Landslide risk profiles for municipal land use planning in Portugal

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1. Introduction

In Portugal disastrous landslides have been triggered by rainfall as most landslides worldwide. Spatial distribution and trends of landslide disasters at the municipal level in Portugal have been related to different causes that can be addressed exploring three components of the disaster risk: hazard, exposure and vulnerability. Landslide risk results from the combination between the severity and frequency of hazard, the number of people, assets and infrastructures exposed to hazard, and their vulnerability to damage (UNISDR, 2015).

In this work we propose a Landslide Risk Index (LRI) at the municipal scale in Portugal, reflecting landslide risk incidence and causal patterns at the municipal level (scale of strategic risk management). This is a critical step to define the appropriate public policy measures for spatial planning and land use management in order to mitigate disaster risk and reduce future losses, knowing the main driving forces of landslide disasters at the municipal level.

The main objectives addressed at the municipal level were the following:
(i) To select a set of variables that characterize the components of landslide risk (hazard, exposure and vulnerability), which were normalized and weighted to compute landslide risk;
(ii) To assess landslide impacts using historical data from the Disaster database (1865-2015);
(iii) To perform a cluster analysis and ranking of the municipal landslide risk profiles.

2. Damaging Landslides

Historical records of damaging landslides and their major human impacts (fatalities, injured people, disappeared people, evacuated people and displaced people) in Portugal mainland are gathered in the Disaster database (1865-2015) (Pereira et al., 2018; Zêzere et al., 2014). Along 151 years, 292 landslides were recorded, which caused 237 fatalities, 434 injured people, 823 evacuated people and 1620 displaced people.

Damaging landslides frequently occur in the northern and central mountain areas of the country and in the hills of Lisbon metropolitan area (Figure 1A). In the south, landslide fatalities are constrained to the coastal cliffs.
Usually, more than half of the landslide fatalities are caused by falls, followed by flows and half of the times fatalities occurred inside buildings (Pereira et al., 2016).
Also, more than 400 displaced people were recorded in Lisbon and Porto (Figure 1B), which are the most populated areas of the country.

