environmental science & policy 51 (2015) 238–255

Available online at www.sciencedirect.com

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Flooding hazard in the Tagus estuarine area: The challenge of scale in vulnerability assessments

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ARTICLE INFO

Article history:
Received 29 January 2015
Received in revised form
9 April 2015
Accepted 12 April 2015
Available online 14 May 2015

Keywords:
Vulnerability
Flood
Storm surge
Tagus estuary
Local scale

ABSTRACT

This paper describes the methodology of the vulnerability assessment to flooding in an estuarine context and presents the final results for the Tagus River estuary, in the metropolitan region of Lisbon (Portugal). Performing a local study adapted to a specific type of hazard posed two initial methodological challenges: the selection of the unit of analysis and the identification of the pertinent and available variables. Both challenges were addressed assuming that the area to be assessed should also include the units outside the inundated area, a buffer zone that would include areas indirectly affected. The application of the statistical procedures established in the SoVI® methodology indicate that certain widely used variables in vulnerability assessments on smaller scales are inadequate at the statistical block scale and that specific variables must be defined and integrated to represent more broadly the dimensions of vulnerability related to social assistance, infrastructures and commutability.

The extracted principal components identified the vulnerability drivers in the riverside and surrounding areas. These drivers identify the urban context, the family structure, and the socio-economic condition expressed in terms of housing characteristics, education, mobility and commuting as the dimensions that most differentiate territorial and individuals' vulnerability. Applications of vulnerability research in risk management are found in the fields of risk communication, stakeholders' involvement and strategic and operational planning in emergency planning as in other concurring sectors.

1. Introduction

The assessment of vulnerability is a complex challenge in regard to data availability and analysis and is a central issue in coastal flood risk governance. Vulnerability, as a major concept, refers to the degree to which communities and individuals are susceptible to – and unable to recover from – the effects of hazardous processes, encompassing the physical, social and organizational components of social systems.

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http://dx.doi.org/10.1016/j.envsci.2015.04.010
1462-9011/

The "condition of a community," in terms of its degree of vulnerability and resilience, can establish whether the disaster threshold is crossed when a hazardous event occurs (Haigh, 2010). Therefore, vulnerability assessments must be conducted considering that vulnerability is an "integral part of the causal chain of risk" and that reducing vulnerability is a cost-effective strategy of risk management (Kasperson et al., 2001) and a key element in any risk governance process. Understanding vulnerability is one of the foundations that support the achievement of the 10 essentials of safe and resilient cities articulated in UNISDR (2012), primarily focusing on the essentials of multi-hazard risk assessment; protection of vital education and health facilities; training, education and public awareness; effective preparedness, early warning and response; and recovering and rebuilding communities.

Assessing vulnerability in estuarine margins is a matter of key importance given the natural susceptibility to flooding in these areas – at the interface between low-energy fluvial conditions and high-energy maritime hydrodynamics – aggravated by the increasing influence of natural and human-induced factors such as sedimentation, sea level rise and settlement of human activities in intertidal and proximal areas (McLean et al., 2001). Estuarine margins, and coastal margins in general, can have a high risk of flooding, as shown by the recent impact of inundation events, as the hurricane Katrina (2005) in New Orleans, the storm Xynthia (2010) in the French coast and the hurricane Sandy (2012) in New York (e.g., Bertin et al., 2014; André et al., 2013). Moreover, the inundation hazard is expected to increase in severity and frequency due to climate change effects, in particular sea level rise and growing storminess.

The study area of the present paper is the Tagus estuary, whose morphological settings and hydrodynamic conditions, as the amplification upstream of the semi-diurnal tides (Fortunato et al., 1999; Guerreiro et al., 2015), promote high risk to flooding of estuarine margins (Rilo et al., 2013). The conjugation of extreme tidal levels and storm surge conditions can lead to inundation episodes along the estuarine margins, such as the one that occurred on February 15th 1941, with high human casualties and property damages (Muir-Wood, 2011). Fig. 1 illustrate the events of 1941 and 1954 as they were reported in national scope newspapers. Historically, flood-prone areas of the Tagus estuary have been used for residential and economic activities. With the growth of the capital, Lisbon, in the northern margin, a consequent growth in the southern margin has occurred, especially in the 20th century. This increasing dynamic between margins merges in the movement of people and goods.

This manuscript presents the social and territorial variables that characterize the Tagus estuary, specifically focusing on the flood hazard, identifying the components of vulnerability to this hazard on a local scale and providing insights into the manner of transferring the knowledge associated with these components of vulnerability to risk management policies and practices. Scale poses a major challenge because a general differentiation of municipalities, or even parishes, is considered inadequate for the purposes of this study. In fact, the goal is to assess the vulnerability of individuals and communities to estuarine flooding at the local level, i.e., classifying neighborhoods and urban zones by their distinctive vulnerability factors.

The development of indexes as a manner of quantifying vulnerability reduces the multidimensional complexity of vulnerability to a single metric (Tate, 2013). Assessments of vulnerability indexes in Portugal, similar to the one here presented, include the application of the SoVI® by Mendes (2009) to 78 municipalities of the central region; and, more recently, Guillard-Gonçalves et al. (2014) applied the same index to a group of 149 civil parishes of Greater Lisbon, in which the final model was performed with 38 variables after multicolinearity elimination. Mendes et al. (2011), based on the statistical procedure behind the SoVI®, developed a new social vulnerability index that considers the components of criticality and support capability. Criticality is the "ensemble of individuals' characteristics and behaviors that may contribute to the system's rupture," and support capability is the "set of territorial infrastructures that enable the community to react in case of disaster" (Mendes et al., 2011: 446). This methodology has since been applied to several Portuguese municipalities at the statistical block level (e.g., Tavares and dos Santos, 2014).

In this study, vulnerability is approached in its territorial and individual dimensions; the considered variables extend beyond social vulnerability to include land use, mobility and infrastructure dimensions. Nevertheless, the adopted concept of vulnerability is closely related to the concept of social vulnerability, which is defined as a pre-existing condition of individuals and communities that influences their preparation, response and recovery from hazard events (Chen et al., 2013; Bergstrand et al., 2014), resulting from both social inequalities and place inequalities (Cutter et al., 2003). Understanding vulnerability is crucial to the development of disaster mitigation plans and policies. In fact, vulnerability sources are not only addressed via civil protection action but also require a broader concerted action among practitioners of distinct public and private sectors and fields. The most relevant fields include health, education, social assistance, the economy, spatial planning and transportation. It is therefore significant that the Portuguese legal transposition of the European Union directive (2007/60/EC), through the Decree-Law no. 115/2010 of 22nd October, which establishes the framework for the management of flood risks, stipulates the necessity of conducting an analysis of the vulnerability of exposed population, equipment, lifelines and environmental values.

2. The Tagus estuary

2.1. *Territorial and socio-economic context*

The Tagus estuary is located in Portugal and named for the transnational river that flows into the Atlantic Ocean near the capital city of Lisbon and its metropolitan area (Fig. 2). In addition to the relevance of social and economic exchanges within margins and between the left and right margins, the area is also sensitive in terms of densely urbanized areas, the exposure of critical and sensitive infrastructures and because of the area's ecological functions, with a portion of its eastern upstream area legally protected as a natural reserve.

Fig. 1 – Photographs printed in newspapers regarding the event of February 15th 1941 (A) and the event of October 24th 1954 (B), in Lisbon, and the event of February 9th 2014 in Oeiras. *Sources*: (A)–(O) Século 1941.02.16; (B)–(O) Século 1954.10.24; (C) Diário de Notícias 2010.02.10.

