National Flood Vulnerability Index

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1. ABSTRACT

Extreme weather events like droughts and floods are increasingly being taken into account in different planning activities like in the insurance sector and land use planning. In this context high resolution vulnerability mapping at National or even International scale are very important to ensure a broader overview, identify hotspots, and have a strong support in the decision making process.

This work is the third step of development of a flood vulnerability index at the national scale which combines the aggregation of three components (physical susceptibility, social susceptibility and exposure) in a high resolution qualitative approach.

Results confirm the index ability to correctly identify the damage potential of flood prone areas in the Portuguese territory, where approximately 70% of flood occurrences, mapped in the project DISASTER, occurred in 2.1% of the territory identified with high and very high vulnerability. These areas are mostly located in the major urban centers of the Atlantic coast, between Setúbal and Viana do Castelo, and the eastern part of Algarve.

2. INTRODUCTION

Floods can cause loss of life, population displacement, damage to property and the environment and undermine business activities. A flood is an overflow of water that submerges land which is usually dry. Flooding may occur as an overflow of water from water bodies, such as a rivers or lakes, in which the water overtops resulting in some of that water escaping its usual boundaries, or it may occur due to an accumulation of rainwater on saturated soil. Some floods develop slowly due to heavy precipitation during days or weeks, while others such as flash floods can develop in just a few minutes. Additionally, floods can be local, impacting a neighborhood or community, or very large, affecting entire river basins (Julião et al., 2009).

The EEA 2012 report on Climate change, impacts and vulnerability in Europe states that hydrological events (floods and mass movements) are responsible for 31% of natural disaster related losses (1980-2011) but when taking into account just the meteorological events floods are responsible for 64% of the total natural disaster related losses (more than EUR 290 bn, EUR 116 bn of these are insured losses). In Portugal the DISASTER project recorded, between 1900 and 2010, 1524 occurrences related with flood events that resulted in 968 casualties (S. Pereira, et al, 2012).

The following work will focus on flood vulnerability which is not an easy concept to define and is highly dependent on the topic where this term is applied. In the context of climate change the IPCC (2007) definition of vulnerability is "*the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity*." The United Nations International Strategy for Disaster Reduction (UNISDR, 2007) defines vulnerability highlighting the characteristics and circumstances of a community, system or asset that makes it susceptible to the damaging effects of a hazard, undervaluing the location and process. Focusing exclusively on floods, the UNESCO-IHE Institute for Water Education considers flood vulnerability "*as the extent of harm, which can be expected under certain conditions of exposure, susceptibility and resilience*" that can be given as a Flood Vulnerability Index (FVI) by the following equation (Balica, S-F., 2012):

Eq. 1 FVI = Exposure + Susceptibility – Resilience

This work adopts this last definition of vulnerability as a methodological framework to calculate the Flood Vulnerability Index for Continental Portugal with the following description of its components:

Exposure represents the values which are present at the location where the floods can occur, such as: cultural heritage, infrastructure, goods, agricultural fields or people (Merz et al., 2007).

Susceptibility is a characteristic of an area, given by its natural terrain configuration and occupation, which determines the propensity of the area to floods.

Resilience, has defined by UNISDR (2009), is "the ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions".

The main difference between this definition and the approach adopted in this paper lies in the fact that not all dimensions of resilience where incorporated into the final index. In fact, resilience in the context of floods includes structural and non-structural measures related to flood defense, such as dams or early warning systems which were not taken into consideration in this work. The used indicators refer only to the socio-economical characterization of the population regarding factors such as age, income and education, which broadly correspond to the representation of flood social susceptibility, a concept often considered as complementary to resilience. As such, the subsequent methodological and results sections of this paper adopt the term flood social susceptibility instead of resilience.

