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A coastal flooding database from 1980 to 2018 for the continental Portuguese coastal zone

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ABSTRACT

Continental Portugal presents an extensive and diversified coastal zone which concentrates the main public and private infrastructures of the different economic sectors, as well as the main critical infrastructures. This area is also characterized by a high population density, being a differentiated territory in geophysical, biological and landscape terms. The wave regime is highly energetic, and storms are frequent. In the last decades, the coast of continental Portugal has been affected numerous times by overtopping and coastal flooding processes. Identifying the critical coastal typologies affected by flooding can contribute to a comprehensive flood risk management framework for the Portuguese coastal zones. Hence, a historical database of coastal flooding occurrences was created for the period 1980–2018 based on national and regional newspapers. For this period 650 occurrences were identified as well as 1708 impacts associated with them. In terms of impacts, the typologies associated with public areas, human impacts, the natural system, environmental degradation and buildings stand out. Results provide relevant temporal and spatial information about coastal historical flood occurrences related to extreme storm events and associated impacts, and contribute to the design of a risk framework.

1. Introduction

Coastal flooding and its associated impacts have become a growing concern in recent decades, as a result of the increasing exposure and changes in the hazard forcers throughout the 20th and 21st centuries (Nicholls & Cazenave, 2010; Weisse et al., 2014; Silva et al., 2017). Among other natural hazards, coastal flooding is responsible for some of the worst human and economic losses worldwide (Kron, 2013). According to the Intergovernmental Oceanographic Commission of UNESCO (IOC/UNESCO et al.,), 40% of the world's population and most economic activities are located within 100 km from the coastline, while in the European Union (EU) 86 million people (19%) live within 10 km of the coastline (EEA, 2006). In Portugal, the coastal zone stands out as an extremely important area, where ¾ of the population and 80% of Gross Domestic Product (GDP) are located (Santos et al., 2017), and where the risk of sea-level rise (SLR) is high (Veloso-Gomes et al., 2004; Antunes & Taborda, 2009; Rocha et al., 2020).

All the projections of the Intergovernmental Panel on Climate Change (IPCC, 2014) predict the continuous rise of the mean sea level and the worldwide increase in storminess. This fact puts several coastal zones at high risk of flooding, including densely populated and economically vital areas. However, coastal areas face not only an increase in SLR but also a range of non-climate-change related factors that contribute to the increase of their fragility. Among them, natural and artificial factors stand out, such as: storm surges, sediment deficit, shoreline retreat; increase in anthropogenic pressure translated by the construction of different types of artificial infrastructure such as harbours, defence structures, urbanization and touristic areas and land use change. The factors mentioned above, combined with the growth of migration to coastal areas, industrialization, urbanization processes, and with the increase in the intensity and frequency of extreme events related to climate change (Bertin et al., 2013), enhances the exposure

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and susceptibility to coastal flooding (IPCC, 2014; Neumann et al., 2015; Rilo et al., 2017).

Several authors have collected historical information related to different natural hazards from newspapers, technical reports and scientific articles, in order to analyse and evaluate past occurrences and impacts associated with natural hazards, and assess future dynamics (Barriendos & Rodrigo. 2006; Raska & Emmer, 2014; Ruocco et al., 2011; Santos et al., 2014). This historical information is often subsequently organized in databases that allow its systematization, treatment and analysis. At a global level, there is a wide range of disaster databases that are distinguished by their temporal and spatial factors, as well as by the types of disasters and insertion criteria considered. Examples of global databases include the EM-DAT from Centre of Research on Epidemiology of Disasters (EM-DAT, 2013), the DesInventar database (La Red, 2009) and the database from Munich Re named NatCatSERVICE (Munich Re, 2011). At national level, some examples can also be mentioned, such as the Spanish Catalonia flood damage database (Barnolas & Llasat, 2007), and the Italian AVI project (Guzzetti & Tonelli, 2004). Specific examples for coastal flooding include a UK database from 1915 to 2016 generated within the project SurgeWatch (Haigh et al., 2017), the US SURGEDAT (Needham et al., 2013) and the Australian Database (Callaghan & Power, 2014). In Portugal, the *DISASTER* hydro-geomorphologic database, with data between 1865 and 2010, stands out (Zêzere et al., 2014).

The Portuguese coastline presents a great diversity of morpho-sedimentary systems such as estuaries, lagoons, barrier islands, beaches, dunes, and cliffs (Ferreira & Matias, 2013; Ponte Lira et al., 2016). This area is also characterized by a multiplicity of land uses, occupations and activities that make it an area of strategic importance at the economic, social and environmental levels. The growth of human settlements in the coastal zone over the last 7 decades, combined with oceanographic and atmospheric forcers and distinct geological and morphological contexts contributes decisively to understand the evolution and current configuration of the coastal zone. The Continental Portuguese coastal zone is also characterized by an asymmetry in terms of wave direction and energy (Andrade & Freitas, 2002). The Atlantic western coast is characterized by high-energetic waves with dominant northwest swell, contributing to high sedimentary transport values. The south coast, although also Atlantic, is protected from the northwest swell and presents a more moderate wave energy (Ferreira & Matias, 2013). The coastal zone is threatened by several hazards, with emphasis on overtopping and coastal flooding, cliff instability, and coastal erosion (Santos et al., 2017; Veloso-Gomes, 2007).

Motivated by the absence of a consolidated national database of coastal floodings and their impacts, a historical database for the continental Portuguese coastal zone between 1980 and 2018 was compiled. This database is part of an effort to develop an innovative methodology to support flood risk management, supported by a better ability to forecast overtopping and flooding occurrences in different coastal typologies. The development of a loss and damage database related to natural disasters is important for risk assessment and regional and local management (Freire et al., 2016; Santos et al., 2014). According to Devoli et al. (2007), the development of this kind of databases is crucial for risk management because they allow the identification and analysis of the relationship between occurrences of disasters, the vulnerable elements, and the respective human and material losses.

The main objectives of this study are: a) to present the methodological aspects related to coastal flooding data collection and the construction of the *MOSAIC* database; b) to present and discuss the spatial and temporal distribution of the coastal flooding occurrences and associated impacts; c) Identify the main oceanographic conditions along the coast, namely water level and wave conditions.

2. MOSAIC database methods

The absence of a consolidated coastal flooding database for the Continental Portuguese coast, combined with the need for the identification and selection of the coastal typologies most affected by floods, led to the creation and development of the database here presented. The hemerographic analysis covers the period 1980–2018 in national and regional newspapers. The general methodology followed to generate the *MOSAIC* database and its analysis is presented in Fig. 1.

2.1. Key concepts

Before presenting the main methodological aspects underlying the construction of the *MOSAIC* database, the main concepts that will be present throughout this study should be clarified. The hazardous processes in this database include coastal flooding and overtopping. The concept of "occurrence" followed the definition of Zêzere et al. (2014) with the necessary adaptations. Occurrence is considered as a specific case related to overtopping or coastal flooding related to a unique spatial location and a specific time period. The concepts of loss (also referred to as human impacts) and damage must also be distinguished. In this study, "loss" or "human impacts" represents the direct hazardous effects on humans, including casualties, injuries, missing, evacuations, and permanent displacement (Santos et al., 2014); "damage" represents the material consequences for any type of facility or property, e.g. road network, buildings, farmland (Santos et al., 2014).

2.2. Database data collection

The main source of information for the *MOSAIC* database were national and regional newspapers. A database of this type can be constructed using a wide range of sources. However, hemerographic analysis presents a set of favourable factors such as the broader coverage of occurrences on a local scale and the same occurrence is, in most cases, reported in different newspapers, allowing a more accurate analysis. The ease of access to newspaper archives, and the broader temporal analysis due to its greater coverage over time are other favourable and preferential factors of the hemerographic analysis over other data sources (La Red, 2013). The information taken from the hemerographic analysis provides a varied set of information. From the start, it allows obtaining quantitative information as to human losses and the number of affected buildings, but also provides qualitative information such as the type of damage observed (Rilo et al., 2017).

The starting point was the selection of the different hemerographic sources to be analysed and that form the basis of the data collection, in order to construct a coastal flooding database for the Portuguese continental coast. The selected newspapers took into account two criteria related to their spatial and temporal coverage: a) the newspaper must have been published continuously for at least 20 years and b) the selected newspaper should guarantee a good national and regional distribution of the news. A total of eight newspapers were analysed according to systematic and punctual analysis, as described below (Table 1). First, daily national newspapers were selected. The first newspaper looked over in a systematic way – i.e., all editions were consulted, either of dates where coastal flooding conditions existed, or of any other dates – was *Público*, which presents two editions with a different regional scope: one focused in the northern Portugal (Porto's edition) and other focused in the central and southern Portugal (Lisbon's edition). The two editions differ in that fact each one includes a local segment with specific information regarding its territorial focus. However, because the *Público* newspaper was only founded in the early 1990's, the period between 1980 and 1990 was systematically explored using the *Jornal de Notícias*. In the punctual analysis (only dates from the hindcast and dates with occurrences resulting from systematic analysis are analysed), one national and five regional newspapers from different areas were considered (Table 1), published in different regions of the country, in order to ensure a wide regional coverage. The dates to consider in the punctual analysis were based on the dates taken from the systematic analysis of the newspapers *Público* and *Jornal de Notícias*, as

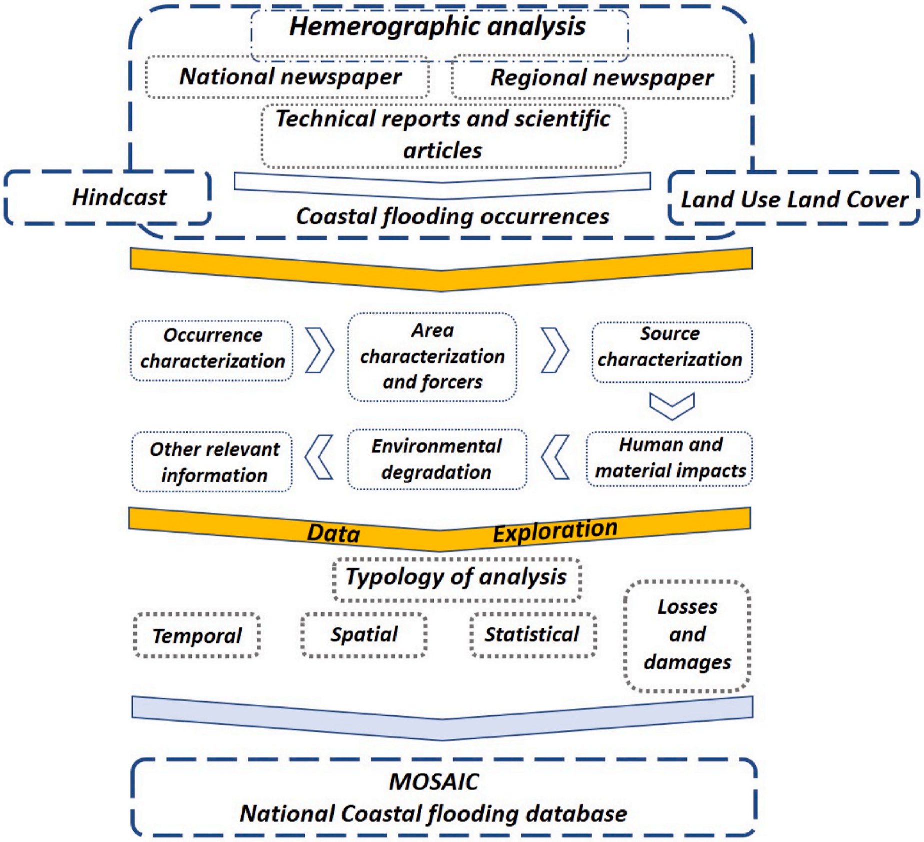

Fig. 1. Scheme of the methodology used in the study.