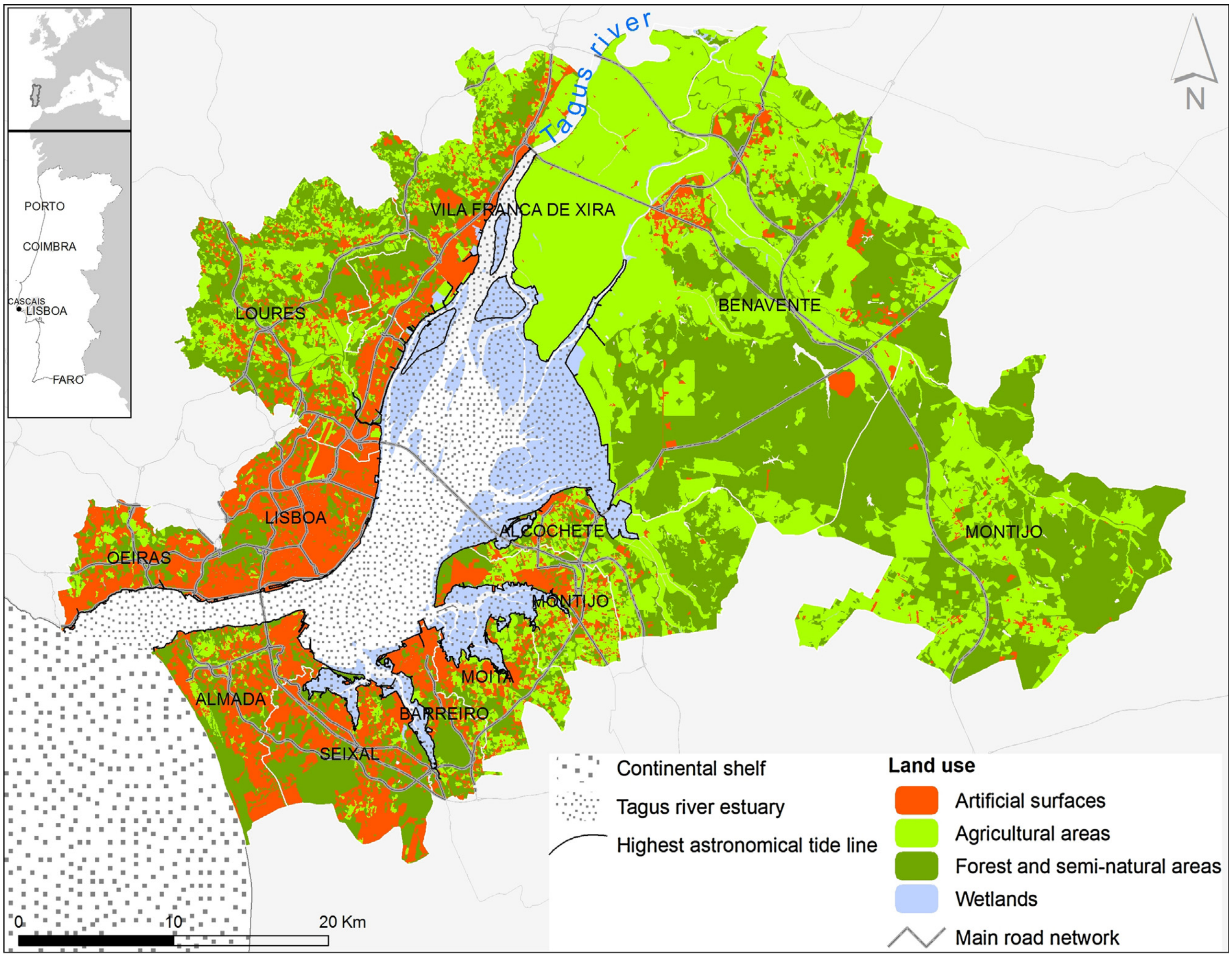

Fig. 2 – Geographical context of the Tagus estuary.

An initial characterization of the territorial and socio-economic dynamics of the estuary's margins contributed to establishing the scope of the vulnerability analysis. This characterization resulted from the analysis of statistical data and sectoral reports regarding the population census, social assistance equipments' and beneficiaries', land use, tourism, mobility and commuting data.

The eleven municipalities that adjoin the estuary margins are home to circa 1.6 million inhabitants, mainly concentrated in the northern (right) margin of the Tagus. The 1998 Lisbon World Exposition was responsible for major territorial changes, particularly in the eastern sector of Lisbon and in the southern margin, following the construction of the Vasco da Gama bridge, which crosses the estuary near Alcochete (cf. Fig. 2) and prompted urban sprawl in the municipalities of the southern margin.

The strategic role of this region in terms of the scale of the country – and thus of its territorial vulnerability – is clearly evident in terms of population and business turnover (Table 1). The effect of the new bridge is evident in the strongly positive demographic variation between 2001 and 2011 in the municipalities of Alcochete, Montijo and Benavente, whereas the municipalities in the northern margin are stabilizing their growth or even experiencing population decreases after decades of constant population influxes from rural Portuguese areas and after the decolonization of the African countries under Portuguese domain in the 1970s. The turnover registered in the Lisbon municipality alone accounts for 25.74% of the total in Portugal. Additionally, some governmental bodies and companies are located near the shoreline of Lisbon and surrounding municipalities and could be directly and indirectly affected by flooding.

Earnings are a key element in understanding the economic development and the social welfare of a region. Table 2 highlights the growing relevance of a labor force in the estuarine municipalities: the country's average grew from 405 € in 1991 to 1084 € in 2011, a variation of 167.54% that is surpassed in 7 of the 11 considered municipalities. Notably, earnings in the female population in the Seixal municipality have increased much less than in the other 10 municipalities, although remaining above the national average. As a result of the recent urban sprawl in Alcochete, this municipality registered a significant improvement in the MAEE, growing from one of the lowest in 1991 to the second highest in 2011.

Table 1 – Demographic and economic context in the 11 municipalities aroundof the Tagus estuary and in Portugal. ***Source:*** **INE (2011a), INR (2011).**

		RP	Var_RP	TO	% TO
	PORTUGAL	*10,557,560*	*1.88*	*331,129*	*100*
Northern margin	Oeiras	172,478	6.24	21,186	6.40
	Lisbon	542,917	−3.62	85,222	25.74
	Loures	206,025	3.54	5919	1.79
	Vila Franca de Xira	137,509	11.47	3348	1.01
Southern margin	Almada	173,906	7.82	3408	1.03
	Seixal	159,261	5.92	2273	0.69
	Barreiro	78,744	−0.28	528	0.16
	Moita	66,091	−1.84	400	0.12
	Montijo	51,777	30.48	763	0.23
	Alcochete	17,740	34.49	1088	0.33
	Benavente	29,186	24.30	713	0.22
RP	Resident population in 2011				
VarRP	Demographic variation 2001–2011 (%)				
TO	Turnover (€ million)				
% TO	Contribution of each municipality to national turnover (%)				

Other vulnerability dimensions such as age, education, employment, and mobility that were analyzed are presented in Table 3. This table highlights the high proportion of residents who study or work outside their municipality of residence—above 50% of the population in Moita municipality, for example. Boats, however, are required to cross the estuary, especially in the Barreiro municipality, in which a major fluvial commuting interface is located, transporting 16.1% of the employed and student population. The population over 65 years old with at least one disability – vision, hearing, mobility or understanding – is significant (8.9%). Educational level is a good indicator of people's vulnerability. The percentage of the population who has not completed any educational level is generally high, particularly in the southern margin, varying between a minimum of 14.9% in of the resident population Lisbon and a maximum of 20.6% in Benavente.

Transportation of commodities and tourism are becoming relevant sectors in the Tagus estuary on an international level. The Port of Lisbon has verified a consistent increase in both tourism and commodities. A total of 353 cruise ship scales in 2013 represented a 20% increase over 2009 with a total of 558,040 passengers in 2013. Commodities commerce recorded 368,450 containers in 2013, an increase of 13% over 2012 (APL, 2014).

2.2. *Flooding context*

An inundation model for the estuarine area was established for several return periods for both present and future mean

Table 2 – Monthly average earnings of employees in the 11 municipalities around the Tagus estuary and in the country, by genre. ***Source:*** **FFMS (2011).**

		MAEE (€)		Var (%)	MAEE_M (€)		Var_M (%)	MAEE_F (€)		Var_F (%)
		1991	2011		1991.0	2011		1991	2011	
	PORTUGAL	*405.10*	*1083.80*	*167.54*	*453.90*	*1195.40*	*163.36*	*321.40*	*945.90*	*194.31*
Northern margin	Oeiras	480.70	1721.20	258.06	530.40	1921.30	262.24	390.10	1444.60	270.32
	Lisboa	576.60	1576.40	173.40	641.90	1785.80	178.21	463.30	1362.10	194.00
	Loures	412.10	1109.30	169.18	454.30	1206.40	165.55	325.60	948.10	191.19
	V.F. Xira	459.00	1129.50	146.08	508.50	1250.00	145.82	333.70	945.20	183.25
Southern margin	Almada	450.50	1040.30	130.92	534.20	1150.00	115.28	304.90	935.00	206.66
	Seixal	431.50	1139.00	163.96	475.70	1365.10	186.97	325.10	853.90	162.66
	Barreiro	470.00	1048.80	123.15	527.70	1193.60	126.19	315.70	898.40	184.57
	Moita	299.80	942.00	214.21	366.20	1041.80	184.49	258.90	817.90	215.91
	Montijo	325.00	975.70	200.22	365.40	1112.60	204.49	259.00	840.80	224.63
	Alcochete	396.80	1673.50	321.75	465.40	2341.90	403.20	277.60	881.70	217.62
	Benavente	354.00	1014.10	186.47	394.30	1129.20	186.38	270.70	836.10	208.87
MAEE	Monthly average earnings of employees (€)									
Var	Variation of the AMEE, 1991–2011									
MAEE_M	Monthly average earnings of male employees (€)									
Var_M	Variation of the AMEE_M, 1991-2011									
MAEE_F	Monthly average earnings of female employees (€)									
Var_F	Variation of the AMEE_F, 1991-2011									

