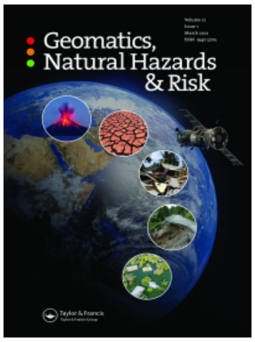

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An exploration of exposure to river flood risk in Spain using the National Floodplain Mapping System

Fulgencio Cánovas-García[a] and Jesús Vargas Molina[b]

[a]Department of Geography, History and Humanities, University of Almería, Almería, Spain;
[b]Geography Department, University of Málaga, Málaga, Spain

ABSTRACT

In Spain, human exposure to flooding continues to increase driven by changes in land use and population growth in urban and coastal areas. This study explores the geography of flood exposure in Spain in relation to human population, economic activities and points of special significance. The analysis is based on public flood hazard and risk mapping generated by water management administrators at the river basin district level. The data are published and accessible through the Spanish National Floodplain Mapping System (NFMS). The results show for first time, the spatial distribution of human population exposure, which amounts to at least 3,263,000 inhabitants nationwide (6.9% of the total Spanish population), the potential economic loss, totalling at least 122,132 million euros across Spain, and points of special significance classified into eleven different categories that have been analysed for all Spanish river basin districts. The results also indicate a higher exposure concentration along the Mediterranean coast.

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Cartography; exposure; flood; river basin district; EU Floods Directive

1. Introduction

Flooding is one of the most devastating natural hazard-related disasters, causing financial damage and loss of life every year around the world (Hasanuzzaman et al. 2022). In Europe, despite considerable efforts to reduce the risk of natural hazard-related disasters, floods remain the most devastating natural hazard. In the period 2000–2022, floods were the most frequent type of disaster, accounting for 46% of all recorded events causing more than 8.5% of life loss and 40% of the economic losses associated with natural hazard-related disasters, affecting more than two billion people (2023 Disaster in number). In Spain, floods are the natural hazard-related disasters that generates the greatest damage (Manrique et al. 2017). In the period 2000–2022, there were 224 deaths caused by floods, which accounted for 20% of deaths caused by natural hazard-related disasters, second only to high temperatures

CONTACT Fulgencio Cánovas-García fulgencio.canovas@ual.es

(Ministerio del Interior, 2022) and financial compensation amounted to almost 7890 million euros, representing 70.5% of the total in the period 1987–2023 (Consorcio de Compensación de Seguros 2024).

In recent decades, a shift in flood risk management strategies has been observed in many countries, in which non-structural measures are gaining prominence due to their effectiveness (Poussin et al. 2012; Thieken et al. 2016; Bubeck et al. 2017). These measures involve numerous actions focused on prevention and mitigation: flood insurance, assessment methods, emergency services, land use planning, flood planning, construction codes, warning and forecasting, etc. but do not include river flow alteration (Ballesteros-Cánovas et al. 2013). Both prevention and mitigation are widely considered to be more cost-effective than ex-post disaster measures (Poljansek et al. 2017).

For the effective implementation of risk prevention and mitigation measures, it is imperative to improve the understanding of the dynamics and interactions among the different risk components (Poljansek et al. 2017). According to the latest IPCC reports (IPCC 2022), flood risk to human and ecological systems is caused by the combination in space and time of the flood hazard (the frequency and/or magnitude of flood events), the exposure of the affected system (the presence of people; real state; livelihoods; species or ecosystems, environmental functions, services and resources, infrastructure or economic, social or cultural assets in places and settings that could be adversely affected) and the vulnerability of the system (the propensity or predisposition of exposed elements to be adversely affected). Regarding flood risk, although uncertainty remains significant (IPCC 2022), there are numerous studies that point to significant changes in flood phenomena due to the influence of climate change (Alfieri et al. 2015; Forzieri et al. 2016; Winsemius et al. 2016). Most recent scientific studies indicate that hydrological risks will generally increase even for warming levels of 1.5 °C. However, the latest IPCC report (2022) determines with a high level of confidence that climate-associated risks to natural and human systems (including flood risk) depend more on changes in their vulnerability and exposure than on differences in climate hazards between emissions scenarios. Risk management strategies should therefore focus on reducing exposure and vulnerability to reinforce prevention and mitigation.

Since the implementation of the European Directive 2007/60/EC on the assessment and management of flood risks (EU Floods Directive, hereafter) the main tool for flood risk prevention and mitigation in Europe at river basin district (RBD) level are the Flood Risk Management Plans. These plans are based on a better characterization of flood risk through hazard and risk mapping. Risk mapping becomes a priority tool to improve knowledge and support decision making for risk management (Ran and Nedovic-Budic 2016; Mileu 2018). In addition, mapping is also a key tool to improve communication and education, which are basic aspects for adequate risk governance (Olcina and Díez-Herrero 2017; Poljansek et al. 2017).

In accordance with the EU Floods Directive, flood hazard maps are designed to indicate the probability of flooding in space and time, while risk maps show the potential adverse consequences associated with flood scenarios referred to in terms of the indicative number of potentially affected inhabitants, the type of economic activity

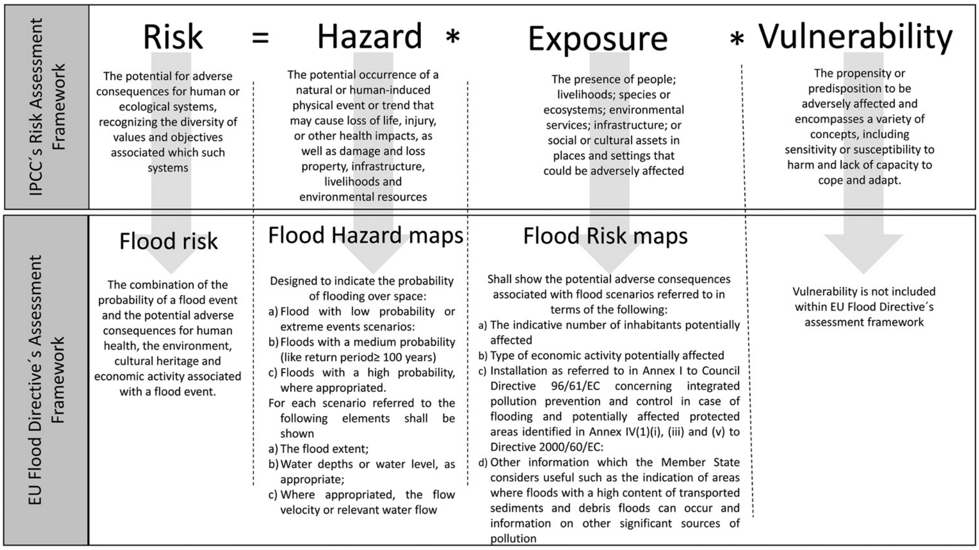

Figure 1. Differences between the risk assessment framework proposed by the IPCC and that proposed by the EU Floods Directive. *Source*: own elaboration based on IPCC (2022) and Directive 2007/60/EC.

in the potentially affected area, those special installations related to integrated pollution prevention and control that may cause accidental pollution in case of flooding, those potentially affected protected areas and other information considered useful by the European Member States. Based on the information generated by flood hazard and risk mapping, Flood Risk Management Plans are prepared at the RBD level. These plans contain a series of measures focusing on prevention, protection, and preparedness, including flood forecasting and early warning systems aimed at ensuring that the current flood risk does not increase.

However, the risk analysis framework proposed by the EU Floods Directive differs from the IPCC (2022) proposal (Figure 1). Firstly, the EU Floods Directive does not *per se* include methodology and guidelines for mapping exposure. Exposure corresponds to the properties (human, material, ecological, economic, and so forth) that may be damaged by the action of the hazard depending on its location (elements at risk). In fact, the parameters proposed for risk mapping by the EU Floods Directive focus on exposure (Perles et al. 2017). These risk maps address exposure of the population; exposure of economic activities; exposure of points of special significance; and areas of environmental significance. They are misnamed risk maps because they are limited to assessing exposure and evaluating losses of exposed elements. Secondly, vulnerability is not addressed and therefore, in the opinion of the authors, and in accordance with the IPCC guidelines (2020, 2022), the characterisation of flood risk is incomplete.

Adequate identification of exposure to flood risk is the next key element, as without exposure there would be no direct impacts. Moreover, identification of exposed elements is a preliminary phase to be able to carry out detailed vulnerability analyses on these elements, and therefore complete the risk characterization.