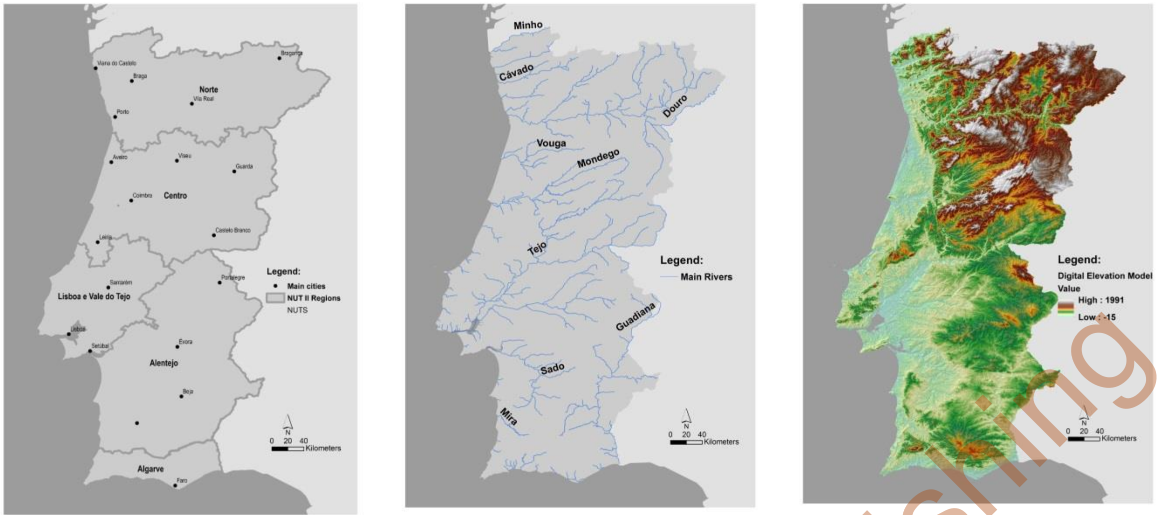
This work is the third step of development of a flood vulnerability index for continental Portugal based on these three components. The first two steps, which are outside the scope of this paper, correspond to the spatial characterization of the flood susceptibility and resilience components, while this work describes the exposed elements and the combination of the different components into a flood vulnerability index.

3. MATERIALS AND METHODS

3.1. Study area

The study area is the continental Portuguese territory, part of the Iberian Peninsula, located in the southwest of Europe.

In mainland Portugal different kinds of hydrologic extreme events occur, varying from those with slow spreading and large duration, normally extending to large areas (so-called progressive floods), and those with very fast spreading, short duration and concentrated impact (flash flood events) (Ramos & Reis, 2002). The flash floods events occur mainly on small watersheds or in urban areas and the progressive floods occur usually at a larger scale such as the Tagus, Guadiana, Mondego and Douro basins (**Figure 1**). The topography of the Portuguese territory is steeper to the north of the Tagus River and in the south, on the Algarve region, and flatter in the Alentejo region between the rivers Tagus and Mira (**Figure 1**).



(i) (ii) (iii)

Figure 1 - Characterization of the study area – Portuguese regions and main cities (i); Portuguese mainland basins and main river network (ii) and; slope (iii).

3.2. Data

As mentioned in the introduction section, the flood vulnerability index is composed of three factors: Exposure (E), Physical Susceptibility Index (PSI) and Social Susceptibility Index (SSI). The last two are described in Jacinto *et al.* (2013) and Grosso *et al.* (2013), respectively and the indexes can be seen in **Figure 2** and **Figure 3**.

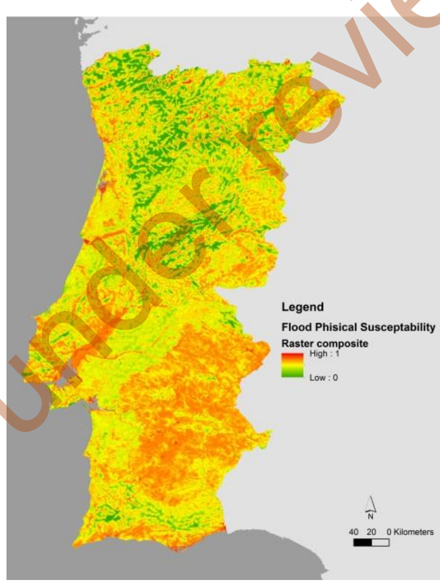


Figure 2– Flood Physical Susceptibility Index (PSI) (raster composite with a 90 m spatial resolution)

