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The unperceived risk to Europe's coasts: tsunamis and the vulnerability of Cadiz, Spain

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Abstract. The development of appropriate risk and vulnerability reduction strategies to cope with tsunami risks is a major challenge for countries, regions, and cities exposed to potential tsunamis. European coastal cities such as Cadiz are exposed to tsunami risks. However, most official risk reduction strategies as well as the local population are not aware of the probability of such a phenomenon and the potential threat that tsunami waves could pose to their littoral. This paper outlines how tsunami risks, and particularly tsunami vulnerability, could be assessed and measured. To achieve this, a vulnerability assessment framework was applied focusing on the city of Cadiz as a case study in order to highlight the practical use and the challenges and gaps such an assessment has to deal with. The findings yield important information that could assist with the systematic improvement of societal response capacities of cities and their inhabitants to potential tsunami risks. Hazard and vulnerability maps were developed, and qualitative data was obtained through, for example, focused group discussions. These maps and surveys are essential for the development of a people-centred early warning and response system. Therefore, in this regard, the Tsunami Early Warning and Mitigation System in the North Eastern Atlantic, the Mediterranean, and connected seas promoted by the UNESCO-Intergovernmental Oceanographic Commission (IOC) should encompass these assessments to ensure that action is particularly intensified and fostered by those potentially exposed. That means that besides the necessary technical infrastructure for tsunami detection, additional response and adaptation measures need to be promoted – particularly those that reduce the vulnerability of people and regions exposed – in terms of national systems. In addition, it is important to develop emergency preparedness and awareness plans in order to create an integrated regional Tsunami Early Warning System (TEWS) by 2011. The findings of the paper are based on research conducted within the framework of the EC funded project TRANSFER: "Tsunami Risk ANd Strategies For the European Region", a project that aims to improve the understanding of tsunami processes in the Euro-Mediterranean region, to develop methods and tools to assess vulnerability and risk, and to identify strategies for the reduction of tsunami risks.

1 Introduction

Work on tsunamis affecting Europe's coasts often provokes scepticism among the public. Most people are unaware of the fact that European coasts on the Mediterranean or Atlantic are tsunami-prone. This unawareness is prominent not only among people living far away from these coasts but, alarmingly, also among people directly exposed to the potential hazards. Although tsunamis are a low-frequency hazard in most regions, the recent tsunami that hit the island of Samoa in September 2009, the tsunami in Indonesia in 2007, and the major Indian Ocean Tsunami in December 2004 revealed the devastating effect of this type of unexpected hazard.

Interestingly, the Mediterranean and adjacent areas rank among the most seismically active regions in the world, together with the Pacific and Indian Oceans as well as the Caribbean (Frisch and Meschede, 2007, p. 18; Schellmann, 2007, p. 269), and are therefore the second largest generators of tsunamis around the globe (NEAMTWS website, 2008). In this regard, the international community, IOC/UNESCO in particular, is promoting the development of a North Eastern Atlantic Tsunami Warning System (NEANTWS). The reason for the seismicity of this region is the collision between the African and the Eurasian tectonic plates. Furthermore, there exist other tsunami-genic sources besides seismicity, such as volcanic eruptions and submarine landslides (Tinti, 2007). The seismic sources provoke small to

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medium scale tsunamis that happen rather frequently within the Mediterranean Sea, but which can also unleash rare but potentially very destructive tsunamis in the Atlantic Ocean (Carreño, 2005). The movement of the plates and the bathymetry of the Mediterranean Sea floor do not allow for large waves within the Mediterranean basin, but the damage caused to fishing boats and docks in the ports of the Balearic Islands in May 2003 provided proof that even small sized tsunamis can be destructive. The best known example of the larger tsunamis that can be generated in the Atlantic Ocean is the one that started in the Gorringe Bank area south-westwards of Cape St. Vincent (Portugal) in 1755. The seaquake that caused the tsunami had a magnitude of 8.5–9.0 and was responsible for significant damage not only in Lisbon, which was the most affected city, but also in Cadiz and other villages along the Spanish coast (Tinti, 2007, p. 3). Tsunamis of comparable size have an estimated recurrence period of eight times in 450 years (Carreño, 2005).

The possibility of this type of event occurring, however, is hardly publicised and therefore rarely known amongst the wider public. This experience from regions with low-frequency but potentially disastrous hazards is mirrored on the Atlantic coasts of Spain: low-frequency often goes hand in hand with the fact that local authorities and people tend to forget the possibility of occurrence. thus becoming complacent about potential tsunami risks and dismissing them psychologically. The result is the aforementioned lack of awareness, the absence of any kind of tsunami warning system such as the one that exists in the Pacific or the one currently being put in place in the Indian Ocean, as well as the absence of education and information about such a potential threat. Science is not completely free from blame for this deficiency since tsunami research including hazard and vulnerability assessments in Europe only started about 30 years ago, and has never received appropriate attention.

Furthermore, the European coasts – in particularly the Spanish coasts on the Atlantic and the Mediterranean – have undergone an enormous physical and socio-economic transformation. While at the beginning of the 1950s most of the coasts were still untouched, today the entire coastline is characterized by large hotel buildings and a dense tourist infrastructure. Thus, the number of people, buildings, and other forms of infrastructure potentially exposed to tsunamis has increased substantially within the last few decades.

This paper focuses on selected results derived from studies carried out by the UNITED NATIONS UNIVERSITY Institute for Environment and Human Security (UNU-EHS) in cooperation with project partners from Spain, Italy, and Switzerland on the project site in Cadiz, Spain, within the TRANSFER project, which aims to detect and estimate the dimensions of the tsunami risk in Europe. UNU-EHS has conducted a vulnerability assessment based on different tsunami inundation scenarios developed by the Ocean & Coastal Research Group, Instituto de Hidráulica Ambiental of the University of Cantabria (UC), in the form of inundation vector data sets (UC and IGN, 2009).[1] These scenarios were used to estimate the potential inundation areas and their respective socio-economic vulnerabilities. Thus, UNU-EHS has estimated the different degrees of vulnerability of social groups and the economy, and particularly critical infrastructures (e.g. electricity networks, etc.) by developing vulnerability indicators and additional criteria that are presented in vulnerability maps.

The conceptual framework applied and key findings will be shown and discussed in the following sections.

1.1 Theoretical background

The topic of risk and vulnerability studies has become a wide field combining the interests and efforts of different academic and non-academic disciplines, policy makers, and development agencies. This is the reason for the existence of many different theoretical and practical approaches on how to define and conceptualize the different terms such as hazard, risk, and vulnerability. Thywissen (2006) has collected 36 definitions for the term "vulnerability" alone. Therefore, it is essential that any vulnerability assessment be based on an approach that clearly outlines how it uses those terms.

This paper and the corresponding research are based on the approach developed by Bogardi and Birkmann in 2004, called the BBC (Bogardi, Birkmann, Cardona) framework. This framework grew out of three discussions: how to link vulnerability, human security, and sustainable development; the need for a holistic approach to disaster risk assessment; and the broader debate on developing causal frameworks for measuring environmental degradation in the context of sustainable development (Birkmann, 2006, p. 35). It describes vulnerability as being composed of the three factors of "exposure", "susceptibility", and "coping capacity". In addition, vulnerability is closely linked to all three spheres of the concept of sustainable development, namely the social, economic, and environmental spheres. If a hazard is likely to strike, the respective vulnerability of all three spheres combines with the hazard to constitute an environmental, social, and economic risk. This risk can be reduced by the respective reduction of the existing vulnerabilities through preparedness and other disaster management measures that intervene in the system through feedback processes. The integration of the coping capacities of the people affected and potential intervention tools as possible ways to reduce vulnerabilities emphasizes the view that vulnerability should be considered within a dynamic perspective. In this way, the framework encompasses a problem-solving perspective and shows the

[1] UCA developed a methodology to elaborate tsunami hazard thematic maps. Using this methodology, deterministic and probabilistic high resolution tsunami inundation maps have been developed for Cadiz. The probabilistic maps combine the occurrence of earthquakes from various potential sources in the zone, source mechanisms, epicenter locations, and sea level (astronomical and meteorological tides).

importance of being proactive in order to reduce vulnerability before an event strikes the society, the economy, or the environment (Birkmann, 2006, p. 36) instead of solely focusing on emergency management after a disaster has occurred. The BBC framework points out that vulnerability reduction in terms of forward-looking and mitigating interventions should be part of the daily political decision-making process which all cost-benefit analyses have clearly revealed to be more effective.

