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Territorial vulnerability to flooding in an estuarine area: Challenges valuing the structural and societal local ensemble

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ABSTRACT: Flooding in estuaries and coastal areas are a major concern for flood risk managers. The challenges they face are related with the highly dynamic nature—both naturally and socioeconomically—of these interchange areas, aggravated by predictable scenarios of sea level rise.

The reduction of vulnerability and the consequent increase in resilience depend on the capacity to address such challenges, requiring a multi-level approach which implies frequently a multi-scale assessment of the existing conditions. In fact, different stakeholders act at different scales with specific competences and information demands.

In this study, a regional assessment of vulnerability for the Tagus River estuary, Central Portugal, is the starting point for the local assessment of vulnerability in the old city centre of Seixal. The selection of the areas is based on the results provided by the inundation model applied.

The regional assessment of vulnerability was conducted through principal component analysis applied to a set of 34 variables expressing demographic, socioeconomic, social care, mobility, land use and critical infrastructure features. For the local study in Seixal, field collected data, Census data and municipality geographic data were used in the definition of four parameters descriptive of territorial vulnerability. Field collected data is discretized at the sub-statistical block level, and gathers data regarding the surrounding physical and urban context, the predominant socioeconomic and residential functions, and the typology of occupancy and people's presence fluctuation on each block. Census data from 2011 quantify the number of potentially affected residents and allows estimating their vulnerability according to age and economic activity. Results of both assessments are then compared with each other and with the results provided by the flood hazard model.

The study evidenced the specific methodology and data required by regional and local vulnerability assessments. A detailed differentiation in the territorial vulnerability classification is obtained and proportionated by the use of different scales of analysis. Results identify as more vulnerable the blocks characterized by aged and vulnerable resident population and the blocks where transient population associated with the collective use of the space is more concentrated.

1 INTRODUCTION

Vulnerability is as an integral part of the causal chain of risk which implies that risk decision makers should understand its assessment as part of a cost-effective strategy of risk management (Kasperson et al. 2001).

Vulnerability assessments provide the risk governance coordinators with information that allow them to convoke and discuss with regional and local stakeholders and communities on the best practices of flood risk management (Kienberger 2012).

The use of indicators to resume into a single value the complexity of major systems is a goal pursued in many research fields and also in regard to vulnerability assessments (Tate 2013). Inherent to this effort, researchers face however three problems derived from the characteristics of vulnerability research: scale issues, dynamism—of social, economic, institutional, legal and natural systems—, and complexity and limited understanding (Adger et al. 2004).

The research presented in this paper is part of the Portuguese funded research project "MOLINES—modeling floods in estuaries: from the hazard to the critical management", whose main goal is the improvement of the hazard and vulnerability knowledge about estuarine flooding under meteorological storm surge conditions, and upon that, to build the most effective risk management strategies at the regional and local levels. The area where this research is being conducted is the Tagus River estuary, located in Portugal near its capital city, Lisbon.

By dealing with coastal areas such as estuaries, this research experiments the three mentioned problems. In fact, estuaries are natural regions which have since early been demanded for their privileged accessibility conditions, resources and geostrategic position. The Tagus River estuary is no exception. The Tagus literally separates the country in two parts, as cities developed over the centuries along the two margins addressing two often contradictory roles: connectivity and defense. Temporal social and economic changes, translated in dynamic urban and demographic spatial representations, have the capacity to change the landscape of hazards and respective losses (dos Santos et al. 2014; Zêzere et al. 2014). Finally, and transversally, the complexity in vulnerability assessments is marked by scale issues (Mendes et al. 2010; Schmidtlein et al. 2008).

In this research project, scale is understood as a driving factor with implications at many levels of risk assessment and risk management. Regarding the later, the efficiency of risk management will be pursued strongly under the scope of risk communication. The vulnerability assessments that are described in the following sections are substantially devoted to support a risk communication and involvement strategy, where early warning systems will play crucial roles in reducing direct and indirect losses. Early warning systems depend on the ability to forecast flooding which, in estuaries, is a particularly complex process due to the diverse sources of hazard at presence (Cluckie et al. 2000). An increased complexity on the side of the technological focus of risk governance requires a thorough preparedness on the side of the societal focus (Tavares 2013). Therefore, the regional and local assessments of vulnerability should attempt to identify the different targets and levels of amplification needed for effective flood risk governance (Aven & Renn 2010).

