 and 30 min. The Total Evacuation Time (TET) A considers the current situation in El Salvador (RT45, response time of 45 min). The evacuation modelling showed that most of the coastal population would not be able to evacuate. The TET B considers a lower response time (RT30) in order to model and understand if this reduction would be enough to achieve a successful evacuation for the whole coast or if further RT reductions are required.

These measures include (i) the reduction of the response time, and (ii) the reduction of the distance to be travelled by the population. These two proposed measures are then tested using evacuation modelling until it is confirmed that the critical area is eliminated and that the entire area evacuates successfully.

A new modelling has been performed for a response time of 30 min (RT30) in order to understand the implications, in terms of people affected, of taking less time to (i) detect the tsunami, (ii) warn the people, and (iii) start evacuating, since this situation would then result in increased time being available for evacuation (Fig. 13). The selection of the several response times to model is site-specific and should be adapted to each case study; the example applied to this case (RT30) and presented below does not imply that this is a suitable time threshold for all cases, or even for El Salvador. The idea is to reduce the response time as much as possible, combined with further measures to reduce the distance to be travelled.

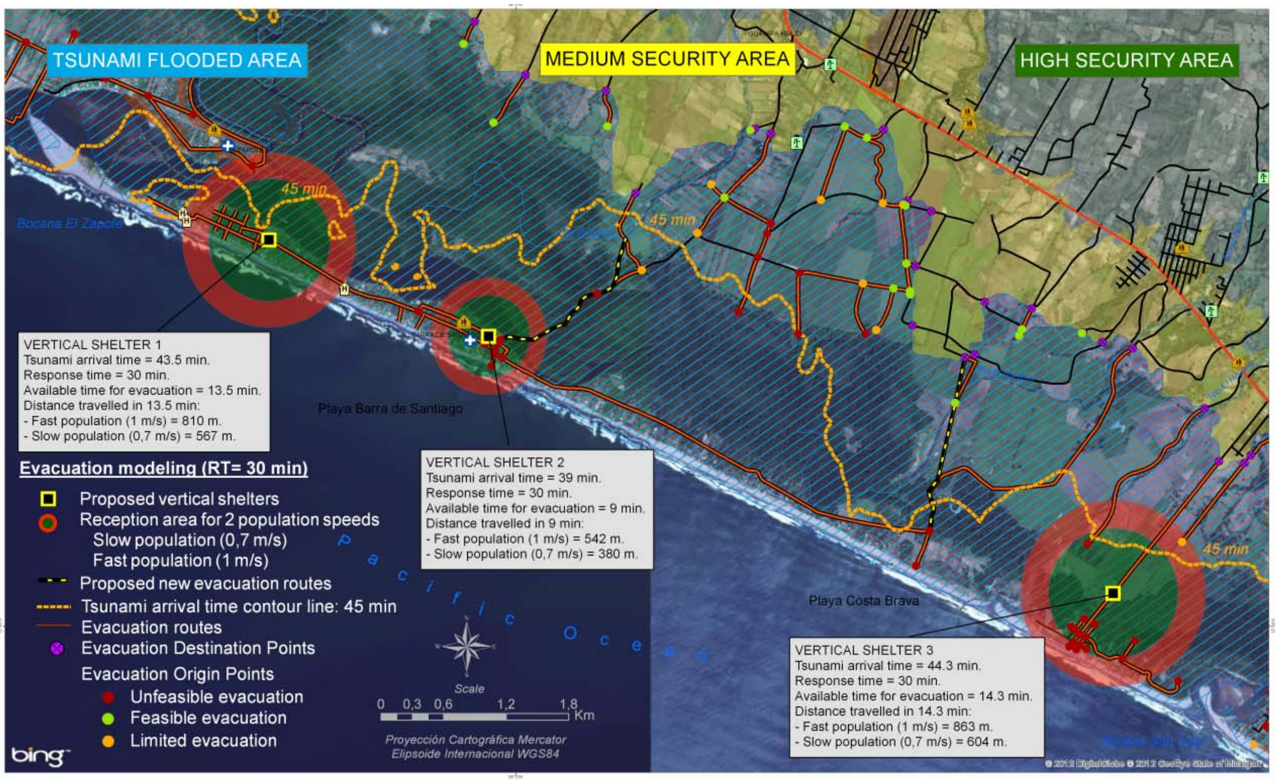

Fig. 14. Evacuation time modelling for a response time of 30 min (RT30) and proposal of alternatives for critical areas – Barra de Santiago, Western Coastal Plain (El Salvador).

Compared to the evacuation modelling for RT45 (Fig. 11), the modelling for RT30 (Fig. 14) shows that the communities located close to safe areas and above the tsunami arrival time contour line of 45 min, would more or less successfully evacuate for this new response time (origin points changed to green and orange). The communities located below the 45 min contour line, however, would not evacuate (origin points still in red) even with the 15 additional minutes afforded by RT30.

For these latter communities which would not able to evacuate in time, further measures are proposed, i.e. the reduction of the distance to be travelled by these communities, by means of building vertical evacuation shelters and/or new evacuation routes. These measures are represented in Fig. 14 by yellow-black elements, with squares representing the new vertical shelters, and lines representing the new evacuation routes. As explained in the methodology, the green and red concentric rings surrounding the towers represent the reception distance for both population speeds. Special attention is paid to the critical buildings (1 school, 3 hotels and 1 health centre in Barra de Santiago) in order to have them included in the reception area of the towers. The combination of this information, together with the amount of people to be evacuated, indicates the number of persons that these shelters should be designed to accommodate (in this case, 2500 persons between towers 1 and 2, and 800 in tower 3, approximately).