Table 1
Newspapers used for data collection.

Title	Periodicity of publication	Type of analysis performed	Publication coverage	Coverage period
Público	Daily	Systematic	National	1990–2018
Jornal de Notícias	Daily	Systematic	National	1980–1989
Diário de Notícias	Daily	Punctual	National	1980–2018
Diário do Minho	Daily	Punctual	Regional	1980–2018
Diário de Aveiro	Daily	Punctual	Regional	1985–2018
Diário de Leiria	Daily	Punctual	Regional	1987–2018
Diário do Sul	Daily	Punctual	Regional	1980–2018
Setubalense	Tri-weekly	Punctual	Regional	1980–2018

well as on dates in which ocean conditions were favourable to the occurrence of storms (hindcast). Regarding this last criterion, the conditions were determined through hindcast simulations described in section 2.4. The data resulting from the hindcast allowed the identification of 67 new dates and 165 occurrences, representing 25% of total occurrences. During the punctual analysis, every six years a systematic analysis (all daily editions of the newspaper were consulted) of the newspaper was carried out in order to validate the applied methodology. From the newspapers with regional coverage, one covers the northern coastal area, two the centre coastal area, and the other two the area located south of Lisbon.

In order to validate the hemerographic analysis, a search for occurrences of coastal floodings in technical reports and scientific articles was also performed. The results led to the identification of new occurrences, providing accurate information for its georeferencing. All occurrences were validated by crossing the information obtained in more than one newspaper, as well as in academic works and technical reports. To ensure the consistency of the database, the process of hemerographic searching, insertion of information in the database and occurrences georeferencing was carried out by a single person.

2.3. *Database structure and temporal and spatial incidence*

The *MOSAIC* database consists of six topics subdivided into different fields that identify and characterize each occurrence in its multiple strands (Fig. 2). Based on the sources identified above, a coastal flooding database presently containing 650 occurrences (see definition of occurrence in section 2.1) was built. The *MOSAIC* is an adaptable and georeferenced historical database with alphanumeric open and closed fields of the numeric and textual types. Each occurrence inserted in the database is subsequently georeferenced using a point shapefile, based on the information from the analysed source, using the ArcGIS 10.5 software. The PT-TM06/ETRS89 projected coordinate system was adopted. Georeferencing is based on satellite images provided by the Esri® World Imagery service. The location accuracy considered was divided into four classes (Zêzere et al., 2014): 1) location with exact coordinates (scale 1:1000); 2) location based on local toponymy (scale 1:10,000); 3) location in the centroid of the parish (only used when no other location besides the parish is mentioned); 4) location in the centroid of the municipality (*idem* regarding the mention to the municipality).

The temporal incidence of the *MOSAIC* database ranges from 1980 to 2018. The spatial incidence is the entire Continental Portuguese coastal zone, extending from the mouth of the Minho River, in the northwest, to the mouth of the Guadiana River in the southeast, totalling about 987 km (Fig. 3).

Throughout the work, the density of occurrences per km^2 will be

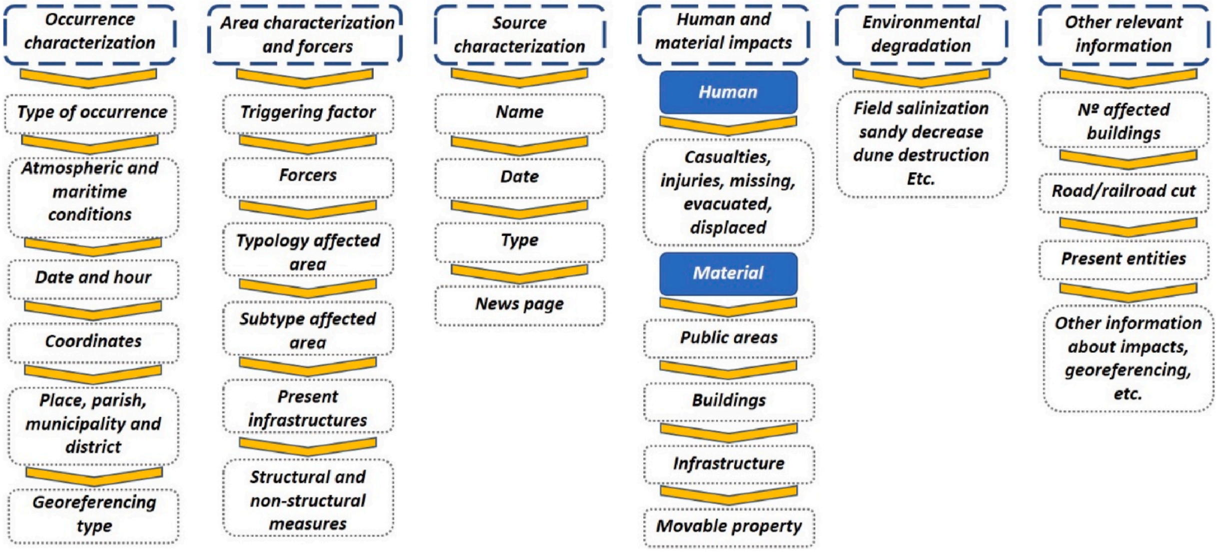

Fig. 2. Topics and main fields of *MOSAIC* database.

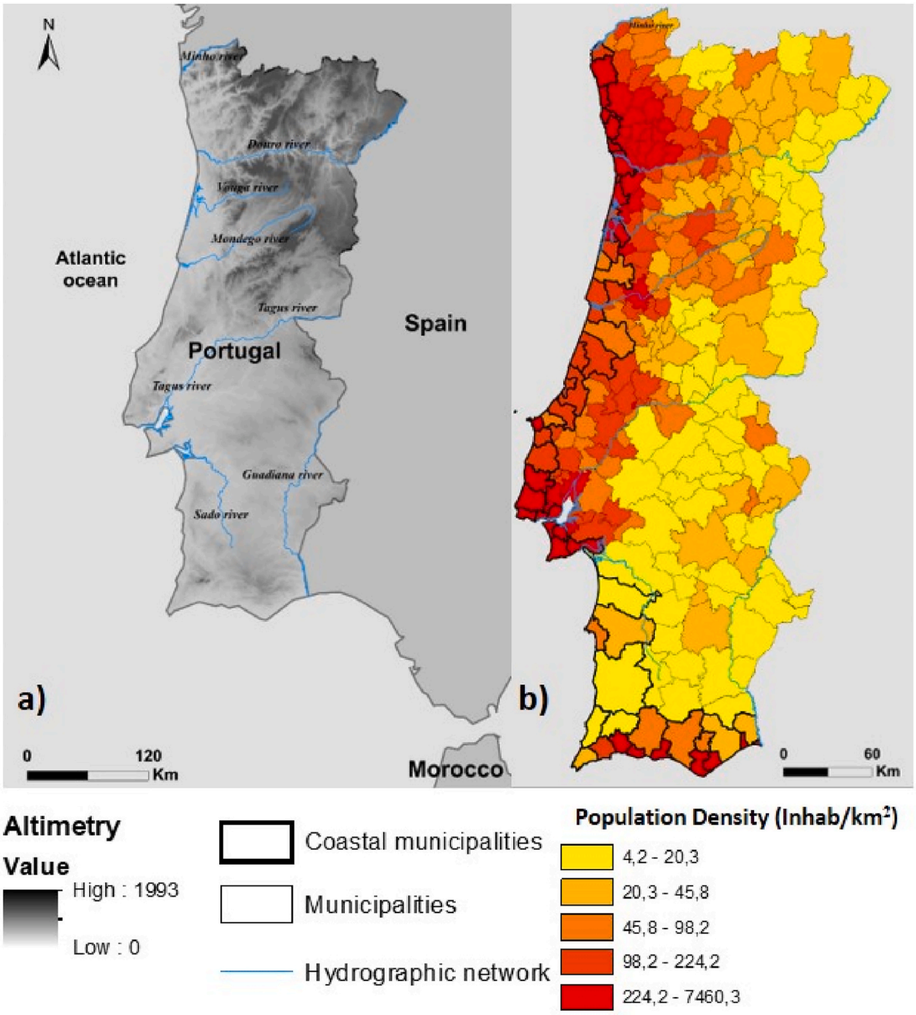

Fig. 3. Location of the coastal area covered by the MOSAIC database: a) Continental Portugal; b) Population density of Continental Portugal by municipality. (color should be used for any figures in print). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

calculated. The calculation is based on an area of 500 m defined from the highest astronomical tide line up to 500 m inland, according to the definition present in the National Strategy for the Integrated Management of the Coastal Zone (ENGIZC, 2009). This delimitation has also taken into account the current historic occurrence as well as the definition of the safeguard strips for overtopping and coastal flooding present in the approved POC.

For the Land Use Land Cover (LULC), two exploratory analysis were carried out considering different territorial areas. The first considers an area of 500 m defined from the highest astronomical tide line up to 500 m inland (referred to in the previous paragraph), called Coastal border. The second is called the Coastal Zone, according to ENGIZC (2009) and extends for 2 km inland, including the Coastal border area. Both analyses are based on the Land Use and Occupation Cartography of 1995, 2007, 2010, 2015, and 2018 provided by the Territory's General Directorate (DGT, nd), with no cartography for previous periods.

2.4. *Hindcast of oceanographic variables*

The information on occurrences was complemented by multi-decadal time series of oceanographic conditions along the coast. Time series were generated for both the water level (due to tides and storm surges) and wave conditions. The time series of water levels were obtained by adding tidal and surge signals. Tides were computed through harmonic synthesis based on the results of a regional tidal model (Fortunato et al., 2016, 2019). This model simulates the generation and propagation of tides in the North-East Atlantic Ocean. Along the Portuguese coast, root mean square errors are of the order of 5 cm. Results were extracted at 7 representative points along the western Portuguese coast. Surges were estimated based on the inverse barometer effect, i.e., assuming that only atmospheric pressure contributes to the surge. This approximation is justifiable in the Portuguese coast (Fanjul et al., 1998) because the wind-generated surge is limited by the small width of the continental shelf. Time series of atmospheric pressure were extracted from the ERA-Interim reanalysis (Dee et al., 2011).

