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Regionalization and susceptibility assessment to daily precipitation extremes in mainland Portugal

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ABSTRACT

The present study aims to identify regions of extreme precipitation in mainland Portugal and to create a single index of extreme precipitation susceptibility (EPSI). For this purpose, twelve extreme precipitation indices were selected from the Expert Team on Climate Change Detection and Indices between 1950 and 2003. By considering only six extreme precipitation indices: R×1day, R×5day, SDII, R20, CWD and R95PTOT for the 10-year return period, between 1950 and 2003, the EPSI was developed to both annual data and meteorological season. The regionalization of extreme precipitation in Portugal were determined using a principal component analysis in T-mode. The results, show three spatial regions obtained from PCA. The three regions were analyzed separate. In the annual EPSI, the highest susceptibility areas are the mountainous regions in northern (e.g. Gerês, Peneda, Alvão, Marão and Montesinho) and central Portugal (e.g. Serra da Estrela), as well as in the Algarve (southern Portugal). Conversely, the lower susceptibility classes are in municipalities of the northeast, Alentejo and along the central-western coast. The results of EPSI show similar results in autumn and winter. In spring, however, the high susceptibility class increases in the Lisbon region and in the Sado Basin. In summer, there is an increase in susceptibility in the northeast, while susceptibility is low over much of Alentejo and Algarve, where precipitation is neglectful. This work presents a first attempt to implement this type of index for mainland Portugal. The first results are very promising, showing a consistent representation of the overall spatial distribution of extreme precipitation susceptibility. The combination of this information by municipalities can be of foremost relevance to civil protection and risk management.

Contents

1. Introduction 129
2. Materials 129
   2.1. Study area 129
   2.2. Precipitation data 130
3. Methods 130
   3.1. Indices for extremes 130
   3.2. Principal component analysis 130
   3.3. Susceptibility assessment 130
   3.4. Validation 132
4. Results 132
5. Conclusions 134

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0143-6228/

Acknowledgements 137
Supplementary data 137
References 137

1. Introduction

Precipitation extremes may have great impacts on the frequency, intensity and duration of natural hazards, such as droughts, floods or landslides, and may seriously compromise human life, economy, natural ecosystems and agriculture (Song et al., 2015; Sun et al., 2016; Zwiers et al., 2013). The average global temperature increased by approximately 0.85 °C between 1880 and 2012, while mid-latitude land areas of the Northern Hemisphere have showed an overall increase in precipitation (IPCC, 2013; Liu et al., 2017). Klein Tank et al. (2006) showed that precipitation events are projected to be more extreme in the future. Therefore, studies on climate extremes are essential in vulnerability assessments and impact research under future climate change scenarios.

Many recent studies have been conducted in order to detect extreme precipitation trends in different regions of the world (e.g. Bennett & Walsh, 2015; Burić, Luković, Bajat, Kilibarda, & Živković, 2015; Khomsi, Mahe, Tramblay, Sinan, & Snoussi, 2016; Merino et al., 2016; Stephenson et al., 2014; van den Besselaar, Klein Tank, & Buishand, 2013; Westra, Alexander, & Zwiers, 2012; Zhou, Xu, Wu, Dong, & Shi, 2016; Zollo, Rillo, Bucchignani, Montesarchio, & Mercogliano, 2016). In the Iberian Peninsula, several studies on observed precipitation changes were carried out, mainly concentrated on the Mediterranean region (Santos, Corte-Real, Ulbrich, & Palutikof, 2007; Sáez de Cámara, Gangoiti, Alonso, & Iza, 2015). These works showed a reduction in precipitation totals accompanied by a concentration of precipitation in fewer days (e.g. Gonzalez-Hidalgo, Lopez-Bustins, Štepánek, Martin-Vide, & de Luis, 2009; González Hidalgo, De Luís, Raventós, & Sánchez, 2003; Hidalgo-Muñoz, Argüeso, Gámiz-Fortis, Esteban-Parra, & Castro-Díez, 2011; Martin-Vide, 2004; Martínez, Lana, Burgueño, & Serra, 2007; Millán, Estrela, & Miró, 2005; Vicente-Serrano & Beguería-Portugués, 2003). For Portugal and for the 1941–2007 period, Lima, Santo, Ramos, and Trigo (2015) reported predominant downward trends in the extreme precipitation indices, but in most of them no statistically significant trends are identified. Nevertheless, several episodes of heavy precipitation have triggered floods and landslides and caused severe damages (Fragoso et al., 2015; Zêzere et al., 2014).

In Portugal, between 1865 and 2010, floods caused 1.012 deaths, 478 injured, 13.372 displaced and 40.283 homeless people. Examples of remarkable disasters occurred on 25 November 1967 in the Lisbon region, when 522 people were killed (Pereira, Zêzere, Quaresma, Santos, & Santos, 2016; Trigo et al., 2016) or on the second half of December 1909, when an exceptional rainfall period was responsible for 35 death people in the north and central Portugal (Pereira, Ramos, Zêzere, Trigo, & Vaquero, 2016).

In addition, Melo-Gonçalves, Rocha, and Santos (2016) evaluated the climate change projections of the Iberian daily-total precipitation for near-future (2021–2050) and distant-future (2069–2098) climates, with respect to a recent past climate (1961–1990). This work showed a decrease in annual precipitation over the entire peninsula, particularly in the north and northwest, where it can decrease to 400 mm by the mid-21st century, except in winter. The number of consecutive dry days (CDD) are projected to increase, in the summer and spring, until the mid-21st century throughout the peninsula, reaching more than three weeks in the southwest. For the maximum 5-day consecutive precipitation (R×5day), a decrease is projected to occur during spring and autumn over most of the peninsula, and during summer in northern Iberia. The very wet days (R95) should decrease around 20% in summer over northern Iberia, and around 15% in autumn over the south-southwest. The combined effect of these projections will potentially aggravate the constraints of water resources management in Portugal, because of the decrease in the river flows and extraction of ground water during a more extended dry season.

In the context of the environmental and societal implications of the above-identified projections and trends, it is critical to regionalize the territory in terms of precipitation extremes. In this study, we apply a multivariate statistical technique aiming at creating a single index to regionalize precipitation extremes in Portugal, as there are no previous studies with such a purpose. This approach allows defining spatially similar areas for climate change research or for providing guidelines to civil protection systems. Hence, our purposes are three: 1) to identify regions of extreme precipitation in mainland Portugal; 2) to create a single index of extreme precipitation susceptibility (EPSI) and 3) to analyze the relationship between the EPSI regionalization and the spatial distribution of disastrous hydro-geomorphological events (floods and landslides) in mainland Portugal (Zêzere et al., 2014).