Studies that attempt to characterize exposure to flooding have gained prominence in recent years (Tate et al. 2021) and this is precisely what is proposed by the EU Floods Directive in so-called risk maps, as shown in Figure 1.

In Spain the process of population growth in urban areas (from 55% in 1960 to more than 80% in 2022) due to the process of uncontrolled expansion and an intensive and disorganized use of flood plains since the second half of the twentieth century has increased exposure and vulnerability to floods in recent decades (Illán and Pérez Morales 2016; Pérez-Morales et al. 2016; Olcina et al. 2018; Ribas et al. 2020).

The study is based on the hypothesis that flood risk exposure in Spain is mostly concentrated along the Mediterranean coast. Therefore, the objective of the study is to analyze the distribution of flood risk exposure across Spain and identify the places of maximum exposure to this risk.

In recent years, several studies have been published assessing exposure to flood risk using different methodologies (Criado et al. 2018; Pérez-González et al. 2022). The present work differs from its predecessors in several key aspects: Firstly, it performs a comprehensive analysis of flood risk exposure for almost the entire Spanish territory (more than half a million km^2 of surface area, more than 48 million inhabitants and the 15th country in the world by GDP in purchasing power parity). Secondly, the analysis is carried out at the river basin district level, recognizing the pivotal role of hydrological planning in the official characterization of flood risk. Lastly, this study goes beyond the limited assessment of specific elements exposed to flood risk by covering a comprehensive analysis of human exposure, economic activities and points of special significance.

This study is important not only for Spain but also in the global context, as it addresses the growing challenge of flood risk management, which, as in other countries, may be exacerbated by rapid and uncontrolled urbanization, population concentration in urban areas, and climate change (Kougaard et al. 2015; Park and Won 2019; Bernardini et al. 2021; Zinda et al. 2021). Furthermore, the methodology applied in this research, the insights gained and the identified limitations may be useful to be applied in other countries, especially those member states of the European Union that also need to adapt to the requirements set by the EU Floods Directive.

2. Study case

In Spain, Royal Decree 903/2010 transposed the EU Floods Directive and created the figure of Flood Risk Management Plans at RBD level. Most of them were approved in 2016 and have recently been updated (2021). These plans are based on a characterization of flood risk through hazard mapping and risk mapping focused on population, economic activities, points of special significance and environmental aspects.

Figure 2 shows the spatial distribution of the RBDs in Spain and includes the location of all sites (cities, river sections, coastal sections, geographical area, etc.) named in the article.

The hazard and risk maps generated by the different RBDs administrations are centralized and made available to the public through the National Floodplain Mapping System (NFMS). At present, it is possible to consult the information

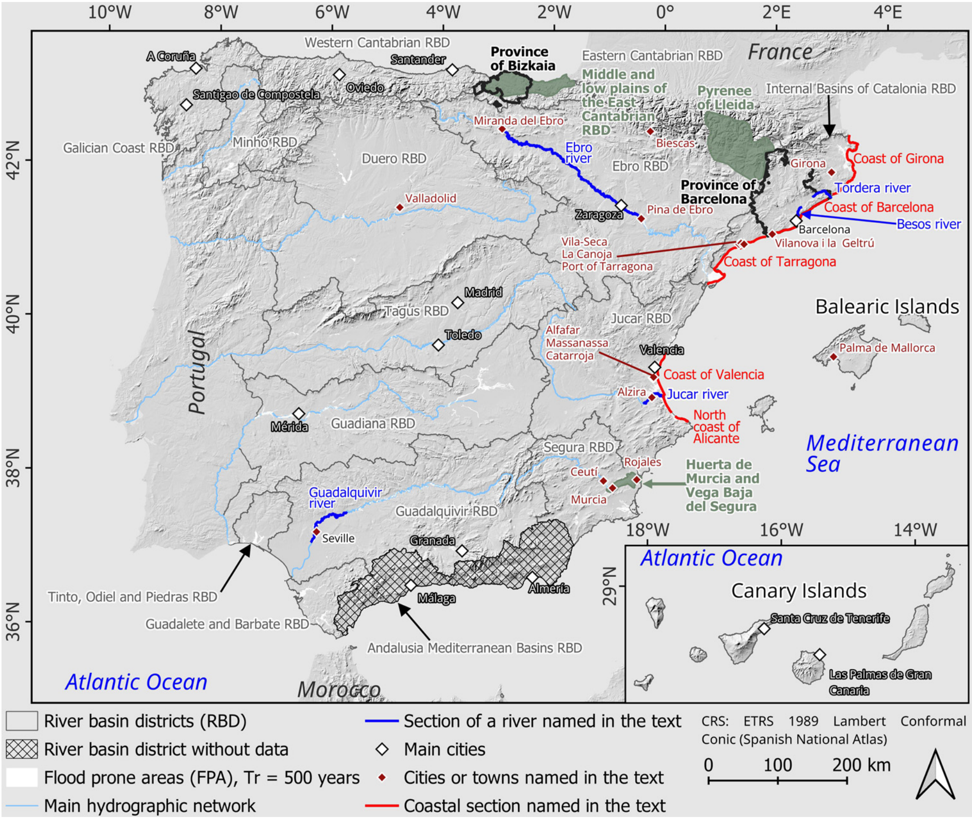

Figure 2. Map of the study area. This figure includes the location of all sites mentioned in the article. *Source*: Author's own elaboration.

produced by all the RBDs in GIS readable format, except for the Andalusian Mediterranean RBD. Therefore, this RBD is not included in the study.

3. Methodology

The methodology consisted of the processing and analysis of the river flood risk layers in GIS format, included in the NFMS. The analysis focuses on the assessment of the risks to the population, economic activities and points of special significance linked to a flood event with a return period of 500 years. This return period plays a fundamental role in the delineation of FPA in Spain. The reference date for these layers is July 2022.

FPA surface information was derived from the polygons that constitute the population risk layers. The geometry of these layers differs from that of flood hazard layers for various return periods due to a number of processes applied on each flood hazard layer. These processes include contour smoothing, removal of internal and external islands, verification of the outer boundary of the envelopes and consistency checks.

Applied to precipitation, for example, the term ‘return period’ or RP represents the inverse of the probability of experiencing precipitation equal to or greater than a specific amount in a given year. For instance, if for a particular weather station and a return period of 500 years, we obtain a rainfall of 250 mm, the probability (P) can be calculated as 1/RP = 1/500 = 0.002, where P denotes the probability in terms of occurrences. In probabilistic terms, this implies a 0.2% chance that the precipitation will be equal or greater than 250 mm in any given year. Alternatively, it can be stated that, on average, a precipitation event equal to or greater than 250 mm will occur once every 500 years. When calculating the flow (hydrological study) from the precipitation (climatic study) and determining the flood sheet for the return period (hydraulic study), it becomes clear that the flood sheet represents the minimum extent for that return period. Consequently, both the risk maps and the quantitative exposure values derived from them should be considered as minimum values for that return period. Therefore, throughout the text, especially when quantitative flood risk exposure values are presented, the terminology 'at least' will be used frequently. This is because, for a return period of 500, all aspects including precipitation, flow, water sheet extent and exposure will be equal to or greater than those documented by the NFMS.

The risk information regarding population was derived from a GIS format layer that incorporated the spatial intersection geometry between each census section and its corresponding flood prone area (FPA). This design ensured that the flood zone of each census section served as the minimum unit of geographic information for this layer. In Spain, census sections represent the smallest administrative units for which statistical information is available. In particular, a key consideration for this research is the dynamic nature of census sections, which are subject to periodic adjustments to align with the number of voters prescribed by law.

Within the GIS population risk layer of the NFMS, each polygon encompasses several attributes, including the resident population in the municipality and in the census section. Particularly significant is the estimate of the resident population in the FPA area of each census section. This data is of paramount importance, as it allows for a comprehensive municipal analysis of the population's exposure to flood risk.

The methodology for determining the resident population in FPA of each census section is outlined in Ministerio para la Transición Ecológica (MITECO) (2022, p.30). According to the document, the resident population value in FPA of each census section is proportional to the urbanized area of the FPA for that specific census section:

$$P_{FPA,y} = \frac{P_{CS,y} \times U_{FPA}}{U_{CS}} \tag{1}$$

Where $P_{FPA,y}$ represents the resident population in FPA for each census section in the reference year y, $P_{CS,y}$ denotes the total population of the entire census section in the year y, U_{FPA} is the urbanised area of FPA in the census section, and U_{CS} represents the urbanized area of the entire census section. It is clear that this method of population estimation is relatively straightforward, as it only considers the urbanized area, without necessarily taking into account its land use or buildability.