The wave characteristics along the western Portuguese coast were determined using the wave model WaveWatch III (Tolman et al., 2009, p. 194) applied to the North Atlantic Ocean, with a nested grid on the Portuguese shelf. The model was run from 1979 to 2018, forced by winds from the ERA-Interin reanalysis. Further details on the application of the model are provided in Fortunato et al. (2017). Significant wave heights (Hs) were stored at hourly intervals.

Subsequently, an analysis of the time series of oceanographic conditions was carried out, considering the daily maxima Hs and sea level (Sl) to perform the punctual analysis related to hemerographic research and to analyse the relationship between overtopping and flooding forcings and the number of occurrences. The parameters used in the present study as representative of the overtopping or coastal flooding forcing conditions are: the daily sea level maxima (Slmax) and the daily maximum significant wave height (Hsmax).

3. Results

3.1. *Spatial and temporal distribution*

The hemerographic analysis allowed the identification of 650 occurrences of coastal flooding and overtopping between 1980 and 2018, with high temporal and spatial variability. However, some geographic hotspots with a high number and density of occurrences can be identified (Fig. 4). Two distinct sectors can be recognized: the first encompasses all coastal municipalities to the north of the Tagus River, which concentrates 77% of the occurrences; the second encompasses the remaining coastal municipalities and represents 23% of the occurrences. Considering the planning and management instruments (Spatial Coastal Zone Plans - POC), that divide the coastal area in six different sectors, results show that 85% of the occurrences are located in the three northernmost sectors (Fig. 4b).

The analysis also shows that only 9 out of 54 coastal municipalities

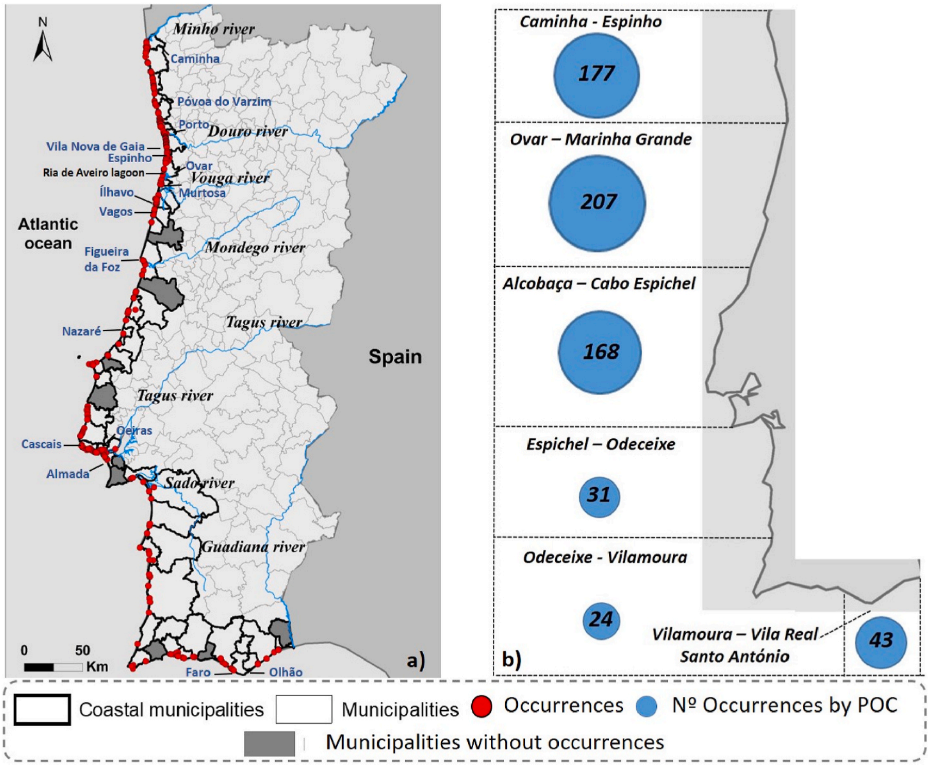

Fig. 4. Spatial distribution of the occurrences: a) Continental Portugal; b) Occurrences in the different POC. (color should be used for any figures in print). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

do not exhibit any occurrence (Fig. 4a). However, the absence of occurrences in a given area does not mean that it is not affected by flooding or overtopping. This absence can be explained either by incomplete documentary coverage of certain areas or by the characteristics of the affected areas, namely areas that are predominantly natural and with little anthropic occupation, that receive less interest in the news coverage.

Fig. 5a shows the five municipalities with the highest number of occurrences (see location in Fig. 4a), both in the entire period, and on each decade. For the period between 1980 and 2018, except for Almada (belonging to the POC Alcobaça-Cabo Espichel), all the municipalities are located north of the Mondego River, belonging to the POC Caminha-Espinho (Porto and Vila Nova de Gaia) and Ovar-Marinha-Grande (Ovar and Ílhavo). This spatial pattern is practically unchanged when the different decades are analysed separately. The ‘80s stands out for presenting a greater spatial variability related to the occurrence of flooding and overtopping. Another fact to highlight is related to the municipality of Porto, which between 1980 and 2018 is the third municipality with the highest number of occurrences. However, these occurrences are essentially concentrated in the ‘80s and ‘90s. Since the end of the ‘90s, the number of occurrences in the municipality of Porto decreased significantly, being this fact related to a set of coastal defence works carried out during the ‘90s. In contrast, in the municipalities belonging to the metropolitan area of Lisbon, in particular Almada, Cascais, and Oeiras, the number of occurrences increased significantly since 2000.

With regard to the density of occurrences, with the exception of the municipality of Almada, all other municipalities are located north of the Tagus River (Fig. 5b). The municipality of Porto stands out as having the highest density of occurrences (24.32 occurrences per km^2).

Fig. 6 shows the monthly and annual distribution of occurrences. Regarding the monthly distribution, the vast majority (93%) occurs during the so-called maritime winter (from October to March) with a clear maximum for January, with 51% of the total occurrences (Fig. 6a). Storm Hercules, which affected mainland Portugal between 3 and 7 January 2014, was responsible for 56% of the total occurrences in January between 1980 and 2018.

As for the annual distribution of occurrences (Fig. 6b), the years 2014, 1996, and 2010 stand out, concentrating 56% of the total between 1980 and 2018. As previously mentioned, in 2014 the storm Hercules was responsible for 75% of the total occurrences identified in 2014 and for 37% in the period 1980–2018. The occurrences resulting from the storm Hercules had a great spatial dispersion with a special focus on the west coast. In 1996, most of the occurrences refer to a period of storms between the 1st and the 14th of January dispersed through the western and southern coast. As for 2010, most of the occurrences are due to the storm Xynthia (27th – 28th February) as well as to a stormy period that occurred on the 8th of October. The first event caused occurrences mainly on the south coast, while the second gave rise to a greater concentration of occurrences between the municipalities of Porto and Figueira da Foz. Fig. 6b shows the temporal evolution of the occurrences, where it is possible to observe an increase in the number of occurrences between 1980 and 2018, with different rhythms. The ‘80s were marked by growth and subsequent stabilization in the number of occurrences, representing 8% of the total. The ‘90s represent 27%, being a decade marked by an initial increase in the number of occurrences followed by a stabilization period that is interrupted by a slight increase in 1994 followed by a more pronounced growth caused by 1996 storms. The first decade of the 21st century represents 13% of the occurrences and is characterized by a period with a slight but constant increase, with 2003 standing out as the one with the highest number of occurrences. The last

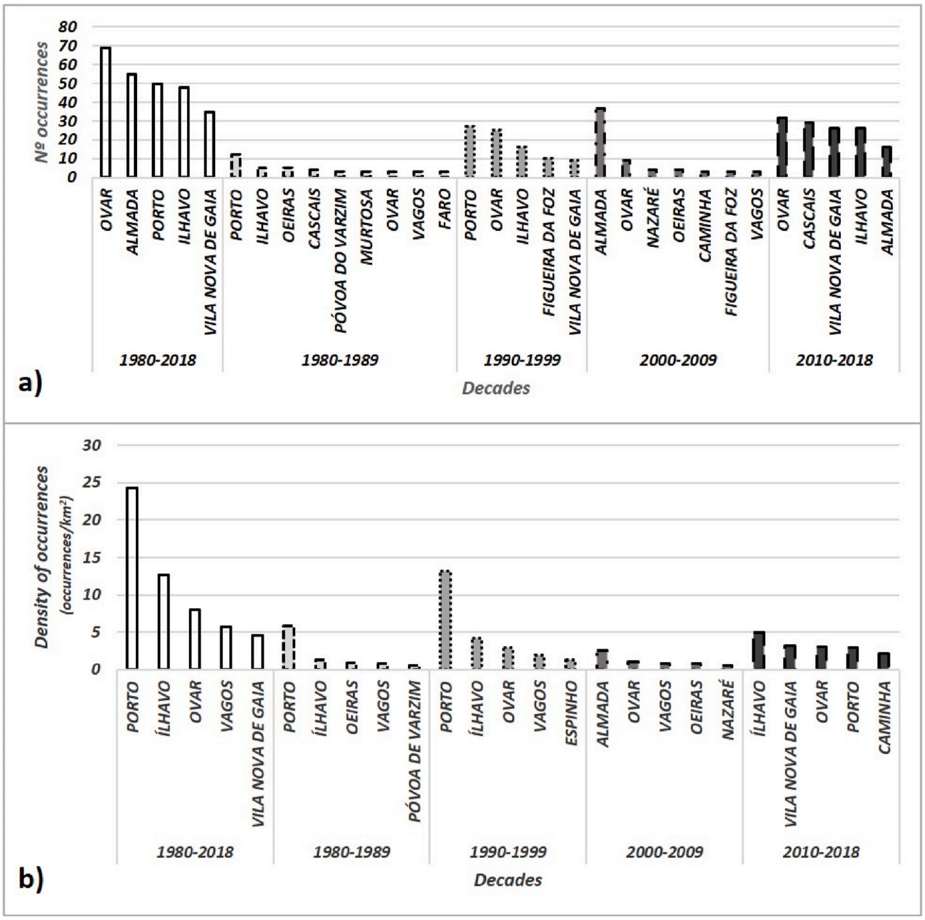

Fig. 5. Municipalities with higher number (a) and density of occurrences (b) in the analysed decades.