2. Materials

2.1. Study area

Mainland Portugal is located in the transitional region between the sub-tropical anticyclonic and the sub-polar cyclonic belts, among the latitudes of 36° 56′ and 42° 09′ N and the longitudes of 6° 10′ and 9° 34′ W. The area North of Portugal is much more mountainous than its southern half (Fig. 1). The main relief systems are roughly parallel to the coastline, forming an efficient orographic barrier against the moist Atlantic winds (Santos & Fragoso, 2013). As such, the spatial variability of precipitation largely reflects the irregular distribution of orography. Others factors influence the spatial and temporal precipitation variability, such as the effect of the Atlantic Ocean proximity, the latitudinal location (between subtropical and mid-latitudes) and diverse weather types (Goodess & Jones, 2002; Melo-Gonçalves et al., 2016; Santos, Belo-Pereira, Fraga, & Pinto, 2016; Santos, Corte-Real, & Leite, 2005; Santos, Santos, & Fragoso, 2015). The mean annual precipitation in mainland Portugal is around 900 mm for the 1961–1990 baseline (Espírito Santo, Ramos, de Lima, & Trigo, 2014), but precipitation exhibits large north–south and east–west variability. In fact, the mean annual precipitation varies from over 2000 mm in the northwest to roughly 500 mm in the inner Douro River valley and over the south-eastern part of the country. Furthermore, the precipitation regime is characterized by a strong annual cycle and, on average, about 40% of the annual precipitation occurs in winter (December to February) (Lima et al., 2015). In summer (June to August), precipitation amounts are of only ca. 6% of the annual amounts. April, May, September and October are transitional months into and out of the rainy season (Trigo & DaCamara, 2000). These months are still relatively rainy in the northwest, while they tend to be dry in the south.

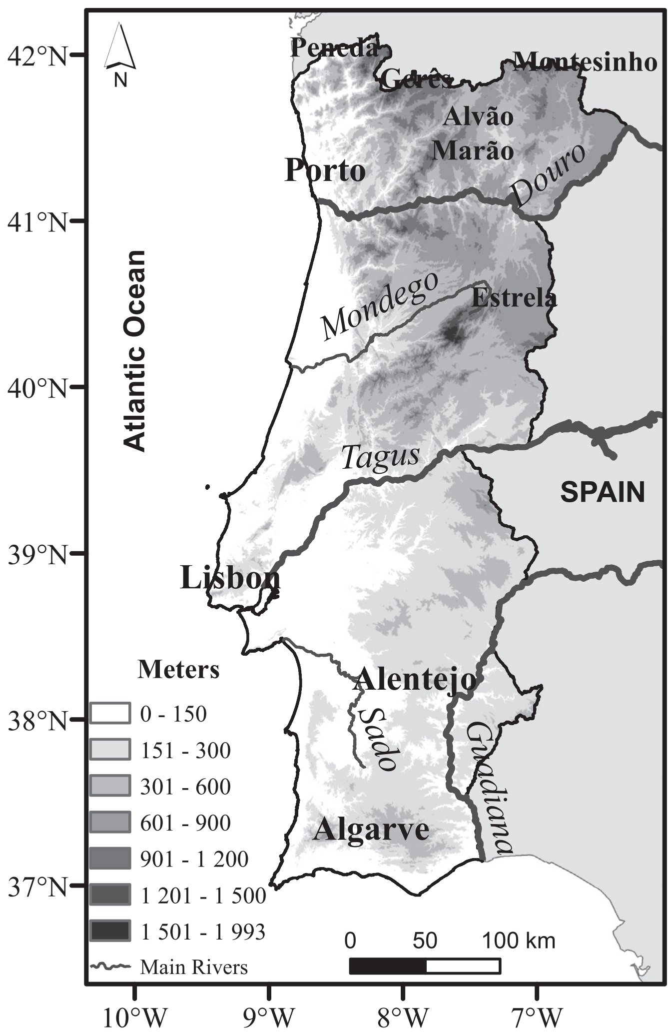

Fig. 1. Hypsometry of mainland Portugal.

2.2. Precipitation data

Daily precipitation data on a 0.20° latitude × 0.20° longitude regular grid (spatial resolution of ~20 km) over mainland Portugal and for the period from 1950 to 2003 are used in the present study, retrieved from the precipitation dataset PT02, which is currently the most complete database of daily precipitation over Portugal (Belo-Pereira, Dutra, & Viterbo, 2011). It is also combined with a Spanish gridded dataset (Herrera et al., 2012). This dataset is based on a dense network of rain gauges over Portugal, all quality-controlled and homogenized, with 188 meteorological stations from the Portuguese Meteorological Service – IPMA – and 618 rain gauges from the Portuguese Environmental Agency – APA (Belo-Pereira et al., 2011). Recently, this dataset has been used in several studies of extreme precipitation in Portugal (e.g. Liberato et al., 2013; Ramos, Trigo, & Liberato, 2014; Trigo et al., 2016).

3. Methods

3.1. Indices for extremes

The characteristics of precipitation events were investigated by analyzing several extreme precipitation indices during the period of 1950–2003. The joint work of the World Meteorological Organization Commission for Climatology (CCI), World Climate Research Programme Project on Climate Variability and Predictability (CLIVAR) and JCOMM Expert Team (ET) on Climate Change Detection and Indices (ETCCDI) (Karl, Nicholls, & Ghazi, 1999) defined a set of extreme climate indices, based on daily precipitation and temperature data. These indices were already applied either globally (Alexander et al., 2006; Westra et al., 2012) or locally (e.g. Aguilar et al., 2005; Boccolari & Malmusi, 2013; Booth, Byrne, & Johnson, 2012; Caesar et al., 2011; Costa, Santos, & Pinto, 2012; Keggenhoff, Elizbarashvili, Amiri-Farahani, & King, 2014; Omondi et al., 2014; Wu et al., 2016; Zollo et al., 2016) in many climate change studies.

In the present study, twelve extreme precipitation indices were chosen from the 27 ETCCDI (Table 1): wet–day precipitation (PRCPTOT), maximum 1-day precipitation (R×1day), maximum 5-day precipitation (R×5day), very-wet-day precipitation (R95), extremely-wet-day precipitation (R99), a simple daily intensity index (SDII), number of heavy precipitation days (R10 mm and R20 mm), consecutive wet days (CWD), consecutive dry days (CDD), contribution from very wet days (R95PTOT) and contribution from extremely wet days (R99PTOT). The calculation of the indices is based on the definition of a wet day, i.e. a day with accumulated precipitation of at least 1.0 mm.