This layer also includes information on the reference year for the resident population. The reference years span from 2011 for most of the RBDs to 2020 for the Balearic Islands RBD and some municipalities in the Guadalquivir RBD. To standardize and update the reference year of the population exposed to flood risk in each census section, a Geometric Rate of Change (Plane and Rogerson 1994) based on the reference population data of the NFMS was used.

$$P_{FPA,22} = P_{FPA,y} \times (1 + AGR_M)^{(2022-y)} \tag{2}$$

Where $P_{FPA,22}$ represents the resident population in FPA for each of the census sections in 2022, and $P_{FPA,y}$ is the resident population in FPA of the census sections according to the NFMS for the reference year (*y*). Additionally, AGR_M denotes the annual population growth rate of the municipality to which the census section belongs from the NFMS reference year to 2022. The calculation of AGR for each municipality was determined as follows:

$$AGR_M = \left(\frac{P_{M,22}}{P_{M,y}}\right)^{\frac{1}{2022-y}} \tag{3}$$

Where $P_{M,22}$ represents the population of the municipality where the census section is located for the year 2022, and $P_{M,y}$ is the corresponding population for the reference year of the NFMS.

After applying Equations (1) and (2) to the polygons that make up the NFMS population risk GIS layer, a new field has been generated to include the estimated population registered in FPA of each census section within the study area for the reference year 2022. This mapping has been aggregated by municipality and by RBD for further analysis.

Regarding the types of economic activities located in FPA, the fluvial-origin FPA GIS layer of the NFMS has been used for the analysis of economic activity. The EU Floods Directive mandates the creation of maps indicating the types of economic activities potentially affected by floods. In the Spanish context, these maps distinguish 20 types of economic activities according to land use. The information, available through the NFMS, is presented as a GIS layer with polygonal geometry, where each polygon represents the spatial delineation of one of the 20 types of economic activities used in the NFMS. The correspondence between these 20 types of economic activities in the NFMS GIS layer and the SIOSE land use land cover maps, as well as the National Topographic Base at scale 1:25,000, mainly used in this study, was established through the application of correspondence tables detailed in Ministerio para la Transición Ecológica (MITECO) (2022, p. 40).

Once the areas with affected economic activities had been identified, the estimated monetary value of the damage that each polygon would incur from a flood was calculated by the NFMS.

This layer includes information such as the type of economic activity, its surface area, whether or not buildings were affected, the reference date of the mapping and the estimated monetary value in euros of the damage that would be caused by the flooding. The reference dates varied between the different RBDs, however, unlike the population risk GIS layer, an updated land use layer with a sufficient scale (at least 1:25,000) was not available for the entire national territory. Therefore, the original GIS layers were used for this purpose. In this study, all economic loss estimates have

Table 1. Economic activities by type. The NFMS categories 'water bodies' and 'other non-at-risk areas' were not included nor analyzed in this work.

Residential properties	Concentrated urban land, dispersed urban land and land associated with urban activities.
Productive activities	Land dedicated to tertiary activities, concentrated industrial land and dispersed industrial land.
Facilities	Buildings or spaces intended for public use, such as public administration buildings, health facilities, educational centres, cultural centres, etc.
Communication infrastructure	Roads, railways, ports and airports.
Energy and telecommunications infrastructure	Areas with facilities to produce energy and its conduits and facilities to provide coverage for telecommunications services.
Water, sanitary and waste infrastructure.	Areas with facilities for water treatment or purification, water desalination and their pipelines.
Agricultural, rural and forestry	Cultivated areas, artificial areas used for activities linked to the primary production sector and areas with forest species exceeding 5 m in height.

Source: Ministerio para la Transición Ecológica (MITECO) (2022).

Table 2. Points of special significance categories and groups.

Industrial emission facilities	Facilities listed in Annex 1 of Royal Legislative Decree 1/2016, approving the revised text of the Law on the prevention and integrated control of pollution.
Radioactive industries	(2) Industries housing a source of ionising radiation, equipment producing ionising radiation or locations where radioactive materials are handled, excluding storage during transport (Ministry for Ecological Transition, n.d.:84).)
Industries subject to the SEVESO Directive on Major Accidents	(3) Those specified by Directive 2012/18/EU on the control of major-accident hazards involving dangerous substances.
Waste Water Treatment Plants (WWTPs).	(4) Operational urban Waste Water Treatment Plants (WWTPs), as per Directive 91/271/EEC. Moreover, it has been confirmed that WWTPs owned by private companies, not initially included in the information provided by the Ministry of the Environment, have been included.
Elements of significance or importance for Civil Protection efforts	(5) Fire stations and (6) State Security Forces and Corps: National Police, Local Police, Autonomous Police, and Guardia Civil.
Educational facilities	(7) Early Childhood Education Schools and (8) Special Education Schools.
Special residential properties	(9) Campsites and (10) facilities for the elderly (sheltered housing, community housing, day centres, nursing homes, and homes for the elderly).
Hospitals	(11) Information from the National Catalogue of Hospitals, produced by the Ministry of Health, Consumption and Social Welfare. It includes both public and private hospitals.

Source: Ministerio para la Transición Ecológica (MITECO) (2022).

been aggregated by RBD and categorized into seven major types of activities (Table 1).

Finally, points of special significance correspond to point geometries of elements located within FPA. They cover several types and, in this study, have been classified into eleven groups (Table 2).

As to educational facilities, the analysis focuses on the centres that offer Early Childhood Education and Special Education, as they are considered to be the most vulnerable within the entire educational system. With regard to the Early Childhood Education Schools, all the centres providing Primary Education and Early Childhood

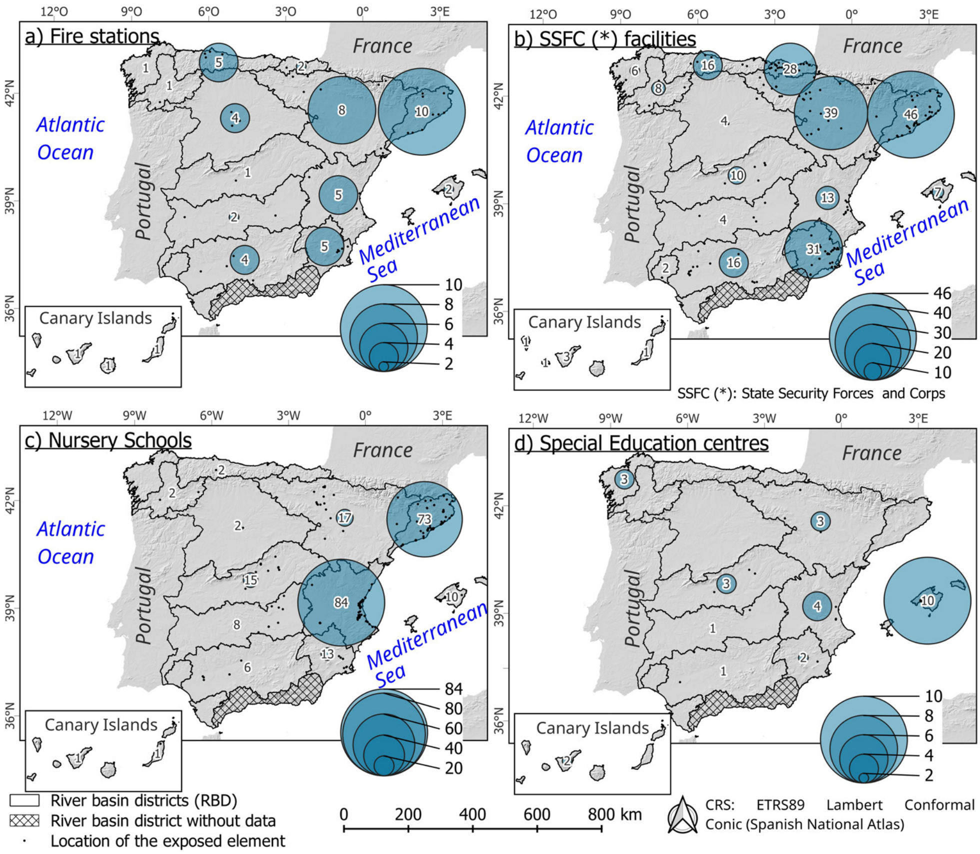

Figure 3. Number of fire stations and State Security Forces and Corps facilities, nursery schools and Special Education centres in flood prone areas by river basin district. *Source*: own elaboration from NFMS.