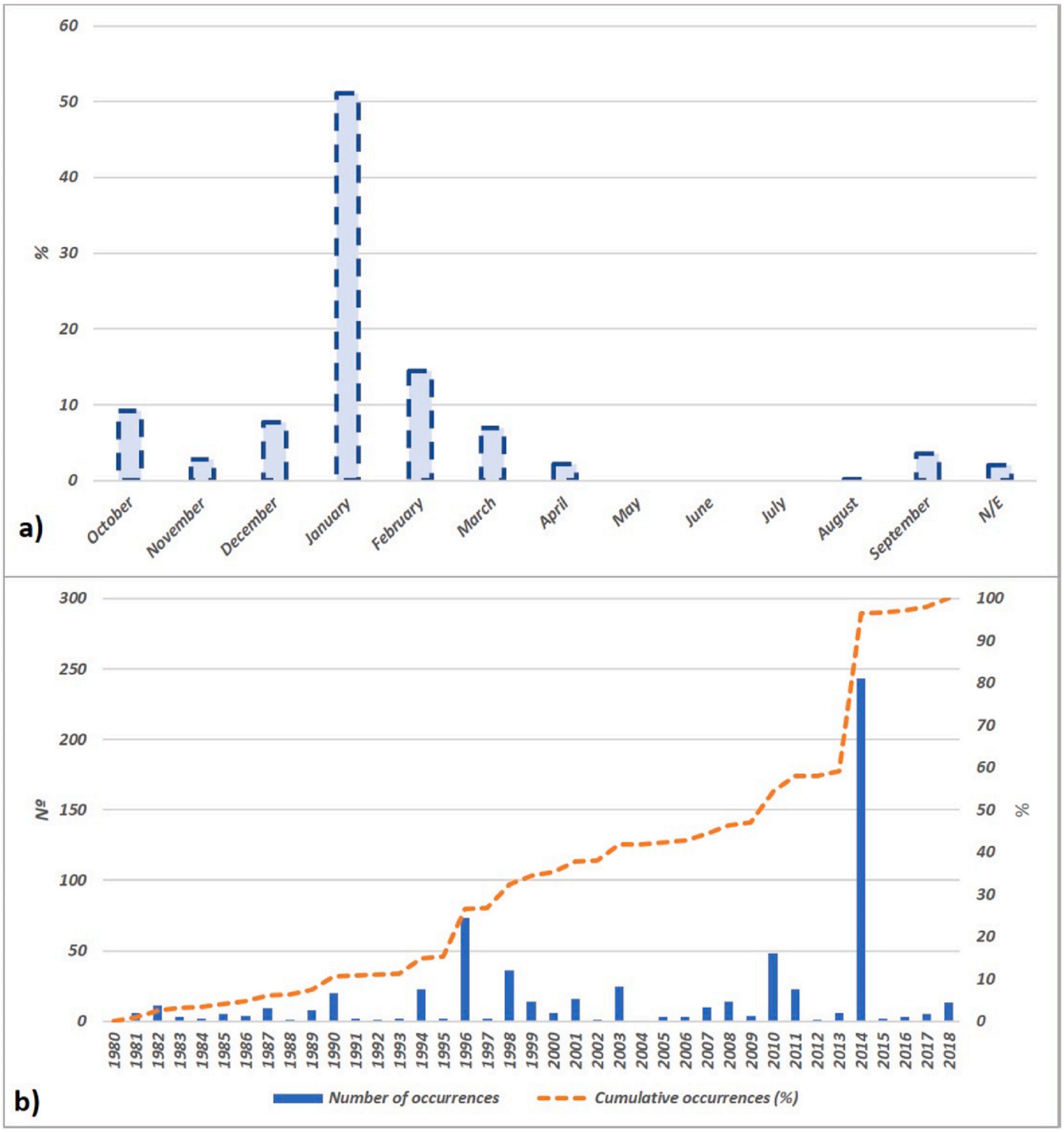

Fig. 6. Temporal distribution of occurrences: a) Monthly distribution; b) annual distribution.

period analysed (2010–2018) less than ¼ of the database's time frame – concentrates 53% of the total number of occurrences and is clearly the period characterized by a huge growth in the number of occurrences, especially in the years 2010 and 2014.

This increase is related to a period in which the Portuguese continental coast was hit by a set of storms, of which Xynthia (February 2010), Hércules (January 2014) and Emma (March 2018) stand out, as well as, a set of stormy periods such as the beginning of October 2010 and February 2011. This could be related to the increase in storminess associated with climate change. According to Santos et al. (2017), the main impacts of climate change that will affect the coastal zone of mainland Portugal will be related to: a) the increase in the global average sea level which will cause a greater frequency of extreme values of sea level; b) the rotation of the direction of the waves on the west coast; c) the change in the storm system with a possible increase in frequency and intensity of extreme weather and climate events.

3.2. Losses and damages

The 650 occurrences of coastal flooding and overtopping between 1980 and 2018 resulted in a total of 1708 losses and damages spread over 7 categories and 56 typologies. Fig. 7 presents the categories identified, as well as the proportion that each typology represents in each of them in terms of number of occurrences.

As some typologies have a residual value, it is important to highlight in each category of losses and damages the main types of resulting impacts. Fig. 8 shows all the loss types, with the displaced and evacuated people representing 85% of the human impacts. Regarding the damages related to the natural system and environmental degradation, they are fundamentally related to the sand/dune system (Fig. 8), representing 93% and 67% of the total of each category, respectively. Damage to urban streets and beach walkways accounts for 57% of the damage in public areas. Regarding the infrastructure category, coastal infrastructure damages stand out (73% of the total category). With regard to buildings, the commercial type stands out, followed by residential and beach support buildings (cabinets, sanitary facilities, bars, etc.), which together account for 86% of the affected buildings.

Fig. 9 presents all losses and damages identified and their temporal distribution. There is a predominance of damages in public areas, followed by human impacts, environmental degradation, and natural system damages. The temporal distribution of the losses and damages show that the 1980s were marked by damages associated with public areas, as well as related to environmental degradation and the infrastructures category. The following decade was characterized by a general increase

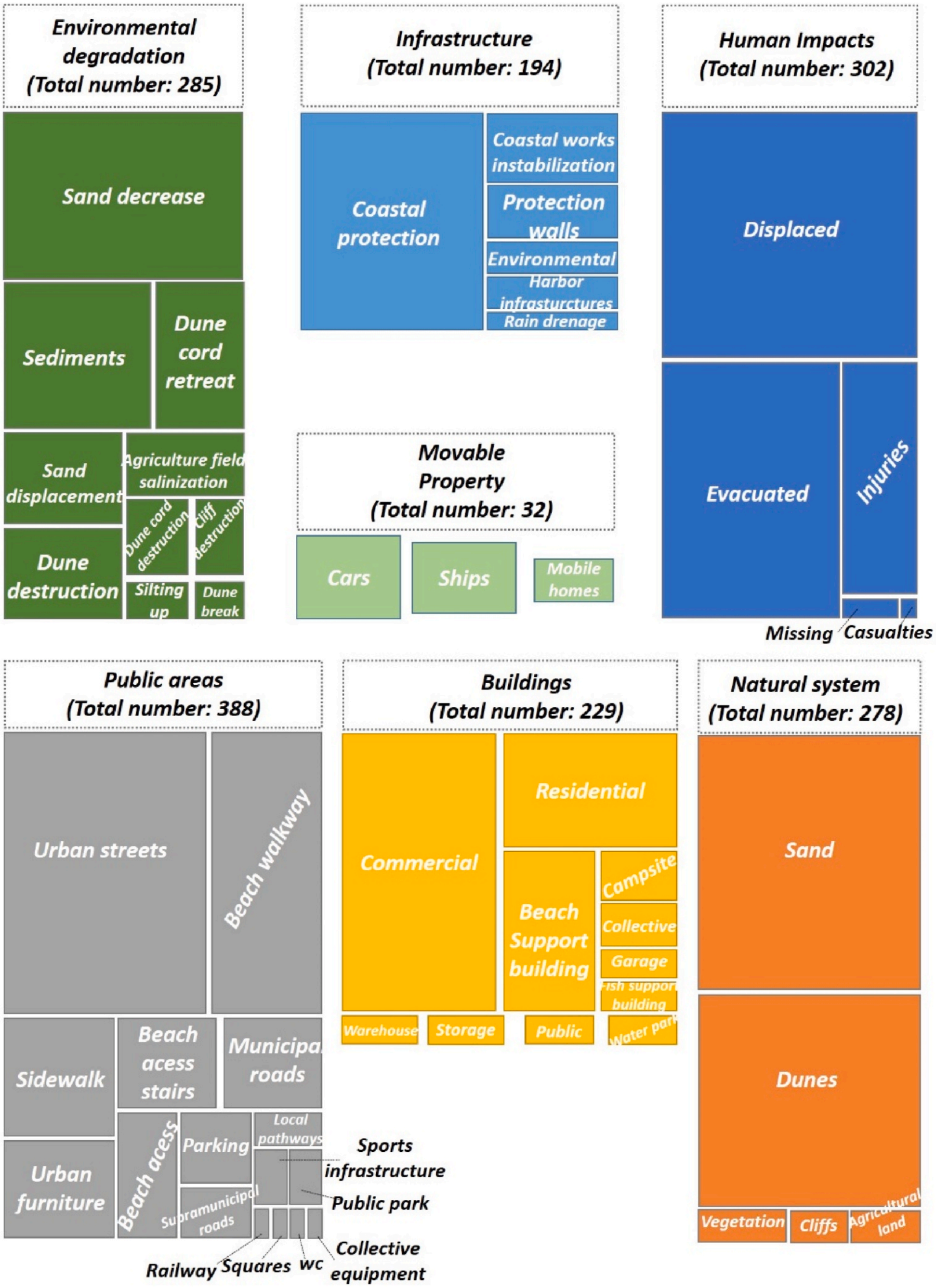

Fig. 7. The categories and typologies of losses and damages differentiated by colors. The size of the polygons is proportional to the number of occurrences in each category. (color should be used for any figures in print). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

in all categories of impacts. It is a period marked by human impacts, that emerge as the category with the highest number of occurrences, highlighting the 73 evacuated people identified in the municipality of Ovar. Also, the damage to buildings grows significantly, particularly in commercial (23) and residential (18) buildings. Between 2000 and 2009 the impacts decrease relative to the previous period, as well as the number of occurrences. This decade is marked by a balance between the different categories, highlighting the damages to the natural system, mainly related to changes in the sand and dunes system.

The period between 2010 and 2018 is marked by a sharp growth in losses and damages, which translates into a growth of 367% compared to the previous decade. Damage to public areas is the category with the highest number of observed impacts, with particular emphasis on damage to walkways, urban streets, and urban furniture. The human impacts category should be highlighted, where 121 displaced people were registered, particularly in the southern municipality of Olhão. These human impacts were mostly verified during January and February 2010, when a stormy period occurred, highlighting the storm Xynthia (27th – 28th February). It is also important to highlight the damage related to the environmental degradation and natural system, with emphasis on the sand and dunes system, causing in many cases important decreases in the sand and retreat in the dune cord. Finally, damage to buildings is highlighted, with emphasis on commercial, residential, and beach support buildings, as well as damage to coastal protection infrastructures.