The empirical return periods were estimated from a Generalized Extreme Value (GEV) distribution using L-moment estimators. The GEV distribution is particularly suitable for studying precipitation extremes (Svensson & Jones, 2010). In fact, precipitation series have been successfully fitted by GEV distributions in many studies (e.g. Murawski, Zimmer, & Merz, 2016; van den Besselaar et al., 2013; Wu et al., 2016; Zamani, Gobin, Van de Vyver, & Gerlo, 2016). The indices were assessed for return periods of 2, 5, 10 and 50 years. The spatial interpolation of these values was undertaken by ordinary kriging, as it is one of the best linear interpolation methods (Ceresetti et al., 2012), widely used in many applications (Herrera et al., 2012).

3.2. Principal component analysis

The principal component analysis (PCA) is a widespread multivariate statistical technique, commonly applied for reducing the dimensionality of a large dataset, for filtering purposes, for developing predictive models or for regionalization (Jolliffe, 2002; Jones, Blenkinsop, Fowler, & Kilsby, 2014; Richman, 1986; Riddle & Wilks, 2013). In the literature, there are several mathematical descriptions of PCA, such as Jolliffe (2002) or Preisendorfer and Mobley (1988). It has been extensively applied to identify spatial and temporal modes of precipitation variability in different regions (e.g. Almazroui, Dambul, Islam, & Jones, 2015; Andrew & Erik, 1998; Aravena & Luckman, 2009; Brienen, Kapala, Mächel, & Simmer, 2013; Jones et al., 2014; Türkeş, Koç, & Sariş, 2009). Aiming at a regionalization of the precipitation extremes in Portugal, PCA was herein applied to the selected 12 extreme precipitation indices during the baseline period of 1950–2003. PCA was based on the correlation coefficient matrix of the extreme precipitation indices and the resulting empirical orthogonal functions/patterns (EOF) are of unit variance. The different regions were outlined by the 0-isoline of the leading principal component (Fig. 2).

3.3. Susceptibility assessment

One main objective of our study is to produce an extreme precipitation susceptibility index (EPSI) over mainland Portugal, based on the indices for the 10-year return period. The magnitude of a given event associated with a 10-year return period has 10% of chance to occur within any one year, thus it is a suitable and

Table 1
Definition of the 12 precipitation extreme indices used in this study, with the abbreviations used in the text, full name, short definition and corresponding units.

Abbreviation	Name	Definition	Unit
PRCPTOT	Annual total wet–day precipitation	Annual total precipitation in wet days (precipitation ≥1 mm)	mm
R×1day	Maximum 1-day precipitation	Annual highest daily precipitation	mm
R×5day	Maximum 5-day precipitation	Annual highest 5 consecutive precipitation days	mm
R95	Very wet days	Annual total precipitation when RR > 95th percentile	mm
R99	Extremely wet days	Annual total precipitation when RR > 99th percentile	mm
SDII	Simple daily intensity index	Annual total precipitation divided by the number of wet days (precipitation ≥1 mm) in the year	mm day^{-1}
R10	Number of heavy precipitation days	Annual count of days when precipitation ≥10 mm	days
R20	Number of heavy precipitation days	Annual count of days when precipitation ≥20 mm	days
CWD	Consecutive wet days	Maximum number of consecutive days with precipitation ≥1 mm	days
CDD	Consecutive dry days	Maximum number of consecutive days with precipitation <1 mm	days
R95PTOT	Contribution from very wet days	Fraction of annual total precipitation exceeding 95th percentile	%
R99PTOT	Contribution from extremely wet days	Fraction of annual total precipitation exceeding 99th percentile	%

balanced indicator of extreme precipitation. Higher return periods (lower probabilities of occurrence) are associated with much lower sample sizes, thus reducing the statistical robustness of the results. In this study, the susceptibility assessment was carried out using GIS technology. Owing to the strong seasonality of the precipitation regime, this methodology was applied to both annual data and meteorological seasons (autumn: September, October, November; winter: December, January and February; spring: March, April and May; summer: June, July and August). For this purpose, a four-stage approach was undertaken, according to the following unidirectional steps:

a. Selection of the most relevant ETCCDI indices that also provide complementary information, seeking for a parsimony solution that maintains the analysis as complete and simple as possible. The chosen indices were: R×1day, R×5day, SDII, R20, CWD and R95PTOT (Fig. 5). The first two describe the precipitation associated with extreme wet spells, while the SDII reflects the daily intensity. R20 is defined as the count of wet days with precipitation ≥20 mm, i.e. moderate-to-high daily precipitation amounts. CWD is defined as the number of consecutive wet days (daily precipitation ≥ 1 mm). R95PTOT was chosen to assess the contribution of daily precipitation extremes to total precipitation, since it is defined as the ratio between the precipitation occurring only in days exceeding the 95th percentile (calculated only for wet days and for the baseline period 1950–2003) and total precipitation. The selection of the indices was preceded by a sensitivity analysis, through which several combinations were