2 METHODOLOGY

2.1 *The study area*

The research in the Tagus River estuary encompasses two scales of analysis: at the regional scale, the study area is a total of 1147 statistical blocks (SB's) distributed by 11 municipalities around the Tagus river estuary (Fig. 1a). At the local scale of analysis, the Old City Center (OCC) of Seixal was selected as the study area (Fig. 1b), which is

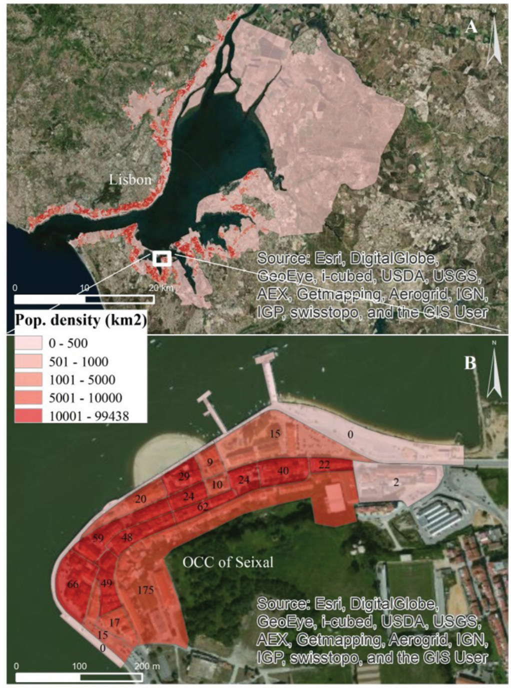

Figure 1. Geographical context of the regional (A) and local (B) study areas. Number of residents of the OCC of Seixal by sub-statistical block in parenthesis.

a built-up area among the most densely inhabited around the estuary's margins.

For the regional study the area identified in Fig. 1A totals 672,016 inhabitants in 670.39 km^2. In the OCC, Census data of 2011 counts 686 inhabitants in an area of 0.1039 km^2.

2.2 *The inundation model*

An inundation model for the estuary, forced by the average fluvial discharge in the Tagus River, was set up for the 20, 100 and 1000 year return periods (Tavares et al., in press). The model was ran considering two scenarios: the present situation in terms of mean sea level; and an expected sea level rise (SLR) of 1 meter by 2100 according to the IPCC last report (Stocker et al. 2013). Extreme water levels in the estuary were determined following the SELFE model whereby measured sea levels at the coastal station of Cascais—distant only 20 km from Lisbon—were statistically analyzed to determine synthetic time series associated with the referred return periods (Fortunato et al. 2013). Those time series were then used to force a circulation model, which describes the hydrodynamics in the estuary (Guerreiro et al. 2015).

2.3 *Territorial vulnerability at the regional scale*

At the regional scale, the purpose of the assessment was to provide an insight of territorial vulnerability that could support decision-making of local practitioners. Providing results disaggregated at the municipal or the parish level wasn't considered as satisfactory to that purpose because they sum, respectively, only 11 and 92 geographical units. Such disaggregation doesn't allow the detail of analysis pursued in the project MOLINES, which aims at providing results that could be useful both at a strategic and a operational level, considering that vulnerability and flood hazard can be geographically very confined to specific critical spots (Few 2003). Therefore, a total of 1147 statistical blocks (SB's) were identified that lay within a buffer of 1000 meters from the maximum spring tide limit, and are simultaneously under an elevation of 10 meters. The application of such criteria follows (a) the results of the inundation model, (b) the need to include areas not directly affected by the flood but that could also suffer from indirect damages, such as lifeline disruptions, (c) and the need to have a statistically significant number of units of analysis to carry out the statistical procedure based in Principal Component Analysis (PCA). Each SB presents and average area of 0.58 km^2 and an average population of 585.89 residents.

