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Discussions

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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 the development of risk reduction strategies for tsunami-prone areas. This paper presents a methodological framework for the integrated tsunami vulnerability and risk assessment. It deals 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; and (iii) a dynamic and scale dependant approach to integrate the spatiotemporal variability considerations. This framework aims at establishing 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 framework is applicable to other types of hazards, having been successfully applied to climate change hazard.

1 Introduction

Tsunamis are relatively infrequent phenomena, but they nonetheless represent a greater threat than earthquakes, hurricanes and tornadoes, and cause the loss of thousands of human lives and extensive damage to coastal infrastructures throughout the globe (González et al., 2012). Advances in the understanding and prediction of tsunami impacts allow 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.

Numerous previous works dealing with vulnerability and risk related to different hazards exist in the literature, with many of them focusing on tsunami risk assessments at various locations and countries. Some examples of previous works are presented here. 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 (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 (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; Koeri et al., 2009; Jelínek et al., 2009), the environmental system (Fundacion-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), some of them concentrating on tsunami evacuation modeling (Van Zuilekom et al., 2005; Aboelata and Bowles, 2005; Mück, 2008; Clervaux and Katada, 2008; Alvear Brito et al., 2009; Kolen et al., 2010).

This review confirms how risk-related works differ according to (i) the risk component analyzed (i.e. hazard, exposure, vulnerability, impacts, resilience, coping capacity, etc.), (ii) the risk dimension dealt with (i.e. human, infrastructural, environmental, social, economic, etc.), and (iii) 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 a holistic understanding of the system dealt with; otherwise management options can produce unexpected and sometimes undesired results.

The management of coastal risks requires the proper understanding of this fragile and complex system in which marine dynamics, the coastal ecosystems and human activities converge. Understanding the interrelationships between human societies and their behavioral patterns, coastal resources and their uses, coastal risks, and policies and institutions that govern human activities is essential for an adequate coastal management. An integrated and multidisciplinary approach is important to analyze the entire system, instead of simply considering specific aspects of a single sector or scientific discipline, allowing the understanding of the interrelationships that control the behavior and balance of the coastal system. According to Rotmans and Dowlatabadi (1998), an integrated assessment can be defined as a process 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 combination of risk components, dimensions and scales, 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.

Besides the complex implementation of the integration concept, according to Brooks (2003), the growing body of literature on vulnerability and adaptation contains a sometimes bewildering array of terms with often unclear relationships between these different elements, and applying different meanings to the same term when used in different contexts and by different authors. Vogel and O’Brien (2004) stresses that vulnerability is (i) multi-dimensional and differential, as it varies across physical space and among and within social groups; (ii) scale dependent regarding time, space and analysis units; and (iii) dynamic, as the characteristics and driving forces of vulnerability change over time. Regarding the vulnerability and risk dimensions, although the international community does not formulate guidelines on how to develop indicators or indicator systems to assess vulnerability, the Hyogo Framework for Action (UN, 2005) underlines the fact that impacts of disasters on social, economic, and environmental conditions should be examined through such indicators (Birkman, 2006). EC (2010) suggests analyzing human, economic, environmental and political/social impacts. The impacts generated in recent tsunami events suggest the need to consider infrastructures and buildings in the vulnerability assessment.

According to Birkman (2006), the current literature encompasses over 25 different definitions, concepts and methods to systematize vulnerability (for example Chambers, 1989; Bohle, 2001; Wisner et al., 2004; Downing et al., 2006; UN/ISDR, 2004; Pelling, 2003; Luers, 2005; Green, 2004; Schneiderbauer and Ehrlich, 2004; Turner et al., 2003; Cardona, 2004). Many conceptual frameworks for vulnerability analysis have also been developed, such as Bohle's double structure of vulnerability (Bohle, 2001), the sustainable livelihood framework (DFID, 1999), a conceptual framework to identify disaster risk (Davidson, 1997; Bollin et al., 2003), a 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., 2004), 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; Cardona, 1999), among others. As stated by Birkman (2006), despite some differences between the frameworks due to the various objectives to be fulfilled by each one, it is commonly agreed that vulnerability represents the inner conditions of a society or community that make it liable to experience harm and damage, being clearly differentiated from the physical event (hazard).

In conclusion, tsunami risk assessments are essential for the formulation of adequate, site-specific and weakness-oriented risk management options. Different partial aspects of tsunami risk are addressed in literature, dealing with different risk components, dimensions and scales; however, several gaps in science are identified. The first gap is that there are some contradictions or disagreements within the scientific community regarding the terms used, such as whether resilience is the opposite of vulnerability or a concept included in it, whether exposure is included or not in the vulnerability or in the hazard, whether coping capacity is included in the vulnerability or not, or the dimensions to be included in the vulnerability assessment, among others. The second one, risk management, requires a holistic and integrated understanding of the system to recognize the interrelationships that control its behavior and equilibrium, a major challenge being the systematic combination and aggregation of different types of data and information from various disciplines, scales and data acquisition methodologies. Another gap has to do with the fact that the vulnerability is multi-dimensional, scale dependent and dynamic; many theoretical and conceptual frameworks exist but very little information on how to apply them is provided. There is also the issue regarding the lack of information on the integration of spatiotemporal variability within the vulnerability. The last gap refers to the risk assessment results, which sometimes do not provide conclusions on how to reduce the risk at the identified areas, lacking a clear correlation between risk assessment and management.

Based on these conclusions, the objectives of this paper are (i) the proposal of a methodological framework for an integrated tsunami vulnerability and risk assessment, establishing the risk components, dimensions and spatiotemporal scales and the method to integrate them; (ii) the establishment of a clear connection to translate the vulnerability and risk assessments into risk reduction measures, bridging the gap between science and management for the tsunami hazard; and (iii) the application of the methodology to the coastal area of El Salvador as a case study.

This paper is structured as follows: after this introduction the conceptual framework is presented in Sect. 2, followed by the description of the proposed methodology throughout Sect. 3. Section 4 presents the application of this methodology to the coastal area of El Salvador, and more specifically at the national level and to the Western Coastal Plain, establishing a discussion on the major findings. Finally, some conclusions are presented.

2 Conceptual framework for integrated risk assessment

Due to the above mentioned bewildering array of terms on risk and vulnerability and the often unclear relationships between them, it is essential to first clarify the conceptual framework proposed here. It is based on a multidisciplinary approach aimed at providing a holistic picture of the possible impacts on the study area and consequently offering adequate target-oriented risk reduction measures. This framework deals with the complexity and variability of coastal zones by means of an integral approach to cover the entire process from the hazard, vulnerability and risk assessment to the final risk management, an integrated approach to combine and aggregate the information stemming from the different dimensions, and a dynamic and scale dependant approach to integrate the spatiotemporal variability considerations.

2.1 Dealing with the complexity and variability of coastal zones

In order to carry out a proper tsunami risk assessment, the concept of risk is analyzed according to its components, dimensions and scales (Fig. 1). Due to the complexity of this structure and all the definitions and technical works included within this conceptual framework, a homogeneous way of expressing the results of the risk assessment is also proposed. The tools applied in this methodology are reviewed in further sections.

2.1.1 Risk components: an integral approach

The conceptual framework of this methodology is based on the definition of *Risk* as the probability of harmful consequences or expected losses (deaths, injuries, property, livelihoods, disrupted economic activity or damaged environment) resulting from interactions between natural or human-induced hazards and vulnerable conditions (UN/ISDR, 2004). The mentioned *consequences* are the negative effects of disaster expressed in terms of human, economic, environmental and political/social impacts (ISO, 2009). Therefore, risk depends on the specific impact analyzed (e.g. loss of human lives), the probability of occurrence 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).

Hazard is a dangerous phenomenon, substance, human activity or condition that may cause loss of life, injury or other health impacts, property damage, loss of

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livelihoods and services, social and economic disruption, or environmental damage (UN/ISDR, 2009). In order to properly understand the hazard, it is essential to identify and analyze 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). *Vulnerability* is understood as the conditions determined by physical, social, economic and environmental factors or processes, which increase the susceptibility of an exposed community to the impact of hazards (adapted from UN/ISDR, 2004). In probabilistic/quantitative risk assessments the term vulnerability expresses the part or percentage of Exposure that is likely to be lost due to a certain hazard (EC, 2010). Within the vulnerability, *Sensitivity* refers to the predisposition to be affected by physical or socio-economic changes, including damage and losses (UN/ISDR, 2004), and is here understood as an intrinsic quality of the exposed element; 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), being conditioned by learning and experience.

2.1.2 Risk dimensions: an integrated approach

The analysis of coastal risks requires the proper understanding of this fragile and complex system where the marine dynamics, the coastal ecosystems and the human activities converge. Understanding the interrelationships between human societies and their behavior patterns, coastal resources and their uses, coastal risks, and policies and institutions that govern human activities is essential for an adequate coastal

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management. An integrated and multidisciplinary approach is important to analyze the entire system instead of simply considering specific aspects of a single sector or scientific discipline, making it possible to understand the interrelationships that manage the behavior and equilibrium of the coastal system.

The aforementioned integrated approach is necessary since the earliest planning stages of the study, as it assists in the effective analysis of the scientific information coming from different disciplines as well as the consideration and integration of the variables controlling the behavior of complex systems. This statement is applied throughout the exposure and vulnerability assessment, as they are fragmented to incorporate different coastal dimensions. For a tsunami risk assessment the human, environmental, socioeconomic and infrastructure dimensions should be analyzed. 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, while the socioeconomic dimension focuses on livelihoods and economic losses. Each dimension's vulnerability is assessed using the appropriate units, this quantification being the starting point to subsequent evaluations to determine if the proposed risk reduction measures are effective and whether the vulnerability is or is not reduced.

