

Chapter 4

Flood Risk Assessment in the Lisbon Metropolitan Area



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Abstract Flood processes are one of the most challenging to risk assessment and management. In many situations, peak flows are generated kilometers away from the places where inundation is observed. Scale in flood risk assessments is a fundamental factor when estimating hazard, exposure, and vulnerability. Municipal, civil parish, and building-level information are used to construct flood risk indexes and profiles. It is observed that, depending on the scale at which it is represented, the same root information provides distinct insights into flood risk expression in the Lisbon Metropolitan Area. When compared with the Flood Directive critical areas, the results show they are mostly consistent with the results at the different scales, identifying the same hotspots of flood risk (in the Loures, V. F. Xira, and Setúbal municipalities) as those selected during the Directive's implementation. Flood loss reduction implies the involvement of distinct risk practitioners and decision-makers, acting at distinct scales and sectors related to risk governance. Interconnections between flood risk components and between flood processes and other potential cascading processes are still insufficiently known and require the priority of society.

Keywords Flood risk assessment · Flood hazard · Flood risk index · Flood vulnerability · Metropolitan scale

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1 Introduction

Small and frequent flood disasters, along with catastrophic and rare events, continue to affect our environmental and socioeconomic living, despite the advances in spatial planning, engineering solutions, monitoring, and early warning systems [29]. As in many other processes, in regard to floods, nature explains only partly the degree of damage observed [22].

Extreme hydrological phenomena, especially river flooding, are considered one of the most important disasters induced by natural processes in Europe in terms of economic losses [6, 19]. Moreover, it is increasingly accepted that global warming modifies the hydrological cycle and increases the occurrence and frequency of flood events in several regions of this continent and worldwide [6].

In 2007, the European Union assumed a new and uniform framework for the assessment and management of flood risks for all its member states. This framework, defined in Directive 2007/60/EC of the European Parliament and Council of 23 October, and transposed into the Portuguese national law by Decree-Law No. 115/2010 of 22 October, introduces a set of challenges to which the scientific community cannot and must not be oblivious.

The approved framework highlights the importance of flood risk mapping, from which the respective management plans (Flood Risk Management Plans—FRMP) are defined. The challenges posed by the development of these planning instruments—the choice of non-structural measures, the possibility of controlled flooding, the scale of analysis adopted, and the linkage with land use plans and civil protection emergency plans—demonstrate the relevance of flood risk studies that bring detailed and comprehensive knowledge, allowing a better connection between the risk assessment and management processes, framed in risk governance models [4].

Conceptual models of risk usually consider the hazard, exposure, and vulnerability components ([7, 24]). In the past, although implicit, exposure was not always considered an autonomous risk component [21, 30, 32]. In flood risk studies within the climate change community until recently, exposure was considered in risk models as a subcomponent of vulnerability [5, 25, 33]. Some risk models incorporate the societal and institutional dimensions of the capacity to cope and adapt to threats [14], for instance).

For the sake of homogeneous applicability in the entire European Union, the vulnerability concept is absent in the Flood Directive. In fact, although being an invaluable concept in risk analysis (IPCC, 2022, WG II), a recent study in Northern Portugal demonstrated that flood damage databases are spatially more correlated with areas of high hazard and exposure than to areas of high vulnerability [26].

Apart from the conceptual dynamics in flood risk analysis, the scale of assessments was and still is an important aspect to consider. Different scales require different data and methods, while the intents of the produced analysis also influence the methodologies to adopt [20]. Consistency and accuracy of results are the more concerning issues when flood risk is compared across scales. Vulnerability and flood protection representation is a critical aspect of national and global flood risk analysis [20]. Global

datasets provided by global Earth observation systems and more powerful computational capacity seem to be shortening, or concealing, some of the constraints imposed by scale, thus allowing for increasingly detailed flood risk analysis to be produced to vaster areas, i.e., smaller scales [2, 12, 15, 31].

In the context of the MIT-RSC project, flood risk was evaluated at distinct scales of analysis aiming to produce distinct risk products. The effect of scale in flood risk assessment was considered a key factor in the representation of results, as they are required by the several stakeholders involved in flood risk governance, at the distinct geographical, administrative, and sectorial levels.

In this chapter, a municipal, a civil parish, and a building-level assessment of flood risk was carried out using scale-specific input data expressing hazard, exposure, physical vulnerability of buildings, and social vulnerability of the resident population. The aim is to contribute to this research area by providing insights into the constraints, particularities, and significance of spatial scale in the design of flood risk indexes.

2 Study Area

The Lisbon Metropolitan Area (LMA) is a statistical and administrative entity that comprises an area of 3,105 km² and 2,813,000 inhabitants (27% of the Portuguese population). The LMA is geographically highly contrasting: dense urban areas near the capital city of Lisbon and along the main road and rail network, contrast with vast areas corresponding to legally protected areas (Tagus and Sado estuaries, Arrábida and Sintra's mountains) and forestry and farmland areas mainly in the southern municipalities of the LMA.

The work developed under the implementation of the Flood Directive identified four areas of significant potential flood risk (ASPFR) in the Lisbon Metropolitan Area (LMA). The 2nd implementation cycle adds a few more, although data is still not available. One of the ASPFR is subject to slow onset flooding, and three areas are subject to flash flooding (Fig. 1):

- Abrantes-Tagus estuary: fluvial, slow onset flooding affecting the Tagus river and part of its estuary covering, in the LMA, the municipality of V.F. Xira;
- Loures-Odivelas: fluvial flash flooding in the Trancão river, a tributary of the Tagus river, covering the homonymous municipalities;
- Torres Vedras: fluvial flash flooding in the Pequeno river (a small tributary in the Mafra municipality, belonging to the Sizandro river basin);
- Setúbal: fluvial flash flooding in the Livramento stream, affecting the Setúbal municipality.

