TOWARDS IMPROVED RISK ASSESSMENT: MAPPING THE SPATIO-TEMPORAL DISTRIBUTION OF HUMAN EXPOSURE TO EARTHQUAKE HAZARD IN THE LISBON METROPOLITAN AREA

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ABSTRACT:

Risk is a function of hazard probability and vulnerability, the latter resulting from a combination of exposure and ability to cope. However, assessment and mapping of human vulnerability has been lagging behind hazard analysis efforts. Furthermore, due to human activities and mobility, the spatial distribution of population is time-dependent, especially in metropolitan areas. Therefore more accurate estimation of population exposure and risk assessment requires moving beyond using simple residence-based census data. Lisbon, Portugal, is subject to significant risk of earthquake, which can strike at any day and time, as confirmed by modern history. The recently-approved 'Special Emergency and Civil Protection Plan' is based on a Seismic Intensity map, and only considers resident population from the census as human exposure. In the present work we map and analyze the spatio-temporal distribution of population in the daily cycle to re-assess earthquake risk in the Lisbon Metropolitan Area. New high-resolution daytime 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. Finally, the population distribution maps are combined with the Seismic Hazard Intensity map to assess potential exposure and produce new daytime and nighttime overall Seismic Risk maps. It is believed this approach improves risk mapping and assessment and can benefit all phases of the disaster management process.

1. INTRODUCTION

1.1 Population distribution and risk assessment

Risk is usually defined as a function of hazard probability and vulnerability, the latter resulting from a combination of exposure and ability to cope (UNDP, 2004). However, assessment and mapping of human vulnerability has generally been lagging behind hazard analysis efforts (Pelling, 2004). Furthermore, due to human activities and mobility, the spatial distribution of population is time-dependent, especially in metropolitan areas. Accurately estimating population exposure is a key component of catastrophe loss modeling, one element of effective risk analysis and emergency management (FEMA, 2004; Chen et al., 2004; NRC, 2007).

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).

Earthquakes are the prototype for a major disaster, being low-probability, rapid-onset, high-consequence events. They often have significant collateral effects such as fire, flooding, and release of hazardous chemicals. Aubrecht et al. (2009) have demonstrated how disaggregated population data can improve estimation of exposure to earthquake hazard.

The region around Lisbon, Portugal, is subject to significant risk of earthquake, which can strike at any day and time, as confirmed by modern history. The recently-approved 'Special Emergency and Civil Protection Plan' (PEERS-AML-CL) for 26 municipalities is based on a Seismic Intensity map and only contemplates census' resident population as human exposure.

In the present work nighttime and daytime population distribution patterns are modeled and mapped at high resolution in order to assess the spatio-temporal human exposure to earthquake risk in the Lisbon Metropolitan Area. Nighttime and daytime population densities are then combined with the Seismic Intensity map to derive and propose new fine-scale composite risk maps. This effort correlates with recent recommendations to improve vulnerability analyses (Cutter, 2003; Balk et al., 2006; Birkmann, 2007; NRC, 2007).

2. DATA AND STUDY AREA

2.1 Study Area

The study area 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.

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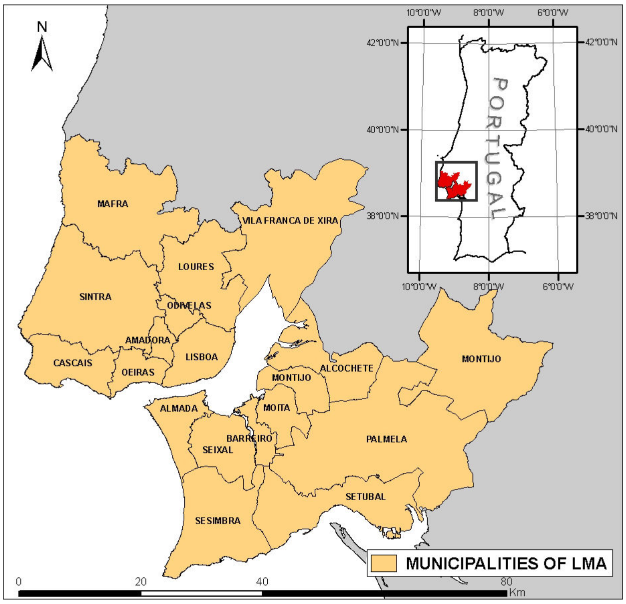

Figure 1. Study area – Lisbon Metropolitan Area (LMA)

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).

