Chapter 8
Multi-hazard Susceptibility Assessment for Land Use Planning in the Lisbon Metropolitan Area

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Abstract The Lisbon Metropolitan Area is a risk hotspot in Portugal due to excessive exposure to natural and environmental hazards. In this work, a multi-hazard susceptibility assessment is performed for the 118 parishes that constitute the study area, considering the spatial incidence of seven hazardous processes: earthquakes, tsunami, beach erosion and coastal flooding, coastal erosion and cliff retreat, landslides, floods, and forest fires. The relative importance of hazardous processes was established through the Analytic Hierarchy Process (AHP), based on the frequency-magnitude relationship of each process and its damage capacity. All the parishes exhibiting very high multi-hazard susceptibility have high earthquake susceptibility and most are located in riverine or coastal zones, thus subjected to floods and/or coastal erosion (affecting beaches and/or cliffs).

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1 Introduction

The Lisbon Metropolitan Area (LMA) covers 3,015 km^2 (3.3% of mainland Portugal) and is distributed by 18 municipalities and 118 parishes. In 2021, the resident population amounted to 2,821,876 inhabitants (1.7% more than in 2011), about a quarter of the Portuguese population. In economic terms, the LMA concentrates nearly 25% of the active population, 30% of national companies, and 33% of employment, and contributes to more than 36% of the national GDP [1].

The LMA has a remarkable geomorphological diversity and encompasses an Atlantic coastline of 150 km and a riverfront of around 200 km. It includes one large estuary (Tagus) and part of another (Sado), and five protected areas, integrated into the Natura 2000 Network. The elevation ranges from 0 to 528 m a.s.l (Fig. 1).

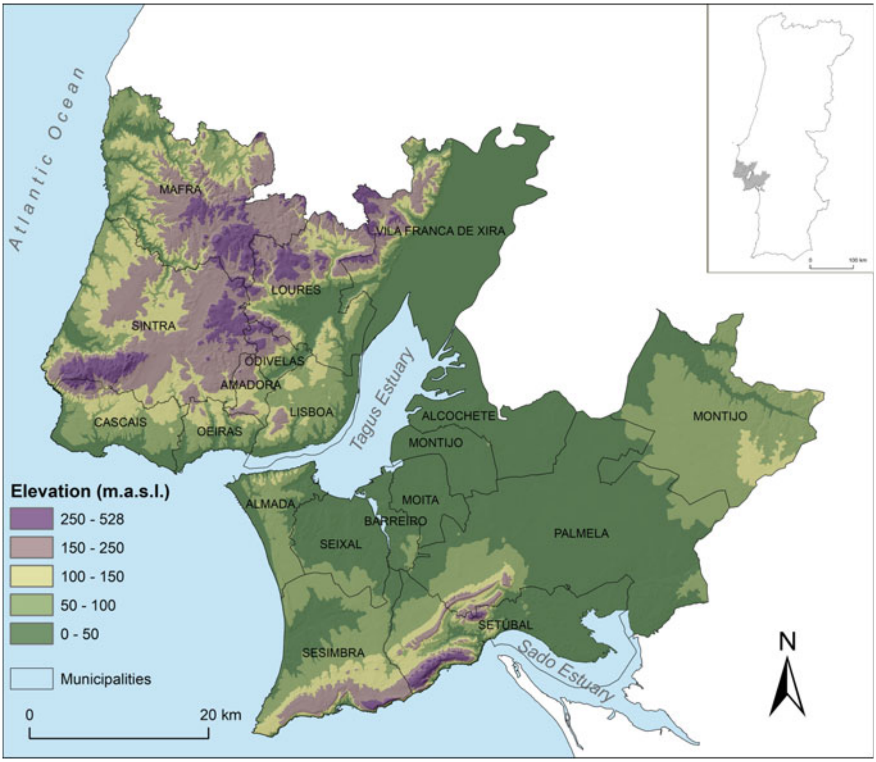

Fig. 1 Location and elevation of the Lisbon Metropolitan Area

The LMA is a major risk hotspot in Portugal due to excessive exposure to natural hazards like earthquakes, floods, and coastal erosion [24]. This area suffered the effects of the two greatest natural disasters that occurred in mainland Portugal in the last 300 years: the Lisbon earthquake and tsunami on November 1, 1755 [3], that caused more than 12,000 deaths, and the flash flood during November 25–26, 1967 [21], that caused more than 700 deaths.

The existing hazards have been causing a significant impact in the study area and need to be accounted for by urban planning and civil protection stakeholders. Therefore, this chapter aims to assess the combined susceptibility of a set of natural and environmental hazards relevant to regional and urban planning in the LMA. The assessment is performed for the 118 parishes that constitute the study area, and it will contribute to improving preventive land use planning by bridging the gap between scientific research and land use planners.

2 Data and Methods

The susceptibility was assessed and mapped for a set of hazardous physical processes with a relevant territorial incidence in the LMA: earthquakes, tsunamis, beach erosion and coastal flooding, coastal erosion and cliff retreat, landslides, floods, and forest fires.

In the first stage, the susceptibility assessment was carried out separately for each type of hazardous process, using recognized but heterogeneous technical-scientific methods adjusted to the regional scale and available data. Details on the methods used are provided in the following subsections.

The susceptibility for each hazardous process was re-scaled for the parish level into a scale ranging from 1 to 5, following a set of rules that are described in Sect. 4.

In the second stage, the Analytic Hierarchy Process (AHP) [15, 16] was used to weigh the relative importance of the hazardous processes considered in the study area. The AHP follows three successive steps [15, 16]: (i) decomposition of the problem into criteria; (ii) parity comparative analysis between the criteria by means of a numerical scale; and (iii) synthesis of priorities by means of eigenvector calculation or least square analysis.

The results provided by the AHP were used to weigh the re-scaled susceptibility scores of each individual hazardous process, which were later added together to obtain the multi-hazard susceptibility at the parish level for the complete LMA. These results are presented with five qualitative classes (very high, high, medium, low, and very low) that were established based on the standard deviation method.