When addressing hazards such as floods, which particularly affect floodplains and some urban areas, the scale of representation of risk components (hazard, exposure, and vulnerability) is of major importance. Figure 2a and b highlights that representing exposed elements as the resident population at an intermediate level like the civil

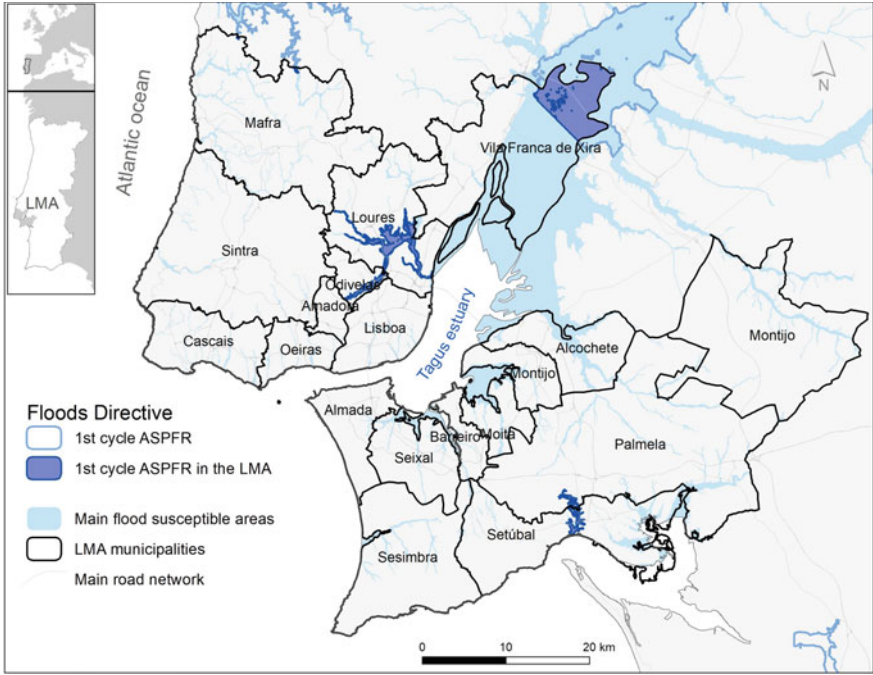


Fig. 1 Municipalities of the Lisbon Metropolitan area and the flood directive’s areas of significant potential flood risk

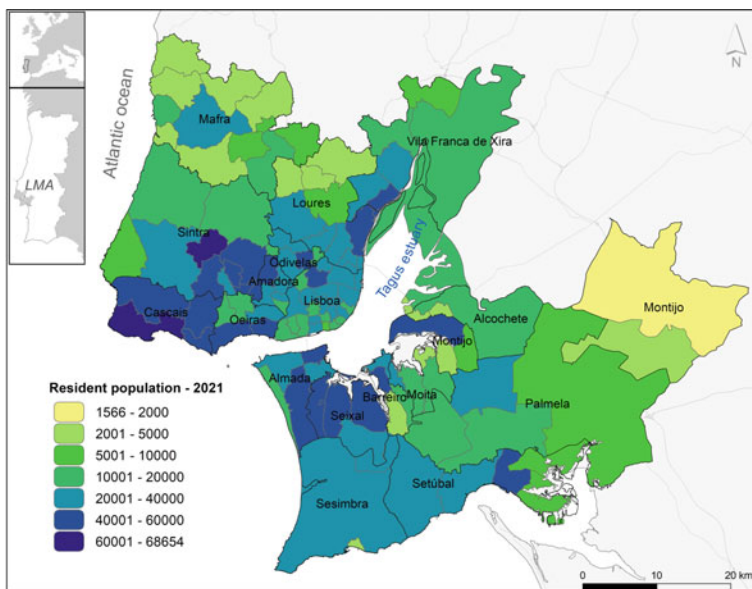
parish conceals the local hotspot of urban concentration that is only visible at the census statistical block level.

3 Methodology

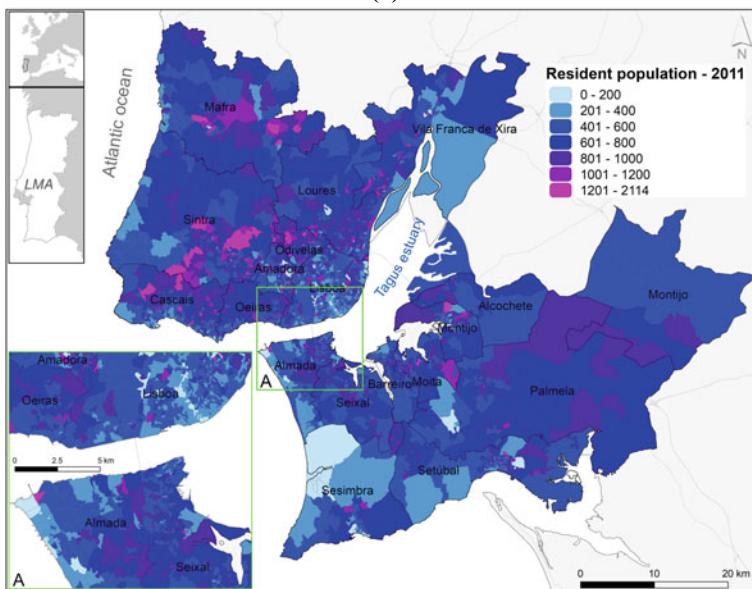
3.1 Hazard Assessment

3.1.1 Municipal Level

Flood hazard was evaluated at the municipal level (*Mun_H*) considering five parameters: maximum flood event recorded (H1), which represents the maximum historical event registered in the last 150 years considering the DISASTER database [34], frequent flood event (H2), representing the total amount of events recorded in the database, and occurred in a given municipality independently of the degree of loss (very often, the cumulative effects of a frequent event can be more impacting in the long term than low probability/high consequence events); annual exceedance probability of the maximum flood event recorded in all the 18 municipalities (H3); annual



(a)



(b)

Fig. 2 Resident population expressed at the civil parish (a) and Census statistical block (b)

exceedance probability of the frequent flood events in the LMA (H4); and spatial scale of the assessment, which measures the impact scale of flood hazard within the entire municipality (H5). Data sources express both the susceptibility, magnitude, and recurrence of floods. All five parameters are represented at the municipal level. A weighted mean valuing H5 with 40% of the weight and assigning 15% to the remaining four parameters was calculated and normalized by the min–max method to the range [0, 1].