The three factors composing vulnerability, namely (a) exposure, (b) susceptibility, and (c) coping capacity, based on the assumption that vulnerability consists of an external side, which refers to the exposure to certain hazards, and an internal side consisting of susceptibility, meaning the "conditions of the exposed element or community" (Birkmann, 2006, p. 16) and the ability to cope with the hazard, namely "the means by which people or organizations use available resources and abilities to face adverse consequences" (Thywissen, 2006a, p. 456). There is no vulnerability if there is no exposure to a certain type of hazard. When developing vulnerability indicators, it is sometimes difficult to distinguish precisely between aspects that reduce susceptibility and those that increase coping capacity. Certain overlaps are therefore unavoidable. The splitting of vulnerability into two sides was first proposed by Chambers (1989) and was then elaborated more prominently by Watts and Bohle in 1993. Assuming a dualistic structure and multiple dimensions (environmental, social, economic, and institutional) of vulnerability, the BBC model represents a conceptual framework that underlines the notion of vulnerability within a dynamic perspective, going beyond a mere exposure assessment (Birkmann, 2006). Thus, this conceptual model also allows for the integration of other approaches such as the sustainable livelihood approach which emphasizes the necessity of having access to various types of assets in order to reduce vulnerability successfully.

Risk and vulnerability assessment is an important aspect of the development of an effective Tsunami Early Warning System and contributes significantly to disaster risk reduction. The development of frameworks and methodologies to conduct risk assessments with the purpose of identifying measures to be implemented to reduce existing risks, or to enhance the capacities of the population to respond efficiently was carried out by Villagran (2008) in Sri Lanka. Post et al. (2009) developed a methodology for the assessment of human immediate response capability related to tsunamis at the sub-national scale for Indonesia, especially the coastal areas of Sumatra, Java, and Bali, in order to integrate this information into intervention measures such as an early warning chain, evacuation and contingency planning, and awareness and preparedness strategies. The vulnerability assessment within the German Indonesian Tsunami Early Warning System (GITEWS) project focuses on vulnerability factors of people exposed to tsunamis in terms of loss of life, injury, and loss of livelihood. The assessment addresses the following components: the susceptibility and degree of exposure of vulnerable elements (population, critical facilities, built environment, and regions affected), and the ability to respond (coping) and recover from the disastrous impact of a tsunami (IOC/UNESCO, 2009; Taubenboeck et al., 2009). According to the BBC framework mentioned above, the vulnerability assessment for Cádiz took into account exposed elements and their susceptibility as well as their coping capacities, both of which influence the likelihood of harm and injury when a hazard strikes (Birkmann and Fernando, 2008, p. 85).

1.2 Study site

The Bay of Cadiz is geographically between longitude 6° W and 6°25′ W and latitude 36°20′ N and 36°40′ N, in the south-west of the Iberian Peninsula (Fig. 1). It faces west to the Gulf of Cadiz and is landlocked by the mainland at its south-western, southern, and eastern margins. This area is a naturally protected zone with large tidal flatbeds, tidal channels, and several beaches. Its geomorphology, being a peninsula, its location between the Strait of Gibraltar and the river mouth of the Guadalquivir, and the natural port formed by the Bay of Cadiz have made the city of Cadiz along with the entire surrounding region a first order strategic area in terms of maritime, commercial, and military activities (PGOU, 2007). Cadiz is not only a city but also an important port in south-western Spain. It is the capital of the province of Cadiz, which represents one of the eight provinces that make up the autonomous community of Andalusia.

Cadiz is the oldest permanently inhabited city of the Iberian Peninsula. It was founded by the Phoenicians between 1104 and 900 BC. Ever since, it has functioned as an important trade, commercial, and naval base under different cultural governances. These have endowed the city with a rich historical and cultural heritage, which now make it a great tourist attraction. Its commercial importance has steadily increased, currently representing the strongest economic sector owing to its local shipyards and ports (PGOU, 2007). The net business revenue at Cadiz port yields about 21.31 million Euros (in 2007, Puerto de la Bahía de Cadiz, 2008), and the port also serves as an important node for cruises to the Canary Islands and South America. In 2006, about 300 cruises arrived at the port, bringing more than 176 000 tourists, which helped to sustain the local economy (PGOU, 2007). The port of Cadiz contributes most to the city's economy since it also stimulates the complementary economic activities in the third sector. In comparison, the industrial sector has been constantly declining in importance, and manufacturing jobs and their spin-off businesses are expected to continue to weaken in the future (PGOU, 2007).

Referring to the demography, in 2007 Cadiz had a population of 128 554 inhabitants (IEA, 2008), making it the city with the highest population density in Spain (29 672 95 inhabitants/km^2). Despite this, the demographic trend is

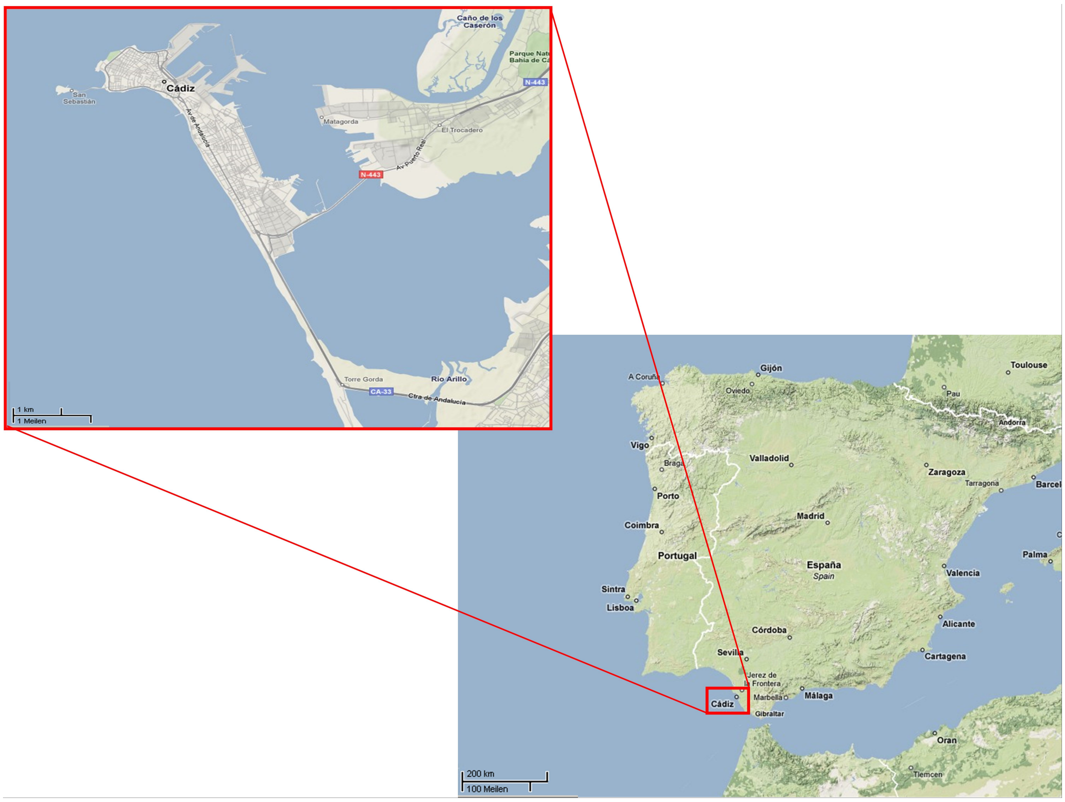

Fig. 1. Overview of the study side. Map information taken from Google Maps.

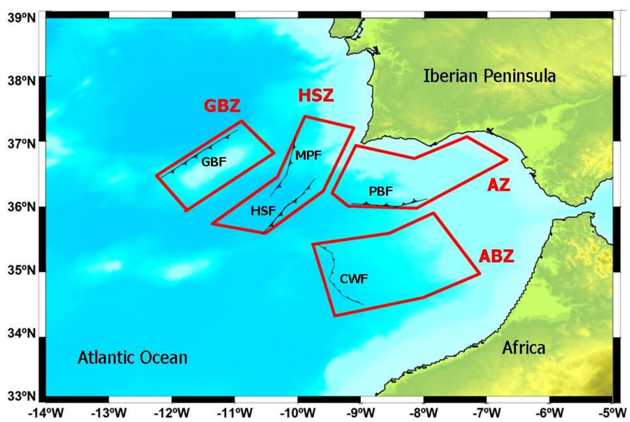

Fig. 2. Main seismogenic faults and source zones that potentially can generate a tsunami affecting Cádiz. Thrusts in solid line correspond to the structures that are candidates for M∼8 events that correspond in this environment to the worst credible case (from TRANSFER, 2009a).

negative. In fact, it is the only city in the Bay of Cadiz whose population is declining. It lost about 14 000 residents between 1995 and 2006, a decrease of 9% (PGOU, 2007). One of the reasons for this decline is the geographical location of the city. Squeezed onto a spit of land surrounded by the Atlantic Ocean, it follows that there is an obvious shortage of vacant building land. A national law governing coastal development prohibits reclaiming land from the sea and since most of its existing housing stock comprises no more than two or three levels, there is simply no space for the population to grow. The buildings in the Old City are not eligible for urban renewal due to their age and historical significance.