The characteristics of the area and the availability of a Seismic Hazard Intensity map, in the context of the above-mentioned Special Emergency and Civil Protection Plan, provide an appropriate context for the present analysis, i.e. improving risk assessment for this particular hazard type.

2.2 Data sets

The main data sets produced and used in the course of the presented analyses were population distribution surfaces and a seismic intensity 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

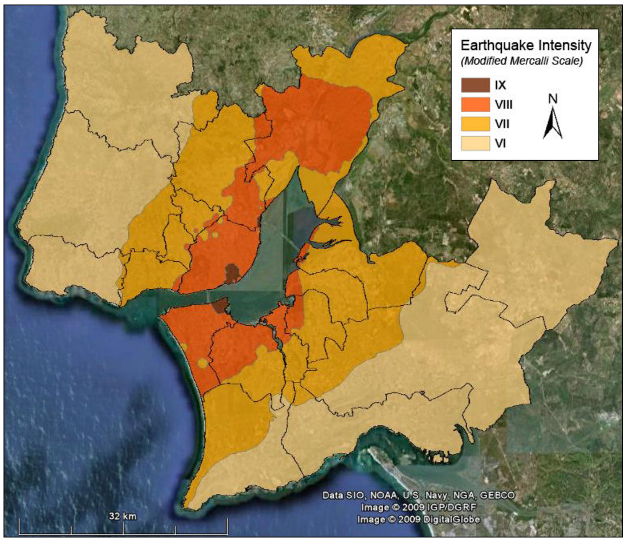

Figure 2. Seismic Intensity map for the study area

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.

3. METHODOLOGY

All processing and modeling of spatial data was conducted in ESRI® ArcGIS 9.3, a Geographic Information System (GIS) application. GIS offers the necessary tools and flexibility to implement raster and vector-based dasymetric methods, and was used for modeling, analysis, validation and mapping the results for presentation.

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).

Four raster population distribution surfaces were produced, at 25 m resolution: (1) nighttime (residential) population, (2) daytime residential population, (3) daytime worker and student population, and (4) total daytime population. The basic methodology was presented and tested previously for Cascais and Oeiras, two municipalities of the LMA (Freire, 2009). However, due to being labor-intensive and costly, the original methodology had to be adapted and improved to expedite the modeling of a much larger area with sufficient accuracy.