2.1 Earthquakes

The seismic hazard in the LMA is generally high due not only to the proximity of active submarine tectonic structures bordering the Portuguese territory to the SW and S, which have the potential to generate the maximum regional earthquakes [5], but also to the fault (or fault zone) of the lower Tagus valley [4].

The Regulation of Safety and Actions for Buildings and Bridge Structures, approved by Decree-law nº235/83 of 31 May, established a seismic risk zoning in mainland Portugal and defined the safety coefficients to be applied in building and bridge constructions in each of the four zones identified. The LMA fits in zone A, which is the highest risk zone.

The seismic susceptibility was defined from the crossing of the isoseismal map of maximum seismic intensity (Modified Mercalli Scale; Source: IPMA) with the Peak Ground Acceleration (PGA) for a return period of 475 years, provided by Peláez and López-Casado [12]. Additionally, the site effects that are likely to produce the amplification of seismic susceptibility were considered, based on two sources: (i) the distribution of unconsolidated sedimentary geological formations, represented in the Geological Map of Portugal at scale 1:500,000 (Source: LNEG); and (ii) 100 m-buffer zones along the active or probably active faults extracted from the Neotectonic Map of Portugal [2].

2.2 Tsunami

The Portuguese coastal zone is exposed to the tsunami hazard associated with earthquake events with epicenter at the sea floor. Destructive earthquake-triggered tsunamis are more probable to be generated in three major regional seismic zones: (i) the Gorringe Bank, SW of Portugal; (ii) active tectonic structures of N-S direction, along the continental margin between Setúbal and Cape S. Vicente; (iii) and the eastern terminus of the Azores-Gibraltar fault, south of the Algarve.

The tsunami susceptibility was assessed with a deterministic approach, using formulas published by Okada [10]. The event of November 1, 1755, is assumed to be the worst-case scenario, with a possible generation source located in the Gorringe Bank [17] and assuming the following earthquake parameters: length = 200 km, width = 80 km, azimuth = 60°, dip angle = 40°, displacement angle = 90°, depth = 8 km, and vertical displacement = 12.1 m.

The tsunami propagation was modeled with the TUNAMI code (Tohoku University, Japan), following the methodology of Imamura [7], in which the equations of the Shallow Water Model are implemented and discretized with the leap-frog finite difference scheme. The model also considers seabed friction, according to the Manning coefficient n = 0.025.

The numerical tsunami model was applied to 5 computational regions; each region is embedded in the previous one, with a smaller area and smaller cell size. Bathymetry data at various scales (GEBCO Digital Atlas, 2003, Nautical charts of the Hydrographic Institute, 2005, 2009, 2012) were used in the construction of each computational region. Computational region 5 is based on topographic maps at scale 1:25,000, which were used to build a detailed digital terrain model (DTM) with a cell size of 25 m. This DTM was used to assess the tsunami flooding along the complete coastal and estuarine zones of the LMA.

The water height associated with the tsunami was classified into 2 classes: 0.1–2 m and more than 2 m, corresponding to tsunami flood susceptibility high and very high, respectively.

2.3 Beach Erosion and Coastal Flooding

The characterization and delimitation of coastal zones experiencing beach erosion and coastal flooding are based on the work promoted by the Portuguese Environment Agency (APA) that supported two Coastal Zone Programmes (Alcobaça-Cabo Espichel and Espichel-Odeceixe).

In the original work, the susceptibility of beach erosion and coastal flooding was assessed for two time periods: 2050 and 2100 [18, 19]. This assessment included the effects of climate change, in particular the rise of mean sea level, together with the future evolution of the coastline, derived from the long-term trend based on the evolution observed in the last 50 years. In addition, the potential for an "instantaneous" retreat of the beach profile (and of the coastline) when acted upon by an extreme storm, with different return periods, was also considered. Therefore, the susceptibility zones combine the cumulative action of the following processes: the long-term shoreline evolution associated with sediment deficit, the retreat due to the ongoing sea-level rise, and the retreat due to storm surge and the wave runup in storm conditions [18, 19]. The retreat zone projected for 2050 was considered of very high susceptibility, while the additional retreat zone for 2100 was considered of high susceptibility.

In the original work of Silva and co-authors [18, 19], the coastal retreat was not classified where beaches are bordered by a cliff or any anthropogenic structure, regardless of the temporal scenario. In these cases, a flood elevation of 8 m above the mean sea level was used as a reference, taking into consideration the mean sea-level variation, the maximum astronomical high tide, the maximum recorded storm surge, and the wave runup. This value is in line with those obtained for the coastal zone of Sintra and Cascais municipalities [8, 20].

2.4 Coastal Erosion and Cliff Retreat

As in the case of beach erosion and coastal flooding, the characterization and delimitation of coastal erosion and cliff retreat are based on research promoted by the Portuguese Environment Agency (APA), which supported the Coastal Zone Programmes Alcobaça-Cabo Espichel and Espichel-Odeceixe [9, 13, 14].

The original work was supported by a systematic inventory of landslides affecting cliffs using photo-interpretation techniques applied to a series of vertical aerial photographs obtained from the late 1940s to 2010 [13]. Moreover, two susceptibility zones adjacent to the cliff crest were defined in the original study, considering the maximum size of landslides affecting each homogeneous cliff sector, together with the geological and geomorphological characteristics of the cliffs [9, 13, 14]. These susceptibility zones were named "I—risk zone" and "II—additional zone", and their extension varies depending on the cliff height (from 0.5 to 2 times the cliff height). In this work, the "I—risk zone" is considered as very highly susceptible to cliff retreat, whereas the "II—additional zone" is considered as highly susceptible to cliff retreat.

2.5 Landslides

The landslide susceptibility was assessed for a larger area bringing together the LMA with three other NUTS III (Oeste, Lezíria do Tejo, and Médio Tejo). The landslide susceptibility modelling was based on the Information Value statistical method [22, 23], using seven landslide predisposing factors: slope, aspect, curvature, topographic position index, topographic humidity index, lithology, and land use. These factors were crossed with a landslide inventory containing 4047 rainfall-triggered landslides. The landslide susceptibility model was validated using the success rate curve and computing the Area Under the Curve (AUC = 0.92).