A multitude of dimensions are present when trying to represent a given territory in terms of its vulnerability to natural hazards. In our research, the most relevant dimension considered was that related directly to the population's safety and resilience, usually connected with the concept of social vulnerability. In such concept the collected variables attempt to represent population's socioeconomic status, gender, race and ethnicity, age, employment, family structure, education, housing conditions, medical services, social dependency and special needs (cf. Chen et al. 2014). Moreover, other dimensions were considered, such as (i) land use and property tax coefficients, in order to analyze the value of the land, (ii) coverage by social equipments, civil protection assets and lifeline infrastructures, in order to assess the support capability and (iii) coverage and dependency on the commuting transport network with an emphasis on fluvial transport between the river margins (Table 1).

Table 1. Examples of variables used in the regional assessment of territorial vulnerability for the Tagus estuary, grouped by the dimension of vulnerability represented.

Dimension of vulnerability	Examples of variables at the SB level
Age and gender	Population over 64 years old (%) Population under 5 years old (%) Female population (%)
Education	Population with higher education (%) Illiterate population (%)
Housing and socio-economic status	Housing units with an area greater than 200 m^2 (%) Housing units without parking spaces (%)
Employment	Ratio between unemployed persons and active population Families with more than one person unemployed (%)
Mobility and commuting	Population that uses a car as a regular means of transportation (%) Mean duration of commute (min) Employed or studying population that potentially uses fluvial transport (%)
Special needs and homeless people	Population with at least one difficulty (%) Homeless persons (%)
Immigration and place familiarity	Immigrant population (%) Population who 5 years earlier lived in another municipality (%)
Family structure	Housing units with only one member (%) Families with 5 or more members (%)
Educational, health, transportation, civil protection and elderly equipments and infrastructures	Social equipments in the fields or childhood and youth (no. of equipments/1000 residents) Retirement homes, health care equipments, fire stations and security forces (no. of equipments inside the SB)
Urban/rural context	Farmland in the total SB area (%) Residential areas in the total SB area (%) Building density (no. of buildings/ km^2)

A total of 126 initial variables were defined and their data collected. After a process of multicolinearity elimination, a final set of data from 34 variables was used to perform PCA. The scores of the resulting principal components (FAC's) are summed without weighing and classified according to the standard deviation (SD) as follows: 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.

2.4 *Refinement of territorial vulnerability to the local scale*

It was a concern since the beginning of the research to produce information that could support

Table 2. Variables used in the local assessment of territorial vulnerability in the OCC of Seixal.

Sub-statistical block level	Source
P1. Profile of the more vulnerable population: – population above 65 years old (%) – population under 5 years old (%) – population without economic activity (%)	Census data
P2. Absolute resident population	Census data
P3. Present population – estimated transient population – permanency to exposure: day/night, punctual (e.g. exhibitions, sport's events)	Field matrix
P4. Surrounding urban context – land use – critical linear (not building type) infrastructures – urban fabric and flood defense infrastructures	Field matrix

managers at different scales of decision and action. Therefore, the OCC of Seixal was selected as a local study area where the territorial vulnerability would be assessed at the sub-statistical block (S-SB) level and at the building level.

So far, only results at the S-SB level will be presented although some data at the building level are already available. For that purpose, a set of parameters was collected from the Census 2011 datasets, from the field and from the Seixal municipality services (Table 2). A total of 20 S-SB's were characterized.

The parameters identified in Table 2 defined four geographical layers in polygonal GIS format aggregated at the S-SB. Data from these parameters provide an expression of the urban and social environment.

The amplitude of values calculated in each of the four parameters is linearly scaled to the interval [0,1]. For example, the amplitude of the percentage of population under 5 years old in the 20 S-SB's is transformed into values ranging from 0 to 1. Data collected through the field matrix (parameters P3 and P4) are directly coded in that interval. Land use, for example, is classified as follows: predominance of residential and commercial buildings (1), predominance of other artificial surfaces (0.5), predominance of farmland, salines and natural areas (0.25), predominance of degraded land (0).