3.1.2 Civil Parish Level

At the civil parish level, flood hazard (CP_{FH}) was assessed considering the flood-susceptible areas identified using a more straightforward approach based on historical data, geomorphological interpretation of topographical maps, and satellite imagery.

Historical data consisted of available documentation from previous works, namely: (i) the areas threatened by floods delimited within the Regional Framework of the LMA National Ecological Reserve; (ii) the floodable areas defined in the Flood Risk Management Plans, made available by the Portuguese Environment Agency [3], (iii) the delimitation of the flood associated with the 1979 Tagus River flood and the delimitation of the centennial flood in the Sado estuary area, produced by the National Civil Engineering Laboratory (LNEC); and (iv) a set of flood-threatened areas delineated at the municipal level, within the scope of the National Ecological Reserve delimitation. Ponds and reservoirs were also identified as permanent water bodies. As regards flood processes, slow onset flood situations were distinguished, associated with the main watercourses in the region (e.g., Tagus River), from cases of flash floods, which occur in small and medium hydrographic basins.

After compiling the flood-susceptible polygons, a simple proportion of that area within the entire civil parish area was calculated and expressed in %, later normalized by the min–max method to the range [0, 1].

3.1.3 Building Level

At the building level, the approach differs significantly from the previous ones. Flood extent, height, and velocity were obtained from 2-D hydraulic modeling [3] performed within the implementation of the Flood Directive. Results were validated with historical marks and georeferencing from flood damage databases. Data is available from the APA's webGIS for the four ASPFR existing in the LMA and presented above.

The buildings' database (BGE) is sourced from the Statistics Portugal database regarding the 2011 population Census. Each building was assigned a flood depth and velocity, considering the mean value in a search radius of 10 m from the point feature.

Clusters of buildings were obtained by running first a Two-Step Cluster Analysis in SPSS©, testing 2–10 clustering solutions with Schwarz's Bayesian Criterion

(BIC). The statistical individuals are the 2766 buildings located in the four ASPFR. The variables considered were the physical vulnerability scores, flood depths, and velocities per building.

3.2 *Exposure Assessment*

The methodology for representing flood exposure at the municipal, civil parish, and building level makes use of the same input data—the Georeferenced Buildings Database (BGE) mentioned above. In fact, this detailed layer of geographical information exists uniformly for the entire LMA.

The exposure module identifies and characterizes the exposed elements in each polygonal unit of analysis (municipality and civil parish), focusing on the residential buildings—approx. 450,000 points of the BGE—and resident population, taken from the Geographic Base for Information Referencing (BGRI, both obtained from Statistics Portugal). The dasymetric distribution of the resident population by buildings with a total or partial residential function was performed [8]. The refinement of exposure to flooding was done by quantifying the number of buildings and respective inhabitants within flood-susceptible areas (the same ones used to define the flood hazard parameter H5), by municipality and by civil parish.

At the municipal level, a transformation to the range [0, 1] was done accounting for the maximum (1813 buildings in the Lisboa municipality) and minimum (5 buildings in the Sesimbra municipality) number of buildings exposed to flooding. This procedure defines municipal buildings' exposure. A similar approach is applied to the resident population (a maximum of 17,675 in Lisboa, and a minimum of 4 in Sesimbra), resulting in a transformation of population exposure to flooding between 0 and 1. A weight of 0.25 was assigned to buildings and 0.75 to population, of which sum results in the final exposure, also ranging [0, 1].

At the civil parish level, the same method was followed. In order to avoid the absorbing effect of zero on the multiplication, scores of 0 were replaced by 0.0001 except in the cases where there's no flood susceptibility or no buildings within susceptible areas.

At the building level, exposure was assessed only in ASPFR polygons. Inside each of the four ASPFR polygons, the number of residents (the one resulting from the dasymetric distribution) and the number of buildings were summed and later converted to the range [0, 1].

3.3 *Buildings' Physical Vulnerability Assessment*

The assessment of the physical vulnerability of buildings (*PhyV*) uses as input data the variables' values collected during the 2011 Census operation. As presented, this data is part of the BGE database which comprises 14 variables describing the

buildings' characteristics. From the set of BGE's 14 variables, 6 were used to assess the physical vulnerability of buildings (Table 1), to which one other (P5) was added from geological and soil characteristics.

The table describes the theoretical and empirical basis that supports both the selection of parameters and their role in increasing or decreasing vulnerability (Table 1).

Table 1 Parameters adopted to represent the physical vulnerability of buildings, their rationale, and supporting academic literature

Parameters		Argumentation/Rationale	Sources
P1	Period of construction	The building age is linked to the building condition (similar to parameter P7). It is considered a common indicator revealing different construction techniques and materials. Therefore, it is ranked as less important to flood vulnerability compared to other parameters	Agliata et al. [1], Pereira et al. [10], Leal et al. [11] and Kappes et al. [23]
P2	No. stories ^a	1. The taller the building, the deeper the foundation and the less prone to be damaged by flooding 2. The taller the building, the more vulnerable to flooding and susceptible to differential settlements considering poor ground conditions and/or shallow footings	1. Agliata et al. [1], Kappes et al. [10], Pereira et al. [23] 2. Miranda and Ferreira [18], Stephenson and D' Ayala [28]
P3	Material-Ext. cladding	The absorption of the cladding material directly affects the building fabric resulting in a direct impact on the building's susceptibility	Common knowledge and Leal et al. [11] and Kappes et al. [10]
P4	Material-Str. system	Depending the type of external cladding material and its absorption, it will affect directly the building fabric. Hence, it is directly related to the building's susceptibility to flooding impact	Common knowledge and Leal et al. [11] and Kappes et al. [10]
P5	Soil classification	The type of soil has a direct impact on the foundations and scour due to flooding	Common knowledge/empirically
P6	Building exposure	This is related to the position of the building and its exposure. It is considered less significant to flooding given the level of uncertainty compared to other indicators	Agliata et al. [1], Kappes et al. [10]

(continued)

Table 1 (continued)

Parameters		Argumentation/Rationale	Sources
P7	Repair Req/condition ^b	Existing condition and maintenance status of a building is linked directly with the building fabric material, as per parameter P3. Hence, parameter P7 is also considered a key influence factor	Agliata et al. [1], Kappes et al. [10], Silva and Pereira 27, Stephenson and D’Ayala [28]

^a Most debated indicator as experts interpret and use it in different ways depending on what building feature and behavior they intend to describe with it [1]

^b Most used indicator reflecting the capacity of construction to resist flood impact

It also provides an overview of the weighting (i.e., importance factor) of parameters that contribute to the building’s potential (i.e., resistance capacity of the building) to withstand a flood impact.