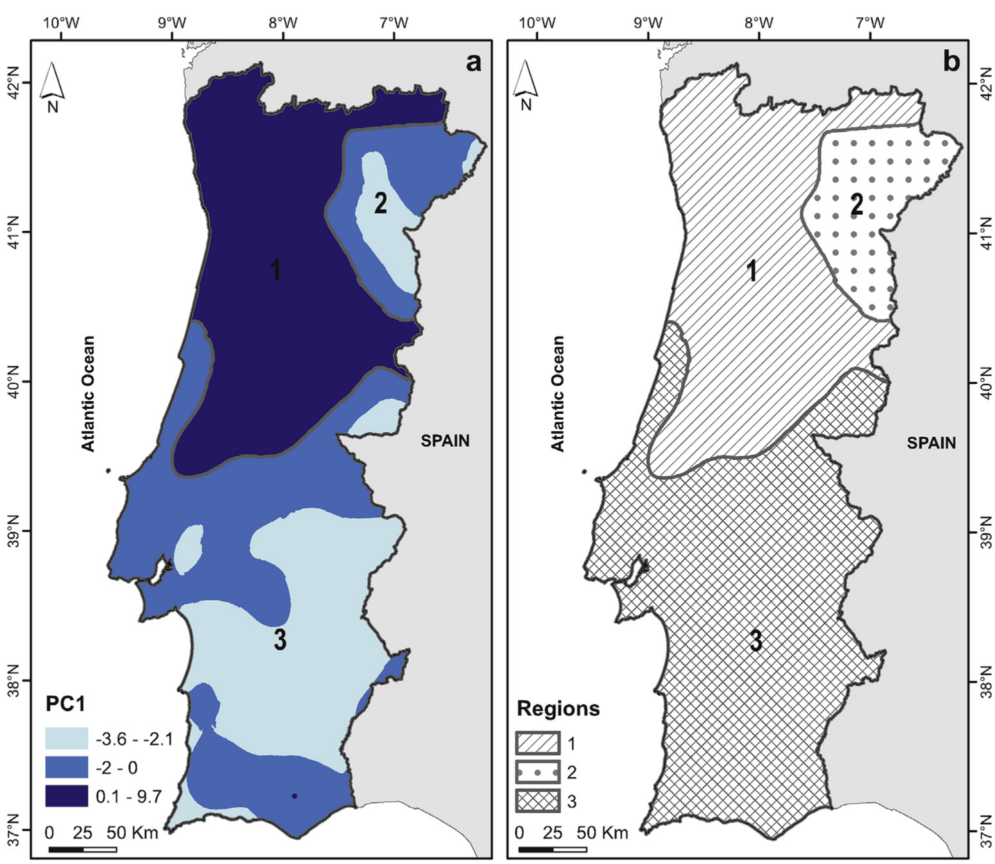

Fig. 2. (a) Leading principal component loading pattern (representing 80.7% of total variance) based on 12 extreme precipitation indices during the period of 1950–2003. (b) Mapping of the three regions delineated by the 0-isoline in (a): Region-1 (northwest), Region-2 (northeast) and Region-3 (south).

tested. The selected indices, although with some inevitable subjectivity, may be considered a suitable choice for the characterization of extreme precipitation in mainland Portugal, which is also in agreement with previous studies (e.g. Costa et al., 2012);

b. A normalization process for all variables was then carried out. They were rescaled to a common 0 to 1 range, where the highest values correspond to a greater propensity to extreme precipitation conditions;
c. The EPSI is subsequently calculated using the following equation on the previous normalized indices:

$$EPSI = \sum(R \times 1day + R \times 5day + SDII + R20mm + CWD + R95PTOT) \tag{1}$$

d. Four susceptibility classes, based on a quantile classification (25% of mainland Portugal in each class), were finally defined.

3.4. Validation

As the spatial variability of precipitation mainly reflects the distribution of orography, the EPSI was crossed with the spatial distribution of hypsometry. Moreover, in order to evaluate the relationship between the EPSI variability and the spatial distribution of rainfall triggered disasters (floods and landslides), a comparison to the DISASTER database was carried out. The specificities of the database are described by Zêzere et al. (2014). This database contains only landslides or flood occurrences that led to casualties or injuries, missing, evacuated or homeless people, independently of the number of people affected. Furthermore, the occurrences have different levels of positional accuracy, so that only the records based on exact coordinates, local toponymy and geomorphology, during the period of 1950–2003, were considered. A total 847 occurrences were selected in the present study. The EPSI was overlaid with the spatial distribution of DISASTER occurrences outside urban areas for the period from 1950 to 2003 (343 occurrences) (Fig. 7). Summer is not considered owing to both the scarcity of precipitation and to the sparse number of occurrences. However, the specific characteristics of the DISASTER database, as well as of the methodology associated with EPSI, requires a careful evaluation of the results. The spatial pattern of DISASTER occurrences strongly reflects human exposure and the vulnerability of the exposed elements (Santos, Bateira, Soares, & Hermenegildo, 2014). Although the most affected areas also tend to exhibit natural conditions that favor floods and landslides, the spatial pattern of DISASTER occurrences strongly reflects the exposure of people to these natural hazards (Pereira et al., 2016). In effect, high population density tends to enhance vulnerability to risk (Zêzere et al., 2014). In addition, some regions are better adapted to mitigating the effects of precipitation extremes than others. The regions of high EPSI are generally better adapted to extreme events, and thus tend to suffer less with an event of the same intensity than regions of low EPSI. Furthermore, in Portugal, the most susceptible regions are mountainous areas with low population density and, therefore, with less attention given by newspapers and, as a result, less occurrences/entries in the DISASTER base.

4. Results

The three spatial regions obtained from PCA are showed in Fig. 2. Four principal components (PCs) were identified, which cumulatively represent 99.1% of total variance. The leading PC represents 80.7% of the variance (Fig. 2). Based on these results, we identified 3 regions (Fig. 2). Region-1, in the northwest, is the rainiest in the country, with 1242 mm of mean annual precipitation (Table 2). Over the whole Iberian Peninsula, this high amount of mean annual precipitation is only reached or surpassed in Galicia and Cantabrian coast (Merino et al., 2016, their Fig. 4). Region-2, in the northeast, features much lower precipitation amounts than Region-1. In the former region, precipitation is significantly mitigated by the condensation barrier effect triggered by the north mountain ranges. Its mean annual precipitation ranges between 493 and 864 mm (Table 2), which are comparable to those in the South of Portugal. Region-3 roughly corresponds to southern Portugal, depicting the driest precipitation regime. In this more typically Mediterranean region, the annual values range between 475 and 886 mm, gradually decreases from the north to the south.

Fig. 3 and Fig. 4 depict the precipitation extreme indices in each region for different return periods (2, 5, 10 and 50 years). For all return periods, Region-1 shows the highest mean values of the following indices: PRCPOT, R×1day, R×5day, R95, R99, SDII, R10, R20, CWD and R99PTOT (Figs. 3 and 4). The mean values of Region-2 and Region-3 are similar, with the later revealing slightly higher values in R×1day, R×5day, SDII, R20, CDD, R95PTOT and R99PTOT. The largest difference between these two regions can be found in CDD (76 days for Region-3 and 47 days for Region-2, Table 2). The same applies to the estimated values for the different return periods: the greatest variation occurs in CDD. Region-3 exhibits the strongest variability and the highest values for the indices over the different return periods: CDD, R95PTOT and R99PTOT (Fig. 4).

The spatial distributions of PRCPTOT, R×1day, R×5day, SDII, R20, CWD, CDD and R95PTOT for the 10-year return period generally confirm the north-south and west-east prevailing gradients (Fig. 5). Overall, precipitation values decrease from the north to south and from the west to east, with the latitude and the mountain ranges driving the transition between the wet northwest and the dry southern/inner regions. The exception to this rule is R95PTOT, for which the highest values occur in the south rather than in the northwest (Fig. 5). Similar considerations can be made for the 2-year return period (Fig. S1).

The second methodological phase corresponds to the application of a spatial aggregation method to the extreme precipitation indices, aiming at systematizing the information in a single index (EPSI). In the annual EPSI (Fig. S2), the highest susceptibility areas are in northern (e.g. Gerês, Peneda, Alvão, Marão and Montesinho) and central Portugal (e.g. Serra da Estrela), as well as in the Algarve (southern coastal area). Conversely, the lower susceptibility classes are in the northeast, in Alentejo and along the central-western coast municipalities. The EPSI is in close connection with the relief, the most determinant factor of the precipitation pattern.