The landslide susceptibility map contains 5 classes (very high, high, moderate, low, and very low) that were defined based on the slope breaks of the success rate curve of the predictive model, and the corresponding percentage of validated landslide-affected areas is 50, 20, 20, 5, and 5%, respectively.

2.6 Floods

The assessment of flood susceptibility took into consideration the available documentation from previous works, namely (i) the flood areas identified by the Flood Risk Management Plans that were promoted by the Portuguese Environment Agency (APA); (ii) the areas threatened by floods identified by the Regional Framework of the LMA National Ecological Reserve; (iii) the delimitation of the extreme flood that occurred along the Tagus River in February 1979 and the delimitation of the centennial flood in the Sado estuary area, produced by the National Civil Engineering Laboratory (LNEC); (iv) the flood extent in the Tagus estuary proposed by Guerreiro et al. [6], based on hydrodynamic modeling; and (v) a set of areas threatened by floods, outlined at the municipal level within the delimitation of the National Ecological Reserve.

The 100-year return period was considered as the flood reference. Riverine floods were distinguished from flash floods, the former occurring along the main river in the region (Tagus River), the latter occurring in small and medium-sized hydrographic basins. Estuarine floods were also considered separately, namely in the Tagus and Sado rivers.

Estuarine floods are generally triggered by storm surges together with the effect of the tide, whereas riverine floods are typically triggered by rainy periods lasting over several weeks, drastically diminishing the regulating effect of dams, which may potentiate flood peaks with the respective discharges. On the contrary, flash floods occur in hydrographic basins with a short concentration time and in response to episodes of very intense rainfall concentrated in a few hours.

2.7 Forest Fires

The forest fire susceptibility was assessed using a Bayesian-based bivariate statistical method: the Likelihood Ratio (LR), applied to mainland Portugal [11]. The predictive model uses slope, elevation, and land use/land cover as conditioning factors, whereas the dependent variable corresponds to the burnt areas registered in the period 1975–2018. The final expression of forest fire propensity was computed through the product of the LR scores by the simple probability of fire occurrence. The latter was obtained for each 25 m cell size as the ratio between the number of times burned and the total number of years within the burnt area's database (44 years). The forest fire predictive model was validated by computing the success rate curve and estimating the Area Under the Curve (AUC = 0.83). The forest fire susceptibility map contains 5 classes (very high, high, moderate, low, and very low) that were defined based on the slope breaks of the success rate curve of the predictive model [11]. The corresponding percentage of validated burnt areas at the national scale is as follows: 50, 40.6, 6.6, 2.8, and 0%.

3 Single-Hazard Susceptibility Assessment

3.1 Earthquakes

The earthquake susceptibility is shown in Fig. 2 and encompasses 3 classes. The very high susceptibility class covers 20.6% of the LMA and corresponds to the areas with, simultaneously, the seismic intensity of degree IX or X, PGA ranging from 3.2 to 4.0 m/s^2, and the existence of unconsolidated Quaternary deposits and/or active faults. The high susceptibility class covers 38% of the LMA and corresponds to the following

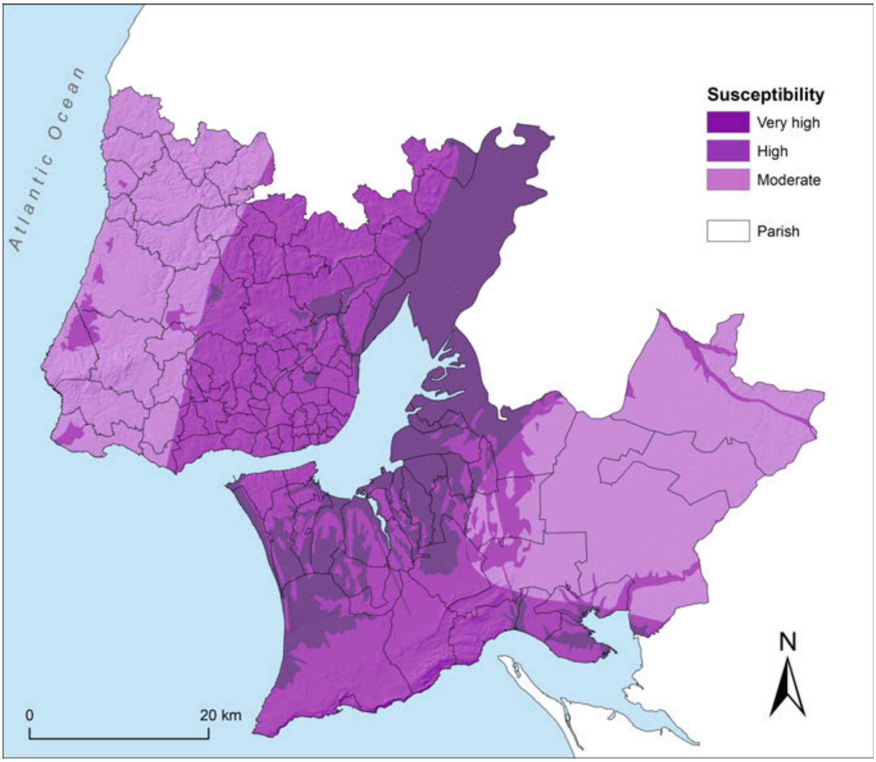

Fig. 2 Earthquake susceptibility in the Lisbon Metropolitan Area

intersections: (i) seismic intensity of degree IX or X + PGA from 3.2 to 4.0 m/s^2; (ii) seismic intensity of degree IX or X + PGA from 2.4 to 3.2 m/s^2 + existence of unconsolidated Quaternary deposits and/or active faults; (iii) seismic intensity of degree VIII + PGA of 3.2 to 4.0 m/s^2 + existence of unconsolidated Quaternary deposits and/or active faults. The moderate susceptibility class covers 41.4% of the LMA and corresponds to the following intersections: (i) seismic intensity of degree IX or X + PGA from 2.4 to 3.2 m/s^2; (ii) seismic intensity of degree VIII + PGA from 3.2 to 4.0 m/s^2; (iii) seismic intensity of degree VIII + PGA from 1.6 to 3.2 m/s^2.