Table 3 – Demographic, social and mobility dimensions in the 11 municipalities around the Tagus estuary. *Source*: **INE (2011a).**

	Municipalities (Northern or Southern margin)	RP	RPnelc	UD	OD	OD65	RPes	RPout	RPesBoat	RPesPT
Northern margin	Oeiras	172,120	25,936	44,719	22 285	12,673	104,233	50.14	0.06	23.81
	Lisboa	547,733	81,690	148,527	93,584	58,463	304,835	14.00	0.07	33.64
	Loures	205,054	36,041	26,281	31,505	16,100	123,468	49.03	0.01	31.81
	V. F. Xira	136,886	24,159	15,506	18,534	8783	88,996	45.67	0.04	27.96
Southern margin	Almada	174,030	28,873	25,275	30,138	16,811	98,056	41.09	1.88	32.96
	Seixal	158,269	26,558	18,070	23,290	11,135	94,586	49.95	2.09	33.31
	Barreiro	78,764	13,129	8653	14,534	8249	42,662	46.04	16.14	37.58
	Moita	66,029	12,482	4858	11,892	5897	37,172	51.67	7.36	30.18
	Montijo	51,222	10,268	6362	8361	4424	30,350	41.53	5.40	19.73
	Alcochete	17,569	3473	2829	2328	1231	11,080	49.39	2.89	19.92
	Benavente	29,019	5987	2513	4440	2316	17,498	30.03	0.01	12.86
	Total	1636,695	268,596	303,593	260,891	146,082	952,936	–	–	–

RP	Resident population
RPnelc	Resident population with no educational level completed
UD	Resident population with a university degree
OD	Resident population with at least one disability
OD65	Resident population 65 or older with at least one disability
RPes	Employed or student resident population
RPout	% of resident population working or studying outside the residing municipality
RPesBoat	% of employed or student resident population using a boat as their main mode of transportation in daily commuting
RPesPT	% of employed or student resident population using public transportation as their main transportation in daily commuting

sea levels. Extreme water levels in the estuary were determined according to the approach of Fortunato et al. (2013), whereby measured sea levels at a nearby coastal station (Cascais) were statistically analyzed to determine synthetic time series associated with specific return periods (20, 100 and 1000 years). Those time series were then used to force a circulation model, which describes the hydrodynamics (velocities and water elevations) in the estuary (Guerreiro et al., 2015). Since the discharge of the Tagus river does not affect the estuarine water levels in the lower 40 km of the estuary (Vargas et al., 2008; Guerreiro et al., 2015), average flow was considered in the predictions.

The inundation model contributed to an understanding of the potential areas that would be directly and indirectly affected. The model thus contributed to the selection of units of analysis and data (Fig. 3). Combined with the analysis of the socio-economic dynamics in the estuary, the determination of the areas susceptible to flooding helped delimitating the area that would be subject to the vulnerability assessment.

3. Assessment of vulnerability

The adopted methodology for the assessment of vulnerability is generically summarized in Fig. 4. The following methodological description emphasizes the processes initially developed to select the variables and units of analysis. After this, the statistical procedure starts with the elimination of multicolinearity between the initial variables and the execution of the principal component analysis (PCA) and culminates in the calculation of the score of each component and the composite score of vulnerability for each of the units of analysis.

3.1. *Territorial variable selection*

The selection of variables is a crucial step in vulnerability assessments. The more dimensions of vulnerability are represented, the more accurate and holistic will be the understanding of vulnerability location, sources and processes. Our study considered an initial set of 126 variables. Table 4 describes the geographical aggregation level, dimension of vulnerability represented and quantity of the initial input variables, classified according to the data source. The following illustrate some of the variables that were collected in order to represent the dimensions identified in Table 4 (cf. also Table 6): from the social chart, the number of social equipments in the fields or childhood and youth per 1000 residents; from the population census at the sub-statistical block, the % of families with one member unemployed, % of women over 65 years old, % of employees in agriculture or the ratio of active population by population over 65 years old; from the population census at the parish level, % of residents with difficulty in walking and climbing stairs, % of homeless people or the % of children aged 3 to 5 attending pre-school education; regarding land use, % of the area of the unit of analysis occupied by farmland or industry; from the data provided by the civil protection national authority, number of retirement homes, health care equipments, fire stations and security forces per unit of analysis.

The majority of variables are provided by the 2011 Population Census, performed by Statistics Portugal (INE).

Data regarding some dimensions of vulnerability are difficult to identify at the local level. Economic activity, income, immigrant and minority population, the homeless or

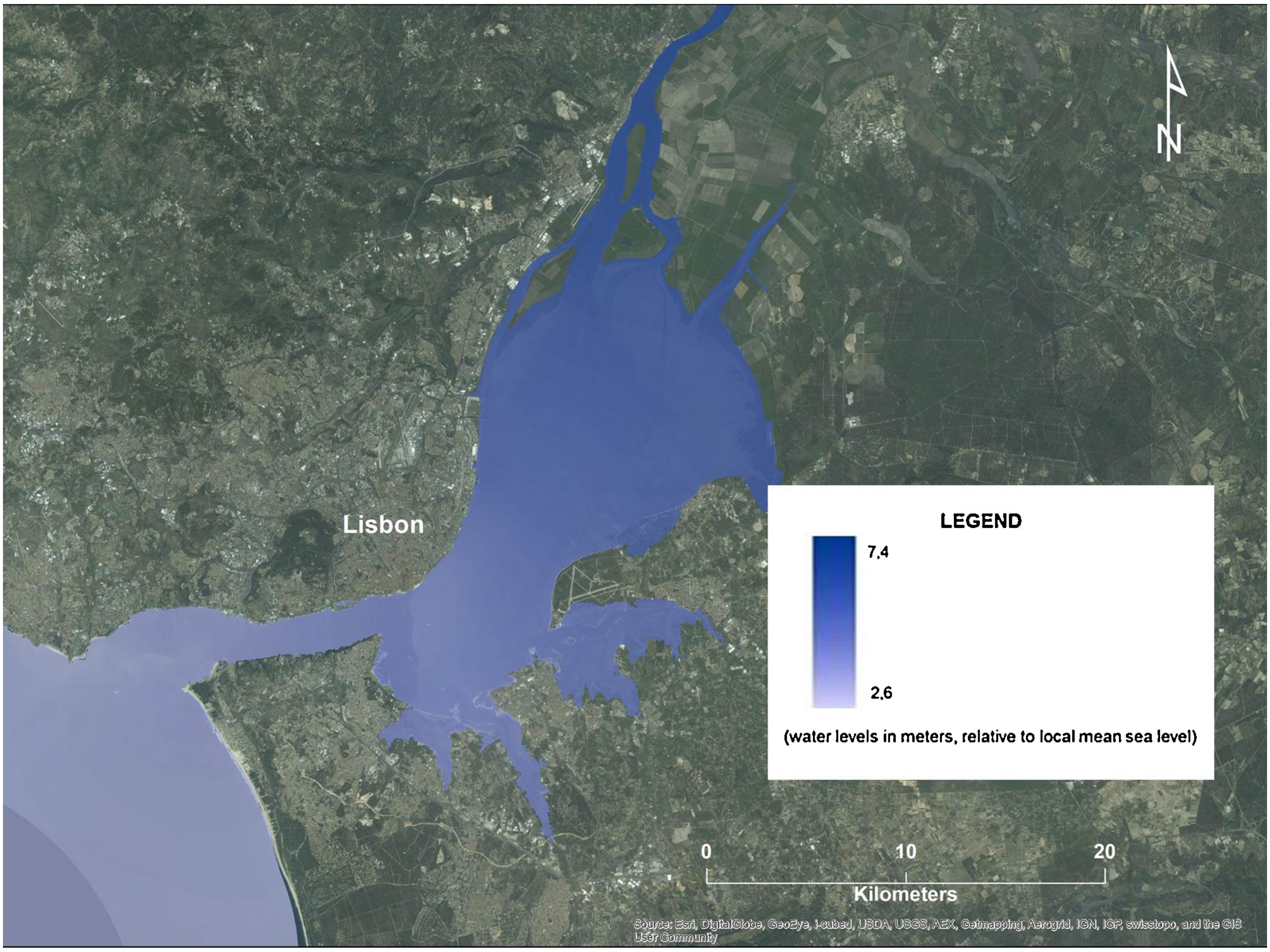

Fig. 3 – Extreme water levels computed with the inundation model, relative to local mean sea level, for a return period of 100 years and with a sea level rise of 1 meter.