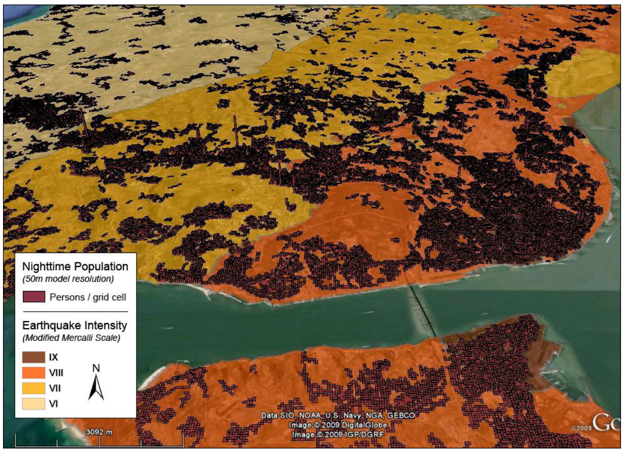

Figure 3. Nighttime population density and seismic zones

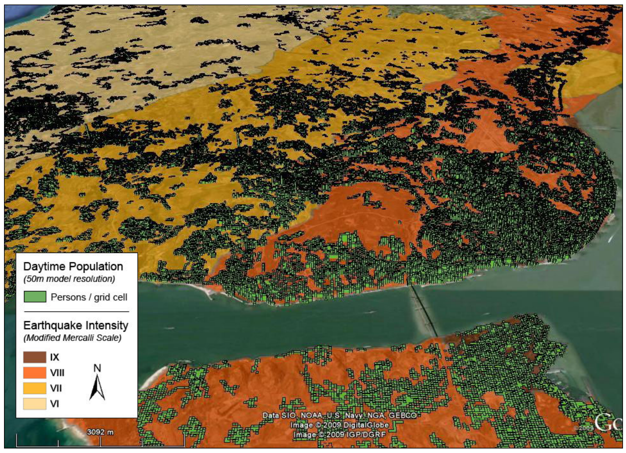

Figure 4. Daytime population density and seismic zones

A major innovation was the use of intelligent dasymetric mapping (Mennis and Hultgren, 2006) to disaggregate official population counts to target zones.

The nighttime population distribution surface was obtained by allocating resident population from census zones to residential streets. First, relevant classes were selected from the LULC maps and combined, in order to identify residential land use. Certain rules were applied to minimize the effect of errors present in the LULC data. Two residential classes were considered and sampled, using the containment method to derive the respective density weights: Continuous Urban Fabric and Discontinuous Urban Fabric. Then, freeways were removed from consideration and the resulting eligible streets were intersected with residential land use from LULC data to obtain residential streets. Subsequently these were rasterized at 25 m resolution and the population from census block groups (source zones) was interpolated to the respective residential street cells (target zones) according to the density weights.

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. The latter is obtained by multiplying the nighttime distribution by the ratio of resident population who, according to official statistics (INE, 2003), does not commute to work or school. The workforce population surface was created by allocating commuters to selected 'labor' streets, in a fashion similar to the one used for modeling nighttime distribution. Two density classes were also defined and sampled, using the previously generated workforce population surface for Cascais (Freire, 2009) to derive density weights. The resulting 25 m population grids were aggregated to 50 m cells for analysis and visualization purposes, thus representing densities by 2,500 m^2 (0.25 ha).

Nighttime distribution was validated using the higher-resolution census blocks as reference (i.e. ground truth) in a correlation analysis. The corresponding correlation coefficient (Pearson's r) was 0.85. Validation of workforce distribution was limited by lack of independent, higher-resolution reference data covering the study area. Correlating the new workforce surface in Oeiras with the one previously generated for that municipality yielded a coefficient of 0.60.

3.2 Human Exposure and Seismic Risk

The Seismic Intensity map was obtained from the PEERS-AML-CL (ANPC, 2007) in image format and was manually digitized and clipped for the study area (Figure 2). Using the Modified Mercalli Intensity Scale (USGS, 2009) it represents the expected intensities generated by a 6.6/6.7 magnitude earthquake with epicenter in the lower valley of the river Tagus. In order to improve the assessment of human exposure and seismic risk in the LMA, two analyses were implemented: (1) quantification of population exposed to seismic intensity levels in nighttime and daytime periods, and (2) deriving and mapping of overall seismic risk in nighttime and daytime periods.

Population earthquake exposure was assessed using zonal analysis to summarize nighttime and daytime population surfaces by seismic zone of the earthquake intensity map. Figures 3 and 4 illustrate the varying population distribution and densities in nighttime versus daytime periods in each intensity zone. The second analysis involved defining major classes for seismic intensity and population density and corresponding subsequent reclassification. Combining these two variables, overall risk categories were mapped and quantified.