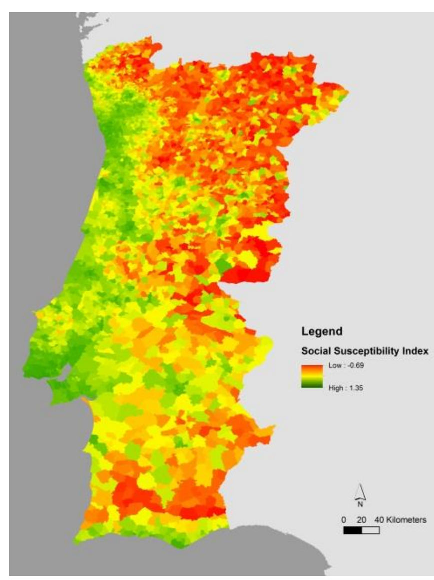


Figure 3 – Flood Social Susceptibility Index (SSI) by parish

It should be noted that the PSI is already classified in four different classes, according to the criteria shown in Table 1. On the other hand, SSI values are given in a continuous scale, where higher values correspond to a higher susceptibility.

Table 1- Flood physical susceptibility index classes (Jacinto et al., 2013)

Physical Susceptibility Class	Area characterization	Susceptibility index interval	Physical characteristics
4 Very High	+ Differentiation of main water lines + Some main urban areas	]0.49; 1]	+ Water Lines and contiguous regions + Regions of impervious soil (e.g. cities)
3 High	+ Differentiation of adjacent flood plains in the main rivers	]0.47; 0.49]	+ Flooding regions associated with large rivers + Regions of permeable soil + Regions with high water accumulation potential.
2 Low	+ Areas with increasing distance to water courses and steeper slopes	]0.42; 0.47]	+ Regions of medium/low water accumulation + Regions with significant water transport cost distance values + Regions of permeable soil
1 Very Low	+ Mountainous areas or with no water courses in their vicinity	[0; 0.42]	+ Regions with no water accumulation potential; + Regions with higher soil permeability + Regions with very high water transport cost distance values

Regarding **Exposure** it is represented in this paper by the buildings density in the Portuguese territory, produced from the national census in 2001 by the Statistics Portugal (INE – Portuguese acronym) and determined for a spatial statistical unit which resembles a city block in more urban dense areas, named "Geographical Base of Referenced Information" (BGRI – Portuguese acronym).

The number of geographically identifiable locations affected by floods, with dead, wounded, missing, and displaced people, in a given event mapped for Continental Portugal between 1865 and 2010 in the scope of the DISASTER project (PTDC/CS-GEO/103231/2008) (Zêzere, J. L. et all, 2013) was used as an independent FVI validation flood dataset.

3.3. Analysis

To create the flood vulnerability index the following steps were taken:

1. Calculation of the buildings density (building per square kilometer) for each BGRI spatial units by dividing the area of each polygon by the correspondent number of buildings;

2. Classification of the exposure and social susceptibility components in four and three classes respectively, by partitioning the respective values into classes defined by the equal quartiles of their distributions;
3. Transformation of the different components into a common spatial resolution
4. Aggregation, by calculating the median, of the physical susceptibility index classes into the BGRI spatial units;
5. Disaggregation of the social susceptibility index from the parish to the BGRI by attributing the parish index value to all BGRI spatial units contained in them;
6. Calculation of the FVI;
7. FVI validation using the flood occurrences DISASTER dataset.

The goals of steps two to five were, in a first stage, to classify the different components of the FVI, maintaining their original spatial resolution (PSI – 90 m; SSI – parish; E – BGRI) and, in a second stage, to transform the susceptibility datasets to the BGRI spatial scale, since this was the chosen spatial unit for the final FVI.

In step six those values were used to calculate the FVI using a modified version of Equation 1, where the resilience term was replace by flood social susceptibility. Since social susceptibility is a negative factor that adds to the total flood vulnerability, its final equation is:

Eq. 2 FVI = Exposure + Physical Susceptibility + Social Susceptibility

The flood occurrences from the DISASTER dataset was aggregated in BGRI units and then compared with each vulnerability class to validate its results.