2.1.3 Risk scales: a dynamic and scale dependant approach

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 must define a reference space-time window. This methodology proposes applying different spatial and time scales for risk calculation. The *spatial scale* considerations are related to the achievement of different technical objectives according to the scale. The small scale (global) assessment aims at having an overview of the possible risks on the different dimensions, allowing the comparison between different analysis units (i.e. municipalities) in order to identify those which are to be prioritized. The large scale (local) assessment focuses on those priority areas which need a detailed analysis to evaluate the specific expected impacts. The *time scale* considerations allow understanding the system behavior and patterns, and their implications to the risk analyzed as, according to Vogel and O'Brien (2004), the characteristics and driving forces of vulnerability change over time; for instance, holidays or nesting periods would increase the vulnerability of the human and environmental dimensions respectively.

2.2 Integration of risk components, dimensions and scales

Considering the above-mentioned approach, the general structure proposed for a tsunami risk assessment is shown in Table 1. Different tsunami risk studies could, according to their objectives, focus on and chose specific aspects from all the possibilities shown in the table; for example, one could decide between carrying out a deterministic or a probabilistic hazard analysis, or maybe both; or choosing the dimensions or time scales which are more representative of the analyzed coastal system.

Due to the complexity of this structure and the amount of information and results obtained, a homogeneous way of expressing the results of the risk assessment is also proposed. Therefore, the results will answer the following question: *What is the RISK of having an IMPACT caused by a THREAT in a defined SPATIAL and TIME SCALE for a specific TIME PERIOD?,* (for example: "what is the risk of having socioeconomic impacts caused by a tsunami flooding in Acajutla during the summer for a return period of 500 yr?").

The application of this structure reveals a difficulty which is commonly faced in every risk assessment, i.e. the integration of concepts. The main challenges faced here are the integration of risk dimensions, and the integration of spatial scales.

Regarding the integration of dimensions, according to EC (2010), this framework proposes two types of results, partial and aggregate results. The first ones allow having the available impacts analyzed separately for the different dimensions and components, while the last one combines all the dimensions. As far as spatial scale integration is concerned, two different kinds of results are also distinguished depending on the scope

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dealt with: general risk results at the global level (small scale, i.e. national) for the four dimensions analyzed as well as the aggregate risk, and detailed expected impacts for the different dimensions at the local level (large scale, i.e. municipalities) on the priority areas previously identified during the global assessment.

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 proposed framework, this translates into the formulation of several risk reduction measures based on reducing the human/environmental/socioeconomic/infrastructural exposure and sensitivities, and increasing the resilience. Therefore, direct risk management measures can be offered based on the collected exposure and vulnerability information.

Figure 2 summarizes the structure of the risk assessment and the different kind of results to be obtained.

This framework, 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 hazard 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).

3 Methodology

A brief description of the proposed methodology is provided, including (i) the hazard assessment, (ii) the vulnerability and risk assessment, and (iii) the formulation of risk reduction measures.

3.1 Tsunami hazard assessment

The hazard assessment is based on the numerical modeling of the dynamics related to the generation and propagation of tsunamis to understand the probability, frequency, intensity and duration of a hypothetical event as well as the potentially affected

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area. Thus, the tsunamigenic sources and other ocean and coastal dynamics shall be characterized and analyzed (Álvarez-Gómez et al., 2013). Simulations of historical and potential tsunamis with greater or lesser affection to the study area's coast shall be performed including distant, intermediate and close sources. Probabilistic or deterministic analyses can be performed 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 potential drag understood as the hazard degree for human instability based on incipient water velocity and depth.

3.2 Tsunami vulnerability and risk assessment

The vulnerability assessment of the identified exposed elements is based on an integrated approach to understand the relations between the different coastal dimensions. A set of indices and indicators will be 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 (GIS) allows storing, managing and analyzing the data and information concerning the study zone, including vector and raster datasets of the physical characteristics of the coast as well as of the societies, economy and infrastructures. The GIS tool aims to support every decision with geo-referenced information. It is an essential tool for the combination of partial maps related to each dimension to then generate an aggregated map, and particularly useful for evacuation modeling and planning (González-Riancho et al., 2013). The following sections describe the set of indicators and the methodology used to integrate them.

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3.2.1 Definition of exposure and vulnerability indicators

The exposure indicators identify the elements located in the hazard area, while the vulnerability indicators measure the characteristics of the exposed elements that make them susceptible to suffer the selected impacts.

According to the Handbook on Constructing Composite Indicators (OECD, 2008), the next ten steps shall be followed in the construction of composite indicators. (1) A theoretical framework should be developed to provide the basis for the selection and combination of single indicators into a meaningful composite indicator under a fitness-for-purpose principle. (2) Indicators should be selected on the basis of their analytical soundness, measurability, country coverage, relevance to the phenomenon being measured and relationship to each other. The use of proxy variables should be considered when data are scarce. (3) Consideration should be given to different approaches for imputing missing values. Extreme values should be examined as they can become unintended benchmarks. (4) An exploratory analysis should investigate the overall structure of the indicators, assess the suitability of the data set and explain the methodological choices, e.g. weighting, aggregation. (5) Indicators should be normalized to render them comparable. Attention needs to be paid to extreme values as they may influence subsequent steps in the process of building a composite indicator. Skewed data should also be identified and accounted for. (6) Indicators should be aggregated and weighted according to the underlying theoretical framework. Correlation and compensability issues among indicators need to considered and either be corrected for or treated as features of the phenomenon that need to be retained in the analysis. (7) The robustness of the composite indicator should be assessed in terms of, e.g., the mechanism for including or excluding single indicators, the normalization scheme, the imputation of missing data, the choice of weights and the aggregation method. (8) Composite indicators should be transparent and fit to be decomposed into their underlying indicators or values. (9) Attempts should be made to correlate the composite indicator with other published indicators, as well as to identify linkages through regressions. (10)

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Composite indicators shall be visualized or presented in a number of different ways, which can influence their interpretation.

Based on these steps, the proposed set of indicators is presented in Table 2. This set is supported by a GIS and adapted to different spatiotemporal scales: the spatial scale includes both national and local levels while the time scale 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.

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 organizing itself both prior to and during times of need (UN/ISDR, 2009). To evaluate the resilience, two of society's capacities are analyzed, one related to the pre/during-event and the second one to the post-event:

- Coping capacity: the ability of people, organizations and systems, using available skills and resources, to face and manage adverse conditions, emergencies or disasters (UN/ISDR, 2009).

- Recovery capacity: the ability of the system to recover after a disaster.

These two capacities are assessed through the analysis of the four phases of emergency management: (i) information and awareness, (ii) warning and evacuation, (iii) emergency response and (iv) disaster recovery. Data collection for the construction of the resilience index is carried out through a short questionnaire which identifies the degree of organization and response within a community in case of an emergency. The questionnaire offers three response alternatives: *yes/no/partially*. 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 analyzed

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together with the sensitivity data. Table 3 shows the relation between the elements of resilience, the phases of emergency management and the questionnaire.

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 time scales 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". Consequently, the indicators "coping capacity" and "recovery capacity" will analyze the lack of resilience and focus on the negative responses of the questionnaire. The aggregation of each type of answer multiplied by its coefficient (positive answer: coefficient 0; negative answers: coefficient 1; intermediate answers: coefficient 0.5) and divided by the total number of questions provides the value of the lack of resilience index. This is necessary for aggregation purposes (i.e. aggregating sensitivity and resilience to build the vulnerability); however, to analyze the resilience itself, the lack of resilience is translated again into the resilience concept through the expression: Resilience = 1 – Lack of resilience.

3.2.2 Method for the integration of risk concepts

The method for the integration of risk concepts, i.e. those 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 normalization; (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.

The units of the variables generating the indicators must be absolute and can cover a wide range of values, i.e., number of people, ecosystems area, dollars, number of buildings, etc. The indicator units, however, must be relative values in order to correct the imbalance caused by the different units and to allow for their comparison and combination. Based on OECD (2008), the transformation of the variables range of values is carried out through the minimum–maximum (Min–Max) method, which normalizes the indicators so as to obtain an identical range [0,1] by subtracting the minimum value and dividing it by the range of the indicator values. Once the indicators have been normalized, a weighted aggregation is applied to them in order to build the partial indices for each dimension. Thus, a weight associated with the importance it represents for the index to which it belongs and the reliability of the information is applied to each indicator. The partial indices obtained are also weighted and aggregated to build the aggregate index. Several weighting techniques exist, derived either from statistical models or participatory methods. No matter which method is used, the weights are essentially value judgments.

To understand the relative importance of the exposure and vulnerability partial/aggregate index obtained for each analysis unit (i.e. municipalities) within the global aggregate unit (i.e. country), an adequate system of indices classification must be established. This index classification system must consider the data distribution to properly represent it. The index value is translated into 5 classes: very high, high, medium, low, very low, with this ranking linked to a color code to geographically represent the information. The Natural Breaks classification method, based on the Jenk's optimization algorithm, is also applied. This method is implemented in ArcGIS software and designed to provide the best arrangement of values into different classes. This is done by minimizing each class's average deviation from the class mean, while maximizing each class's deviation from the means of the other groups. In other words, the method reduces the variance within classes and maximizes the variance between classes (Jenks, 1967). 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 by combining the classes obtained for the hazard and the vulnerability indices through a risk matrix. As this framework proposes two types of results (i.e. partial risk for each dimension and aggregate risk), the risk matrices applied are slightly different: partial

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risks are obtained by combining the classes associated with hazard and sensitivity, while aggregate risk is obtained by combining the hazard and vulnerability classes. Figure 3 shows the aggregate risk matrix. The sensitivity and vulnerability are calculated on the exposed elements; therefore, the exposure is implicitly incorporated into the matrix.

