Assessing Spatio-Temporal Population Exposure to Tsunami Hazard in the Lisbon Metropolitan Area

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ABSTRACT

The coastal region of Lisbon, Portugal, is potentially subject to tsunami hazard. Mapping and assessing tsunami risk requires giving adequate consideration to the population exposure. In the present work we model and map the spatio-temporal distribution of population in the daily cycle and analyze it with a tsunami hazard map to better assess tsunami risk in the Lisbon Metropolitan Area. New high-resolution daytime and nighttime population distribution surfaces are developed using 'intelligent dasymetric mapping' to combine best-available census data and statistics with land use and land cover data. Mobility statistics are considered for mapping daytime distribution. Finally, the population distribution maps are combined with the Tsunami Inundation Susceptibility map to assess potential human exposure to tsunami in daytime and nighttime periods. Results show that a significant amount of population is potentially at risk, and its numbers increase from nighttime to daytime, especially in the zones of high susceptibility.

Keywords

Tsunami, population exposure, dasymetric mapping, Lisbon.

INTRODUCTION

The Lisbon Metropolitan Area (LMA), Portugal, is subject to significant risk of tsunami, as confirmed by the occurrence of numerous events in the past (Baptista and Miranda, 2009). Although the probability of occurrence is lower than other natural hazards, impacts can be extremely high and tsunamis are a major risk for Lisbon coastal areas (Baptista, Soares, Miranda and Luis, 2006).

Tsunami hazard is usually represented by inundation maps that identify areas and depths of tsunami flooding or run-up. The Regional Plan for Territorial Management for the Lisbon Metropolitan Area (PROTAML), under discussion, includes a Tsunami Inundation Susceptibility map for the area, showing that significant urbanized areas may be at risk (CCDR-LVT, 2010). Assessment and mapping of communities' risk to natural hazards requires estimation of social vulnerability, of which population exposure is probably the most critical variable. However, more effort has been put into understanding of tsunami hazard than into estimating potential impacts on people and infrastructure (Wood, 2007), despite quantitative assessment of tsunami risk being necessary to support spatial planning and for local authorities to provide population protection (Lima, Miranda, Baptista, Catalão, Gozalez, Otero, Olabarrieta, Álvarez-Gómez and Carreño, 2010). Therefore step one of tsunami preparedness includes assessing and mapping concentrations of population present (NSTC, 2005; IOC, 2008), since all human beings are equally vulnerable in case of tsunami (Villagrán de León, 2008).

On November 1st, 1755 following a large earthquake, the city of Lisbon was hit by a major tsunami having an estimated run-up height of 6 m that caused much loss of life (Baptista, Heitor, Miranda, Miranda and Victor, 1998; Chester, 2001). This very destructive event occurred during the daytime period, sometime after 10:00h. The spatial distribution of population, and hence exposure to hazards, is time-dependent, especially in metropolitan areas. Therefore a more accurate assessment of population exposure and risk analysis requires going beyond residence-based census maps and figures. The development of the LandScan Global Population Database (Dobson et al., 2000) represented a great improvement over residence-based population data sets. However, its spatial resolution (30 arc-seconds) is still too coarse to adequately support analysis at the local

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level, and the representation of "ambient population" corresponds to a temporal averaging that is not ideal for using in time-specific hazards such as a tsunami. To overcome these limitations, population distribution databases having higher temporal and spatial detail are being developed for the territory of the USA (McPherson and Brown, 2003; Bhaduri et al., 2002).

This effort aims at improving the assessment of tsunami risk and contributing to more efficient and effective Emergency Management (EM) by modeling and mapping the spatio-temporal distribution of local population in the daily cycle and integrating it with a tsunami hazard map for quantitative analysis of human exposure.

STUDY AREA AND DATA

The study area encompasses the Lisbon Metropolitan Area (LMA), the main metropolitan area in Portugal (Figure 1). The region includes eighteen municipalities and accounts for 36% of the national GDP and 30% of the country's companies are located there.