Fig. 10 presents the spatial distribution of the occurrences,

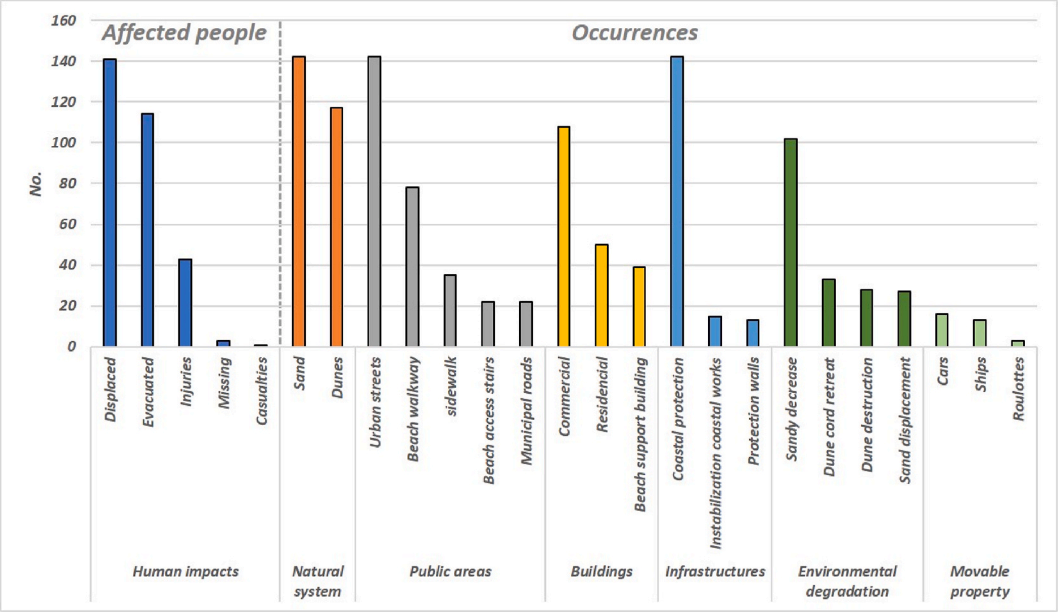

Fig. 8. Principal losses and damages in each category. Human impacts are expressed by the number of affected people. The other categories are expressed by the number of occurrences. (color should be used for any figures in print). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

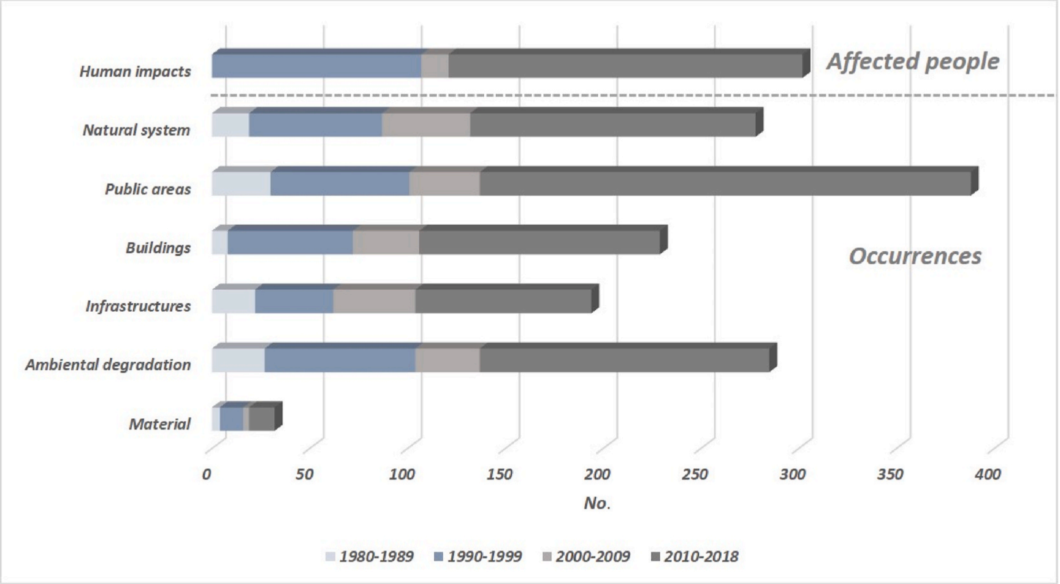

Fig. 9. Number of occurrences and affected people for every decade (colour scale) by categories of losses and damages. Human impacts are expressed by the number of affected people. The other categories are expressed by the number of occurrences. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

considering the different POC. Results show that the areas north of Cabo Espichel (see Fig. 4b) suffer more losses and damages than the other areas to the south. The exception is the POC Vilamoura-Vila Real Santo António with the highest number of human impacts (115 displaced), for which the municipality of Olhão contributes the most. In all areas, the period between 2010 and 2018 is the one with the highest number of losses and damages. Damages in public areas stand out as the category with the highest number of occurrences in almost all areas. In Espichel-Odeceixe and Vilamoura-Vila Real Santo António damages in buildings and human impacts are, respectively, the most frequent categories. In the areas north of Cabo Espichel, damages related to the natural system and environmental degradation are the most important. Globally, with the exception of the 2000–2009 decade, results show an increase of the losses and damages and diversity across all areas between 1980 and 2018.

If we take into account the municipal scale, namely the five municipalities with the highest number of occurrences, there are also different trends (Fig. 11). In the municipality of Porto, most of the impacts (65%) were observed between 1980 and 1999, with emphasis on the damage in public areas and related to environmental degradation. However, during the Hercules storm in 2014, the human impacts, such as evacuations and injuries, are the most relevant ones. Vila Nova de Gaia and Ílhavo show a temporal distribution of impacts different from the other municipalities, as 78% and 70%, of losses and damages, respectively, arose between

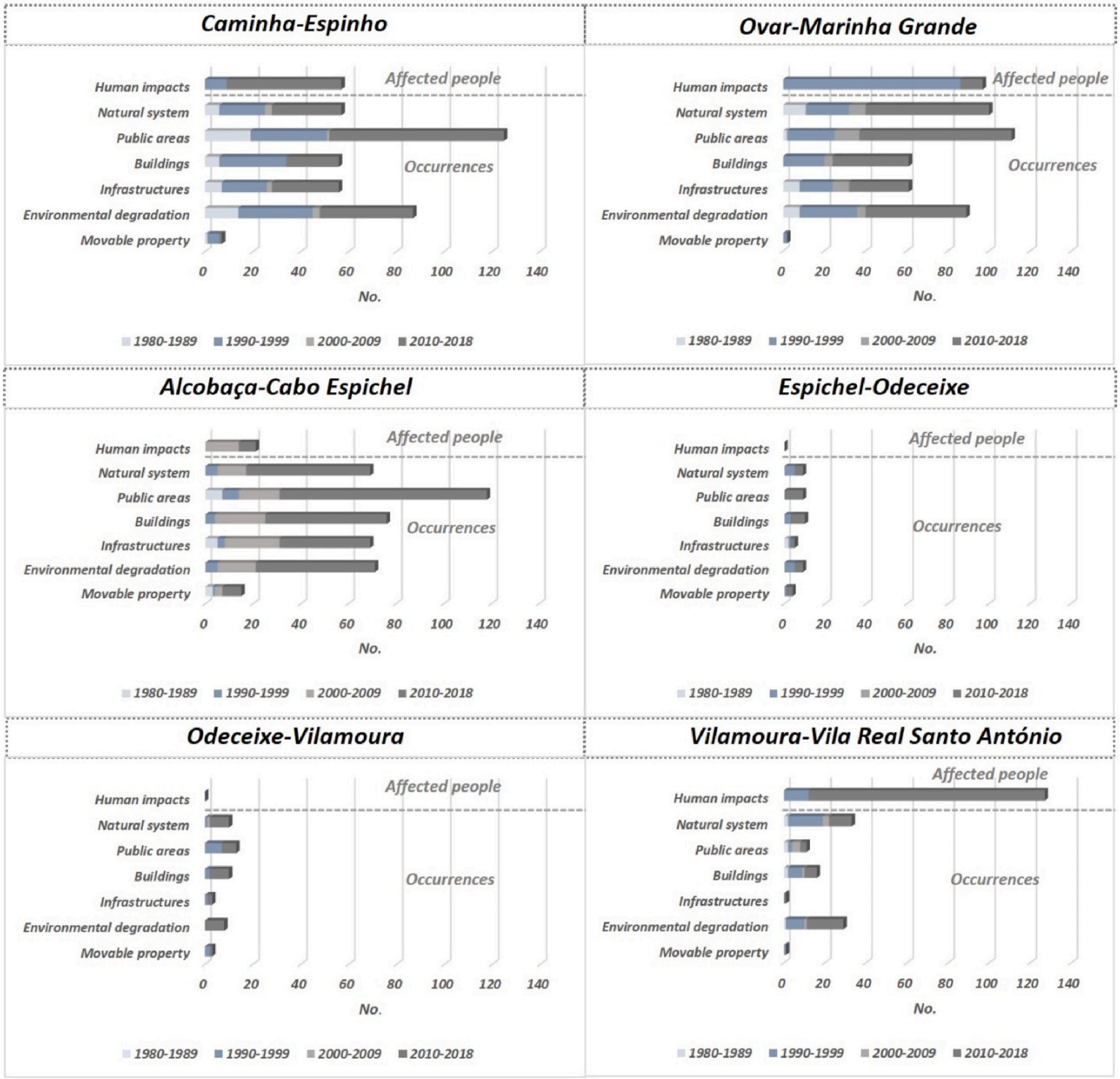

Fig. 10. Losses and damages in the different POC for every decade (colour scale). Human impacts are expressed by the number of affected people. The other categories are expressed by the number of occurrences. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

2010 and 2018. In Vila Nova de Gaia, damages to public areas and infrastructures stand out, with emphasis on beach walkways, beach access and coastal protection infrastructures (Fig. 11), while in Ílhavo damages to the natural system and environmental degradation predominate with relevant changes in the beach/dune system (Fig. 11).

In terms of the losses and damages types, the municipalities of Ovar and Almada show different trends from the rest (Fig. 11). In Ovar, 54% of the impacts occurred in the ‘90s, with an emphasis on the series of the 1996 events, where the human impacts stand out, namely the 73 evacuees recorded in January of that year. Also, noteworthy was the damage observed in 38 buildings during the period under analysis, with emphasis on commercial and residential typology, mainly affected during 2010 and 2018. In Almada, 72% of the losses and damages observed occurred between 2000 and 2009, with a particular peak in 2001. It is possible to verify the relevance of damage to infrastructures and buildings (Fig. 11, on the left), with emphasis on coastal protection infrastructures and commercial buildings, respectively (Fig. 11, on the right).

3.3. *Land use land cover change*

In the present study, LULC changes in the five municipalities of the continental Portuguese coastal zone with the highest number of occurrences are analysed.

3.3.1. *Coastal border*

The analysis of LULC change on the coastal border (defined from the highest astronomical tide line up to 500 m inland) carried out at national level shows distinct territorial dynamics. In 2018, 61% of this territory was occupied by forest, shrub vegetation, and sparsely vegetated areas. However, it is necessary to underline the increase in artificial areas between 1995 and 2007 and subsequent stabilization afterwards. In the opposite direction there is a continuous decrease in the agricultural area until 2015, with a slight increase in 2018.