Figure 4 shows the entire risk calculation process. The construction of aggregate indices (exposure, sensitivity, vulnerability) is performed through weighted aggregation (vertical arrows) while the risk calculation, both partial and aggregate risks, is performed through the risk matrix (horizontal arrows).

The main advantage of this methodology 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 thereby providing essential information for risk management.

3.3 Formulation of risk reduction measures

The risk assessment carried out helps identify the appropriate risk reduction measures according to the definition of disaster risk reduction (UN/ISDR, 2009) as the concept and practice of reducing disaster risks through systematic efforts to analyze and manage the causal factors of disasters, including those factors related with reduced exposure to hazards, lessened vulnerability of people and property, wise management of land and the environment, and improved preparedness for adverse events.

There are two types of risk reduction measures (RRM): (i) adaptation measures, the adjustment in natural or human systems in response to actual or expected stimuli and their effects, which moderate harm or exploits to receive beneficial opportunities (UN/ISDR, 2009); and (ii) mitigation measures, the structural and nonstructural measures taken to limit the adverse impact of natural hazards, environmental degradation and technological hazards (UN/ISDR, 2004).

Therefore, 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

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vulnerability (by reducing the sensitivity or improving the resilience) as shown in Fig. 5. 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.

The RRM are classified based on the type of implementation required, depending on whether or not they imply physical construction:

- Structural measures: any physical construction to reduce or avoid possible impacts of hazards, or the application of engineering techniques to achieve hazard-resistance and resilience in structures or systems (UN/ISDR, 2009).
- Non-structural measures: any measure not involving physical construction that uses knowledge, practice or agreement to reduce risks and impacts, in particular through policies and laws, public awareness raising, training and education (UN/ISDR, 2009).

Some examples of adaptation and mitigation measures, classified into structural and nonstructural, are shown in Table 4.

4 Application to the coastal area of El Salvador

This chapter presents the application of the described methodological framework for tsunami vulnerability and risk assessment to the coastal area of El Salvador. The study area is located in an area of high seismic activity which has been hit by 15 tsunamis between 1859 and 2012, nine of which were recorded in the twentieth 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.

The application of the presented framework to the case study of El Salvador is described below and detailed in Table 5 (equivalent to the theoretical Table 1).

- The human, environmental, socioeconomic and infrastructure dimensions are considered. Therefore the risk of having impacts (negative consequences) on these four dimensions is analyzed.
- The spatial scale considers the national and local levels. As the planning unit is the municipality, the national level includes the 29 coastal municipalities while the local scale focuses on 3 specific areas (ten municipalities): Western Coastal Plain (San Francisco Menéndez, Jujutla and Acajutla), La Libertad and Jiquilisco Bay (Jiquilisco, Puerto El Triunfo, Usulután, San Dionisio, Jucuarán and Concepción Batres). The results obtained for the Western Coastal Plain are presented in this paper.
- The time scale considers the population movements due to holiday patterns (rainy season/dry season, week/weekend) in the human system, both at the national and local scales, and the migration patterns or breeding/nesting periods for the environmental system at the local level.
- The hazard assessment is carried out through a deterministic analysis to understand the worst possible case scenario.
- The threats analyzed are the drag (depth and water velocity) for the human dimension, the flooded area for the environmental, socioeconomic and infrastructure dimension, and the water depth for the analysis of impacts on buildings.
- To calculate the expected consequences on the four different dimensions, the exposed elements and their sensitivity have been assessed through a set of indicators described below.

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- The resilience assessment has been carried out at the municipality level in order to understand the preparedness and recovery capacities of each exposed municipality.

Some examples of the hazard, sensitivity and resilience assessments results, followed by the vulnerability and risk results, are offered. These examples include cartographic and numerical analyses of the national and local scale assessments, as the first one aims to identify the municipalities which are more at risk within the country and the second one to carry out a detailed analysis on them. The risk assessment results are presented according to the spatial scale analyzed: (i) national scale results, and (ii) local scale results for the Western Coastal Plain. The complete results of the work are available at IH Cantabria-MARN (2010, 2012).

4.1 Risk assessment at the national scale

The hazard assessment is based on propagation models for earthquake-generated tsunamis (Álvarez-Gómez et al., 2013), developed through the characterization of tsunamigenic sources – seismotectonic faults – and other dynamics (waves, sea level, etc.). Simulations of historical and potential tsunamis with greater or lesser affection to the country's coast have been performed (Fig. 6), including distant sources (distances greater than 2000 km to the coast, with tsunami travel times greater than 4 h), intermediate sources (between 700 and 2000 km with tsunami travel times between 1 and 4 h), and close sources (located in the subduction trench off the country's coast with tsunami travel times of less than one hour).

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 (Wang and Liu, 2005) 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 this case, 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. A detailed tsunami hazard analysis is presented in Álvarez-Gómez et al. (2013).

A deterministic analysis (aggregated analysis that combines the 23 worst credible cases of tsunamis that could impact on the Salvadoran coast) has been carried out, with the main output being different hazard maps (maximum wave height elevation, maximum water depth, minimum tsunami arrival time, maximum flooding level or “run-up”, and potential drag – understood as the hazard degree for human instability based on incipient water velocity and depth –, along the coast of El Salvador and at some relevant locations with high resolution analysis.

Figure 7 shows the tsunami hazard map generated at the national level, which includes information about the maximum total water depth (m), the maximum run-up (m), the estimated flooded area and the minimum tsunami arrival time (min). These results allow identifying the areas subjected to a tsunami energy concentration and consequently to a higher impact.

The hazard area calculated allows identifying the number and type of exposed elements for the four dimensions. Therefore an inventory of the exposed population, ecosystems, socioeconomic activities and infrastructures has been carried out as input for the sensitivity assessment. As previously described, the vulnerability assessment

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includes the analysis of the sensitivity of each dimension and the resilience of the community.

The partial sensitivity results for the coastal area of El Salvador are analyzed and mapped in Fig. 8. These Sensitivity Index numerical and cartographic results explain how sensitive the exposed municipalities are regarding the human, socioeconomic and infrastructure dimensions (represented in columns on the graphs and color coded on the maps). The municipalities are organized geographically in the graphs, thereby facilitating the comparison of numerical and cartographic results. 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 colors within the columns representing the contribution of the different indicators to their index. The results obtained will feed the risk reduction measures for each dimension.

It is worth noting that the most sensitive areas in the case of a possible tsunami event vary according to the dimension analyzed: (i) for the human dimension, the most active and populated municipalities are emphasized; (ii) for the environmental dimension, those municipalities with large areas of mangroves which are extremely relevant in terms of biodiversity and ecosystem services to the community, and/or with endangered species are emphasized; (iii) for the socioeconomic dimension, those municipalities with more developed tourism, agricultural, industrial and port activities are highlighted; and finally, (iv) for the infrastructure dimension, those municipalities having the most relevant industrial, commercial and fishing ports in the country have resulted to be more sensitive.

The human graph shows seven municipalities (out of 29) which are highly sensitive due to the great number of people exposed to the tsunami flooding, and the sensitivity of the population (approximately the 70 % in every municipality belong to the sensitive age, illiteracy and extreme poverty groups), being Acajutla and San Luis de la Herradura the most sensitive ones. The environmental graph highlights the area of Jiquilisco Bay, together with the municipalities of San Francisco Menéndez and Pasaquina due to their mangroves, and Conchagua, as it hosts the unique and

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endangered Geoffroy's spider monkey communities. Within Jiquilisco bay, all the municipalities are sensitive due to the presence of mangroves, especially Usulután, however, the sensitivity of Jiquilisco and Puerto El Triunfo is also generated due to the important spots for endangered species, such as several species of sea turtles (Carey, Baule, Prieta, Black turtle) and crocodiles (*Crocodylus acutus*). Regarding the socioeconomic sensitivity, 5 municipalities stand out: most of them have higher contributions to the Gross Domestic Product and to the job generation than other municipalities; besides that, in La Libertad the sensitivity is also attributable to a higher contribution to the foreign trade of the exposed socioeconomic areas. As far as the infrastructure graph is concerned, 4 municipalities stand out based on the sensitivity of their exposed infrastructures with clearly identifiable differences between them: while Acajutla is sensitive due to the amount of industrial (hazardous) infrastructures exposed, La Unión is affected in terms of emergency infrastructures (which are essential in case of a tsunami) exposed, and La Libertad and Puerto El Triunfo have a combination of sensitive infrastructures exposed. The importance of this analysis lies in the subsequent straightforwardness to define appropriate risk reduction measures by reducing the sensitivity of specific targets.

Figure 9 shows the results of the resilience index at the national level, which is based on the two indicators – coping and recovery capacity. The graph shows the analysis of the four phases of the emergency management which has been carried out for each municipality based on the answers to the resilience questionnaires, filled in by the person in charge of the Municipal Civil Protection Committees, and at least one influential non-governmental organization in the area and three community leaders from different municipalities. These results allow understanding the main weaknesses in emergency management and proposing site-specific corrective measures. As an example, there is a lack of warning and evacuation aspects in most of the municipalities that could be affected by a more extensive flooded area (i.e. between Tecoluca and Concepción Batres) and a complete lack of information and awareness in several municipalities, such as Jicalapa, Santiago Nonualco, Tecoluca and Puerto El Triunfo.