The results of the 10-year extreme precipitation susceptibility index show similar results in autumn and winter. The main differences in autumn are a decrease in the very high susceptibility area in the Algarve and in the Sado Basin. However, in spring, the high susceptibility class increases in the Lisbon region and in the Sado Basin. In summer, there is an increase in susceptibility in the northeast, as summertime thunderstorms can be particularly strong and frequent in the Douro River catchment, particularly in the Spanish mountain ranges encircling it (Santos, Reis, De Pablo, Rivas-Soriano, & Leite, 2013). In summer, susceptibility is low over much of Alentejo and Algarve, being precipitation neglectful. When analyzing the dominant class of the EPSI index, it was found that the high or very high susceptibility classes are dominant in more than 60% of the municipalities, in terms of both annual data and meteorological seasons (Fig. 6 and Table S1).

The influence of rainfall on landslides differs substantially

Table 2
Mean, maximum and minimum for 12 precipitation extreme indices for the period 1950–2003 and for the three regions (1, 2 and 3). See Fig. 2 for the location of the regions.

PRCPTOT	**1**	**2**	**3**	**R×1day**	**1**	**2**	**3**	**R×5day**	**1**	**2**	**3**
Mean	1242	686	649	*Mean*	58	38	43	*Mean*	147	90	92
Maximum	2061	864	886	*Maximum*	88	48	62	*Maximum*	232	121	129
Minimum	837	493	475	*Minimum*	40	32	33	*Minimum*	102	72	73
R95	**1**	**2**	**3**	**R99**	**1**	**2**	**3**	**SDII**	**1**	**2**	**3**
Mean	261	144	141	*Mean*	93	49	48	*Mean*	11	7	8
Maximum	452	197	198	*Maximum*	155	69	68	*Maximum*	15	9	11
Minimum	172	103	107	*Minimum*	58	36	37	*Minimum*	8	6	6
R10	**1**	**2**	**3**	**R20**	**1**	**2**	**3**	**CWD**	**1**	**2**	**3**
Mean	43	22	22	*Mean*	18	6	7	*Mean*	15	12	10
Maximum	67	28	30	*Maximum*	35	10	12	*Maximum*	19	15	15
Minimum	29	16	15	*Minimum*	9	4	3	*Minimum*	9	8	6
CDD	**1**	**2**	**3**	**R95PTOT**	**1**	**2**	**3**	**R99PTOT**	**1**	**2**	**3**
Mean	43	47	76	*Mean*	21	21	22	*Mean*	7.5	7.1	7.4
Maximum	63	61	112	*Maximum*	23	23	25	*Maximum*	8.6	8	11
Minimum	32	42	46	*Minimum*	18	20	19	*Minimum*	6.2	6.1	6.6

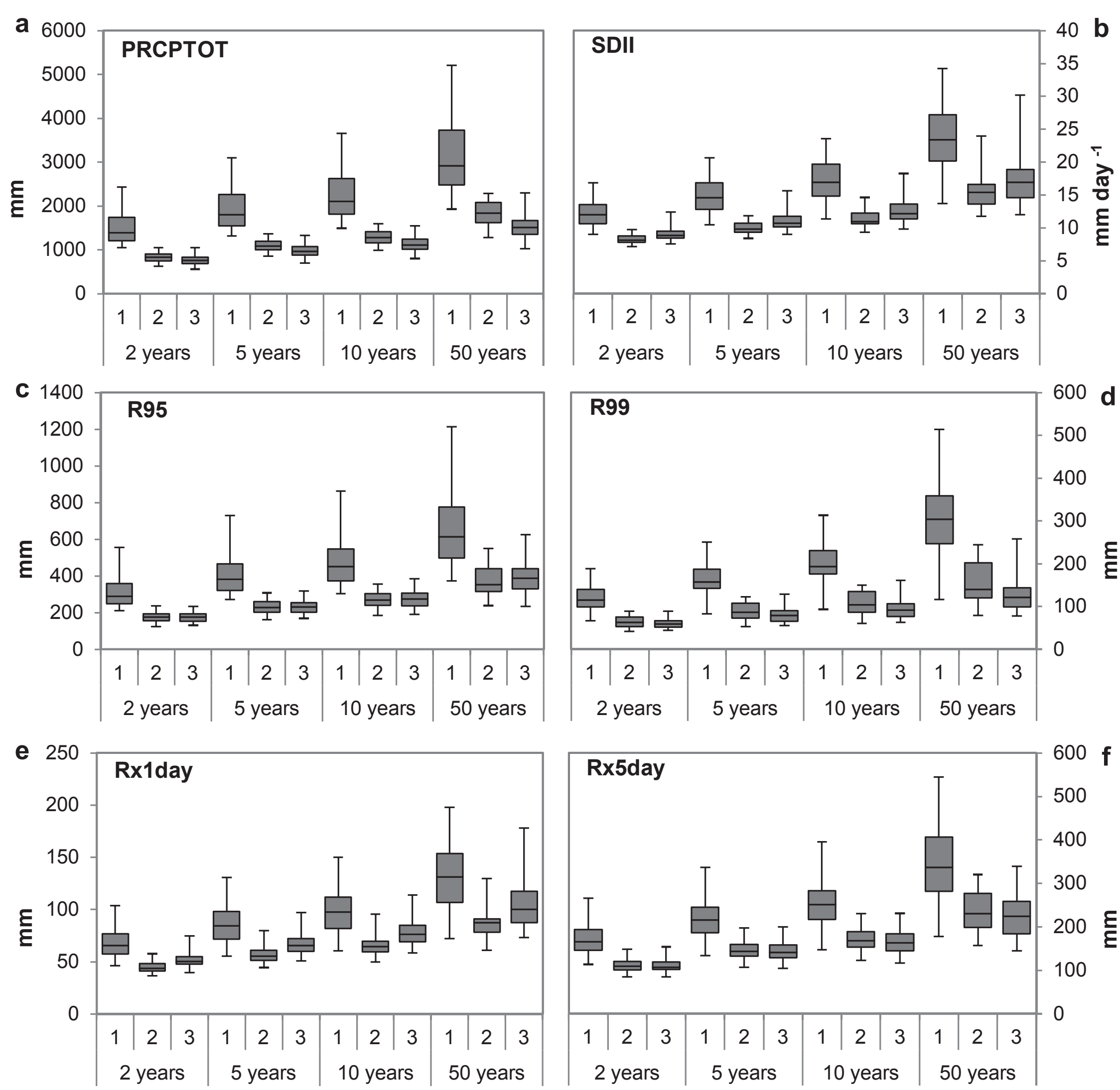

Fig. 3. Box-plots of the precipitation extreme indices: (a) PRCPTOT, (b) SDII, (c) R95, (d) R99 (e) R×1day and (f) R×5day for the three regions and for the different return periods (2, 5, 10 and 50 years).