Regarding the 5 considered municipalities, the analysis of Fig. 12 allows concluding the presence of territories with different dynamics and trends. However, it should be noted that in all of them there is an increase in artificial areas between 1995 and 2018. Porto and Vila Nova

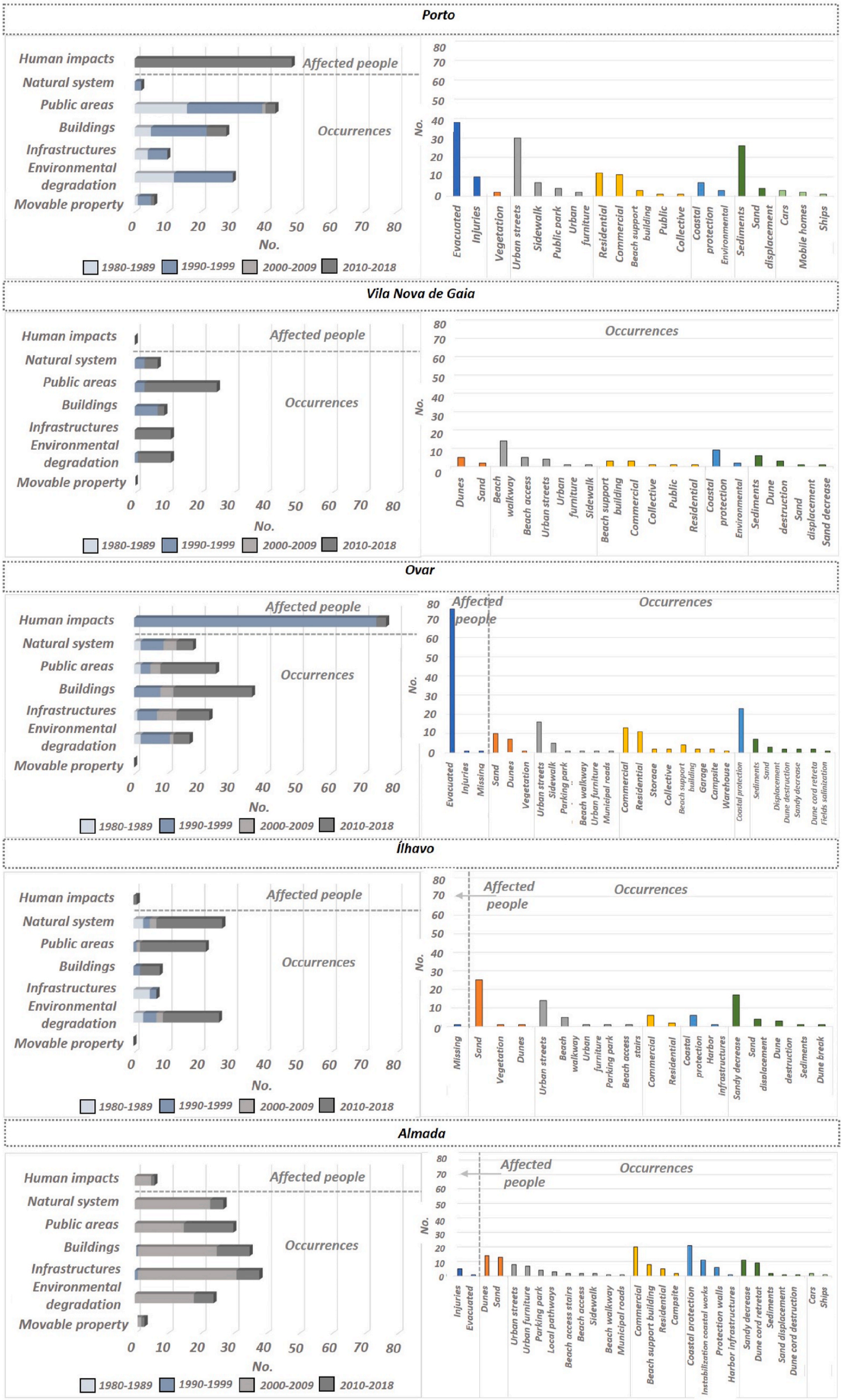

Fig. 11. Losses and damages in the municipalities with highest number of occurrences: Evolution by decade (on the left side); Typology of losses and damages (on the right side). (color should be used for any figures in print). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

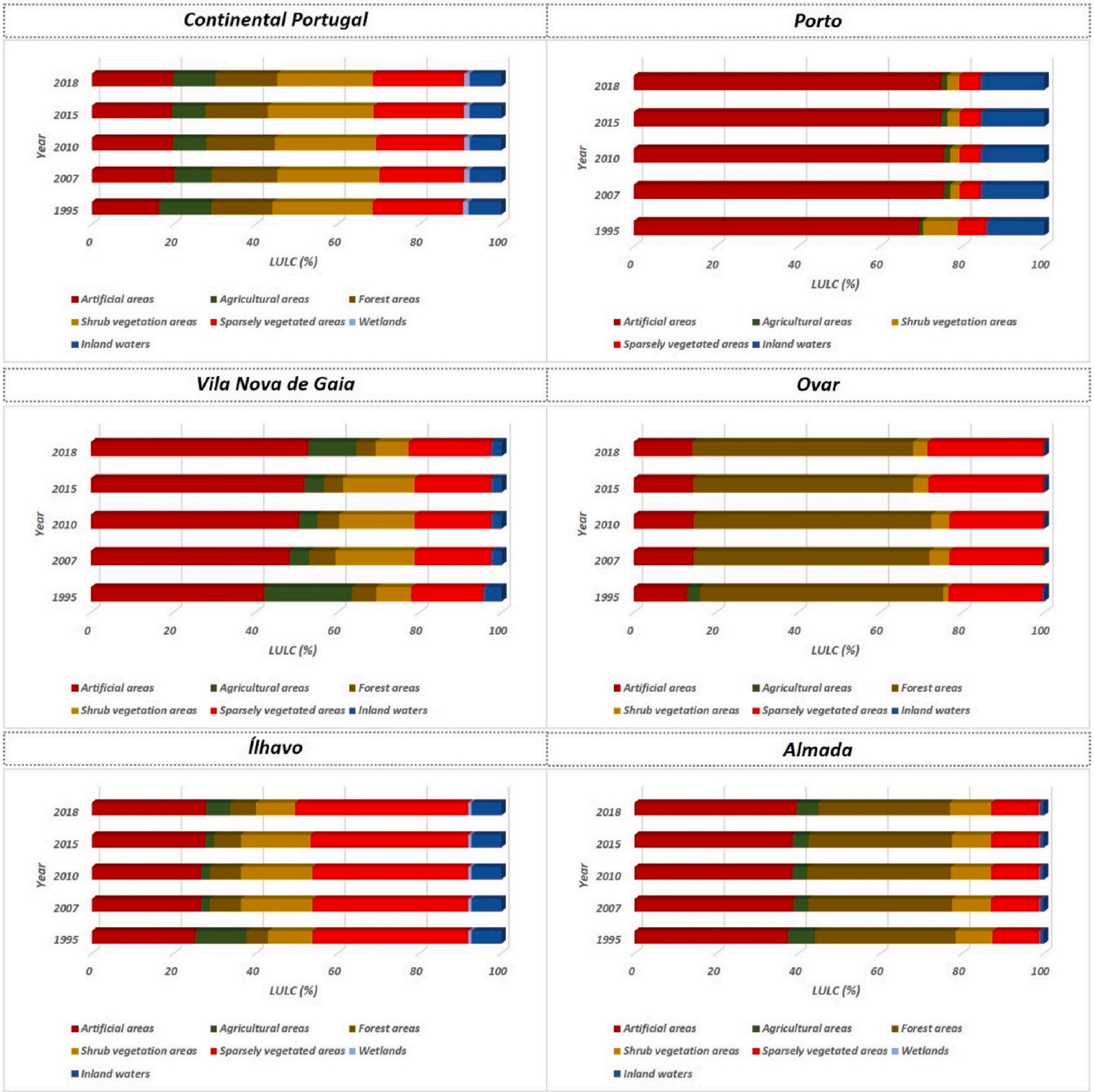

Fig. 12. Coastal border Land Use Land Cover. (color should be used for any figures in print). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

de Gaia assume themselves as municipalities with a coastal border mostly occupied by artificial areas, respectively 75% and 53% in 2018. The growth of soil artificialization between 1995 and 2007 and the later stabilization in the subsequent periods for the municipality of Porto is noteworthy, while in Vila Nova de Gaia uninterrupted growth is shown between 1995 and 2018.

The coastal border of the municipalities of Ovar and Ílhavo stands out for the predominance of natural areas. In 2018, forest areas (54%) and sparsely vegetated areas (28%) dominated territorially in Ovar, while in Ílhavo the predominance is for sparsely vegetated areas (42%) followed by artificial areas (28%). In Almada, the artificial areas predominate, representing 40% of the coastal border in 2018, with a continuous growth from 1995. However, it is highlighting the importance of forest areas that represent 32% of the municipality coastline.

Considering the relationship between the prevalent categories of impacts in each analysed municipality and the respective evolution of LULC in the considered periods different dynamics stand out. The increase in the artificialization of the soil across the five municipalities, verified between 1995 and 2018, is not directly related to the increase in the number of occurrences with material impacts or the number of affected people, with the exception of the municipalities of Ílhavo and Almada. In Ílhavo, the highest number of losses and damages related to material impacts and affected people occurring between 2010 and 2018 and in Almada between 2000 and 2009.

The greatest variability in terms of impacts occurs in municipalities where natural areas predominate and where the lowest growth in artificial areas is observed in the analysed periods. In Ílhavo, the predominance of damages in the natural system and environmental degradation occurs in all the analysed decades, with the same trend occurring in Ovar in the '80s. However, in Ovar, there is a change in the pattern of impacts since the '80s, with the predominance of human impacts in the '90s, with material impacts predominating in the last two decades, with emphasis on damage to buildings, public areas and coastal protection infrastructures. Regarding the municipality of Almada, marked by a constant growth of artificial areas and shrub vegetation areas, with the exception of the '80s, in which there was no occurrence, material impacts predominate, with emphasis on damage in public areas, buildings, and coastal protection infrastructures.

In the municipalities that have a predominance of artificial areas (Porto and Vila Nova de Gaia), there is less variability in the impacts. The material impacts stand out over the analysed decades, namely related to damage to public areas and buildings. However, it is worth noting the exception that occurred in the period 2010–2018, in the municipality of Porto, where human impacts predominate.

3.3.2. *Coastal zone*

Regarding the LULC analysis carried out for the coastal zone (extends for 2 km inland, including the Coastal border) for the mainland Portugal, it is possible to note the predominance in 2018 of forest areas (26%) followed by agricultural (22%) and artificial areas (21%). The uninterrupted growth of artificialization between 1995 and 2018 should be noted (Fig. 13), as well as, a decrease in agricultural areas, in the same period. In relation to the other land use classes, their dynamic is marked by stability over the period observed. The analysed municipalities, as previously verified for the coastal border, are characterized by different trends. Porto and Vila Nova de Gaia are distinguished by the predominance of artificialization with emphasis on the increase verified between 1995 and 2018.