Education were classified by the NFMS under the generic denomination of 'schools'. Therefore, the centres classified by the NFMS as Early Childhood Education can be considered as those in which the first cycle of Early Childhood Education (from 0 to 3 years of age) was taught, also known as nursery schools. This simplification by the NFMS is an oversight that hinders effective information retrieval. For example, it hides the exact number of second-cycle Early Childhood Education centres (from 4 to 6 years of age) within FPA, a crucial detail for analyzing flood risks attributable to the vulnerability of their occupants.

Special Education schools comprise centres attended mainly by students with special education needs. According to Ministerio para la Transición Ecológica (MITECO) (2022, p.77), in cases where schools have multiple categories, the educational phase with the highest proportion is assigned. Thus, Special Education schools that were located on the same centre as primary schools were classified by the NFMS as 'schools' and therefore do not appear on the map of Special Education centres (Figure 3(d)).

4. Results

4.1. Population exposure

The estimated resident population in FPA for the study area is a minimum of 3,263,000 inhabitants, constituting at least 6.9% of the total Spanish population in 2022. This figure could increase by a few percentage points if the RBD not included in the NFMS was taken into account. When examining the distribution between RBDs, differences are found, as illustrated in Figure 3. The Segura RBD leads with over 577,000 residents in FPA, closely followed by the Guadalquivir RBD with more than 560,000. Overall, the southeast and south of the Spanish Iberian Peninsulás RBD have the largest contingents of resident population in FPA.

In contrast, Guadalete-Barbate RBD, Miño-Sil RBD, with a minimum of 30,000 inhabitants, and Tinto-Odiel-Piedras RBD, with values above 14,000 inhabitants, have lower population concentrations. When analyzing the percentages of population residing in FPAs, the Segura RBD stands out with at least 27.4%, followed by the Duero RBD with at least 20.5%.

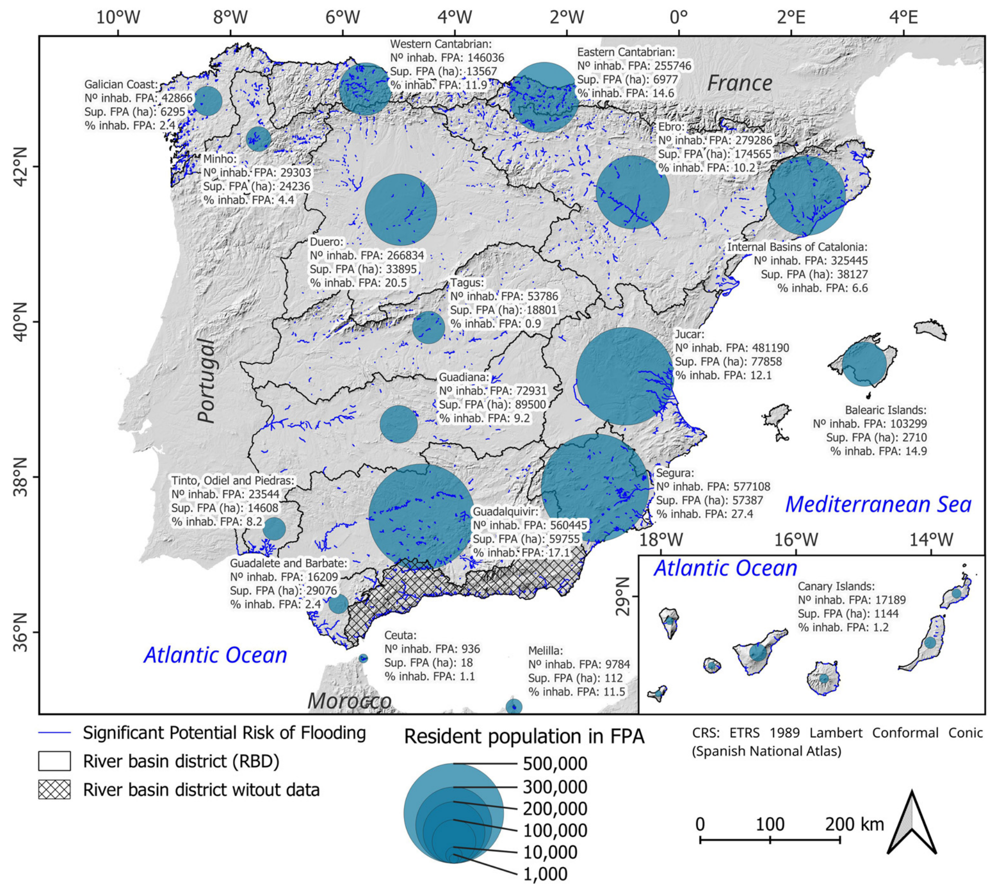

Figure 4. Map illustrating the exposure of the population to flood risk across river basin districts. *Source*: own elaboration from NFMS and the Spanish National Statistics Institute.

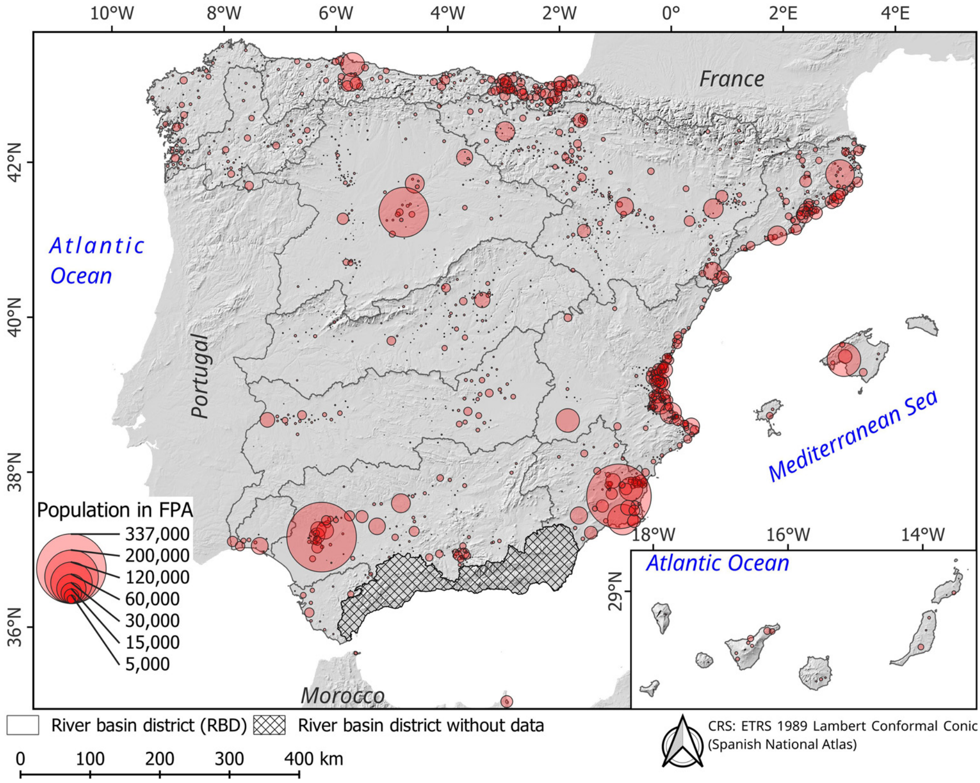

Figure 5. Number of inhabitants living in flood prone areas in each municipality. *Source*: own elaboration from NFMS and the Spanish National Geographic Institute.

Two RBDs stand out above the others in terms of population density in their FPA: the Balearic Islands with at least 3812 inhabitants/km^2 and the Eastern Cantabrian with at least 3666 inhabitants/km^2.

Figure 4 shows the number of inhabitants residing in FPA in each municipality. There are six main hotspots in the study area:

1. Guadalquivir Valley, especially the municipalities close to the city of Seville: the population living in areas at risk of floods in this region exceeds 411,000. Seville is the most affected municipality, with more than 337,000 people living in areas at risk of floods, making it the most affected municipality in Spain.
2. Huerta de Murcia and Vega Baja del Segura: over 410,000 people live in areas at FPA, with the city of Murcia being the most affected. In the municipality of Murcia alone, more than 290,000 people live in areas at risk of floods, making it the second most affected area in Spain.
3. The coast of the province of Valencia and a small area of the north coast of the province of Alicante: at least 331,400 people live in areas at risk of floods in this hotspot. No specific municipality stands out, but Alzira has the highest number of people living in FPA, with more than 32,000 inhabitants.