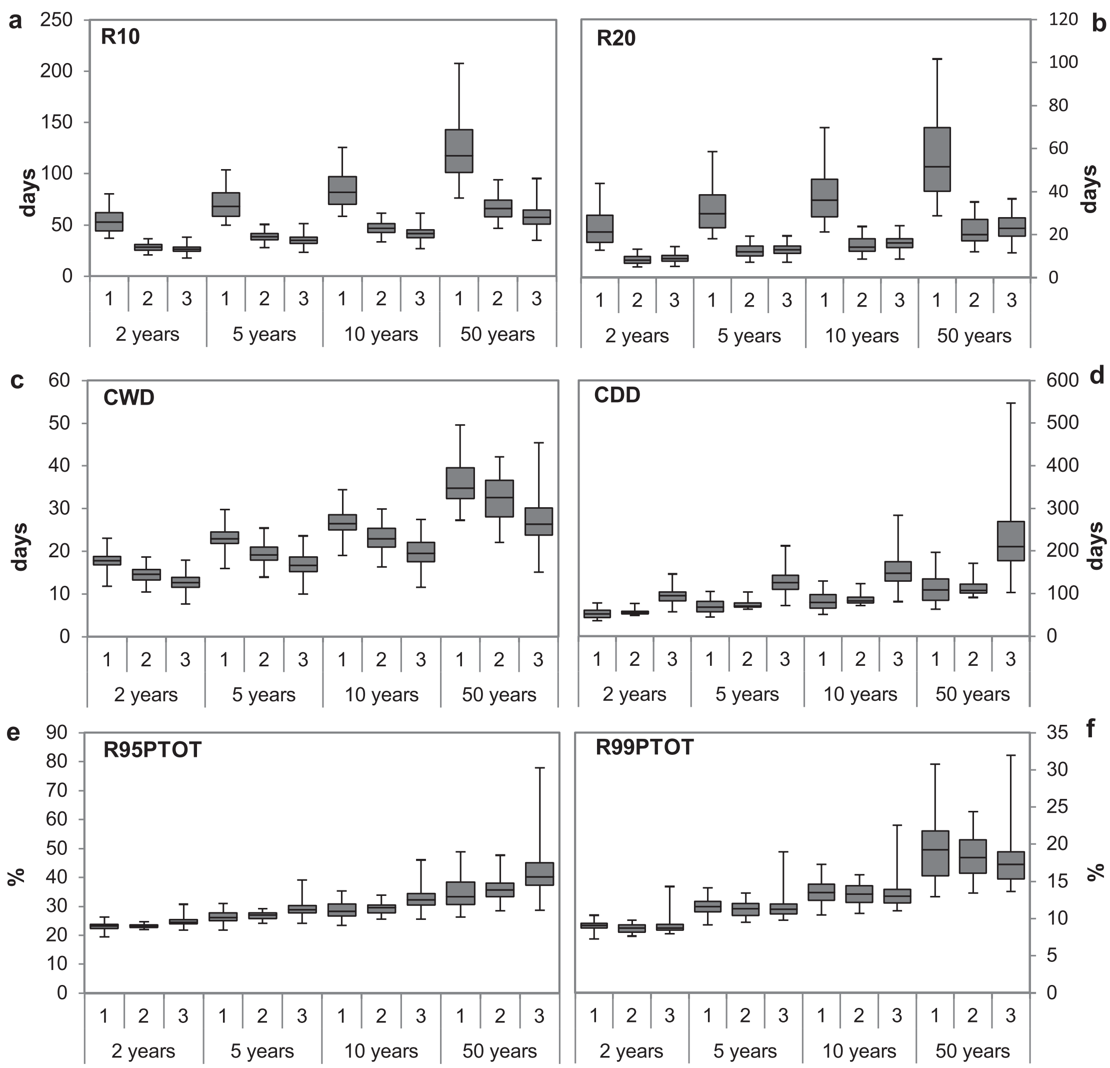

Fig. 4. Box-plots for the precipitation extreme indices: (a) R10, (b) R20, (c) CWD, (d) CDD (e) R95PTOT and (f) R99PTOT for the three regions and for the different return periods (2, 5, 10 and 50 years).

depending upon landslide dimensions, kinematics, material involved, among others. Shallow landslides are usually triggered by short, intense storms, while most deep-seated landslides are usually related with rainfall periods lasting from several weeks to several months (Marques, Zêzere, Trigo, Gaspar, & Trigo, 2008). Floods are extreme and temporary events, triggered either by persistent and moderate precipitation or by abrupt heavy rains. The occurrence and intensity of floods depend on weather conditions prior to the event (Kron, Steuer, Löw, & Wirtz, 2012), but other conditions, such as soils, surface run-off characteristics, protection measures or land-use and seasonality in the hydrological regimes, are also important (Santos et al., 2014). Floods usually occur downstream to heavy precipitation take place, while landslides clearly exhibit a closer spatial correspondence with EPSI at municipality scale. Approximately, 79% of the total number of landslides occurs in municipalities with high or very high susceptibility. Therefore, the EPSI map (Fig. 6) emerges as an important tool to assess the role of precipitation among the key driving forces of disastrous landslides in mainland Portugal, particularly outside urban areas, where these phenomena are controlled in a lesser extent by people exposure (Figs. 7 and 8). Fig. 7 shows the distribution of occurrences outside urban areas (total of 343 occurrences). It can be seen that 66% of the occurrences of floods in winter are registered in the higher classes. The percentages are higher when compared to landslides: 81% of occurrences are recorded in the two highest classes. The EPSI map reflects only the precipitation regimes dominant in each municipality (Figs. 6 and 8). In addition to extreme precipitation, there are other very important conditioning factors for landslides and floods, such as: physiographic conditions of the basins, soil types, relief, slope or lithological units, in mainland Portugal (e.g. Henriques, Zêzere, & Marques, 2015; Santos, Santos, & Fragoso, 2017; Santos & Reis, 2017; Zêzere et al., 2015).