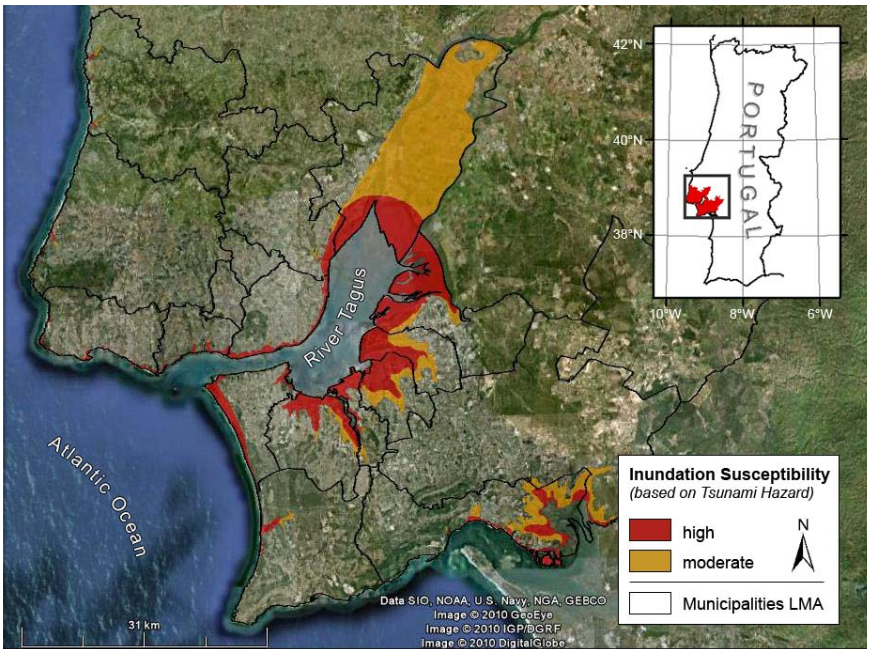

Figure 1. Study area and Tsunami Inundation Susceptibility map, over Google Earth imagery

The LMA occupies a total land area of 2,963 km^2 and is home to 2,661,850 residents, 26% of the country's population (INE, 2001). Although the average population density is 898 inhabitants per square kilometer, these densities vary widely in space and time. Beyond the more urbanized core the region still includes vast rural areas with scattered settlements whose uneven population density is not well captured and represented by census polygons, which can be heterogeneous even at the block level. Also, due to daily commuting for work and study, the daytime population of municipalities in the metro area of Lisbon can differ by more than 50% of the residential figures from the census (INE, 2003).

The geographic situation of the LMA, bordering the Atlantic Ocean and the large estuary of the Tagus River, puts it at risk of tsunami, as confirmed by modern history (Baptista and Miranda, 2009).

A map of tsunami hazard for the LMA was produced for the PROTAML report (CCDR-LVT, 2010) and was obtained in digital vector format. This map depicts areas susceptible to inundation by tsunami using two classes or levels, *High* and *Moderate* (Figure 2). The Tsunami Inundation Susceptibility map was not obtained using propagation modeling for a theoretical tsunami, being based instead on a detailed Digital Terrain Model and maximum expected run-up height to model tsunami run-in and derive inundation areas. Although the reach of the tsunami waves inland and respective total area of hazard zones may be overestimated for a specific event, these can be considered to represent potential tsunami-inundation zones and be more appropriate for use in pre-event EM actions such as risk assessment. Also, in the context of EM, overestimation is preferable to under-estimation by adhering to the precautionary principle, and small variations in the characteristics of the tsunami source may not be too significant for impact assessment (Lima et al., 2010).

MODELING AND ANALYSIS

Population Distribution Modeling

The modeling of population distribution for the LMA is based on raster dasymetric mapping using street centerlines as spatial reference units to re-allocate population counts. The most recent statistical and census data (2001) provide the population counts for each daily period, while physiographic data sets (land use and streets) define the spatial units (i.e., grid cells) used to disaggregate those counts (McPherson and Brown, 2003). To obtain the nighttime population distribution surface, detailed census data is further refined by re-allocating residential population to effective residential areas. This procedure was initiated by identifying and selecting strict residential land use from Land Use/Land Cover (LULC) maps. Two residential classes were considered and sampled, using the containment method to derive the respective population density weights: *Continuous Urban Fabric* and *Discontinuous Urban Fabric*. Then, eligible streets (i.e., all except freeways) were intersected with residential land use from LULC data to obtain residential streets, which were rasterized. Finally, the population from census block groups (source zones) was interpolated to the respective residential street cells (target zones) according to the density weights.

Population mobility statistics are considered for mapping daytime distribution, and empirical parameters used for interpolation are obtained from a previous modeling effort of part of the study area (Freire, 2010). The total daytime population distribution results from the sum of two surfaces on a cell-by-cell basis: (1) the daytime population in their places of work or study – the workforce population surface, and (2) the population that remains home during the day – the daytime residential population grid. A major innovation was the use of 'intelligent dasymetric mapping' (Mennis and Hultgren, 2006) to disaggregate official population counts to target zones. More details can be found in Freire and Aubrecht (2010).

Using this methodology, four raster population distribution surfaces were produced, at 50 m resolution: (1) nighttime (residential) population, (2) daytime residential population, (3) daytime worker and student population, and (4) total daytime population. Nighttime and workforce distributions were validated using correlation analysis with higher resolution reference data, yielding correlation coefficient (Pearson's r) of 0.86 and 0.64, respectively.

Earlier versions of similar spatio-temporal population distribution surfaces, although generic, were developed and tested for EM applications, specifically earthquake risk assessment (Freire and Aubrecht, 2010). Such detailed and high-resolution population surfaces make them more appropriate for local-level quantification of human exposure, enabling a more thorough assessment of potential risks.

Population Exposure to Tsunami

Population exposure to tsunami in the LMA was assessed in GIS using zonal analysis to summarize nighttime and daytime population surfaces by each susceptibility zone of the Tsunami Inundation Susceptibility map. It was assured that both datasets were in the same projected coordinate system.

Figure 2 illustrates in 3-D for part of the study area the varying population distribution and densities in nighttime versus daytime periods in each tsunami susceptibility zone.