The iterative modelling of subsequent measures ensures that all the starting evacuation points change to green, indicating the evacuation of the entire exposed population in the time available.

It is important to point out that these analyses and mapping resources are oriented to and designed for risk and emergency managers, in order to provide them with technically sound information to assist in the formulation of optimal evacuation planning for specific areas. The evacuation maps which are to be provided to the exposed local communities, based on the results obtained from the presented framework, must however be simplified to ensure they are intuitive and can be easily understood by the members of the communities.

4 Conclusions

Advances in the understanding and prediction of tsunami impacts allow the development of risk reduction strategies for tsunami-prone areas, with evacuation planning being an essential requirement to save lives during emergencies. This paper presents an integral framework for the formulation of tsunami evacuation plans based on tsunami hazard and vulnerability assessment and evacuation modelling. This methodology considers (i) the hazard aspects (tsunami flooding characteristics and arrival times), (ii) the characteristics of the exposed area (people, shelters and road network), (iii) the current tsunami warning procedures and timing, (iv) the time needed to evacuate the population, and (v) the identification of measures to improve the evacuation process. The presented framework aims to bridge the gap between science and management in terms of tsunami evacuation and presents evacuation modelling as a vital tool for disaster risk management and evacuation planning. The framework has been applied to the El Salvador case study, demonstrating its applicability to site-specific response times and population characteristics.

The hazard assessment, through the tsunami numerical modelling, permits the generation of different hazard maps (i.e. maximum wave height elevation, maximum water depth, minimum tsunami arrival time, maximum flooding level or "run-up", and maximum drag regarding people instability) which provides knowledge about the exposed area, the locations which would receive higher impacts and the tsunami first wave arrival time, all being critical information for evacuation purposes. The worst case scenario is the most conservative in terms of risk management.

The vulnerability assessment of the exposed population assists in the designing of specificity-oriented measures in order to deal with specific weaknesses in terms of evacuation (see Table 1). Several characteristics of the population have been analysed: (i) the total number of exposed people, (ii) the number of people in critical buildings (schools, hospitals, geriatrics, hotels, etc.), together with illiteracy and intellectual disability, providing information about reaction times; (iii) slow groups (the elderly and children) and physical disability which are directly related to the travel speed; and (iv) badly connected areas which translate into community isolation, impacting both the reception of an alert and the subsequent evacuation. The analysis of the existing road network and safe areas provides knowledge about the current evacuation infrastructure and may highlight the need for repairs and improvements.

The proposed evacuation modelling helps by identifying (i) the shortest routes that people have to travel from their places of origin to destination points, considering the slope and different population speeds, and (ii) the evacuation degree of success for the available evacuation time. This modelling also considers the response time, understood as the time from the tsunami generation until the population begins to evacuate: (i) the current emergency protocols and the experience of the responsible authorities both provide essential information about the time needed for tsunami detection, issuing of warnings, alert transmission and reception, all of which are extremely important for the population, as a shorter response time directly translates into longer time available for the population to evacuate; (ii) the population reaction time is assumed to be 15 min (Post et al., 2009; Strunz et al., 2011). It is important to mention that the proposed framework permits the application of more complex evacuation models as required and/or further research advances such as those regarding the slope calculation or the optimization process for shelter location. Modelling the current response time gives the real evacuation situation, which is the starting point for risk management. The evacuation degree of success obtained for the current response time helps in defining alternatives for those communities that do not have options to evacuate in the current situation, by means of reducing the response time and/or shortening the distances to be travelled (through additional routes and/or shelters). This sensitivity analysis of the evacuation model represents a powerful tool for managers to reduce the risk in specific areas, by ensuring the successful evacuation of the population, as it allows predicting the results of specific management options.

A method for the identification of possible locations for vertical evacuation shelters is proposed, providing useful information for each shelter, such as the tsunami arrival time, the response time, the time available to evacuate, and the reception distance for both population speeds. The combination of this information with the amount of people to be evacuated indicates the capacity that these shelters should accommodate.

Finally, the proposed framework permits the organization, classification and prioritization of the gathered information, in order to better define the several risk management measures to be included in an evacuation plan.

Regarding some of the results obtained for El Salvador, the evacuation modelling for the current response time of 45 min (RT45; i.e. warning time 30 min, reaction time 15 min) highlighted that improvements to the warning process must be made to ensure the success of the evacuation, as most of the coastal communities would be reached by the tsunami before being warned about it. A reduction of 15 min in the response time (RT30) showed that a higher percentage of populations evacuates (proving the importance of working on this issue); however, the communities located closer to the coastline would not be able to reach the safe areas. For these communities an attempt to identify alternative measures to ensure their evacuation is proposed, such as building new evacuation routes and new vertical shelters. These combined measures (reducing response time and reducing distances to travel) have been demonstrated to be useful for achieving the desired results. The repetition of the evacuation modelling for each group of measures proposed ensures the control and reduction of critical areas.

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