Another reason for Cadiz's diminishing population is the high unemployment rate of the city, which is the highest of all provincial capitals in Spain.[2] The growing tourism sector is apparently not able to change this situation much. Although Cadiz attracts an increasing number of tourists every year,

[2]Young people between 18 and 30 years tend to migrate to other Spanish, Latin American, or European cities to seek jobs. Therefore, the unemployment rate of people younger than 25 has actually decreased since 1994, whereas the rate of the remaining sector of the population, especially the female population over 25 has increased (PGOU, 2007). In total, the outward migration has caused a slight but constant decrease in unemployment from 15 835 in 1994 to 10 379 in 2005 (PGOU, 2007). In the near future, employment will be concentrated in about 90% of cases in the services sector, whereas jobs in the fishery, industry, and construction sectors will continue to decline. The fact that the residents under 20 years account for only 17.99% of the whole population while those over 65 account for 17.23% makes Cadiz one of the most aging cities in Spain (IEA, 2008).

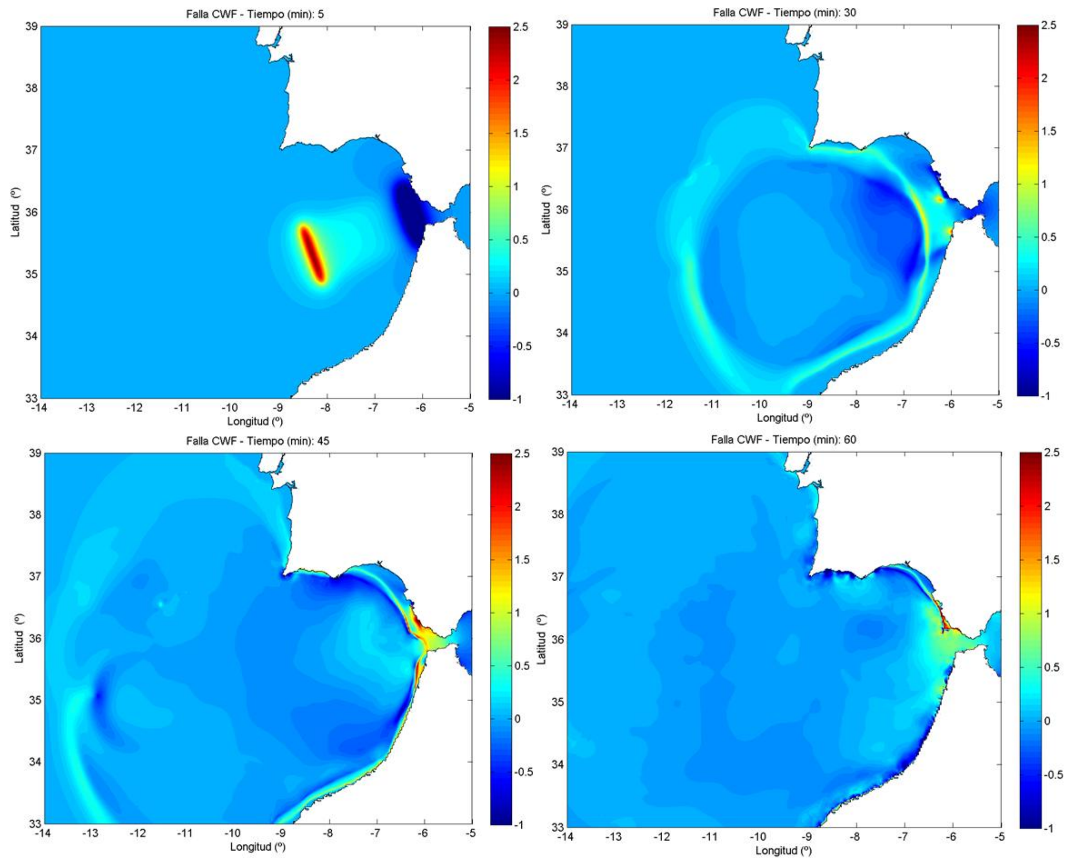

Fig. 3. Initial surface displacement for the worst case scenario for the CWF fault (see location in Fig. 2) and the propagation of the tsunami (from TRANSFER, 2009a).

mainly because of its beautiful beaches, the tourism sector does not significantly increase the income of families or reduce the unemployment rate. In general, the economic situation of Cadiz is quite alarming, which has meant that the governorate has had to call on federal support several times and the city has received financial support from the European Union (PGOU, 2007).

1.3 Exposure to tsunamis

Cadiz's geographical location (Fig. 1) as a peninsula reaching into the open Atlantic makes it especially exposed to all sorts of ocean-related hazards, such as storm surges and tsunamis. It follows that several historical records of destructive tsunamis have surfaced. The oldest accounts date back to the years 218–210 BC, and were determined by historical, geo-morphological, sedimentary, palaeontological, and geo-chronological data records (Luque et al., 2002, p. 623; Fernández Reina, 2001). In fact, the seismic chronicles summarized in a catalogue by Galbis (1937, 1940, cited in Luque et al., 2002) speak of 18 tsunamis affecting the Spanish Atlantic coast between the third century BC and 1900. The most prominent occurrence, described in great detail, was the earthquake and subsequent tsunami in 1755 which originated about 200 km southwest of Cape St. Vincent. Sedimentary records prove that this event must have had a minimum wave height of at least the 1.5 m required to overtop the barrier of the city, but the extent of deposition suggests an event with a wave of a much greater height of approximately 10 m (Carreño, 2005; La Voz, 2008). It had its strongest impact on the city of Lisbon, but it also accounted for 270 victims in Cadiz (La Voz, 2008).

The most damaging earthquakes and tsunamis that have affected the coasts of Portugal, Morocco, and Spain were probably generated in the SWIT zone (the Azores – Gibraltar fault zone), including the mega tsunami that struck on 1 November 1755. In order to define the location and characteristics of possible tsunami-genic sources in the frame of the TRANSFER Project (see TRANSFER, 2009a), four individual source zones including five potential tsunami sources and source mechanisms were distinguished in the SWIT area (see Figs. 2 and 3). The identified areas were the Gorringe Bank zone (GBZ), the Horseshoe/Marques de Pombal zone (HSZ), the South Algarve zone (AZ), and the Alboran Slab zone (ABZ). The five potential tsunami sources are the Gorringe Bank Fault (GBF), the Horseshoe Fault (HSF), the Marques

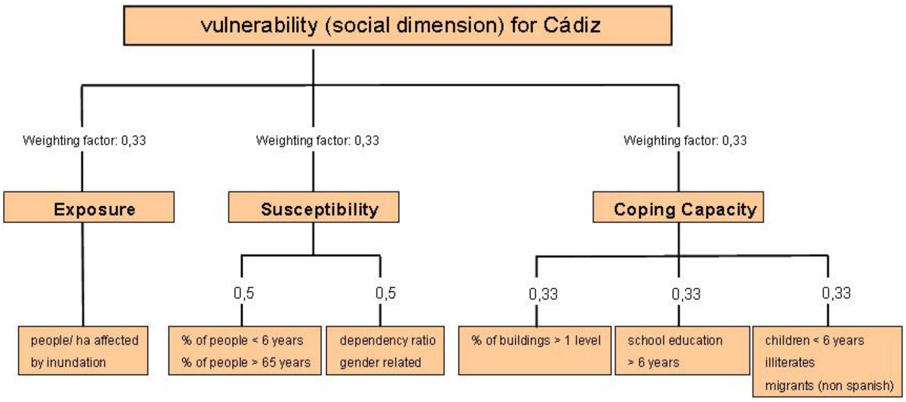

Fig. 4. Adapted BBC-framework for the social dimension of vulnerability.

de Pombal Fault (MPF), the Portimão Bank Fault (PBF), the Cadiz Wedge Fault (CWF). In each source zone a Maximum Credible Earthquake (MCE) was envisaged. This maximum credible earthquake was associated with the typical faults in each source, generating the maximum credible tsunami scenario for each fault. As additional data for the probabilistic inundation maps, the magnitude of the scaling relationship based on fault lengths and length/width relations was used. The dip attributed to the faults is due to taking into consideration the geodynamic significance and evolution.