The modeled population surfaces represent maximum expected densities on a typical workday, assuming that everyone is at home at night and all workers and students are in their workplaces and schools, and the remainder in their residences during the daytime period. Although this is still a simplification of reality, it is a major improvement over existing data sets that can benefit analyses from regional to local scale.

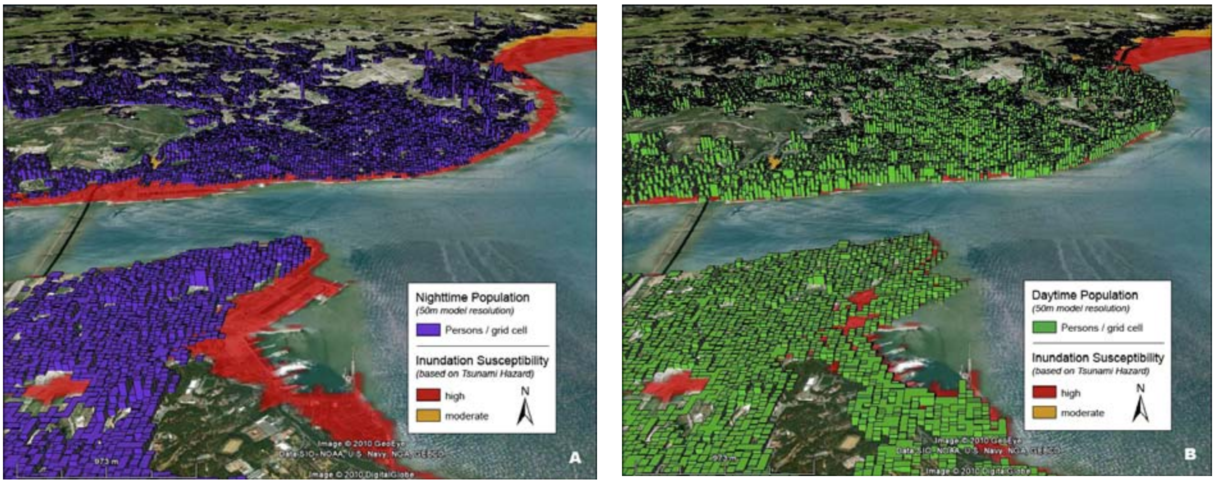

Figure 2. Nighttime (A) and daytime (B) population densities and Tsunami Inundation Susceptibility zones, over Google Earth imagery

Table 1 summarizes the results of the zonal analysis and highlights the differences between nighttime and daytime exposure. The population potentially exposed to some level of tsunami inundation hazard significantly increases from nighttime to daytime periods. The majority of the population exposed is associated with the 'high inundation susceptibility' zone. Particularly these 'high risk' areas also feature a significant increase in population from nighttime to daytime. While during nighttime around 60% of the potentially exposed population is located in areas having a high tsunami hazard level, daytime population movement results in more than 200,000 persons additionally exposed in that area, corresponding to a factor of increase greater than 2.5.

	Nighttime Population		Daytime Population		Difference	
Tsunami Hazard level	Abs. [Pers.]	Rel. [%]	Abs. [Pers.]	Rel. [%]	Abs. [Pers.]	Rel. [%]
High	125,730	59	334,000	78	208,270	166
Moderate	86,929	41	93,444	22	6,515	7
Total	*212,659*	*100*	*427,444*	*100*	*214,785*	*101*

Table 1. Population potentially exposed to Tsunami Inundation Susceptibility levels in nighttime and daytime periods

Considering the total population of the Lisbon Metropolitan Area, 16% of the daytime population is potentially exposed, compared to 8% of the resident population during the nighttime period. While population exposure to the moderate hazard level remains relatively stable at 3%, a considerable increase from 5% during nighttime to 12% during daytime is observed in the highly susceptible areas.

These results reflect the location of human economic activities closer to the coastline, and the more intensive occupation of these areas during the daytime period.

CONCLUSIONS AND OUTLOOK

This research is a first approach towards considering the spatio-temporal population distribution to assess risk of tsunami in a large metropolitan area that was severely affected by this type of event in the past. Previously unavailable detailed spatial resolution datasets of nighttime and daytime population were combined with Tsunami Inundation Susceptibility zones to estimate human exposure in those periods in the LMA. The analysis shows, despite being a generalized estimation, that a significant amount of population is potentially at risk, and its numbers increase from nighttime to daytime, especially in the zones of high susceptibility (i.e., lower elevation and closer to the coastline).

We believe this improved characterization of vulnerability and risk can benefit all phases of the disaster management process where human exposure should be considered, namely in emergency planning, risk mitigation, preparedness, and response to an event. Given the availability of input data sets, this approach could also be applied to the Oporto Metropolitan Area, further encompassing nine municipalities and 1,260,680 inhabitants.

Planned future developments include the use of an improved Tsunami Inundation map for analysis, conducting a more detailed modeling of population distribution in space (preferably at the building level considering its height and elevation) and time (e.g., rush hour, week-ends), as well as modeling evacuation to a hypothetical tsunami scenario. Also, contingency plans should be addressed, considering the presence of important services in the hazard zone.

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