5. Conclusions

The first purpose of this study was to regionalize precipitation extremes in Portugal. For this purpose, 12 precipitation indices were calculated from a very high resolution daily gridded precipitation dataset. The results of regionalization depend on the choices of the variables, methods, data series and target period (Dambul & Jones, 2008). Therefore, it is difficult to compare the performances of different classification methods (Almazroui et al., 2015). Our study is based on a high-resolution grid dataset and identifies three

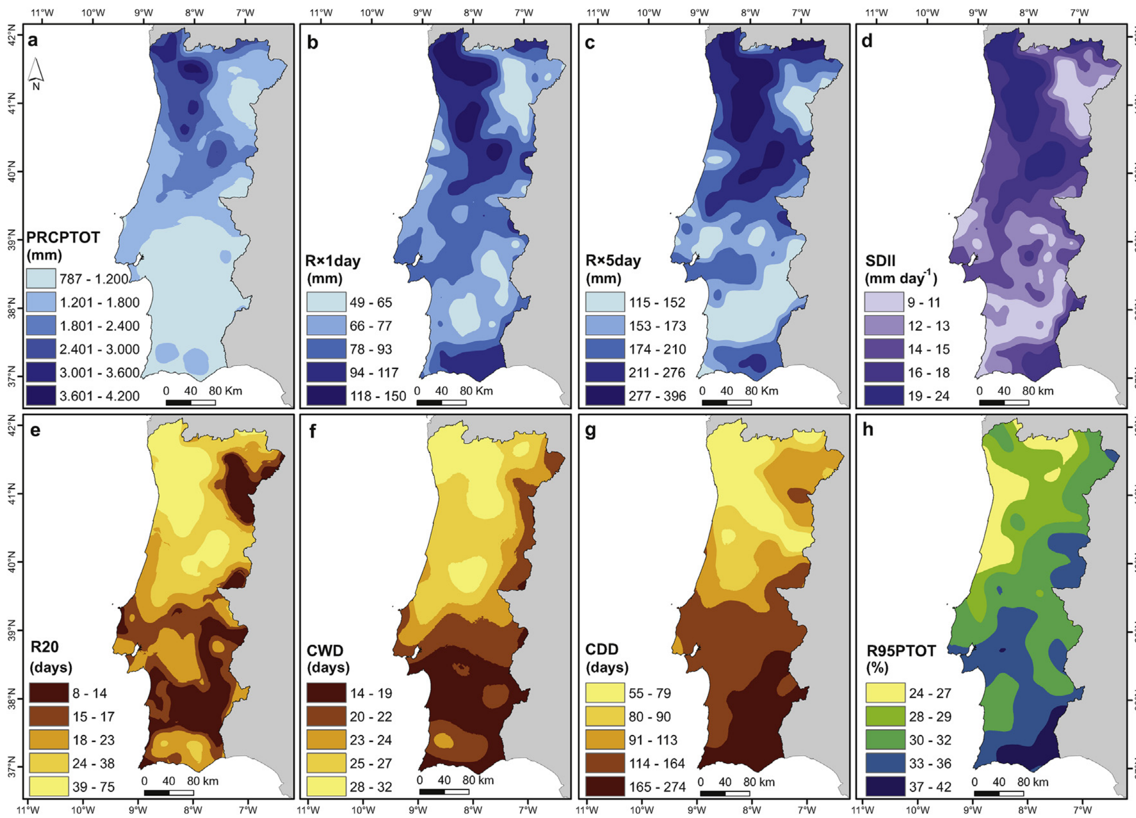

Fig. 5. Spatial distributions of the extreme precipitation indices: (a) PRCPTOT, (b) R×1day, (c) R×5day, (d) SDII, (e) R20, (f) CWD, (g) CDD and (h) R95PTOT for the whole mainland Portugal and for the 10-year return period.

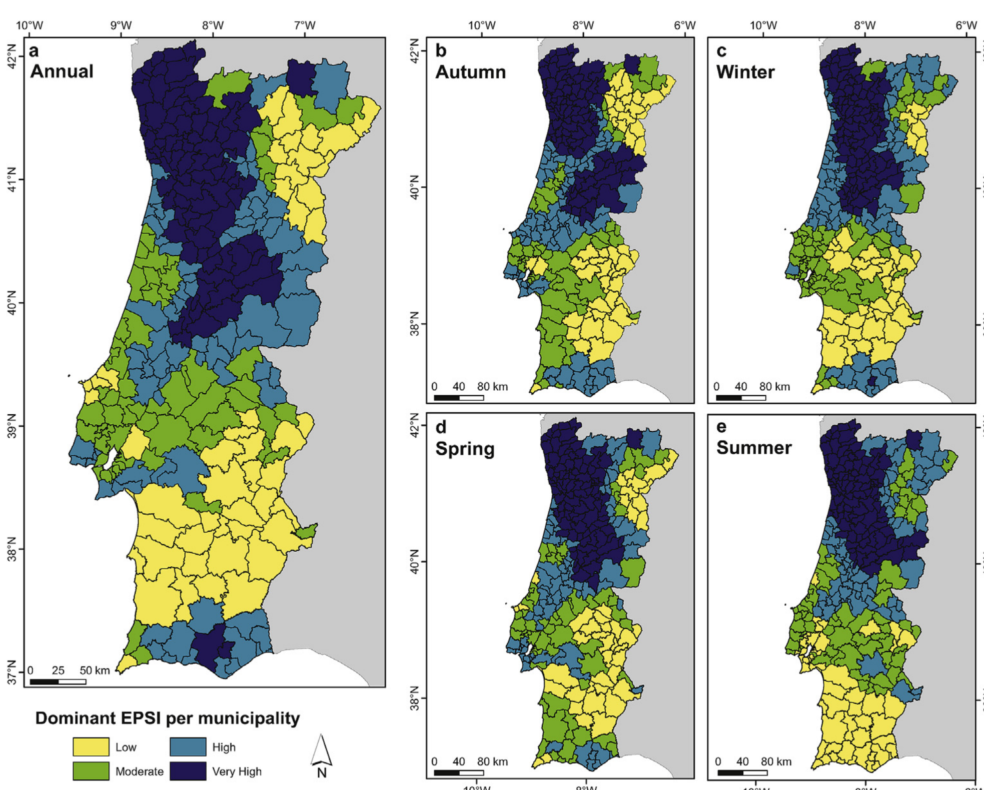

Fig. 6. (a) Annual, (b) winter, (c) autumn, (d) spring and (e) summer dominant extreme precipitation susceptibility index (EPSI) aggregated by municipality over Portugal.