3.2 *Tsunami*

The results of tsunami numerical modeling (Fig. 3) show that the tsunami inundates all beaches in the LMA. Additionally, coastal, riverine, and estuarine areas with elevations less than 3 m a.s.l. show inundation extent up to about 2.5 km. The coastal zone of Costa da Caparica, together with the inner zones of Tagus and Sado estuaries, are the most exposed to the tsunami hazard.

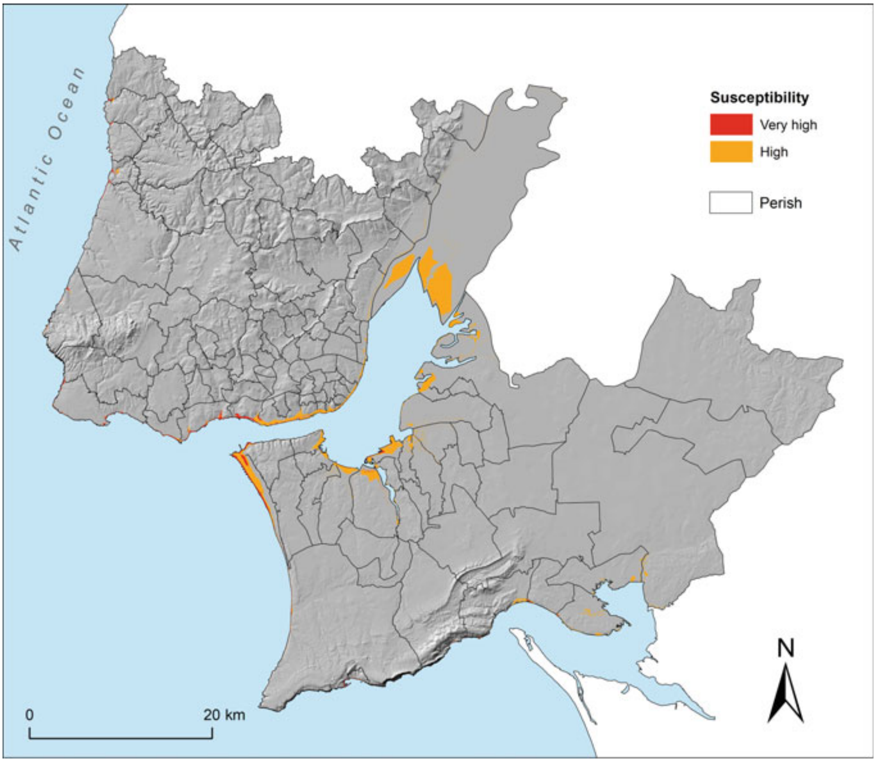

Fig. 3 Tsunami flooding susceptibility in the Lisbon Metropolitan Area

The very high class of tsunami flood susceptibility (water height above 2 m) covers 4.52 km^2, whereas the high susceptibility class (water height ranging from 0.1 to 2 m) covers 43.51 km^2.

3.3 Beach Erosion and Coastal Flooding

The beach erosion and coastal flooding susceptibility in the LMA are shown in Fig. 4. The very high susceptibility class corresponds to the setback line projected for 2050, whereas the high susceptibility class corresponds to the additional area between the previous line and the setback line projected for 2100. The coastal zone between the Meco beach and the Cova do Vapor is the most susceptible to beach erosion and coastal flooding within the LMA.

The very high susceptible zone extends over an area of 2.22 km^2, while the high susceptible zone covers an area of 3.75 km^2.

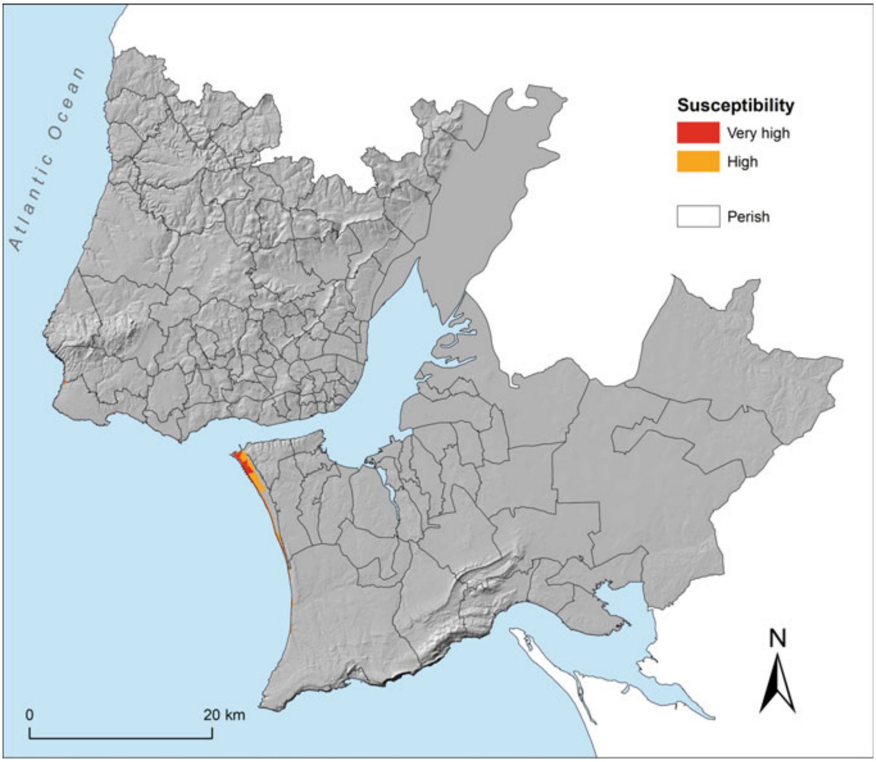

Fig. 4 Beach erosion and coastal flooding susceptibility in the Lisbon Metropolitan Area

3.4 Beach Erosion and Coastal Flooding

The coastal erosion and cliff retreat susceptibility in the LMA are represented in Fig. 5. Besides the identification of the unstable coastal slopes, two susceptibility zones are distinguished: very high and high. The first corresponds to the risky zone adjacent to the cliff crest, while the second reproduces the additional protection zone, as defined in the Coastal Zone Programmes. Figure 5 also represents the zone adjacent to the cliff bottom that is susceptible to the propagation of slope movements originating from the cliff.