2 Assessment data and methodologies to estimate Tsunami vulnerability and risk

Based on the BBC conceptual framework (see Birkmann, 2006, p. 34), this study only considers the social and the economic dimension of vulnerability – including critical infrastructure. In order to derive information for all three variables of vulnerability – exposure, susceptibility, and coping capacity (see Fig. 4), statistical as well as spatial data were needed. The data were obtained from following institutes: statistical data based on socio-economic factors from the National Institute of Statistics of Spain (INE; http://www.ine.es/welcoing.htm), demographic and socio-economic data from the regional government in Andalucia, and geospatial data from the Plan General de Ordenación Urbanistica, Ayuntamiento de Cádiz (http://www.cadiz.es/app). Based on the quality criteria for indicators, a list of desired data and indicators to be obtained for Cádiz was developed (Nardo et al., 2005). However, due to different limiting factors, not all of these data could be received and therefore included in the vulnerability assessment.

2.1 Tsunami hazard assessment and potential inundation areas

The analysis of those areas and elements exposed to tsunami impacts requires the development of hazard scenarios and their respective inundation areas. In this regard, the exposure was calculated according to specific tsunami scenarios termed Worst Case scenario and Probability 5000 scenario. Both scenarios and respective inundation maps were developed by the University of Cantabria. In methodological terms, that means that deterministic as well as probabilistic high resolution tsunami inundation maps were developed for Cadiz. The deterministic approximation combines the worst scenario for each potential tsunami-genic source with the local tides. Based on this methodology, inundation lines, maximum water depth, maximum water velocities, the maximum Froude number, as well as maximum hydrodynamic and hydrostatic forces of the Worst Case scenario coinciding with the most probable tidal level were elaborated, derived from the hazard analysis. The second level of analysis encompassed probabilistic maps based on Monte Carlo methods. This method combines the occurrence of earthquakes in the potential sources, source mechanisms, epicentre locations, sea level (astronomical and meteorological tides), and more than 800 numerical simulations using a specific model, the so-called C3 model (Olabarrieta et al., 2009). Respective inundation scenarios for Cadiz and the larger region around Cadiz could be generated for return periods of 500, 1000, 5000, and 10 000 years.

For this study we chose two scenarios, the first one called Probability 5000. Scenarios are useful to include the effects of different variables or uncertainties in the calculation of the probabilistic hazard due to tsunamis. Within these methods, the tidal effect as well as other random variables can easily be taken into account. Hence the maximum wave elevation for a 5000-year return period was used to derive the inundation scenario and respective exposure estimations (see Fig. 5). The second scenario is called the Worst Case

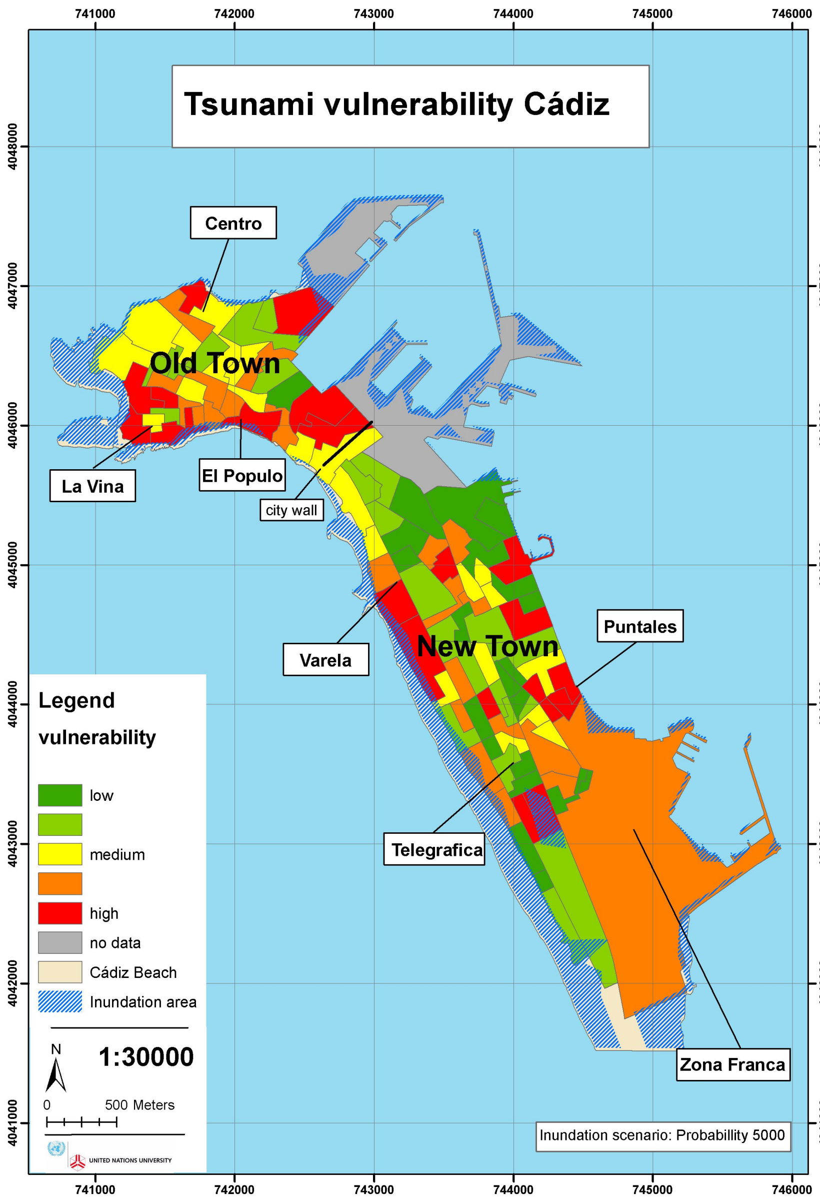

Fig. 5. Vulnerability (social dimension) for Cádiz based on the Probability 5000 scenario.

scenario. This was a deterministic approach calculated by means of the aggregation of all the worst cases (different tsunami-genic sources) including the maximum wave elevation during high tide (see Fig. 6). Based on these inundation scenarios, the respective maps and analyses were carried out regarding the potential population as well as the infrastructure exposed. However, since exposure analysis is just one layer of vulnerability, the analyses of susceptibility and coping capacity were developed as additional information layers derived from demographic and socio-economic data obtained from the National Institute of Statistics of Spain (INE) and the Plan General de Ordenación Urbanística, Ayuntamiento de Cadiz.

2.2 Methods for the estimation of vulnerability

2.2.1 Calculation of the population exposed

The municipal area of Cadiz is divided into 10 districts, which are in turn subdivided into 112 sections. The exposure of Cadiz to tsunami hazards is calculated for each section based on the inundation vector data (Probability 5000 and Worst Case Scenarios) from the Instituto de Hidráulica, Universidad de Cantabria. The unit of exposure is people/ha or total number of people that could potentially be affected by the different inundation scenarios in each section. An additional analysis with the same principle has been undertaken for the critical infrastructure exposed.

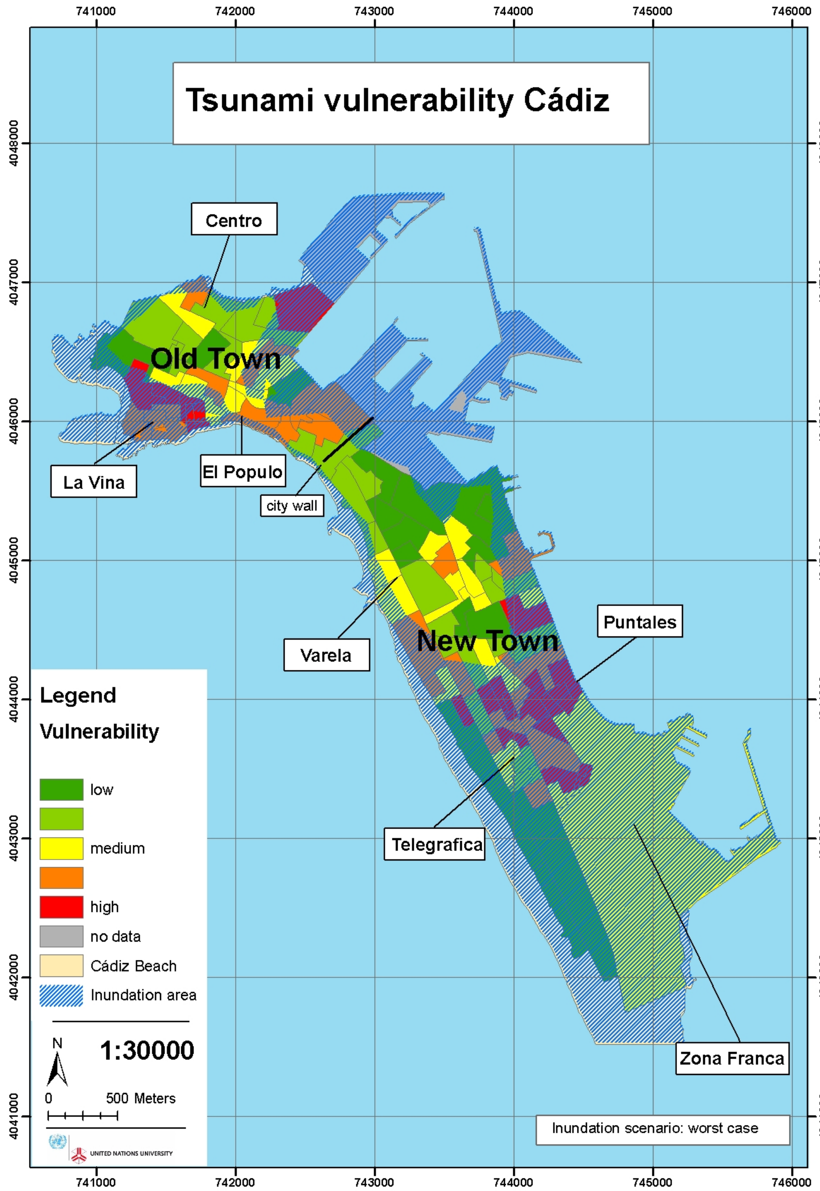

Fig. 6. Vulnerability (social dimension) for Cádiz based on the worst case scenario.