The vulnerability assessment to flooding considers the period of construction (P1), the number of stories (P2), the material of the external cladding (P3), the material of the structural system (P4), soil/lithological substrate (P5), building exposure (P6), and building condition (P7) (see Fig. 3). Each parameter is then evaluated using four vulnerability classes A to D, where A represents the least vulnerable condition, and D represents the most vulnerable one.

The physical vulnerability of buildings to flooding (*PhyV*) method is based on the estimation of an index for each building as the weighted sum of a set of seven parameters, as listed above, using Eq. 1. For easier interpretation of results and integration with hazard and exposure results, *PhyV* scores were normalized to the

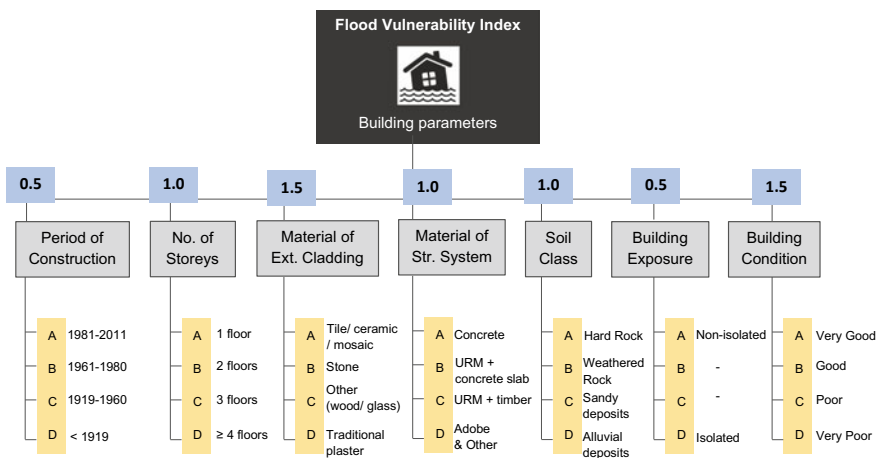


Fig. 3 Parameters, properties, and respective weights used in the assessment of buildings’ physical vulnerability to flooding

range [0, 1] using the min–max method.

$$PhyV = \sum_{p=1}^7 (C_p \times W_p) \quad (1)$$

where C_p is the score assigned through classes A to D in each parameter p , and W_p is the weight assigned in each parameter p .

3.4 Social Vulnerability

Social vulnerability (*SocV*) was evaluated for the entire LMA using the Census statistical block level and is the result of the product of criticality (*Cr*) and support capability (*SC*) [17], as formulated in Eq. 2.

$$SocV = Cr \times (1 - SC) \quad (2)$$

In the LMA there are 4521 statistical blocks. The proposed method incorporates not only the individual characteristics of the population and risk groups as it also considers the territorial context in which they are supported, i.e., the public and private equipment, infrastructure, and services that might play a role in attenuating losses and enhancing recovery [16].

Criticality (*Cr*) expresses the characteristics of individuals that make them prone to loss, considering their age, socioeconomic condition, health and housing conditions, social assistance, mobility, educational level, and employment. Support capability (*SC*) expresses the set of systems, networks, public and private infrastructures, and collective equipment aimed at supporting communities and their activities, which—in the eminence or occurrence of a dangerous process—make it possible to reinforce a community’s capacity to mitigate and/or recover from a hazardous event. Common dimensions covered are the economic dynamism, the coverage by social equipment (for example, health centers), civil protection resources, and public and private businesses that provide essential goods and mobility. For each of these components, a principal component analysis is performed, and interactively, the most robust and interpretable set of variables is selected, from which principal component (PC) scores are extracted. Those scores are summed according to the weights provided by the percentage of variance explained by each principal component. Prior to the application of Eq. 2, the final criticality and support capability scores were linearly transformed to the range [0, 1]. For a detailed description of variables and methods, please refer to Chap. 3.

3.5 Risk Analysis

At the municipal level, municipal flood risk (Mun_{FR}) was calculated as follows (Eq. 3):

$$Mun_{FR} = Mun_{FH}^{1/3} \times Mun_E^{1/3} \times Mun_{PhyV}^{1/3} \quad (3)$$

where Mun_{FH} is the municipal flood hazard, Mun_E is the municipal exposure, and Mun_{PhyV} is the municipal physical vulnerability of buildings.

At the civil parish level, flood risk was calculated using the physical vulnerability of buildings on one side and the criticality (Cr) of social vulnerability on the other. Civil parish flood risk using criticality is calculated as follows (Eq. 4):

$$CP_{FR_Cr} = CP_{FH}^{1/3} \times CP_E^{1/3} \times CP_{Cr}^{1/3} \quad (4)$$

Civil parish flood risk using physical vulnerability (CP_{FR_PhyV}) is calculated as follows (Eq. 5):

$$CP_{FR_PhyV} = CP_{FH}^{1/3} \times CP_E^{1/3} \times CP_{PhyV}^{1/3} \quad (5)$$

Like in the municipal level analysis, all scores expressing hazard, exposure, and vulnerability are normalized to the range [0, 1] before the INFORM alike formulation is applied by calculating the product of the power of each component to 1/3.