The unstable coastal slopes cover an area of 4.74 km^2. The very high susceptible zone follows the cliff crest and extends over 7.13 km^2, while the high susceptible zone covers an area slightly smaller (5.92 km^2). The zone of potential impact adjacent to the cliff bottom covers 2.45 km^2 and extends to the sea floor in many areas, like on the Arrábida coast.

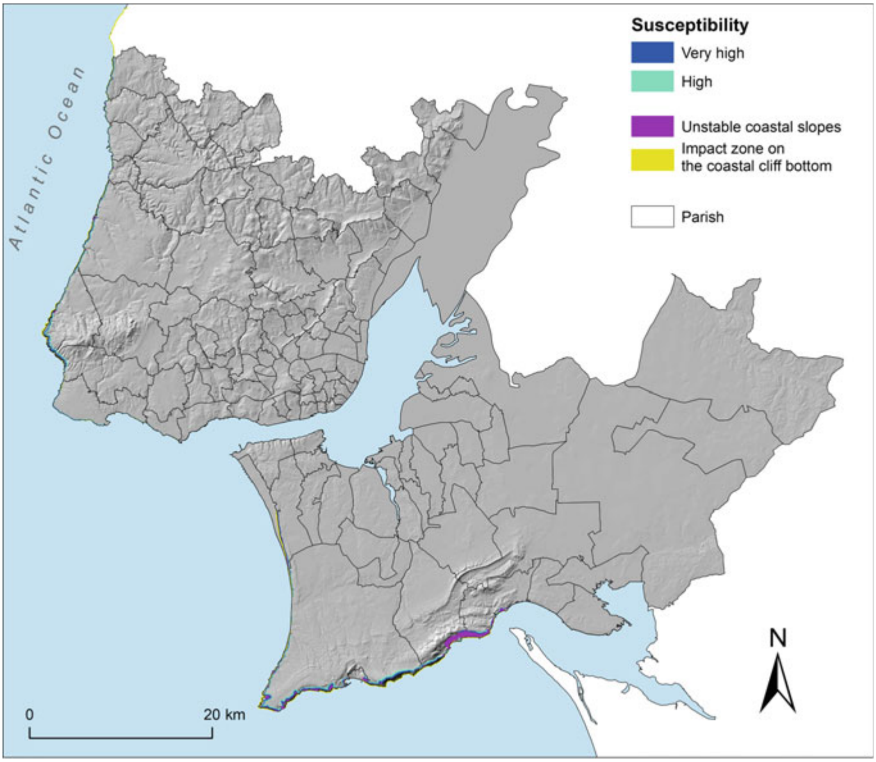

Fig. 5 Coastal erosion and cliff retreat susceptibility in the Lisbon Metropolitan Area

3.5 Landslides

Figure 6 illustrates the distribution of the landslide susceptibility in the LMA, which is highest along the Arrábida chain and in the hilly landscape located north of Lisbon. The very high susceptibility class validates 50% of the landslide inventory and covers 6.7% of the LMA, while the high susceptibility class validates 20% of the landslide inventory and extends over 4.9% of the study area. The moderate susceptibility class covers 7.8% of the LMA and the two lowest susceptibility classes cover, together, 80.6% of the total surface in the LMA.

3.6 Floods

The areas susceptible to flooding cover 444.78 km^2 in the LMA (Fig. 7), most of which correspond to estuarine flooding in the Tagus and Sado estuaries (179.14 km^2, 40.3%). The area susceptible to riverine flooding occurs along the lower Tagus valley

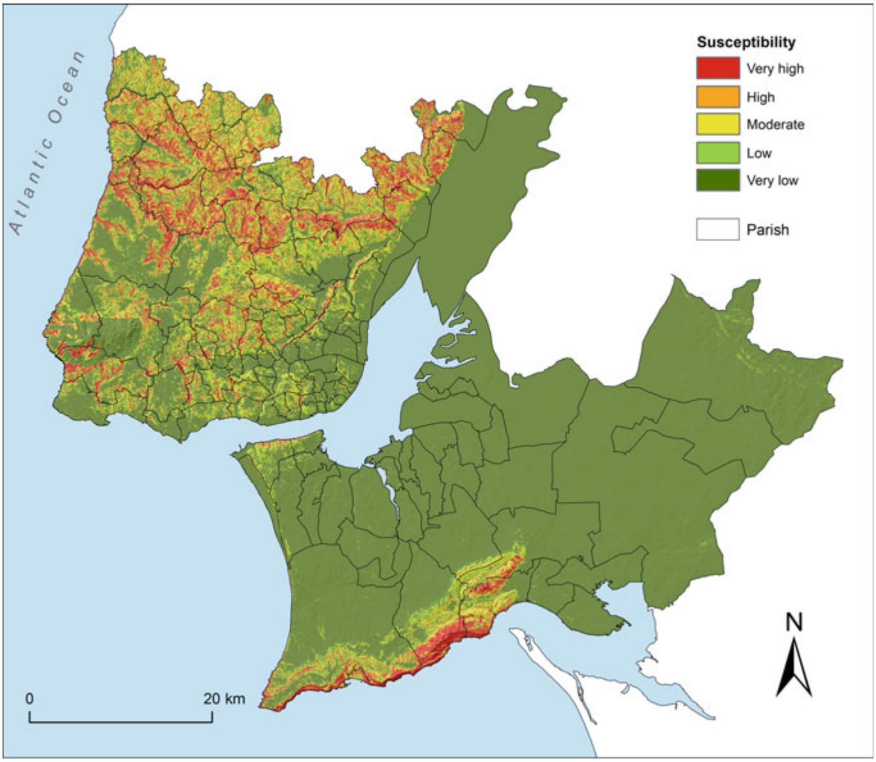

Fig. 6 Landslide susceptibility in the Lisbon Metropolitan Area

and corresponds to 32.5% (144.28 km^2) of the total flood susceptible area. The areas susceptible to flash flood cover 121.36 km^2 (27.3% of the total flood susceptible area).