4. Middle and low plains of the eastern Cantabrian river basins: this area has more than 234,000 people living in FPA. The population is dispersed, with no single municipality standing out significantly.
5. Municipality of Valladolid, the third largest municipality in Spain by number of inhabitants in FPA, with more than 172,000 inhabitants.
6. Catalan Coast, especially in the province of Tarragona and Barcelona: at least 158,100 people live in FPA in this hotspot.

4.2. Economic activities exposure

Table 3 provides data for each RBD based on seven categories of economic activities. However, some clarifications should be made: (1) Surface areas were derived from the summation of individual polygon surface areas within the population risk layer. (2) The surface area of Cuencas Mediterráneas Andaluzas RBD was not included in the analysis. (3) The total surface area in Table 3 does not coincide with the sum of the surface area made available by the NFMS due to some FPA surfaces not featuring eligible economic activities. For example, the 'bodies of water' category was not considered by the authors as an economic activity and was excluded from the table and from de analysis.

The area of economic activities considered in this study in FPA amounts to 543,000 ha. Table 3 shows that the category 'agriculture, rural, and forestry' is the most dominant economic activity with more than 466,500 ha, followed by the category 'residential property' with more than 42,000 ha (86 and 7.78% of the surface area of the economic activities taken into account in this work). The remaining categories of economic activities listed in Table 3 have surface values ranging from 0 to 3%. The distribution of economic activities by RBDs reveals five outstanding ones: Ebro (27.2% of the total), Guadiana (12.4%), Júcar (11.9%), Segura (10.1%) and Guadalquivir (9.6%).

When assessing the potential economic losses derived from a 500-year return period, the methodology involves multiplying the economic value assigned to each type of activity by the respective unit of surface area. The potential losses amount to at least 122,132 million euros throughout Spain. However, the results show significant differences compared to those of surface, both when analyzing the categories with the highest economic loss values and when conducting the analysis by RBD. Table 4 summarises the results of potential economic losses by categories and RBD.

The categories with the greatest economic losses are residential properties (40% of the total) and productive activities (22.5%). The analysis by RDB highlights the Ebro RBD (21.6% of total losses), Guadalquivir (16.4%), and Internal Basins of Catalonia (16.1%), significantly surpassing the rest of the RBDs. It is also necessary to highlight the anomaly found in the Canary Islands RBD, which reports an estimated economic loss of zero euros. This value is highly implausible given the more than 17,000 inhabitants living in FPA, covering an area of 11,140 hectares. A detailed analysis of these results is shown in Figures 5 and 6, indicating the differences for each of the categories and RBD. Figure 5 outlines the estimated loss values in three groupings of

Table 3. Surface area (ha) of flood prone areas according to type of economic activities by RBD.

	Residential properties		Facilities		Productive activities		Agriculture, rural and forestry		Communications infrastructure		Energy and telecommunications		Hydrology, sanitation and waste		Total	
River basin district	Ha	%	ha	%	ha	%	ha	%	ha	%	ha	%	Ha	%	ha	%
Internal Basins of Catalonia	3051	7.2	372	5.8	3204	7.6	27,418	5.9	737	8.1	20	1.9	95	2.7	**34,897**	6.4
Minho	1188	2.8	188	2.9	37	0.1	19,288	4.1	154	1.7	4	0.4	57	1.6	**20,915**	3.8
Galician Coast	619	1.5	115	1.8	142	0.3	3761	0.8	90	1.0	1	0.1	31	0.9	**4759**	0.9
Eastern Cantabric	2293	5.4	457	7.1	1508	3.6	1278	0.3	329	3.6	20	1.9	13	0.4	**5897**	1.1
Western Cantabric	1783	4.2	302	4.7	1148	2.7	5714	1.2	522	5.7	58	5.7	39	1.1	**9567**	1.8
Duero	3408	8.1	483	7.5	519	1.2	26,708	5.7	402	4.4	4	0.4	64	1.8	**31,588**	5.8
Tagus	1280	3.0	537	8.3	876	2.1	12,916	2.8	235	2.6	38	3.7	82	2.4	**15,965**	2.9
Guadiana	1553	3.7	229	3.6	1355	3.2	63,367	13.6	534	5.9	189	18.6	130	3.7	**67,357**	12.4
Guadalquivir	4089	9.7	1422	22.1	2434	5.8	41,344	8.9	1968	21.6	530	52.0	468	13.5	**52,255**	9.6
Guadalete and Barbate	275	0.7	39	0.6	83	0.2	22,924	4.9	564	6.2	14	1.4	421	12.1	**24,319**	4.5
Tinto, Odiel and Piedras	219	0.5	73	1.1	64	0.2	3715	0.8	189	2.1	0	0.0	767	22.1	**5027**	0.9
Segura	7335	17.4	585	9.1	647	1.5	45,397	9.7	956	10.5	38	3.7	133	3.8	**55,091**	10.1
Jucar	8293	19.6	475	7.4	1093	2.6	53,499	11.5	820	9.0	30	2.9	223	6.4	**64,433**	11.9
Ebro	5389	12.8	971	15.1	776	1.8	138,156	29.6	1443	15.9	58	5.7	899	25.9	**147,692**	27.2
Balearic Islands	1039	2.5	159	2.5	336	0.8	945	0.2	124	1.4	14	1.4	34	1.0	**2652**	0.5
Ceuta	3	0.0	1	0.0	3	0.0	1	0.0	0	0.0	0	0.0	0	0.0	**9**	0.0
Melilla	65	0.2	4	0.1	3	0.0	8	0.0	2	0.0	2	0.2	0	0.0	**84**	0.0
Canarias	371	0.9	28	0.4	40	0.1	318	0.1	31	0.0	0	0.0	11	0.3	**800**	0.1
Total Spain (ha)	42,253	100	6438	100	14,269	100	466,757	100	9102	100	1020	100	3467	100	543,306	100
Total Spain (%)	**7.78**		**1.19**		**2.63**		**85.91**		**1.68**		**0.19**		**0.64**		**100**	

Source: Own elaboration from NFMS.

Table 4. Potential economic losses (millions of euros) by categories and river basin district.

	Residential properties		Facilities		Productive activities		Agriculture, rural and forestry		Communications infrastructure		Energy and telecommunications		Hydrology, sanitation and waste		Total (RBD)	%
River basin district	Mill. €	%	Mill. €	%	Mill. €	%	Mill. €	%	Mill. €	%	Mill. €	%	Mill. €	%	Mill. €	
Internal Basins of Catalonia	6822.6	13.8	517.7	8.6	9562.3	34.8	730.0	7.1	1467.2	10.0	59.0	1.7	234.0	2.2	19,392.9	16.9
Minho	1723.7	3.5	332.9	5.5	121.8	0.4	443.7	4.3	400.4	2.7	18.4	0.5	137.4	1.3	3178.2	2.8
Galician Coast	1029.9	2.1	149.5	2.5	427.9	1.6	17.4	0.2	143.3	1.0	4.8	0.1	72.9	0.7	1845.7	1.6
Ceuta	7.3	0.0	2.0	0.0	9.7	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	18.9	0.0
Eastern Cantabric	1453.3	2.9	142.9	2.4	711.5	2.6	4.7	0.0	133.8	0.9	16.1	0.5	13.8	0.1	2476.1	2.2
Western Cantabric	2651.0	5.4	452.3	7.5	3319.2	12.1	54.7	0.5	1013.3	6.9	238.5	6.9	143.0	1.3	78,712.0	6.9
Duero	4538.5	9.2	604.3	10.1	961.5	3.5	552.1	5.3	676.3	4.6	11.7	0.3	237.3	2.2	7581.9	6.6
Tagus	1466.2	3.0	587.6	9.8	953.0	3.5	627.5	6.1	280.2	1.9	27.7	0.8	66.3	0.6	4008.5	3.5
Guadiana	40.2	0.1	1.7	0.0	8.4	0.0	4.1	0.0	12.8	0.1	1.8	0.1	6.1	0.1	75.1	0.1
Guadalquivir	5979.3	12.1	566.1	9.4	5343.8	19.4	1467.5	14.2	2549.1	17.4	2537.9	73.7	422.8	3.9	18,866.4	16.4
Guadalete and Barbate	442.4	0.9	51.2	0.9	175.2	0.6	192.5	1.9	1017.7	7.0	35.0	1.0	1626.2	15.0	3540.2	3.1
Tinto, Odiel and Piedras	301.8	0.6	111.8	1.9	131.0	0.5	13.6	0.1	439.3	3.0	0.0	0.0	2899.2	26.7	3896.8	3.4
Segura	4515.9	9.1	122.5	2.0	1403.8	5.1	70.1	0.7	1417.7	9.7	84.2	2.4	557.0	5.1	8171.2	7.1
Jucar	7059.6	14.3	504.1	8.4	1230.9	4.5	1657.8	16.0	1416.5	9.7	64.9	1.9	825.3	7.6	12,758.2	11.1
Ebro	8948.4	18.1	1656.0	27.6	2494.8	9.1	4489.4	43.4	3391.3	23.2	269.6	7.8	3515.0	32.4	24,764.5	21.6
Balearic Islands	2174.0	4.4	188.8	3.1	630.4	2.3	15.3	0.1	249.3	1.7	63.7	1.9	105.8	1.0	3427.4	3.0
Melilla	224.7	0.5	6.7	0.1	10.1	0.0	59.0	0.0	5.9	0.0	9.5	0.3	0.0	0.0	256.9	0.2
Total Spain	49,378.7	40.4	5,998.2	4.9	27,494.5	22.5	10,340.6	8.0	14,614.0	12.0	3442.7	2.8	10,862.182	8.9	122,131.0	100.0

Source: Own elaboration from NFMS.