Building-level flood risk was assessed using a cluster analysis that provides flood risk profiles. For each of the 2766 buildings located in the four ASPFR, a cluster membership is calculated that considers the hazard (flood depth and velocity) and the physical vulnerability ($PhyV$) scores as described in Sect. 2.3.

4 Results

4.1 Municipal Level

Flood hazard in the LMA is significantly conditioned by the Tagus river floodplain, the Tagus estuary, and the small watersheds that drain to the Tagus, directly to the Atlantic ocean or to the municipalities outside the LMA. The maximum flood event (H1) in each municipality differs, although two events stand out: the flash floods of November 1967 and November 1983, which mostly impacted the municipalities of V.F. Xira, Loures, Odivelas, and Oeiras (Fig. 4). Adding to these municipalities, the higher scores in regard to the frequent events (H2) include the district capitals of Lisbon and Setúbal, as well as Almada and Mafra. Parameter H3 assumes the major of the maximum events could, theoretically, have affected evenly any of the

18 municipalities. For this reason, an equal score was assigned to all municipalities with a low probability event [13]. The same principle was applied to the probability of the frequent event in parameter H4. Finally, H5 highlights the municipalities of V.F. Xira, Odivelas, and Loures due to the highest proportion of flood-susceptible areas in the corresponding territory (60.4, 11.5, and 11.1%, respectively). These four municipalities and Oeiras are characterized by a very high and high flood hazard (Fig. 4) as a result of a high spatial propensity and historical record of floods, either with a high magnitude or a high degree of loss. Exposure is higher in the most urbanized municipalities, and it is linked to the occupation of the small streams valley floors, particularly in Lisbon, Odivelas, and Setúbal (Table 2). Globally, 2.5% of the LMA residents live in flood-susceptible areas. When exposure is combined with the physical vulnerability of buildings, it becomes more evident where the most critical contexts for potential flood losses are located. The mean PV in the AML is 0.35, with maximum average values of 0.50 in Lisbon and 0.44 in Setúbal. Nevertheless, a detailed analysis of PV needs to consider each parameter individually; this is because, for example, the general condition of the buildings (Table 1)—as it was recorded in the Census—may not be concerning, but other parameters like lithological substrate, the material of the external cladding, and structural system do act as stronger drivers of physical vulnerability.

When analyzing the hazard and risk index, mapped, respectively, in Fig. 4 and Fig. 5, it is interesting to see that when $PhyV$ is included in the analysis, it considerably changes the results obtained for the hazard alone. This is very clear for the municipality of Setúbal, which stands out strikingly in the risk map in Fig. 5, but not in the hazard maps provided in Fig. 4. In fact, analyzing the proportion of the risk index that is explained by the hazard score, it represents less than $\frac{1}{4}$ of the final risk index, while exposure (in brown) and vulnerability (in violet) represent the vast proportion of the risk components. It should be highlighted that E and $PhyV$ were only accounted for within the flood-susceptible areas. In the opposite case, the municipality of Loures, previously assigned a very high hazard Index, drops to an intermediate position in the risk index. This is explained by the proportionally low contribution of exposure and physical vulnerability of buildings.

By taking into account the data from the BGE and the BGRI, crossed with a precise assessment of susceptibility based on geomorphological criteria, the analysis carried out makes it possible to locate exactly where the buildings susceptible to flooding are, to know their main physical characteristics, and to estimate their resident population. For future works, these results can be aggregated at different levels of representation, such as statistical section, parish, or municipality, and thus provide an assessment with a view to defining inter-municipal risk management policies. Such policies should not be restricted to the sole focus on emergency and civil protection, as cross-sectoral and comprehensive responses to disaster risk reduction include domains such as social, environmental, urban planning, mobility, and land use management policies.

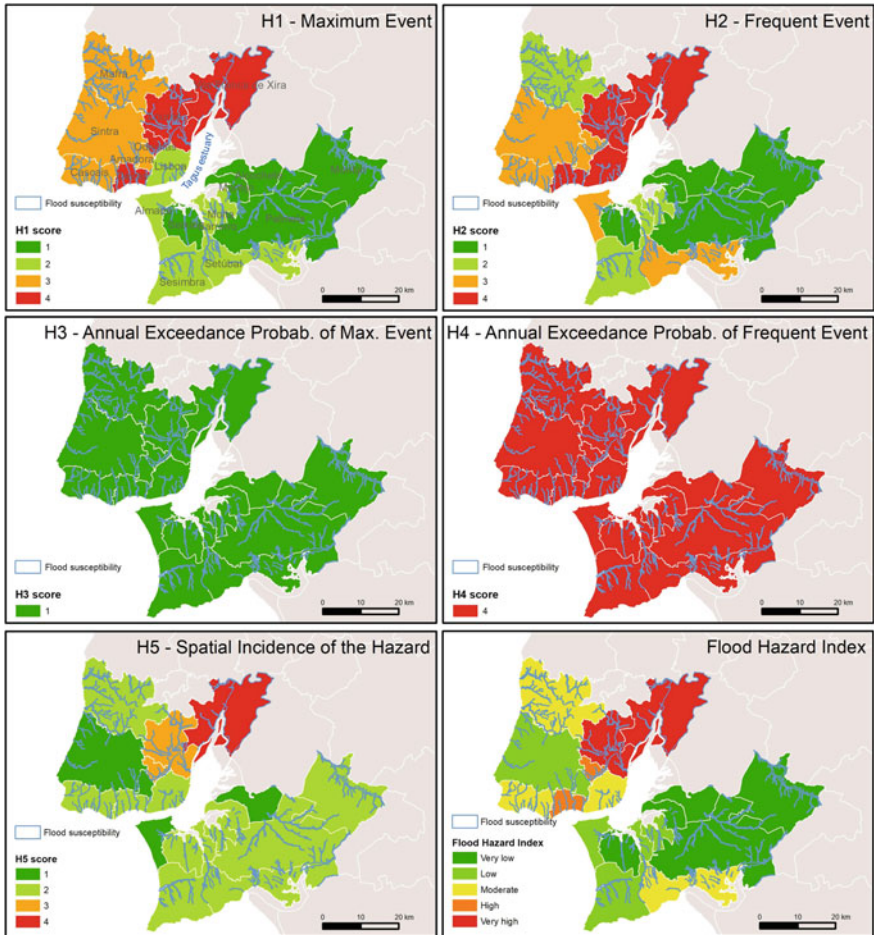


Fig. 4 Flood hazard parameters and index in the Lisbon Metropolitan area at the municipal level