As presented in the methodology, the partial sensitivities are combined to build the aggregate sensitivity index, which is aggregated with the resilience index to obtain the vulnerability index (Fig. 10), the entire process being based on weighted aggregation (assigned weights on the top left corner of each map). 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 ten technicians from the Ministry of Environment and Natural Resources of El Salvador and the team from the Institute of Environmental Hydraulics in Cantabria (Spain), in order to reflect political and social priorities or technical factors related to the tsunami hazard.

The risk assessment which combines the hazard and vulnerability results through the risk matrix (Fig. 11) has allowed identifying the critical areas, in which a more detailed analysis is needed, shown in boxes. Risk analyses at the local level have been developed for the three areas, with the results for the Western Coastal Plain (left box) being presented in the next chapter. These local analyses allow obtaining in depth information on sensitivity hot spots or resilience weaknesses and provide essential knowledge for risk management and the formulation of adequate risk reduction measures.

4.2 Risk assessment at the local scale

Regarding the results obtained at the local level, Fig. 12 shows the local hazard maps for the Western Coastal Plain of El Salvador, including aggregated maps combining the worst scenarios of distant, intermediate and close tsunamigenic sources to show (i) the maximum wave height elevation, (ii) the maximum water depth, and (iii) the drag (depth * velocity).

Figure 13 shows, as an example, two (out of six) human sensitivity indicators for the Western Coastal Plain, the census segment being the analysis unit. The sensitive age groups indicator presents the number and distribution of elderly people and children (which will need support in case of an emergency) showing an irregular distribution throughout the territory. The isolation indicator highlights the areas with people suffering greater difficulty for evacuation due to the difficult accessibility of its territory, whether caused by the deterioration of roads or because historically communities have remained isolated due to river/coastal flooding; few areas are identified, i.e. Garita Palmera, Barra de Santiago, Bocana San Juan and Metalío, this last one (in dark red) being especially sensitive due to the number of people located there. Figure 14 shows the human risk map, where the influence of the two above-presented indicators on the final result can be appreciated. The pie chart presented within the figure shows that 20 429 persons are at risk in the Western Coastal Plain, with 75 % found at high and very high risk areas.

In order to compare the scope applied in the analysis of different spatial scales (see above-shown Fig. 8 for the national analysis), Figs. 15 and 16 show the expected impacts on the socioeconomic activities and infrastructures of the Western Coastal Plain, respectively. Regarding Fig. 15, the largest area of socioeconomic activity which would be lost is mainly focused on agriculture in the three municipalities, although a small exposed area is dedicated to tourism, trade, construction and services, mainly in urban areas. However, this small multi-activity area would imply the biggest impacts in terms of loss of jobs and loss of contribution to GDP. The foreign trade in the country is based mainly on agriculture, so the loss of contribution would be associated to this activity.

Figure 16 shows some examples of the analysis of impacts on infrastructures for the Western Coastal Plain. Approximately half of the existing road segments are exposed in the three municipalities (63 % in San Francisco Menéndez, 44 % in Jujutla and 42 % in Acajutla), being essential information for evacuation planning and emergency action. Five wells (1 in both San Francisco Menéndez and Jujutla, 3 in Acajutla) out of 19, are exposed and therefore subjected to temporary/permanent pollution and uselessness, information which must be considered in the case of an emergency for the long term water supply of the adjacent communities. Five industrial infrastructures out of 10 are exposed in Acajutla (1 petrochemical industry, 2 storage infrastructures and 2 industrial parks), the petrochemical industry having the ability to generate cascading impacts due to hazardous substances. Out of the seven emergency infrastructures located in the Western Coastal Plain, all of them are exposed (6 health centers and 1 military), which could worsen the impacts of the tsunami due to the lack of assistance to the communities. Besides that, although it is not shown in these graphs, 1 maritime and 1 fishing port as well as several railroad infrastructures would also be affected.

As far as the resilience assessment is concerned, the questionnaire has been answered by the person in charge of the Municipal Civil Protection Committees, at least one non-governmental organization with a large presence in the area and three community leaders from different localities. The final results for each municipality in the Western Coastal Plain are presented in Table 6. The results show that San Francisco Menéndez is the most resilient municipality of the three (Resilience Index 0.72) while Acajutla is the least (Resilience Index 0.22). The main shortcomings regarding the emergency phases can also be identified and consequently tackled, both at the municipality level (for example, Acajutla does not have temporary tsunami shelters) and transversally for a more coherent regional planning (for example, the Western Coastal Plain lacks a tsunami early warning system and does not have proper tsunami insurance for its properties).

4.3 Risk reduction measures

Based on the results of the risk assessment carried out for the Western Coastal Plain of El Salvador and the main expected impacts due to the modeled tsunami event, different adaptation and mitigation measures can be proposed. These measures are aimed towards reducing the exposure and sensitivity of the different dimensions, and improving the resilience identified shortcomings.

Due to the great amount of information obtained for the Western Coastal Plain, Table 7 focuses on the vulnerability results and expected impacts and the consequently proposed risk reduction measures for the municipality of Acajutla.

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5 Conclusions

Advances in the understanding and prediction of tsunami impacts allow the development of risk reduction strategies for tsunami-prone areas. This paper presents a methodological framework for the integrated tsunami vulnerability and risk assessment, which deals with the complexity and variability of coastal zones by means of (i) an integral approach to cover the entire process from the hazard, vulnerability and risk assessment to the final risk management; (ii) an integrated approach to combine and aggregate the information stemming from the different dimensions; and (iii) a dynamic and scale dependant approach to integrate the spatiotemporal variability considerations. This framework, although presented here for the tsunami hazard, can also be used for other types of hazard, having been already applied to climate change hazard in Peru and El Salvador (IH Cantabria, 2012).

Regarding the integration of dimensions, according to EC 2010 this framework proposes two types of results, partial and aggregate results; the first ones provide the available impacts analyzed separately for the different dimensions and components, while the last one combines all the dimensions.

The hazard assessment is based on propagation models for earthquake-generated tsunamis. A deterministic analysis (aggregated analysis that combines the 23 worst credible cases of tsunamis that could impact on the Salvadoran coast) has been carried out, the main output being different hazard maps (maximum wave height elevation, maximum water depth, minimum tsunami arrival time, maximum flooding level or "run-up", the potential drag understood as the hazard degree for human instability based on incipient water velocity and depth, along the coast of El Salvador and at some relevant locations (high resolution analysis).

The exposure and vulnerability assessments are based on a set of indicators supported by a GIS. The exposure indicators identify the elements located in the hazard area, while the vulnerability indicators measure the characteristics of the exposed elements making them susceptible to suffer the previously selected impacts.

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A straightforward method for the resilience assessment is also provided. It is based on the evaluation of two of society's capacities, one related to the pre/during-event (coping capacity) and the second one to the post-event (recovery capacity). These two capacities are assessed through the analysis of the four emergency management phases: (i) information and awareness, (ii) warning and evacuation, (iii) emergency response and (iv) disaster recovery. Data collection is carried out through a short questionnaire identifying the degree of organization and response within a community in case of an emergency and which has been answered by the of the person in charge of the Municipal Civil Protection Committees and at least one influential non-governmental organization in the area and three community leaders from different municipalities.

The process for the conceptual integration (risk components, dimensions and scales) has several steps: (i) building indicators through normalization; (ii) building partial and aggregated indices through weighted aggregation, (iii) indices classification through the natural breaks method; and (iv) risk assessment through the risk matrix.

A clear connection to translate the vulnerability and risk assessments into risk reduction measures has been established, trying to bridge the gap between science and management for the tsunami hazard. The methodology has been designed to facilitate the identification of ways to reduce the sensitivity of each dimension and to increase the resilience of communities is provided.

A dynamic model to update the risk results is expected to be incorporated in the methodology as an effective tool for adaptive risk management. This dynamic model 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.

The methodology can be applied to any coastal area, a pilot case for the coastal areas of El Salvador being shown in this paper.

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Table 1. Generic structure for a tsunami risk assessment.

Risk			Hazard			Exposure	Vulnerability	
Consequences	Time scale	Spatial scale	Probability	Dynamics	Threat	Exposed elements	Sensitivity	Resilience
Human impacts	Annual	Regional	Deterministic analysis	Tsunamigenic sources	Flooding area	Human exposure	Human sensitivity	Information and awareness
Environmental impacts	Seasonal	National		Sea level	Wave depth	Environmental exposure	Environmental sensitivity	Warning and evacuation
Socioeconomic impacts	Weekly	Sub-national	Probabilistic analysis	Tsunami waves	Wave velocity	Socioeconomic exposure	Socioeconomic sensitivity	Emergency response
Infrastructures impacts	Daily	Local		Tides	Drag	Infrastructures exposure	Infrastructures sensitivity	Recovery

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

Aggregate index		Partial indices	Indicators	Variables	Spatial scale
Exposure		Human Exposure	Exposed population	Number of persons permanently exposed Number of persons temporally exposed (holidays)	N–L N–L
		Environmental Exposure	Exposed ecosystems	Area of exposed ecosystems	N–L
		Socioeconomic Exposure	Exposed socioeconomic activities	Area of exposed activities (agriculture and herding, fishing, aquaculture, tourism, industry, trade, services)	N–L
		Infrastructures Exposure	Exposed infrastructures	Number of exposed infrastructures (water, energy, waste treatment, transport, industrial, emergency)	N–L
			Exposed buildings	Number of exposed buildings	L
Vulnerability	Sensitivity	Human Sensitivity	Sensitive age groups	Number of persons under 10 yr Number of persons over 65 yr	N–L N–L
			Illiteracy	Number of illiterate persons	N–L
			Extreme poverty	Number of persons in extreme poverty conditions	N–L
			Disability	Number of disabled persons	L
			Isolation	Number of persons in isolated areas	L
			Critical evacuation	Number of persons in critical buildings	L
		Environmental Sensitivity	Protection	Area of protected ecosystems	N–L
			Singularity	Area of singular ecosystems	N–L
			Threat	Area of threatened ecosystems	N–L
			Degradation	Area of degraded ecosystems	L
		Socioeconomic Sensitivity	Job generation	Number of workers per activity	N–L
			Contribution to GDP	Millions of dollars contributed per activity	N–L
			Contribution to foreign trade	Millions of dollars contributed per activity	N–L
		Infrastructures Sensitivity	Sensitive 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
			Critical buildings	Number of critical buildings (hospitals, schools, hotels . . .)	L
			Vertical evacuation	Number of buildings with less than 3 stories	L
			Building materials	Number of non-resistant buildings	L
	Resilience	Resilience	Coping capacity	Information and awareness Warning and evacuation Emergency response	N–L N–L N–L
			Recovery capacity	Post-disaster recovery	N–L

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Table 3. Resilience elements, related emergency phases and questionnaire applied.