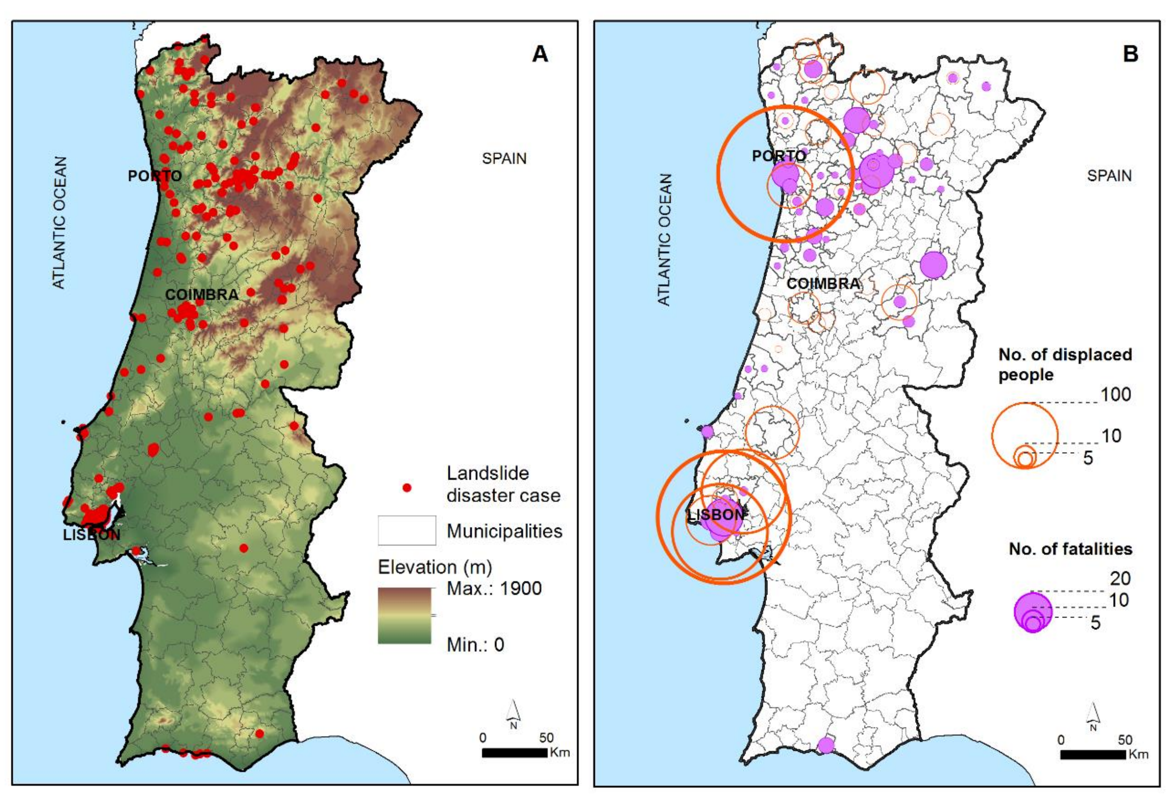

Figure 1 Landslide disaster cases in Portugal mainland (A), number of fatalities and displaced people caused by landslides per municipalities (B) for the period (1865-2015).

3. Data and methods

3.1 Landslide risk index

Landslide risk of each municipality was identified as the interaction of hazard, exposure and vulnerability, which . These three dimensions of risk are conceptualized as three major forcers of landslide risk, each one normalized between 0 (low) and 1 (very high). Landslide risk index (LRI) at the municipal level is calculated with a multiplicative equation (Eq. 1) where each of the dimensions is equally weighted (e.g. INFORM methodology).

LRI= (Hazard⅓)*(Exposure⅓)*(Vulnerability⅓)..............................Eq. 1

3.1.1 Hazard

Landslide hazard assessment at the municipal scale combines the rainfall triggering conditions and the landslide susceptibility.