3.7 Forest Fires

Figure 8 illustrates the distribution of forest fire susceptibility in the LMA. Artificialized areas, wetlands, and water bodies are not exposed to this hazard and were not classified. The forest fire susceptibility is highest along the Arrábida chain, the Sintra mountain, and the hilly zones of Mafra and Loures. The highest susceptibility classes (very high and high) have a small territorial expression (1.6 and 9.5% of the total classified area, respectively). The moderate susceptibility class covers 15.2% of the area, whereas the two lowest susceptibility classes cover together 73.7% of the total classified area.

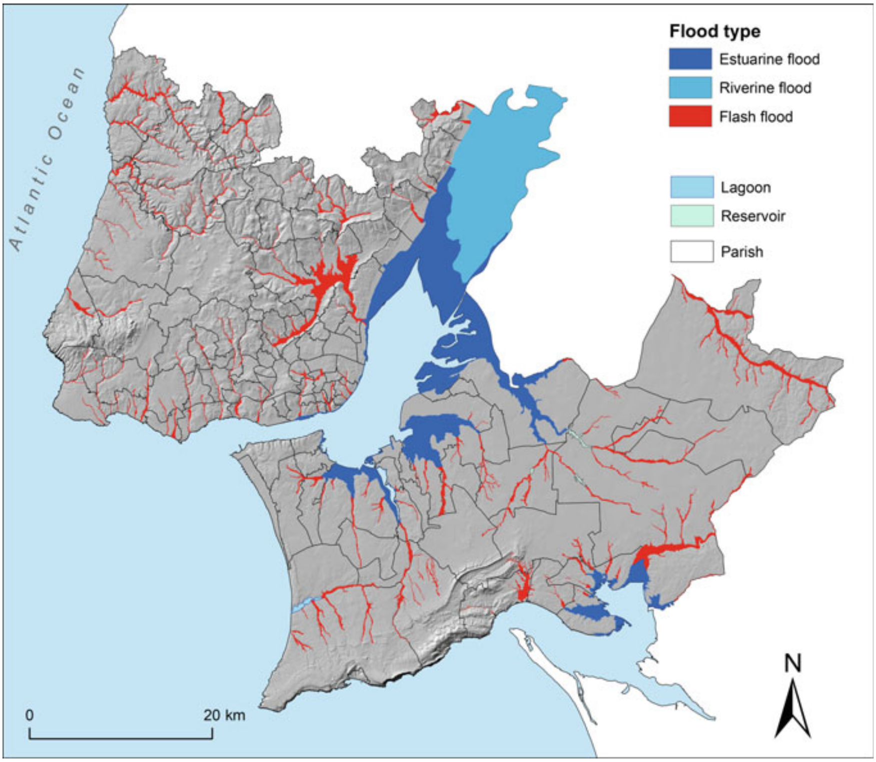

Fig. 7 Flood susceptibility in the Lisbon Metropolitan Area

4 Multi-hazard Susceptibility Assessment

Fig. 9 represents the multi-hazard susceptibility zoning of the Lisbon Metropolitan Area showing in superposition:

1. The three earthquake susceptibility zones that constitute the background of the map;
2. The areas subjected to tsunami flooding (susceptibility very high + high);
3. The areas subjected to beach erosion and coastal flooding (susceptibility very high + high);
4. The areas subjected to coastal erosion and cliff retreat (susceptibility very high + high + unstable coastal slopes + impact zones on the coastal cliff bottom);
5. The most susceptible areas to landslide occurrence (susceptibility very high + high);
6. The areas susceptible to floods (estuarine, riverine, and flash floods);
7. The most susceptible areas to forest fire occurrence (susceptibility very high + high).

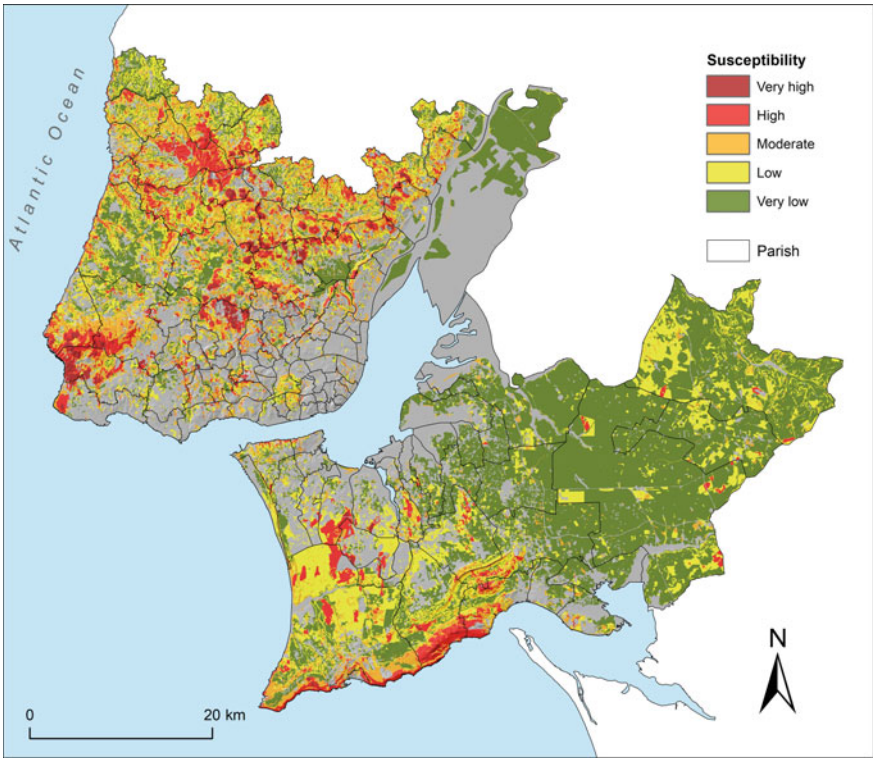

Fig. 8 Forest fire susceptibility in the Lisbon Metropolitan Area

The layers contained in the multi-hazard map were used to re-scale the susceptibility for the parish level into a scale ranging from 0 to 5, based on the territorial expression of each hazard and respecting the rules described in Table 1.