			Population Density [Persons/ha]			
			401-	201-400	101-200	0-100
		Risk Class	**VH**	**H**	**M**	**L**
EQ Intensity [M. Mercalli Scale]	XII	**VH**	VH	VH	H	M
	XI	**VH**	VH	VH	H	M
	X	**VH**	VH	VH	H	M
	IX	**VH**	VH	VH	H	M
	VIII	**H**	VH	H	H	M
	VII	**H**	VH	H	H	M
	VI	**M**	H	H	M	M
	V	**M**	H	H	M	M
	IV	**M**	H	H	M	M
	III	**L**	M	M	M	L
	II	**L**	M	M	M	L
	I	**L**	M	M	M	L

VH (very high), H (high), M (moderate), L (low)
Framed in black: Seismic intensity levels in the study area

Table 2. New overall seismic risk classes

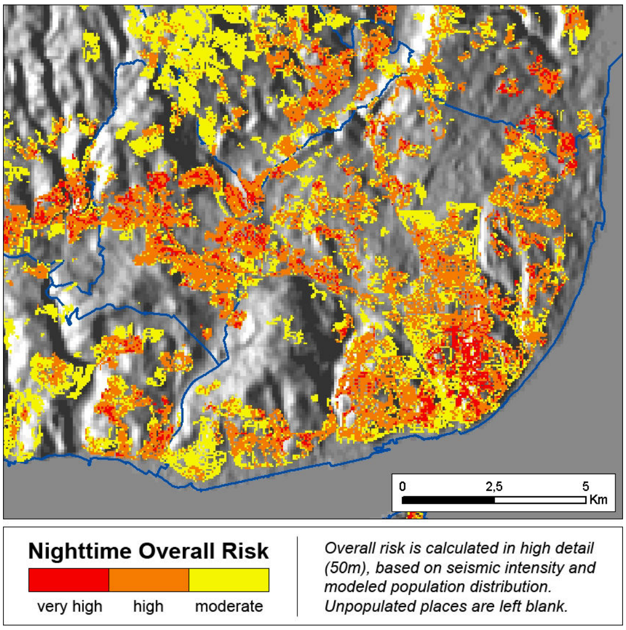

Figure 5. Map of overall seismic risk in nighttime period

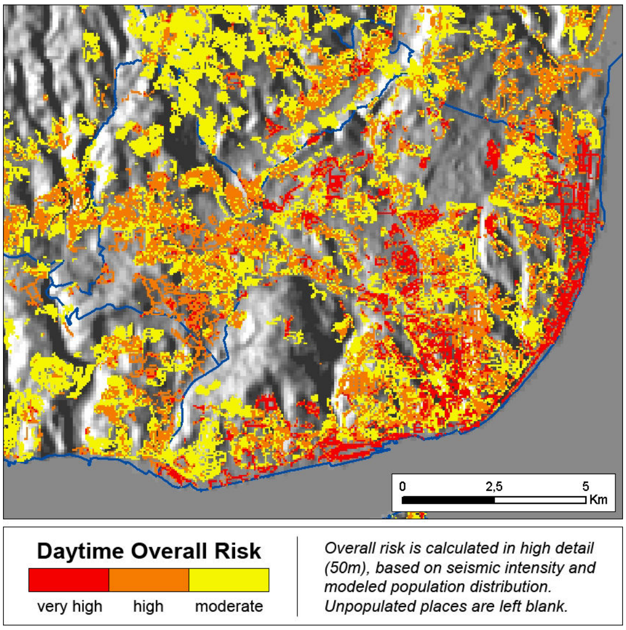

Figure 6. Map of overall seismic risk in daytime period

Ranking risk using just few categories helps in having a clear perspective of risk distribution that can assist in prioritizing areas for mitigation and response measures. Therefore, in order to reclassify the two variables (i.e. population density, seismic intensity) into a common ordinal scale, four main risk categories were defined: (1) Very High, (2) High, (3) Moderate, and (4) Low.