2.2.2 Calculation of susceptibility

Based on the age structure of the demographic dataset, we extracted the predisposition of people easily affected or influenced by tsunamis. The following two indicators were defined for susceptibility: the first indicator comprises the percentage of population younger than six and older than 65 years. These thresholds are based on findings from studies in Sri Lanka and Indonesia that were carried out after the December tsunami 2004 (Rofi and Doocy, 2006). Examinations of dead and missing by age group demonstrated that small children and people older than 61 were most affected and thus were more vulnerable compared with other age groups (Jayasingam and Birkmann, 2007). The second indicator is derived from the following Eq. (1):

$$\left(1-\left(\frac{\text{male}(15-65\text{ years})}{\text{total\_population}}\right)\right)\cdot 100 \quad (1)$$

This equation encompasses a combination of dependency ratio and gender ratio and states the percentage of the total population to be supported in case of a tsunami. That means it outlines areas that need external assistance the most, and is therefore a relative measure of vulnerability. Both indicators were tested on normal distribution but the gender-related dependency ratio was not normally distributed. Hence, this indicator was denominated as a logarithm and thereafter both indicators were z-transformed. Each indicator was half weighted and added up to obtain one aggregated indicator for susceptibility (see also Fig. 4). The rationale of focusing on the dependency ratio and the gender ratio is based on findings of research on the Indian Ocean Tsunami that clearly underlined that these sudden-onset hazards impact the young, elderly, and female population more significantly than the male population of working age (see also Birkmann and Fernando, 2008).

2.2.3 Calculation of coping capacity

The coping capacity comprises the means by which people use available resources and abilities to face the adverse consequences of a hazard (see UN/ISDR, 2004). In our study we chose the following indicators to derive one value indicating coping capacity: the percentage of buildings with more than one level to which people could vertically evacuate; the percentage of people that had received school education for more than six years; the number of children aged under six, illiterates, and non-Spanish-speaking migrants who would have difficulties in reading and understanding a warning message. The first two indicators are positive coping factors – that means buildings with more than one level allow in general for vertical evacuation in the event of a tsunami – whereas the last aggregated indicator describes coping deficits. The factors of building height and the sum of people who could not understand a warning were expressed in a logarithm to get a normal distribution afterwards they were z-transformed. The percentage of people that received more than six years of school education was normally distributed and thus z-transformed. All three coping factors were weighted by 0.33 and summed up in one coping indicator (see Fig. 4).

2.2.4 Vulnerability related to the social dimension

In order to aggregate the three key components of vulnerability (a) exposure, (b) susceptibility, and (c) coping capacity each factor had to be weighted. Due to the fact that there are a number of weighting techniques which could be derived from statistical models or from participatory methods, the authors chose the equal weighting method, since all variables are worth the same in the composite indicator (Nardo et al., 2005) (see Fig. 4). Subsequently the following equation was used for the aggregation: Aggregated vulnerability = Exposure + Susceptibility – Coping Capacity.

3 Analysis and interpretation

The calculation of the indicators for each of the three key parameters of vulnerability (exposure, susceptibility, and coping capacity) and the aggregated vulnerability of the social and economic dimension as well as some qualitative data on both social and economic aspects of vulnerability revealed the following distribution and patterns of vulnerability in the city of Cadiz with respect to the two inundation scenarios of Probability 5000 and Worst Case (see Figs. 5 and 6). It is important to note that the economic dimension focused on the aspect of critical infrastructure in particular, since a disruption or loss of the services provided by critical infrastructure would imply major impacts on economic activities (e.g. the harbour and the hotel industry) within the city. Additionally the dependence on critical infrastructure is a major challenge, especially for and within industrialized countries.

3.1 Social vulnerability

3.1.1 Exposure

Under the inundation scenario with a probability of a 5000-year re-occurrence period, the areas most exposed are those lying in the western part of the city, reflecting the fact that a potential tsunami would hit the city from a south-westerly direction. Due to a larger inundation area and a higher population density these sections show a higher overall exposure of people compared to sections lying on the eastern side of the city. The sections with the highest number of people exposed are located on the coast in the south-west of the old town ("La Viña") and in the south of "La Telegrafía" (see Fig. 5) in the southern part of the city. The sections in the centre of "Varela", in the western and north-western parts of "La Viña" and in the north-east of "Centro" rank in the middle regarding exposure. All other sections exposed either comprise only small parts of inundated areas, or the population density and therefore the percentage of people exposed is low. It is important to note, however, that the grey colouring of sections around the port areas (especially Cadiz City port) does not indicate that these areas are not exposed. The only reason for the grey colour is that there are no permanent residents in those section and they therefore do not appear in any statistical references. Nevertheless, the total number of people working within these port sections is estimated to be more than 1000, of which about 500 are permanently physically present in the port facilities during the day, and about 100 during the night. Therefore, the physical exposure (the inundated areas) of the port infrastructure as well as of the employees is quite large.

With respect to the Worst Case scenario, large parts of the city would be completely covered by water (see Fig. 6). Only a few sections in the centre of the old town and in the northern part of "Varela" would not be affected at all. Nevertheless, the sections still show differences in their exposure since their respective areas and resident numbers are different. For example, the sections in "La Viña" and in "Varela" have a higher population density than other areas that are also completely covered by water, so their exposure is higher compared to the other sections. Overall, the exposure assessment underlines that about 7700 people would be at risk in a tsunami impact when considering the Probability 5000

Table 1. Root causes of vulnerability and possible measures of prevention in different sectors.

Elements of vulnerability	Demography	Tourism	Education	Urban structure	Infrastructure	Planning	Communication
Aspects	Elderly citizens	Lack of knowledge about the risk	Different behaviour of children	Different geological levels within the city	Infrastructure not adapted/prepared	(1) Lack of risk maps and plans (2) Lack of plans of shelters	Low probability and high uncertainty with respect to tsunami occurrence
Principal causes	Aging population	Tourism sector interested in ignoring the risk	Existing plans not appropriate (e.g. evacuation)	Natural causes			
Possible measures of prevention		(1) Information in various languages provided by tourist offices	(1) Adopt evacuation plans (legally)	Define non floodable areas of the city/ shelters on higher grounds	(1) Hermetic protection (at low cost)	Regular revisions and updates and evacuation exercises in the most important institutions	(1) Regular education and communication
		(2) Information tourist centres staff	(2) Educate and train teachers and parents		(2) Identify critical infrastructure and adapt it		(2) Identify critical institutions
		(3) Monitoring regulations at local, regional, and national level	(3) Simulations and exercises				
Responsible institution			Civil protection Education centres				

Table 2. Total number of people and area exposed for probability scenario 5000 years.

Exposure of	Number	% of all
People	7684	5.9
Area in [ha]	83.32	11.7

Table 3. Total number of people and area exposed for worst case scenario.

Exposure of	Number	% of all
People	79 854	61.2
Area in [ha]	83.32	73.7

scenario, and nearly 80 000 people (61% of the total population of Cadiz) are at risk when considering the Worst Case scenario (see Tables 1 and 2).

3.1.2 Susceptibility

As the susceptibility of the population living in Cadiz was basically calculated on the basis of age and gender distribution – due to non-availability of other indicators such as health, employment, and income data at a finer resolution – the different levels of this factor of vulnerability show the following distribution.