4.2 Civil Parish Level

At the civil parish, 16 of the 118 territorial units don't have flood susceptibility significant enough to be considered. They are visible in Figs. 6a and 7a, represented with scores of 0 in flood hazard. In those 18 civil parishes, exposure and vulnerability (whether physical vulnerability of buildings or that of the resident population) are absent as well. Tagus river civil parishes, as well as those drained by the small watersheds north of Lisbon, present the highest hazard scores. Exposure of buildings is also high north of Lisbon (civil parishes of the Odivelas and Loures municipalities) and in the civil parishes at the mouth of small watercourses of Setúbal and Cascais municipalities (Fig. 6b; the name of municipalities can be checked in Figs. 1 and 5). Population exposure partly offsets that of buildings.

Table 2 Population and buildings' exposure and physical vulnerability

Municipality	No. Bldg	No. Inhab	Mean PV	Inhab. per building condition (parameter P7)			
				Very poor	Poor	Good	Very good
Alcochete	12	24	0.38	0	3	11	10
Almada	194	888	0.33	0	9	146	733
Amadora	28	226	0.23	7	0	29	190
Barreiro	46	190	0.41	11	6	62	111
Cascais	779	3304	0.30	67	46	1028	2163
Lisbon	1813	17,675	0.50	1062	922	6050	9641
Loures	991	3503	0.31	88	123	832	2460
Mafra	255	523	0.33	14	4	145	360
Moita	124	235	0.30	14	3	90	128
Montijo	39	66	0.35	2	2	30	32
Odivelas	1314	13,419	0.40	88	281	5508	7542
Oeiras	340	2726	0.39	25	82	589	2030
Palmela	336	876	0.31	7	4	128	737
Seixal	532	4691	0.37	15	77	941	3658
Sesimbra	5	4	0.25	0	0	0	4
Setúbal	1781	14,485	0.44	191	754	4623	8917
Sintra	577	5311	0.36	19	107	1479	3706
V. F. Xira	1035	4515	0.38	17	203	1335	2960
Sum/Mean	10,201	72,661	0.35	1627	2626	23,026	45,382

Highest population's vulnerability in the southern sector of LMA—fortunately, for the sake of a low-risk index—does not coincide with areas of high hazard (civil parishes in Almada, Seixal, or Barreiro municipalities), Fig. 7a and c.

Even with hazard being the only common component between flood risk at the civil parish using exposure and vulnerability of population (Fig. 8a) and exposure and vulnerability of buildings (Fig. 8b), the differences between the two maps are not as expressive as eventually expected. This fact can be explained by two arguments:

- Civil parishes where the vulnerability of people is high coincide with civil parishes where the physical vulnerability of buildings is equally high. In simple terms, this would mean that vulnerable persons tend to reside in vulnerable buildings and vice-versa;
- The role of vulnerability and of exposure, combined, is not strong enough to have an impact on the final risk score after their multiplication by hazard. We recall that equal weights are applied to all three components of risk.

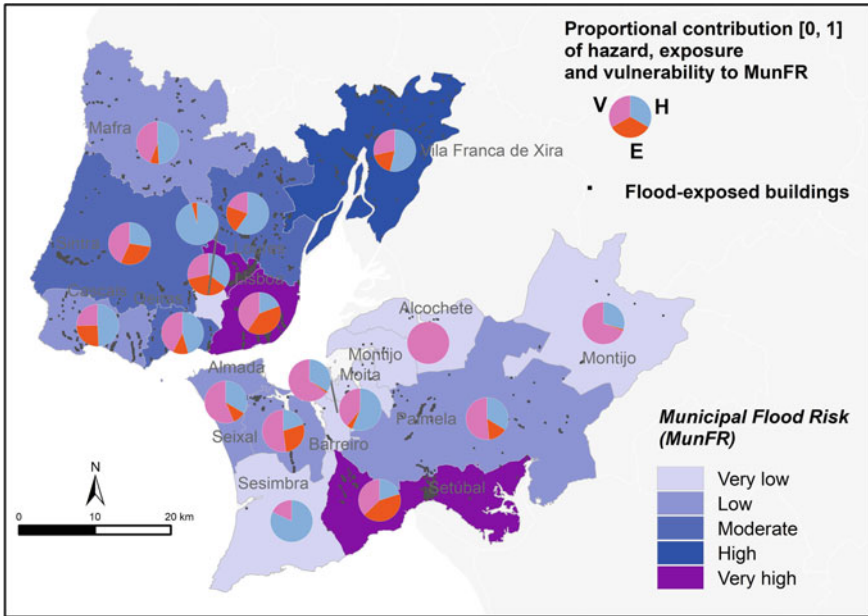


Fig. 5 Flood risk index as an expression of flood susceptibility, buildings' and population's exposure, and buildings' physical vulnerability, at the municipal level in the LMA