Resilience assessment		
System capacities	Emergency management phases (description based on US IOTWS, 2007)	Questionnaire
Coping capacity	**Information and awareness.** Leadership and community membersare aware of hazards and risk information is utilized 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 lations, and individuals acting on the alert.	3. Existence of Early Warning System (EWS) 4. Existence of evacuation routes 5. Existence of maps/drawings with hazard areas and critical spots popu- 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 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

Table 4. Example of mitigation and adaptation measures.

	Mitigation	Adaptation
Structural	– Strengthening of structures – Construction of defense items (flood levees, dams.) – Ocean wave barriers – Removal and relocation of exposed infrastructure and elements – Earthquake/tsunami-resistant construction	– Construction of evacuation shelters – Construction of vertical evacuation structures – Improvement of existing evacuation routes – Construction of new evacuation routes – Building alternate power systems for emergencies
Non-structural	– Improvement of the national tsunamis warning system, integration into regional warning systems – Placement of DART buoys (Deep-ocean Assessment and Reporting of Tsunamis) – Reforestation – Restoration of mangroves	– Information and awareness campaigns for communities – Capacity building for technicians – Insurance against natural disasters – Establishment of flood easements and setbacks – Earthquake and tsunami-resistant building codes – Urban and land use planning. Building codes – Evacuation plans. Signaling evacuation routes – Research

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Table 5. Structure for the Tsunami Risk Assessment of 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 for understanding a warming message • bad housing materials and lack of recovery capacity • difficulties for receiving a warning and for evacuating in bad-communicated areas • difficulties for 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 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	

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Table 6. Resilience results for the Western Coastal Plain of El Salvador.

Emergency management phases	Questions	Answers by municipality		
		San Francisco Menéndez	Jujutla	Acajutla
Information & Awareness	1. Social Awareness	YES	NO	NO
	2. Institutional Awareness	YES	YES	PARTIALLY
Warning and Evacuation	3. Tsunami Early Warning System	PARTIALLY	NO	NO
	4. Evacuation Routes	YES	NO	NO
	5. Hazard Mapping	YES	YES	NO
	6. Evacuation Drills	PARTIALLY	NO	PARTIALLY
Emergency Response	7. Municipal Civil Protection Commission	YES	YES	PARTIALLY
	8. Tsunami Contingency Plan	PARTIALLY	NO	NO
	9. Communal Committees	YES	YES	NO
	10. Coordination Networks	YES	YES	YES
	11. Emergency human resources	PARTIALLY	YES	YES
Recovery	12. Temporary shelters	YES	YES	NO
	13. Municipal funds to cover immediate expenses	PARTIALLY	NO	NO
	14. Natural disasters insurance	NO	NO	NO
	15. Health human resources	PARTIALLY	YES	NO
	16. Development human resources	PARTIALLY	NO	NO
TOTAL	Positive answers	8	8	2
	Intermediate answers	7	0	3
	Negative answers	1	8	11
	LACK OF RESILIENCE INDEX	0.28	0.5	0.78
	RESILIENCE INDEX	0.72	0.5	0.22

Table 7. Example of RRM based on expected impacts in Acajutla municipality.

	Vulnerability results and expected impacts in Acajutla	Risk Reduction Measures for Acajutla
Human dimension	**9262 people affected.** From this amount: – high percentage of highly sensitive population: – 30 % sensitive age (below 10 yr or above 65 yr) – 67 % illiterate – 32 % extreme poverty – 4 % disability – 37 % isolated areas – 15 % critical evacuation – 70 % located at High and Very High Risk areas	*EXPOSURE REDUCTION* Relocation of exposed communities especially those at very high risk. *SENSITIVITY REDUCTION* Establishment of a national tsunami EWS to alert the population from local and regional tsunamis. Information and training campaigns. Establishment, by Civil Protection and local authorities, of tsunami emergency plans together with community information and training programs. Improve accessibility of isolated areas. Evacuation planning (González-Riancho et al., 2013) and drills, with emphasis on (1) people with limited mobility, disabilities, and difficulties to understand a warning message, (2) isolated communities, and (3) the critical buildings due to the complicated evacuation of large numbers of people. Community organization of evacuation. Construction of vertical evacuation shelters in strategic locations.
Environmental dimension	**6.26 km^2 of ecosystems area affected**, representing the 71 % of the existing ecosystems in the municipality. From this area: – 88 % is protected due to its value, including important spots for endangered species (turtles, cocrodiles). – Practically the entire area is already at certain level of degradation. – 1.35 km^2 of mangrove area and related ecosystem services affected.	*SENSITIVITY REDUCTION* Protection and reforestation of mangrove areas. Community awareness campaigns. Protection of endangered species to improve their conservation status (turtle nurseries to avoid predation or poaching). Protection of ecosystems and restoration of degraded areas.

Table 7. Continued.

	Vulnerability results and expected impacts in Acajutla	Risk Reduction Measures for Acajutla
Socioeconomic dimension	**29.45 km^2 of socioeconomic area affected** (47 % agriculture, 52 % urban activities, 1 % fisheries and acquaculture). This will imply: – Loss of 3918 jobs (8 % agriculture, 83 % urban activities, 9 % fisheries and acquaculture). – Reduction of GDP contribution: 29.86 millions of dollars (4 % agriculture, 95 % urban activities, 1 % fisheries and acquaculture). – Reduction of contribution to foreign trade: 0.47 millions of dollars (73 % agriculture, 27 % fisheries and acquaculture).	*EXPOSURE REDUCTION* Relocation or strengthening of the constructions associated to the exposed activities (tourism, trade, etc.) *SENSITIVITY REDUCTION* Awareness campaigns for workers and entrepreneurs. Insure the exposed socioeconomic areas and activities against tsunamis. Seeds bank. Capacity building for the diversification of activities.
Infrastructures dimension	**Several infrastructures affected**: – 3 wells; – 3 emergency infrastructures (2 health centers and 1 military); – 42 % of existing road segments; – 1 maritime and 1 fishing port; – railroad infrastructure; – 5 (out of 10) industrial infrastructures (1 petrochemical, 2 storage, 2 industrial parks).	*EXPOSURE REDUCTION* Relocation of exposed infrastructures when possible. Relocation of exposed emergency infrastructure to safe areas. If not possible, plan an alternative relief in case of tsunami. Relocation of exposed industrial infrastructure to safe areas. If not possible, protection from the tsunami impact and insurance against natural disasters. *SENSITIVITY REDUCTION* Any new emergency and industrial infrastructure must be located in safe area. Alternative water supply system for long-term supply to affected communities after the tsunami event. Pavement of strategic roads for effective evacuation and emergency assistance. Urban planning considering tsunami risk areas. Prohibiting or regulating specific developments. Special attention to emergency and critical buildings.

Table 7. Continued.

	Vulnerability results and expected impacts in Acajutla	Risk Reduction Measures for Acajutla
Buildings dimension	**3364 buildings affected**. From this amount: – 90 % non resistant materials – 26 % (758 buildings) will suffer a damage level betweel important and Collapse **Several critical buildings affected**: – 2 hotels – 5 schools – 2 churches – 2 health centers.	*EXPOSURE REDUCTION* Relocation of critical buildings that could be affected, especially education and health buildings. *SENSITIVITY REDUCTION* If relocation of critical buildings is not possible, construction of vertical evacuation shelters to evacuate the population. Establishment of an earthquake and tsunami-resistant building code for new buildings. Assistance and grants to strengthen existing Type I-buildings located in critical areas.
Resilience	**Limited coping capacity** due to: – Lack of social awareness. Insufficient institutional awareness – Lack of tsunami hazard mapping, EWS and evacuation routes. Insufficient evacuation drills – Incomplete establishment of Municipal Civil Protection Commission and lack of communal Committees – Lack of Tsunami Contingency Plan **Limited recovery capacity** due to: – Lack of temporary shelters – Lack of emergency municipal funds and natural disasters insurance – Lack of health and development human resources	*RESILIENCE IMPROVEMENT* Increasing Information and awareness, through social awareness campaigns and institutional capacity building Improving warning and evacuation, through the implementation of a tsunami EWS, an accurate hazard mapping, a community-based design of evacuation routes, and the development of evacuation drills to ensure the authorities' and communities' are properly functioning in case of a tsunami event. Improving the emergency response, through the consolidation of the Municipal Civil Protection Commission and Communal Committees, and the development of a tsunami contingency plan. Improving the recovery capacity through the construction of temporary shelters, the allocation of municipal funds to tsunami emergency, insurance of specific assets against tsunami, and the promotion and training of sufficient human resources dedicated to health and community development.

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Fig. 1. Risk conceptual framework.