Most of the sections representing high susceptibility lie in the old town of Cadiz. Some others can be found in the north western part of "Varela" and some are distributed throughout the central part of "Puntales". A main hypothesis that was verified during the Indian Ocean Tsunami (see Birkmann and Fernando, 2008; Rofi and Doocy, 2006; Jayasingam and Birkmann, 2007) posited that the population over 65 and under six years had greater difficulty in taking flight and seeking rescue in the event of a tsunami since children are usually dependent on their parents, not aware of the potential threat, and not able to take the necessary decisions. Old people would be less able to escape to higher levels of buildings and might have greater difficulty in receiving and understanding warning messages. The gender ratio combined with the dependency ratio also shows that in these population segments, a high number of people beyond working age are economically dependent on the male population of working age. Thus, the economic dependency on the male population is very high and consequently the susceptibility of the entire segment is higher than in those areas where the main population is male and of working age. The generally higher employment numbers of males compared to females is also evident for Spain, which means that higher economic dependency can be assumed.

In general, the distribution of the levels of susceptibility reflects the fact that a large proportion of the population of Cadiz is composed of old people that would have greater difficulty in dealing with a tsunami situation and would have to receive strong economic support from the working

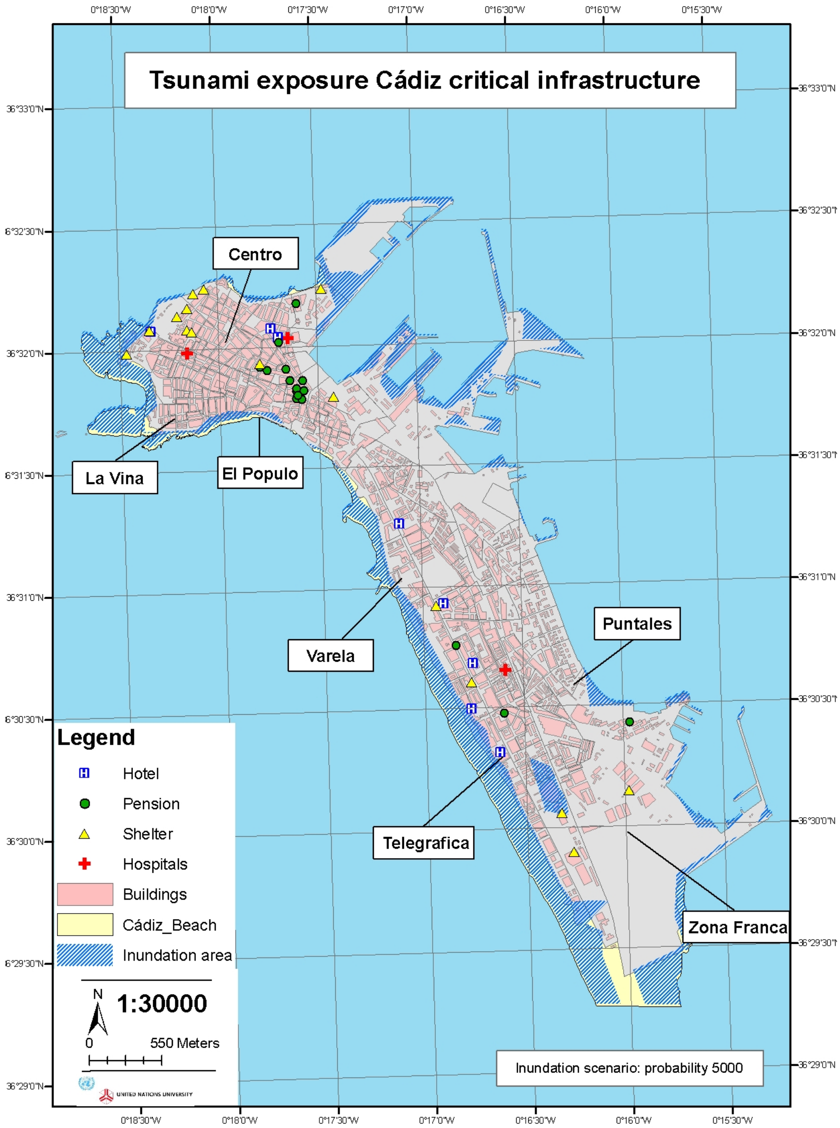

Fig. 7. Exposure of critical infrastructure for Cádiz based on the Probability 5000 scenario.

population in order to recover. The current population data does not allow for factoring in the fluctuations in numbers of people during the winter and summer periods (the tourist season) as well as the exposure of people at their workplace.

3.1.3 Coping capacity

The lowest coping capacity can be observed in the urban sections in the south-east of Cadiz, in "Zona Franca" and "Puntales", in the quarters around the city wall separating the old and new town, and in some sections in the west and north of the old town. The reason for the poor coping capacity in the south-eastern sections is the low level of education of the inhabitants and the high number of migrants and illiterates who are unlikely to be able to understand information on tsunami risks and warnings properly in the case of an acute hazard event. The reason for the low coping capacity in the sections of "Puntales" is also poor levels of education and a high number of children under six years who would have the same difficulties as those described for migrants and illiterates. The same factors also account for the low coping capacity in the sections around the border between the old and the new parts of the city as well as parts in the old town.

The higher levels of coping capacity throughout most of the sections in the old town can be explained by the large number of buildings that have more than one level, thus offering evacuation opportunities (vertical evacuation). In

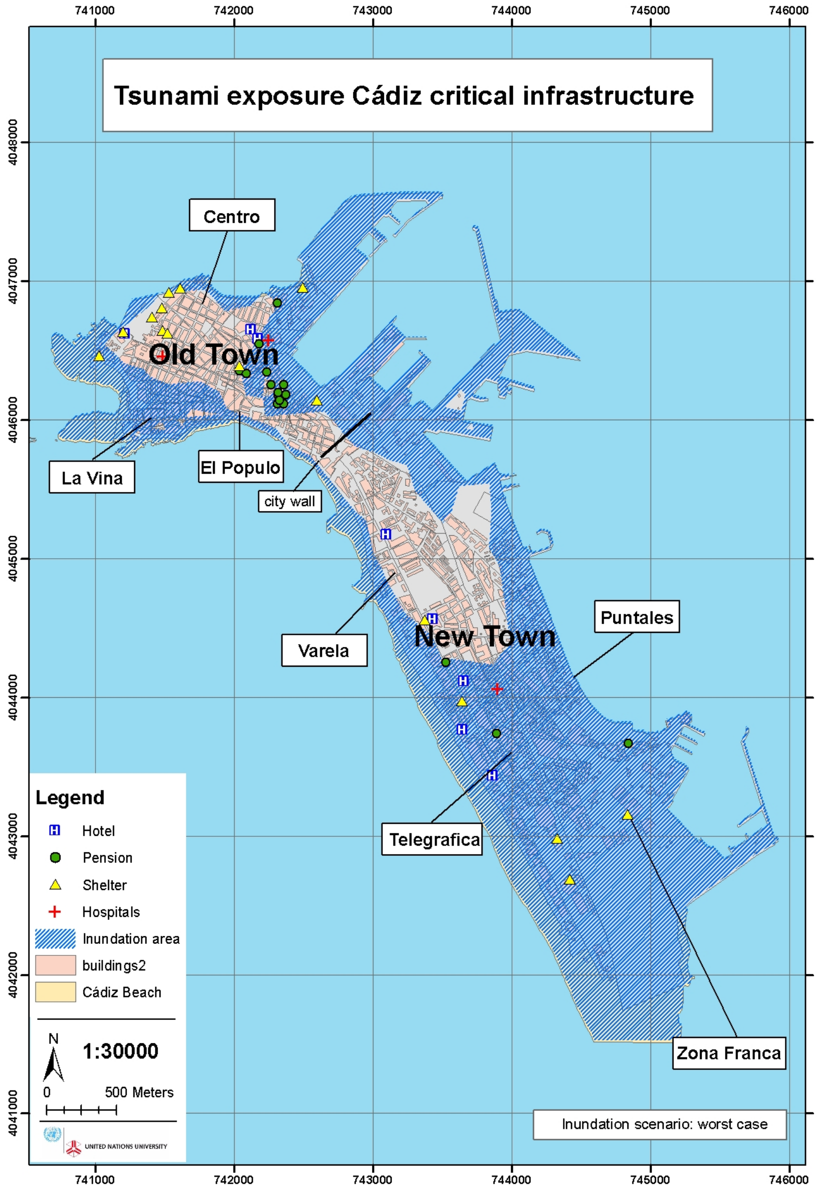

Fig. 8. Exposure of critical infrastructure for Cádiz based on the worst case scenario.

addition, the level of education in this part of the city is comparatively high and the number of migrants and illiterates is low.

3.1.4 Social dimension of vulnerability

Following the distribution of the levels of (a) exposure, (b) susceptibility, and (c) coping capacity throughout the city of Cadiz, the following results can be outlined:

Referring to the Probability 5000 scenario , the most vulnerable sections lie in the coastal areas of the old town, especially in "La Viña", "El Pópulo", and in the north of "Centro". This is due to the high exposure of these sections, the high percentage of old people living in them (high susceptibility), and a low coping capacity, especially in the sections located in "La Viña" and the central-northern sector of "Centro" (see Fig. 5).