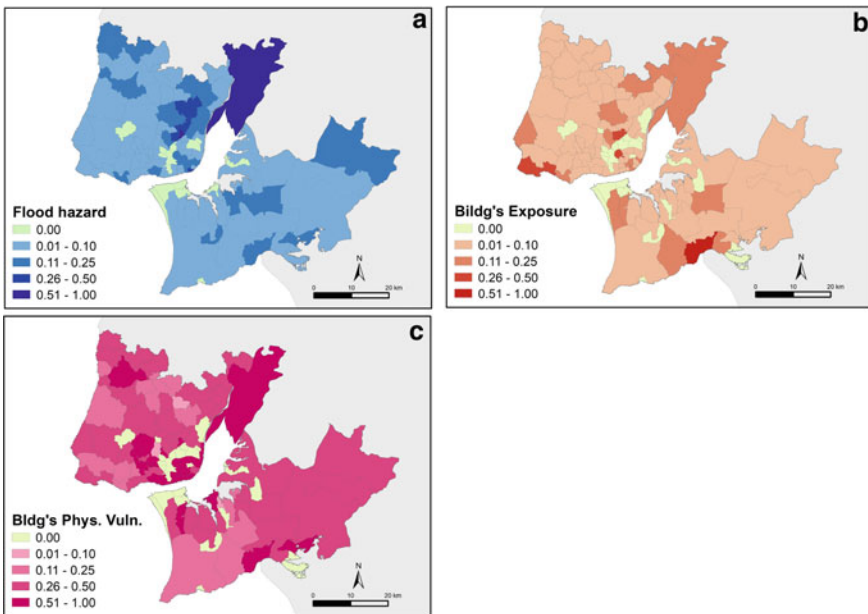


Fig. 6 Risk components at the civil parish level considering the exposure of buildings, in the LMA

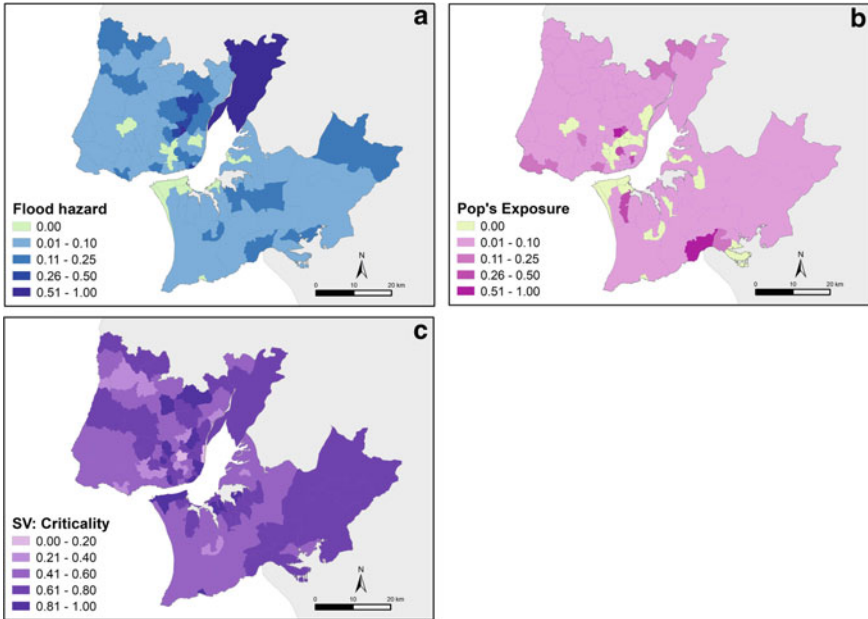


Fig. 7 Risk components at the civil parish level considering the exposure of population and its criticality in the LMA

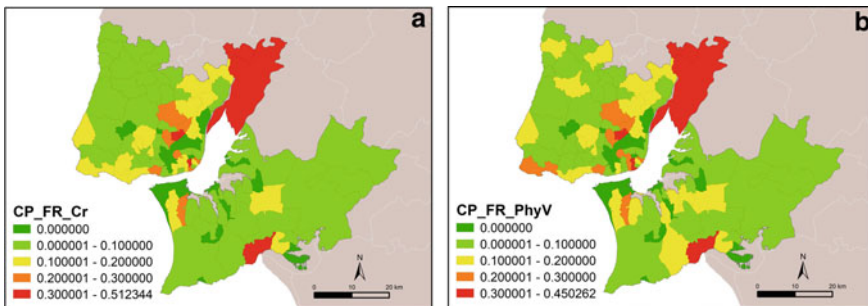


Fig. 8 Flood risk at the civil parish level considering the exposure of population (a) and buildings (b), in the LMA

4.3 Building Level

The LMA ASPFR areas differ significantly: Torres Vedras area, in the Mafra municipality, sums only five residential buildings, while Setúbal's ASPFR comprises 1411 (Table 3). The BPVF mean in the four EU's Flood Directive areas is 37.7, a value higher than the mean in the entire LMA (28.5), in a range from 0 to 100.

Table 3 Summary of results from the building-level cluster analysis in the ASPFR. The building's physical vulnerability to flooding (BPVF), flood depth and velocity, and vulnerability parameters (P1–P7) are expressed by the average within each cluster

ASPFR	Cluster	No. inhabitants	No. buildings	BPVF	Flood depth (m)	Veloc (m ² /s)	P1 (Age)	P2 (Floors)	P3 (Cladding mat)	P4 (Struc. sys.)	P6 (Expos.)	P7 (Repair Cond.)
<i>Loures and Odivelas (L&O)</i>	1	2	4.0	75.3	0.4	0.1	92.5	77.5	100.0	100.0	32.5	77.5
	2	2866	204.0	51.2	0.8	0.3	49.7	77.1	48.1	41.9	15.7	33.5
	3	2003	559.0	26.1	0.4	0.2	37.8	24.0	10.9	20.6	28.2	26.2
	4	6562	550.0	38.6	0.4	0.2	39.3	72.8	12.1	21.3	28.8	23.4
ASPFR L&O		11,432	1317.0	35.4	0.5	0.2	40.5	52.8	17.4	24.4	26.5	26.3
<i>Setúbal</i>	1	2	4.0	75.8	0.2	0.2	100.0	85.0	92.5	100.0	32.5	100.0
	2	2214	361.0	50.5	0.3	0.3	85.1	63.6	32.9	60.6	14.5	43.8
	3	794	342.0	28.3	0.1	0.2	56.1	19.7	10.0	29.3	27.9	31.6
	4	8283	704.0	39.9	0.2	0.3	56.3	57.9	13.8	39.2	20.1	30.7
ASPFR Set		11,293	1411.0	39.9	0.2	0.3	63.7	50.2	18.0	42.4	20.6	34.5
<i>Tagus floodplain</i>	3	9	4.0	29.5	0.8	0.4	32.5	10.0	10.0	32.5	55.0	17.5
	4	30	29.0	34.7	1.5	0.6	39.0	12.1	11.0	40.0	100.0	16.2
	ASPFR Tagus		39	34.0	1.4	0.6	38.2	11.8	10.9	39.1	94.5	16.4
	3	2	1.0	32.0	0.0	0.0	70.0	10.0	10.0	10.0	100.0	10.0
<i>Torres Vedras (T.V.)</i>	4	9	4.0	34.0	0.2	0.1	10.0	40.0	10.0	10.0	100.0	10.0
	ASPFR T.V.		11	33.6	0.1	0.1	22.0	34.0	10.0	10.0	100.0	10.0
LMA's ASPFR		22,776	2766.0	37.7	0.3	0.2	52.3	50.9	17.6	33.8	24.4	30.3

