SPATIO-TEMPORAL POPULATION DISTRIBUTION AND EVACUATION MODELING FOR IMPROVING TSUNAMI RISK ASSESSMENT IN THE LISBON METROPOLITAN AREA

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ABSTRACT:

Lisbon, Portugal, is subject to significant risk of tsunami, and was hit by a very destructive earthquake-triggered tsunami during daytime in 1755. The Regional Plan for Territorial Management for the Lisbon Metropolitan Area (PROT), under discussion, includes a tsunami hazard map, showing that significant urbanized areas may be at risk of inundation.
In order to consider the time dependence of population exposure to tsunami threats, we map and analyze the spatio-temporal population distribution in the daily cycle in the Lisbon Metropolitan Area. High-resolution day- and nighttime population distribution maps are developed using 'intelligent dasymetric mapping', i.e. using areal interpolation to combine best-available census data and statistics with land use and land cover data. 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. In combination with the tsunami hazard map, information on infrastructure, land use and terrain slope, the modeled population distribution is used to assess people's evacuation times, applying a GIS-based evacuation modeling approach to the city of Lisbon. The detailed spatio-temporal population exposure assessment allows producing both day- and nighttime evacuation time maps, which provide valuable input for evacuation planning and management.
Results show that a significant amount of population is potentially at risk, and its numbers increase dramatically from nighttime to daytime, especially in the zones of high susceptibility. Also, full evacuation can be problematic in the daytime period, even if initiated immediately after a major earthquake. The presented approach is considered to greatly improve risk mapping and assessment and can benefit all phases of the disaster management process.

1. 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 et al., 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 et al., 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). Updated and detailed mapping of population distribution is important for decision support in practically every phase of the emergency management cycle, if produced at appropriate spatial and temporal scales (Sutton et al., 2003).

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 et al., 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. Due to human activities and mobility, the distribution and density of population varies greatly in the daily cycle. 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 level, and the

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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).

The present work aims at improving the assessment of tsunami risk and contributing to more efficient and effective Emergency Management (EM) by quantifying the spatio-temporal population exposure to this hazard, and modeling and analyzing their evacuation times.

2. DATA AND STUDY AREA

2.1 Study Area

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

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 captured and represented by census polygons, which can be quite large 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).

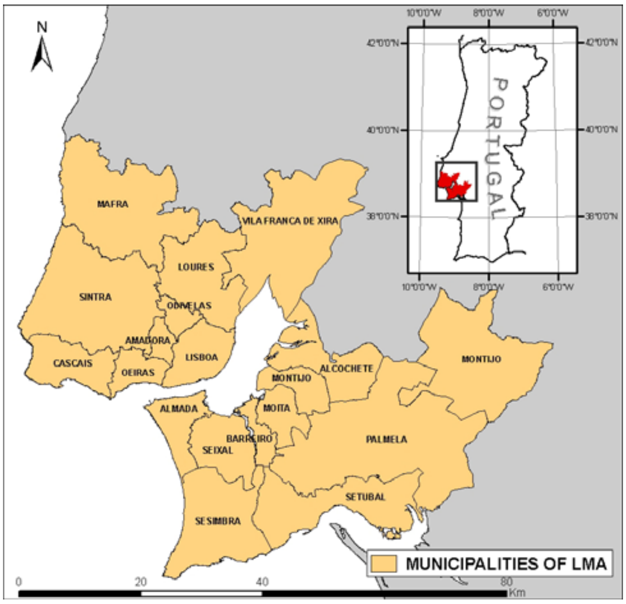

Figure 1. Study area – Lisbon Metropolitan Area (LMA)

The geographic situation of the LMA, bordering the Atlantic Ocean and the large estuary of the Tagus River, provides an appropriate context for assessing multi-temporal exposure to tsunami.

2.2 Data sets

The main data sets produced and used in the course of the presented analyses were population distribution surfaces and a Tsunami Inundation Susceptibility map (Figure 2).

Data set	Date	Data type
Street centerlines	2004	Vector polyline
Land use/cover maps (COS90; CLC2000)	1990; 2000	Vector polygon
Census block groups	2001	Vector polygon
Census statistics	2001	Database (MS Access)
Commuting statistics	2001	Table (O/D matrix)
Daytime worker/student population distribution	2001	Raster (25 m)

Table 1. Main input data sets used for modeling population distribution

Input variables used for modeling population distribution include both physiographic and statistical data. The first group comprises street centerlines and land use and land cover (LULC) maps, while the second includes census counts (INE, 2001), data on workforce, and commuting statistics (INE, 2003) for the study area. These data were obtained from various sources and in different formats which are listed in Table 1. COS90 is a digital LULC map at the scale 1:25,000 covering almost the entire country, however it dates from 1990. Therefore, to ensure temporal consistency among input data sets, it was decided to update it to some extent using the more recent CORINE Land Cover database for the year 2000.