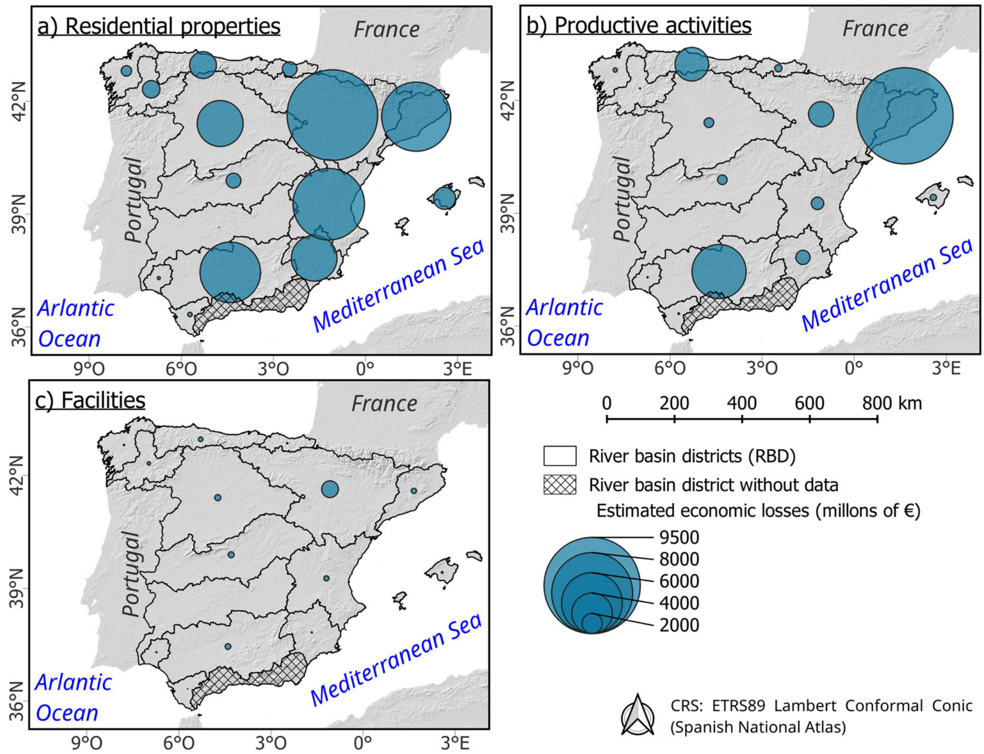

Figure 6. Map illustrating the estimated value of economic losses caused by a hypothetical flood corresponding to a 500-year return period in 'residential properties', 'productive activities' and 'facilities'. *Source*: Own elaboration from NFMS.

economic activity. Specifically, for 'residential property' (Figure 5(a)), the estimated value of losses in FPA is around 49,379 million euros.

Once again, the Ebro RBD stands out with a minimum value of potential losses of 8948 million euros, closely followed by the Júcar RBD and the Internal Basins of Catalonia RBD, both with values close to a minimum of 7000 million euros. Figure 5(b, c) detail the losses in 'productive activities' and 'facilities'. In this context, the Internal Basins of Catalonia RBD takes prominence, registering more than 9500 million euros in productive activities, constituting almost half of the potential losses for the whole RBD. In contrast, RBDs with notably high values of exposure in terms of population or FPA surface area, such as the Segura, Júcar or Ebro RBDs, present comparatively lower values in this context.

The Ebro RBD is currently experiencing the most significant damage to infrastructures, while the Guadalquivir RBD is significantly impacting energy and telecommunications infrastructures. Similarly, the Tinto, Odiel, and Piedras RBD are performing exceedingly in terms of hydrological, sanitary and waste infrastructure losses, with an estimated value of around 2900 million euros (Figure 7).

4.3. Points of special significance exposure

Eleven different categories have been analyzed. The results show an observed concentration of points of special significance in FPA along the Mediterranean coast.

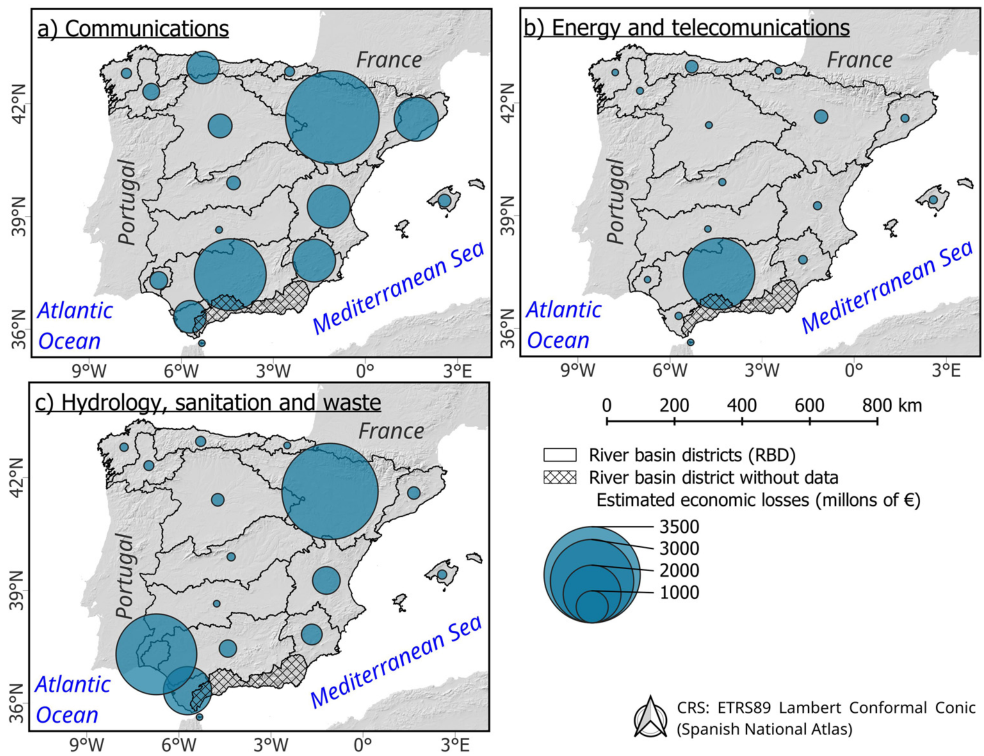

Figure 7. Map illustrating the estimated value of economic losses caused by a hypothetical flood corresponding to a 500-year return period in 'communications infrastructure', 'energy and telecommunications' and 'hydrology, sanitation and waste'. *Source*: Own elaboration from NFMS.

However, there are important territorial differences depending on the analyzed category, which calls for a more detailed analysis of the results.

With regard to industrial activities regulated by integrated pollution prevention and control (hereinafter 'industrial emissions') (Figure 7(a)), there are at least 462 such industries in FPA of the study area. The three contiguous RBDs with the highest number of exposed elements are, in decreasing order: the Internal Basins of Catalonia RBD, the Ebro RBD and the Eastern Cantabrian RBD. The first two RBDs have high values, each hosting approximately 100 facilities.

Within the Internal Basins of Catalonia RBD, two points stand out. Firstly, there is an area of higher density, with at least 19 such sites within 362 hectares in an industrial area located between the towns of Vila-Seca, La Canonja and Tarragona. This industrial area is only 2 km from the port of Tarragona. Secondly, in the vicinity of the Besós river (Barcelona province) and its tributaries closest to the main stream, there are at least 34 sites in FPA within a section of riverbed of less than 38 km.