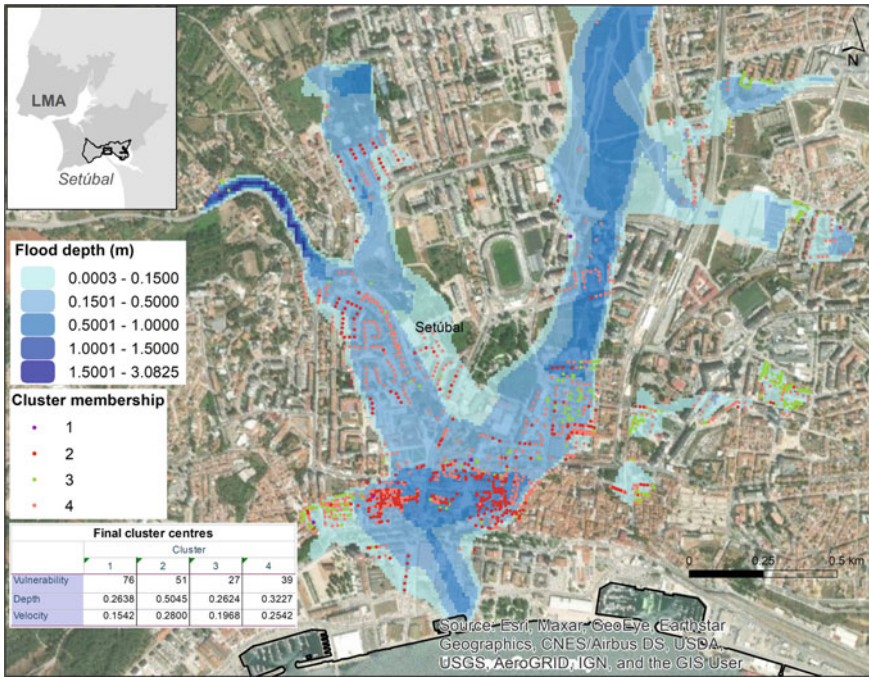


Fig. 9 Flood depths from the European Union’s Floods directive and cluster membership of buildings in the city of Setúbal, Portugal

The resulting four clusters can be interpreted as follows: cluster 1 aggregates 8 buildings, characterized by high scores of physical vulnerability, while flood depth and velocity are, in general, low; cluster 2 aggregates 565 buildings, characterized by moderate scores of BPVF but generally high flood depths and velocities (the high hazard is the distinctive factor); cluster 3 (906 buildings) is the “safest” cluster, expressing low physical vulnerability, flood depths, and velocities; finally, cluster 4 (1287 buildings) represents an intermediate context between clusters 2 and 3. Figure 9 illustrates this in Setúbal city.

5 Final Remarks

Flood processes are complex in their triggering and conditioning factors. When societal aspects like those that define exposure and vulnerability are added to risk analysis, such complexity becomes even higher. Their representation at distinct scales, as performed in this study, denotes how specific hotspots of flood risk can remain hidden if detailed levels of analysis are neglected.

On the component of exposure and vulnerability alone, this analysis shows the potential of Census data in supporting local-level flood studies. It is fundamental to dispose of updated sociodemographic data at the statistical block and the building level, without the need to conduct dasymetric estimations from polygonal to point-type representations of residents. However, fieldwork remains essential, namely in verifying to which extent the buildings' characteristics are inadequate to the levels of flood hazard they are exposed to. Geomorphological analysis, along with hydraulic modeling, is key in preventing the generation of risk hotspots through both upstream and valley-level spatial planning, urban planning, and retrofitting.

In general, the results achieved allow concluding that the current Flood Directive's critical areas were sustainably selected. Three out of the four areas of significant potential flood risk present high scores of hazard, exposure, and vulnerability.

Risk practitioners and decision-makers at the metropolitan, municipal, and neighborhood levels have different information needs. Recent flood events (December 2021 in the region of Lisbon) highlighted the unpredictability of the exact location where rainfall intensities will record higher. Early warning systems are undoubtedly useful tools for emergency services. However, attention must be given to the flood risk components more accessible to societal control. They include the care with the artificialized stream courses in urban areas, the strict enforcement of land use restrictions in channels and valleys' bottoms and construction codes, and the care with the more vulnerable persons. Evidence shows that ground floors in specific locations should be prohibitive to the residential function. In summary, flood loss reduction implies the involvement of distinct actors acting at distinct scales and sectors related to risk governance, both upon the scale of the basin and the scale of the floodplain.

Acknowledgements The project 'MIT-RSC—Multi-risk Interactions Towards Resilient and Sustainable Cities' (MIT-EXPL/CS/0018/2019) leading to this work is co-financed by the ERDF—European Regional Development Fund through the Operational Program for Competitiveness and Internationalisation—COMPETE 2020, the North Portugal Regional Operational Program—NORTE 2020 and by the Portuguese Foundation for Science and Technology—GCT under the MIT Portugal Program at the 2019 PT call for Exploratory Proposals in 'Sustainable Cities'. RISKCOAST is funded by the Interreg Sudoe Programme (SOE3/P4/E0868). Pedro Pinto Santos is financed through FCT I.P., under the contract CEECIND/00268/2017.

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