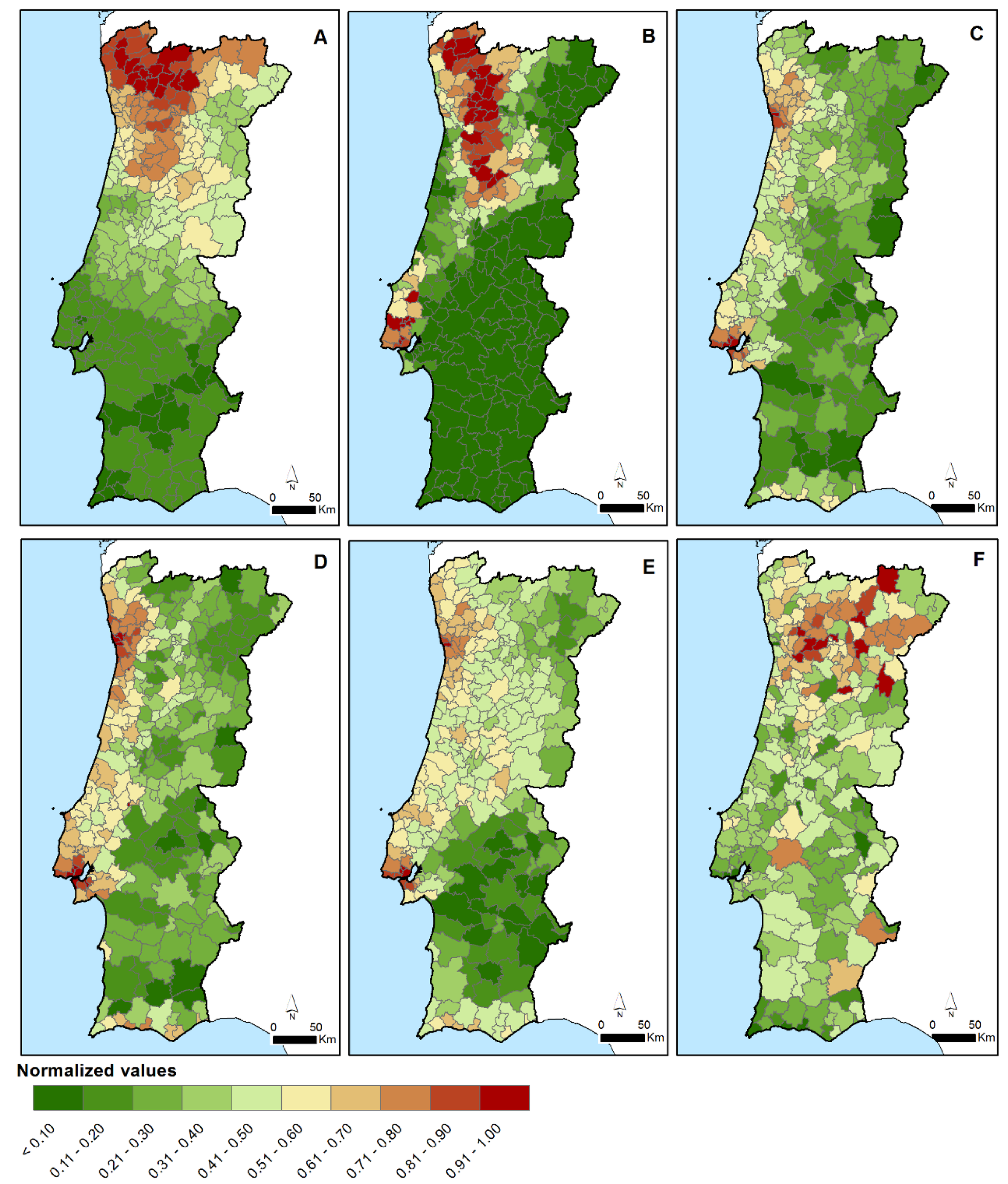

Figure 2 Weather and climate events index (A), landslide susceptibility (B), Population density (C), Average degree of imperviousness (D), average road density (E) and Social Vulnerability (F) normalized between 0 and 1 per municipality.

3.1.2 Exposure

The exposure assessment to landslides at the municipal level was based on three sources: population density (PD), road density (RD) and the average degree of imperviousness (ADI), also mentioned as the degree of soil or surface sealing.

3.1.3 Vulnerability

Social Vulnerability (SV) includes the specific characteristics of the individuals and their social and economic relations, including its physical environment. Social Vulnerability assessment is an important tool to characterize and understand the degree of exposure of the individuals and communities, to evaluate their capacity for resilience and recovery from hazardous events. SV of the municipalities was assessed in 2017 for the 278 Portuguese municipalities by Tavares et al. (2018).

Table 1 *Landslide risk variables adjusted to the municipality level.*

Landslide risk component	Variables adjusted to the municipality level	Units	Code
HAZARD	Weather and climate events index	adimensional	WCE
	Area with positive values of the Information Value (>0)	%	SUSCL
EXPOSURE	Population density	No. of Inhabitants/km^2	PD
	Average degree of imperviousness	%	ADI
	Average road density	km/km^2	RD
VULNERABILITY	Social vulnerability in 2017	adimensional	SV

Landslide hazard variables (WCE and SUSCL) were empirically weighted assuming that the landslide susceptibility has a major importance on the landslide location.

H = (WCE*0.25) + (SUSCL*0.75)..(Eq.3)

Exposure (E) variables' weights were tested for seven combinations based on expert opinion. The initial combinations extreme one of the input variables and evolve to an equal weight combination. The best combination of exposure was selected (Eq. 4) according to the evaluation of the internal consistency of each model through the Cronbach Alpha and the Guttman Lambda-2 measures.

E = (PD*0.1)+(RD*0.8)+(ADI*0.1)...(Eq.4)

3.2 Cluster analysis of the landslide risk

A hierarchical cluster analysis was made using SPSS to characterize groups of municipalities. The results per municipality of H, E, V and the LRI obtained with the best landslide risk model were used to select the best number of clusters of municipalities.
According to the results obtained with the Ward algorithm, the link tree and the agglomeration cost tables, the best number of clusters is selected, to reduce the number of clusters until there is a jump in the cost of agglomeration. Then we use the number of clusters ascertained before that jump. Euclidean distances (not standardized) were used as metric distances.

4. Results

4.1. Landslide risk of the municipalities

The hazard class <0.1 includes 31.3% of the municipalities most of them located southwards the Tagus valley. Hazard above 0.8 occurs in the NW sector of the country and include 12.6% of the municipalities (Figure 3).
The highest percentage of the municipalities are included in the class 0.41 – 0.5 of exposure. The highest values are found in the Lisbon and Porto metropolitan areas.
The highest values of SV are found in the N and NE sector of the country, along the Douro valley, where ageing population, population with less education and activities related with agriculture are found.