The high vulnerability in the sections in "Varela" is due to a very low coping capacity (especially in the sections on the eastern coast of the city) and the high susceptibility in some of them. The high vulnerability in the section around the Free Port Zone ("Zona Franca") is the result of a very low coping capacity (very low education levels and a high number of migrants and illiterates).

With respect to the Worst Case scenario, the most vulnerable sections are concentrated in "La Viña", the north of "Centro", and "Puntales". Their high vulnerability compared to

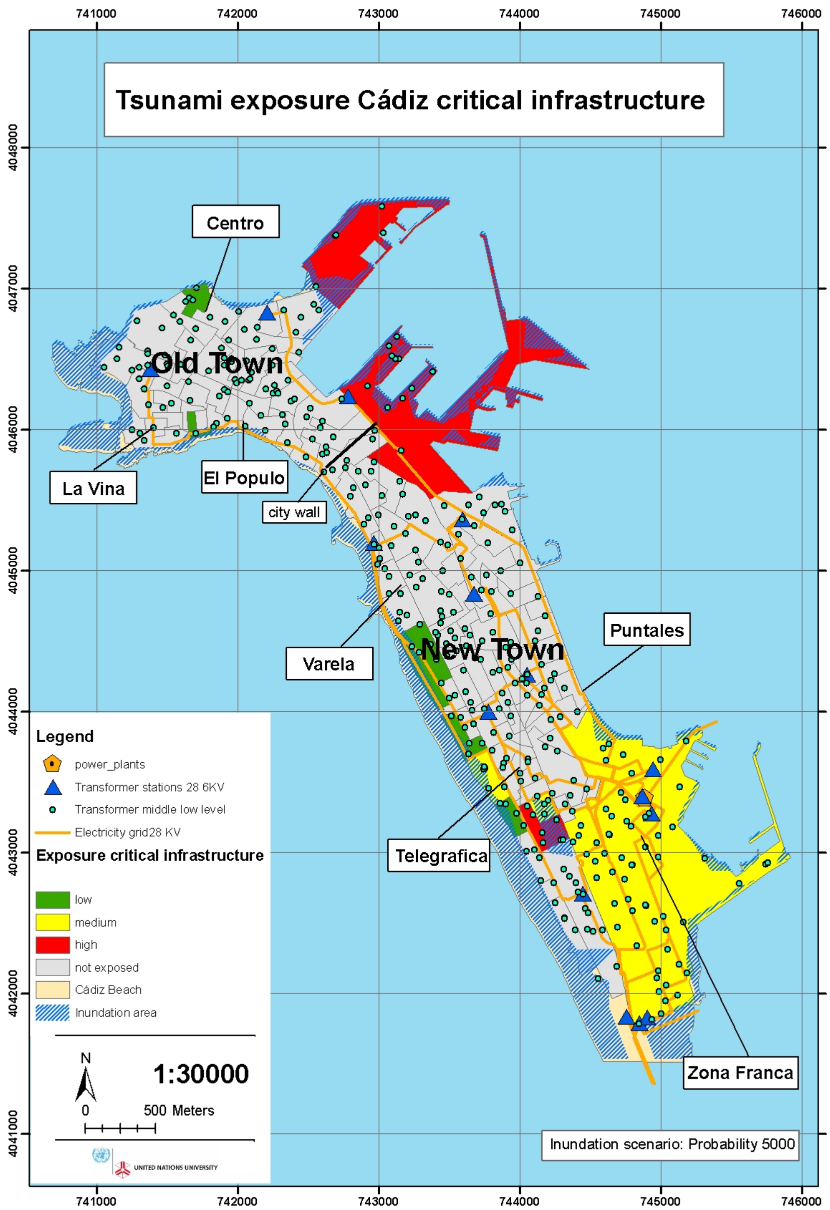

Fig. 9. Exposure of critical infrastructure for Cádiz based on the worst case scenario.

the Probability 5000 scenario is explained by a higher exposure in comparison to the other sections. Furthermore, the degree of susceptibility and coping capacity is the same as in the Probability 5000 scenario.

3.2 Economic vulnerability/vulnerability of critical infrastructures

Only the exposure of critical infrastructure (transformer stations for the provision of electricity, hospitals, hotels and pensions as well as evacuation shelters) has been calculated when analysing the city's economic vulnerability (see Figs. 7–10). Diverse geospatial data such as transformer stations, hospitals, hotels, and pensions were combined with the modelled inundation scenarios (Probability 5000 and worst case scenario) using GIS-techniques in order to establish the potential impact on diverse elements of critical infrastructure. The physical susceptibility of individual infrastructure elements could not be derived from the existing data. However, qualitative studies such as expert interviews, laymen interviews, and focus group discussions carried out during an empirical field trip in March 2009 allow for some estimations of the coping capacity, which in this case would consist of evacuation plans or measures of prevention and preparation.

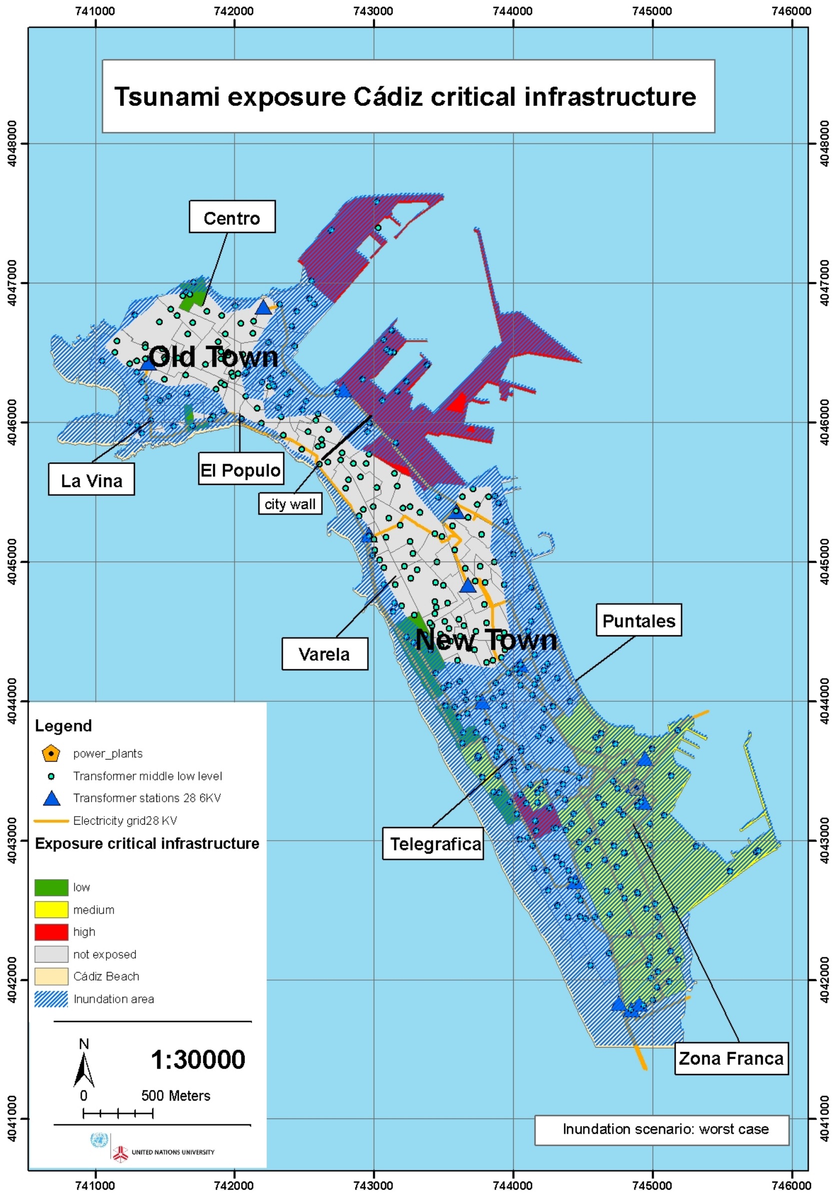

Fig. 10. Exposure of critical infrastructure (electricity supply) for Cádiz based on the worst case scenario.

