Multi-scale characterization of flood risk components: a case study at the municipal level

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Abstract. Floods are complex processes that combine local and global factors, causing recurrent and significant human and material losses worldwide. The presented research consists of a multi-scale flood risk assessment process based on data sources collected at distinct scales, expressing hazard, exposure and physical vulnerability of buildings. Detailed Census-derived parameters are essential in representing exposure and vulnerability, while flood hazard is quantified from geomorphologically validated susceptibility maps combined with historical data that characterize events' magnitude and frequency. The results allow a cross-scale analysis of risk, from the building to the municipality level, by identifying exposed populations, buildings, and physical vulnerability. The Lisbon Metropolitan Area is a highly contrasting territory regarding flood risk: some areas are susceptible to slow-onset floods in extensive floodplains but with low exposure, while densely urbanized areas are susceptible to flash floods in small watersheds. While the building level assessment is valuable for local civil protection and urban planning, municipal-level indices provide a comparable inter-municipal perspective of flood risk.

Keywords: Flood, Hazard, Exposure, Vulnerability, Multi-scale.

1 Introduction

Globally, floods are the most recurrent natural hazard, ranked among the natural processes with the highest social and economic impact. Along with highly recurrent processes with moderate losses, low probability flood events with significant human, environmental, and economic impacts are observed worldwide, whether in developed or developing countries. Despite the increasing research on the drivers of flood-related disasters, flooding is one of the most complex processes to model due to the wide range of variables necessary to describe flood scenarios (UNDRR, 2020) accurately. This short paper describes a flood risk assessment process that combines data from detailed to municipal-level scales, expressing hazard, exposure, and vulnerability. For this exploratory research, the selected case study is the Lisbon Metropolitan Area (LMA), a Portuguese NUT III administrative region composed of 18 municipalities with 2.8 million inhabitants and around 3000 km^2.

2 Data and methods

Input data with high resolution – expressing historical occurrences, flood susceptibility and buildings' vulnerability, for example – is processed to reach a lower-scale expression of risk, at the municipal level. Flood hazard is evaluated using five parameters: maximum event recorded (H1), which represents the maximum historical flood event registered in the last 150 years considering the DISASTER database (Zêzere et al., 2014); 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 event recorded in the entire LMA (H3); annual exceedance probability of the frequent events in the LMA (H4); and spatial scale of the assessment, which measures the impact scale of the hazard within the entire unit of analysis (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].

The exposure module identifies and characterizes the exposed elements in each municipality, focusing on the residential buildings (approx. 450,000 points of the BGE - Georeferenced Buildings Database and resident population from BGRI - Geographic Base for Information Referencing, both obtained from Statistics Portugal). The dasymetric distribution of the resident population by buildings with a total or partial residential function was performed (Garcia et al., 2015). The refinement of exposure to flooding was done by quantifying the number of buildings and respective resident populations within flood susceptible areas (the same ones used to define the flood hazard parameter H5). The vulnerability module focuses on the characteristics of residential buildings. The assessment of their physical vulnerability (PV) to flooding takes into account the period of construction (P1), the number of storeys (P2), material of the external cladding (P3), the material of structural system (P4), soil/lithological substrate (P5), building exposure (P6) and building condition (P7) (see Fig. 1). 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 classes and weights are based on expert opinion and dedicated literature, namely Kappes et al. (2012), Agliata et al. (2021), D'Ayala et al. (2020) and Ferreira and Santos (2020).

Finally, a weighted risk index is calculated (Eq. 1), which adopts the exponentiation followed in the EU/Joint Research Centre INFORM risk index, although applied to distinct risk components than those used in that global index:

$$Flood\ risk = H^{1/3} * E^{1/3} * PV^{1/3} \quad (1)$$

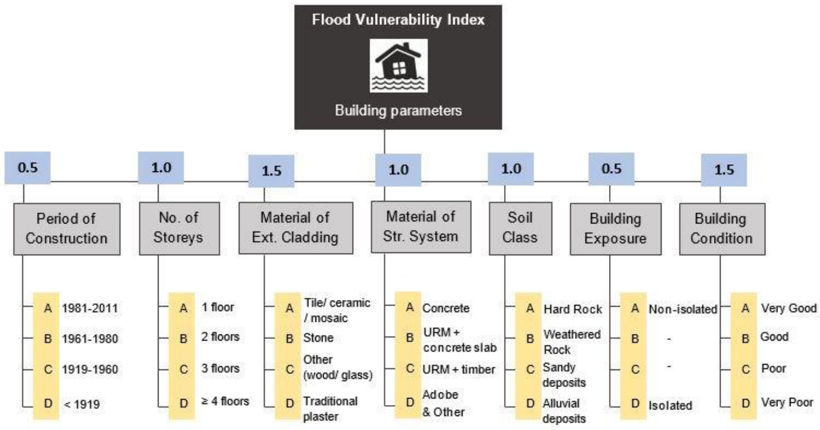

Fig. 1. Parameters, properties and respective weights used to assess buildings' physical vulnerability to flooding.