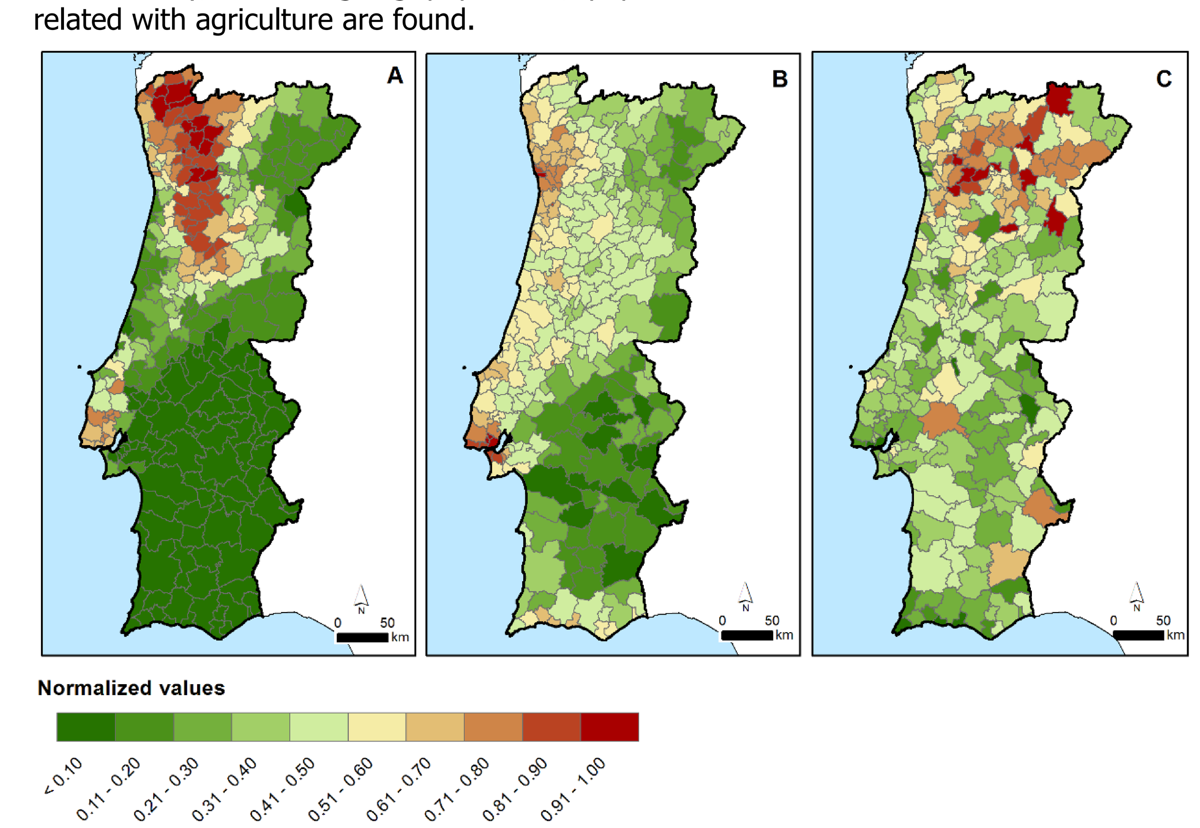

Figure 3 Hazard (a), exposure (b) and vulnerability (c) values obtained with the best reliability model (HE3V) per municipality.