The class breaks for population density (in persons/ha) were derived based on histogram analysis and adjusted by logical rounding. For the seismic risk, the Modified Mercalli scale varying from I to XII was reclassified based on intensity levels and definitions (see USGS, 2009). Referring to the manner in which the earthquake is felt by people, the lower six levels were grouped in the Low and Moderate categories. The higher six levels, referring to observed structural damage, were classified as High and Very High. Table 2 shows original levels and classes, corresponding categories, and combined overall seismic risk classes.

In the study area, the seismic intensity levels vary from VI to IX (cp. Figure 2). The reclassified seismic intensity map was rasterized at 50 m resolution and combined with the reclassified nighttime and daytime population density maps resulting in overall seismic risk maps for each of those periods (Figures 5 and 6). Total population and area were then summarized for the resulting overall risk categories in LMA.

4. RESULTS

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 a simplification of reality, it is a major improvement over existing data sets that can benefit analyses from regional to local scale.

Table 3 quantifies the total population potentially exposed to each seismic intensity level in the nighttime and daytime periods. It shows that from night to day the population exposed to the two highest seismic levels increases while the number of persons exposed to the two lower levels decreases.

More specifically, exposure to the highest seismic level (i.e. level IX) increases by 22% to affect 5% of the total daytime population (137,222 people). Even more important, from nighttime to daytime period an additional 204,786 persons are exposed to the levels VIII and IX, which then contain 52% of the daytime population. The level VIII zones concentrate the largest share of the population both in nighttime and daytime periods, while not occupying the largest share of the area.

EQ Intensity	Population		
[M. Mercalli S.]	*abs. [Pers.]*	*rel. [%]*	
IX	112,826	4	Night
VIII	1,076,180	41	Night
VII	887,493	34	Night
VI	569,940	22	Night
Total	2,646,439	100	Night
IX	137,222	5	Day
VIII	1,256,570	47	Day
VII	746,992	28	Day
VI	535,767	20	Day
Total	2,676,551	100	Day
IX	24,396	22	Differ.
VIII	180,390	17	Differ.
VII	-140,501	-16	Differ.
VI	-34,173	-6	Differ.
Total	30,112	1	Differ.

Relative differences are relative to the night numbers

Table 3. Population exposed to seismic intensity levels in nighttime and daytime periods in the study area

Risk	Area		Population		
	abs. [ha]	rel. [%]	abs. [Pers.]	rel. [%]	
VH	884	3	423,112	16	Night
H	6,390	21	1,308,780	49	
M	22,617	76	914,550	35	
Total	29,891	100	2,646,442	100	
VH	1,154	3	626,753	23	Day
H	6,022	17	1,062,020	40	
M	27,611	79	987,772	37	
Total	34,787	100	2,676,545	100	
VH	270	31	203,641	48	Differ.
H	-368	-6	-246,760	-19	
M	4,994	22	73,222	8	
Total	4,896	16	30,103	1	

VH (very high), H (high), M (moderate), L (low)
Relative differences are relative to the night numbers

Table 4. Population by overall seismic risk levels in nighttime and daytime periods in the study area

The area and total population of overall seismic risk levels in nighttime and daytime periods are presented in Table 4. It shows that most of the area and population of the LMA are in Moderate or High risk classes. However, while only 3% of the populated area is classified as Very High risk, this class includes 23% of the total population in the daytime period. This represents an increase of 48% in population and also 31% in area from nighttime to daytime. This also indicates a significant increase in population density in the risk class between those periods.

As an annex, assessment of spatio-temporal exposure to seismic intensity and overall risk for each individual municipality within the study area are presented in Table 5.