In regard to parameter P3, input data is based in two types of information: the average number of present and visiting persons per building and the type of permanency to exposure, which depends on the function of the building (residential, commercial, administration, etc.). In regard to parameter P4, input data is based in three field collected items: type of land use; existence of critical lifelines; and the surrounding urban context which is derived from 3 sub-questions (benefit from flood defense infrastructures; presence of mobile objects between the coastline and the buildings; and flow constraints based in urban and building typology).

A simple arithmetic average is calculated with all the parameters—i.e. without weighting—in Excel® and such tabular data are then connected to the respective geographical unit in GIS environment using ArcGIS® software. As performed for the regional scale assessment, the results are classified according to the standard deviation in the same five classes from very low (VL) to very high (VH).

3 RESULTS

3.1 *Regional level*

Cutting the explicative components at an Eigenvalue of 1, a total of eight principal components (FAC's) is obtained that explains 75.1% of the total variance among the 1147 units of analysis. This fact and a Kaiser-Meyer-Olkin (KMO) value of 0.813 testify for the robustness of the data set.

The eight FAC's are representing some of the dimensions of territorial vulnerability initially considered: 1 – Old neighborhoods and population with constraints (21.9% of the total variance); 2 – Residential areas of families with care-giving responsibilities (15.7%); 3 – Residential areas of population with high economic status (10.5%); 4 – Population mobility (9.2%); 5 – Building size (6.5%); 6 – Old urban areas with an aged population (4.2%); 7 – Educational level of the population (3.9%); 8 – Urban development (3.2%).

After summing algebraically the scores in each FAC, a final score of territorial vulnerability is obtained. From the 1147 SB's considered for the estuary level assessment, 88 are classified with very high territorial vulnerability. In these SB's live around 43,000 people.

Fig. 2 zooms in the regional assessment to the SB level in the Seixal bay. The area of the CCO of Seixal is covered by 4 SB's where one presents high vulnerability, two present moderate vulnerability and one, low vulnerability (cf. also Table 3). At this point it was expected that field collected data in the OCC of Seixal would identify significant variations inside each of these SB's.

3.2 *Local level*

The cartographic representation of the parameters P1 to P4 allows to detail and preview the final composition of territorial vulnerability disaggregated

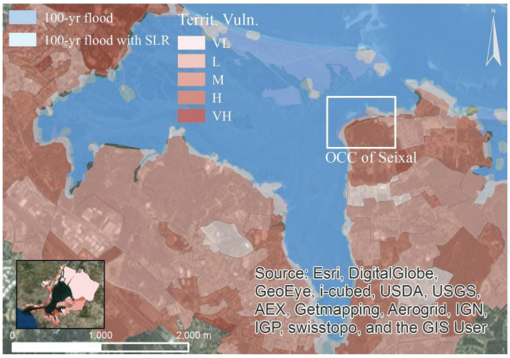

Figure 2. Territorial vulnerability at the SB level in the Seixal Bay and in the OCC of Seixal.

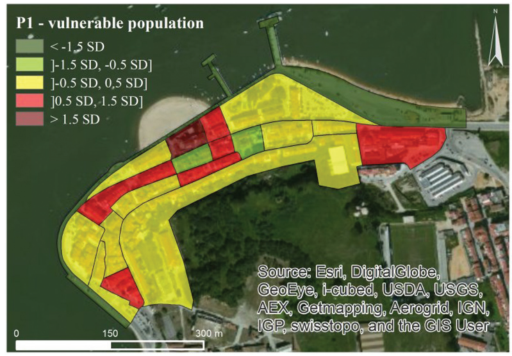

Figure 3. Parameter P1 of territorial vulnerability at the S-SB level in the OCC of Seixal.

Table 3. Comparison of the classification of territorial vulnerability (TV) at the SB and S-SB levels.