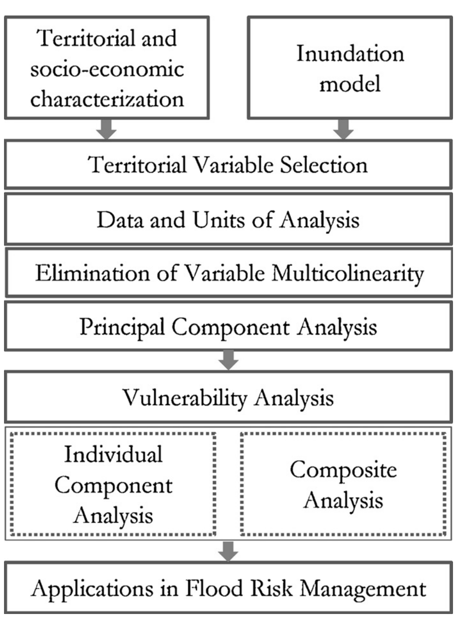

Fig. 4 – Methodological sequence of the vulnerability analysis.

persons with disabilities, for example, are only represented at the municipal or parish level because the parish level is the maximum disaggregation level of the respective variables. In some cases, the values of parish-aggregated data (27 from the census and 9 from the social chart) can be extended to all the statistical blocks (SBs) inside the respective parish boundary. However, some variables at the SB level allow inference regarding some of those dimensions. For example, big households with parking spaces, coinciding with a high percentage of persons with higher education, can be associated with high-income individuals, and such data are available at the sub-statistical block (S-SB) level. To represent more thoroughly the territorial vulnerability, a set of variables representing particular dimensions of vulnerability – lifelines, social equipment and commuting data – were selected. These variables are not associated with either the parish level or any of the lower statistical disaggregation levels. In such cases, GIS tools were used to calculate a given density, the amount of equipment inside each unit of analysis, or a minimum distance to a given piece of equipment. These data were provided by competent authorities in the fields of mapping, civil protection and fluvial transport (Table 4).

Table 4 – Characteristics of data sources and the dimensions of vulnerability they represent.

Source	Aggregation	Dimension of vulnerability represented by the variables	Nos.
Population census	Sub-statistical block	Age, gender, education, housing, employment, socio-economic status, mobility and commuting	76
Population census	Parish	Particular features of vulnerability dimensions (mobility and commuting, persons with special needs, immigration, housing accessibility, homelessness)	27
Social chart	Parish	Child, youth, adult and community social support (no. of beneficiaries and equipment)	9
Official mapping institute	Polygonal	Land use	7
Civil protection national authority	Point, linear and polygonal data	Educational, health, transportation, civil protection, road network and elderly equipment and infrastructure	6
Fluvial transport company	Point data	Passengers between fluvial stations	1

3.2. *Data and units of analysis*

The understanding of the Tagus estuary provided by the inundation model and the socio-economic characterization led to the necessity for a wider approach to the vulnerability assessment. Thus, our concept of the estuarine area attempts to encompass both the estuary's biophysical and human dimensions. A direct implication of this assumption is the consideration that the outer limit of the study area should extend beyond either the limit of the highest astronomical tide line or the maximum flood extent to incorporate the socio-economic relations that occur along and between river margins not directly affected by flooding. The definition of the study area and the definition of the units of analysis are interdependent processes, given that the number of units of analysis depends on the dimension of the study area. Moreover, the vulnerability assessment is based on Principal Component Analysis (PCA), thus requiring an adequate balance between the number of variables and the number of units of analysis.

Three options of units of analysis were considered: the parish (or commune, ''freguesia'' in Portuguese), the statistical block (SB) and the sub-statistical block (S-SB). Their polygonal boundaries are made available in GIS format by Statistics Portugal through the Geographical Base for Information Indexing (BGRI) (INE, 2011b). The parish is a traditional administrative level whose area can vary greatly between a rural and an urban context. An aggregation process occurred in 2014 that attenuated such differences; however, the 2011 Census data used in this study still use the previous boundaries. Lisbon municipality, for example, is characterized by small parishes whereas Benavente municipality comprises larger parishes. The SB and S-SB are defined for statistical purposes to organize and conduct census data collection. The SB and S-SB allow the analysis and presentation of results in greater detail; for example, an S-SB can comprise a single building, thus having the capability of differentiating between built-up areas and even small neighborhoods.

Three distinct criteria were applied to the definition of the study area,: (1) fluvial geomorphology led to the exclusion of areas upstream at the beginning of the estuary or located on the seashore; (2) from the resulting area, units within a buffer of 1000 m from the maximum spring tide limit were included; (3) units with more than 20% of the area under 10 m in height were also included; (4) finally, urban connectivity was considered to avoid the exclusion of relevant urbanized areas and the existence of enclaves.

The number and average area of each of the three types of geographical units of analysis that fulfilled such criteria are presented in Table 5. Considering the optimal relation between the interpretative capacity provided by the average area and the minimum number of units necessary to allow the application of the vulnerability model, the statistical block was selected. In fact, the number of parishes is too small to perform PCA considering that the number of variables is normally between 20 and 40. On the other hand, the number of

Table 5 – Options for units of analysis of the vulnerability assessment.

Municipalities	Area (km^2)	Parishes		Blocks		Sub-blocks	
		Nos.	Average area (km^2)	Nos.	Average area (km^2)	Nos.	Average area (km^2)
Alcochete	88.37	3	29.46	27	3.27	311	0.28
Almada	17.09	8	2.14	118	0.14	492	0.03
Barreiro	21.66	8	2.71	113	0.19	626	0.03
Benavente	291.88	1	291.88	2	145.94	31	9.42
Lisboa	19.49	31	0.63	266	0.07	1239	0.02
Loures	33.13	12	2.76	116	0.29	969	0.03
Moita	19.56	6	3.26	86	0.23	523	0.04
Montijo	34.19	4	8.55	52	0.66	695	0.05
Oeiras	12.34	6	2.06	119	0.10	669	0.02
Seixal	28.37	5	5.67	144	0.20	681	0.04
V. F. Xira	104.32	8	13.04	104	1.00	763	0.14
Total study area	**670.39**	**92**	**7.29**	**1147**	**0.58**	**6999**	**0.10**

S-SBs is adequate for PCA although the interpretative capacity is reduced because of the high heterogeneity and dispersion of areas. Nevertheless, the disaggregation of S-SBs will be used in further steps of the research project regarding local risk assessments in two selected sites. In summary, the combined application of the above criteria resulted in the selection of 1147 statistical blocks with a mean area of 0.58 km^2. The total study area can be observed in the results section in Fig. 5.

The original outer limit of SBs, as provided by the BGRI, is delimited by the water level in the vertical datum (the Mean Sea Level) on the estuarine side. However, in this study, only the areas above the highest astronomical tide line were considered, which required the clipping in GIS environment of the SB polygons between this limit and the water level limit.

3.3. *Elimination of variable multicolinearity*

In this step, a set of methods was applied to the 126 initial variables to select the most robust and adequate variables for PCA. The first method consists of calculating the Pearson coefficient's correlation between all the pairs of variables and deciding which variable in the pairs that present a correlation higher than 0.7 is more relevant and easily interpreted in terms of vulnerability. A typical example is the strong correlation between the aging index and the percentage of people over 65 years old; generally the latter is preferred because it provides a clearer interpretation. In addition, the variables that present communality extraction values inferior to 0.6 were disregarded. These operations were iteratively executed, and the general robustness of the data set – and its suitability to PCA – was monitored through the verification of the Kaiser–Meyer–Olkin (KMO) measure, which must be higher than 0.8 to be classified as ''good'' (Kaiser, 1970). Following these steps, a final set of 34 variables was identified whose KMO measure was 0.813 (cf. Table 6).

All of the 34 variables present communality extraction values higher than 0.6, which indicates that in all the variables, at least 60% of the variables' variance is being explained by the resulting principal components. These parameters represent the adequacy of the resulting variables to perform PCA. It is interesting to observe that, initially, 76 and 27 variables were derived from census data at the SB and parish levels, respectively (cf. Table 4), and that, from these final 34 variables, 22 come from the census data at the SB level and 8 at the parish level. One can conclude that ratios of 2.82 and 2.75 were obtained respectively for the relation between initial and final census-derived variables at both levels, which may indicate that the decision to include specific and complementary variables at the parish level added value to the represented dimensions of vulnerability.