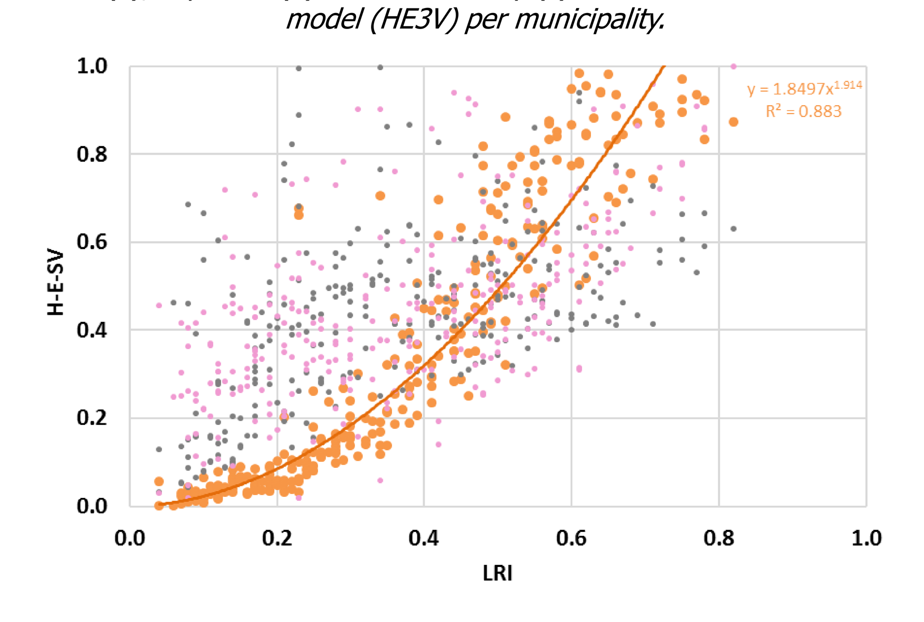

Figure 4 Landslide risk index crossed with the hazard, exposure and social vulnerability values per municipality.

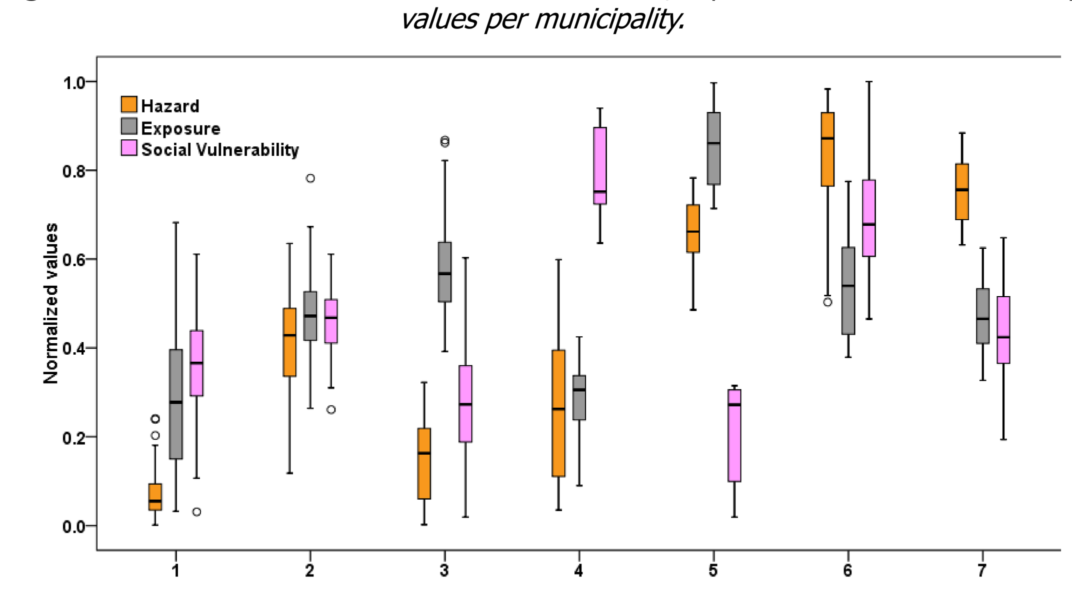

Figure 6 Clusters according to the hazard, exposure and social vulnerability characteristics of the municipalities.