SB level		S-SB level			
SB code	*TV Class*	TV Class	No. of S-SB's	No. of buildings	No. of residents
		VL	-	-	-
		L	-	-	-
001	*L*	M	2	15	24
		H	-	-	-
		VH	-	-	-
		VL	2	1	0
		L	2	38	64
003	*M*	M	1	34	66
		H	1	16	17
		VH	-	-	-
		VL	-	-	-
004	*H*	L	1	16	24
		M	6	88	160
		H	4	57	156
		VH	-	-	-
		VL	-	-	-
		L	-	-	-
005	*M*	M	-	-	-
		H	1	79	175
		VH	-	-	-
	Total		*20*	*344*	*686*

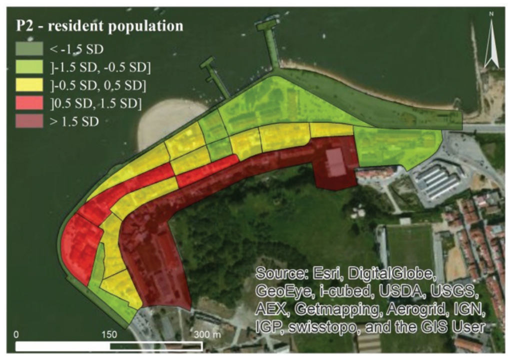

Figure 4. Parameter P2 of territorial vulnerability at the S-SB level in the OCC of Seixal.

at the S-SB level (Figs. 3–6). The classification is according to the SD as previously described.

The parameter P1 considers age and economic activity as descriptive of demographic and socio-economic vulnerability. Some S-SB's located near the shoreline are identified as highly vulnerable, although in some of them parameter P2 allows to observe that their absolute number of inhabitants is very small (cf. Fig. 1 and 4). The S-SB located in front of the semi-circular sand beach is illustrative of this dichotomy: the high value in parameter P1 in this unit is based on the fact that, according to Census data, 13 of the 29 residents are over 65 years old, and 17 have no economic activity. This fine reading is, eventually the bigger advantage of such local assessments.

Parameter P3 characterizes the fluctuation of present or transient population, emphasizing the concentration of people in small areas and buildings. The higher values in this parameter are associated with the collective and concentrated use of the space, where the commercial, administration and social care functions predominate over the residential function.

The existence of docking structures and movable objects of big dimensions such as boats, vehicles in parking lots and containers, results in high values of vulnerability in parameter P4.

The values of the final territorial vulnerability at the sub-statistical block level are ranging from a minimum of 0.14 to a maximum of 0.54, in the

Figure 5. Parameter P3 of territorial vulnerability at the S-SB level in the OCC of Seixal.

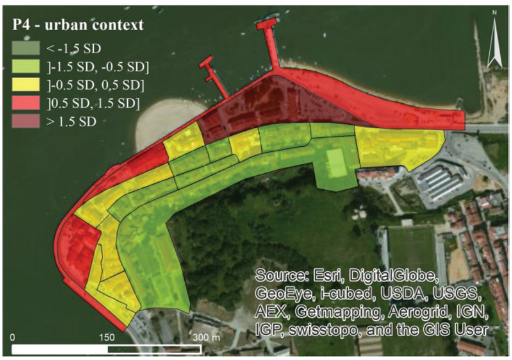

Figure 6. Parameter P4 of territorial vulnerability at the S-SB level in the OCC of Seixal.

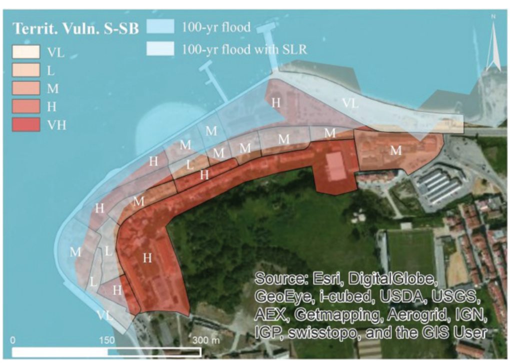

Figure 7. Final territorial vulnerability at the S-SB level in the OCC of Seixal.

theoretical range of 0 to 1. According to the classification using the standard deviation no class of very high (VH) territorial vulnerability is found in OCC of Seixal (Fig. 7). Even so, it is concerning to observe that three S-SB's classified with high vulnerability are partially affected by the 100-yr flooding scenario without SLR.

Table 4. Potential applications of territorial vulnerability information in early warning and planning of estuarine flood risk management.