Following the methodology for elimination of multicolinear, or redundant, variables led to the exclusion of some of the variables related to land use and social equipment. Even so, the resulting variables continue to represent many dimensions recognized as descriptive of territorial and individual vulnerability, namely socio-economic status, age, a community's economic wealth, rural/urban dichotomy, household characteristics, infrastructure and lifelines, household ownership and occupation, family structure, education and special needs populations, which are closely related to the concept of social vulnerability (Cutter et al., 2003).

3.4. *Principal component analysis*

After the identification of the variables, the following steps of the vulnerability assessment are a sequence of statistical procedures first defined in Cutter et al. (2003): (1) execution of Principal Component Analysis (PCA) with the final variables; (2) interpretation of principal components and attribution of their cardinality, according to their role in explaining vulnerability; (3) the sum of component scores without weighting; (4) the linear transformation of values to an interval between 0 and 1; (5) cartographic representation of the score of each statistical block according to the standard deviation (SD) both in regard to each of the principal components as to the final composite score of vulnerability: very low (VL) to values lower than −1.5 SD; low (L) to values between −1.5 SD and -0.5 SD; moderate (M) to values between −0.5 SD and 0.5 SD, high (H) to values between 0.5 SD and 1.5 SD and very high (VH) to values higher than 1.5 SD (Chen et al., 2013).

The second step – interpretation of the principal component – is the step requiring more expertise. The name of the component is defined considering the variables with loading superior to 0.5 or inferior to −0.5—generally, two to six variables in each component. The signals of these same variables also allow defining the cardinality of the component, which is important in verifying whether the score in each geographical unit of analysis is in accordance with the sign of the component (Schmidtlein et al., 2008). For example, if the variable ''% of population with higher education'' presents a positive loading in a given component, the score of all SBs in that component must be inverted so that high percentages of the population with higher education correspond to low levels of vulnerability.

The third step is an assumption made from the beginning by the authors who developed the SoVI® (cf. Cutter et al., 2003), followed since then by others (e.g., Zhou et al., 2014). In fact, despite the different percentages of variance explained by each component, one cannot assume that components should be weighted unevenly. The linear transformation performed in the 4th step was introduced by the authors because although z-scores are used, presenting an average of zero, the range of values among components differs significantly. The transformation allows for an easier comparison of the scores.

4. Results

4.1. *Principal components of vulnerability*

Cutting the explicative components at an Eigenvalue of 1, a total of eight principal components (FAC) explains 75.1% of the variance among all units of analysis. The principal components extracted from the PCA analysis express dimensions of vulnerability such as population age, socio-economic status, education, employment, mobility and commuting, urban typology, housing conditions, family structure and special

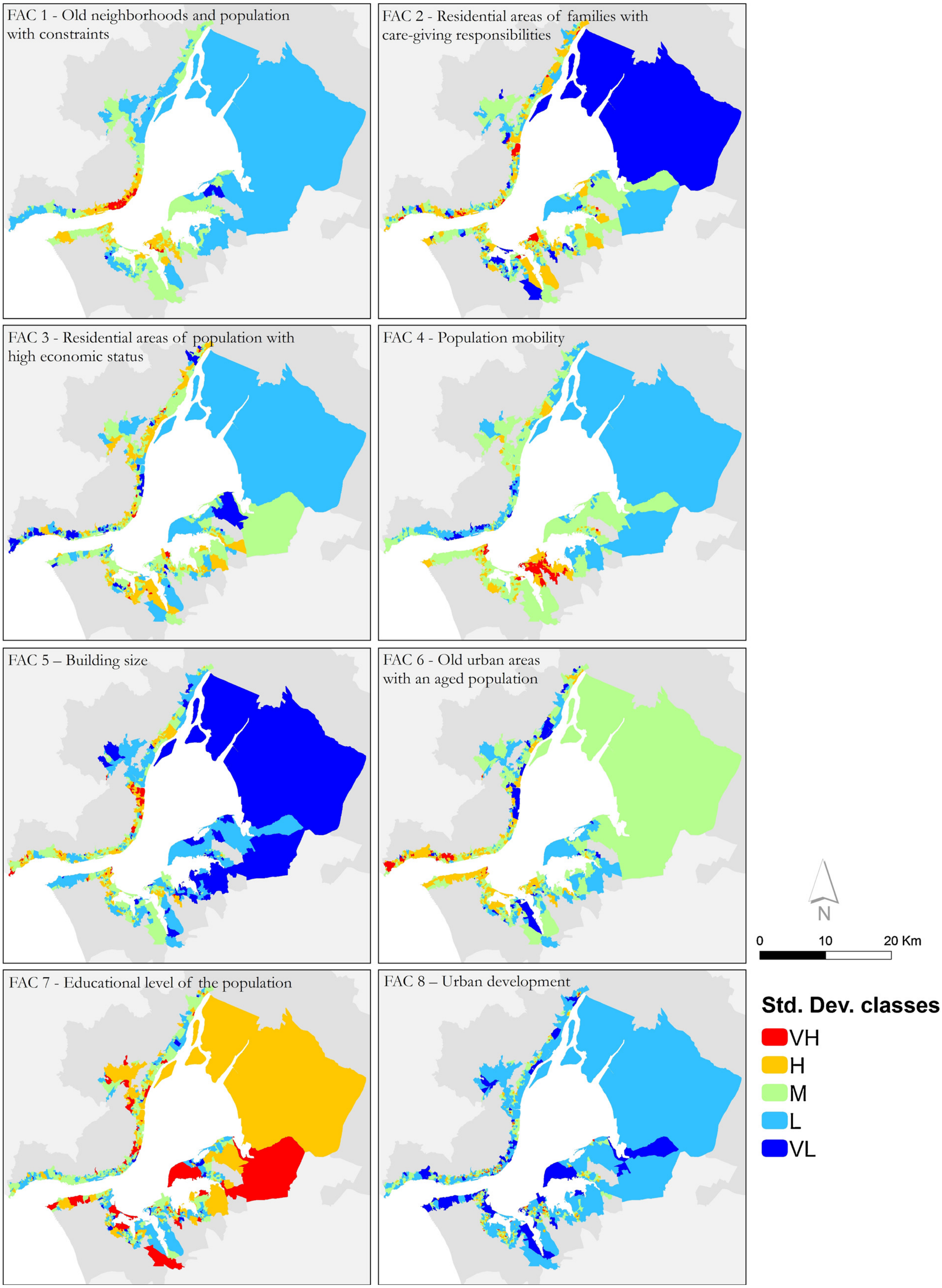

Fig. 5 – Principal components of vulnerability in the Tagus estuary.

Table 6 – Final variables used in the territorial vulnerability assessment.

Vulnerability dimension	Description (unit)	Code
Age & population with special needs	Resident population with at least one difficulty (%)	pop_1_difi
	Resident population over 65 years old (%)	n_individuos_resident_65
	Resident population between 15 and 24 years old (%)	n_individuos_resident_15a24
Family structure	Housing units with only one member (%)	fam_unipe
	Monoparental families (%)	fam_monopa
	Families with 5 or more members (%)	fa_c_5mais*
	Mean family size (no. of individuals)	fa_dim_med*
Education	Resident population attending secondary school (%)	n_ind_resident_fensino_sec
	Resident population with higher education completed (%)	n_ind_resident_ensincomp_sup
	Resident population with 3rd cycle of primary education completed (%)	n_ind_resident_ensincomp_3bas
	Resident population between 3 and 5 years old attending pre-primary education (%)	ed_pre_esc
	Resident population with secondary education completed (%)	n_ind_resident_ensincomp_sec
	Illiterate resident population (%)	n_indiv_resident_n_ler_escrv
Familiarity with place of residence	Resident population who 5 years earlier lived in another municipality (%)	res_5_mun
Urban context	Population density (no. of residents/km^2)	n_individuos_resident
	Building density (no. of buildings/km^2)	n_edificios_classicos
Housing & urban context	Buildings needing repair (%)	ed_ne_repa
	Residential construction built before 1919 (%)	n_edificios_constr_antes_1919
	Residential construction built between 1971 and 1991 (%)	n_edificios_constr_1971a1991*
	Residential construction built between 1991 and 2011 (%)	n_edificios_constr_1991a2011*
	Housing units with 5 or more rooms (%)	n_res_habitual_5_div*
	Buildings with 5 or more floors (%)	n_edificios_5ou_mais_pisos
	Buildings with 3 or more housing units (%)	n_edificios_classicos_3oumais
	Floors by building (no. of floors)	piso_ed
Housing and purchasing power	Housing units with an area between 50 m^2 and 100 m^2 (%)	n_res_habitual_area_50_100
	Housing units with an area greater than 200 m^2 (%)	n_res_habitual_area_200
	Renter-occupied housing units (%)	n_res_habitual_arrend
	Housing units without parking spaces (%)	n_res_habitual_s_estac*
Mobility & commutation	Resident population that uses a car as a regular means of transportation (%)	desl_auto
	Resident population attending school in the municipality of residence (%)	in_est_mun*
	Mean duration of commute (min)	mov_pend
	Employed or studying resident population that potentially uses fluvial transportation (%)	SecUsaBarco*
	Resident population studying or working in the municipality of residence (%)	n_ind_resid_et_mun_resid
Lifelines	Road network density (km/km^2)	DensRV*

* Variables defined from other source variables.

needs populations (Table 7). As mentioned, only the variables with loading above the module of 0.5 are considered to be explicative of each component. Fig. 5 contributes to the geographical and social representation of each of the FACs.