4.2. Risk profiles of the municipalities

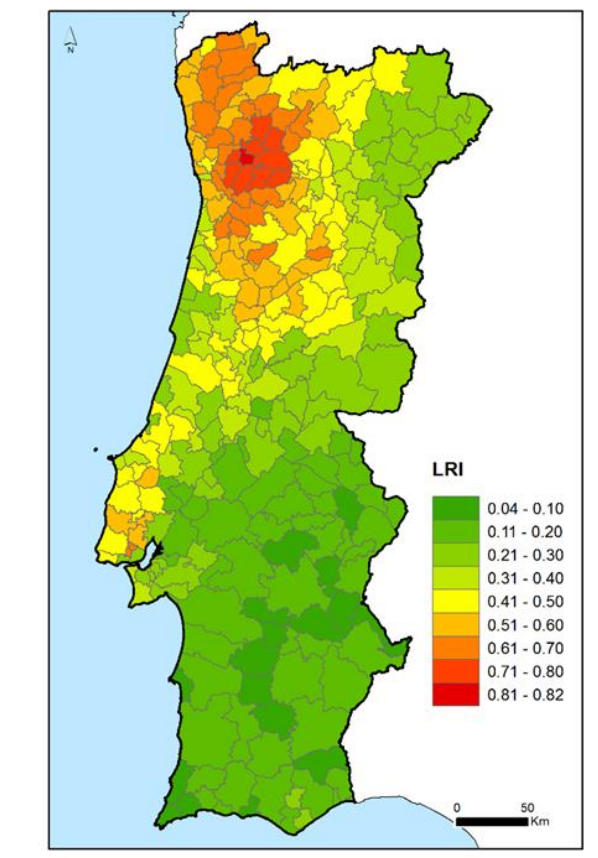

Figure 4 Landslide risk index

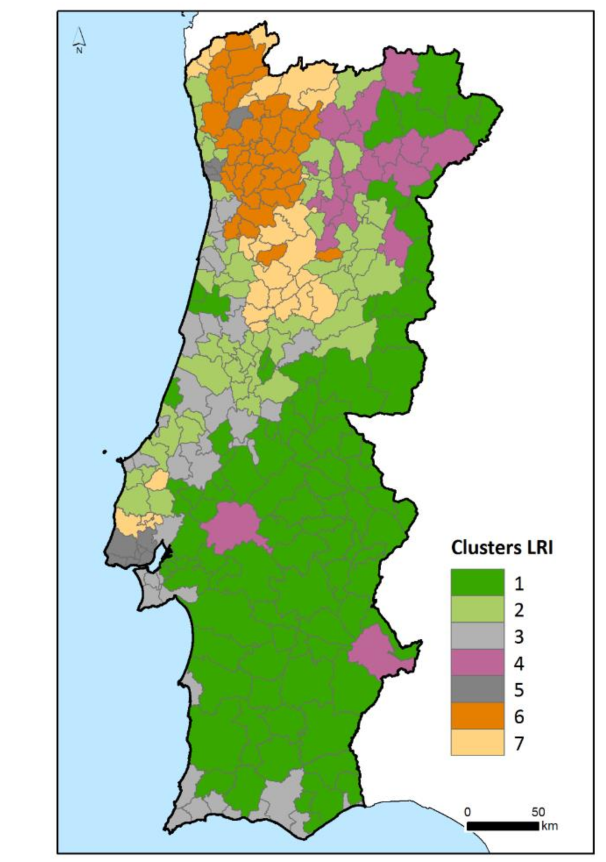

Figure 5 Landslide risk index clusters of the municipalities.

Cluster 1 - includes 90 municipalities located in the north-east and east border with Spain and south of the Tagus valley including flat surfaces. This cluster is characterized by the lowest average values of hazard and moderate values of exposure and social vulnerability.

Cluster 2 - includes 52 municipalities widespread in the Center region, west and north-west coastal area. These municipalities are characterized by average values around 0.5 in hazard, exposure and social vulnerability.

Cluster 3 - includes 41 municipalities characterized by an average exposure value of 0.59 and low average values of hazard and social vulnerability.

Cluster 4 - includes 20 municipalities with the highest average values of social vulnerability, located in the north-east sector of the country along the Douro river basin. Here the hazard ranges from 0.04 to 0.6 and the average value of exposure is 0.29.

Cluster 5 - includes only 11 municipalities located in Porto and Lisbon metropolitan areas, where the highest average values of exposure are found (0.85) and simultaneously the lowest average values of social vulnerability (0.21) and an average hazard of 0.66.

Cluster 6 - includes the 36 municipalities with the highest average landslide risk index, which are located in the north-west part of the country. These municipalities have the highest values of hazard, average social vulnerability of 0.7 and average exposure of 0.54.

Cluster 7 – includes 28 municipalities characterized by lower average values of hazard, exposure and vulnerability when compared with cluster 6, but the hazard is still the main driving force of disastrous landslides in these area located near the high hazard municipalities. Municipalities show an average landslide risk index of 0.53.

Each cluster presented a risk component that can be identified as a major driving force of the landslide risk. For instance, clusters 6 and 7 are guided by the hazard, clusters 5 and 3 are guided by the exposure, and cluster 4 is guided by the social vulnerability. Cluster 1 has the least importance of the hazard component and cluster 2 presents a similar contribution of each landslide hazard component.

FORLAND project website: http://www.ceg.ulisboa.pt/forland/

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Acknowledgments

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