In the Ebro RBD, the distribution of facilities with 'industrial emissions' in FPA is less spatially concentrated. Most are located near the main riverbed, but there is a certain degree of concentration in specific sections, extending from Miranda del Ebro (Castilla y León) to Pina de Ebro (Aragón). This distribution covers approximately 240 km in a straight line (although, if measured along the riverbed, the distance would be considerably longer).

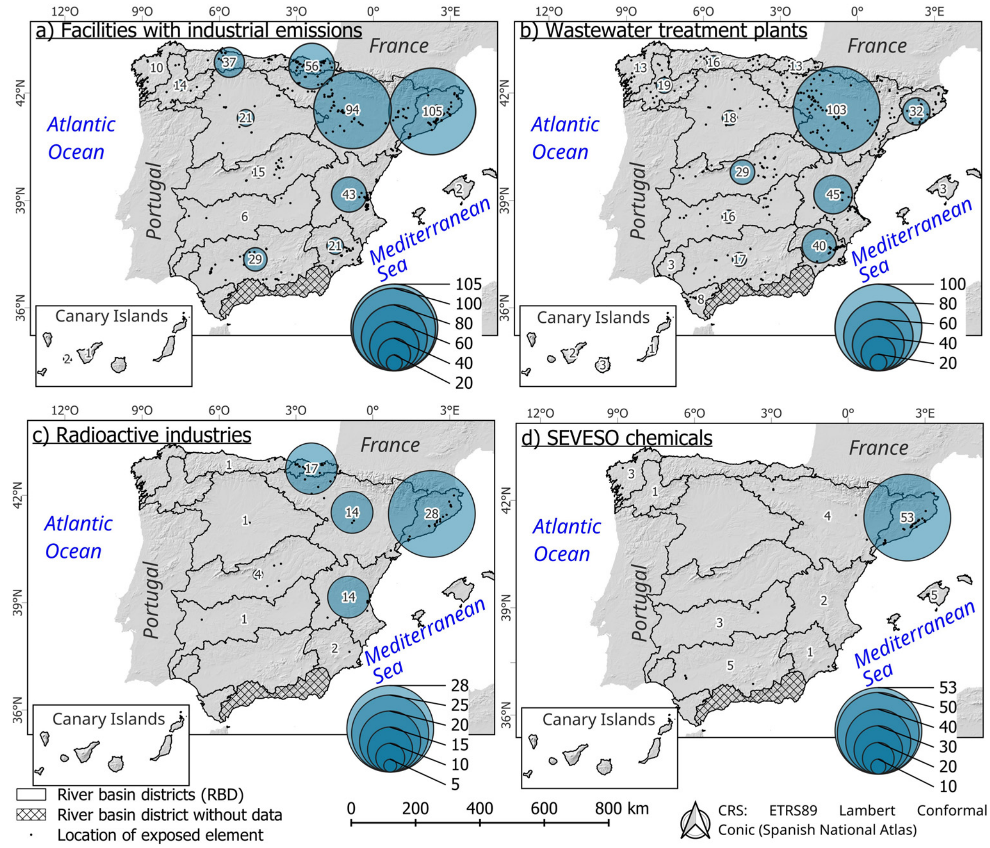

Figure 8. Number of industries included in annex 1 of the integrated pollution prevention and control law ('facilities with industrial emissions'), wastewater treatment plants, 'radioactive industries' and 'SEVESO chemicals' in flood prone areas by river basin district. *Source*: Own elaboration from NFMS.

As shown in Figure 7(b)

, according to the NFMS, there are a minimum of 387 wastewater treatment plants in FPA, constituting at least 16.4% of the urban wastewater treatment plants (Directive 91/271/EEC). There are two areas with the highest concentration of wastewater treatment plants in FPA. One is located in the middle and lower plains of the Segura River, extending from Ceutí to almost the mouth (Rojales) in a river stretch of approximately 75 km, hosting a minimum of 26 wastewater treatment plants in FPA. Another area is located along the southern coast of the province of Valencia and the final section of the Júcar river, with at least 23 wastewater treatment plants in FPA. In addition, the Ebro RBD stands out for having a significant number of wastewater treatment plants in FPA.

Figure 7(c) illustrates the spatial distribution of 'radioactive industries' and 'SEVESO chemicals' (Figure 7(d)). 'Radioactive industries' are mainly concentrated in the east and northeast of the Iberian peninsula, especially in Catalonia. There are at least 82 such industries in FPA. The provinces of Barcelona and Bizkaia lead in number, with at least 12 and 11 industries each, respectively. When considering municipalities, La Canonja, a small municipality adjacent to Tarragona, emerges as the location with the highest concentration of this type of industry in FPA. At least 59 municipalities out of the 7958 analysed have at least one radioactive industry in FPA.

In the case of 'SEVESO chemicals' (Figure 7(d)), the Internal Basins of Catalonia RBD asserts absolute dominance, concentrating these industries in the same area highlighted above—the industrial zone of La Canonja. Here, at least 16 industries are located in barely 400 hectares. In addition, in the vicinity of the Besós river (Barcelona), there are at least 10 industries in 7.5 km of riverbed, and near the Tordera river (Barcelona), a minimum of 8 industries are identified in 4.1 km of riverbed. It should be noted that in many cases, the same industrial facility may be classified by the NFMS as having 'industrial emissions,' as a 'radioactive industry' and also as a 'SEVESO chemical' facility. However, due to distinct industrial activities, inputs or machinery, it is advisable to disaggregate these classifications as much as possible.

Figure 8(a,b) shows the number of fire stations and facilities of the State Security Forces and Corps in FPA. The identification of these facilities is crucial for Civil Protection efforts. The Spanish Mediterranean coast is particularly notable for the high number of exposed elements.

In terms of educational facilities, according to the NFMS, there are a minimum of 1423 educational centres in the study area within FPA. It's important to note that dance, art or music schools, adult education centres, hospital classrooms, language schools, sports training centres, vocational training centres, distance education centres and military training centres are not considered in this calculation (Ministerio para la Transición Ecológica (MITECO) 2022, p. 73). Palma de Mallorca is the municipality in the study area with the highest number of educational centres in FPA, with at least 62, followed by Valladolid with at least 56. In the whole study area, a minimum of 423 municipalities have at least one educational centre in FPA, out of the 7958 municipalities considered.

Figure 8(c,d) illustrates the number of nursery schools and Special Education centres in FPA, categorised by RBD. In the study area, according to the NFMS, there are a minimum of 236 nursery school centres (for ages 0 to 3 years) in FPA. The Júcar RBD stands out with at least 87 centres of this type in FPA, closely followed by the Internal Basins of Catalonia RBD. A significant cluster is made up of 18 centres located in FPA of the Rambla del Poyo, in the towns of Massanassa, Catarroja and Alfafar, with an area of less than 380 hectares, to the south of the city of Valencia. However, this cluster is part of a larger conglomerate of 43 centres belonging to municipalities adjoining Valencia and forming part of its metropolitan area. Another cluster is located in the city of Girona. In this area, there are at least 11 such centres in FPA. Girona and Catarroja are the municipalities in Spain with the highest number of early childhood education centres in FPA (9 centres), followed by the municipality of Vilanova i la Geltrú (8 centres). In the whole study area, a minimum of 142 out of 7958 municipalities have one or more centres of this type in FPA.

As for Special Education centres (Figure 8(d)), the Balearic Islands RBD stands out, with at least 10 centres within FPA. Palma de Mallorca alone is home to seven of these centres.