3 Results

Flood hazard in the LMA is conditioned by the Tagus river floodplain, the Tagus estuary and the small watersheds that drain to the Tagus, directly to the Atlantic ocean or 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 impacted more the municipalities of V.F. Xira, Loures, Odivelas and Oeiras (Fig. 2). Adding to these municipalities, the higher scores concerning 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 have affected the 18 municipalities evenly. For this reason, an equal score was assigned to all municipalities with a low probability event (Loat and Petrascheck, 1997). 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. 2) 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 1). 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.

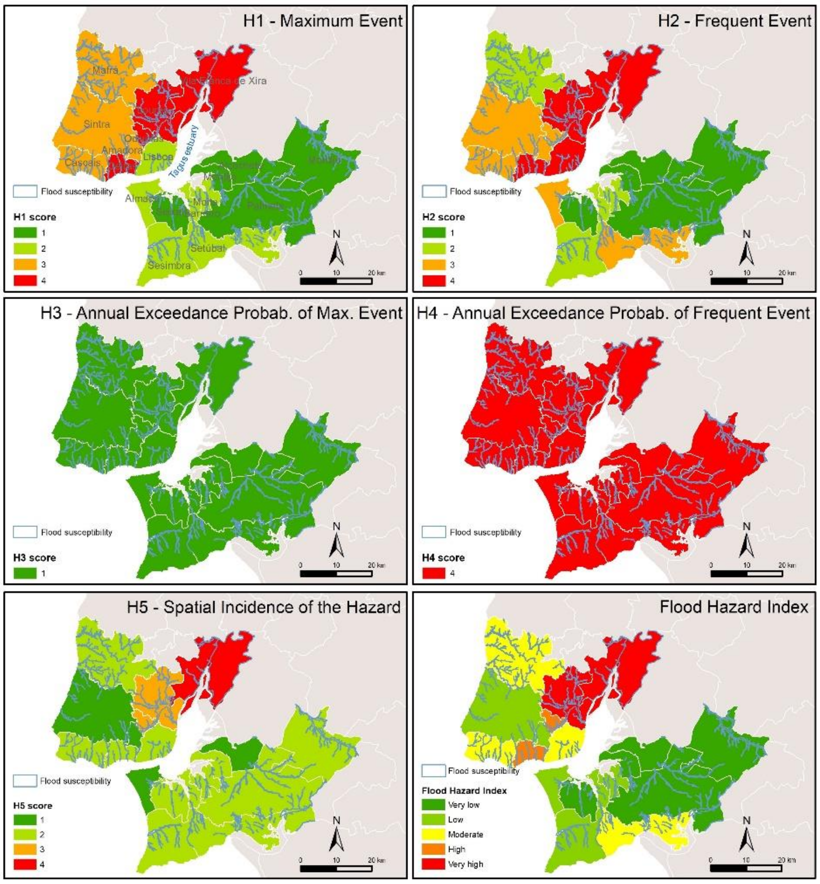

Fig. 2. Flood hazard parameters and index in the Lisbon Metropolitan Area at the municipal level.

When analyzing the hazard and risk index, mapped respectively in Fig. 2 and Fig. 3, it is interesting to see that when PV is included in the analysis, it changes considerably 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. 3, but not in the hazard maps provided in Fig. 2. Analyzing the proportion of the risk index explained by the hazard score represents less than ¼ 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 PV accounted only with 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.

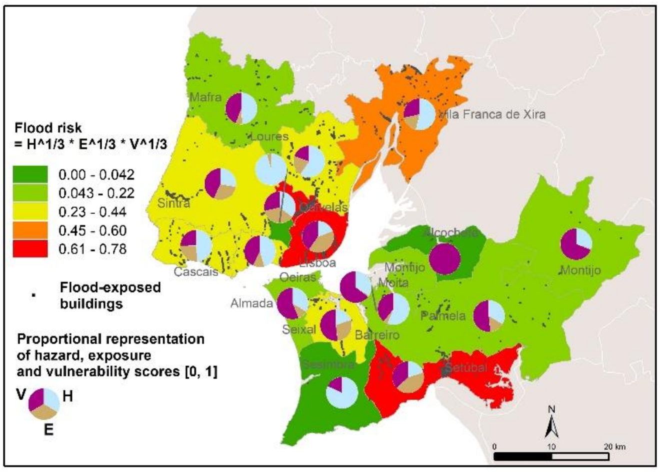

Fig. 3. Flood risk index as an expression of flood susceptibility, buildings' and population's exposure, and buildings' physical vulnerability at the municipal level in the LMA.

Table 1. Population and buildings' exposure and physical vulnerability.

Municip.	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	17675	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	13419	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	14485	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*	10201	72661	*0.35*	1627	2626	23026	45382

4 Concluding remarks

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 precisely where the buildings susceptible to flooding are, to know their main physical characteristics and to estimate their resident population. For a lower scale of inter-municipal strategic decision, such data was processed to obtain municipal-level risk indices which, however, may conceal critical local hotspots. Inter-municipal risk management 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 social, environmental, urban planning, mobility and land use management policies.

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