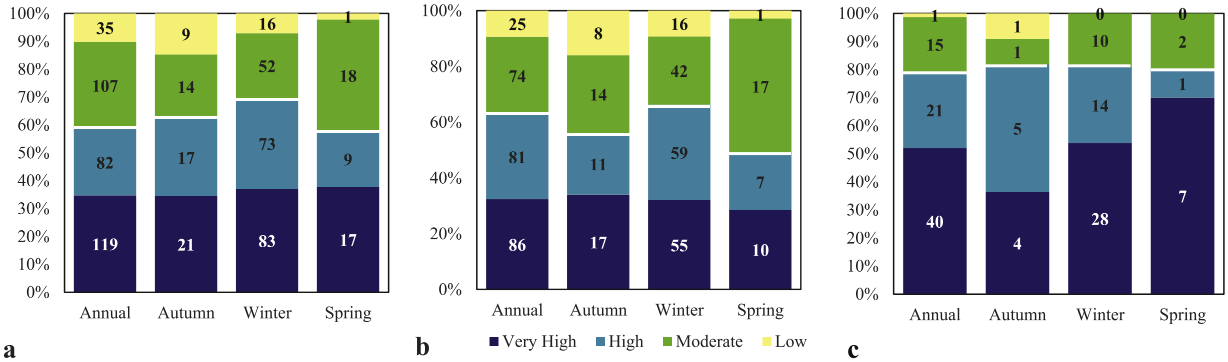

Fig. 7. Frequencies of (a) total (flood and landslide), (b) flood and (c) landslide occurrences for the different EPSI classes and only for DISASTER occurrences outside urban areas (Corine Land Cover 2012) in mainland Portugal (1950–2003). Relative and absolute (within bars) annual and seasonal frequencies are shown. Summer is not considered owing to both the scarcity of precipitation and to the low number of occurrences. The white bars represent the boundary between the two lowest classes and the two highest classes.

areas with similar extreme precipitation patterns in Portugal.

The development of a susceptibility index (EPSI) comprises several challenges, e.g. owing to the difficulty in capturing the different extreme precipitation dynamics. In Portugal, frontal storms play a key role on the occurrence of precipitation, particularly in winter and late autumn, while convective storms are more frequent in summer and spring (Espírito Santo et al., 2014). By considering only six extreme precipitation indices (R×1day, R×5day, SDII, R20, CWD and R95PTOT), for the 10-year return period, between 1950 and 2003, the EPSI was developed. In the annual EPSI, the highest susceptibility areas are the mountainous regions in northern (e.g. Gerês, Peneda, Alvão, Marão and Montesinho) and central Portugal (e.g. Serra da Estrela), as well as in the Algarve (southern Portugal). Conversely, the lower susceptibility classes are in municipalities of the northeast, Alentejo and along the central-western coast. The EPSI shows similar results in autumn and winter. In spring, however, the susceptibility changes for moderate to high. In summer, there is an increase in susceptibility in the northeast, while susceptibility is low over much of Alentejo and Algarve, where precipitation is scarce.

The present study is a first attempt to implement this type of index in Portugal. The first results are very promising, showing a consistent representation of the overall spatial distribution of extreme precipitation. However, it should be noted that the EPSI map reflects only the dominant precipitation regimes in each municipality, not integrating other important natural conditions (e.g. land use, relief, slope, lithological units) for triggering floods or landslides. Although the meteorological conditions are critical for triggering landslides and floods, there are other physical constrains (hydrological and geomorphological) that contribute to their occurrence. In addition to precipitation, other causes can be investigated in further studies. The spatial pattern, as illustration, of landslide and flood induced disasters reflects population distribution and infrastructures. However, the most affected areas also tend to reveal the influence of other predisposing and triggering factors for their occurrences. The factors affecting the development of landslides can be classified as external and internal. External factors comprise precipitation, earthquakes and anthropic activities that act as occasional triggering factors. Internal factors, on the other hand, include lithology, slope angle, slope aspect, and slope profile and are related to natural factors that are static and inherent to the terrain (Henriques et al., 2015; Wu & Qiao, 2009). For landslides, GIS techniques are used for their modelling and prediction in Portugal (e.g. Garcia, Oliveira, & Zêzere, 2016; Zêzere, Garcia, Oliveira, & Reis, 2008; Zêzere, Pereira, Melo, Oliveira, & Garcia, 2017). For floods, according to Llasat et al. (2014), other causes, such as land-use and land-cover changes, changes in runoff and the growing occupation of flood areas, may also play a key role. Moreover, the devastation caused by a flood will be influenced by hydraulic characteristics of the flood, such as water depth, flow

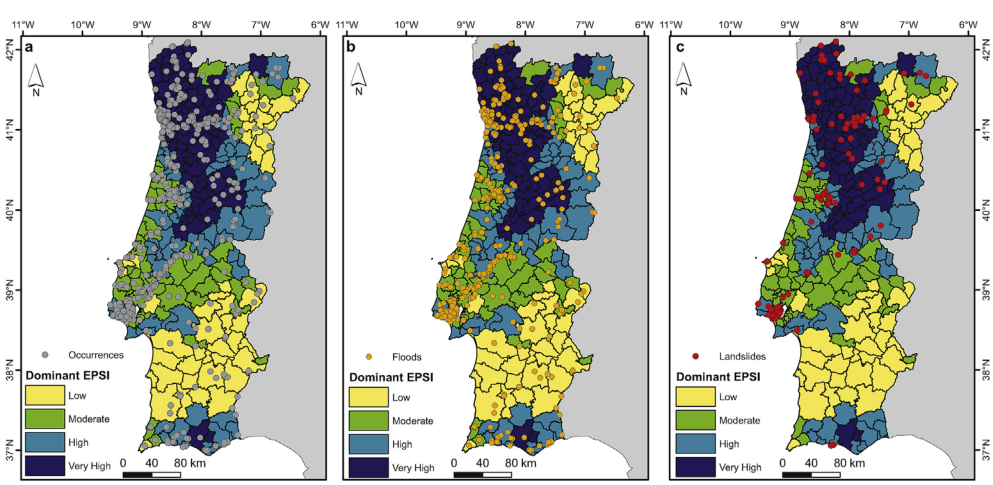

Fig. 8. Relationships between the dominant annual EPSI classes per municipality and the spatial distribution of the DISASTER occurrences over mainland Portugal (1950–2003): a) total occurrences, b) floods, and c) landslides.

rates and rate of water-level rising (Jonkman, 2005).

The 10-year EPSI comprehensively summarizes the characteristics of extreme precipitation, being a starting point for understanding extreme precipitation by the general public. The EPSI is a useful indicator of the spatial propensity to the occurrence hydro-meteorological hazards, particularly landslides. Further, our methodology can be applied to similar studies in other regions. Future work will also include a) an analysis of EPSI historical trends, also considering the consistency with recent studies on extreme precipitation trends, and b) the assessment of EPSI climate change projections and their corresponding potential impacts. Reducing the scale of the analysis in forthcoming research will also enable applying basin models and integrating the EPSI along with other natural triggers into specific river basins. This analyzes will also allow outlining adaptation measures under climate change projections for precipitation in Portugal.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.apgeog.2017.06.020.

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