Regarding Ovar and Ílhavo, there is a clear predominance of natural areas, with Ovar standing out for its forest areas which currently represent 69% of municipal coastal zone. In Ílhavo, despite a slight increase in artificial areas between 1995 and 2018, currently representing 23% of the coastal zone, the inland waters, agricultural areas and wetlands stand out, which together represent 58%. The importance of inland waters and wetlands is related to the presence in the analysed area of The Ria (estuary) de Aveiro. In Almada, the artificial areas present a continuous and uninterrupted growth representing in 2018 48% of the analysed area. Also noteworthy are the forest and agricultural areas, which, despite a decrease in the period under analysis, represented in 2018 42% of the total coastal zone.

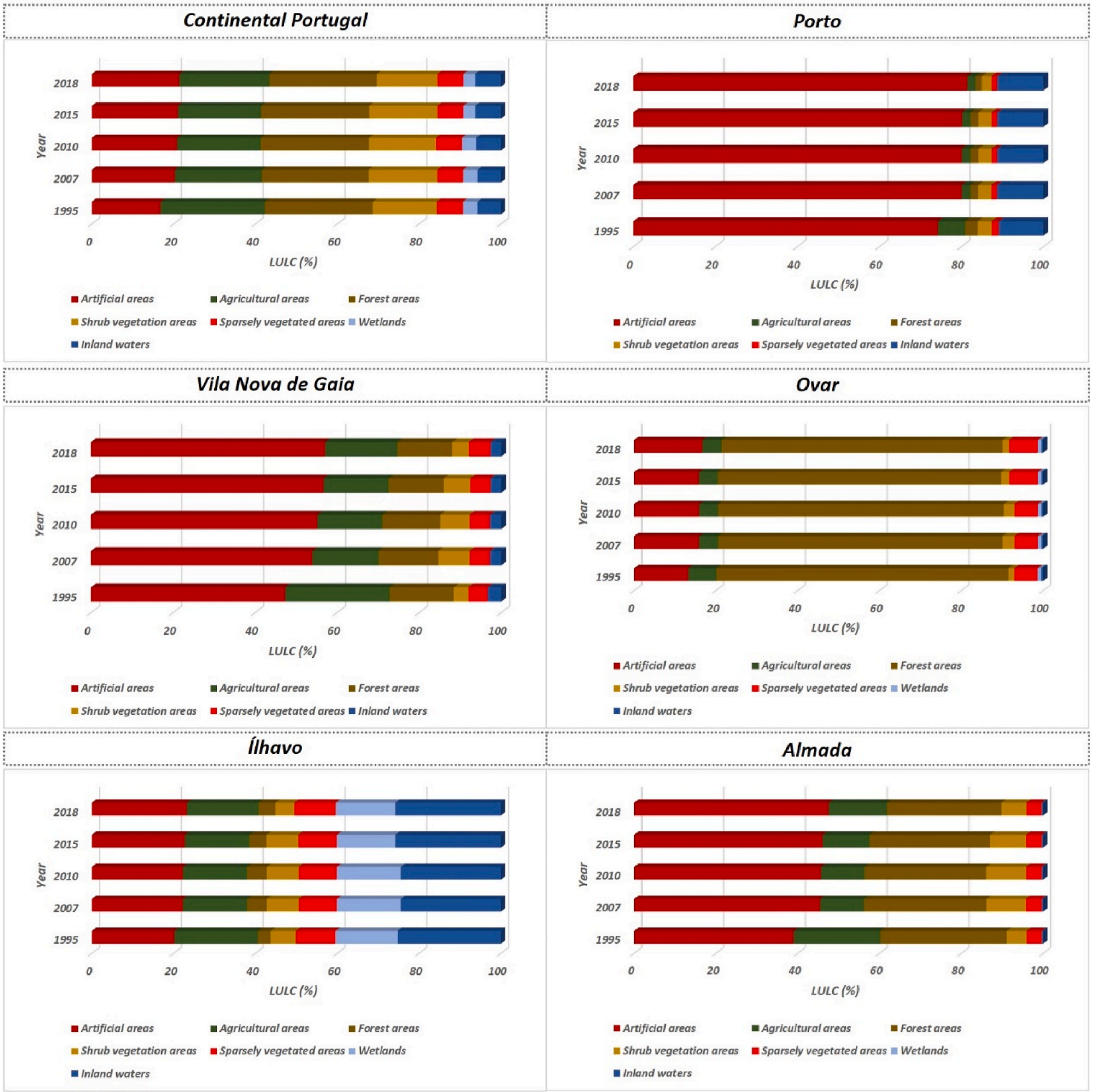

Fig. 13. Coastal zone Land Use Land Change. (color should be used for any figures in print). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

3.4. *Overtopping and flooding forcings*

An analysis of the flooding forcing conditions, obtained by hindcast (Fortunato et al., 2016, 2019), was also carried out based on two parameters: maximum daily Hs (*Hsmax*) and maximum daily sea level (*Slmax*). Fig. 14 shows the relationship between each of these parameters and the total number of occurrences between 1980 and 2018. Results indicate that there is a greater dispersion when the *Hsmax* is related to the occurrences than when they are related to the daily *Slmax*.

Regarding the analysis of *Hsmax*, there is a greater concentration of occurrences from *Hsmax* $\geq$ 4.0 m (Fig. 14a), with 61% of occurrences related to Hs higher than 4.0 m (Fig. 14b). It should also be noted that for a number of occurrences $\geq$10, *Hsmax* values $\geq$ 6.7 m are associated. Regarding the correlation between the values of the daily *Slmax* and the occurrences, there is a concentration starting from values $\geq$ 2.0 m and 3.1 m (Fig. 14a), noting that 74% of the occurrences appear in this interval (Fig. 14c). If we consider the dates with number of occurrences larger than 10, we find that the daily *Slmax* varies between 2.2 m and 2.6 m (Fig. 14a). The greatest number of occurrences occur when either Hsmax, or Slmax are very high. This is partly due to the fact that wave setup was considered at the levels.

The highest number of occurrences (identified in Fig. 14a) are related to the storm Hercules, namely on January 6th and 7th, 2014. In these two days the daily *Hsmax* varied between 6.7 m and 7.8 m, while the daily *Slmax* varied between 2.2 m and 2.6 m. However, there is a distinct temporal and spatial expression in relation to the occurrences concentrated on these two dates. The west coast (from Caminha to Vila Nova de Gaia) was particularly affected on the 6th and 7th of January 2014 with *Hsmax* between 6.9 m and 7.8 m and *Slmax* between 2.4 m and 2.6 m. The coastal stretch between Vila Nova de Gaia and Vagos is particularly affected on the 6th with values of *Hsmax* = 7.3 m and *Slmax* = 2.5 m. The area south to Nazaré is mostly affected on the 6th with values of *Hsmax* = 7.3 m and *Slmax* = 2.4 m. Regarding the stretch between Nazaré and Almada is the one with the lowest values of Hsmax (6.7 m) and Slmax (2.2 m) in relation to the areas mentioned above. However, this is the area with the highest number of occurrences (Fig. 14a) concentrated in one day (6 January 2014) related to the storm Hercules.

4. Discussion

The present study demonstrates, like other studies (Raska et al., 2014; Rilo et al., 2017; Ruocco et al., 2011; Santos et al., 2014; Zêzere et al., 2014) the importance and potential of a database based in hemerographic analysis. However, there are some limitations to this approach, as suggested by several authors (Barriendos & Rodrigo, 2006; Ruocco et al., 2011; Taylor et al., 2015), namely the greater over representation of some occurrences in relation to others, and the inconsistency or absence of relevant information about them. In relation to the first, it relates to the greater coverage of events with human impacts or that cause relevant economic and social changes and disruptions. With regard to the second, it relates to the absence or imprecision of information that helps in the identification and characterization of the occurrence, namely in terms of the location, time period, and impacts' characterization. The frequent absence of scientific accuracy in the information collected in this type of sources is also worth noting. In this regard, the lack of specific information regarding triggering factors related with each occurrence is highlighted. In this sense and as advocated by Rilo et al. (2017) the analysis of media sources, specifically newspapers may not be the most suitable for the identification and analysis of the various triggering factors responsible for the occurrence of natural hazards.

Despite the limitations mentioned above, the methodology adopted proved to be effective and assertive in the identification and analysis of flooding and overtopping occurrences on the Portuguese continental coastal zone, between 1980 and 2018. This database is distinguished from others existing at national level, namely the Disaster database, which considers only occurrences related to floods and landslides

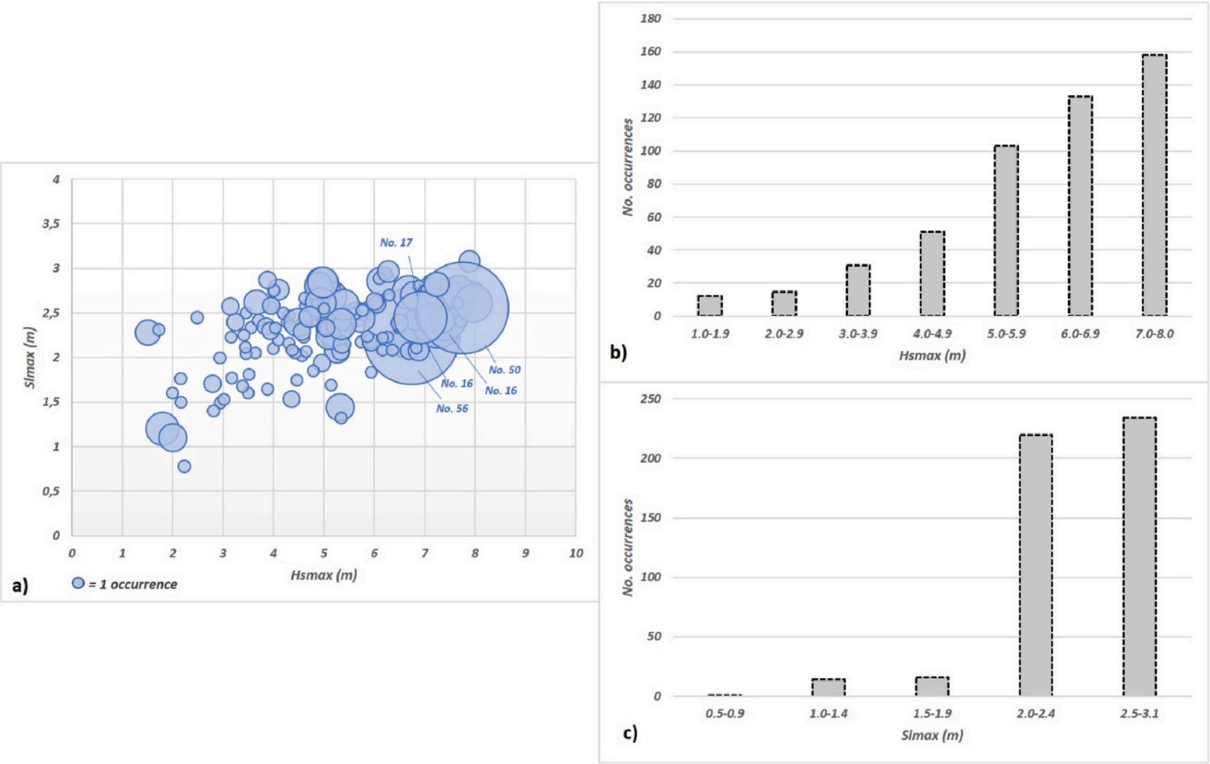

Fig. 14. Hindcast parameters: a) relation between daily Hs maximum (*Hsmax*) and occurrences; b) occurrences by daily HS maximum (*Hsmax*) classes c) occurrences by sea level max (*Slmax*) classes.