The map for the exposure of hotels, pensions, hospitals, and shelters in the case of the 5000 year probability shows that none of the hospitals or pensions would be at risk. Some of the hotels that are situated close to the south-western coast of Cadiz and some of the shelters lying in the western and eastern parts of the old town would be affected (see Fig. 7). Additionally, hotels, pensions, and hospitals might be affected indirectly if the tsunami event hit the major power supply plants. However, compared to the Worst Case scenario, this is a rather minor problem. In the Worst Case scenario, two hospitals would be exposed (Hospital Universitario Puerta del Mar, Clínica de la Salud), at least nine of the 16 shelters, and more than half of the pensions and hotels (see Fig. 8). These installations would not only lose their ability to function, but could not serve as shelters in the event of a worst case tsunami. Interviews with representatives of all three types of infrastructure (hospitals, hotels, and pensions) revealed that none of them have prepared evacuation plans or measures of prevention and preparedness. Thus, the vulnerability of these types of critical infrastructure – hospitals, in particular – is quite high and is compounded by a lack of coping capacities.

Regarding the power supply situation, in the Probability 5000 scenario, the only power plant of the city close to the Free Port Zone would not be affected. Nevertheless, two of the 15 larger transformer stations and 7.5% of the medium to low level transformer stations would probably be impacted and inundated. According to the technical director of the electricity provider of Cadiz, a water level higher than one metre would render each transformer inoperative. Considering that each of the 371 transformers provides 1–200 houses with electricity, an electricity outage could affect a maximum of 5565 houses, with severe consequences for the basic functions of living (see Fig. 9).

If the Worst Case scenario became reality, not only would 12 of the larger transformer stations and 65% of the medium to low level transformer stations collapse, but in addition, the power plant would be inundated by sea water. That would mean that power outages could affect around 65–100% of the households in Cadiz.

Although water pipes are not explicitly shown on the map, an interview with the technical director of the water supply company in Cadiz has revealed that there are only two water pipes that deliver fresh water to the whole city. Both pipes are installed along the route between San Fernando and Cadiz. Since this route is only a narrow land connection, a tsunami hitting this route from the west would probably seriously damage or even destroy both pipes. In this case, there would only be a fresh water supply for 24 h, since the water tanks for emergency situations can only cater for this amount of time.

Although not classified as critical infrastructure, the possibility of a larger break in the functionality of the port of Cadiz poses an additional threat to the city. The importance of the port of Cadiz can be illustrated by the fact that in the year 2007, the port possessed real estate with a value of 239 million Euros. Its working capital was 16 million Euros and the net amount of business totalled 21 million Euros. In addition, about five merchant vessels (around 66 000 tons) entered the port each day and around 1884 passengers transited due to the arrival and departure of cruises that sail to other European as well as Latin American and North American coasts. About 3918 employees are directly dependent on the functioning of services provided by the port. These figures underline even further the serious economic and social consequences that a large tsunami could imply, including the disruption of the port activities.

3.2.1 Institutional awareness and lack of preparedness

Besides the revealed levels of vulnerability using socio-economic and demographic data and qualitative assessments the research highlights a very low awareness of tsunami risk in the city of Cadiz and in local government authorities.

In the risk guide provided by the Civil Protection Agency, the risk of inundation caused by tsunamis is classified as "practically non-existent in this area of the globe". Additionally, the chapter on seismic risks includes one paragraph about tsunamis, but it just describes their genesis in general, and no specific information is given that can be used as a real basis to develop appropriate preparedness and coping strategies (see also Aparicio, 2002, p. 2).

The General Urban Development Plan (Plan General de Ordenación Urbanística) developed by the local government (Ayuntamiento de Cadiz) in 2007, also includes a chapter on natural and technological risks. However, the risk of inundation caused by tsunamis which would bring about massive destruction is not included. Furthermore, interviews carried out with local people as well as expert interviews confirmed that the potential threat of a tsunami is not present in the minds of most residents and officials. In the cases where they knew about past events, such as the tsunami in 1755, they were not aware of the present risk or of possible signs to identify a tsunami, and even less of appropriate measures of prevention or vulnerability reduction. Interviews with representatives of schools, the tourist sector, the port authority and public and private companies showed that no risk or emergency plans or educational measures exist with respect to tsunami risk awareness and tsunami response. Overall, the interviews conducted also demonstrate the absence of a local perception of tsunami risk, and that organizational and institutional strategies for risk reduction do not yet include tsunamis. Therefore, the so-called institutional dimension of vulnerability is also an important aspect that needs to receive more attention in the future in order to create a basis for effective preparedness strategies.

4 Results and outlook

The hazard and vulnerability assessment of Cadiz regarding tsunamis revealed that although the probability of a tsunami is relatively low, its consequences – particularly considering the Worst Case scenario possibility - would have severe negative consequences for the city and its inhabitants. The systematic analysis of the key components of vulnerability: (a) exposure, (b) susceptibility, and (c) coping capacities, revealed that some parts of the population and some areas within the city are clearly more vulnerable than others. That means the assessment also allows for identifying priority areas where future development should consider tsunamis as one of the risk factors stemming from the sea. It is important to note that until now there has been no mention of tsunamis as a possible hazard in the coastal region. Moreover, the awareness and also the knowledge of what a tsunami means is very limited among the population potentially exposed to them. Furthermore, the assessment criteria used emphasize that measures for improving coping capacities – such as vertical evacuation options – could become part of strategic future urban development planning. However, to date, these measures or aspects have not been taken into account. Additionally, the survey and the underlying framework also shows that the mapping of potential inundation areas for tsunami hazards is important, but not sufficient if the aim is to develop a more comprehensive risk and vulnerability reduction strategy. Besides physical inundation, vulnerability also depends – as shown by the selected indicators – on the social composition of the population exposed and their response capacities in terms of the ability to cope with the potential impact of a tsunami. In this context, one is confronted by the fact that in a European city like Cadiz, a quantitative vulnerability assessment is hampered by a lack of appropriate data. While at the sub-national scale additional data for important socio-economic indicators such as unemployment, etc. existed, this data was not available at a fine spatial resolution to cover, for example, parts of the city of Cadiz. Therefore, it is recommended to combine quantitative and qualitative approaches within a vulnerability assessment. This would allow the vulnerability to tsunami risk to be captured in a more comprehensive way than just by mapping the exposure.

Moreover, the issue of critical infrastructure, where data could be obtained for power plants, middle and low level transformer stations, and electricity lines, also shows that a potential tsunami could cut off 5565 households (based on Probability 5000 scenario) from electricity within seconds. This could entail particularly severe consequences for other critical elements of infrastructure such as the piped water supply or the ability of hospitals to run normally. Therefore, tsunamis – even if the probability of occurrence is relatively low – should be considered within the further development and renewal of critical infrastructure, particularly since such infrastructure is critical in emergencies and crisis situations. In addition, it is characterized by lack of mobility and high cost.

Lastly, it is worth pointing out that the discussion of the assessment results in Cadiz has also allowed the identification of the first measures and actions required to reduce risk and vulnerability. During an expert meeting conducted in March 2009 in Cadiz, the different vulnerable sections of the city, the root causes of their vulnerability, as well as potential measures to reduce vulnerability were discussed within a focused group discussion. Interestingly, the key measures that participants and experts proposed should be taken as a first step do not require large financial resources, but mainly encompass information and communication as well the identification of the most critical infrastructure (see Table 1). Furthermore, the discussion revealed that the evacuation of the city would not be an option for Cadiz, since the only two routes leading out of the city (N-443 and CA-33) could only accommodate the exit of 4000 cars per hour, while the total number of cars in Cadiz is about 50 000. Thus, the only possibility of rapid evacuation is a vertical evacuation within buildings that have more than one floor and that are constructed in a suitable fashion. This is an important message that must be communicated to the people via all possible information channels, starting in schools and through the media. In addition, evacuation simulations and exercises should be carried out on a regular basis in schools and other important public and private institutions. In this regard, lessons could be learned from countries in South East Asia where awareness raising campaigns and school training on tsunami risk have been conducted in every country, e.g. Indonesia (Taubenboeck et al., 2009). The experts concluded that these measures are relatively easy to implement and require only limited funding. Conversely, it was admitted by local stakeholders that more costly and intense activities would probably be difficult to put in place due to the lack of governmental (and therefore financial) support because of the high level of uncertainty and the infrequencyof tsunamis in Cadiz. However, vulnerability maps clearly indicate that different features of vulnerability should be considered and that priorities can be defined in terms of improving the situation, particularly in the most vulnerable parts of the city with respect to social groups and critical infrastructure. The main purpose of this assessment and the information it has developed is to help local decision-makers and civil protection managers to approach the people in greatest need of direct protection before an adverse event occurs.

Particularly in the context of the further development of the NEAMTWS (http://www.ioc-tsunami.org/content/view/35/1035/), it needs to be underlined that besides the warning infrastructure and the detection of geomorphological faults likely to cause tsunamis, people-centred early warning also requires appropriate information about the people and regions potentially affected, their vulnerability, and response capacities. In this regard, the maps presented in this study provide an essential basis to better understand the susceptibility and response capacity of communities and cities exposed to potential tsunami threats in Europe.

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