Munic.*	Risk	Population			
		Night		Day	
		abs. [Pers.]	rel. [%]	abs. [Pers.]	rel. [%]
1	VH	141,839	25	551,312	62
	H	345,971	62	258,528	29
	M	73,630	13	83,516	9
	Total	561,440	100	893,356	100
2	VH	0	0	0	0
	H	1,263	2	10,983	22
	M	53,082	98	38,979	78
	Total	54,345	100	49,962	100
3	VH	55,437	15	4,033	1
	H	162,374	45	105,769	37
	M	142,397	40	179,834	62
	Total	360,208	100	289,636	100
4	VH	0	0	0	0
	H	19,884	12	32,795	22
	M	150,881	88	118,456	78
	Total	170,765	100	151,251	100
5	VH	24,327	15	14,788	10
	H	93,818	58	93,004	62
	M	43,692	27	41,636	28
	Total	161,837	100	149,428	100
6	VH	50,924	30	16,901	12
	H	105,815	63	100,723	73
	M	12,297	7	20,095	15
	Total	169,035	100	137,718	100
7	VH	19,675	15	18,737	19
	H	80,826	60	47,276	49
	M	33,551	25	30,485	32
	Total	134,051	100	96,498	100
8	VH	43,488	22	4,144	2
	H	94,704	48	101,486	61
	M	60,791	31	61,916	37
	Total	198,982	100	167,545	100
9	VH	17,569	14	1,203	1
	H	75,391	61	54,457	53
	M	29,866	24	47,496	46
	Total	122,826	100	103,156	100
10	VH	33,468	21	7,259	5
	H	66,668	41	81,360	56
	M	60,656	38	57,003	39
	Total	160,791	100	145,621	100
11	VH	20,257	13	860	1
	H	79,761	53	49,319	42
	M	50,297	33	66,014	57
	Total	150,315	100	116,192	100
12	VH	9,809	12	0	0
	H	53,084	67	48,625	71
	M	15,799	20	19,384	29
	Total	78,692	100	68,009	100
13	VH	5,907	9	5,518	11
	H	44,268	65	28,998	56
	M	17,509	26	17,681	34
	Total	67,685	100	52,197	100
14	VH	0	0	0	0
	H	17,592	45	13,030	34
	M	21,584	55	25,244	66
	Total	39,177	100	38,274	100
15	VH	0	0	0	0
	H	5,780	45	5,503	48
	M	7,186	55	5,889	52
	Total	12,966	100	11,392	100
16	VH	20,257	13	860	1
	H	79,761	53	49,319	42
	M	50,297	33	66,014	57
	Total	150,315	100	116,192	100
17	VH	0	0	0	0
	H	46,142	41	16,065	14
	M	67,345	59	98,845	86
	Total	113,487	100	114,910	100
18	VH	127	0	0	0
	H	13,360	26	11,990	22
	M	38,609	74	41,930	78
	Total	52,096	100	53,920	100

* 1 (Lisboa), 2 (Mafra), 3 (Sintra), 4 (Cascais), 5 (Oeiras), 6 (Amadora), 7 (Odivelas), 8 (Loures), 9 (Vila Franca de Xira), 10 (Almada), 11 (Seixal), 12 (Barreiro), 13 (Moita), 14 (Montijo), 15 (Alcochete), 16 (Sesimbra), 17 (Setúbal), 18 (Palmela)

Table 5. Population by overall seismic risk levels in nighttime and daytime periods for all municipalities of the LMA

5. CONCLUSIONS

The presented approach yields a nighttime population distribution having higher resolution than census data and a comparable daytime population surface previously unavailable for the study area. This enables a more thorough assessment of potential human exposure and improves mapping earthquake risk. By combining refined exposure with seismic intensity, new overall seismic risk was classified and analyzed. Results indicate that significantly more people are potentially exposed to higher seismic intensity levels in the daytime period.

The improved population surfaces can be used as input in earthquake simulators for modeling of human casualties. Additionally, such population exposure datasets can be combined with different hazard maps to improve spatio-temporal assessment and risk mapping for any type of hazards, natural or man-made. 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.

Future developments include improving the population distribution models by using more up-to-date land use/cover data detailing functional use. A more complete risk assessment would benefit from considering in addition to the population density also their characteristics, in order to account for more vulnerable groups (e.g. children, elderly people, etc.).

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