4.1.1. *FAC 1—Old neighborhoods and population with constraints*

The first FAC aggregates variables that identify SBs simultaneously characterized by old neighborhoods and specific individuals who are characterized by real or potential sources of vulnerability such as persons with disabilities, renters and single-parent families. These individuals live mainly in the municipalities of Lisbon and Barreiro (Fig. 5).

4.1.2. *FAC 2—Residential areas of families with care-giving responsibilities*

FAC 2 expresses a residential context that can be designated as traditional or conventional families with care-giving responsibilities. All the variables are related to a given family context. Geographical dispersion is high; however, in general, this component shows low scores in recent and well planned urban developments, as exemplified in some SBs in the municipalities of Oeiras and Benavente.

4.1.3. *FAC 3—Residential areas of population with high economic status*

This FAC represents the population with high economic status as inferred by the grouped variables related to housing

Table 7 – Principal components of vulnerability in the Tagus estuary.

No. of FAC—component (% variance explained)	Signal	No. of variables	Explicative variables (loading >0.5 or <−0.5)
1—Old neighborhoods and population with constraints (21.9)	+	9	Buildings needing repair (0.820) Resident population who use a car as a regular means of transportation (−0.778) Housing units with only one member (0.699) Resident population with at least one difficulty (0.667) Residential construction built before 1919 (0.613) Renter-occupied housing units (0.543) Single-parent families (0.534) Residential construction built between 1971 and 2011 (−0.504) Resident population studying or working in the municipality of residence (0.563)
2—Residential areas of families with care-giving responsibilities (15.7)	−	6	Resident population between 15 and 24 years old (0.865) Families with 5 or more members (0.753) Resident population attending secondary school (0.737) Mean family size (0.681) Resident population attending secondary school in the municipality of residence (0.659) Resident population over 65 years old (−0.537)
3—Residential areas of population with high economic status (10.5)	−	6	Housing units with an area greater than 200 m^2 (0.796) Resident population with higher education completed (0.696) Housing units with an area between 50 m^2 and 100 m^2 (−0.676) Housing units with 5 or more rooms (0.650) Resident population with 3rd cycle of primary education completed (−0.570) Housing units without parking spaces (−0.596)
4—Population mobility (9.2)	-	4	Mean duration of commute (−0.840) Employed or studying resident population who potentially use fluvial transportation (−0.799) Resident population between 3 and 5 years old attending pre-primary education (0.684) Resident population studying or working in the municipality of residence (0.600)
5—Building size (6.5)	+	3	Buildings with 3 or more housing units (0.810) Buildings with 5 or more floors (0.783) Floors by building (0.772)
6—Old urban areas with an aged population (4.2)	+	3	Residential construction built between 1991 and 2011 (−0.778) Resident population over 65 years old (0.674) Housing units without parking spaces (0.609)
7—Educational level of the population (3.9)	−	2	Resident pop. with secondary education completed (0.818) Illiterate resident population (−0.780)
8—Urban development (3.2)	+	3	Road network density (0.823) Population density (0.766) Building density (0.766)

conditions and education (Table 7). Conversely, high scores in this FAC correspond to individuals living in smaller houses and/or without parking spaces whose educational level comprises 9 years of attending school, i.e., the 3rd cycle of primary education.

4.1.4. *FAC 4—Population mobility*

Application of PCA grouped variables is related to mobility and transportation in FAC 4. The signal opposition between variables that imply high mobility and commute times and variables that indicate less mobility – population between 3 and 5 years old attending pre-primary education and population studying or working in the municipality of residence – is evident. Higher values, above 1.5 SD, are located particularly in the southern margin near fluvial stations or along urban settlements in which the population must use a second mean of transportation or a car to move to the fluvial station. This occurs in many SBs in the Seixal, Almada and Barreiro municipalities.

4.1.5. *FAC 5—Building size*

The explicative variables of FAC 3 are all related to the size and capacity of the buildings. These variables provide more an image of the building typology and urban planning than the pressure over public infrastructures and lifelines. The peripheral rural areas in the eastern sector of the estuary (e.g., in the Benavente and Alcochete municipalities) are characterized primarily by sparsely distributed 1- and 2-story buildings, which justifies the low scores of its SBs in this FAC.

4.1.6. *FAC 6—Old urban areas with an aged population*

The 6th component identifies areas in which new or rehabilitated urban areas (buildings built between 1991 and 2011) contrast with areas with buildings without parking spaces and a large proportion of the population over 65 years old. More vulnerable areas are located in old and consolidated settlements, particularly in the municipality of Oeiras (Fig. 5). High scores are concentrated in the eastern sector of Lisbon in a dynamic and vibrant urban area that received in 1998 the Lisbon World Exposition, called "Parque das Nações" (cf. place **a** in Fig. 6).

4.1.7. *FAC 7—Educational level of the population*

The proportion of illiterate residents loads negatively in this FAC whereas the residents who have completed 12 years of education (secondary education) load positively, which implies the inversion of the cardinality of the component, so the scores could be in accordance with the role of each variable in explaining vulnerability. The dispersion is high as SBs with very low scores are bounded by SBs with very high scores. In general, Oeiras municipality presents the best position with no SBs ranked above the 1.5 SD. Some SBs in the Alcochete municipality, near the area that registered the previously mentioned urban sprawl, also have low scores in this education-related FAC, indicating that these new areas attracted highly qualified individuals.

4.1.8. *FAC 8—Urban development*

The vulnerability dimension expressed in FAC 8 refers partially to the same dimension of FAC 5, building size. Nevertheless, this FAC completes FAC 5 because road networks and population density represents more directly the presence of the resident population in "hot-spots" of urban development. In this component, only the extremely dense SBs are identified in the class above 1.5 SD.

4.2. *Composite score of vulnerability*

The algebraic sum of the scores of the eight principal components results in the final composite score of vulnerability mapped in Fig. 6 and summarized in Table 8. The classification according to the standard deviation aims at identifying the extremes of vulnerability. Notably, nearly 29% of the 1147 SBs present high or very high vulnerability.

As a composite result of the various components, the geographical distribution of vulnerability across the estuary could be anticipated by analyzing the spatial patterns evidenced by FACs 1 to 8. Population density appears not to be, in fact, a differentiating factor of vulnerability because equally highly populated settlements are classified at both extremes of the classification scale. Older construction, an elderly population and low levels of education appear to be defining the units of analysis associated with high and very high vulnerability, as are areas located near fluvial transportation interfaces.