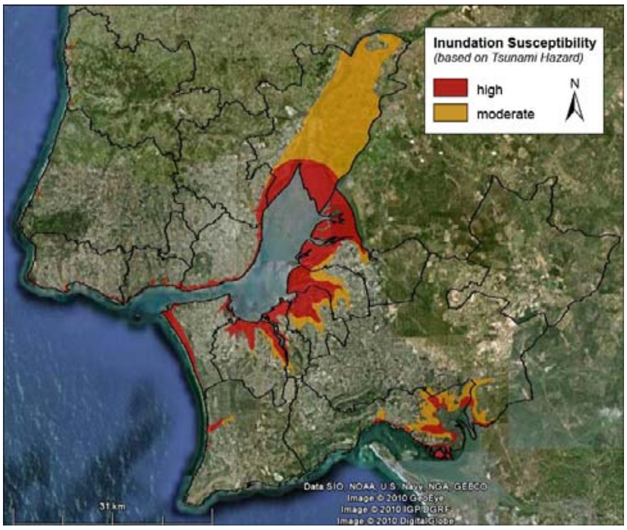

Figure 2. Tsunami Inundation Susceptibility map for the LMA, over Google Earth imagery

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). This can be considered to represent maximum generic tsunami hazard for the LMA, given that small variations in the characteristics of the tsunami source may not be too significant for impact assessment (Lima et al., 2010).

3. METHODOLOGY

3.1 Modeling Population Distribution

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 define the spatial units (i.e., grid cells) used to disaggregate those counts (McPherson & Brown, 2003).

To obtain the nighttime population distribution surface, detailed census data (INE, 2001) 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 (INE, 2003) 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).

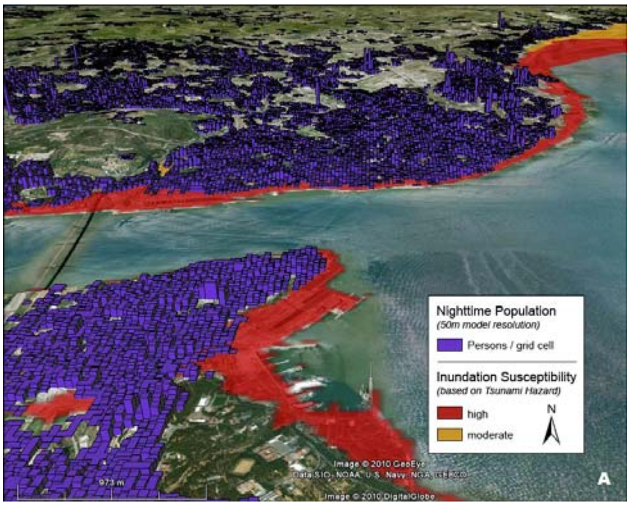

Figure 3. Nighttime population density and Tsunami Inundation Susceptibility zones

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. Although this approach was developed and presented in more detail in Freire and Aubrecht (2010), both the input data and modeling rules were refined, improving final accuracy.

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. The new 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 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.

3.2 Assessing Population Exposure to Tsunami

In order to improve the assessment of human exposure and tsunami risk in the LMA, two analyses were implemented: (1) quantification of population exposed to tsunami inundation levels in nighttime and daytime periods, and (2) modeling evacuation in nighttime and daytime periods for a subset of the study area.

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.

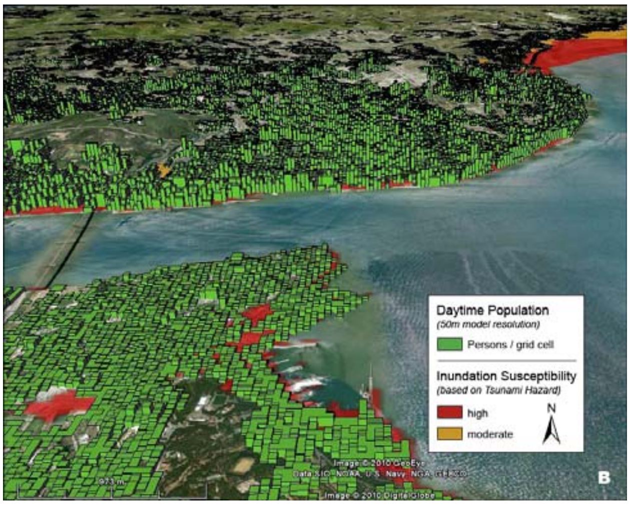

Figure 4. Daytime population density and Tsunami Inundation Susceptibility zones

Figures 3 and 4 illustrate 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.