Table 2 summarizes the weighting of the considered seven hazard processes, based on the Analytic Hierarchy Process. The AHP was performed during a brainstorm involving all the authors of this chapter and considered the typical frequency-magnitude relationship of each process as well as the corresponding damage capacity.

Three processes stand out as the most important, namely for spatial planning purposes: earthquakes, floods, and beach erosion and coastal flooding. In the following position of the ranking, three other processes were identified: coastal erosion and cliff retreat, landslides, and forest fires. Tsunami has the lowest ranking, essentially due to its low probability of occurrence.

Figure 10 shows the multi-hazard susceptibility obtained for each parish by adding the susceptibility scores of Table 1 that were weighted with values of Table 2. The five susceptibility classes were defined using the standard deviation method.

Eleven parishes exhibit a very high multi-hazard index, having in common a high earthquake susceptibility score (4 or 5). The Costa da Caparica (parish ID: 19)

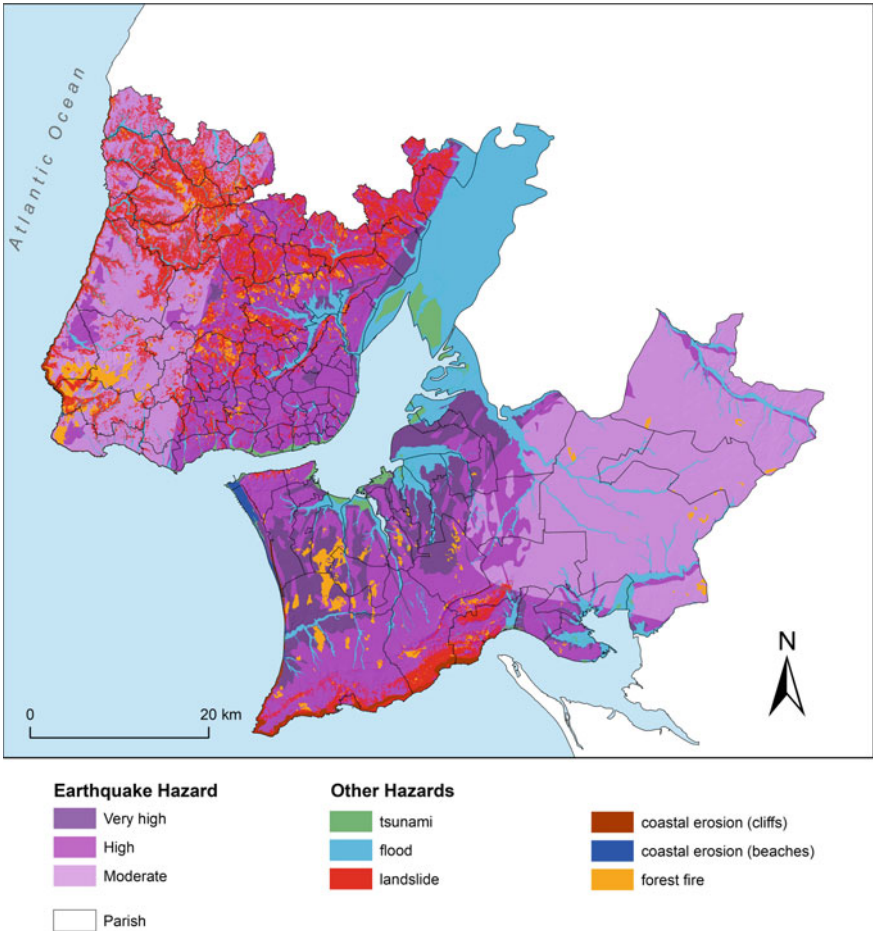

Fig. 9 Multi-hazard susceptibility in the Lisbon Metropolitan Area

registers the highest multi-hazard index, essentially due to the high susceptibility scores associated with earthquake, tsunami, beach erosion, and coastal flooding. The Arrábida territory, in the southern part of LMA, includes 4 parishes covered by the very high multi-hazard index class (Sesimbra-Castelo (ID: 6), Azeitão (ID:7), Setúbal (ID:3), and Sado (ID:2)), essentially due to the combination of the following hazards: earthquake, tsunami, flood, landslide and coastal erosion, and cliff retreat. Also, the Tagus estuary includes 4 parishes in this multi-hazard class (Samouco (ID:46), Alcochete (ID:86), Vila Franca de Xira (ID: 116), and Baixa da Banheira-Amoreira (ID: 24)), due to earthquake, tsunami, and floods. Finally, the very high multi-hazard index class covers 2 parishes north of the Tagus River: Cachoeiras (ID: 113) and S. António dos Cavaleiros-Frielas (ID: 89). The former is explained by the