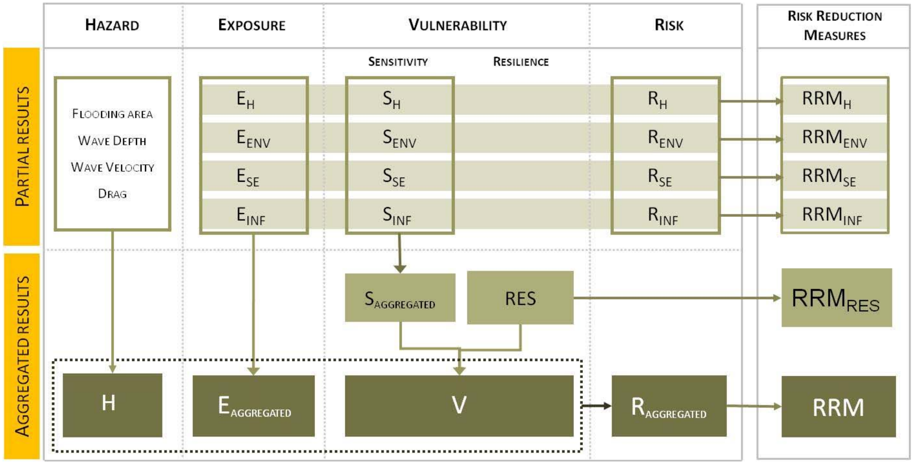
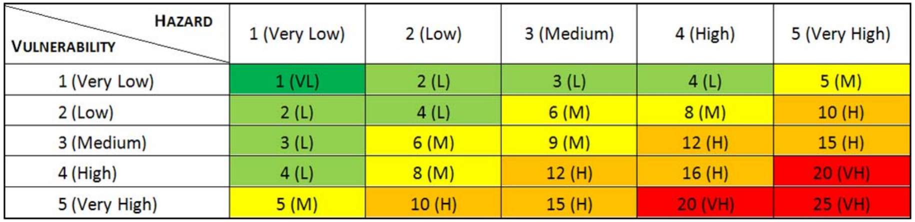


Fig. 2. Structure of the risk assessment and different kind of results to be obtained.



HAZARD VULNERABILITY	1 (Very Low)	2 (Low)	3 (Medium)	4 (High)	5 (Very High)
1 (Very Low)	1 (VL)	2 (L)	3 (L)	4 (L)	5 (M)
2 (Low)	2 (L)	4 (L)	6 (M)	8 (M)	10 (H)
3 (Medium)	3 (L)	6 (M)	9 (M)	12 (H)	15 (H)
4 (High)	4 (L)	8 (M)	12 (H)	16 (H)	20 (VH)
5 (Very High)	5 (M)	10 (H)	15 (H)	20 (VH)	25 (VH)

Fig. 3. Risk matrix.

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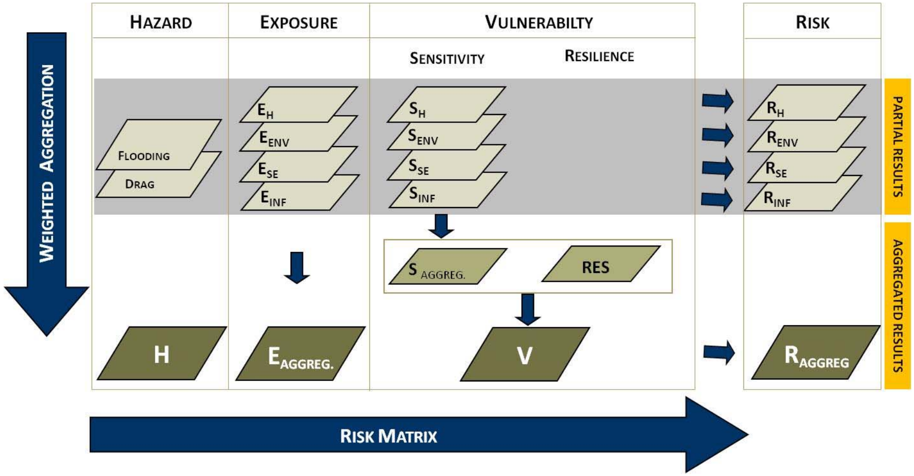

Fig. 4. Aggregation methods for risk dimensions and components: weighted aggregation and risk matrix.

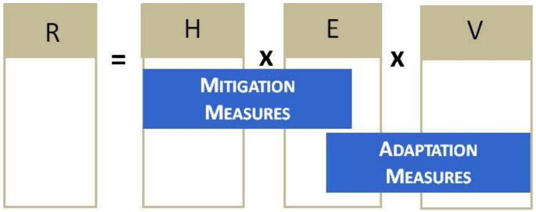

Fig. 5. Risk reduction measures: mitigation vs. adaptation measures.

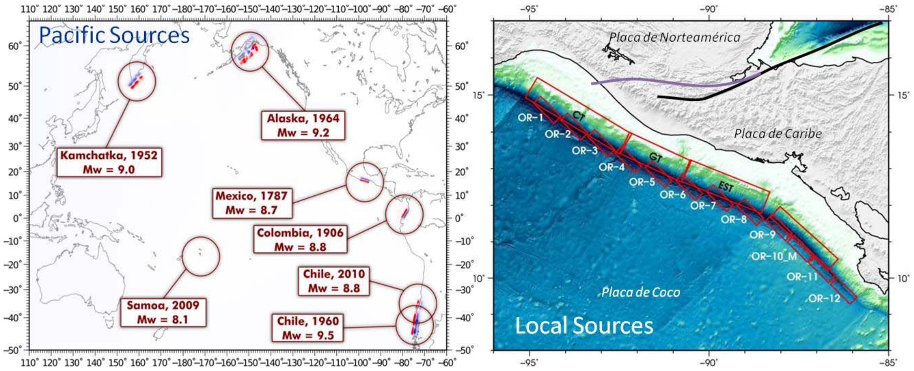

Fig. 6. Tsunamigenic sources.

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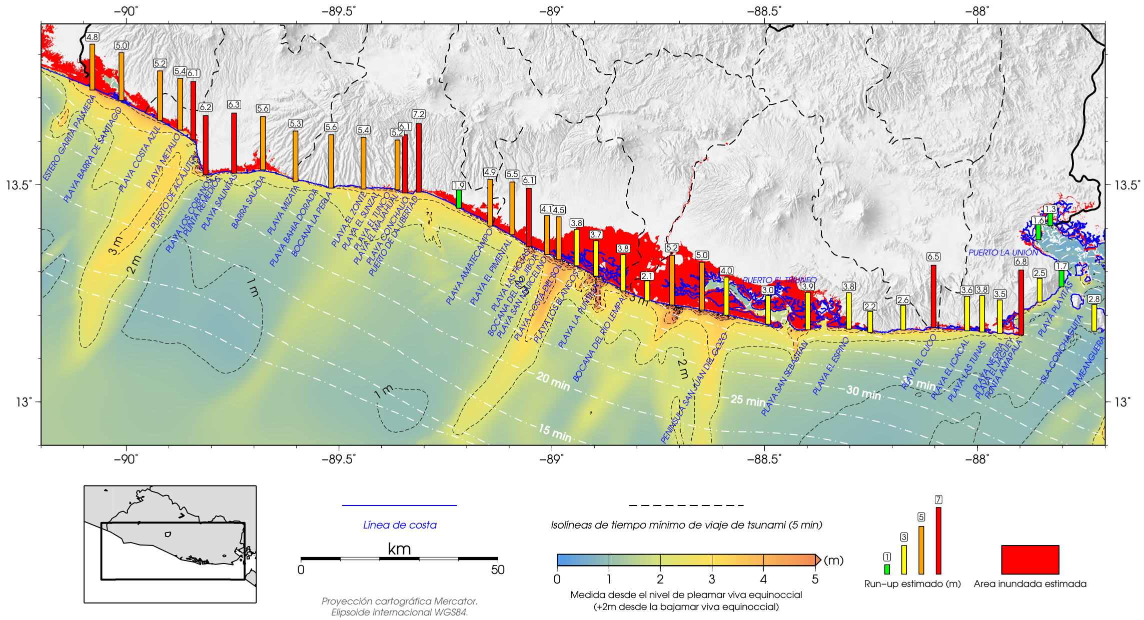

Fig. 7. Tsunami Hazard Map – El Salvador (global map). Maximum total water depth (m), maximum run-up (m), estimated flooded area and minimum tsunami arrival time (min). Aggregated map combining the worst scenarios of distant, intermediate and close tsunamigenic sources.