3.3 Tsunami Evacuation Modeling

A second analysis departs from the spatio-temporal population distributions and potential tsunami inundation zones to model and estimate evacuation time in nighttime and daytime. This demonstration is conducted for three *freguesias* (communes) of the municipality of Lisbon, located on the western part of the city: Santa Maria de Belém, Ajuda, e Alcântara. (Figure 5).

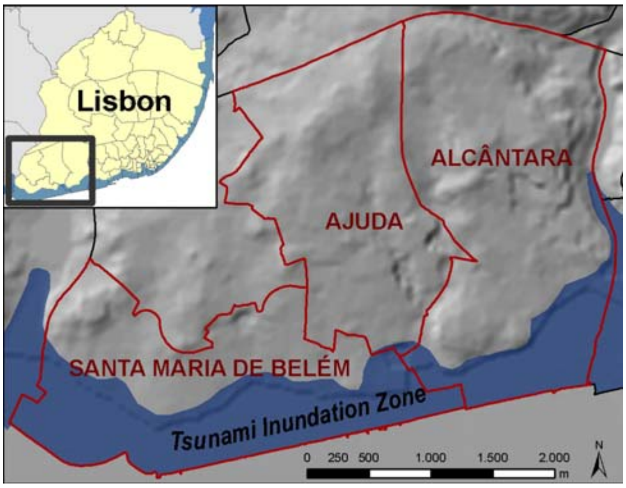

Figure 5. Study area for Tsunami evacuation modeling

The evacuation analysis assesses the time needed, after an evacuation is initiated, for the population to reach safe areas outside of the inundated zone, assuming they are travelling by foot. The methodology was developed in the frame of the German-Indonesian Tsunami Early Warning System (GITEWS) project (Post et al., 2009; Strunz et al., 2011; Wegscheider et al., 2011).

The evacuation modeling is performed with a GIS analysis based on a cost-weighted distance approach, where the best (i.e. the fastest) evacuation route from any given location to a safe area is defined, and the time needed to reach it is calculated. The output of the model, the time needed for evacuation towards a safe area, is based on several parameters: (i) extent of the hazard impact area (i.e. potential inundation area), (ii) characteristics of the evacuation paths (slope, land cover, street network.), (iii) population density and (iv) location of critical facilities (i.e. facilities with people of reduced or lacking abilities to evacuate such as hospitals). For more details see Post et al. (2009) and Wegscheider et al. (2011). Data from the Urban Atlas (www.eea.europa.eu/data-and-maps/data/urban-atlas) was used as source of land cover information.

The derived evacuation time surfaces are used in combination with the detailed population distributions to calculate the number of successful evacuees after certain time intervals.

4. RESULTS AND DISCUSSION

Results of the analysis of population exposure to tsunami in the LMA are presented in Table 2.

Tsunami hazard	Population		
[Inundation levels]	*abs. [Pers.]*	*rel. [%]*	
High	125,730	59	**Night**
Moderate	86,929	41	
Total	*212,659*	*100*	
High	334,000	78	**Day**
Moderate	93,444	22	
Total	*427,444*	*100*	
High	208,270	166	**Differ.**
Moderate	6,515	7	
Total	*214,785*	*101*	

Relative differences are relative to the night numbers

Table 2. Population exposed to Tsunami inundation levels in nighttime and daytime periods in the LMA

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.

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.

Regarding the modeling of tsunami evacuation, Figures 6 and 7 show the modeled surfaces of evacuation time and access points to safe areas, for the nighttime and daytime periods, respectively.

These figures illustrate the different surfaces of evacuation time obtained for nighttime and daytime because the evacuation modeling considers densely populated areas to be slower to evacuate, as a higher "traffic volume" of evacuees slows down the speed of every individual (Klüpfel, 2005; Rogsch, 2005). Therefore, longer evacuation periods are registered in daytime, since about 40,000 people are estimated to be present in the three communes in this period, compared to 8,000 residents in nighttime.