4. RESULTS AND DISCUSSION

4.1. Classification and aggregation of the exposure, physical and social susceptibility FVI components

The social susceptibility index and exposure classes, defined using the equal quartiles of their respective distributions, are described in **Error! Reference source not found.** and Table 2.

Table 1- Flood social susceptibility index classes

SSI class	SSI value	Class Description
4 Very high	[-1.5; -0.75[	Highly susceptible populations with very low capacity to act or avoid consequences of flood damage and restore their environment into the same conditions prior damage.
3 High	[-0.75; 0[	Susceptible populations with low capacity to act or avoid consequences of flood damage and restore their environment into the same conditions prior damage.
2 Low	[0; 0.75[	Population with a low level of susceptibility that is globally prepared to act with the consequences of flood damage and restore their environment into the same conditions before suffering damage.

1 Very low	[0.75; 1.5[	Population with a very low level of susceptibility that is more prepared to act with the consequences of flood damage and restore their environment into the same conditions before suffering damage.

Table 2- Flood exposure index classes

Exposure Level	Exposure Value (buildings/km^2)	Class Description
4 Very high	[354; 20790 [	Areas with high buildings density mainly representing urban areas.
3 High	[136; 354 [	Areas with medium buildings density usually villages and regions close to urban areas.
2 Low	[58; 136 [	Areas with sparse buildings usually in rural areas.
1 Very low	]0; 58 [	Areas with scarce structures.

The definition of classes and aggregation into the BGRI units of the different FVI components are presented in Figure 4 and 5 and 6.

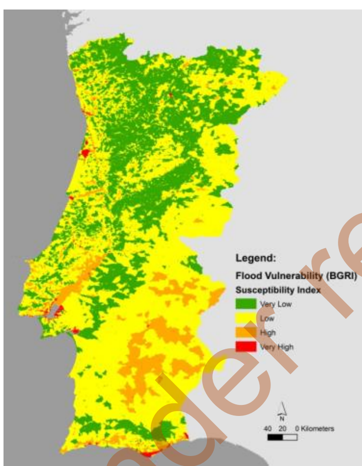


Figure 4– Flood Physical Susceptibility index

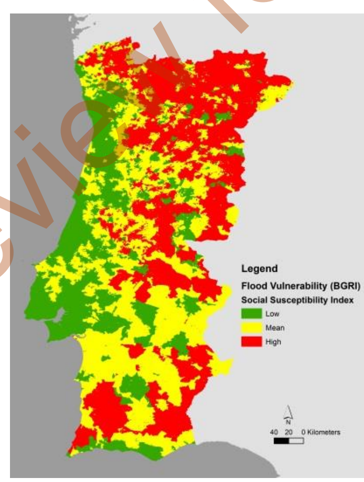


Figure 5 – Flood Social Susceptibility Index

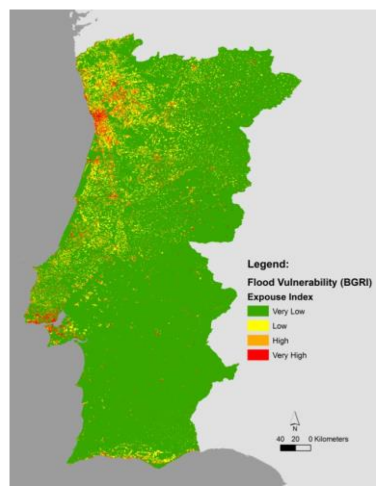


Figure 4 - Flood exposure index

Higher physical susceptibility values can be found in the vicinity of major rivers, in major cities with a high percentage of impermeabilized artificial surfaces (e.g., Lisbon, Oporto, Coimbra, Setúbal, Aveiro), the coastal Algarve region and Alentejo (Jacinto et al. 2013).

The social susceptibility component of the FVI shows a higher ability to cope with floods in coastal areas, mainly associated with more urbanized areas with higher education and income (Figure 5). Higher social susceptibility values are located in more inland regions, with a focus on the north and center regions and the northern and southern part of Alentejo (Grosso et al., 2013). As expected, the metropolitan areas of Lisbon and Oporto have the lowest SSI values, mainly due to their higher per capita incomes and education and lower unemployment.