Early Warning		
Communication		*Involvement*
Risk groups Families Citizens		Civil Protection Sectorial Risk Managers Local Municipalities Transport Entities
Planning		
Social Assistance	*Population Mobility*	*Emergency Response*
Critical infrastructure management	Redundancy system capacity	Contingency plan

As the figure shows, without SLR, 1.86 hm^2 of the OCC of Seixal is inundated with a probability of 1 in 100 years. In the worst scenario of climate change, for the same frequency, an estimated 57% of the area would be in risk of flooding (5.90 hm^2).

3.3 *Comparison of assessments at both scales in the OCC of Seixal*

Results obtained from the regional and the local assessment of territorial vulnerability can't be directly compared, as the scores and classification depend on the totality of the units of analysis. Nevertheless, an exercise can be done that illustrates how inside the same unit of analysis at the regional assessment—the statistical block—vulnerability can vary significantly at the local level using the sub-statistical block (Table 3). In this table, the total of 20 S-SB's is distributed by the respective vulnerability classes and compared with the assessment at the regional level.

Both assessments result in the absence of geographical units of analysis with very high territorial vulnerability. On the other extreme of the classification, only the two S-SB's located near the shoreline (cf. Fig. 7) present very low vulnerability which is partly justified by the legal and physical impossibility of inhabiting such areas (cf. Fig. 1) and the existence of one non-residential building. As for the other S-SB's, significant variations exist inside the same SB.

One of the SB's, coded "005", is composed of 3 S-SB's but only one of them is part of the OCC of Seixal. This means that the regional assessment at the SB level included Census data that is geographically outside the area of the local assessment. This may, in part, justify the difference in the classification found in this SB: moderate at the regional level and high at the local level.

4 DISCUSSION AND APPLICATIONS

Based on flood hazard scenarios for distinct return periods, with and without the expected effect of sea level rise by 2100, two methodologies for assessing territorial vulnerability have been developed: one for the regional scale encompassing the entire Tagus river estuarine area, and another at the local scale, in the built-up area of Seixal. Both try to address the different needs of vulnerability information that the distinct stakeholders acting at those scales require, in the fields of risk and emergency management.

When searching for variables that could represent the considered territorial dimensions of vulnerability at the regional level, scale assumed itself as a critical factor. In fact, many variables are only available at upper levels of disaggregation, e.g., those related to the socioeconomic status, minorities and risk groups (homeless and people with special needs).

In regard to the local level, most data was collected from the field in direct observation. Additional data at the building level will be further incorporated in the assessment of territorial vulnerability for the OCC of Seixal, in a way that each building—apart from its own descriptive parameters—will also be characterized by the values of the four parameters assessed in the respective S-SB.

A future major challenge consist in understanding which proportion of the differences found between the two assessments is justified by the differences in the input variables, and which part is justified by the geographical scale of analysis, as exemplified regarding the SB "005".

The individual and crossed interpretation of vulnerability indicators provides a good understanding of local disparities that smaller scales of analysis might not identify. Nevertheless, frequently, the use of vulnerability indicators based on a set of individual variables faces the risk of dissolving or hiding specific vulnerability characteristics and drivers. Therefore, the interpretation of results is not suggested to be made independently from the respective input data.

The contribution of planning to reduce vulnerability that arises from estuarine flood risk lays on the ability to manage three key areas: social assistance, population mobility and emergency response (Table 4). It is a purpose of the research project to provide an assessment that could be simultaneously applicable for strategic and operational planning. The level of geographical detail adopted in the assessment of territorial vulnerability will enable

In terms of communication, the regional assessment of territorial vulnerability identified components that represent urban and social contexts. Early warning has a key role in addressing the population's needs in the imminence and occurrence of a flood event. Such role is potentiated if preventive sensitization, effective information and a trained response conduct to anticipated actions. Such actions, in the scope of early warning systems need to be coordinated at the regional level, with extending sublevels of decision that prepare, and disseminate the appropriate level of warning to local communities and individuals. At the level of the main stakeholders, involvement must be promoted to allow the desirable implementation of redundant and contingent systems.

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