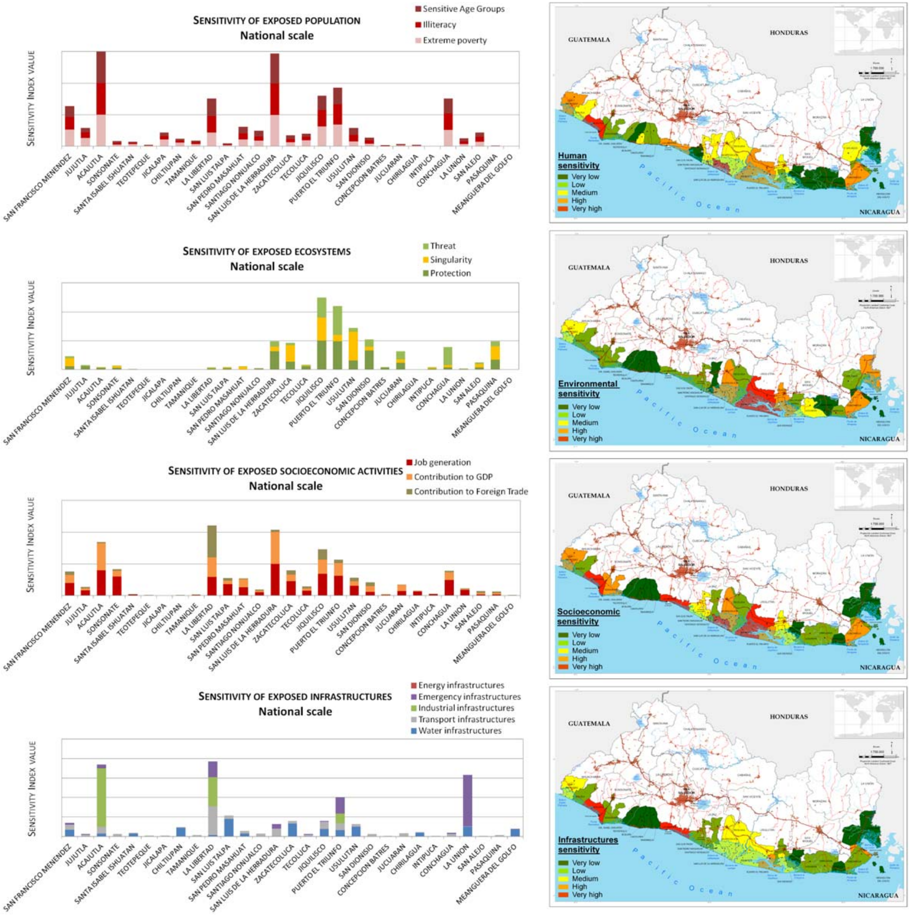

Fig. 8. Sensitivity partial results (national scale): sensitivity of each dimension for El Salvador coastal area.

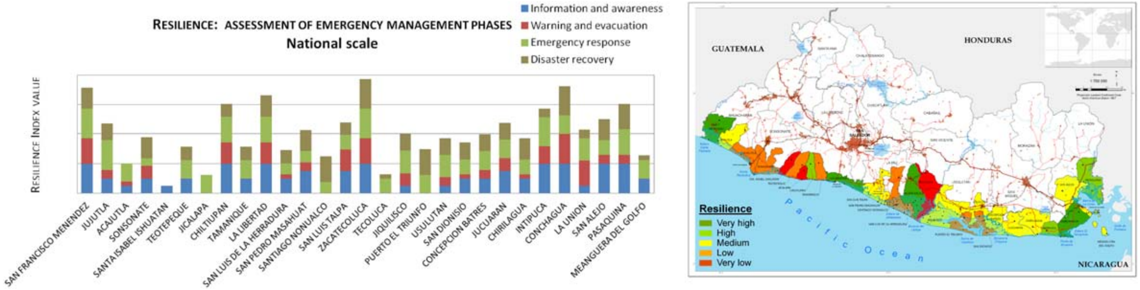

Fig. 9. Resilience: assessment of emergency management phases (national scale).

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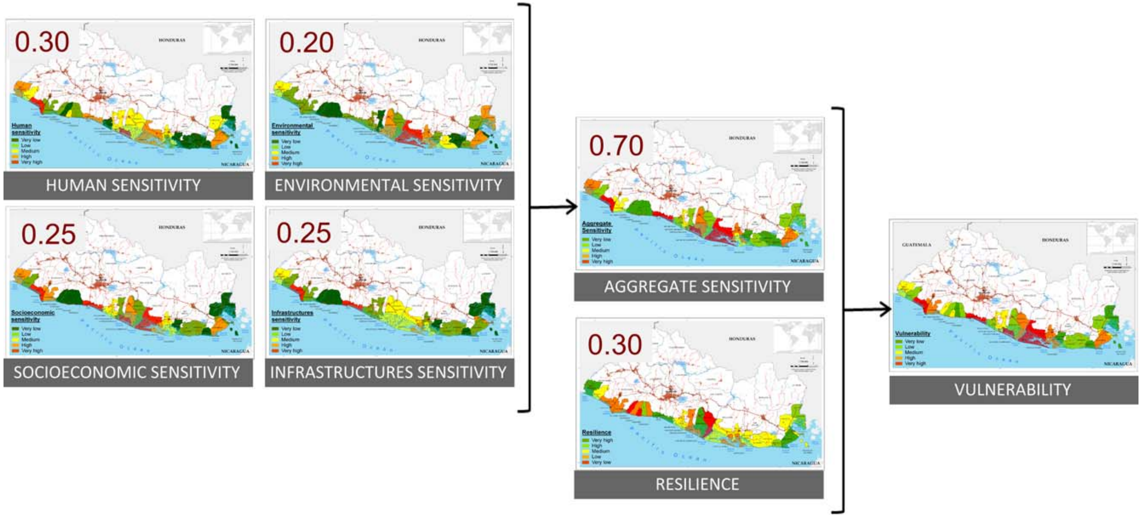
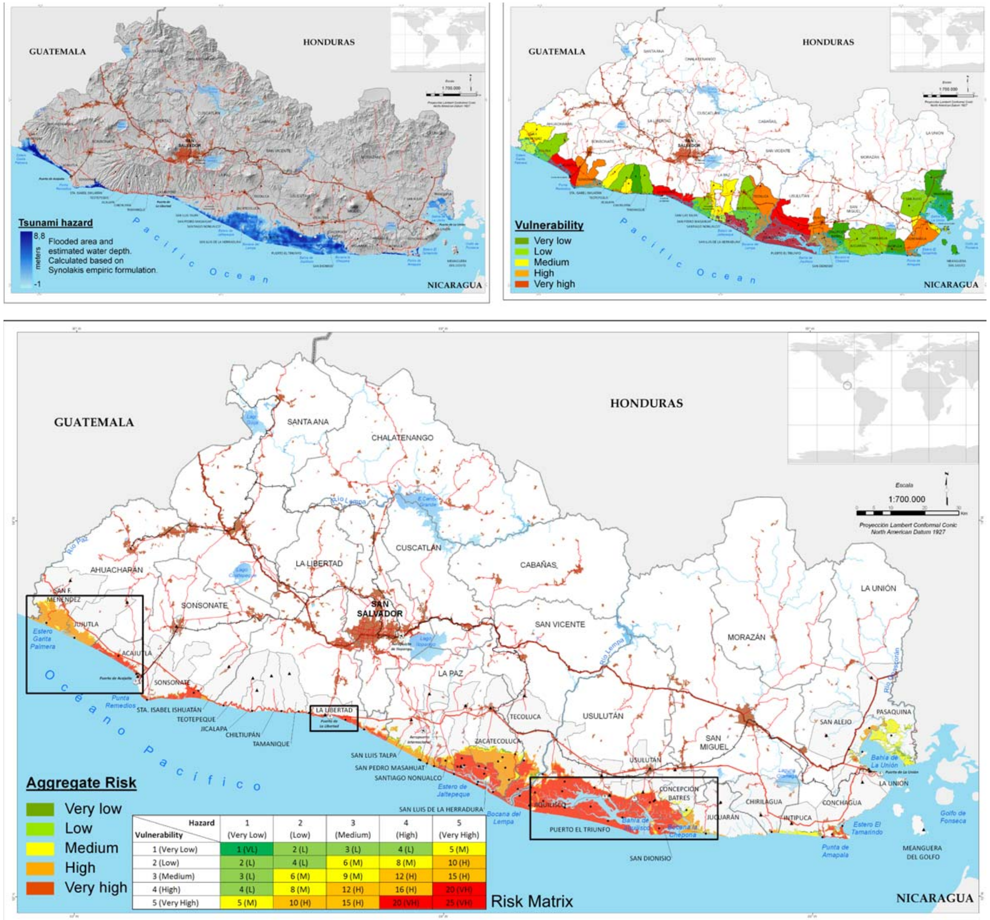


Fig. 10. Vulnerability calculation process (national scale).



Hazard / Vulnerability	1 (Very Low)	2 (Low)	3 (Medium)	4 (High)	5 (Very High)
1 (Very Low)	1 (VL)	2 (L)	3 (L)	4 (L)	5 (M)
2 (Low)	2 (L)	4 (L)	6 (M)	8 (M)	10 (H)
3 (Medium)	3 (L)	6 (M)	9 (M)	12 (H)	15 (H)
4 (High)	4 (L)	8 (M)	12 (H)	16 (H)	20 (VH)
5 (Very High)	5 (M)	10 (H)	15 (H)	20 (VH)	25 (VH)

Fig. 11. Tsunami hazard (above left), vulnerability (above right) and risk (below) maps for El Salvador coastal area (national scale).