Table 1 Rules to re-scale hazard susceptibility for the parish level

Hazard process	Susceptibility score	Rule (SA: Susceptible area)
Earthquakes	5	Very high class > 50% of parish surface or very high class > 35% and moderate class absent
	4	High class > 50% and very high class < 35% of parish surface, and moderate class is absent
	3	Moderate class = 50–90% of parish surface
	2	Moderate class > 90% of parish surface
Tsunami	5	SA > 100 ha or SA > 10% of parish surface
	4	SA = 40–100 ha or SA = 5–10% of parish surface
	3	SA = 20–40 ha or SA = 2–5% of parish surface
	2	SA < 20 ha or SA < 2% of parish surface
Beach erosion and coastal flooding	5	SA > 200 ha
	4	SA = 50–200 ha
	3	SA = 10–50 ha
	2	SA = 1–10 ha
	1	SA < 1 ha
Coastal erosion and cliff retreat	5	SA > 200 ha
	4	SA = 100–200 ha
	3	SA = 50–100 ha
	2	SA = 10–50 ha
	1	SA < 10 ha
Landslides	5	SA > 20% of parish surface
	4	SA = 10–20% of parish surface
	3	SA = 5–10% of parish surface
	2	SA = 0–5% of parish surface
	1	SA = 0% of parish surface
Floods	5	SA > 30% of parish surface
	4	SA = 20–30% of parish surface
	3	SA = 10–20% of parish surface
	2	SA = 5–10% of parish surface
	1	SA = 0–5% of parish surface
Forest fires	5	SA > 20% of parish surface

(continued)

Table 1 (continued)

Hazard process	Susceptibility score	Rule (SA: Susceptible area)
	4	SA = 10–20% of parish surface
	3	SA = 5–10% of parish surface
	2	SA = 0–5% of parish surface
	1	SA = 0% of parish surface

Table 2 Weighting of hazard processes considered in the Lisbon Metropolitan Area based on Analytic Hierarchy Process (AHP)

Hazard process	Weight
Earthquakes	0.234
Tsunamis	0.050
Beach erosion and coastal flooding	0.234
Coastal erosion and cliff retreat	0.083
Landslides	0.083
Floods	0.234
Forest fires	0.083

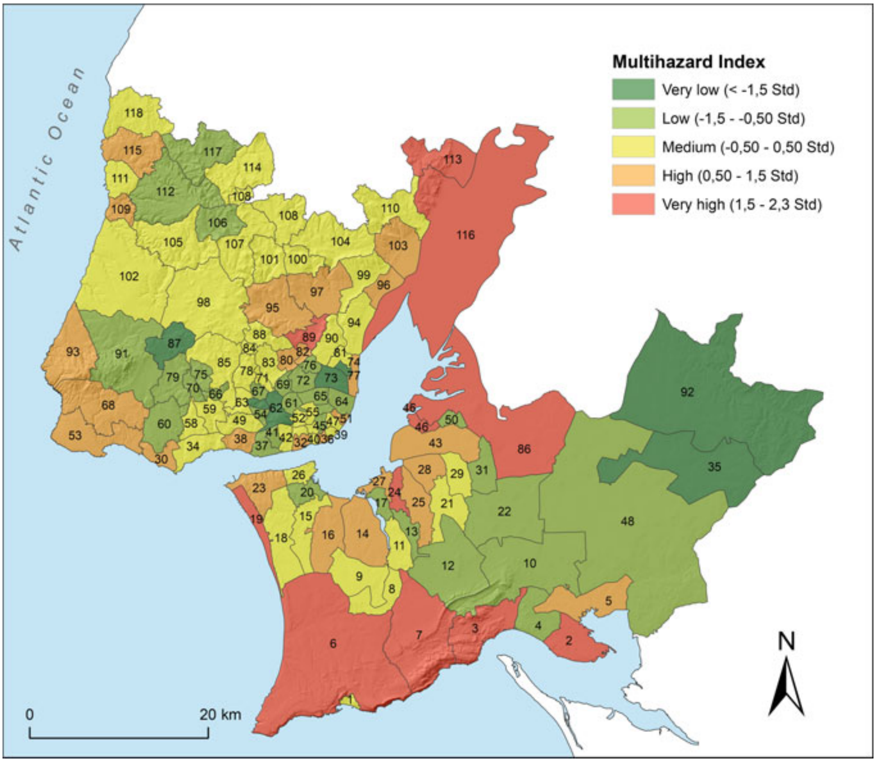

Fig. 10 Multi-hazard susceptibility in parishes belonging to the Lisbon Metropolitan Area. Numbers represent the parish ID

high susceptibility scores of floods and landslides, whereas the latter is explained by forest fire together with floods and landslides.

In opposite condition, 7 parishes exhibit a very low multi-hazard index, having in common the location far from the coast and the geographic position in the upper part of hydrographic basins, which explains the low susceptibility to floods: Algueirão-Mem Martins (ID: 87), Águas Livres (ID: 57), Benfica (ID: 62), Olivais (ID: 73), Moscavide and Portela (ID: 74), Canha (ID: 92), and Pegões (ID: 35).

5 Final Remarks

This work assessed the susceptibility to the occurrence of 7 natural and environmental hazards in the Lisbon Metropolitan Area. The susceptibility zonation maps were crossed with the 118 parishes that constitute the LMA, which were used as reference terrain units. Therefore, the susceptibility of occurrence of each hazard in each parish was re-classified on a scale of susceptibility scores (from 1 to 5), based on the territorial fraction of the parish exposed to that hazard.

The multi-hazard susceptibility of each parish resulted from the sum of the susceptibility scores, weighted based on an AHP, which valued essentially three physical processes: earthquakes, floods, and beach erosion and coastal flooding. Hence, the results of the multi-hazard susceptibility at the parish level is influenced by the decisions taken in the AHP.

All the parishes exhibiting very high multi-hazard susceptibility index have high earthquake susceptibility. In addition, with only two exceptions, these parishes are located in riverine or coastal zones, thus subjected to floods and/or coastal erosion (affecting beaches and/or cliffs). On the other hand, parishes with low and very low multi-hazard susceptibility index are typically located in the inner part of the LMA, in the upper part of small watersheds, thus less exposed to floods and coastal erosion.

The Lisbon Metropolitan Area is subjected to natural and environmental hazards, and some highly susceptible zones are densely inhabited and include important economic activities and critical infrastructures. In these circumstances, the obtained results should be considered by land use planning stakeholders and decision-makers in order to prevent the use of hazardous zones and mitigate existing risks.

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