Finally, the exposure index highlights the more dense urban and peri-urban regions between Viana do Castelo and Setúbal, with a higher incidence in the Lisbon and Oporto metropolitan areas. The index reflects two different urban morphology realities. In the northern coastal region higher exposure values are related to urban sprawl in the vicinity of major cities such as Oporto, Aveiro, Braga and Viana do Castelo, whereas in the Lisbon metropolitan area they are associated with more compact and dense occupation.

4.2. Flood Vulnerability Index

The sum of the FVI components (Eq. 2) typifies the flood vulnerability of the exposed elements, taking into account the social and physical components associated with flood events.

To distinguish between the "natural" and social aspects of the FVI two analyses were carried out:

1. $FVI_{(EPS)}$ = Exposure (E) + Physical Susceptibility (PSI) + Social Suceptibility(SSI)
2. $FVI_{(EP)}$ = Exposure (E) + Physical Susceptibility (PSI)

The results from the aggregation of the FVI components sum are described in table 4.

Table 3- Flood Vulnerability index classes

	E+PSI+SSI	E+PSI	Class Description
4 Very High	]8; 11]	]6; 8]	Areas very likely to suffer damage during flood events (E, PSI), with highly susceptible communities (SSI).
3 High	]6; 8]	]4; 6]	Areas likely to suffer damage during flood events (E, PSI) and with susceptible communities (SSI).
2 Low	]5; 6]	]3; 4]	Areas unlikely to suffer damage during flood events (E, PSI), and where communities tend to be less susceptible (SSI).
1 Very low	[3; 5]	[2; 3]	Areas unlikely to have flood events (E, PSI), and where communities are less susceptible (SSI).

The national distribution of FVI_{EP} (Figure 8) shows a large portion of territory (≈85%) with a very low flood vulnerability, associated with low population density and very low or low physical susceptibility classes, such as the coastal and south regions of Alentejo, the north mountainous area of Algarve and most of the center and north inland region.

The low vulnerability values cover about 14% of the territory and are concentrated in three distinct areas: a) the low exposure flood plains of major rivers like the Tagus, Mondego and Vouga;

b) the center Alentejo and parts of Algarve due to higher physical susceptibility values related with a highly dense hydrographic network and impervious soils (e.g., rock, clay) and; c) the peri-urban areas with low physical susceptibility, more visible along the coastal area between Setúbal and Viana do Castelo but also present in the vicinity of other major inland cities (e.g., Bragança, Vila Real, Castelo Branco).

Finally the high and very high flood vulnerability areas, covering approximately 2% of the Continental Portuguese territory are mostly represented by high population density urban areas with low to very high physical susceptibility, usually associated with low soil permeability. These areas can be found in the Lisbon and Oporto metropolitan areas, the east part of Algarve as well as all the major cities indicated in Figure 1.

The analysis of Fig. 8 and 11 shows that the resilience component of the FVI is generally enhancing rural areas, in terms of flood vulnerability, while reducing it in coastal and urban areas. In figures 7 and 9 it's also interesting to note that despite of the resilience indicator the area allocated to the level 4 (very high) of the vulnerability index are practically the same in both FVI's. In the other hand, when the resilience component is added, the FVI level 1 decreases almost 40% while level 2 and 3 increases by 33.2% and 7.1%, respectively.

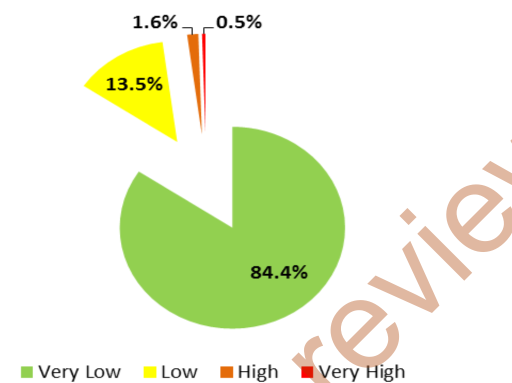


Figure 7 – Attributed area in %, in relation with the total main land Portugal area, for each FVI-EP level.