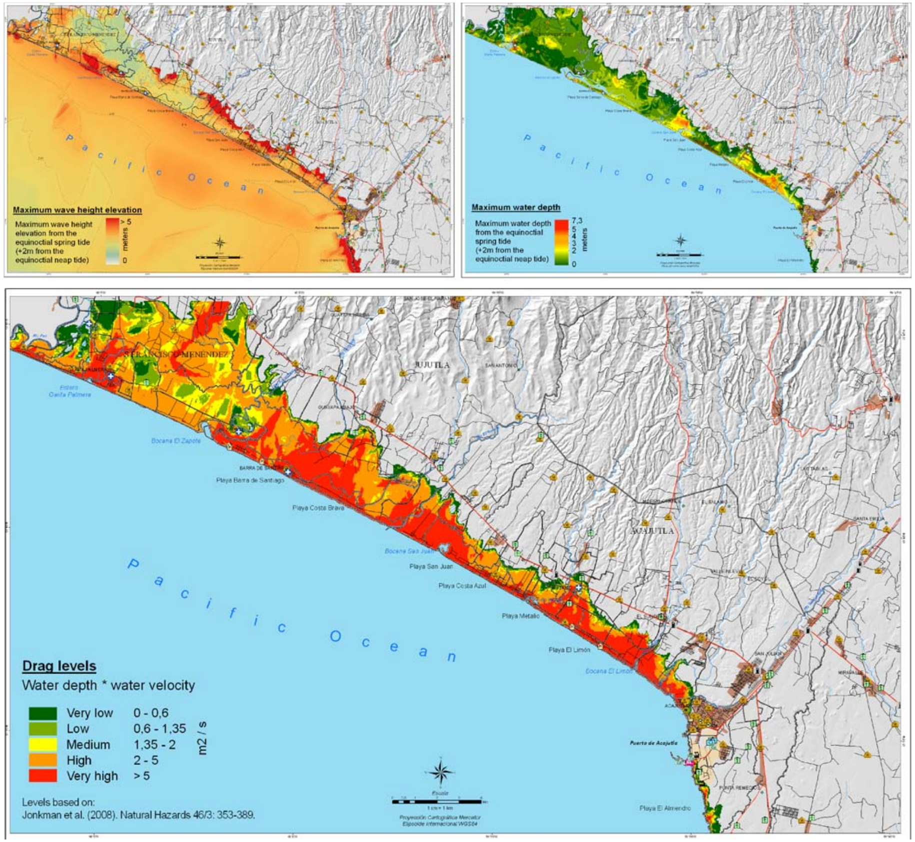


Fig. 12. Local hazard maps for the Western Coastal Plain of El Salvador: maximum wave height elevation (above left), maximum water depth (above right) and drag = depth ∗ velocity (below). Aggregated maps combining the worst scenarios of distant, intermediate and close tsunamigenic sources.

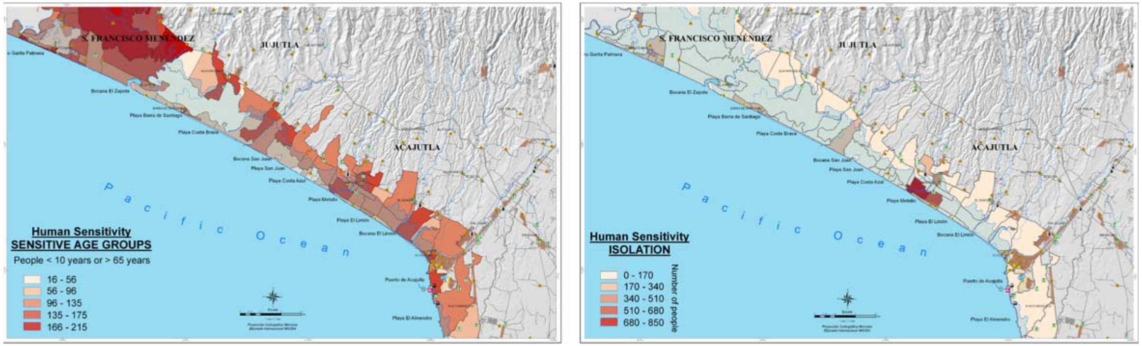
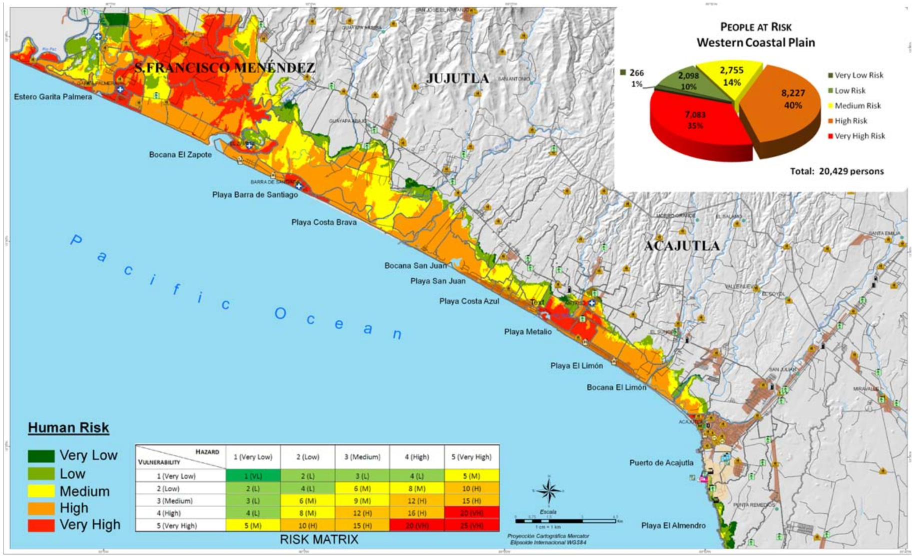


Fig. 13. Human sensitivity indicators – local scale Western Coastal Plain: sensitive age groups (left) and Isolation (right).



HAZARD / VULNERABILITY	1 (Very Low)	2 (Low)	3 (Medium)	4 (High)	5 (Very High)
1 (Very Low)	1 (VL)	2 (L)	3 (L)	4 (L)	5 (M)
2 (Low)	2 (L)	4 (L)	6 (M)	8 (M)	10 (H)
3 (Medium)	3 (L)	6 (M)	9 (M)	12 (H)	15 (H)
4 (High)	4 (L)	8 (M)	12 (H)	16 (H)	20 (VH)
5 (Very High)	5 (M)	10 (H)	15 (H)	20 (VH)	25 (VH)

Fig. 14. Human risk – local scale Western Coastal Plain.

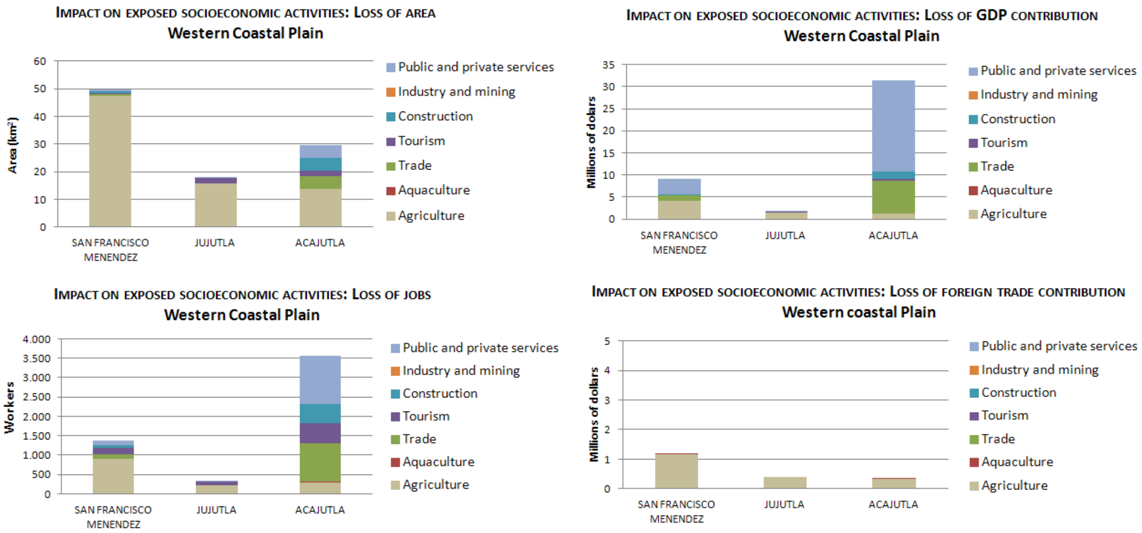


Fig. 15. Expected impacts on the socioeconomic dimension at the local level.

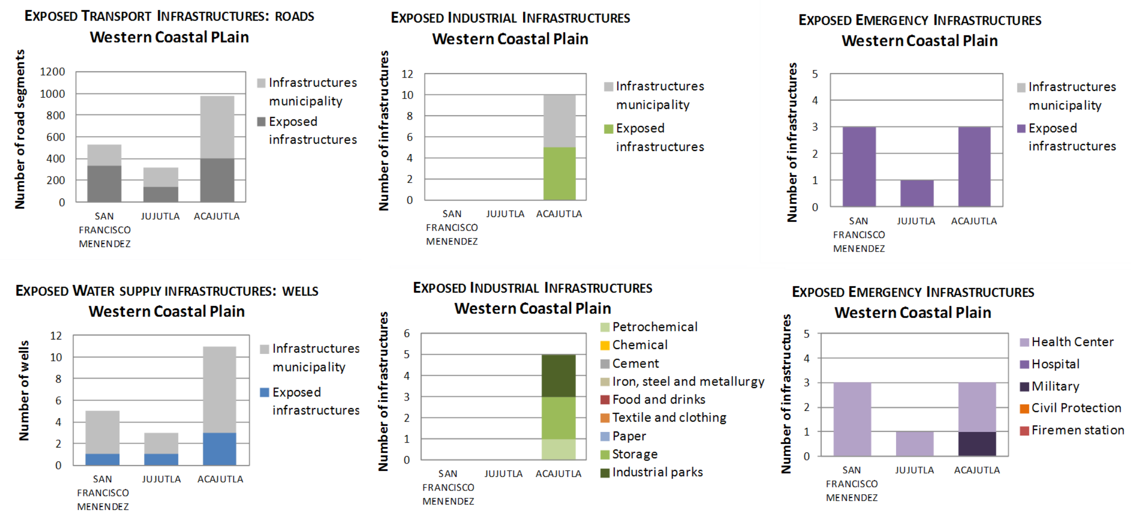


Fig. 16. Expected impacts on the infrastructures dimension at the local level.