(Zêzere et al., 2014), because it is the only one that identifies and analyses exclusively occurrences related to coastal floods and overtopping. The database is based in six major topics each divided into a total of 50 fields that identify, analyse and characterize each occurrence in its multiple strands. The presented database is also differentiated by the fact that all occurrences were validated by crossing the information obtained in more than one newspaper, as well as in the analysis of academic works and existing official reports. This aspect associated with the field work carried out in different areas, allowed a complete and exhaustive analysis of the set of 650 identified occurrences, with the exact location of 60% of the occurrences and the approximate location of 32% of them. In most cases, the different impacts associated with each occurrence were fully identified and characterized. The adopted methodology presents as main innovation the inclusion of the flooding forcing conditions, obtained by hindcast, as a basis for the realization of punctual hemerographic analysis. Based on the hindcast data obtained, it was possible to select a set of dates not identified in the systematic analysis – the analysis conducted in two national coverage newspapers (cf. Table 1). The data from hindcast allowed to add a set of new dates to be searched in the journals where the punctual analysis was done. Dates derived from the hindcast represent 35% of the total dates with occurrences, and it also allowed to identify a varied set of losses and damages that represent 25% of the total.

The spatial analysis of the occurrences clearly differentiates two distinct areas: the west coast from the municipality of Caminha to Cabo Espichel, where 70% of the identified occurrences are located, and the rest of the west and south coast. The predominance and concentration of occurrences in this area is related to a diverse set of forcers. From the outset, morphosedimentary forcers that translate into a great multiplicity of existing environments. The area that concentrates the highest percentage of occurrences, is characterized by low and sandy coast, coinciding with the areas of highest concentration of occurrences and impacts, as well as stretches of low rocky and cliff coast (Ferreira & Matias, 2013; Santos et al., 2014). In terms of LULC, this area is also characterized by an increase in artificial areas in the analysed period, with a special focus between 1995 and 2007. In the opposite direction, the constant decrease in agricultural areas stands out, with the maintenance and increase, in some areas, since 2015. Maintenance, and in some cases, the increase in areas related to the forest and shrub vegetation areas is also noteworthy. It also stands out the significant reduction, from the end of the 19th century, of sedimentary supply associated with anthropic activities (e.g. construction of dams, inert extraction, agricultural practices). Also related to anthropic forcers, the investment in structural coastal defences and the increasing anthropic occupation in coastal areas in the last decades stand out, which translates into a relationship between the occurrences and the population density of coastal municipalities. It is worth to remind that along the coastline, from Caminha to the Cabo Espichel, the density varies between moderate (98.2 inhab/km^2) to very high (7460.3 inhab/km^2). Oceanographic forcers are also noteworthy. They relate to the maritime agitation regime that, on the west coast, is characterized by having high energetic waves, decreasing in latitude (Santos et al., 2017). The mapping of the occurrences belonging to the *MOSAIC* database shows that the areas identified with the highest number of coastal flooding occurrences match with the ones that were identified in other studies as vulnerable locations due to factors such as energetic wave climate, coastal erosion and significant decrease in sedimentary supply (Andrade & Freitas, 2002; Coelho et al., 2009; Pereira & Coelho, 2013; Ponte Lira et al., 2016; Santos et al., 2017).

The analysis carried out also allows to identify a great increase in the number of occurrences and associated impacts between 2010 and 2018. During this period the coast of mainland Portugal was affected by several stormy periods, as well as by a set of storms, in which Xynthia, Hercules and Emma stand out. This increase in the number of occurrences and impacts cannot be dissociated from a possible relationship with the increase in storminess in the region, related to climate change. Santos et al. (2002) and Santos & Miranda (2006) argue that the Portuguese continental coast will face changes in the climate of maritime agitation that is reflected in a change in the direction of the waves, due to climate change. On the other hand, several authors such as Francis and Vavrus (2012), Screen (2013) and Tang et al. (2013), advocate a change in the storm regime in the middle latitudes due to the so-called "amplification of the Arctic" that can imply an increase in the frequency and intensity of extreme weather and climatic events. However, it is important to note that there is still a lot of uncertainty about future developments related to the change in storm regimes.

As for the occurrences, the impacts also feature an heterogenous spatial distribution. With regard to human impacts, it appears that they occur mostly (54%) in the coastal strip between Porto and Almada, with the exception of displaced persons who appear almost exclusively (90%) on the south coast, specifically in the municipalities of Olhão and Loulé. In this regard, the number of displaced persons (115) in Ilha da Fuzeta (Olhão) stands out. These events occurred in January and February 2010, affecting mostly illegal and second homes, in an area that between 1958 and 2010 presented a coastline retreat, that varies between 0.2 and 4.0 m/year (Ponte Lira et al., 2016). Regarding the impacts related to the natural system and environmental degradation, there is a concentration (54%) in coastal areas belonging to municipalities located north of Figueira da Foz. Regarding the impacts related to anthropic activities (public areas, infrastructure and buildings), there is a greater dispersion throughout the study area, although the impacts observed in Porto, Vila Nova de Gaia, Ovar, Ílhavo, Figueira da Foz, Cascais and Almada which represent 55% of the total.

The methodology adopted in the present study through the identification, analysis and spatialization of the occurrences and the respective damages and impacts, allowed the identification of different coastal typologies. This diversity is evidenced in the analysis made to the different POC, as well as in the coastal strip belonging to the five municipalities with the highest number of occurrences, not only with regard to their damage and impacts, as well as the respective territorial context, expressed in the analysis of the LULC. They have in common, despite different dynamics and trends, the increase in artificial areas between 1995 and 2018, in line with previous studies (Freire et al., 2009; Pinto et al., 2009). However, the different areas have intrinsic characteristics that distinguish them. It is possible to identify areas with an eminently natural coastal typology, but with a very marked anthropic influence in the territory. It also stands out, the existence of coastal urban agglomerations with relevant urban and population dynamics, as well as an important port (Ílhavo) and coastal defense (Ovar) infrastructures that locally influence natural and anthropic dynamics. Other coastal typologies are distinguished by the clear artificialization of their coastal strip, presenting consolidated urban agglomerations that are densely packed by activities and population. In these areas, impacts related to anthropic activity were predominant. Finally, other coastal typologies are characterized by their LULC change dynamics, contributing to the diversity of coastal exposure and vulnerability contexts. Regarding the impacts and damages observed, it is possible to verify a clear diversity and different trends between the analysed coastal areas. This identification and analysis of the different coastal typologies is central to the development of an integrated risk analysis methodology.

The analysis of the oceanographic conditions through the parameters *Hsmax* and *Slmax* allowed us to verify a great variability and dispersion of values associated to the identified occurrences. This fact indicates that in addition to the natural, climatological and oceanographic forcers associated with the occurrence of overtopping and coastal flooding, other forcers are also associated, namely anthropic ones that modify coastal areas over the period under analysis and that contribute decisively to changes in coastal dynamics. The crossing and analysis between the occurrences and the hindcast prove to be fundamental in the elaboration of alerts, through the definition of thresholds that identify the probability of occurrences of flooding and coastal overtopping. On the other hand, this information and its crossing with the different coastal typologies identified allows the definition of territorially differentiated alerts. This matter will later be subject to further analysis and study.

The construction and development of a database, such as the one presented in this article, is an important contribution for the assessment of territorial vulnerability and coastal risk management. From the start, the results contribute to satisfy some of the requirements that emanate from the EU Floods Directive (European Parliament and Council of the European Communities, 2007). Among them, it contributes to the collection of historical data on coastal flooding occurrences and their associated impacts, even as, the spatial and temporal identification of the most affected areas. The results can also provide a wide and improved temporal and spatial knowledge about coastal historical flood events that can contribute to the validation of flood predictive models and the design of the risk framework. The information from historical data could also be used for the assessment of territorial vulnerability and the definition of tools for the management of coastal flooding risk, assisting decision-makers for the establishment of adaptation and resilience measures based on knowledge of past events. These data allow the understanding of the dynamic relationships existing between coastal floods and the different coastal communities, allowing the communication and mediation between the local population and the different authorities.

5. Conclusions

The present study demonstrates the importance of historical databases of natural hazardous processes from hemerographic sources. The analysis of the database made it possible to identify, explore and evaluate the different occurrences of flooding and coastal overtopping, allowing the identification of its impacts. Consequently, it also allowed locating the most vulnerable areas, the spatial and temporal characterization of occurrences and impacts, as well as the respective forcers. The present database differs from others carried out in other countries, due to its range of topics and primary fields that allow the detailed and comprehensive characterization not only of the identified occurrences, but also of the associated impacts and damages. The database presented here is still characterized by its interdisciplinary nature, consistency, and user-friendliness. The construction of a national database of disasters plays an important role in risk management, namely through the prevention, reduction and mitigation of its consequences. The results from this database, its crossing with real-time forecasting and monitoring models of coastal flooding forcers, and the consideration of the different dimensions of the territorial vulnerability, will allow the development of an innovative reference framework to support risk management. It is intended that the data and results obtained become known, so they can be discussed and considered by the different stakeholders and official entities in order to create more resilient communities, in line with the national and regional key strategies and towards the Sendai Framework for Disaster Risk Reduction (UNISDR, 2015). The results and analysis of the present database provide useful information on the past, present and future of coastal areas and consequently of their exposure to coastal flooding. The information resulting from the present database, its integration in sea-level rise models, can work as an important tool for the process of adaptation of coastal zone to climate change, namely through processes of relocation, accommodation or artificial defence of these areas. The present study intends to promote and contribute to a risk and emergency planning and management more focused on the differentiating characteristics of the different coastal typologies that exist in continental Portugal.

Credit author statement

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Paula Freire: Conceptualization, Methodology, Investigation, Writing - Review & Editing, Supervision, Project administration, Funding acquisition.

Pedro Pinto Santos: Formal analysis, Resources, Writing - Review & Editing.

Luis Perdiz: Investigation, Data acquisition.

André Bustorff Fortunato: Investigation, Writing - Review & Editing.

Declaration of competing interest

None.

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