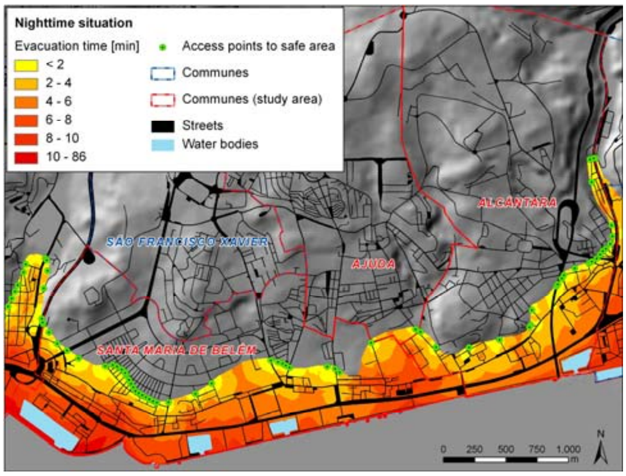

Figure 6. Nighttime Tsunami evacuation modeling

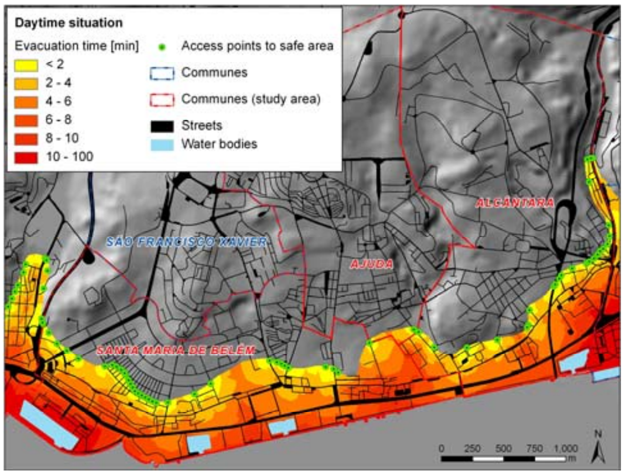

Figure 7. Daytime Tsunami evacuation modeling

Results of the evacuation modeling are summarized in Table 3.

Commune	Elapsed time	Population		
	[min]	*Remaining*	*Evacuees*	
Santa Maria de Belém	0	4,300	0	Night
	5	1,600	2,700	
	10	0	4,300	
Santa Maria de Belém	0	25,800	0	Day
	5	19,900	5,900	
	10	4,600	21,200	
	15	500	25,300	
	20	400	25,400	
	75	0	25,800	
Alcântara	0	3,800	0	Night
	5	300	3,500	
	10	0	3,800	
Alcântara	0	17,700	0	Day
	5	9,200	8,500	
	10	900	16,800	
	15	200	17,500	
	20	200	17,500	
	90	0	17,700	
Ajuda	0	200	0	Night
	5	0	200	
Ajuda	0	200	0	Day
	5	0	200	

Table 3. Population remaining in hazard zone and successful evacuees after different time intervals of tsunami evacuation

The analysis reveals significant differences in the magnitude and speed of evacuation between night and day. Differences are especially striking in the commune of Alcântara, due to configuration of hazard zone and population distribution. Overall in the study area, all resident (nighttime) population is able to evacuate to safety after 10 minutes. In daytime, although more than 95% of the population reaches safety after 20 minutes, it takes as long as 90 minutes for a full evacuation. This duration is longer than the travel time to this location for the devastating 1755 tsunami (Baptista et al., 1998), implying that for a similar scenario there would be approximately 700 people in the study area who would not reach safety on foot.

Furthermore, this is assuming that everyone present in the hazard zone would immediately initiate evacuation following a large earthquake or tsunami warning, but no early warning system for tsunamis is yet implemented in Portugal. Therefore, it would be important to consider other safety options, such as vertical evacuation. Also, this analysis would be improved by further considering non-residents and non-students/workers (e.g., tourists) present and involved in leisure activities, which are especially relevant in the Alcântara (nightlife) and in the Belém (daytime) communes.

5. CONCLUSIONS

This research is an initial 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, and evacuation was analyzed for a subset of the study area.

Results indicate, 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). Evacuation modeling reveals that full evacuation can be problematic in the daytime period, even if initiated immediately after a major earthquake. This analysis can provide valuable information for evacuation planning and management measures, not yet implemented in the area.

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. The improved population surfaces can be used as input in loss simulators for modeling of human casualties. 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 conducting a more detailed modeling of population distribution in time (e.g., rush hour, week-ends) and space (preferably at the building level considering its height and elevation), enabling the modeling of vertical evacuation.

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