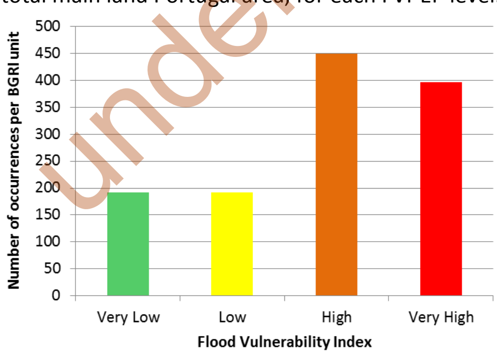


Figure 9 – Number of occurrences per FVI-EP class between 1865 and 2010.

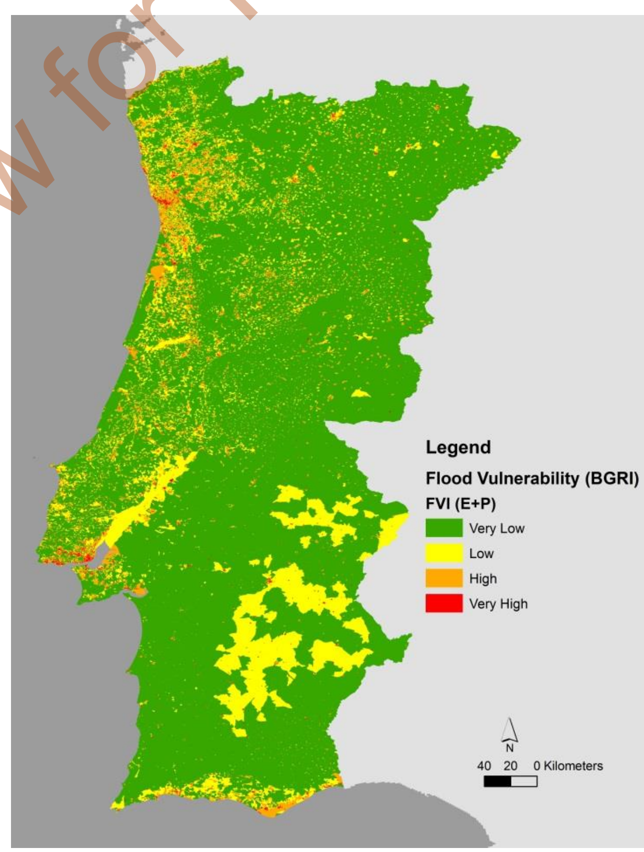


Figure 8 – FVI-EP for main land Portugal (1- Very low; 2- Low; 3 – High; 4- Very high)

The results from the validation procedure (Figure 11) shows that approximately 70% of the occurrences related with flood events and mapped in the project DISASTER occur in the 2.1% of the Portuguese mainland territory identified with high and very high vulnerability.

When the social susceptibility is added to the final vulnerability index (FVI_{EPS}), the main changes are: a) a significant vulnerability increase from very low to low or, occasionally, from low to high (e.g., in some areas of central Alentejo) in the more socially susceptible inland regions of the Portuguese territory and in some regions of Alentejo ; b) a vulnerability decrease from low to very low in the flood plain areas of the above mentioned major rivers; c) a vulnerability decrease from high to low in the peri-urban areas, located in Lisbon and Oporto regions and in the larger coastal cities located between them; d) a persistence of the very high vulnerability areas, although with a slight attenuation in the costal metropolitan areas, compensated by an increase in small villages located in the inland North part of Portugal.

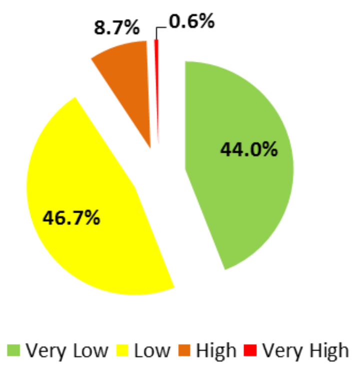


Figure 10 – Attributed area in %, in relation with the total main land Portugal area, for each FVI-EPS level.