Areas **a** to **e** in Fig. 6 illustrate local urban zones in which the vulnerability classification was analyzed along with the expert knowledge of the demographic and socio-economic contexts of these areas. Place **a** (Parque das Nações) refers to a vibrant and dynamic cultural, residential and economic hub rehabilitated in the context of the 1998 universal exposition, with new buildings, economically high-powered families and high-density lifelines and support infrastructures, resulting in very low vulnerability. Place **b** represents the generic so-called "Baixa Pombalina" – after the name of the Marquis of Pombal, who coordinated the rebuilding of this downtown area after the 1755 Lisbon Earthquake – which remains a vital zone in

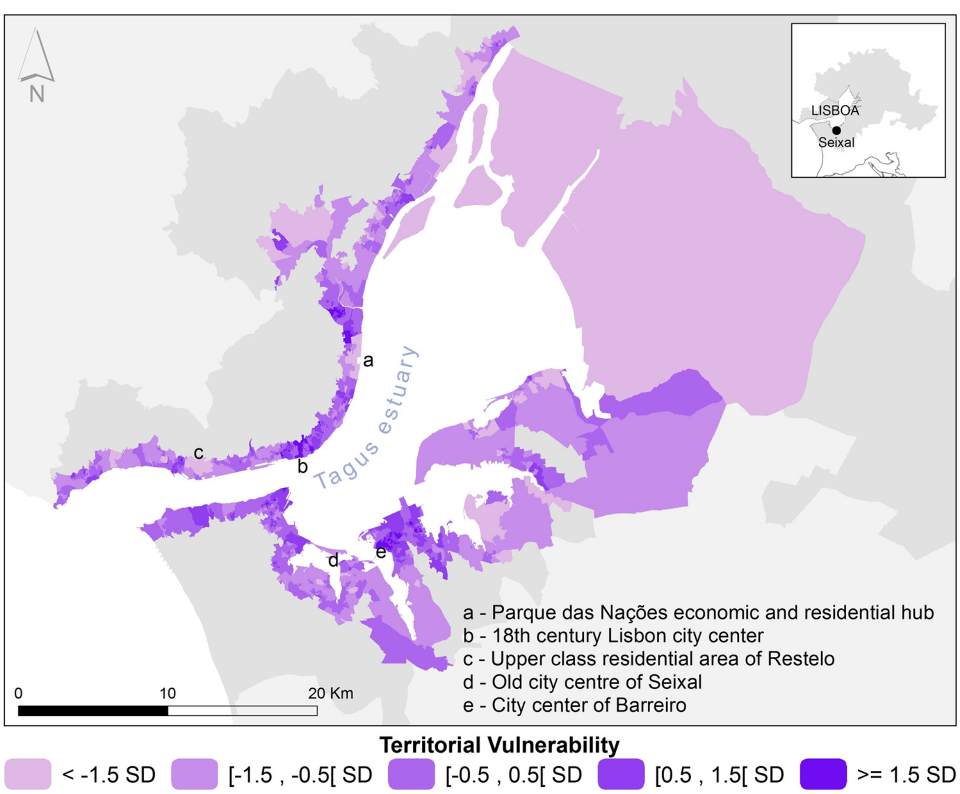

Fig. 6 – Composite score of vulnerability in the Tagus estuary.

Table 8 – Frequency of statistical blocks by class of vulnerability in the Tagus estuary.

Vulnerability		Very low	Low	Moderate	High	Very high
Statistical blocks	No.	68	286	462	243	88
	%	5.9	24.9	40.3	21.2	7.7

terms of economic, administrative and political activity, although old buildings, an aged population and the concentration of fluvial, metro, train and road interfaces render this area highly and very highly vulnerable, particularly to disruptions caused by flooding. Place **c** (Restelo) refers to a low urban-density area with single-family houses occupied by high-income families; several of these residences are embassies, resulting in very low vulnerability. Place **d** is the Seixal old city center, one of the local case studies to be assessed in more detail in the next phases of the research, adding a complementary type of vulnerability knowledge that is being gathered in the area, framed in risk assessment processes promoted in partnerships between the municipality and academic institutions (cf. Santos et al., 2013). Place **e** is the Barreiro built-up area center, particularly the Verderana parish. This area is marked by highly populated SBs from the middle and lower social classes who depend greatly on fluvial transportation for their daily commute to the workplaces on the other margin of the river. This urban area is also characterized by high unemployment rates and an aged population, which is consistent with the classification of high and very high vulnerability.

To allow a more summarized overview of the vulnerability patterns among the estuary's municipalities, the number of SBs and the number of the resident population were calculated according to the vulnerability class and grouped by each of the 11 municipalities (Figs. 7 and 8). When interpreting Fig. 8, one must consider that this is a statistical exercise, i.e., it is not accurate to state that a given total of residents living in an SB classified with a given vulnerability class does in fact possess that vulnerability condition. From the 88 SBs classified with very high (VH) vulnerability, 78 belong to the municipalities of Barreiro, Lisbon and Loures. With the exception of Loures, the other two municipalities – and at a smaller level, Almada – depend to a greater extent on the commutability offered by the estuary, regardless of the fact that several other components contribute to these scores, namely the characteristics of the buildings and the age and qualifications of the population. In terms of the estimated population figures, these three municipalities represent 39,000 of the 43,000 living in SBs classified with very high vulnerability. If we consider also the class of high (H) vulnerability, these municipalities represent 101,000 of the 672,000 inhabitants living in the 1147 SBs.

Comparatively, the municipalities with the highest percentages of residents living in SBs classified with the least vulnerability – low (L) and very low (VL) – are Benavente (100%),

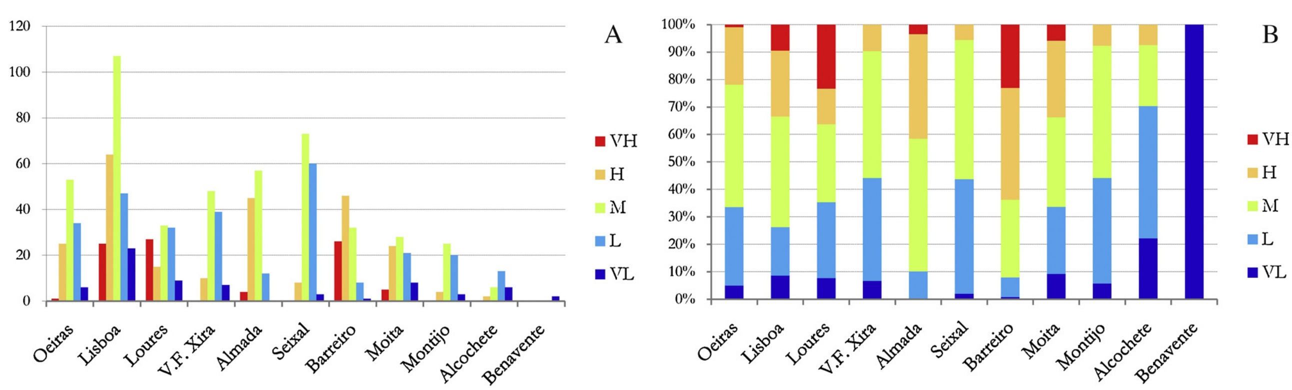

Fig. 7 – Absolute (A) and relative (B) frequency of number of statistical blocks by class of vulnerability, by municipality.

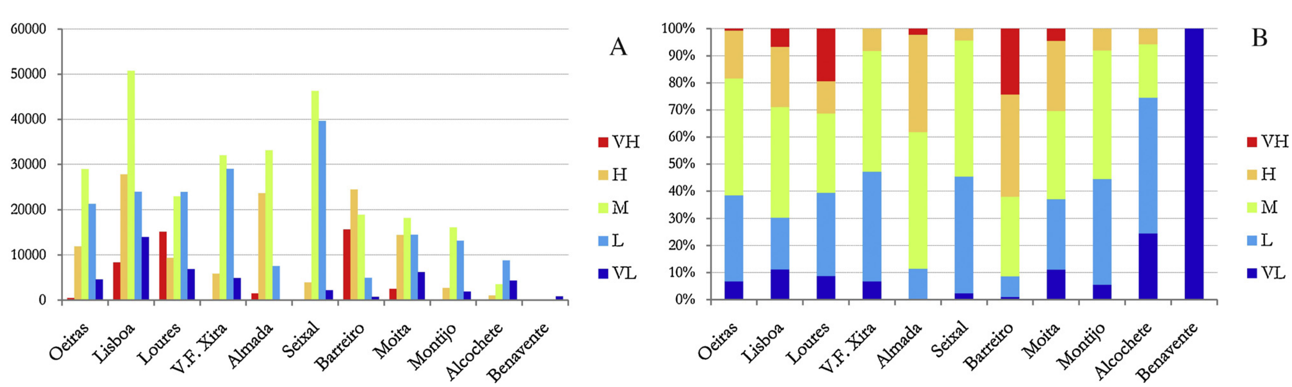

Fig. 8 – Absolute (A) and relative (B) frequency of resident population by class of vulnerability, by municipality.

Alcochete (74.5%), V.F. de Xira (47.2%), Seixal (45.4%) and Montijo (44.5%).

5. Endnotes

5.1. *Drivers of vulnerability*

This manuscript exemplifies a vulnerability assessment for the Tagus River estuary in Portugal. Notwithstanding the fact that this is a regional study, the adopted methodology and the wide range of available variables related to vulnerability allowed to clearly identify the territorial and individual vulnerability at a local level. The nature of the hazard – flooding in an estuarine context with the effect of storm surge – prompted us to identify specific variables that could represent the vulnerability dimensions related to commuting, considering the estuary as a connectivity resource. The age of buildings, the age and educational level of individuals and the proximity to fluvial transport interfaces are the drivers of vulnerability most evidenced in the analysis, which must be considered in the risk management process.