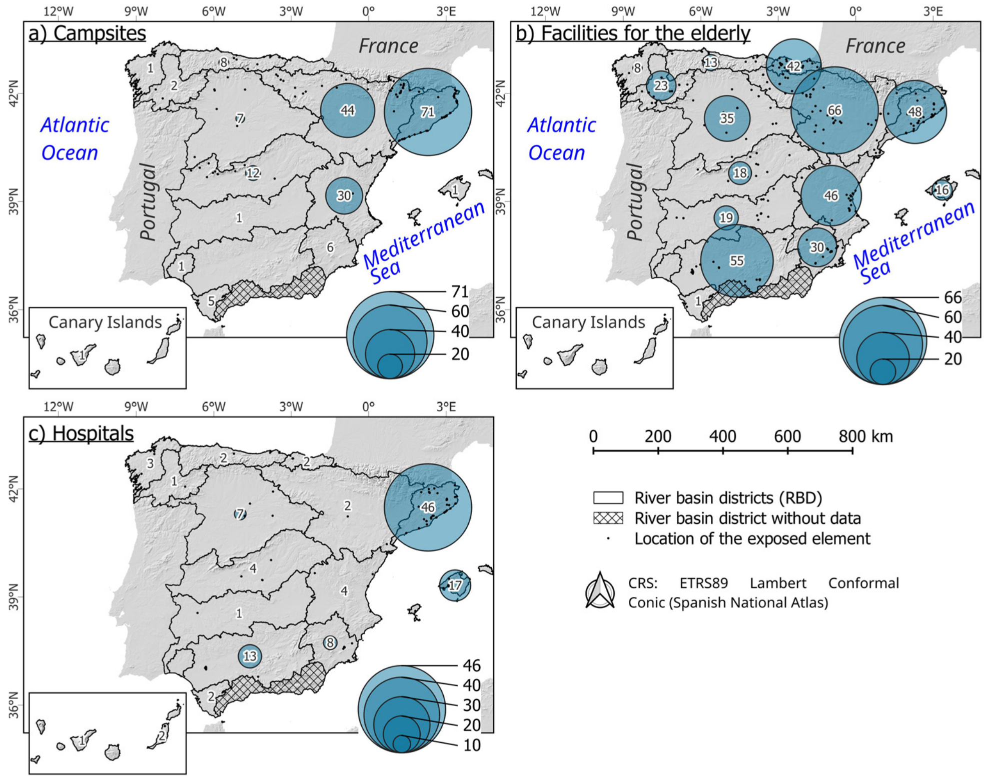

Figure 9. Number of campsites, facilities for the elderly and hospitals in flood prone areas by river basin district. *Source*: Own elaboration from NFMS.

In the context of campsites (Figure 9(a)), there are at least 191 establishments in FPA. A significant concentration is observed along the central and northern Mediterranean coast, ranging from the north coast of Alicante to the north coast of Girona. Approximately 53% of the total, or at least 101 campsites, are located in this coastal region. Another notable cluster is found in the Catalan Pyrenees, with at least 22 campsites, especially in the province of Lleida. Consequently, the Ebro RBD and the Internal Basins of Catalonia RBD have the highest number of campsites in FPA. It should be noted that a total of at least 119 municipalities, which constitute 1.5% of the municipalities under study, have at least one campsite within FPA in their respective territories.

Centres for the elderly have a remarkably wide distribution across the different RBD analysed (Figure 9(b)). Practically all RBDs, with the exception of the Canary Islands, have some of these facilities within FPAs. The Ebro and the Guadalquivir RBDs stand out. However, if we focus on individual municipalities, Seville appears as the main centre for such facilities, with at least 38, closely followed by Valladolid, with at least 17 establishments. It is worth nothing that among the ten municipalities with the highest concentration of facilities for the elderly in FPA (5 or more), six are provincial capitals. The prevalence of these facilities extends to at least 219 municipalities, which constitute 2.8% of the total number of municipalities analysed, each of them having at least one of these facilities within FPA.

Finally, the hospitals located in FPA are analysed (Figure 9(c)). In the case of this facility, the RBD of the Internal Basins of Catalonia clearly stands out with 46 hospitals in FPA, followed by that of the Balearic Islands and that of the Guadalquivir RBD. In total there are 118 hospitals in FPA, with the Mediterranean coast being the most important agglomeration, as 64.4% are in provinces bordering the Mediterranean Sea. However, if we look at the local scale, the municipality of Seville stands out with 12 hospitals in FPA, the highest value of all the municipalities analysed. It is followed by the municipality of Girona (9) and Palma de Mallorca (8).

5. Discussion

Despite the conceptual distinctions observed between the EU Floods Directive and the risk characterisation framework articulated by the IPCC. (2022), the development of official flood risk mapping and its subsequent dissemination through the NFMS represents a significant step forward in improving our understanding of flood risk. This cartographic representation not only serves as a crucial legal instrument that validates flood risk, but also establishes connections with other sectoral legislations integral to risk management, including domains such as land use planning, urban development and civil protection (Olcina et al. 2021; Vargas and Cánovas-García 2022).

Nevertheless, a number of potential areas for improvement have been identified. The integration of these results, together with conclusions drawn from other academic contributions (Perles et al. 2017; López-Martínez 2020; Gallegos et al. 2024), provides a roadmap for refining existing flood risk mapping. Looking at the analysis and results presented in this study, particularly regarding exposure mapping, a notable observation emerges: the SNCZI does not produce river flood risk maps for all documented watercourses across the different Spanish RBDs. Instead, it restricts this mapping activity to sections of watercourses known as areas with potential significant flood risks. Consequently, it can be inferred that the area designated as FPA may be underestimated, leaving certain FPA areas unmapped. However, it is argued that these omissions may not pose a substantial risk, as there is minimal exposure risk, especially when it does not impact significant population centres. The GIS population risk layer of the NFMS uses different reference years for data and in many cases outdated, so it is necessary to standardize and update these years to obtain a current value for all RBDs.

Gaining more nuanced insights within each river basin district across the various analysed categories is imperative to implement mitigation and adaptation measures tailored to specific contextual differences. As highlighted by Pérez-Morales et al. (2016), information derived from cadastral data emerges as a fundamental element to characterize exposure to flood. Despite latest IPCC report (2022) determines with a high level of confidence that climate-associated risks to natural and human systems (including flood risk) depend more on changes in their vulnerability and exposure than on differences in climate hazards between emissions scenarios. However, vulnerability assessment is an aspect not explicitly addressed by the UE Floods Directive. The wide territorial scope covered by the delineation of RBDs, together with its limitations on measures unrelated to hydrological planning, makes the detailed analysis of the vulnerability component a challenge where other scales and public policies, such as territorial planning and especially urban planning, can further characterize vulnerability with greater precision.

On the other hand, the entire flood risk exposure analysis presented here is based on the 500-year return period flood delineation carried out by the public authorities. Therefore, the quality of the analysis will depend on how well the methodology proposed in Ministerio de Medio Ambiente and Medio Rural y Marino (2011) has been applied. In this respect, it is important not to be overconfident, as it has been verified, for example, that the dejection cone of the Arás ravine, a section studied by the NFMS, does not appear as a FPA. This is hard to believe since it was precisely here in 1996 that one of the biggest flood disasters of the twentieth century in Spain occurred: the tragedy of the Nieves campsite in Biescas (Pyrenees) in which 87 people died (Cancer Pomar 1996). The site where the campsite was located and which was devastated by a flood does not appear in the NFMS as a FPA. Moreover, the historical-hydrological information provided by the NFMS tells us that there have been no historical floods in this stretch.

Conclusions

The results of the study provide for the first time an estimate of the potential impacts of flood risk throughout Spain in relation to population exposure, economic activities and points of special significance. Moreover, it allows us to highlight hotspots where the highest levels of exposure are concentrated for each of these exposed elements. The exposure of the population encompasses at least 3,263,000 people, with almost 52% concentrated in six hotspots: Huerta de Murcia and Vega Baja del Segura, Valle del Guadalquivir, Province of Valencia and northern province of Alicante, Costa Catalana, Middle and low plains of the eastern Cantabrian, and the municipality of Valladolid. In terms of economic activities, the potential economic losses amount to at least 122.130.957.000 € in the study area. The largest economic losses are concentrated in residential properties (40% of the total) and productive activities (22.5%). The analysis by RBD highlights the Ebro RBD (21.6% of total losses), Guadalquivir (16.4%) and Internal Basins of Catalonia (16.1%) as the most exposed territories. Special interest points exposure shows territorial differences depending on the category analysed, but a territorial pattern is observed in which Ebro RBD and Internal Basins of Catalonia RBD prevail over the others. A significantly higher concentration of exposure is observed along the Mediterranean coast for nearly all the elements analysed.

This exposure analysis can also serve as a reference for a more thorough vulnerability assessment of the exposed elements. In this regard, territorial planning, especially urban planning, can provide the appropriate scale at which to conduct vulnerability analyses of the exposed elements. Therefore, coordination between hydrological planning and territorial planning is crucial for a proper and comprehensive characterization of risk, which is essential for its future mitigation and management.

The analysis carried out is based on official public data provided by RBD. However, some limitations to this data have been found and need to be improved to a better flood risk characterization. Besides, a more detailed analysis on specific areas and elements should be completed in further research.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Data availability statement

Part of the data that support the findings of this study are available on request in Zenodo on https://zenodo.org/records/13648694. Original GIS data of Tables 3 and 4 and Figures 5 to 9 were downloaded from https://www.miteco.gob.es/es/cartografia-y-sig/ide/descargas/agua/riesgo-inundacion-fluvial-t500.html in July 2022.

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