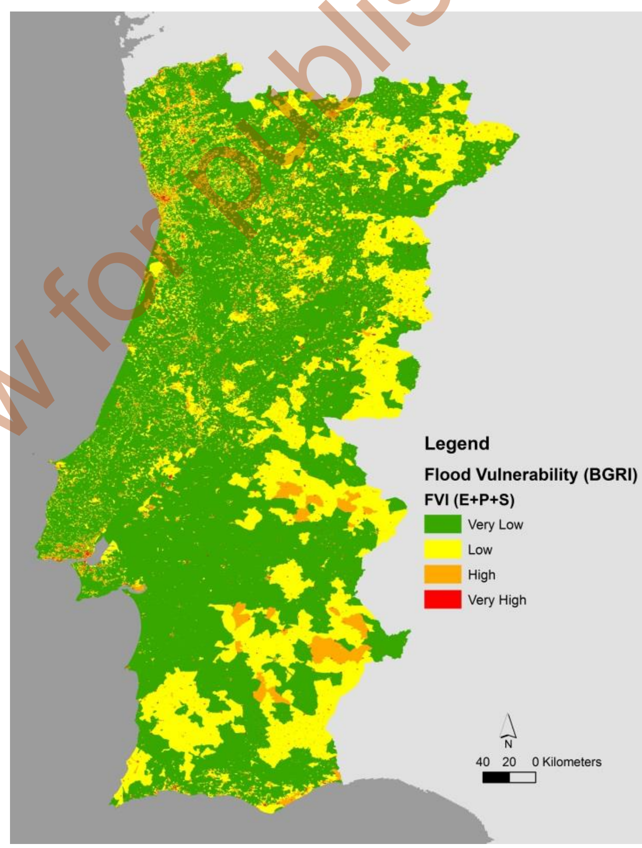


Figure 11 – FVI-EPS for main land Portugal (1- Very low; 2- Low; 3 – High; 4- Very high)

5. CONCLUSIONS

The FVI developed in the scope of this work aims to provide combined information at the BGRI scale on the territorial physical characteristics that increase flood propensity, the exposed building elements and the societal capacity to recover from damage.

The analysis and validation processes described above confirm the index ability to correctly identify the damage potential flood prone areas in the Portuguese territory, mostly located in the major urban centers of the Atlantic coast, between Setúbal and Viana do Castelo, and the eastern part of Algarve. Nevertheless, their vulnerability is decreased if social susceptibility is taken into account because they correspond to younger population with higher income and education. In the case of Alentejo, another highlighted region, some flood vulnerability overestimation might be observed, driven mostly by the physical and social susceptibility dimensions of the final index. This possible artifact can be attenuated if, in the future, this study is complemented by a parallel analysis of the precipitation flood triggering factor at the national scale.

The modular nature of this index provides different component aggregation options that can give distinct perspectives on the territorial vulnerability to floods. In the scope of this work two of those perspectives were explored with the FVI_{EP} and FVI_{EPS} indexes. Using the first will provide a possible stakeholder with an overview of the territorial physical characteristics that determine flood vulnerability, while the second adds information about any relevant socioeconomic factors that could increase it. A third alternative is to use only the physical susceptibility map that provides a baseline for potential flood vulnerability which can be useful, for instance, in land use planning.

Future work will focus in improving this index by:

- adding other vulnerability components such as environmental vulnerability and resilience (e.g., structural and non-structural flood defense measures);
- adding other exposure components such as industrial and agricultural areas, national interest infrastructures and natural parks of particular interest;
- adding other exposure components related with critical structures like hospitals, roads and railways;

Finally, future work should also include the development of a flood risk map at the national scale. This approach could be based on systematic flood surveys such as the ones developed in the scope of the DISASTER project and complemented by information on flood event frequency and damages compiled by the insurance industry and the national civil protection. Complementarily, a weather characterization of these events will provide flood frequency information associated with the different precipitation intensity probabilities. After this characterization it is also possible to assess the impact of climate change by evaluating the changes in precipitation frequency in the different climate scenarios.

6. REFERENCES

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