The major dimensions of vulnerability are represented in the extracted principal components, which confirm the potential to replicate the statistical procedure used in the SoVI® in other contexts and scales. The separate analysis of each of the components complements and increases the understanding of specific dimensions of vulnerability and its geographical distribution (Tate, 2013).

5.2. *Scale and data availability*

When embracing such local studies, scale is of primordial significance. Potential effects of disasters can be substantially underestimated whether a micro-scale assessment or a meso-scale and national-scale assessment are performed (Sterr, 2008). Although the study embraces a regional scale, which includes eleven municipalities, the study's focus on detailed data collection and cartographic representation is reflected in the individualization and characterization of local areas as small as neighborhoods and groups of buildings, in which the average number of residents by unit of analysis is approximately five hundred. A major challenge when attempting to characterize vulnerability in a given area is finding the best balance between the scale of analysis and the adequacy, depth and pertinence of the variables that seek to represent each of those concepts.

The boundaries of the SB are not always the most appropriate to represent the territorial characteristics, for example, to distinguish urban and rural areas or low- and high-density urbanization. Despite of this mismatch, statistical blocks are used to aggregate census data and, therefore, similarly to the previous vulnerability assessments made in Portugal and mentioned above, this study highlight the relevance of the census data provided by Statistics Portugal as the data source that best combines comprehensiveness and geographical disaggregation for conducting vulnerability assessments.

The use of the statistical block – and not bigger units of analysis such as the municipality or the parish (e.g., Mendes et al., 2011) – as the geographical unit of analysis presented challenges in terms of data availability and interpretation capacity. Previous vulnerability assessments at the municipal level, for example, resort to variables that can only be interpreted at that scale of analysis. The variable ''% of population covered by water treatment facilities'', for example, can in fact be used to differentiate the municipalities' vulnerability in terms of the quality of the water that is supplied to the population. The values of that variable have a meaning at that administrative level. Nevertheless, this same variable cannot be used when working at the statistical block level. The presence or proximity of such facilities in a given SB can be, conversely, representative of lower environmental quality – because of noise, smell, landscape degradation, etc. – and thus of higher vulnerability. This same conclusion can be extended to other variables normally used in vulnerability assessments. Moreover, a great variety of relevant and widely used variables in vulnerability literature exist at the municipal level but are scarce or absent at the SB level in the Portuguese context, and therefore in the Tagus estuary. Examples of such variables are, for example, cash withdrawal at ATMs, municipal expenses for health, and purchase power. These variables are not specifically relevant to assess vulnerability to flooding, as they can and should be used in regard to other hazardous processes (earthquakes or heat waves, for example). However they transversely help describe the general socioeconomic condition of a community. They also help define the degree to which individuals, communities and authorities are able to respond and recover from disaster events. Notwithstanding the constraint posed by the absence of such macro-scale type of variables at the SB level, the selection of that statistical unit of analysis is considered to have been advantageous, given the level of detail that it allowed using the available variables.

By assuming a local scale of analysis, this study addresses specific and localized needs in terms of flood risk management in an estuarine context. As demonstrated, the geographical distribution of vulnerability is not homogeneous inside a municipality or even a parish, and at those levels, the vulnerability assessment would not satisfactorily address the information that distinct private and public stakeholders require.

5.3. *Applications in risk management*

A balance between conceptual comprehensiveness and geographical detail is required to render vulnerability assessments effective tools in risk management, a concern that this study attempts to address. We believe that the information in this study can be applied to the following areas (Fig. 9):

- Emergency response: Civil protection managers can more accurately estimate the direct and indirect effects of flooding and comparatively predict the recovery capacity of each local area and social group. More broadly, social responses can become more effective, both in *ex ante* measures – with the goal of increasing resilience and reducing vulnerability – and in post-disaster measures that promote the continuity of day-to-day activities and the efficient operations of rescue and recovery in the most disastrous events. Institutional communication must be promoted and trained.

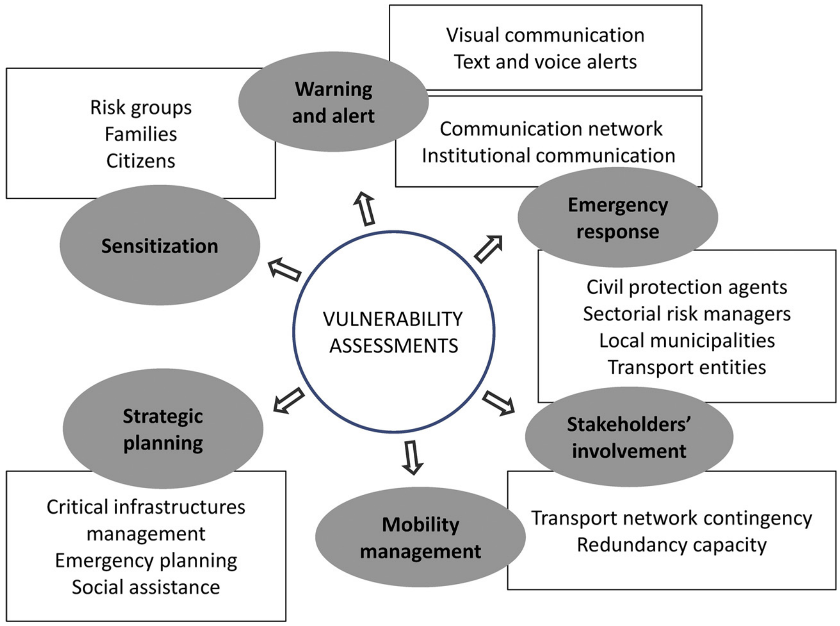

Fig. 9 – Applications of vulnerability assessments in risk management.

- Sensitization, warning and alert: Specific risk communication methods and tools can be defined for each of the identified social groups that are more vulnerable as well as to the entire population according to the characteristics extracted from the principal components.
- Strategic planning: The location and management of critical infrastructures in the medium- and long-term, i.e., not in terms of emergency response. The areas of education, health, energy, industry and welfare should consider and plan for the potential effects of the disruption of lifelines and equipment to the target publics that they serve.
- Mobility management: Mobility managers should plan redundant systems, i.e., systems that can provide identical or approximately the same level of service coverage in situations of disruption of one or more of its nodes and lines. This requires the existence of contingency planning that encompasses and establishes protocols and procedures between the different means of transportation—fluvial, subway, train and road. In short, a new mobility framework that considers vulnerability caused by service disruptions and establishes a contingency plan characterized by redundancy of the transportation and communication networks, which reduces indirect effects caused by transportation failures.
- Stakeholders' involvement: The efficiency of risk governance depends greatly on this capacity. Scientific data regarding the flood hazard and flood risk must flow to civil protection authorities, who are responsible for the coordination of emergency planning and early warning actions, and from the civil protection authorities to the remaining stakeholders: multi-sector and multi-level private and public stakeholders. An increase in resilience and a reduction in vulnerability imply long-term policies. Spatial planning, economic, health and social assistance policies are distinct sectors that can improve interventions based on vulnerability information, requiring high levels of involvement and cooperation.

Assuming as wise and valid the premise that flood risk management should be defined and applied according to the local socio-economic characteristics of individual households and neighborhoods (Koks et al., 2015) and not homogeneously to vast areas, vulnerability assessments at the local level represent crucial information and should be thoroughly considered in the assessment of flood risk foreseen in the European Union directive 2007/60/EC and in the respective transposition to the Portuguese legislation through the Decree-Law no. 115/2010 of 22nd October. Although the term "vulnerability" itself is not prominent in the document, the full embodiment of the directive through the flood risk management plans requires a deep consideration of such analysis, to which the present research attempts to contribute. The assessment of vulnerability is consistent with the need for long-term estuarine flood risk management strategies that focus on mitigation and adaptation to the adverse effects of flood hazards. Risk governance strategies should adopt the major objective of promoting a durable reduction in vulnerability. Assessment, as one of the pillars of risk governance, is key to the understanding of hazards, the contexts in which they can occur, and the potential for loss and recovery, thereby supporting the adoption of the most efficient and adequate risk management strategies.

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Acknowledgments

The research presented in this study was conducted under the project ''MOLINES - Modeling floods in estuaries: From the hazard to critical management'' (PTDC/AAG-MAA/2811/2012) funded by the Foundation for Science and Technology (FCT).

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